Numerical simulation of post-construction deformation of a concrete face rockfill dam

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Abstract

In this paper a novel hypoplastic constitutive model is used to investigate post-construction deformations of a concrete face rockfill dam caused by water impounding and creep. Creep deformations are related to the time dependent process of degradation of the solid hardness of the weathered rockfill material, in which the solid hardness and its rate is introduced into the constitutive model in the sense of a continuum description. The hypoplastic model captures the influence of pressure, density and state of the solid hardness on the incremental stiffness, the peak friction angle and the volume strain behaviour as well as the influence of a degradation of the solid hardness on creep and stress relaxation in a unified manner. The material parameters considered in the present study are relevant for weathered broken granite. The results obtained from the finite element simulations are compared with monitoring data of four different concrete face rockfill dams. It is demonstrated that the solid hardness and its degradation velocity are key parameters for modelling long-term deformations. For the constitutive parameters assumed long-term deformations after 15 years are more pronounced than the instantaneous deformation caused by the first water impounding.

Keywords: Concrete Face Rockfill Dam, Solid Hardness, Creep, Hypoplasticity.

1. INTRODUCTION

Post-construction deformations of concrete face rockfill dams (CFRDs) can be caused by various events such as among others repeated changes of the water table in the reservoir, seepage-driving internal erosion processes, earthquake, and the progressive mechanical and hydro-chemical weathering of the rockfill material. The latter leads to a degradation of the solid hardness and as a consequence to grain fragmentation and rheological deformations [1-3]. The process of weathering can be initiated in a complex manner by different environmental conditions and has a strong influence on long-term deformations. For moisture sensitive rockfill materials a change of the moisture content can lead to an acceleration of degradation of the solid hardness. Rheological deformations are related mainly to the state of weathering of the rockfill material, the degree of compaction, the geological conditions of the dam foundation, the seepage behaviour, local defects of the sealing and other construction details of the individual CFRD.

The prediction of long-term deformations of CFRDs is a challenging task. In this context the selection of an appropriate constitutive model and the accurate calibration of the constants involved are of great importance for the quality of the calculated results. Depending on the type of the rockfill material various constitutive concepts for the numerical modelling of the rheological behaviour are proposed in the literature, e.g. [4-8].

The focus of this paper is on numerical simulation of post-construction deformations of a CFRD caused by water impounding and creep of the rockfill material. To this end, an artificial CFRD with a height of 100 m is considered. The slope ratio of upstream and downstream slope of the dam is for both 1:1.5. The upstream water level is 94 m after water impounding. As illustrated in Figure 1, the dam body is decomposed of the main rockfill, the transition layer, the concrete slab and the concrete toe slab. The thickness of the concrete slab is 0.3 m at the top and 1.1 m at the bottom.

For numerical simulations of long term deformations of the rockfill material the version of the hypoplastic constitutive model proposed by Bauer in 2009 is used [8]. In this model the solid hardness is introduced to reflect the state of weathering of the material on its stiffness. This state parameter does not mean the hardness of a single grain, but it is related to the stiffness of the grain skeleton in the sense of a continuum description. In the proposed model long-term deformations are related to the degradation of the solid hardness. Thus, in addition to the hypoplastic constitutive equation an additional evolution equation for modelling the degradation of the solid hardness is needed.

The paper is organised as follows. In Section 2 the main constitutive relations for modelling the mechanical properties of rockfill materials are summarized. The model captures the influence of pressure and density on the incremental stiffness, the peak friction angle and the volume strain behaviour as well as the influence of a degradation of the solid hardness on creep and stress relaxation in a unified manner. The numerical model and the constitutive parameters used are outlined in Section 3. In particular, finite element calculations are carried out to investigate the deformations after water impounding and the evolution of creep within a period of 15 years after finishing the construction of the dam. The results of the numerical simulations are discussed and compared with monitoring data in Section 4.

