Stress-dependent permeability in the foundation of Alqueva dam

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Abstract

This paper describes the study carried out in order to establish a relation between stress and permeability in some areas of Alqueva arch dam foundation. The study was conducted taking into account the results of global three-dimensional mechanical and hydraulic models, both validated against field data, and carrying out independently uncoupled mechanical and hydraulic analyses. The established stress/permeability curves were introduced into the hydraulic model, allowing discharges to be calculated for different levels. The difficulty of assessing the dependence of permeability on stress is highlighted and some conclusions are drawn about suitable models to study the dam foundation behaviour.

Introduction

The behaviour analysis and safety assessment of concrete dams involves the modelling of both the foundation's mechanical and hydraulic behaviour in normal operating scenarios. Although both phenomena may be studied independently, it is well known that there is a significant interdependence between them. In fact, in a rock mass the majority of the flow takes place through a complex interconnecting system of discontinuities, whose aperture may vary with variations in stresses and/or strains within the foundation, due to changes in the reservoir level or due to changes in the structure's temperature, which give rise to arch displacements towards upstream, if the temperature increases, or towards downstream otherwise. Even slight changes in apertures can lead to significant changes in the quantity of water flowing through the discontinuities. Changes in flow patterns cause changes in mechanical loads, which, in turn, are responsible for changes in the state of stress. Although this hydro-mechanical behaviour of rock joints has been the subject of extensive laboratory and in situ research, the application of such results to the field conditions of dam foundations is still difficult.

In this paper, after a brief description of Alqueva arch dam, the numerical mechanical and hydraulic models are presented. The mechanical model, which was validated against field data, made it possible to obtain stresses in the areas in which water flowed, which had been identified with *in situ* tests [1]. The hydraulic model was developed in accordance with knowledge of actual seepage paths and was calibrated for different reservoir levels taking into account recorded discharges. The results from both models allowed us to establish stress/permeability curves for some areas of the dam foundation. This data was introduced into the hydraulic model, allowing discharges to be calculated for different water levels. A comparison of numerical and recorded discharges is presented, showing the accuracy of the numerical results.

General description of Alqueva dam

Alqueva dam (Figure 1) is located on the River Guadiana, in the southeast of Portugal, and is the main structure of a multipurpose development designed for irrigation, energy production and water supply. It is a double curvature arch dam, with a maximum height of 96 m and a total length of 348 m between the abutments at the crest elevation. The powerhouse is located at the toe of the dam with a dam-wall downstream [2]. The foundation consists of green schist of good quality on the right bank and the river bottom and of quite good phyllite on the left bank. The area of the phyllite is crossed by several faults, of which the most important is fault 22, along which the green schist/phyllite interface occurs.

For foundation seepage control, grout and drainage curtains were installed from the foundation gallery of the dam and of the downstream dam-wall. To evaluate the efficiency of the relief system a network of piezometers was installed.

The first filling of the reservoir began in February 2002 and is still under way.

Figure 1: Downstream view of Alqueva dam

Numerical mechanical and hydraulic models

Three-dimensional global mechanical and hydraulic models of the entire structure and foundation were developed using the code 3DEC [3], which is a discrete element code developed mainly for discontinuous media, particularly in rock masses. Special routines are included in the 3DEC code which allow the adequate geometric fitting of the concrete structure, represented by finite element blocks, and the rock mass in the foundation, represented by regular polyhedral deformable blocks [4].

