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QUANTITATIVE INTERPRETATION OF DISCHARGES RECORDED IN CONCRETE DAM FOUNDATIONS

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Abstract. *This paper presents a study focused on the viability of using simplified statistical methods of quantitative interpretation in the analysis and prediction of foundation behaviour. The shape of the curve which represents the influence that changes in reservoir level have on discharges in a concrete dam foundation was established using a hydromechanical numerical model. Discharges recorded in both single drains and seepage measuring weirs of two large Portuguese dams were analysed. The study carried out highlights the difficulties in interpreting recorded discharges, as they are not the sum of a series of structural responses which can be clearly identified. Conclusions are drawn regarding the accuracy of these methods when used in the analysis of the hydraulic behaviour.*

1 INTRODUCTION

The behaviour of an operating dam can only be properly understood through the careful interpretation of the readings from the most relevant instruments, based on their analysis over time. This gives the best indication of how the dam is going to behave in the future and provides a means to detect the occurrence of sudden or gradual changes in dam behaviour, which may require further attention.

The evaluation of the dam's actual performance during normal operation, particularly the foundation, and its safety assessment are greatly improved if the monitoring data is compared with predicted values by means of models, which conceptually simulate dam behaviour. These can be either numerical or statistical models.

The most representative structural behaviour effects measured on each date, namely displacements, strains and stresses, are mainly the result of the coupled action of variations in the reservoir level and variations in ambient temperature. As these loads act simultaneously, it is essential to separate and identify each one of the loads' contribution to the observed effects, in order to properly analyse and interpret concrete dam behaviour. This separation can be done in a systematic way using quantitative interpretation methods which, from the

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simultaneous consideration of a large number of monitoring results, try to establish a correlation between a given observed structural effect and the variations in each of the main loads.

Quantitative interpretation methods have been regularly employed in the analysis of displacements of concrete dams, which reflect a structural global performance, but are seldom used in the analysis of foundation hydraulic behaviour. In fact, foundation monitoring results include foundation movement, water pressures and seepage, but the use of statistical models of quantitative interpretation to study the behaviour of the foundation, has almost always been limited to the analysis of displacements recorded with plumb lines and foundation extensometers. It is not easy to use these methods to study the hydromechanical behaviour of dam foundations as it is non linear, due to the influence of stress on both permeability and strength and to the possible time gap between the variation in the main loads and the variation in the measurement data. Thus, the principle of superposition of effects must be carefully used.

This paper starts by briefly mentioning the basis of the traditional simplified methods of quantitative interpretation, and previous studies in which these methods were used in the analysis of the foundation hydraulic data. A procedure based on these methods, which was developed for the analysis of the recorded discharges and that takes into account the non-linear hydromechanical behaviour of dam foundations, is then presented.

2 ANALYSIS OF THE MONITORING DATA ON THE BEHAVIOUR OF DAM FOUNDATIONS

2.1 Current practice

In the first phase of dam operation, monitoring data on the behaviour of the foundation is usually compared with the results of models developed in the design stage. Once the first filling of the reservoir has begun and a large number of monitoring results have been collected, quantitative interpretation methods may be used.

The current practice in studies of the behaviour of concrete dam foundations is to:

i) analyse the monitoring data taking into account the variations over time of different measurements (such as total and partial discharges, uplift and corresponding percentage of hydraulic head, and displacements measured in inverted plumb lines and in foundation extensometers);

ii) compare measurements taken on different dates in which the main loads have similar values; and

iii) analyse the correlation between discharges and water levels in the reservoir.

Whenever possible, analysis is carried out in order to correlate readings taken in different instruments. This is the case of discharges and water pressures which are usually analysed together, as their simultaneous analysis provides an indication of the efficiency of both grout and drainage systems (Figure 1a). Seasonal discharges have also been analysed alongside seasonal joint or global dam displacements in the upstream-downstream direction[1] (Figure 1b).

In addition to the above-mentioned analysis, it is also usual to perform statistical studies of quantitative interpretation of the recorded displacements. Regarding the hydromechanical behaviour, only in a few cases is the monitoring data compared with the results of numerical or physical models of the dam-foundation system.

