Practical methodology for inclusion of uplift and pore pressures in analysis of concrete dams

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Uplift and pore pressures are fundamental loading conditions that affect the strength and stability of concrete dams. Historically, these loads have been difficult to quantify and to implement in finite element analysis (FEA). Some dam design guidelines propose different techniques to apply the estimated uplift pressure for its use in FEA of concrete dams. These methodologies are, in general, quite dated and predominately applicable to simplified 2-D models, reflecting the limited capability of the software and computer power of that time. With the advancement in computer capability and continuous development of FE packages, large 3-D models for all types of concrete dams are not a rarity, and consequently, it is necessary to develop more practical methods to implement and analyse uplift and pore pressure loading in combination with all other loads imposed on the dam. This paper presents a practical methodology for the simultaneous inclusion of uplift and pore pressure in the structural analysis of concrete dams using finite element (FE) techniques. The methodology accounts for the inclusion of a prescribed uplift and pore pressure condition in the FE model, in a way that it can be readily combined with the other loads acting on the dam, and a final effective state of stress can be calculated. This paper presents a worked 3-D example of a generic arch-gravity dam subjected to a static structural analysis, from the initial calculation of the prescribed pore pressure and uplift to the resulting effective stresses in the dam body.

Keywords: *Uplift, pore pressure, concrete dams, finite elements, effective stress.*

Introduction

Historically, uplift and pore pressures have been difficult to quantify and to implement in finite element analysis (FEA). Uplift and pore pressure result from the interaction between the dam wall, the impounded water, the tailwater and the foundation. Pore pressures develop when water percolates into and pressurises the voids in the concrete, consequently affecting the strength of the dam by imposing a gradient of tensile stress. Uplift forces are caused by pore pressure acting normal to discontinuities such as cracks and lift joints in the dam, de-bonded dam/foundation interfaces and jointing in the foundation rock. As a result, the uplift pressure affects the stability of the dam by reducing the effective normal stress and consequently reducing the frictional resistance, making the structure more susceptible to sliding failure.

The methodology described in this paper is applicable to any prescribed state of uplift and pore pressures, including pressure fields measured by instrumentation installed in the dam, or from formulations recommended by dam design guidelines. A brief discussion of the most common formulations for uplift and uplift pressure recommended by dam design guidelines are presented below. This discussion is presented for reference only; this paper does not pretend to investigate, endorse or dismiss any of the recommended formulations by any design guidelines.

Estimation of uplift and pore pressures

Different guidelines have proposed various methodologies for the estimation of uplift pressures in concrete dams. Some of the most complete guidelines in terms of uplift pressure estimation are those from the Federal Energy Regulatory Commission (FERC), the US Army Corps of Engineers (USACE) and the US Bureau of Reclamation (USBR). A complete discussion of the similarities and differences between uplift formulations according to these three entities is presented in USACE (2000).

In general, the uplift estimation depends on the reservoir and tailwater levels, the presence or not of a drainage gallery, the effectiveness of the drainage system, the presence of a crack at the upstream heel of the dam, and the elevation of the gallery (if any) with respect to the tailwater level. In the absence of a drainage system or an upstream heel crack, all guidelines agree that the uplift pressure under the dam varies linearly from 100% of the reservoir head at the upstream face to 100% of the tailwater head on the downstream face (or to atmospheric pressure if there is no tailwater).

For dams with a drainage system, a reduction of uplift at the drainage line is allowed. The uplift reduction can only be adopted if the diameter and the spacing of the drains comply with recommended limit values. Uplift reduction factors range between 0.25 and 0.66 are normally adopted to take into account drain effectiveness. It is commonly assumed that uplift pressures are unchanged during earthquake loads, although the uplift for post-earthquake conditions may increase as a result of damage in the dam-foundation interface.

Uplift in portions of the dam or foundation planes not in compression is assumed to be equal to 100% of the hydrostatic head of the water field closest to the non-compression zone (i.e., the reservoir head or the tailwater head). This is because the potential crack may become large enough, so that the dam-foundation interface could be exposed to the reservoir and the drains could become completely ineffective. For illustration, the uplift distribution for the particular scenario of a dam with drains, zero compression along the base to downstream of the drains, and existing gallery below tailwater level, is presented in Figure 1. Scenarios other than the one illustrated here have different uplift distributions.

