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NUMERICAL MODELLING OF INLET WATER TESTS

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ABSTRACT: Inlet water tests allow measurement of discharges and water pressures in isolated sections of boreholes. A series of inlet water tests were carried out in an area of the foundation of an arch dam. In this paper, after a brief description of the tests, detailed three-dimensional numerical models developed for the analysis of the tests data are presented. Numerical and experimental results are compared and some conclusions are drawn about the usefulness of the information provided by inlet water tests and about suitable models to study the dam foundation's hydraulic behaviour.

KEYWORDS: Concrete dams; Rock foundations; Hydraulic behaviour; Inlet water tests; Numerical models

INTRODUCTION

The behaviour analysis and safety assessment of concrete dams involves the modelling of the foundation's hydraulic behaviour in normal operating scenarios. Models used to analyse the hydraulic behaviour of dam foundations must not only simulate flow with reasonable accuracy but also be realistic and computationally efficient. Although a wide variety of models suitable for the analysis of rock masses are available, their use in the interpretation and operational monitoring of the hydraulic behaviour of dam foundations is not common. To study the hydraulic behaviour in detail three-dimensional models of foundation rock masses should be used. To make more widespread the use of these models to interpret dam behaviour it is necessary to check methods reliability, comparing the numerical results with analytical solutions, whenever possible, and with the results of other methods, tests, and monitoring data (Lemos 1999).

In a rock mass the majority of the flow takes place through an interconnecting system of discontinuities. Models of flow in discontinuous media are available but difficult to apply in most practical cases, thus the hydraulic behaviour of dam foundations is usually studied using equivalent continuum models.

The monitoring data usually available gives no information about the depth at which the main seepage paths cross the drains or about the distribution of water pressures along the piezometric boreholes. Inlet water tests with single and double packers, which allow measurement of discharges and water pressures in isolated sections of the holes, can be very useful to better define the complex flow system in site-specific zones of the foundations of dams in use.

In this paper, after a brief description of inlet water tests, the data obtained in a series of tests are analysed. These tests were carried out in an area of the foundation of Alqueva dam – a double curvature arch dam recently built in the southeast of Portugal – in order to understand the results of the hydraulic monitoring system. Numerical models were developed for the analysis of the flow in site specific areas of the rock mass and to support the field results. A comparison between numerical and experimental results is presented. Some conclusions are drawn about the usefulness of the information provided by inlet water tests and about suitable models to study the dam foundation's hydraulic behaviour.

INLET WATER TESTS

The main aim of inlet water tests is to understand the way in which flow occurs in a site-specific area of the foundation. These tests consist only of measuring the discharges and water pressures in isolated sections of boreholes. Figure 1 shows the various stages in which inlet water tests are carried out: in a single borehole, fixed test intervals are considered and isolated and the hole is tested in consecutive sections along its length. For each test interval, flow rates and water pressures are recorded until steady state conditions are achieved. This data is collected not only in the hole being tested, as shown in Figure 1, but also in the nearby boreholes.

Inlet water tests are better carried out with both single and double packers, as the two sets of results provide different and additional information. In the former case the test interval is defined by the bottom of the borehole and the packer and in the latter is the area between the two packers.

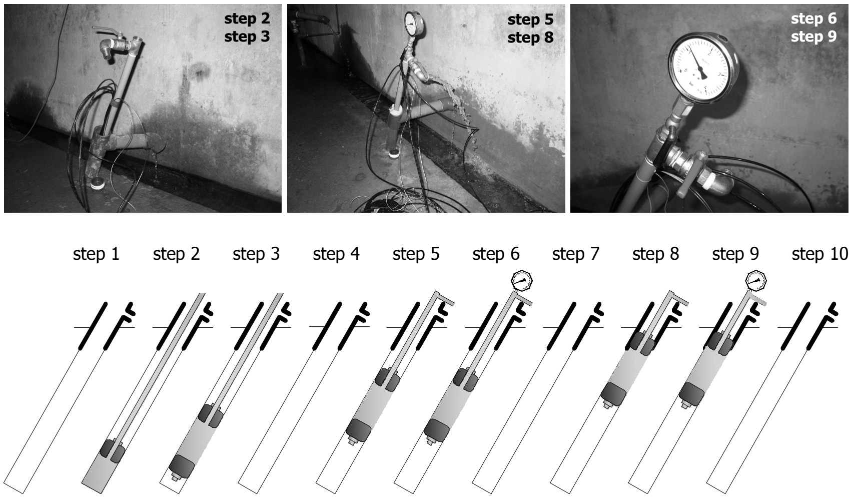

Figure 1. Borehole inlet water tests.