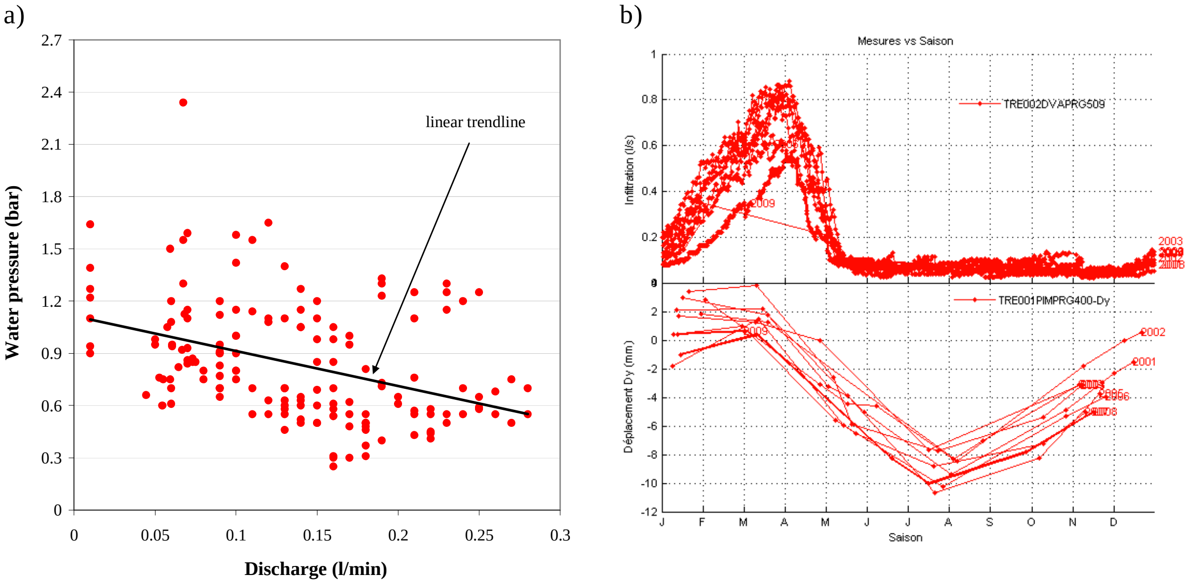


Figure 1: Correlation between discharges and water pressures in the foundation of one block of an arch dam (a) and between discharges and global upstream-downstream displacements (after[1]) (b)

2.2 Quantitative interpretation methods

The first studies on concrete dam behaviour using quantitative interpretation methods analysed recorded displacements, and tried to identify the elastic parts of the displacement due both to hydrostatic pressure and to variations in temperature linked to the annual thermal wave. The part of the displacement which could not be explained by the above-mentioned elastic parts was the “time effect”. A new procedure was later presented, in which the correlations between the main loads and the structural effects took into account the results of structural models[2, 3]. Doboz[4] and Ramos[5] found a way to separate the part that could be explained by the non-elastic behaviour of the dam concrete from the time effect.

Currently, work is focused on the development of models which include thermal corrections to the so called HST models (hydrostatic, seasonal, time models in which it is assumed that the seasonal thermal effects are properly modelled by a cyclical annual wave) by taking into account recorded temperatures. The need for these new models is based on the observation that the HST model is not entirely suitable when there are cyclic water level variations in phase with the seasonal thermal variations, and on the fact that the climate is changing and therefore dams are now subjected to unusual temperature conditions[6, 7].

Quantitative methods have been classified according to the materials´ rheologic behaviour, mainly elastic and visco-elastic, or according to the structural numerical models on which they rely, which are statistical, deterministic, and mixed[8].

In elastic methods, the different effects associated to an observation date *i*, on a given point, are related by means of a function of the type:

$$U_i\,(h_i,\theta_i,t_i) = U_h\,(h_i) + U_\theta\,(\theta_i) + U_t(t_i) + k + r_i = \tag{1}$$

$$= \sum_i a_i\ f_i\,(h) + \sum_j b_j\ g_j\,(\theta)\ + \sum_k c_k\ p_k(t) + k + r$$

where $U_i\ (h_i,\theta_i,t_i)$ is a given observed effect observed on date i, and $U_h(h)$, $U_\theta(\theta)$ and $U_t(t)$ represent, respectively, the parts due to the elastic effect of variations in reservoir water level, due to the elastic effect associated with thermal variations and due to the time effect with the starting point at the beginning of the period under analysis. Each one of these parts can be approximated by pre-established sums of level, temperature and time functions, f_i, g_j, and p_k, and depend on the coefficients a_i, b_j and c_k, which need to be calculated. Separation of effects requires the consideration of the constant k due to the fact that on the observation reference date the calculated value is not zero. The residue r_i represents the deviation between the value observed on date i and the result of the quantitative interpretation model. Thus r_i represents observation errors and errors due to model's unsuitability.