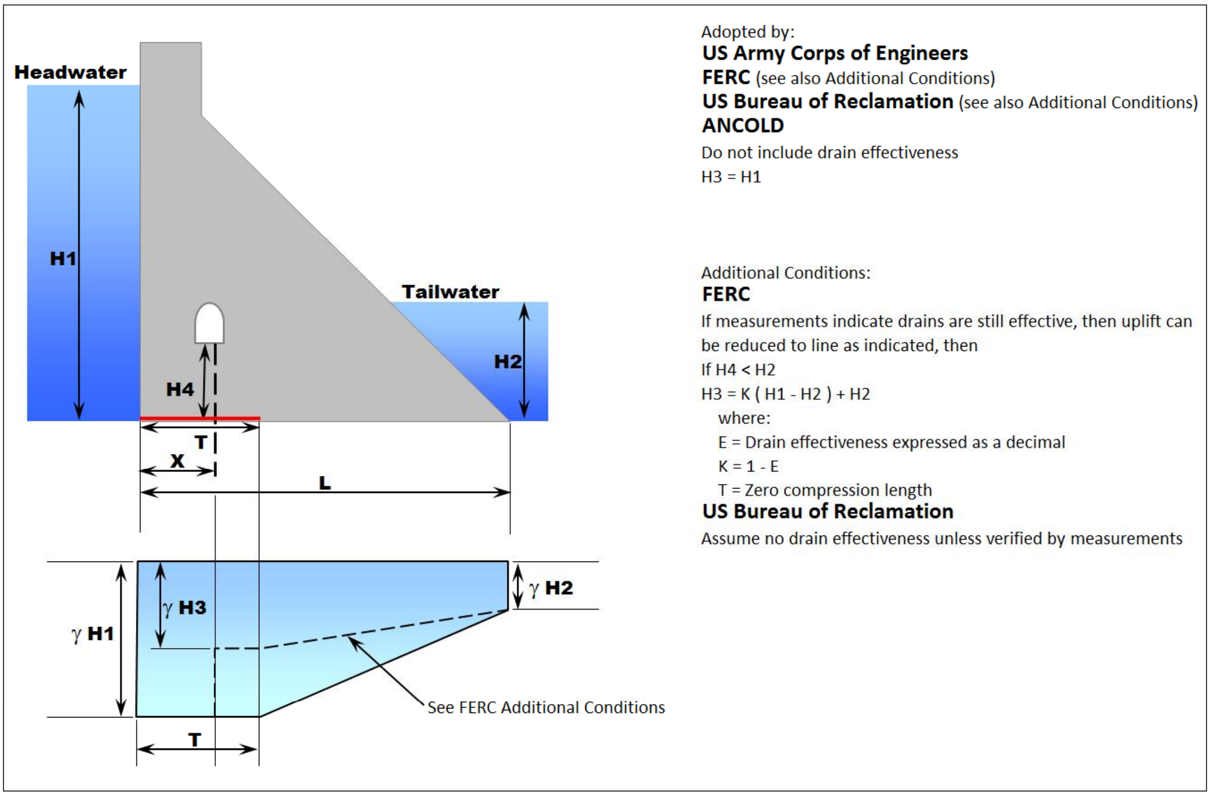

Figure 1. Uplift formulation for cracked base beyond the drainage line (gallery below tailwater)

Uplift and pore pressure in analysis of concrete dams

There are several methodologies to account for the uplift and pore pressure in analysis of concrete dams. On one hand, dam design guidelines in general propose very simplistic approaches predominately applicable to simplified 2-D models, reflecting the limited capability of the software and computer power at the time when these approaches were formulated. These are briefly discussed later in the following paragraph. On the other side of the spectrum are several complex techniques for modelling of uplift and pore pressures which are impractical for conventional professional practice of dam engineering, and are more appropriate for applied research. These complex methods include coupled fluid-structure analysis with linear stress-strain relationships for dam and foundation materials (poro-elastic approach), and explicit numerical modelling of the flow of water through low permeability media with discontinuity surfaces (rock joints, cracks, rock-concrete interface, lift joints, etc.). These methods are discussed in detail in ICOLD European Club (2004).

Current formulations for application of uplift and pore pressure in FE models

There is scarce information in the literature regarding the application of uplift in FE models of concrete dams. One of the few recommendations available is presented by FERC (2002). FERC proposes a method of application using a thin interface layer of elements, which allows the uplift pressure to be applied to the bottom of the dam and the top of the foundation. The resulting stress output for these interface elements includes the effects of uplift. A cracked base analysis may be performed in an iterative way by deleting elements in the cracked zone and manually recalculating the uplift distribution. While this procedure may be easily implemented in 2-D models, its application in 3-D models is impractical because it constraints the geometry of the foundation to simple geometries (for instance, abutments with inclined excavations need to be modelled as stepped excavations), and also because it increases the number of elements in the model when the thin layer interface elements are projected to the foundation domain. The FERC guidelines make no reference to the application of pore pressures within the dam body. Figure 2 below illustrates the procedure suggested by FERC.

