# EFFECT OF STATIC CYCLIC LOADING AND AGEING OF CONCRETE ON THE STRENGTH OF A GRAVITY DAM

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*This work focuses on a technique of static retrospective analysis of old gravity dams. An attempt is made to match the material and structural model of a dam with the actual operation history of the structure. The proposed technique consists of: a) nonlinear-elastic fracture constitutive model for concrete in the plane strain condition, b) cyclic-induced degradation of stiffness and strength for dam concrete and c) ageing-induced change of stiffness and strength for concrete (ageing of concrete). Under cyclic loading the cycles of reservoir filling up-discharge is implied, i.e. loading-runloadingl of hydrostatic pressure to the dam and bottom of a reservoir. The number of cycles depends on the type of reservoir regulation.*

**The salient features of the various aspects of a numerical model for the analysis of existing old and “tired” gravity dams, which takes into account past loading history of the structure, are presented. The constitutive model for the analysis of these dams is based on the nonlinear-elastic fracture formulation. The main advantage of this approach is that it can be easily implemented in any numerical analysis with the required input data for the model easily obtainable from the traditional uniaxial tests on concrete specimens. This model takes into account the effect of material fatigue under slow static cyclic loading and process of ageing. To this end, the value of uniaxial compressive strength of concrete in the constitutive equation can be substituted by the value of the strength of concrete which has been appropriately modified in accordance with the number of loading-unloading cycles *n* and ageing of concrete *t*.**

**The constitutive model based on the hypo-elastic (nonlinear-elastic fracture) formulation, is employed. This model realistically simulates a path-dependent irreversible stress-strain relationship. The main advantage of this approach is that it can be easily implemented in any numerical analysis with the required input data for the model easily obtainable from the traditional uniaxial tests on concrete specimens. The four-parameter failure criterion [1] is employed. This model is modified in order to take into account the effect of material fatigue under slow static cyclic loading and ageing of concrete.**

**This approach allows us to account for the effect of change of concrete strength (fatigue) under cyclic loading and ageing of concrete. To this end, the value of uniaxial compressive strength of concrete $\sigma_c$ can be substituted by the value of the strength of concrete which has been appropriately modified in accordance with the number of loading/unloading cycles *n* and the time-period of the operation of a dam *t*:**

$$\sigma_c = \sigma_c(n,t). \tag{1}$$

**The value of strain $\varepsilon_c$ associated with the maximum uniaxial compressive stress of concrete may also be modified in accordance with the number of loading-unloading cycles *n* and the time-period of the operation of a dam *t*:**

$$\varepsilon_c = \varepsilon_c(n,t) \tag{2}$$

**It is obvious that cyclic loading causes the degradation of concrete stiffness. At the same time, the passage of time causes the concrete modulus of elasticity to increase. These two effects are taken into account in the present model by means of modifying the value**

of the initial modulus of elasticity in accordance with the number of loading-unloading cycles *n* and the time-period of operation of a dam *t*:

$$E_0 = E_0(n,t) \tag{3}$$

Cycling loading as well as ageing of concrete exhibit significant nonlinear behaviour and drastic changes in material properties of concrete. The result is a change of material properties of concrete as the number of applied loading-unloading cycles and ageig time increase. In the present work, the empirical relationships based on the experimental findings on cyclic and ageing behaviour [2] are adopted. Very briefly, following the tests carried out on the concrete specimens of Enguri arch dam, which were subjected to slow static cyclic compressive loading, the following relationships were established to define the degradation of the material properties of concrete in relation to loading-unloading cycles:

$$\begin{aligned} \sigma_c(n) &= \left(1 - a_\sigma^n \lg n\right)\sigma_c \\ E_0(n) &= \left(1 - a_E^n \lg n\right)E_0 \\ \varepsilon_c(n) &= \left(1 - a_\varepsilon^n \lg n\right)\varepsilon_c \end{aligned} \tag{4}$$

where parameters $a_\sigma^n$, $a_E^n$ and $a_\varepsilon^n$ define the degradation of the material properties of concrete under slow static cyclic loading, and *n* is the number of loading-unloading cycles in accordance with the operation history of a gravity dam (it corresponds to the number of filling up-discharge cycles of the reservoir during the operation of the dam).

The specific values of these parameters may only be determined by carrying out cyclic tests on concrete specimens. Nevertheless, a careful study of the results of the investigations suggests that the values of the above parameters do vary within the following ranges:

$$\begin{aligned} 0.05 \le a_\sigma^n \le 0.25 \\ 0.10 \le a_E^n \le 0.30 \\ 0.10 \le a_\varepsilon^n \le 0.30 \end{aligned} \tag{5}$$

Generally, the degree of the degradation of the material properties of concrete increase with increases in the number of loading-unloading cycles *n*.