Inlet water tests are rarely applied but can be very useful in investigating fluid flow through the foundation of dams in use. These tests provide valuable information about:

i) the depth at which the main seepage paths cross the boreholes;
ii) the distribution of discharges and water pressures along the boreholes; and
iii) seepage paths linking different boreholes.

The simultaneous analysis of uplift water pressures and discharges at each test interval can give information about the aperture of the discontinuities through which water flows.

The analysis of data collected in these tests should be carried out also considering other available information, such as geological and geotechnical data of the dam-site, boreholes logs, information given by the borehole driller, and results of other complementary tests, including electrical conductivity tests and chemical analysis of water (pH values, concentration of calcium, sodium, sulphates and total dissolved solids).

TESTS CARRIED OUT IN ALQUEVA DAM FOUNDATION

General description of Alqueva dam

Alqueva dam (Figure 2) is located on the Guadiana River, 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 (EDP 1988).

The foundation consists of green schist of good quality on the right bank and the river bottom and of quite good phyllite, with several faults, on the left bank.

For foundation seepage control, grout and drainage curtains were installed from the foundation gallery of the dam and of the downstream dam-wall. Drainage boreholes are located 3.0 m apart. To evaluate the efficiency of the relief system a network of piezometers was installed. Figure 3 shows the central cross section of the dam, which measures 140 m.

Figure 2. Alqueva dam.

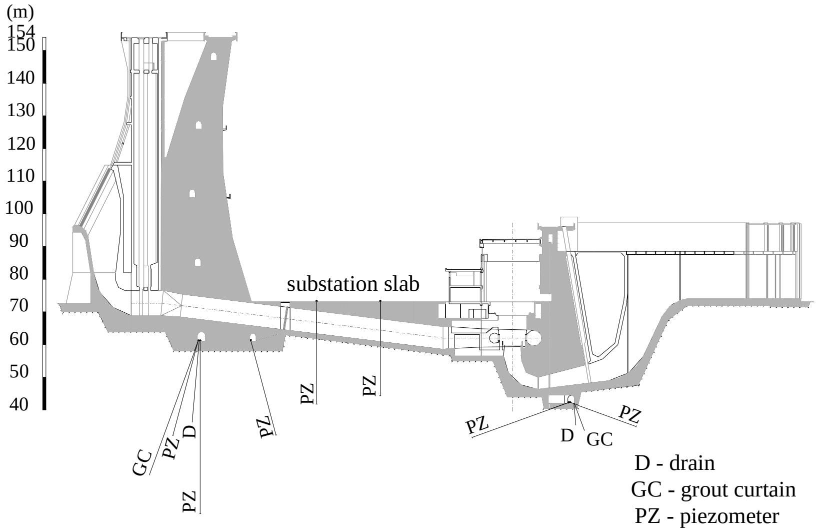

Figure 3. Central cross section of Alqueva dam.

Inlet water tests and water electrical conductivity analysis

Inlet water tests in six drainage and piezometric boreholes were carried out in the area of the foundation where the highest discharges are recorded, where the bottom of the valley meets the right hand side abutment. Tests were carried out in three different weeks with the reservoir at various elevations: in October 2006, with water level around 143.6 m; in March 2007, with the water level around 150.0 m; and in September 2007, with a water level of about 148.0 m.

In May 2007, with the reservoir at around 149.3 m, water electrical conductivity and temperature analysis tests were carried out in the majority of the drainage boreholes located in the bottom of the valley and in the first two blocks at the base of the slope, on the right bank. The electrical conductivity of water is a parameter which can be easily and quickly measured and usually provides information about the depth at which seepage paths cross each one of the holes, unless the discharge is high, which leads to similar readings along the borehole, or very low, which makes seepage paths undetectable.

