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STABILITY ANALYSIS OF A CONCRETE GRAVITY DAM USING SHEAR STRENGTH REDUCTION METHOD

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Abstract: In the design of a concrete gravity dam, the key problem is to provide adequate stability against sliding due to the operational loads. When a dam is built on a rock mass foundation with complex geology as in the case considered in this paper, the stability analysis problem becomes considerably complicated. The analytical solution of this problem is very difficult or impossible, so it is necessary to use appropriate numerical methods. To solve such a problem in the design of a concrete gravity dam on the Ibar River nearby Kraljevo, an algorithm for elasto-plastic material model was adopted and implemented in the program PAK. In order to simulate the gradual loss of stability due to the rock mass strength reduction, the shear strength reduction method was implemented and used. The analysis shows that the calculated safety factor can reach the requirements of stability against the collapse in the deep foundation layers.
Keywords: concrete gravity dam, finite element method, Hoek-Brown, stability analysis, shear strength reduction

1. INTRODUCTION

Shear strength reduction (SSR) method, used in this analysis, is based on the definition of the slope safety factor as a ratio of the actual material shear strength to the ultimate material shear strength that is required to maintain the slope in equilibrium, first introduced by Zienkiewicz [1]. In other words, the safety factor of the slope represents the maximal value of the SSR factor, which fulfills a condition of stability. In numerical analysis, safety factor represents the value of shear strength reduction factor right before the numerical solution begins to diverge.

The application of the SSR method using constitutive models with a linear yield surface is most often considered due to the fact that reduced parameters of this models can be calculated by simple reducing of the initial material parameters [2, 3]. However, in most cases, the material models with a linear yield surface cannot represent the real material behaviour. In this case, the reduced strength of material cannot be obtained by direct reducing of material parameters, with respect to the original yield criterion [4-8].

This paper presents the use of the SSR method to identify critical failure mechanism of the concrete gravity dam foundation as well as to determine the safety factor in the layers of the dam foundation. For this purpose, the algorithm for stress integration using generalized Hoek-Brown material model was developed and implemented in the program PAK [9]. The SSR method was used to simulate progressive failure and possible unstable modes of the dam foundation system. Numerical integration of constitutive relations is carried out using the governing parameter method [10].

2. GOVERNING PARAMETER ALOGORITHM

Complex elastic-plastic constitutive models used in the geotechnical analysis demand reliable and robust numerical procedures for stress integration. In the case described in this paper, an algorithm for elastic-plastic constitutive model is developed and implemented using governing parameter method.

At the beginning of the time step (t) the known variables are: stress ${}^{t}\boldsymbol{\sigma}$, total strain ${}^{t}\mathbf{e}$, plastic strain ${}^{t}\mathbf{e}^{p}$, inner parameter ${}^{t}\beta$.

At the end of time step ($t+\Delta t$) the only known variable is total strain ${}^{t+\Delta t}\mathbf{e}$ and unknown variables are:

stress ${}^{t+\Delta t}\boldsymbol{\sigma}$, plastic strain ${}^{t+\Delta t}\mathbf{e}^p$, inner parameter ${}^{t+\Delta t}\boldsymbol{\beta}$ .Application of the governing parameter method is performed through steps:

1. Declare one unknown as the governing parameter (p),
2. Express unknowns at the end of the time step using governing parameter p,
3. Form the function $f(p)$ and solve the nonlinear equation by the parameter p,
4. Calculate all the unknown variables using the calculated governing parameter.

3. CONSTITUTIVE MODEL

For the strength definition of the rock mass nonlinear yield surfaces is usually used. In the case presented in this paper the generalized Hoek-Brown material model [5] was used. An algorithm for implicit stress integration, using mentioned model, was developed and implemented in program PAK. Relation between minimal and maximal principal stresses in the case of Hoek-Brown model has a following form:

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b\frac{\sigma_3}{\sigma_{ci}} + s\right)^a \tag{1}$$

Members of equation (1): σ_{ci}, m_b, s and a represent the material parameters, while σ_1 and σ_3 represent maximal and minimal principal stress. These material parameters can be obtained using geological strength index (*GSI*), rock disturbance factor (*D*) and parameter m_i according to [5].