The same approach is used to describe the change in material properties of concrete due to ageing of the material. Again, the logarithmic function seems to predict well the variations of the material properties of concrete with time. Namely, the relationships can be expressed as:

$$\begin{aligned} \sigma_c(t) &= \left(1 + a_\sigma^t \lg t\right)\sigma_c \\ E_0(t) &= \left(1 + a_E^t \lg t\right)E_0 \\ \varepsilon_c(t) &= \left(1 + a_\varepsilon^t \lg t\right)\varepsilon_c \end{aligned} \tag{6}$$

where the parameters $a_\sigma^t$, $a_E^t$ and $a_\varepsilon^t$ define the modification of the material parameters of concrete due to ageing of concrete, and *t* is the number of years in accordance with the operation history of a gravity dam.

A careful study of the final results suggest that the values of the above parameters may lie within certain fairly well-defined ranges, depending on the type of concrete: obviously, specific values of these parameters are best found by in-situ measurements on concrete specimens. Tests reported in [2], which were based on concrete specimens from Enguri arch dam, suggest the above coefficients to lie within the following ranges:

$$\begin{aligned} 0.05 &\le a_{\sigma}^{t} \le 0.15 \\ 0.05 &\le a_{E}^{t} \le 0.15 \\ 0.05 &\le a_{\varepsilon}^{t} \le 0.10 \end{aligned} \qquad (7)$$

The "dam-foundation-reservoir" system within the plane strain problem was considered. As a prototype of gravity dam the 60 m height Greis dam (Switzerland) was adopted, which has vertical upstream face and downstream face with varying slope (0,68-0,85). The slope of upper part of this dam (between $\nabla$ 2387,5 and $\nabla$ 2378,0 m a.s.l.) equals 0,25. The dam has rock and uniform foundation. Its modulus of elasticity $E_f$ = 1*$10^6$ t/m$^2$ and Poisson's ratio $\nu = 0{,}25$. The initial modulus of elasticity of dam concrete $E_0$ = 2*$10^6$ t/m$^2$ and Poisson's ratio $\nu = 0{,}2$. The system is divided into a mesh of triangular elements. The total number of elements is 17022. From this amount the dam itself has 3526 elements. The total number of nodes is 8790. The major part of calculation scheme is shown on Fig. 1. The reservoir is of seasonal regulation. 48 years passed since its commissioning, i.e. $n$ = 48.

Computations were carried out according to the following sequence:

1. The design version of the system "dam-foundationreservoir" was considered. As a modulus of elasticity of dam concrete its initial value $E_0$ was adopted. Hydrostatic pressure and dead load are acting on a dam. Hydrostatic pressure is applied to the bottom of reservoir. The nodal displacements, strains, stress components, major stresses and their directions were determined;
2. The major stresses were analysed by the expressions (4), (5), (6) and (7) taking into account the number of filling up-discharge cycles $n$ = 48. The values of the modulus of elasticity were specified. The initial modulus of elasticity $E_0$ = 2*$10^6$ t/m$^2$ was transformed into $E_{n=48}$ = 0,4*$10^6$ t/m$^2$ due to the cycles and it was transformed into $E_{t=48}$ = 0,4*$10^6$ t/m$^2$ due to ageing;
3. The system was computed again taking into account the specified values of the moduli of elasticity.