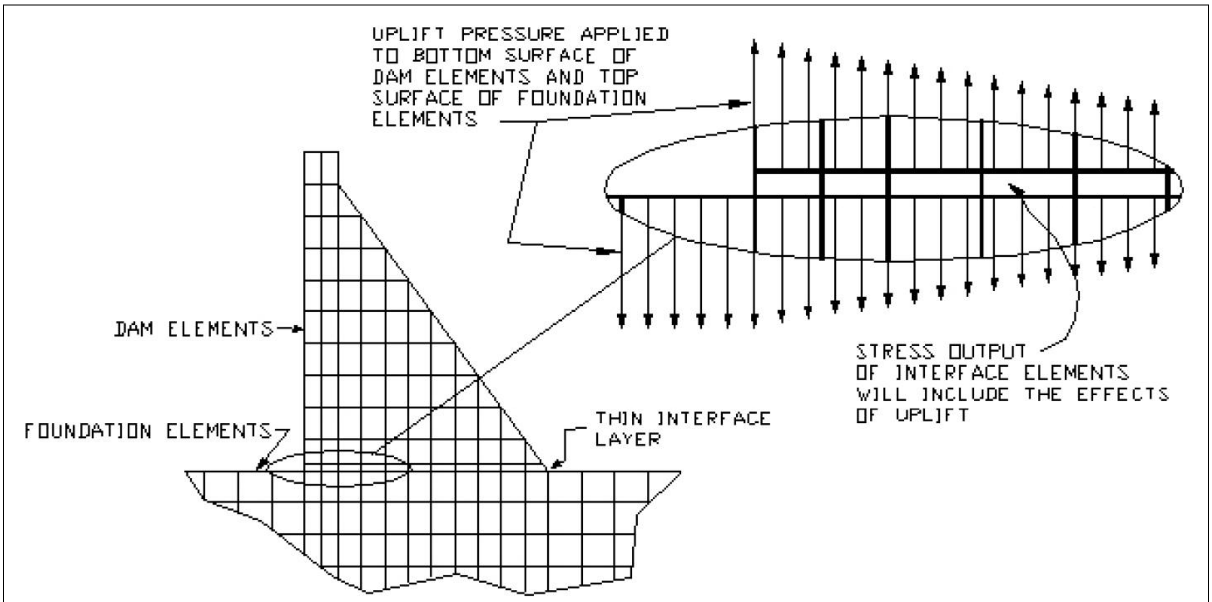

Figure 2. Application of uplift in a FE model of a concrete dam (from FERC,2002).

USBR (2006) mentions that the uplift pressures can be applied as surface pressures to the opposite faces of contact elements. This method can be implemented in 2-D and 3-D models, but it is limited to geometric nonlinear models, where the dam-foundation interface is able to crack.

In terms of the pore pressure application, USBR indicates that it could be added to each of the orthogonal stress components, although it does not indicate how to implement it. In our experience, such methodology implies the manual computation and assignation of the pore pressure or forces node by node. This method can therefore be relatively time consuming for 2-D models and totally impractical for 3-D models. This is the reason why USBR has historically not computed the effective stress in the concrete when determining the cracking potential of a structure when using finite elements. Instead, USBR accounts for the uplift and pore pressure in a post-processing phase. For stress analysis, the post-processing consists of extracting the tabulated list of relevant stresses at the nodes from the finite element runs. Then the adopted uplift and pore pressure profile is manually added at each node, producing the effective stress field. Finally, contours of effective stresses are produced using separate contouring software.

Practical methodology for inclusion of uplift and pore pressures

With the advancement in computer capability and the continuous development of FE packages, large 3-D models for all types of concrete dams are not a rarity, and consequently, it is necessary to develop more practical methods to implement and analyse uplift and pore pressure loading in combination with all other loads imposed on the dam.

Given the observed limitations of the existing methodologies previously discussed in this paper, a more practical approach for the inclusion of uplift and pore pressures in the analysis of concrete dams is presented herewith.

Objective

The objective of this methodology is to input prescribed uplift and pore pressure conditions, (either estimated in accordance with adopted guidelines or from records of existing instrumentation installed in the dam), into a FE model of the dam and the foundation, in such a way that the demand from the uplift and pore pressure can be quantified and readily combined with the other loads acting on the dam, and a final effective state of stress in the structure can be calculated. The effective state of stresses obtained with this method can be directly compared with the strength of the concrete in the structural assessment of the dam, without the need for additional post-processing and/or contouring. Also the effective forces at different planes of interest can be immediately used to determine the stability of the structure, with no need for inclusion of uplift forces manually. While these benefits may be appraised as only marginal when compared with manual methods for 2-D models, in large 3-D models, application of the practical methodology may significantly reduce the time required to estimate the effective stress on the dam.

Description of the method

Broadly speaking, the method consists of performing a coupled steady-state flow and stress analyses of a concrete dam. In our practice (and also in the worked example presented in this paper) we use the package DIANA (TNO DIANA 2012). It is expected that the proposed methodology can be applied in other packages with similar capabilities.