Mechanical model

The global mechanical model developed in order to assess stresses in the foundation rock mass is shown in Figure 2. This model includes the location of fault 22, so as to simulate the area of lower modulus of elasticity, where the phyllite occurs. Phyllite deformability is assumed above the lower wall of the fault and green schist deformability in the remaining rock mass. Fault 22 is assumed to be 10 m wide. The dam is simulated by a group of FE elastic blocks separated by joints, which represent vertical contraction joints. In the foundation, due to the size of the area being studied, zone sizes are very large. In order to simplify the model, the grout curtain is modelled adjacent to the upstream edge, not underneath the dam itself. A joint is assumed at the dam/rock mass interface ("foundation joint"), and, as the grout curtain is simulated adjacent to the upstream edge, two hypothetical joints were assumed between the grout curtain and the rock mass, at the upstream and downstream faces of the grout curtain, respectively ("grout curtain/rock interface"), so as to estimate the aperture of discontinuities in the uppermost strata of the foundation. The grout curtain/rock interface is considered only in an area which encompasses the valley bottom and the base of each slope (between dam joints 6 to 21).

Both dam concrete and foundation, as well as the dam contraction joints, are assumed to follow elastic linear behaviour. Foundation joint and grout curtain/rock interface are assigned a Mohr-Coulomb constitutive model. Dam Young's modulus is assumed to be 20 GPa. It is assumed that rock mass Young's modulus is 10 GPa where schist occurs and that the phyllite area is two times more deformable. Grout curtain properties are the same as those in the rock mass foundation, either schist or phyllite. Non-linear behaviour of both the upstream area of the foundation joint and of the grout curtain/foundation interface was assumed, with a friction angle of 35° and zero cohesion and tensile strength.

Dam and foundation displacements and stresses were obtained considering three successive loading stages: i) *in situ* stresses due to the weight of the rock mass, before dam construction; ii) dam weight; and iii) hydrostatic load at various reservoir elevations.

Comparison of recorded and numerical results (arch displacements, vertical displacement at foundation joint, stresses in the foundation rock mass due to increase in reservoir level and aperture of discontinuities through which water flows) showed that the geomechanical model developed is quite realistic, simulating the actual dam/foundation behaviour reasonably well.

The mechanical model described allows the calculation of stresses for different reservoir and tailwater levels. However, it does not take into account the influence that variations in ambient and reservoir temperature have on the arch's displacements and, consequently, on variations in rock mass stresses.

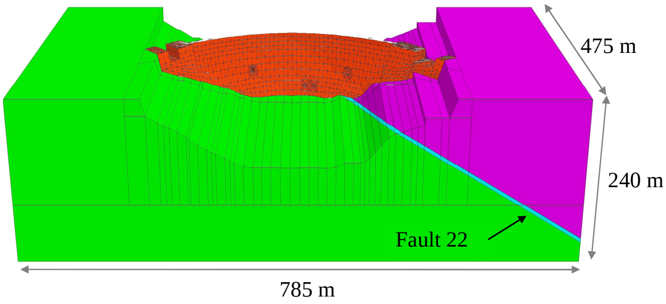


Figure 2: Perspective of the global mechanical model

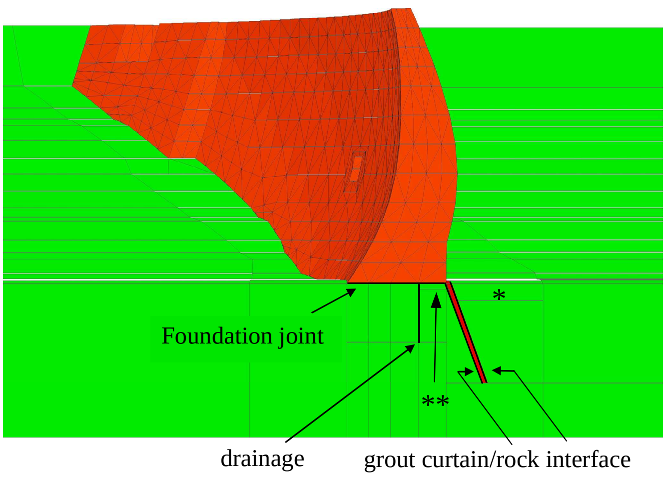
Hydraulic model

A simplified global hydraulic model of the dam foundation was developed, in which the drainage system is simulated in a simplified way by a hypothetical continuous trench with the same depth as the drains. The existence of vertical fissures at the heel of the dam is simulated by a near-surface area of higher permeability upstream from the grout curtain, between dam joints 6 to 21. Horizontal layers of higher permeability between the above-mentioned near-surface area and the drainage curtain are assumed close to the concrete/rock mass interface to simulate the main seepage paths. Figure 3 shows the relative position of the grout and drainage curtains, of the near-surface area of higher permeability upstream from the grout curtain and of the horizontal layers of higher permeability. The foundation joint and the grout curtain/foundation interface are also represented.