The yield surface of the generalized Hoek-Brown material model can be expressed using following equation:

$$f = \frac{I_1}{3}m_b\sigma_{ci}^{\left(\frac{1}{a}-1\right)} - s\sigma_{ci}^{\frac{1}{a}} + 2^{\frac{1}{a}}\left(\sqrt{J_{2D}}\cos\theta\right)^{\frac{1}{a}} + m_b\sqrt{J_{2D}}\sigma_{ci}^{\left(\frac{1}{a}-1\right)}\left(\cos\theta - \frac{1}{\sqrt{3}}\sin\theta\right) \tag{2}$$

while equation of plastic potential surface has the form:

$$g = \frac{I_1}{3}m_{dil}\sigma_{ci}^{\left(\frac{1}{a}-1\right)} - s\sigma_{ci}^{\frac{1}{a}} + 2^{\frac{1}{a}}\left(\sqrt{J_{2D}}\cos\theta\right)^{\frac{1}{a}} + m_{dil}\sqrt{J_{2D}}\sigma_{ci}^{\left(\frac{1}{a}-1\right)}\left(\cos\theta - \frac{1}{\sqrt{3}}\sin\theta\right) \tag{3}$$

where I_1 is the first stress invariant and J_{2D} is the second deviatoric stress invariant, while σ_{ci}, m_b, m_{dil}, a and s are previously defined parameters of material model. Variable θ in the equations (2) and (3) represents the Lode's angle which can be calculated using stress invariants.

4. STABILITY ANALYSIS OF THE CONCRETE GRAVITY DAM

For the ultimate bearing capacity analysis of the dam using finite element method, the overload or SSR method are commonly used. Overload method is usually used in cases where there is uncertainty in the determination of external loads whereas the mechanical properties of materials are known. SSR method is used in cases where there is uncertainty in determination of mechanical characteristics of materials whereas the loads are relatively well known. This method is more suitable for this type of analysis considering inhomogeneities which occur in soil and rock-mass. In addition to determining factor of safety, it is possible to analyze the failure that occurs in the material, the potential instability modes, progressive failure and the degree of stability of the dam foundation and the surrounding rock-mass.

4.1. Application of shear strength reduction method to the Hoek-Brown model

As previously mentioned, yield surface of the generalized Hoek-Brown model has nonlinear character, so the new parameters of the reduced yield surface cannot be calculated using simple reduction of the initial material parameters, as in the case of the linear yield surface. Material parameters of the reduced envelope of the nonlinear material models can be obtained using following steps:

» reduce the initial yield envelope using SSR factor F,
» determine the material parameters corresponding to the reduced envelope using fitting method,
» use new parameters in repeated FEM analysis.

The relations between the normal and shear stresses in the case of generalized Hoek-Brown material model according to [5], have following form:

$$\sigma_n = \frac{1}{2}(\sigma_1+\sigma_3) - \frac{1}{2}(\sigma_1-\sigma_3)\frac{d\sigma_1/d\sigma_3 - 1}{d\sigma_1/d\sigma_3 + 1} \tag{4}$$

$$\tau = (\sigma_1-\sigma_3)\frac{\sqrt{d\sigma_1/d\sigma_3}}{d\sigma_1/d\sigma_3 + 1} \tag{5}$$

Using equation (1), reduced shear stresses (5)using SSR factor F can be expressed in following form [7]:

$$\tau^{red} = \frac{\tau_f}{F} = (\sigma_1 - \sigma_3)\frac{\sqrt{1 + a^{red} m_b^{red}\left(m_b^{red}\frac{\sigma_3}{\sigma_{ci}^{red}} + s^{red}\right)^{a^{red}-1}}}{2 + a^{red} m_b^{red}\left(m_b^{red}\frac{\sigma_3}{\sigma_{ci}^{red}} + s^{red}\right)^{a^{red}-1}} \quad (6)$$

where σ_{ci}^{red}, m_b^{red}, s^{red} and a^{red} represent the material parameters for description of the reduced envelope and these parameters need to be determined. New material parameters from (6) are not possible to be determined directly, but they can be estimated using the fitting method, as follows:

$$\varepsilon(\sigma_n)^2 = \left(\tau^{apr} - \tau^{red}\right)^2 \quad (7)$$

where τ^{apr} and τ^{red} represent the approximated and reduced shear stress, respectively. The parameters calculated in this manner where used in the repeated analysis of the dam stability until reaching the ultimate bearing capacity of the dam.