Coefficients a_i, b_j and c_k are determined through the calculation of a system of n equations, in which n is the number of selected observations. The system of equations can be solved by the Gauss criterion which establishes the parameters that minimize the sum of the squares of the errors r_i (least square method). In a quantitative analysis a reference date has to be given in order to calculate the time effect. This date must be prior to the first date considered in the analysis, but the curves obtained are the same regardless of the given date, as the result is adjusted with the independent term (k).

3 QUANTITATIVE INTERPRETATION OF RECORDED DISCHARGES

3.1 Previous studies

The difficulties regarding the quantitative interpretation of discharges and water pressures were highlighted by Fanelli[3] who came to the conclusion that the interpretation of seepage and uplift using deterministic models was not always satisfactory because the elastic scheme very often did not work for the foundation rock mass. He thought that statistical models should be used after being adjusted to the peculiarity of foundation behaviour, and highlighted that equipment installed within the foundation rock mass often showed long time lags and hystereses in relation to variations in external factors (such as variations in reservoir level) and therefore a simple correlation between synchronous values of causes and effects would generally be inadequate. Only a few attempts have been made using statistical modelling in the analysis of piezometric levels and seepage discharges recorded in concrete dam foundations, and are briefly referred to in the following paragraphs.

Breitenstein et al.[9] analysed discharges recorded in five Austrian large concrete dams of the same hydro-electric development using a method of quantitative interpretation in which not only the reservoir level and ambient temperature measured on each date are taken into account but also their variation in the preceding weeks.

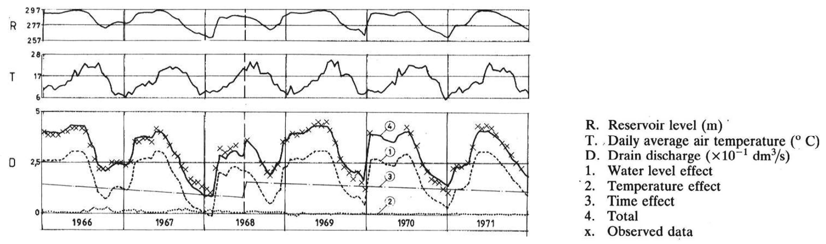
Gomes and Matos[10] analysed drain discharges and water pressures recorded in the foundation of two Portuguese large dams using a procedure in which the curve which represents the influence that changes in reservoir level have on discharges, obtained with a quantitative interpretation, was adjusted taking into account results from a numerical model. Figure 2 shows that the numerical results obtained in both cases are very close to the recorded data.

Guedes and Coelho[11] calculated the piezometric pressure recorded in a piezometer installed in the Funil dam and the seepage discharge close to the Itaipu dam spillway, both in Brazil, using simple methods with only a water height and time, but a time lag taken into account. Results of the quantitative interpretation of discharges are shown in Figure 3.

Silva[12] made quantitative interpretations of discharges and water pressures recorded in the foundation of Cahora Bassa arch dam, in Mozambique, in which the effect of the hydrostatic pressure was represented by a polynomial curve, obtained from data recorded during a period in which the reservoir level had increased significantly.

Lombardi et al.[13] applied an algorithm developed to analyse the functional delays observed in the behaviour of concrete dams, especially those related with the thermal field, in the analysis of discharges recorded in the foundation of an arch dam. A delay of about six days was used for the part of the discharges caused by variations in water level, obtained by an optimisation process.

(a) Cabril Dam — Drain PE 17



(b) Venda Nova Dam — Drain M1

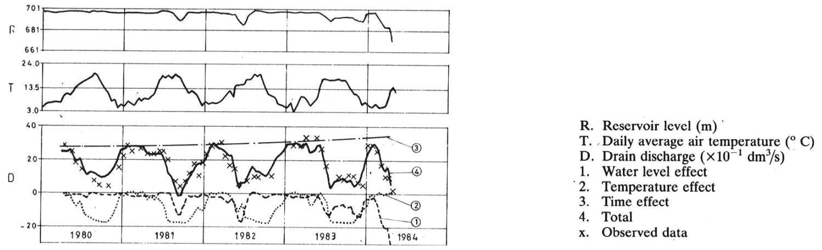


Figure 2: Results of quantitative interpretation of discharges in drains located in a) Cabril arch dam and b) Venda Nova arch-gravity dam, and comparison with recorded discharges (adapted from[10])