In the foundation of some of the dam blocks located in the valley bottom, the permeability of the horizontal layers between the near-surface area of higher permeability and the drainage curtain was adjusted in order to obtain numerical discharges close to average discharges recorded in October 2006, with the reservoir at an elevation of 143.6 m (H) and the water downstream from the dam-wall at an elevation of 81.95 m.

Comparison of both numerical and recorded discharges and water pressures showed that the model can provide mean water pressures and flow rates for each dam foundation block. Figure 4 shows how close the total discharges recorded in arch blocks located in the valley bottom and at the base of each slope (between dam joints 6 and 21) are to the numerical results obtained with the foundation model described above.

Figure 5 shows the hydraulic head contours. The graphical interface used to show the results (GID) only shows the hydraulic head contours on block surfaces, therefore when the phreatic surface is below the top of the block, that block appears empty. In order to represent the hydraulic head more accurately it is necessary to show cuts, as in Figure 6. In this figure part of the drainage curtain is visible in the cut perpendicular to the main river channel
Comparisons between recorded and numerical discharges for other water levels led to the conclusion that the apertures of the discontinuities through which water flows vary with changes in reservoir level, as the model overestimates discharges for reservoir levels lower than 143.6 m and underestimates discharges for water levels higher than that. It was concluded that the model can not be employed for the lower reservoir levels.



* near-surface area of higher permeability upstream from the dam
** horizontal layers of higher permeability

Figure 3: Three-dimensional global mechanical and hydraulic models

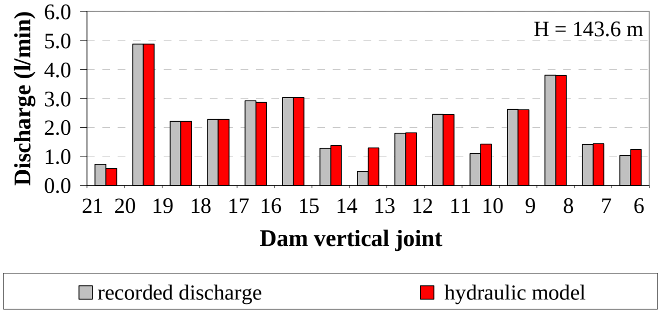


Figure 4: Recorded discharges in the foundation of each arch block located in the valley bottom and at the base of each slope and comparison with numerical results

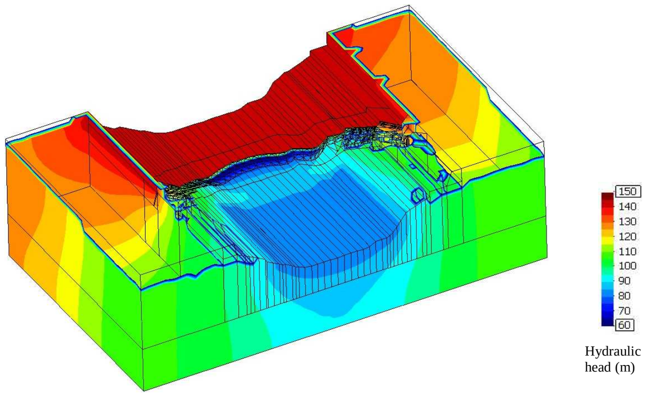


Figure 5: Hydraulic head contours (m) in the global hydraulic model of the dam foundation