5. IMPLEMENTATION OF THE SHEAR STRENGTH REDUCTION METHOD

Using this method, shear strength of the material is reduced iteratively until reaching the ultimate capacity of the object, so it is necessary to estimate when the stage of ultimate bearing capacity of the material is reached. When stress exceeds yield stress in the element, plastic strain will occur, so local failure will also occur. However, that is not representation of the dam and rock-mass foundation failure. During progressive reduction of material shear strength, plastic yield of more elements will occur. When several plastic zones in dam foundation joint, potential ultimate bearing capacity of the dam is reached. The new material parameters of reduced envelope are obtained using fitting method and the FEM analysis is repeated using new material parameters. Reduction factor is increased and the analysis is repeated until there is a convergence of numerical solutions. The maximal value of the SSR factor for which there is a convergence of numerical solutions represents the safety factor of the object.

6. CASE OF STUDY

Concrete gravity dams represent complex objects which exceed other modern buildings in their size, areas that they occupy and influence on the environment. Thus, during construction and exploitation, global safety of the objects must be provided and any possible risk must be reduced to the minimum. Safety conditions that dam must satisfy in their service life are: global stability, stability of upstream and downstream slopes, safe evacuation of flood water and proper operation of the equipment.

The stress-strain analyses of the dam safety are performed using program PAK [9]. Since the dam lies on the rock-mass fundament, the Hoek-Brown material model is adopted.

6.1. Geometry of the dam

The dam is founded on the complex geology so determination of the safety factor of the failure in the deeper layers of foundation is not possible using traditional methods [11]. For analysis, calculation and evaluation of the possible unstable modes and ultimate bearing capacity of the dam's foundation and surrounding rock-mass, the nonlinear finite element method was used. Due to the complex geology, the stability analysis is not possible to be performed using any traditional method without significant approximations which often reach unrealistic results [12].

Since the powerhouse geometry is very complex, and this complexity does not obviously affect the object stability, the geometry is simplified using dam contour and using equivalent concrete material unit-weight. Since this section of the dam also lies on complex geology, accordingly the analysis of stability was also performed using the finite element method and SSR method for obtaining safety factor of the dam.

6.2. Boundary conditions and load cases

Two separated finite element models of the overflow and powerhouse dam sections are formed. In order to minimize the influence of the boundary condition, the model includes a wider area around the object. Dimensions of the models are 130×60 m for the overflow section and 110×60 m for the powerhouse section. The boundary conditions are specified using displacements on the model boundaries: vertical displacements of the model lateral boundaries are allowed, whereas displacements of the nodes on model's bottom boundary are completely fixed. Material parameters of the rock-mass used in the analysis are taken from ''Study of geological research results – Preliminary project'' [13] presented in Table 1.

Table 1. Material properties of the geological environment

Material	Label	E [GPa]	ν	γ [kN/m³]	σ_{ci} [MPa]	m_b	s	a
Peridotite-low cracked	σ	14.78	0.340	27.4	12.0	0.280	0.002	0.552
Peridotite-moderately cracked	σ’	6.72	0.344	27.3	10.0	0.180	0.0005	0.563
Peridotite-intensely cracked	σ’’	3.10	0.353	27.5	7.8	0.114	0.00004	0.569
Weathering crust of peridotite	σ’’’	1.84	0.356	24.5	9.0	0.076	0.0001	0.591

Prior to the structure build-up, there was the initial stress state in the rock mass. This stress state is caused by the deadweight of the rock mass so it is used as the first load step (step 1). The structure build-up process as well as a gradual filling of accumulation, do not influence considerably on the final distribution of stress and strain, so the numerical calculation can be performed with assumption that the dam body is formed in one step (step 2). The structure build-up is simulated using the element birth option. Loads during accumulation operation are specified within the next step (step 3). In the load cases definition normal operating conditions was considered.