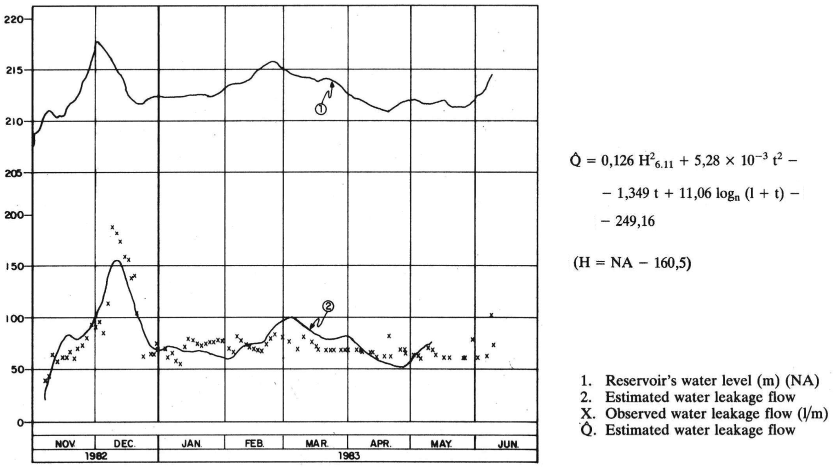


Figure 3: Comparison of the discharges recorded close to the Itaipu dam spillway with the results of a quantitative interpretation (adapted from[11])

3.2 This study

In this study, an attempt was made to analyse recorded discharges using methods of quantitative interpretation, taking into account the non-linear rock mass hydromechanical behaviour. It is generally accepted that water pressures and discharges depend on the foundation deformations. They are thus, theoretically, influenced by the same variables: reservoir level, temperature and time. Whenever seepage discharge is influenced by precipitation, it is appropriate to include this as a variable[14]. The time effect, which when analysing dam displacements can often be explained by the rheologic behaviour of dam concrete or by a swelling process is, in the case of discharges, due to unpredictable effects. These can be changes in seepage paths caused by clearing, erosion or dissolution, or more commonly, clogging of both seepage paths and drainage boreholes, and can not be correlated with variations in the main loads nor be represented by any curve or law. The cyclic variations in both the water level in the reservoir, due to the dam operating regime, and in annual temperature, add complexity to the dam foundation behaviour as they also contribute to changes in seepage paths.

The shape of the curve which represents the influence that changes in reservoir level have on discharges in a concrete dam foundation was first established from the results of a numerical model that properly simulates the hydromechanical behaviour. Using polynomial functions whose graph adequately follows the shape of the above-mentioned line, a series of quantitative interpretation analysis was carried out. Discharges recorded in both single drains and seepage measuring weirs of two different dams were analysed.

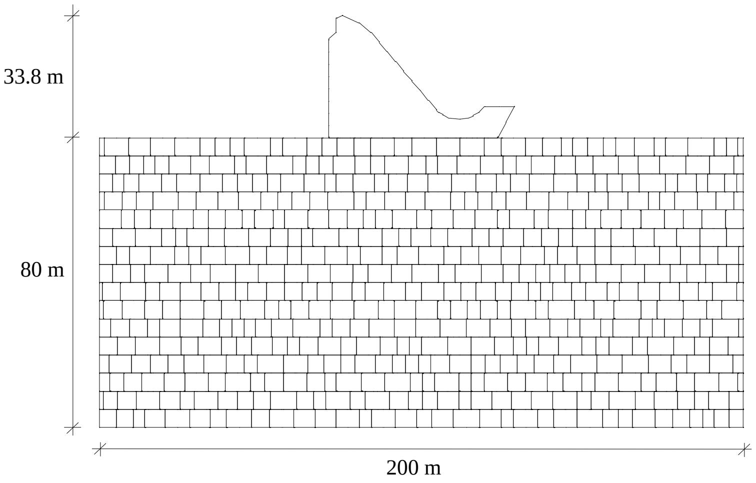
3.3 Variations in discharges due to variations in reservoir level

Due to the hydromechanical behaviour of rock masses, the permeability depends on the state of stress and strain within the foundation and, consequently, discharges vary with these changes in rock mass permeability. The permeability of the rock mass in the upstream area, close to and underneath the heel of the dam, is often greater than that at the downstream area, which causes variations in permeability along seepage paths. In order to be able to separate the effect of the hydrostatic pressure on discharges, the shape of the non-linear curve which represents the relation between the water height in the reservoir and the quantity of water collected in a concrete dam drainage system was established using a two-dimensional discontinuous model of a gravity dam foundation (Figure 4).

Three different rock mass foundations were considered, with the same geometry but with different deformability, with the discontinuities' normal stiffness varying 100 times (k_n = 1 GPa/m, k_n = 10 GPa/m and k_n = 100 GPa/m). A friction angle (φ') of 30° was assumed in the foundation discontinuities, which is close to friction angles commonly observed in rock masses of average quality. The discontinuities' apertures were adjusted in such a way that the discharge at the drainage line with a low reservoir level was the same for the three different models. Analysis was done simulating the filling and subsequent emptying of the reservoir.