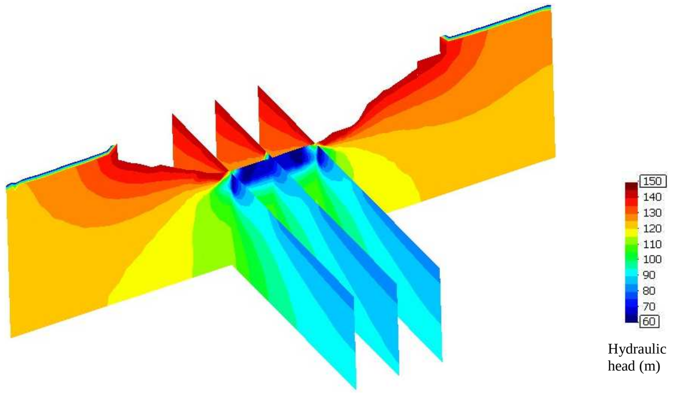


Figure 6: Hydraulic head contours (m) in three cuts parallel and in one cut perpendicular to the main river channel, shown in their relative positions

Relation between stress and permeability

To establish the relation between stress and permeability, the numerical hydraulic model was first run for different reservoir levels and, for each level, the permeability of the horizontal layers which simulate water conductive joints was adjusted so that numerical discharges in the foundation of each dam block were close to recorded discharges. Secondly, the mechanical model was run assuming the same water levels, and average vertical stresses in the foundation blocks below the heel of the dam which, in the hydraulic model, simulate water conductive joints were obtained. Finally, the above-mentioned results of both models allowed the plotting of graphs of stress versus permeability, from which a different relation for some dam blocks could be established.
In order to assess the dependence of permeability on stress, ensuring that discharges were mainly due to the effect of the hydrostatic loading, with small changes due to variations in dam temperature, only discharges recorded in the same month (February/beginning of March) were taken into account. Recorded discharges with the reservoir at low elevations were

neglected, as it had been concluded that the hydraulic model could not be employed for the lower reservoir levels. Discharges monitored on six different dates were considered, with the reservoir level varying around 18 m, from 132.2 m up to 150.1 m.

Recorded discharges in the foundation of the dam blocks located in the valley bottom and at the base of each slope on the above-mentioned dates showed that field data is not always consistent, as discharges do not always increase with the reservoir level. Around 20% of the readings were discarded due to inconsistency.

Permeability depends not only on average vertical stresses but also on local geological features, which vary from one dam foundation block to another. Therefore, to establish stress/permeability curves taking into account the influence of local geology it was necessary to choose a reservoir level as a reference and to plot graphs, for each dam block, of (σ_{yy} / $\sigma_{yy\ ref}$) versus (k / k $_{ref}$), where σ_{yy} is the vertical stress and k is the equivalent permeability of the horizontal layers which simulate water conductive joints. When a water level is chosen as a reference and regression analysis is used to adjust curves to the values obtained, more weight is given to the permeability and stress obtained with that level. In order not to give more weight neither for the higher levels nor for the lower, monitored discharges and stresses obtained with the reservoir at 144.8 m, approximately mid-way between the lowest and the highest reservoir levels considered in the analysis, were used as reference.

Figure 7 shows the variation of the permeability of the horizontal layers which simulate conductive joints below the heel of the dam of four arch blocks with vertical stress. Exponential curves were adjusted to each block's set of data, using regression analysis, and the R-squared values, displayed on the Figure's charts, varying from around 0.81 to 0.99, show that this type of curves fit the available data well. Figure 7 analysis shows that variations in vertical stresses have less influence on permeability in the more pervious layers in the foundation of blocks 12-13 and 16-17, and a large effect in blocks 8-9 and 19-20.

Discharges in each dam block were afterwards determined using the established curves shown in Figure 7, and the numerical results were compared with recorded discharges. The charts in Figure 8 show the accuracy of numerical results when shown alongside recorded discharges. In this figure, dam blocks in which the hydro-mechanical effect was considered are highlighted with an arrow.