Main conclusions drawn from tests

Tests carried out in Alqueva dam foundation led to the conclusion that water flows into the majority of the boreholes in an area very close to the concrete/rock mass interface. Figure 4 shows where water flows into each borehole in the area where the bottom of the valley meets the right hand side abutment. From the inlet water tests it was also possible to conclude that, in this area of the rock mass, discontinuities through which water flows have a very small width, as recorded discharges and water pressures in the borehole's area of influence only stabilize after about an hour and a half.

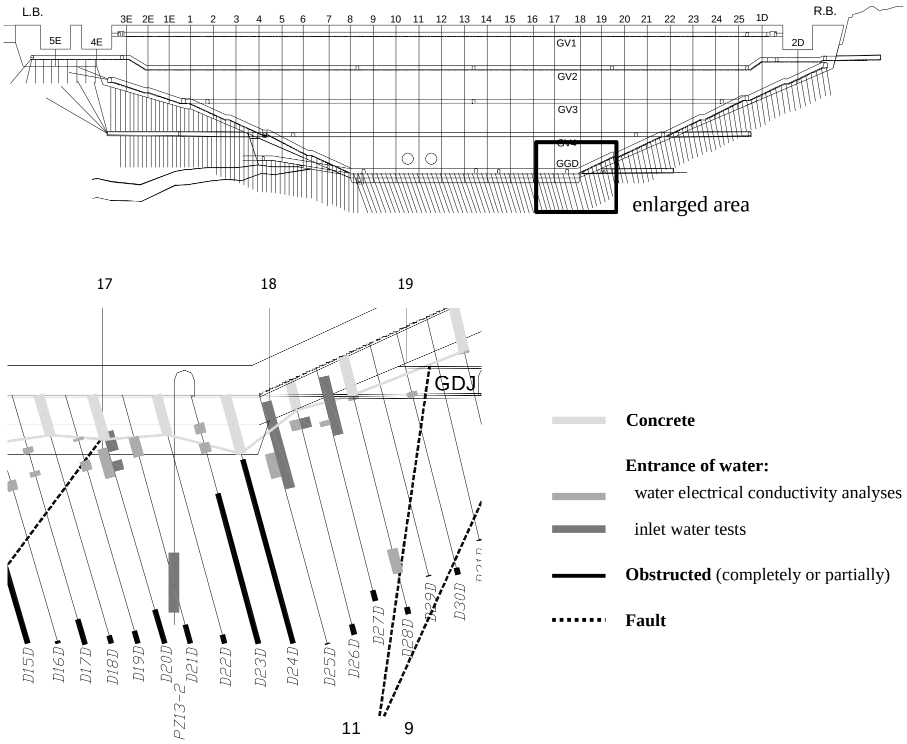

Figure 4. Entrance of water into each borehole in the area where the bottom of the valley meets the right hand side abutment.

NUMERICAL MODELLING OF TESTS

Model description

Modelling each one of the drains in three-dimensional models of dam foundations leads to excessively fine meshes, which are very difficult to use. However, these models are extremely useful in the analysis of seepage in site-specific areas, when relatively small foundation volumes are involved and a low number of drains are modelled.

A detailed 3D model was developed, formed by a series of adjacent vertical strips, which extend from about 50.0 m upstream from the upstream face of the dam to 50.0 m downstream from the dam-wall. Strips have two different widths: the inner strips are 3.0 m wide, the distance between drains, and, due to symmetry, the outer strips are 1.5 m wide, corresponding to half the distance between drains. Each strip has a vertical length of 78.0 m. The modelling of each strip takes into account both the horizontal and vertical curvatures of the dam where it meets the foundation. Figure 5 shows the position of the foundation model in the area where the bottom of the valley meets the right hand side abutment. This model includes three drains, thus being only 9.0 m wide.

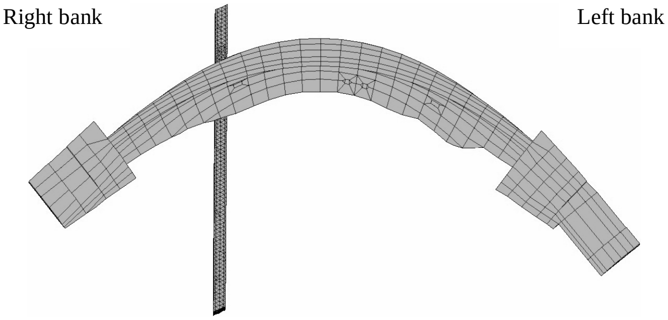

Figure 5. Position of the foundation model 9.0 m wide in the area where the bottom of the valley meets the right hand side abutment. View from above.