Loads influencing the dam in operating regime are: deadweight of the dam and surrounded rock-mass, water pressure on the upstream and downstream faces of dam, uplift pressure on the dam foundation, seepage body force under the dam, and silt pressure on the upstream side of dam. Dynamic analysis is performed using maximal horizontal acceleration and hydrodynamic pressure load according to Zangar’s method [14]. Analysis was performed for all defined load cases, whereas one load case was presented.

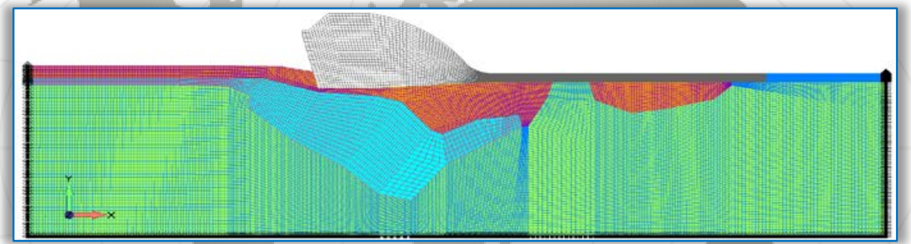


Figure 1. FE model of overflow dam section

The unmodelled part of the overflow dam section is taken into account using the loads on the upper object contour, whereas the equipment influence is taken into account as the concentrated forces on the binding spot. Different colors of the finite elements are used for different materials (Figure 1 and Figure 2).

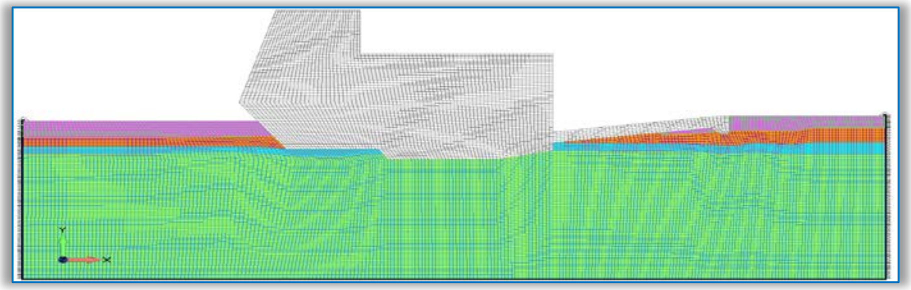
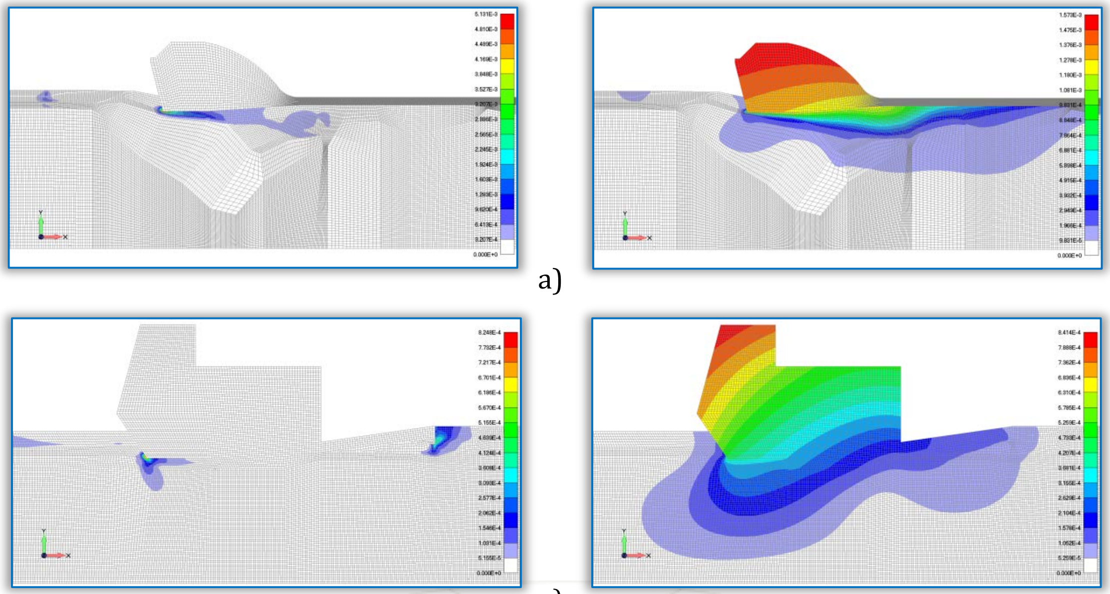