Relation between permeability and local rock mass deformability

According to most authors it is more correct to relate permeability with strain than with stress, in an equivalent continuum, as the aperture of discontinuities with a very high

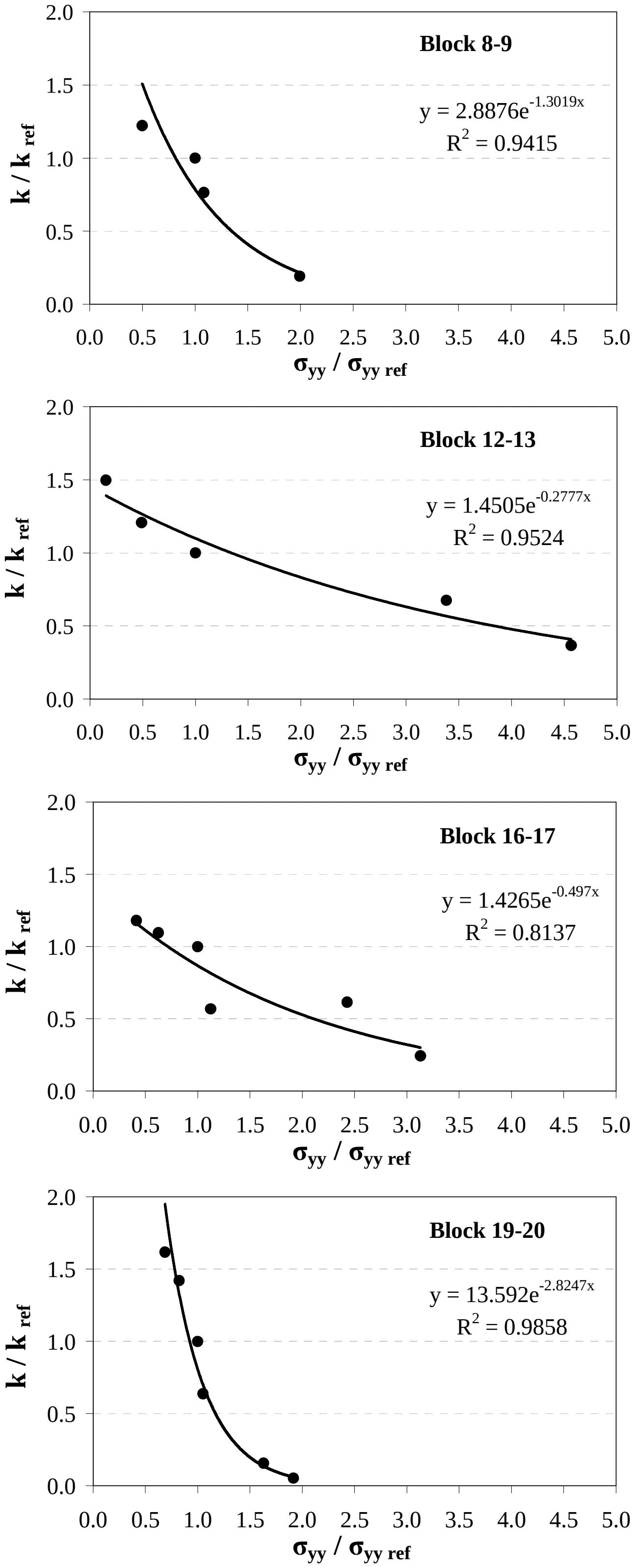


Figure 7: Variation of the permeability of the horizontal layers which simulate conductive joints below the heel of different dam blocks with vertical stress. Adjustment of exponential curves