Figure 5 shows a series of polynomial curves which were adjusted to the curves that represent the variations in numerical discharges due to variations in reservoir level. In the most deformable foundation (k_n = 1 GPa/m) it was found that a function of the type $q = \mathrm{f}\,(h^4)$ would roughly fit the numerical results. Such deformable concrete dam foundations do not actually exist, as concrete dams are built on rock masses which are not easily deformed when subjected to high stresses. In the stiffer foundations, polynomials of the type $h^3 + h$ or $h^4 + h$ are adequate.

Due to the non-linearity of the model, there are slight differences in the discharges calculated in the load and unload cycles. These differences, however, are lower than 1.7% for the stiffest foundation and lower than 15% for the more deformable rock masses, and thus it can be concluded that with the assumed friction angle the behaviour concerning drain discharges is almost elastic and therefore the use of quantitative interpretation methods is feasible.



Concrete:
unit weight = 2400 kg/m^3
Young´s modulus = 30 GPa
Poisson's ratio = 0.2

Foundation blocks:
unit weight = 2650 kg/m^3
Young´s modulus = 10 GPa
Poisson's ratio = 0.2

Foundation discontinuities:
k_n = 1 or 10 or 100 GPa/m
$k_s = 0.5\ k_n$
φ' = 30°

Figure 4: Model of a concrete gravity dam on a jointed rock foundation

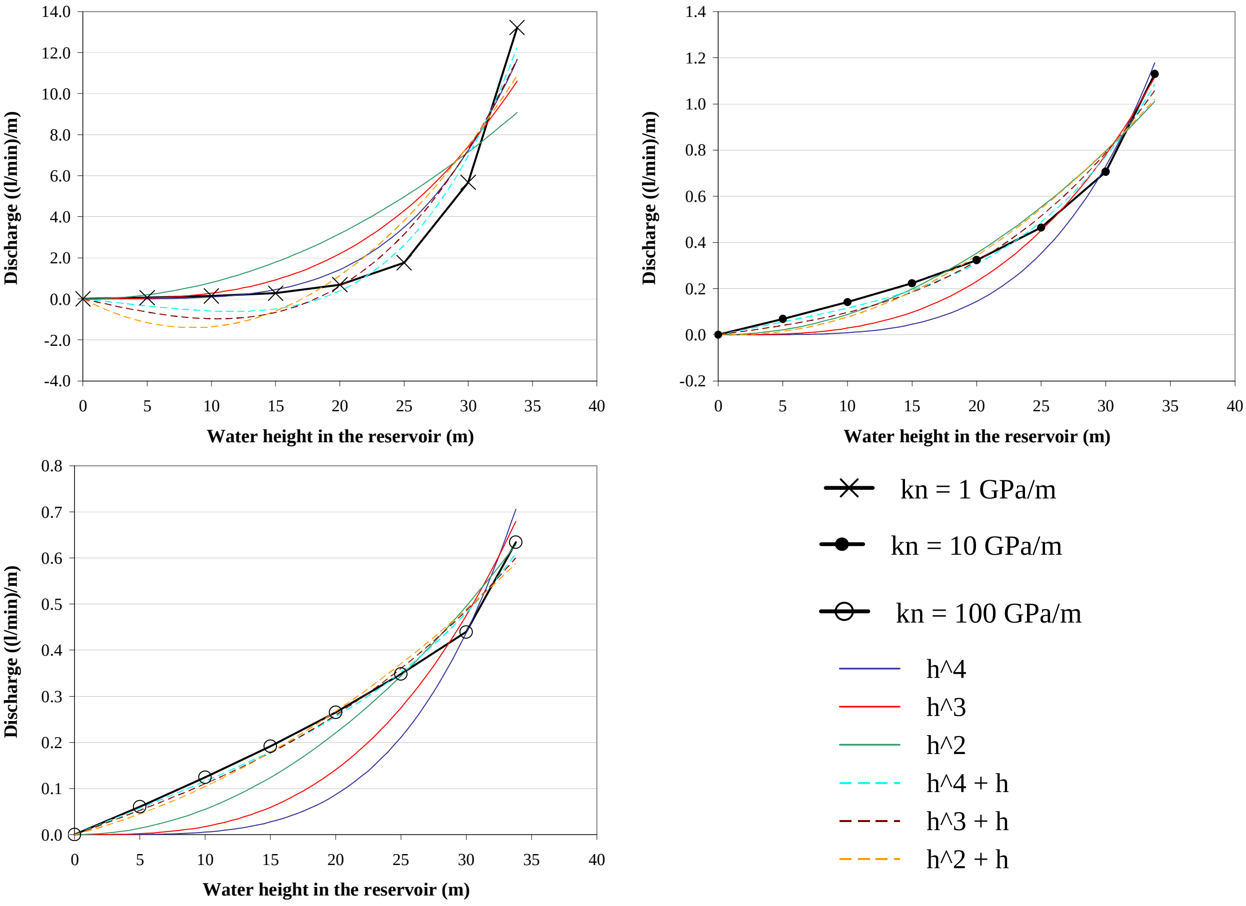


Figure 5: Adjustment of polynomial curves to the numerical variations of discharges due to variations in the water level in the reservoir, taking into account the hydromechanical behaviour, for different discontinuities' normal stiffness

4 QUANTITATIVE INTERPRETATION OF DISCHARGES RECORDED IN ALTO LINDOSO DAM