The model used for this methodology can be either 2-D or 3-D, and must include both the dam and the foundation. There is no need to explicitly model the reservoir or the tailwater. Being a coupled analysis, both the steady-state flow and the stress analysis are performed in the same model. In the steady-state analysis the water heads corresponding to the reservoir and the tailwater are applied and the boundary conditions of the system are calibrated until the resulting hydraulic pressure in the body of the dam and the foundation replicates the prescribed uplift and pore pressure field. In the stress analysis, the hydraulic pressures obtained from the steady-state flow analysis are automatically converted into a load case that can be combined with other conventional loads in the dam such as gravity, temperature, hydrostatic and hydrodynamic solicitations.

During the steady-state flow analysis the pressure and flux are determined at the element integration points. Upon completion of the flow analysis, the resulting pressure heads are input into the model for the stress analysis. The pressure field is then calculated as the pressure head multiplied by the density of the water and gravity.

Element type, boundary conditions and material properties

A description of the typical finite element model types, boundary conditions and material properties necessary for the coupled steady-state flow and stress analyses is presented in the following paragraphs. Figure 3 presents a schematic definition of a typical model for coupled analysis, including the components of the system, the type of finite elements, and the required material properties.

Structural / groundwater elements

Conventional 2-D or 3-D structural elements are used to represent the concrete dam and the foundation rock for the stress analysis. One of the main advantages of the package DIANA is that only one mesh of the dam and the foundation needs to be created. Initially, the mesh is created using structural elements. However, when performing the steady-state flow analysis, the program internally and automatically converts the structural elements into groundwater elements. After the steady-state flow analysis is complete, DIANA automatically re-converts the groundwater elements into structural elements, to complete the stress analysis.

For the steady-state flow analysis the required material properties for the groundwater elements representing the dam and the foundation are the hydraulic conductivity, the density and porosity of the material being percolated (concrete and rock), and the density of the percolating fluid (water).

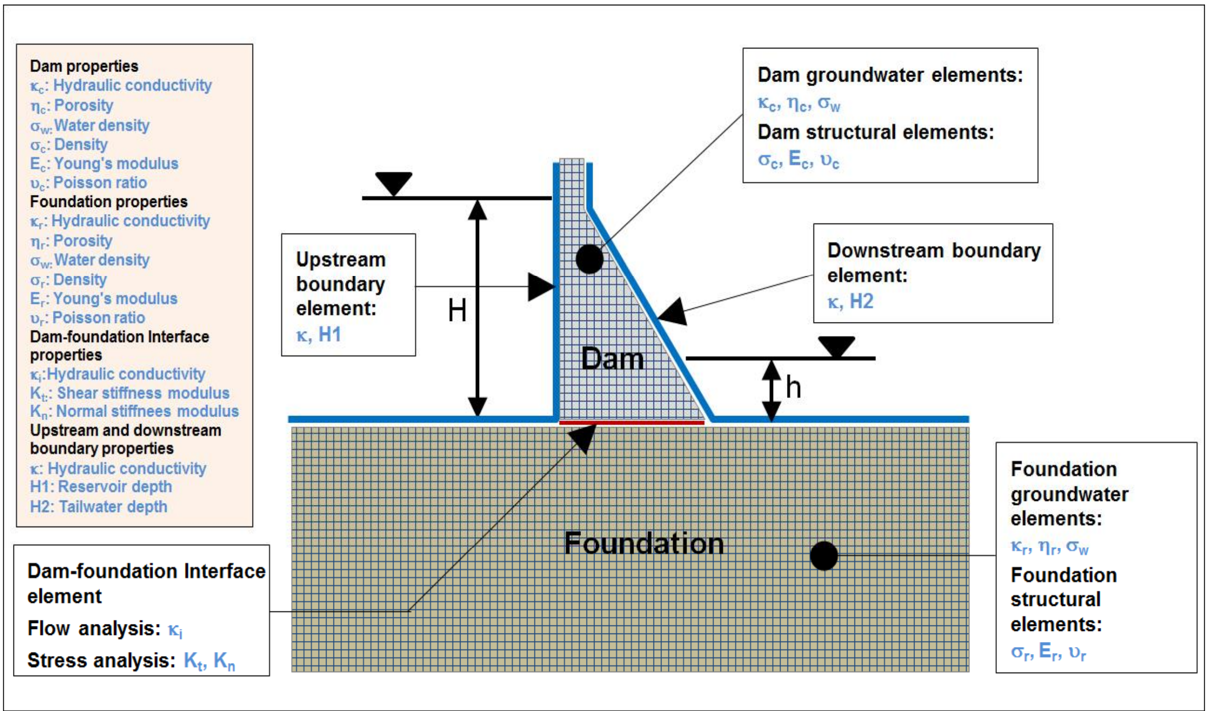

Figure 3. Schematic FE model for coupled steady-state flow and stress analyses

In the context of a flow analysis, the hydraulic conductivity can be described as the ease with which water can move through pore spaces, fractures or cracks. It depends on the intrinsic permeability of the material, the degree of saturation, the density and viscosity of the fluid and the hydraulic pressure (i.e., at atmospheric pressure, the hydraulic conductivity is zero).