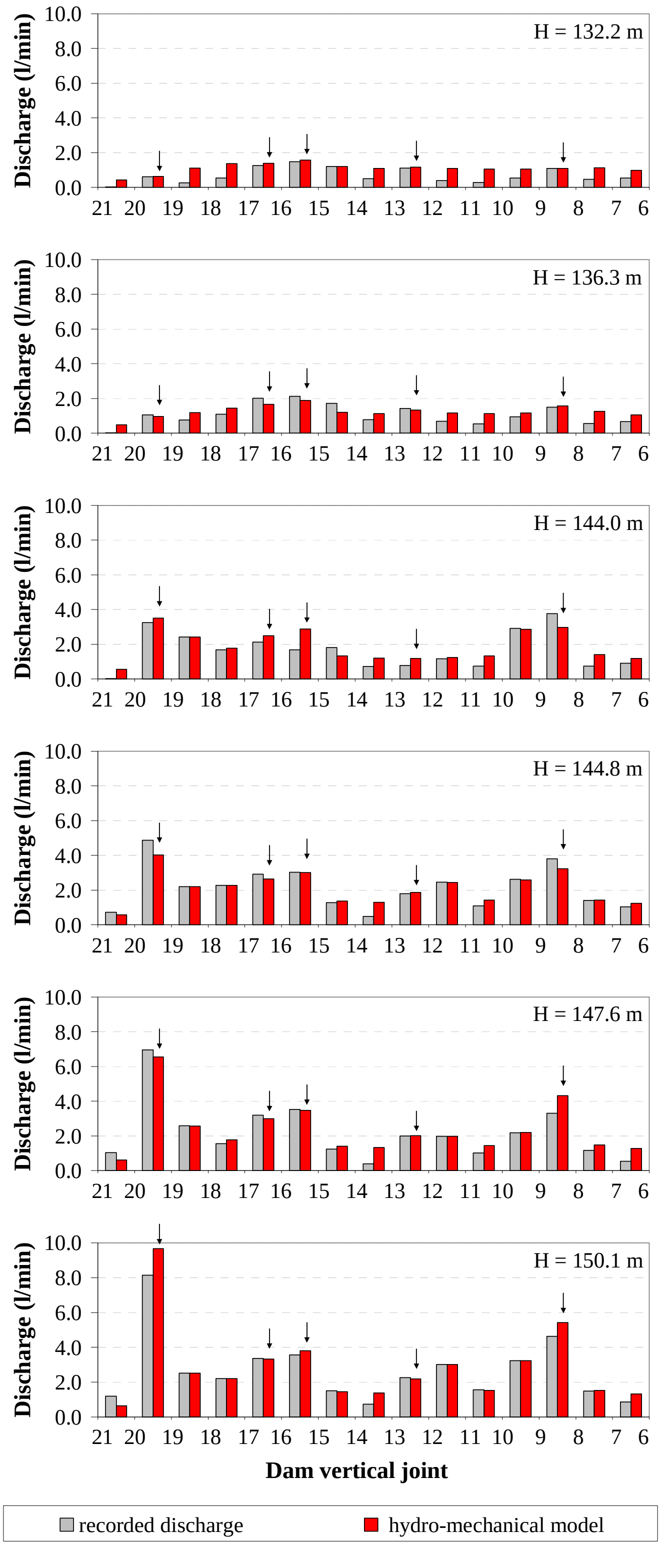


Figure 8: Recorded discharges in the foundation of each dam block with different reservoir levels and comparison with the results of the uncoupled hydro-mechanical model

normal stiffness barely changes with variations in stresses [5], [6].

The curves which establish the dependence of permeability on stress, shown in Figure 7 follow the pattern:

$$k_{horizontal} = k_0 \; e^{-\alpha \, \sigma_{vertical}} \tag{1}$$

Taking into account that stresses in the vertical direction are given by:

$$\sigma_{vertical} = E \; \varepsilon_{vertical} \tag{2}$$

the stress can be replaced by the strain, and equation 1 can be written in the following way:

$$k_{horizontal} = k_0 \; e^{-\alpha \, E \, \varepsilon_{vertical}} = k_0 \; e^{-\beta \, \varepsilon_{vertical}} \tag{3}$$

In the previous equation,

$$\beta = \alpha \; E \tag{4}$$

Assuming that the average value of β is given by

$$\overline{\beta} = \overline{\alpha} \; \overline{E} \tag{5}$$

and that the rock mass is the same in every foundation block, with an average Young's modulus of 10 GPa, the different curves shown in Figure 7 can be due to differences in the horizontal layer's deformability. In dam blocks 8-9 and 19-20, the curves are steeper, therefore the horizontal layers of higher permeability are probably in more deformable rock mass areas, with a Young's modulus lower than that assumed. On the contrary, the curves established for dam blocks 12-13 and 16-17, which are less steep, probably correspond to rock mass areas with a higher Young's modulus.