4.1 Main characteristics of Alto Lindoso dam

Alto Lindoso dam (Figure 6), designed and owned by Electricidade de Portugal (EDP), is located on the River Lima in the north of Portugal and is part of a hydraulic power system which consists, in addition to the dam, of a hydraulic circuit and an underground powerhouse. It is a double curvature arch dam, almost symmetrical, with a maximum height of 110 m and a total length of 297 m between the abutments at crest elevation. The dam was concluded in 1991 and the first filling of the reservoir took place from 6 January 1992 to 28 April 1994.

The foundation consists of granite with medium to coarse-sized grains and is of good quality, showing, however, some heterogeneity.

For foundation seepage control two drains per dam block were first drilled from the drainage gallery, with the exception of the foundation of one of the blocks, in which four boreholes were drilled. Permeability values of 3.0 to 7.0×10^{-8} m/s were obtained in Lugeon type tests carried out in drains. To evaluate the efficiency of the relief system one piezometer per block was installed from the downstream area of the drainage gallery, with the exception of the central cantilever in which two piezometers were installed. Figure 7 shows the drain and piezometric systems in the dam foundation.

4.2 Monitoring and hydraulic behaviour of the dam foundation

During the first filling of the reservoir, percentages of hydraulic head of about 30 % to 40 % were recorded in the valley bottom in the foundation of blocks 12-13, 13-14 and 14-15. The greatest discharges were recorded in the foundation of blocks 10-11, 11-12, 12-13 and 14-15, in the valley bottom, which make up around 50 % of the total discharge in the drainage gallery.