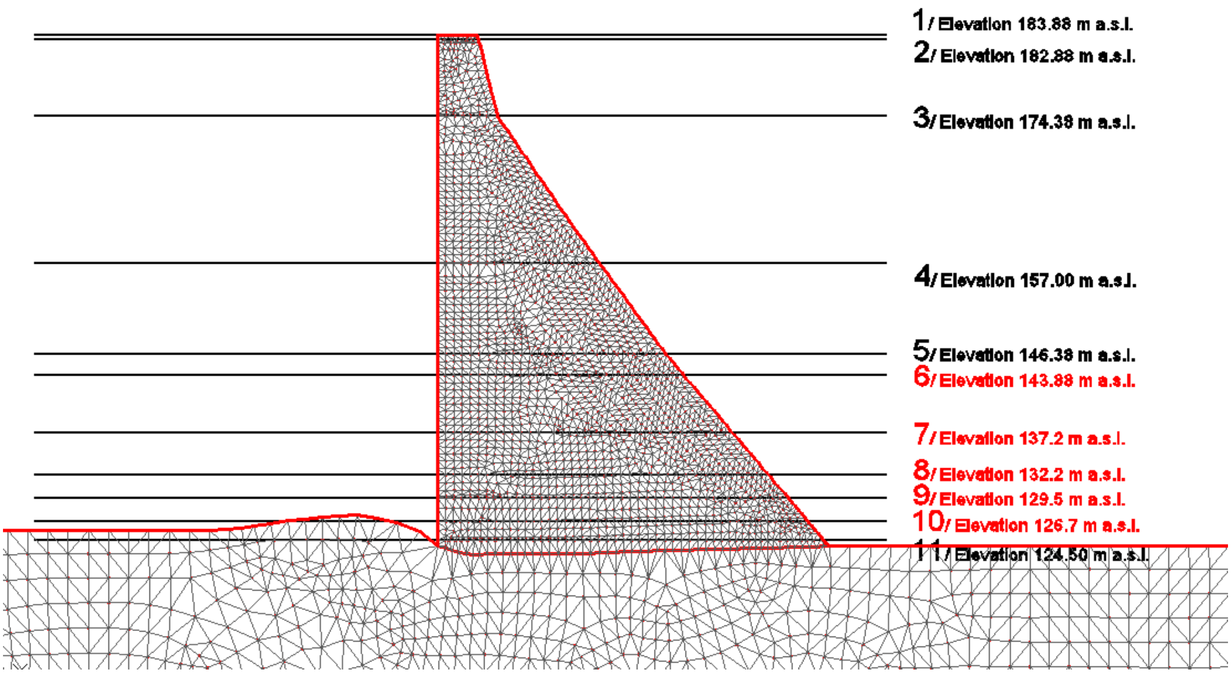


**Fig. 1. Computing scheme of the system "Greis dam-foundation-reservoir" be the FEM**

**From the large number of results the only one, distribution of $\sigma_y$ stresses along the section #10 (close to contact surface between dam and foundation), is presented on Fig. 2. The results clearly show that due to cyclic loading the values of compressive stresses are significantly reduced at the upstream and downstream faces. At the other points of the section the values of stresses are changed to a little degree. As to effect of ageing, the values of compression stresses are increased at the upstream and downstream faces to a little degree. At the other points of the section the values of compression stresses are changed also to a little degree.**

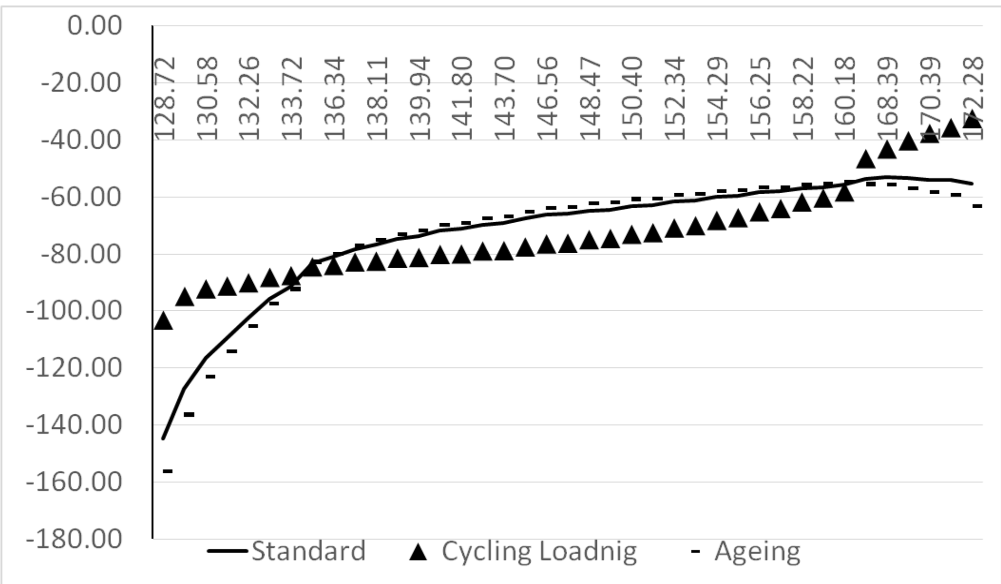


**Fig. 2. $\sigma_y$ stresses along the section #10 above the contact surface (see Fig. 1) in t/m$^2$**

## CONCLUSION

**It is necessary to take into account the number of slow static cyclic loadings and ageing of concrete when computing the mode of deformation of existing old gravity dams, since they significantly change the picture of stress distribution at the both, upstream and downstream faces. Trend of changes in case of cyclic loading is negative, i.e. the compressive stresses are reduced toward the tension stresses. As to ageing of concrete, it plays positive role due to the increase of value of modulus of elasticity.**

## R E F E R E N C E S


1. **Hsieh, S. S., Ting, E. C. and Chen, W. F. (1979) 'An Elastic-Fracture Model for Concrete',** ***Proc. 3d Eng. Mech. Div. Spec. Conf., ASCE, Austin, Tex., 437-440;***
2. **Osidze, V. I., Khoperia D. L. (1987) "Deformation Parameters of Concrete of Inguri Arch Dam subject to Static Cyclic Compressive Loading",** ***in Construction of Hydro Power Stations in Mountainous Regions, EnergoAtomIzdat, Moscow., pp. 52-58, (Rus).***


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