It is assumed that the grout curtain, which crosses the whole model width, is 1 m wide. Drains are modelled by the axis (diameter zero), with the same length as the holes drilled in the foundation. The relative position of the grout and drainage curtains is respected, but, to simplify the model, the drainage curtain is assumed to be vertical.

The main weakness of this model is the assumption that, in the area being studied, water flows in the upstream-downstream direction, parallel to the main river channel.

In the numerical models presented, it is assumed that the foundation rock mass is homogeneous and isotropic and that the grout curtain is 10 times less pervious. Numerical analysis was carried out with the code 3DEC (Itasca 2003), which simulates the media as a group of convex blocks internally divided into tetrahedra. 3DEC is a discrete element code developed mainly for block systems. The results presented, however, are based on an equivalent continuum model, all blocks assumed to be joined. The mesh is finer close to the drains and along the drains' whole length and was defined by the average edge length of the tetrahedral zones. Studies about two and three-dimensional modelling of seepage in concrete dam foundations previously carried out with codes FLAC (Itasca 2002) and 3DEC led to the conclusion that, in both 2D and 3D analyses, when the drain is modelled by its axis the most suitable size of the elements in the vicinity of the drain is about three and a half times the drain diameter (Farinha and Lemos 2006). Figure 6 shows the division into blocks and internal mesh generation of a 1.5 m wide strip, as well as the position of the grout curtain and the drain, of which the depth is about half of the grout curtain's length.

Hydraulic boundary conditions

Numerical analysis was carried out assuming the water level in the reservoir and the hydraulic head recorded at the piezometers installed at the substation slab, at the toe of the dam. The hydraulic head along each drain is the same as the drain head's elevation.

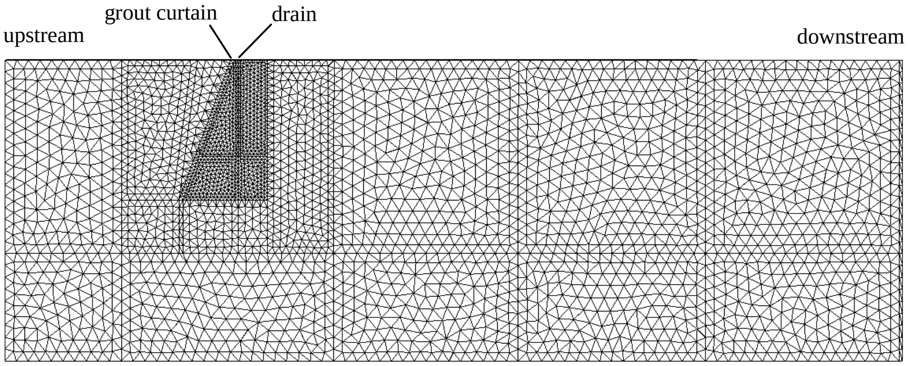

Figure 6. Cross section of the three-dimensional model of the foundation. Division into blocks and internal mesh generation.

Numerical experiments

Inlet water tests carried out in some drains have been simulated using models 9.0 m wide which include the drain being tested and the two adjacent drains. The following paragraphs present a description of the model's development for drain D25 D, where only a single inflow of water into the borehole was observed.

Results on two different dates had been recorded with differences in the water level in the reservoir of 6.5 m. The model should simulate two different situations:

i) the water flowing in normal operating conditions;
ii) drain D25 D closed.

In this study the closed borehole was simulated with the same hydraulic head along the whole borehole's length, at the same time not allowing water to flow out of the hole. Areas where flow paths cross the drains were modelled by bands of elements of higher permeability.

The model was progressively developed and calibrated, in various steps. In each step the two situations to be simulated were taken into account and the different parameters were adjusted in order to make the numerical results correspond more closely to those observed.