Figure 6: Downstream view of Alto Lindoso dam

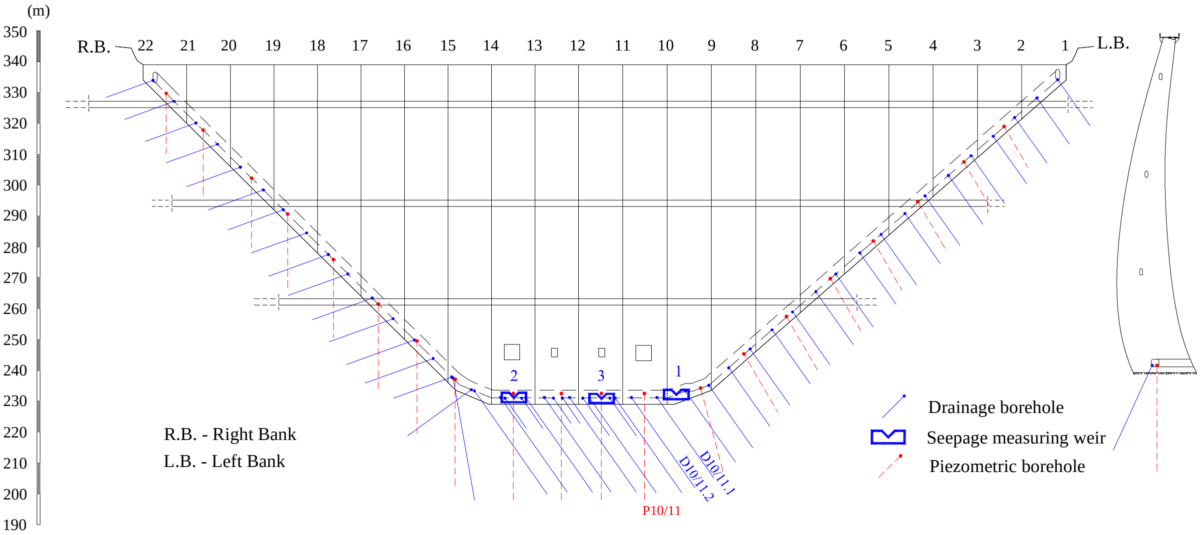


Figure 7: Drainage and piezometric systems in the foundation of Alto Lindoso dam

After the first filling of the reservoir, percentages of hydraulic head varying from 34% to 42% were still recorded in the foundation, in the valley bottom, below dam blocks 11-12, 12-13 and 13-14, and in the right bank, below block 18-19. These percentages of hydraulic head, however, were not accompanied by significant discharges. Between March and May 1998, new drains were drilled in those areas, to reduce water pressures, and a new piezometer was installed in the foundation of block 11-12. Work carried out allowed a significant decrease in water pressures in the foundation of the blocks in the bottom of the valley. More recently, in January 2004, due to an increase in piezometric readings, the drains located in blocks 7-8 and 8-9 were cleaned and unblocked when necessary. Further cleaning was carried out in June 2005 in all drains and piezometers located in several blocks in the lower area of each slope.

The drained water, together with that from leakage, is collected in three seepage measuring weirs, which separate the discharges by specific areas (Figure 7): the first measures the discharges from the left bank, the second those from the right bank, and the third collects not only the water from the first two, but also that collected in the valley bottom. In this dam, the quantity of water from leakage is very low. Figure 8 shows recorded discharges in these three seepage weirs plotted versus time. The same figure shows the variation in the reservoir level. Chart analysis shows that discharges have been decreasing, most probably due to clogging of both the rock mass discontinuities and the drainage system.

4.3 Quantitative interpretation of discharges recorded in a single drain

In Alto Lindoso dam, the highest discharges are recorded in the foundation of the blocks located in the valley bottom. The only block in which no drains or piezometric boreholes have been drilled since the beginning of the first filling of the reservoir is block 10-11 and thus the decision was made to analyse discharges recorded in drain D10/11.1 located in this block (Figure 7). Although the opening of new drains can affect the flow pattern in quite a wide foundation area, it was assumed that in the foundation of block 10-11 there had been no significant changes, which allowed quantitative interpretation of recorded discharges to be made taking into account discharges recorded since the beginning of reservoir filling. Figure 9 shows the variation of recorded discharges and water pressures in block 10-11 over time. Discharges in both drains have been decreasing (drains D10/11.1 and D10/11.2 shown in Figure 7). The water pressure in piezometer P10/11 (Figure 7) increased from the end of 1998 until the beginning of 2003, but has apparently been stable since then, varying with the variations in the reservoir level.

The study started with a very simple quantitative interpretation with the effect of the hydrostatic pressure represented by a function of $h^3 + h$ and the time effect represented by a cubic polynomial (t^3, t^2, t), as shown in Figure 10. The independent term (k), was added to the time effect. The curve that better fits data recorded until the end of 2006 was used to calculate discharges from then until mid-October 2010, and these calculated discharges were compared with measured discharges. A series of quantitative interpretations was afterwards carried out, only changing one function or introducing one new function each time, in order to analyse its influence on the results. Figure 11 shows the results of an analysis in which the thermal effect was included, simulated with the simplified method developed by Willm and Beaujoint[15].

Results analysis showed that:

i) as expected, the effect of hydrostatic pressure is of the same order as the time effect, because the discharge recorded in drain D10/11.1 tends to a very small amount;

ii) the hydrostatic pressure effect can be either simulated by a function of $h^3 + h$ or of $h^4 + h$ and, in this case, the linear term is dominant;

iii) the thermal effect is very low;

iv) the time effect is well approximated by a cubic polynomial.

The general trend in discharge variations is reasonably approximated by the interpretations in which the time effect is represented by a cubic polynomial. However, the calculated curves do not fit recorded discharges well neither in the period of the first filling of the reservoir, in which there are significant differences between recorded and calculated discharges, nor in the subsequent period.