For the stress analysis, the required material properties for the structural elements representing the dam and the foundation are the material density, the Young's Modulus of elasticity and the Poisson's ratio. Other material properties may be required depending on the type of analysis being performed (for instance material damping in the case of dynamic analyses), or on the nature of the applied loads (for instance thermal properties if temperature loading is included).

It should be noted that the density (weight) of the water filling the voids of the concrete have an impact in the calculation of the uplift and pore pressures, and combined with the flexibility of the foundation, may lead to certain stress redistribution. The dry density is commonly used to define the weight of the dam. To account for the mass of water filling the voids of concrete, the porosity of the material and the density of the water are used to quantify the additional weight of the fluid.

Boundary elements

As indicated in Figure 3, boundary elements are required in the model along the bottom of the reservoir, the upstream and downstream faces of the dam and along the downstream region of the model (bottom of the tailwater, if any).

The boundary elements define the external loading conditions on the free faces of the model, in this case, the hydraulic heads of the reservoir and tailwater fields. In the case of the steady-state flow analysis, the boundary elements represent seepage on the free faces of the groundwater elements. The boundary elements for 2-D models are one dimensional, with two or three nodes. For 3-D models, 2-D triangular or quadrilateral boundary elements can be used.

The boundary elements require the definition of the hydraulic conductivity and the depth of the reservoir and the tailwater. The hydraulic conductivity of the boundary elements should be large enough so it does not inhibit free fluid flow into the dam and into the foundation.

Interface elements

Irrespective of the type of structural analysis to be performed (linear or non-linear cracked analyses), when coupled steady-state flow and stress analyses are conducted the connection between the dam and the foundation needs to be modelled by means of interface elements.

Similarly to the boundary elements, for the steady-state flow analysis the interface elements require the definition of hydraulic conductivity to represent the ease with which water can move between two different materials, in this case concrete and rock.

For the stress analysis the required material properties for the interface elements are the normal and shear stiffness moduli. If a nonlinear (cracked) interface is being used in the stress analysis, nonlinear material properties such as cohesion and angle of friction of the interface, would also need to be included.

Modifications to the standard linear variation of uplift

With the previously described methodology, linear variations of the uplift pressure are obtained, from full reservoir head to full tailwater head. However, the model can be adjusted to reflect a prescribed uplift inside an upstream crack (for instance, the crack can be assumed to be fully pressurised with reservoir head), or to reflect a field of pressure measured with installed instrumentation. To adjust the uplift pressure in these cases, boundary elements are introduced in the dam base, at the particular zone or zones to be modified. By manually modifying the pressure heads assigned to each boundary element in an iterative process, a specific prescribed uplift condition can be obtained.

Worked example

A worked example of the methodology for the inclusion of uplift and pores pressures in finite element analysis of concrete dams is presented herewith.

In the example, a 3-D model of a generic arch-gravity concrete dam and its foundation is used. It is assumed that the static conditions induce a non-compression zone that generates a crack of 3 m at the upstream side of the dam-foundation interface (heel). It is assumed that there is no gallery or drainage system and that there is no tailwater. The adopted prescribed uplift is full reservoir head at the heel of the dam and along the cracked interface (0.29 MPa), then varies linearly to atmospheric (zero) pressure at the toe of the dam. The adopted prescribed pore pressure in the dam body is a linear variation from the corresponding water pressure in the upstream face (for example 0.1 MPa at a depth of 10 m) to atmospheric pressure on the downstream face of the dam. The dam will also be subjected to gravity and hydrostatic loads for the stress analysis.

Figure 4 presents the geometry of the maximum cross section of the dam, the prescribed uplift and pore pressure formulations, and the material properties of all model elements required for the coupled steady-state flow and stress analyses.