Figure 2. FE model of powerhouse dam section

The overall dam stability is influenced by various factors such as: dam constructions, loads, characteristics of the foundation, filtration and stress-strain phenomena, characteristics of the dam’s material, etc. The gravity concrete dam is stable if resisting tumbling and floating as well as any other mechanism of failure in the foundation layers including the sliding along dam’s foundation. Also, stresses and displacements of the dam and rock-mass must remain within the safety limits. The safety factors are defined depending on the function of the potential instability mechanism of the analyzed dam.

6.3. Analysis results

The plastic strain and total translation field on the dam body and surrounding rock-mass are presented on Figure3.

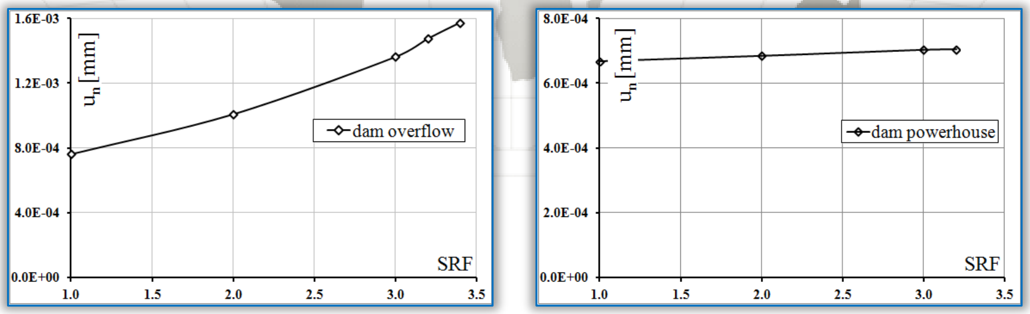


a) b) c) d)

Figure 3. Plastic strain and total translation for maximal SSR factor

Significant zones of plastic strains occur under the overflow dam section during the reduction of material strength, a zone of compression shear failure occurs at the toe zone of the dam, and the plastic strain zone of the dam heel continues to increase (Figure 3a and Figure 3c).According to the displacement results (Figure 3b and Figure 3d), it is clear that displacement of the overflow dam section is dominant. For the same value of SSR factor the displacement of powerhouse is relatively small.

Diagrams of maximal horizontal displacement as function of SSR (Figure4) shows constant displacement increment of the overflow section up to SRF=3, after which there is a considerate increase of horizontal displacement, and for SRF=3.4 comes to the loss of stability of this section.



a) b)

Figure 4. Maximal horizontal displacement of the dam in function of SRF

In the case of the powerhouse section, there is no significant increment of horizontal displacement during the increase of SSR factor but there is an sudden loss of stability for *SRF*=3.2.For the global safety factor against the failure in the deep dam foundation layers, the lower calculated value is adopted, i.e., S=3.2.

7. CONCLUSIONS

The presented study uses a shear strength reduction (SSR) method for the determination of safety factor against collapse in the deep layers of the dam foundation, which lies in the complex geology. For the stability analysis of the dam, the generalized Hoek-Brown material model was used and the SSR method was used for determination of safety factor. The stress-strain analyses and increase of the plastic strain zones until the dam stability loss were done. The mechanical behavior of rock-mass was based on real mechanical properties of geological materials presented in the dam profile.

The SSR method was used to determine the global safety factor. Used method can also identify the possible sliding planes and stability loss mechanisms. The SSR factor was gradually increased to the maximal value until the reaches of ultimate bearing capacity. Based on this data, it is possible to take appropriate measures to prevent loss of dam stability.

The plastic zone gradually extends with the increase of SSR factor to the whole area under the dam foundation on the overflow dam section. The plastic strain occurs near the dam heel and below the dam toe on the powerhouse dam section. There are no tensile stresses in the dam foundation. The stress appearing in the object foundation is several times lower than the ultimate bearing capacity of the rock mass. Analysis results show that it is not necessary to adopt reinforcement measurements. All obtained displacements in the dam and rock mass are within the safety limits.

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Note

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