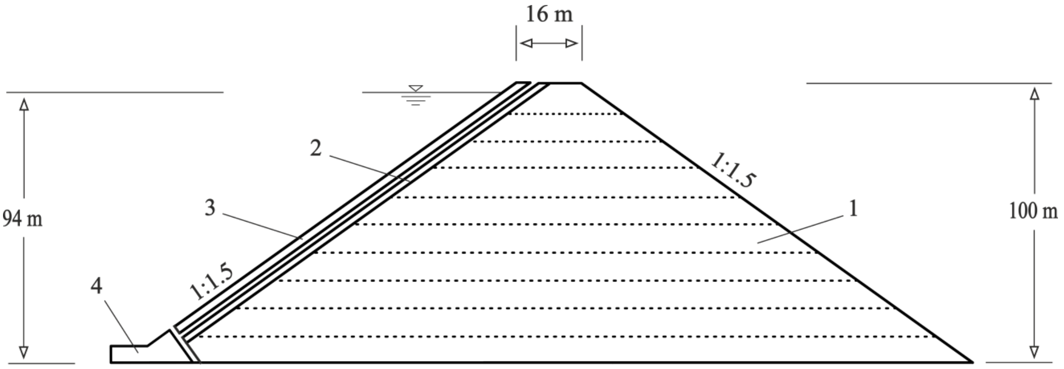


Figure 1. Sketch of the cross section of the CFRD: <1> main rockfill; <2> transition layer <3> concrete slab layer; <4> concrete toe slab.

2. HYPOPLASTIC MODEL FOR CREEP SENSITIVE ROCKFILL MATERIALS

In hypoplasticity, the constitutive equation is of the rate type, where the objective stress rate, $\overset{\circ}{\boldsymbol{\sigma}}$, is expressed by an incrementally non-linear isotropic tensor-valued function that depends in the simplest case on the current effective Cauchy stress tensor, $\boldsymbol{\sigma}$, and the strain rate tensor, $\dot{\boldsymbol{\varepsilon}}$, i.e. [9]:

$$\overset{\circ}{\boldsymbol{\sigma}} = (\boldsymbol{\sigma}, \dot{\boldsymbol{\varepsilon}}) \,. \tag{1}$$

To model the influence of the degree of compaction of the material on the peak friction angle and dilatancy behaviour, the hypoplastic concept was extended with the current void ratio e, i.e.:

$$\overset{\circ}{\boldsymbol{\sigma}} = (e, \boldsymbol{\sigma}, \dot{\boldsymbol{\varepsilon}}) \,. \tag{2}$$

In the particular models by Wu and Bauer [10], Gudehus [11] and Bauer [12-14] the current void ratio was related to the pressure dependent critical void ratio, e_c , and for simulating of the influence of grain damage on the incremental stiffness, the so-called solid hardness, h_{s0} , was introduced in the sense of a continuum description [13]. These models are based on the concept of Critical State Soil Mechanics [15] and applicable for modelling rate independent material properties of granular materials like sand.

In order to take into account time-dependent effects like creep and stress relaxation of rockfill materials, the constant solid hardness, h_{s0} , was replaced by a solid hardness, h_{st} , depending on the state of weathering. Taking into account a time dependent process of degradation of the solid hardness, the rate of the solid hardness, $\dot{h}_{s0}$, is also included as an additional quantity in the model, i.e. [8]:

$$\overset{\circ}{\boldsymbol{\sigma}} = (e, h_{st}, \dot{h}_{st}, \boldsymbol{\sigma}, \dot{\boldsymbol{\varepsilon}}) \ . \tag{3}$$