The arithmetic mean of the different α determined in the curves established for the five different dam blocks is 1.05, therefore the average value of β is 10.5. Table 1 shows the Young's modulus of each layer, determined by:

$$E_i = \frac{\overline{\beta}}{\alpha_i} \qquad i = 1 \; to \; 5 \tag{6}$$

TABLE 1: YOUNG'S MODULUS OF THE HORIZONTAL LAYERS OF HIGHER PERMEABILITY IN THE FOUNDATION OF DIFFERENT DAM BLOCKS

Dam block	Young's modulus of the horizontal layer of higher permeability (GPa)
8-9	8.03
12-13	37.67
15-16	31.83
16-17	21.05
19-20	3.70

Taking the highest Young's modulus as a reference (block 12-13), analysis of Table 1 leads to the conclusion that the layer in the foundation of block 15-16 is 1.2 times more deformable, that in block 16-17 is 1.8 times more deformable, that in block 8-9 is 4.7 times more deformable, and that in block 19-20 is 10.2 times more deformable.

The modulus of deformation of the rock mass is given by:

$$\frac{1}{E_{RM}} = \frac{1}{E_R} + \frac{1}{k_n\ s} \qquad (7)$$

where E_R is the modulus of deformation of the rock matrix, k_n is the fracture normal stiffness, and s is fracture spacing. Therefore, when the normal stiffness is very high, the dominant term is $1/E_R$, and when normal stiffness is low, the dominant term is $1/(k_n\ s)$. It is concluded that, in a discontinuum model high normal stiffness numbers should be considered in the more pervious layers in blocks 12-13, 15-16 and 16-17, and low numbers in blocks 8-9 and 19-20.

Conclusion

This paper presents a methodology which can be used to establish rules which, from a hydraulic model calibrated for a specific water level in the reservoir, allow the calculation of discharges for both higher and lower reservoir levels, taking into account that permeability depends not only on the stress level but also on local geological features. This simple methodology, which uses an uncoupled mechanical-hydraulic analysis, has been applied successfully in the analysis of recorded discharges in the foundation of some blocks of Alqueva dam. The simplicity of the method makes it very useful in the safety assessment of concrete dams.

Due to the influence of local geology it was found that it was impossible to establish a single rule relating stress and permeability, and therefore different rules were established for different foundation areas. Exponential laws were found to fit the considered data well.

Study of the hydro-mechanical interaction required a careful selection of recorded discharges, in order to use only coherent data. Incoherent field data is due to the fact that discharges depend not only on discontinuities' aperture but also on seepage paths, which may vary with changes in the reservoir level or ambient temperature. When these changes occur, a portion of the water that flows into the foundation of one of the dam blocks can change its path and flow into the foundation of adjacent blocks, as a result of the opening and closure of discontinuities

Equivalent continuum models were used to carry out both 3D hydraulic and mechanical analysis. In the simplified global hydraulic model of the dam foundation the main seepage paths were simulated by regions of different permeability. Although models of flow in discontinuous rock masses are available, the complexity of jointing patterns and the lack of data on hydraulic properties of the discontinuity sets makes them difficult to apply in most practical cases. Thus, the assumption of an equivalent continuum remains the most widely used tool to study the hydraulic behavior of dam foundations.

Acknowledgements

Thanks are due to EDIA, Empresa de Desenvolvimento e Infra-Estruturas do Alqueva, SA for permission to publish data relative to Alqueva dam.

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