Firstly, a homogeneous and isotropic media was assumed and the rock mass hydraulic conductivity necessary to obtain the average value of the discharges in drain D25 D's area of influence was determined. Secondly, a near-surface area of higher permeability upstream from the dam was considered, in order to simulate the existence of vertical fissures at the heel of the dam. These fissures are opened by the development of tensile stresses in this area, due to the filling of the reservoir. Thirdly, a horizontal layer of higher permeability between the upstream area and the drains was considered, corresponding to the orientation of one of the main joint sets in this area. This layer crosses the grout curtain, simulating a probable area of the foundation where the total sealing of discontinuities with very small apertures was not achieved (gap in the grout curtain). The layer width was gradually changed, in order for numerical values to correspond to recorded discharges and water pressures. Finally two different layers were modelled upstream from drains D25 D and D26 D; both layers are 3.0 m deep but the layer at D26 D is 2.0 m higher to take into account the point at which discontinuities cross each one of the drains. With this final change numerical results were closer to observed values.

Numerical results were compared to the monitoring data collected in October 2006 and in March 2007. Figure 7 shows the parameter values used in the final model.

Results analysis

In October 2006, discharges of about 3.33×10^{-5} m^3/s (2.0 l/min) were recorded in drain D25 D and, when the drain was closed, a water pressure of 4.83×10^{2} kPa (4.83 bar) was reached, which corresponded to almost 60 % of the hydraulic head. In March 2007 it was observed that the increase in the water level in the reservoir from elevation 143.6 m up to elevation 150.0 m led to a slight increase not only in flow rates recorded in the drain being tested and in the two adjacent drains (8.5 % up to 19 %) but also in the water pressure when the drain was closed (about 9 %).

Taking into account the boundary conditions in October 2006, the numerical value of the discharge at drain D25 D is 3.63×10^{-5} m^3/s (2.18 l/min), which is about 8 % higher than that recorded. The water pressure is 4.18×10^{2} kPa (4.18 bar), 13 % lower than recorded. Differences of the same order, in percentage, to recorded discharges and water pressures are found in the adjacent drains, which can be considered sufficiently accurate.

Results analysis also led to the conclusion that there is no change in the layers' hydraulic aperture due to increase in the water level in the reservoir from elevation 143.6 m up to 150.0 m. The model's assumed rock mass hydraulic conductivity corresponds to the results of "in situ" permeability tests. The layers upstream from the drains simulate horizontal discontinuities with an average hydraulic aperture of 0.16 mm.

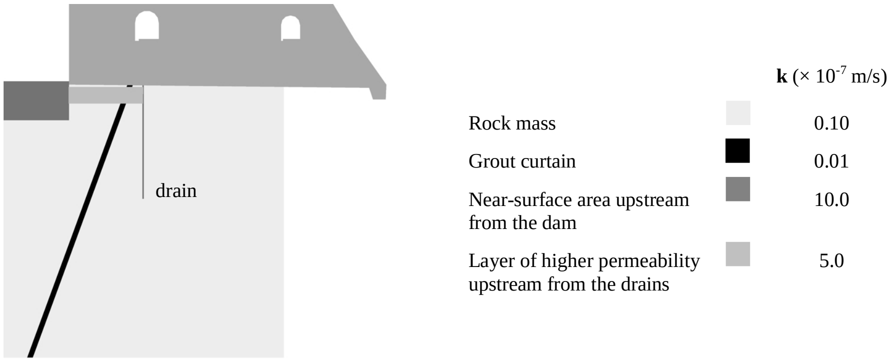

Figure 7. Seepage model in the vicinity of drain D25 D. Model parameters.

CONCLUSIONS

Inlet water tests provide additional information to the usual monitoring data, which improves our ability to analyse the behaviour of concrete dam foundations. The information provided by these tests can be used not only to validate hydraulic models and to improve numerical models that take into account the existence of rock mass discontinuities, but also to choose the best place to locate piezometric chambers or to choose suitable remedial or supplementary seepage control measures in areas of the foundation where the discharges and/or the uplift pressures are excessive.

A numerical simulation of inlet water tests has been carried out, in which results of rock mass permeability tests and areas where seepage paths cross each borehole are taken into account. Models of flow in discontinuous rock masses are difficult to apply in most practical cases but the analysis presented here shows that equivalent continuum models can be used successfully to model the hydraulic behaviour of site-specific areas of the foundation. Models developed are very simple and only a few parameters are used, all of them with physical meaning. Models are validated against data collected “in situ”.

Further work is under way to use the information provided by inlet water tests to improve models that take into account the interaction between the hydraulic and the mechanical behaviour of the dam foundation.

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