The specific hypoplastic version by Bauer [8] for modelling creep sensitive rockfill materials can be represented in index notation as follows:

$$\dot{\sigma}_{ij} = f_s \left[\hat{a}^2 \dot{\varepsilon}_{ij} + (\hat{\sigma}_{kl}\, \dot{\varepsilon}_{kl}) \hat{\sigma}_{ij} + f_d\, \hat{a}\, (\hat{\sigma}_{ij} + \hat{\sigma}^*_{ij}) \sqrt{\dot{\varepsilon}_{kl}\, \dot{\varepsilon}_{kl}} \right] + \left(\frac{\dot{h}_{st}}{h_{st}} \right) \left[\frac{1}{3} \sigma_{kk} \delta_{ij} + \kappa\, \sigma^*_{ij} \right] , \tag{4}$$

$$\dot{e} = (1+e)\dot{\varepsilon}_v \ , \tag{5}$$

$$\dot{h}_{st} = -\frac{\left(h_{st} - h_{sw} \right)}{c} \,. \tag{6}$$

In equation (4) $\hat{\sigma}_{ij} = \sigma_{ij} / \sigma_{kk}$ and $\hat{\sigma}_{ij}^{*} = \hat{\sigma}_{ij} - \delta_{ij}/3$ are the normalized components of the stress tensor and of its deviatoric part, respectively. δ_{ij} is the Kronecker delta and function $\hat{a}$ is related to the critical friction angle, φ_c, and to the stress limit condition by Masuoka and Nakai [16] as illustrated in Figure 2(b). More details about function $\hat{a}$ are outlined in [13]. The influence of the current void ratio, e, and the mean pressure, $p = -\sigma_{ii}/3$, on the incremental stiffness is taken into account with the stiffness factor, f_s, and the density factor, f_d. In these factors the current void ratio is related to the maximum void ratio, e_i, the minimum void ratio, e_d, and the critical void ratio, e_c, according to:

$$f_d = \left(\frac{e - e_d}{e_c - e_d} \right)^{\alpha}, \tag{7}$$

and

$$f_s = \left(\frac{e_i}{e} \right)^{\beta} \frac{1}{\hat{\sigma}_{kl}\,\hat{\sigma}_{kl}} \frac{(1+e_i)\,h_{st}}{n\,h_i\,e_i} \left(\frac{3p}{h_{st}} \right)^{(1-n)}. \tag{8}$$

Herein α and β are material constants and h_i can be derived from a consistency condition [8]. According to the postulate by Gudehus [11] the pressure dependency of e_i, e_c and e_d are related to the compression law by Bauer [12], i.e.:

$$\frac{e_i}{e_{i0}} = \frac{e_c}{e_{c0}} = \frac{e_d}{e_{d0}} = \exp\left[-\left(\frac{3p}{h_{st}} \right)^{n} \right]. \tag{9}$$

As illustrated in Figure 2(a) in the phase diagram of void ratios the range of possible void ratios is bounded by the pressure dependent maximum void ratio e_i and minimum void ratio e_d. The upper bound, e_i, is related to an isotropic compression starting from the loosest possible skeleton with grain contacts [12]. The curve e_c represents the pressured dependent critical void ratio. In equation (9) the quantities e_{i0}, e_{c0} and e_{d0} are the corresponding void ratios for $p \approx 0$. The dimensionless exponent n is a material parameter.

Investigations by Bauer et al. [17] show that the deviatoric stress has a significant influence on the amount of rheological deformation. For a refined modelling, the deviatoric stress in the second term on the right hand side of the constitutive Equation (4) is therefore scaled by factor κ. It can be noted that with this term creep and stress relaxation are modelled in a unified manner. Equation (5) describes the relationship between the rate of the void ratio, $\dot{e}$, and the volume strain rate, $\dot{\varepsilon}_v$, which is obtained from the balance equation of mass. Equation (6) represents the evolution equation for the solid hardness. With respect to the initial state, i.e. at time $t = 0, h_{st} = h_{s0}$ and the final state, i.e. $t = \infty$, $h_{st} = h_{sw}$, the integration of equation (6) yields for the solid hardness as a function of the degradation time *t*:

$$h_{st} = h_{sw} + (h_{s0} - h_{sw}) \exp\left\{ -\frac{t}{c} \right\}, \tag{10}$$

where parameter c controls the velocity of degradation. Experiments indicate that the delayed deformation of stressed rockfills, i.e. the progressive particle breakage and contact plastification, is mainly influenced in a relatively complex manner by an interaction between the state of weathering, the humidity, the local stress state and the pre-compaction of the material, e.g. [4, 5, 18]. In the present paper parameter c is assumed to be a constant for the sake of simplicity. The applicability of this model to rockfill materials was demonstrated by comparison of the numerical simulations with data from laboratory tests for instance in [7, 8, 17].