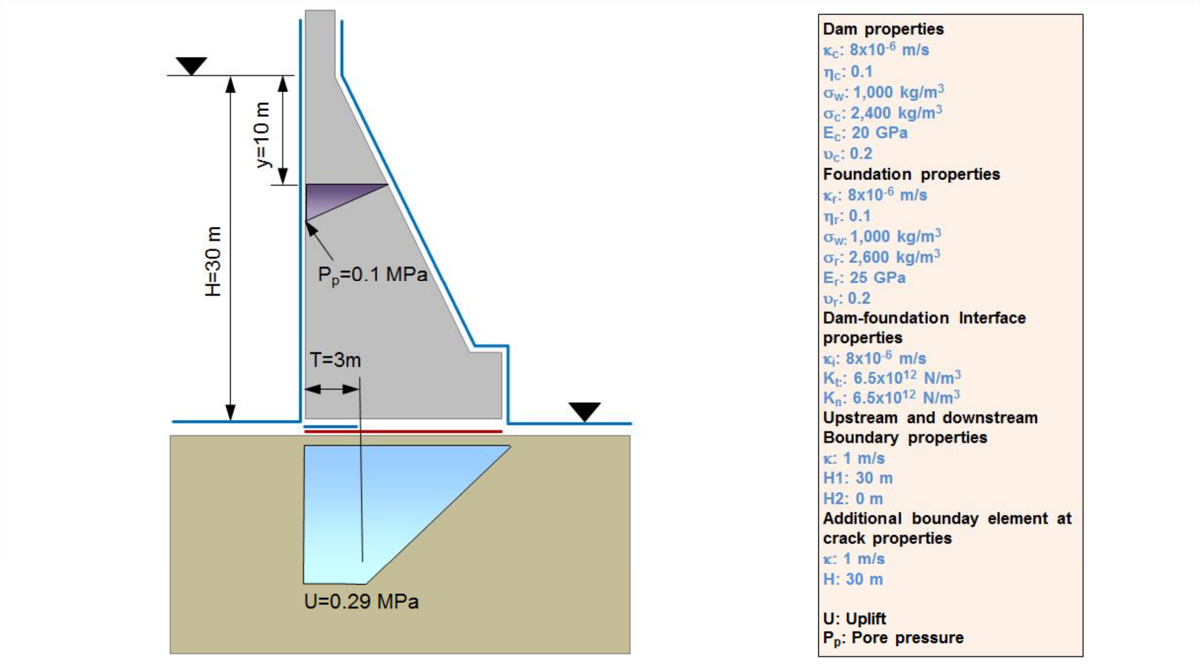

Figure 4. Example description and material properties

The pressure heads in the dam body resulting from the steady-state flow analysis are presented in Figure 5, for both the upstream elevation and the maximum cross section of the dam. It is observed that the obtained pressure heads reflect the conditions imposed by the reservoir and tailwater levels (i.e., a linear change in the upstream face, from nil head in the reservoir surface to 30 m of water head in the heel of the dam), and also by the crack in the dam-foundation interface (i.e., maintaining an approximately constant water head of 30 m along the crack, then reducing linearly to nil head at the toe of the dam).

After the pressure heads from the steady-state flow analysis are obtained, they are converted into a loading case for the subsequent stress analysis. Figure 6 presents the field of principal stresses in the dam body resulting from the stress analysis, for the case of uplift and pore pressure loading only.

The results show a very good agreement between the prescribed and modelled uplift and pore pressures. The results of the stress analysis show an uplift pressure of 0.28 MPa along the cracked interface of the dam, and an approximately linear reduction to zero at the toe of the dam. In terms of pore pressure in the body of the dam, a pressure of 0.11 MPa was obtained at the face of the dam at 10 m deep, with an approximately linear reduction to zero at the downstream face of the dam.