(a) (b)

Figure 2. (a) Trace of the critical stress surface in the π plan; (b) Illustration of the pressure dependent maximum void ratio e_i, minimum void ratio e_d and critical void ratio e_c.

3. NUMERICAL MODEL AND CONSTITUTIVE PARAMETERS

The commercial program Abaqus [19] is used for finite element simulation. The idealised CFRD shown in Figure 1 is discretised by 4841 four-node bilinear quadrilateral elements for plane strain condition. The foundation of the dam is assumed to be rigid and immovable, thus the element nodes along the bottom surface of the dam are fixed. The interface behaviour between concrete slab and the transition layer, as well as between the concrete toe slab (plinth), the concrete slab, transition layer and rockfill material is simulated using the concept of contact pairs provided by Abaqus. For simulating of post-construction deformations, the following steps are considered:

Step 1: The initial stress distribution in the rockfill material as a result of gravity load is obtained by simulation of the influence of the construction of the rockfill dam in 10 layers with same heights. In this step only the main rockfill material <1> and plinth <4> are activated;

Step 2: The concrete slab <3> and transition layer <2> are activated with respect to the interface between these two materials and the plinth. In order to investigate the post-construction behaviour the deformation induced by the construction of the CFRD is set to zero;

Step 3: Calculation of the deformation caused by water impounding;

Step 4: Simulation of long-term deformation as a result of stiffness degradation of the main rockfill material <1> and of the transition layer <2>.

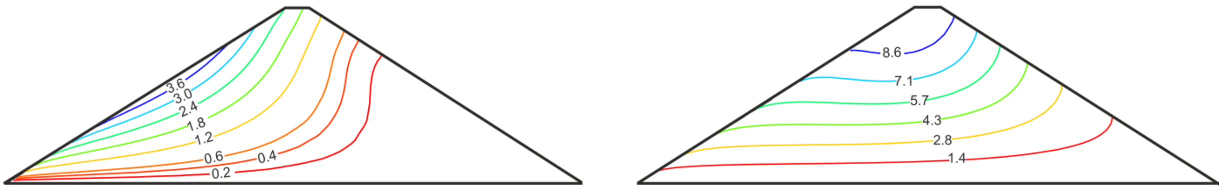
The material behaviour of the concrete slab and the plinth are described as linear elastic material with an elastic modulus of E=20 GPa, a Poission ratio of υ =0.17 and a density as ρ =2400 kg/m^3. The hypoplastic constitutive model for the rockfill material and the transition layer presented in Section 2 is implemented into a user defined material subroutine. The constitutive model includes 11 parameters which are tabulated into Table 1. Parameters h_{s0}, n, φ, e_{d0}, e_{c0}, e_{i0}, α and β are calibrated based on experimental results obtained for weathered granite [6]. For the parameters h_{sw}, c and κ three different sets are considered to simulate the influence of this parameter on the long-term behaviour. For the compacted rockfill material an initial void ratio of e_0 =0.33, and a density of ρ =2200 kg/m^3 is considered in all calculations.

Table 1. Constitutive parameters for three different rockfill materials

Parameter	h_{s0} [MPa]	n	h_{sw} [MPa]	c [years]	κ	φ_c [°]	e_{d0}	e_{c0}	e_{i0}	α	β
Set A	75	0.6	68.4	0.91	1.0	42.0	0.2	0.39	0.85	0.125	1.05
Set B	75	0.6	68.8	2.0	1.0	42.0	0.2	0.39	0.85	0.125	1.05
Set C	75	0.6	70.7	3.3	1.0	42.0	0.2	0.39	0.85	0.125	1.05

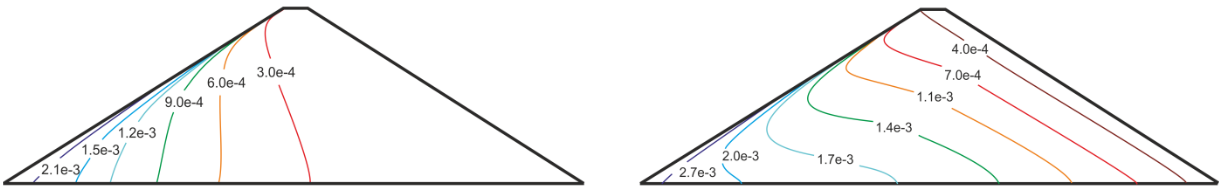
4. INTERPRETATION OF THE NUMERICAL RESULTS

The numerical results obtained with the constitutive parameter Set A are shown in Figures 3-5. In particular, the contours of vertical displacements after water impounding and the corresponding change of the void ratio is shown in Figure 3(a) and Figure 4(a), respectively. While additional compaction is mainly concentrated in the upstream part of the dam, the deformation in the downstream part is almost zero. In particular, the vertical displacement is extremal approximately at the half height of the concrete slab, and the maximum compaction occurs in the vicinity of the dam toe. As a results of degradation of the solid hardness creep settlements occur in the whole rockfill dam. The additional compaction can be explained by grain fragmentation and reorientation of the particles into a denser state. Figure 3(b) and Figure 4(b) show the resulting quantities caused by water impounding and the degradation of the solid hardness after 15 years. It is evident that with the assumed parameters for degradation of the solid hardness the corresponding long-term deformation is more pronounced than the deformation caused by water impounding.



(a) (b)

Figure 3. Contour of vertical displacement (unit: cm):
(a) After reservoir filling; (b) After 15 years.



(a) (b)

Figure 4. Contour of reduction of the void ratio:
(a) After reservoir filling; (b) After 15 years.

Figure 5 shows the normal deflection of the concrete slab after reservoir filling (curve 2), at the end of the first year (curve 3), after 7 years (curve 4) and after 15 years (curve 5). Although the water pressure increases with the depth, the deflection of the concrete slab is nearly the same at the top and bottom after water impounding. The maximum deflection occurs close to the centre which is similar to the distribution of the vertical displacements of the rockfill material shown in Figure 3(a). The long-term deformation, however, leads to a monotonic increase of the deflection of the concrete slab at the top.

The evolution of crest settlements within a 15-year period after water impounding is shown in Figure 6 for three different sets of the constitutive parameters h_{sw} and c. The numerical simulations are compared with monitoring data of four CFRDs. It is evident that with the present model the amount of creep deformation mainly depends on the difference between the final, asymptotical value of the solid hardness and the initial value, i.e. $h_{sw} - h_{s0}$, while the velocity of creep deformation is related to the rate of the solid hardness which is scaled by the parameter c. As experimental data of the material behaviour are not available, the parameters h_{sw} and c are.

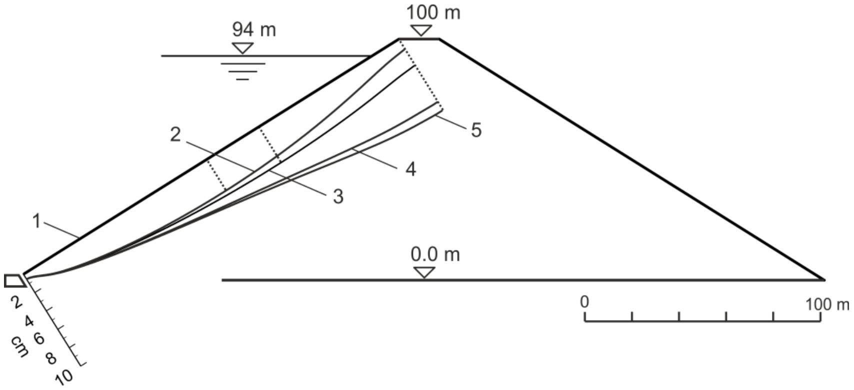


Figure 5. Normal deflection of the concrete slab: <1> at the end of construction; <2> after reservoir filling; <3> at the end of the first year; <4> after 7 years; <5> after 15 years.