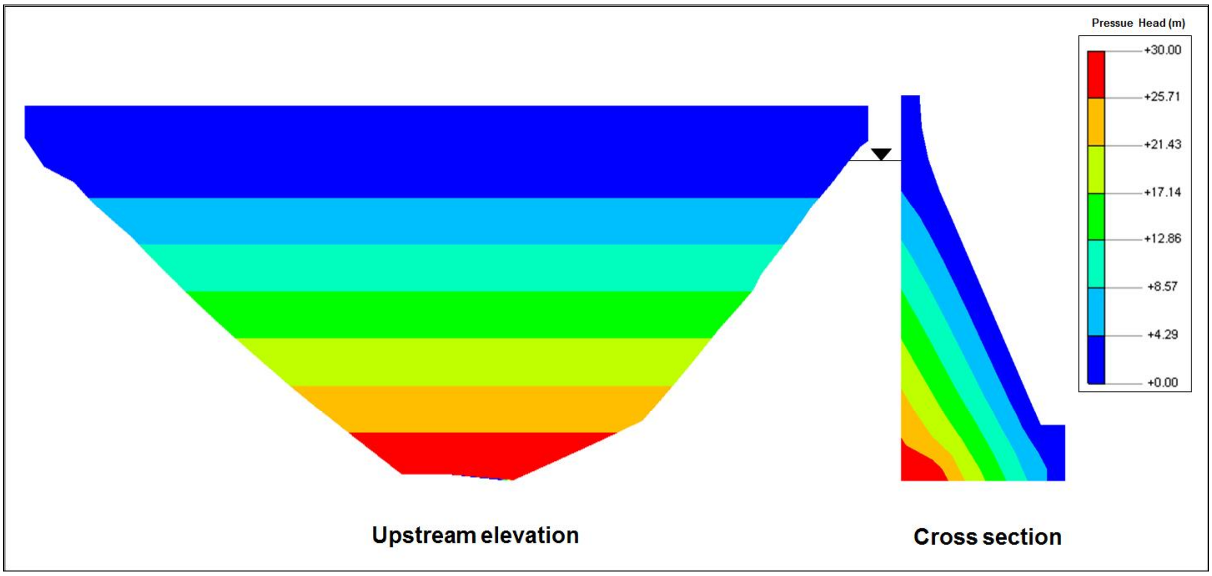

Figure 5. Resulting pressure heads from prescribed uplift and pore pressures

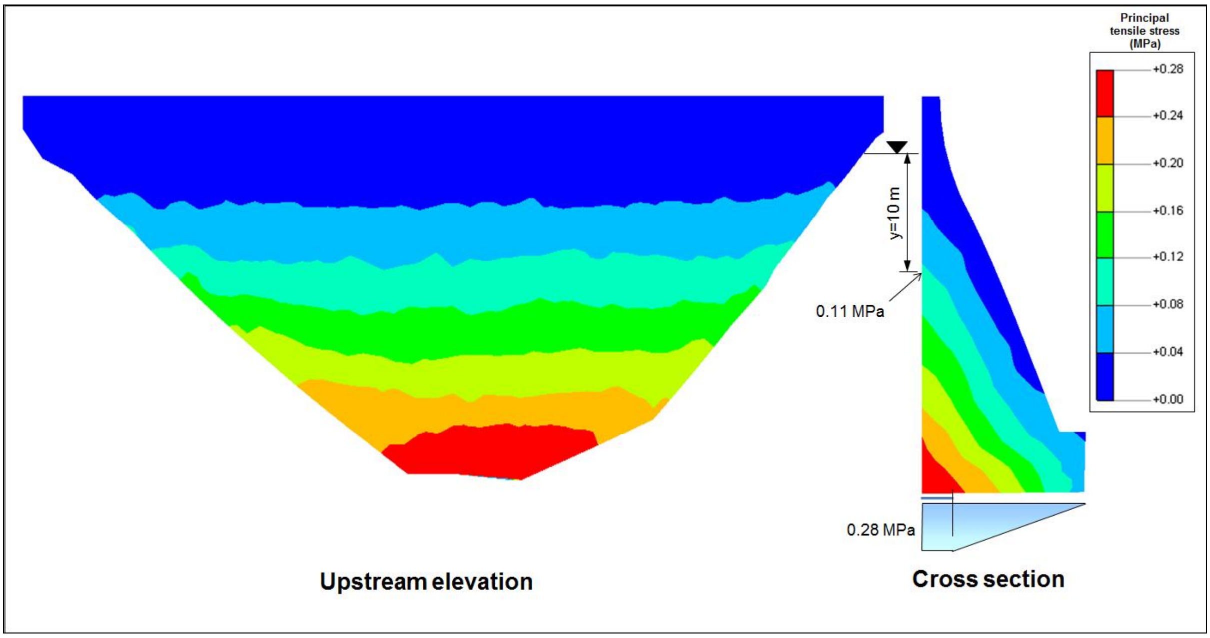

Figure 6. Principal tensile stresses (uplift and pore pressure loading case only)

When the stresses in the dam are combined with the stresses from other static internal and external loads, in this case gravity force and hydrostatic pressure, the effective state of stress in the dam is determined. Figure 7 presents the field of effective vertical stresses in the dam body. For comparison, the total stress field, that is, when uplift and pore pressure is neglected, is presented in Figure 8.

It is observed that the present methodology captures the contribution of the uplift and the pore pressure to the state of effective stress in the body of the dam. This contribution is illustrated with the fact that the obtained vertical stress at the heel of the dam is 0.71 MPa for the effective stress condition, and 0.43 MPa for the total stress condition. The difference of 0.28 MPa corresponds to the prescribed uplift pressure at the heel of the dam. In this example, the effective vertical stress at the heel of the dam is 1.65 times larger than the corresponding total stress. If the vertical tensile strength of the concrete was, for example 0.6 MPa, neglecting the contribution of the uplift and pore pressure to the overall demand of stress in the dam (i.e. using the total stress concept) would have led to the unsafe conclusion that the concrete would not have cracked.