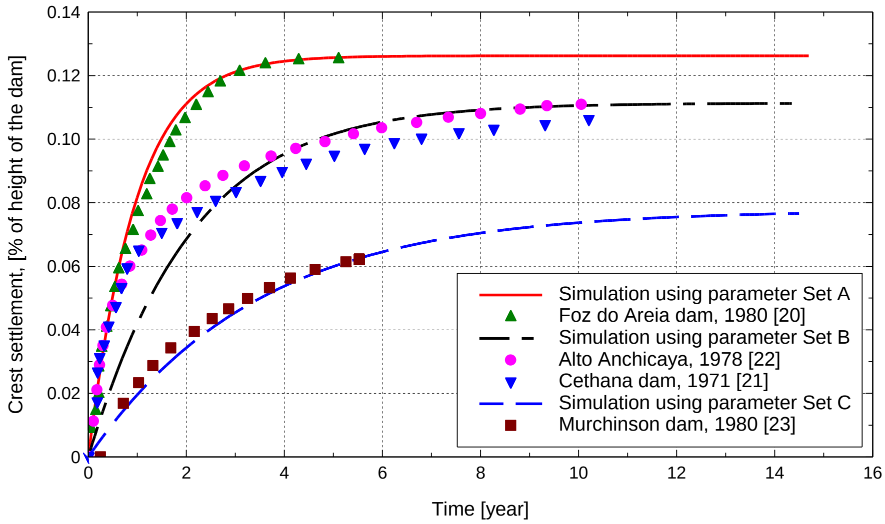


Figure 6. Evolution of crest settlements within a 15 year period after water impounding: numerical simulations (solid and dashed curves); monitoring data (markers).

calculated by back analysis to obtain the best agreement with the monitoring data. In this context it should be noted that neither the influence of the relevant 3-D geometries nor the individual properties of the different rockfill types and grain size distributions are taken into account, which of course would be necessary for an accurate calibration. The present study should therefore only demonstrate the capability of the current hypoplastic constitutive model to simulate long-term deformations. The comparison of the simulation with the monitoring data shows, that the parameter Set A and Set C fit well with the monitoring data of the Foz do Areia CFRD [20] and of the Murchison CFRD [23], respectively. On the other hand, the adaptation of the constitutive parameters to the crest settlements of the Alto Anchikaya CFRD [22] and the Cethana CFRD [21] is less satisfactory for the first three years. It can be noted that this imperfection was the motivation to develop a more sophisticated evolution equation for the degradation of the solid hardness shown in the paper by Bauer [24].

4. Conclusions

A hypoplastic constitutive model is used for investigating post-construction deformations of a concrete face rockfill dam (CFRD), which is suitable for describing the rheological properties of rockfill materials. The key parameters for modelling rheological properties such as creep and stress relaxation are the state of the solid hardness and its rate. These quantities are introduced into the constitutive model in the sense of a continuum description. A change of the solid hardness leads to creep deformations and/or stress relaxation. For numerical simulations of the rockfill material the constitutive parameters used are relevant for a weathered granite. The numerical results show that the instantaneous normal deflection at the top of the concrete slab is small compared to the long-term deformations after 15 years. The same can be concluded for the computed crest settlements. The comparison of the calculated crest settlements with monitoring data of four CFRDs shows that the amount of the crest settlement depends on the difference between the final, asymptotical value of the solid hardness, while the velocity of creep deformation is related to the rate of the solid hardness.

5. ACKNOWLEDGMENT

The authors wish to thank Dr. A. Niemunis from the Institute of Soil Mechanics and Rock Mechanics at Karlsruhe Institute of Technology, and Dr. Z. Fu from the Nanjing Hydraulic Research Institute in China for helpful remarks. The second author wishes to thank the Chinese Scholarship Council for the financial support.

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