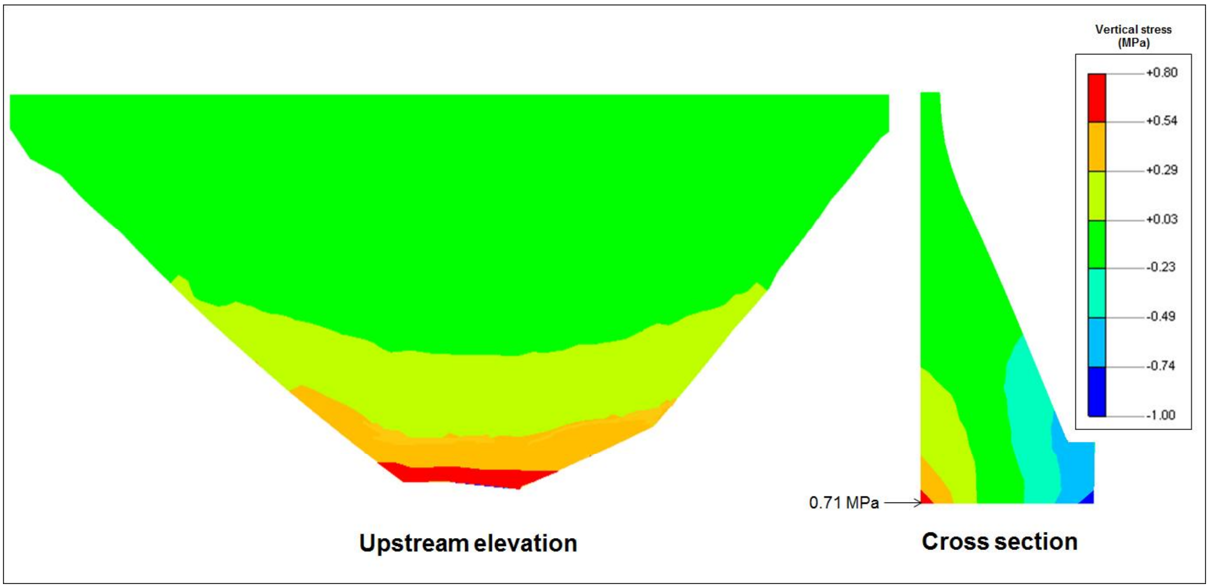

Figure 7. Resulting effective stresses (uplift and pore pressure combined with static loads)

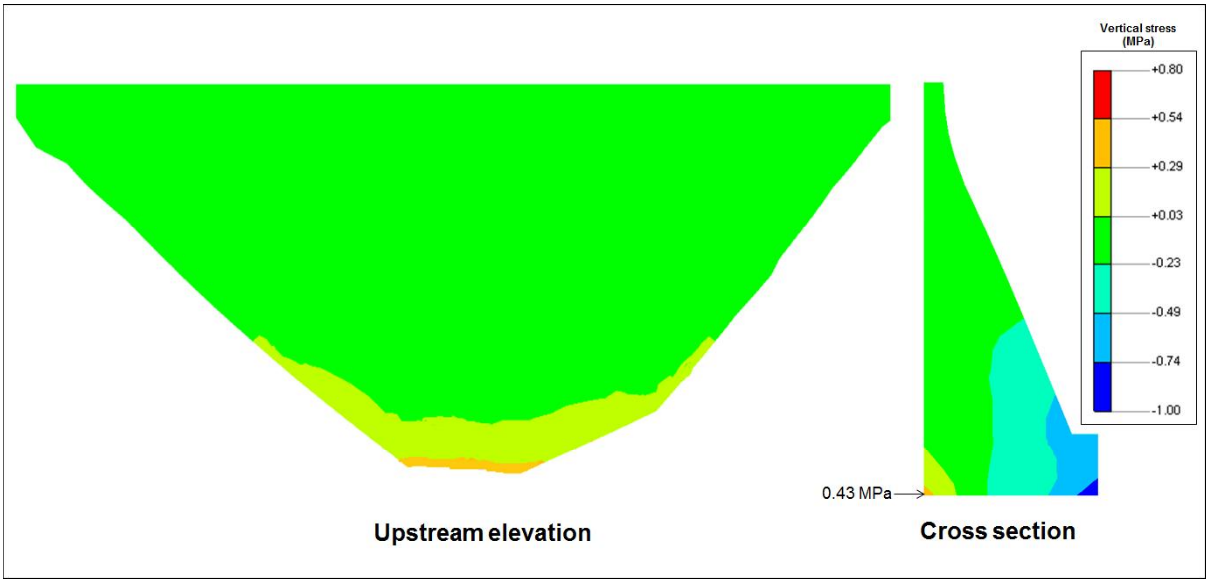

Figure 8. Resulting total stresses (uplift and pore pressure neglected)

Conclusions

A practical methodology for the inclusion of uplift and pore pressures in finite analysis of concrete dams has been presented in this paper.

With the proposed methodology a prescribed uplift and pore pressure condition, either from adopted guidelines or from records of existing instrumentation installed in the dam, and for either cracked or uncracked dam base conditions, can be included in the FE analysis of concrete dams.

This practical methodology overcomes the limitations of the current simplistic or overly complicated methodologies for the application of uplift and pore pressure effects in the finite element analysis of concrete dams.

The proposed methodology was proven with a worked example of an arch-gravity concrete dam. The results of the example for the steady-state flow analysis showed that the model reproduced the prescribed state of uplift and pore pressures in the dam body. In the example the stress analysis results showed the significant difference between the effective and total stresses, and hence, the importance of including the effect of the uplift and pore pressure in the structural analysis of concrete dams.

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