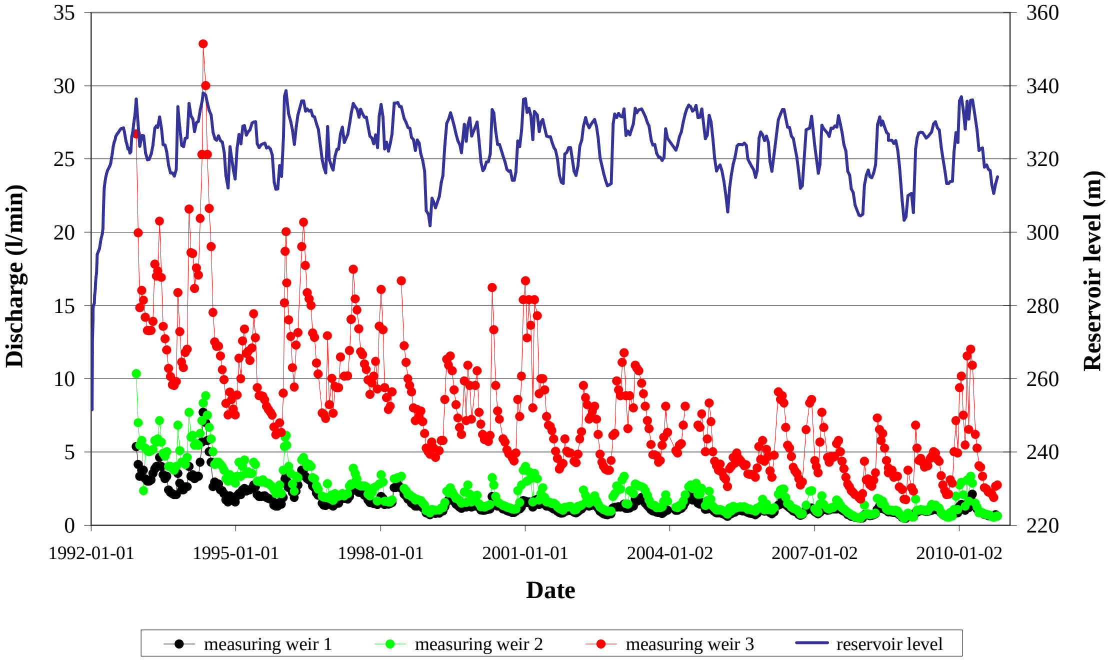


Figure 8: Variation in the reservoir level and recorded discharges in the measuring weirs

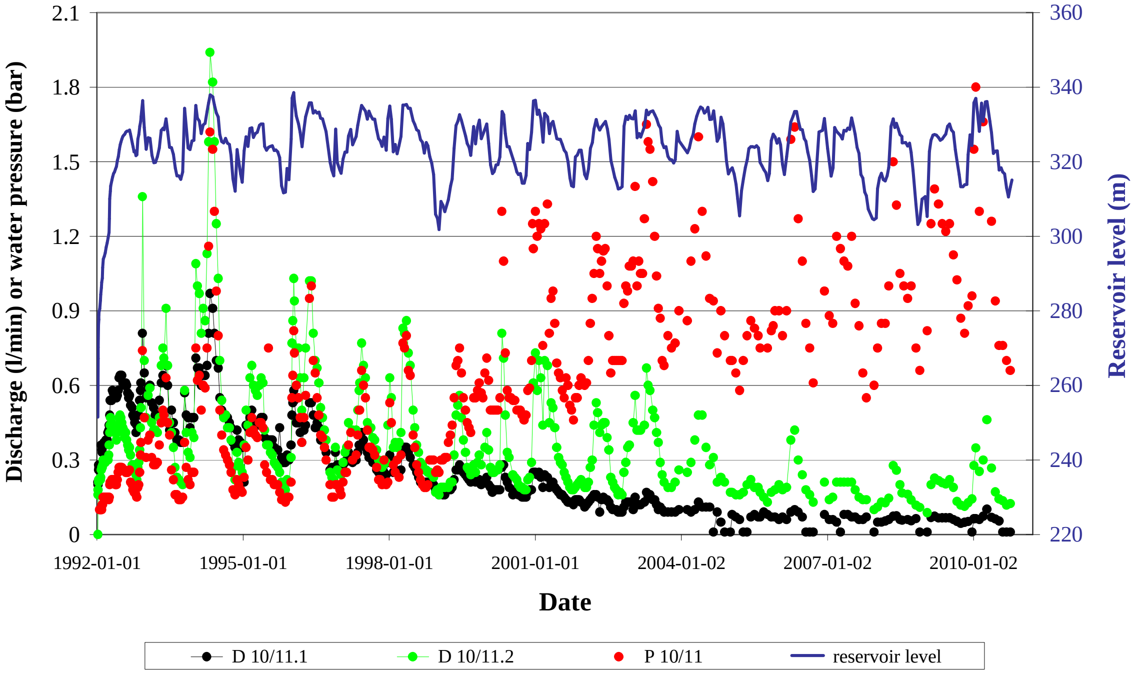


Figure 9: Recorded discharges and water pressures in the foundation of block 10-11

None of the curves was considered adequate to calculate discharges over a period of time subsequent to that used for quantitative interpretation, as errors increase in that period. In some cases, like those presented here, quantitative interpretations can not be used as a model to predict future behaviour.

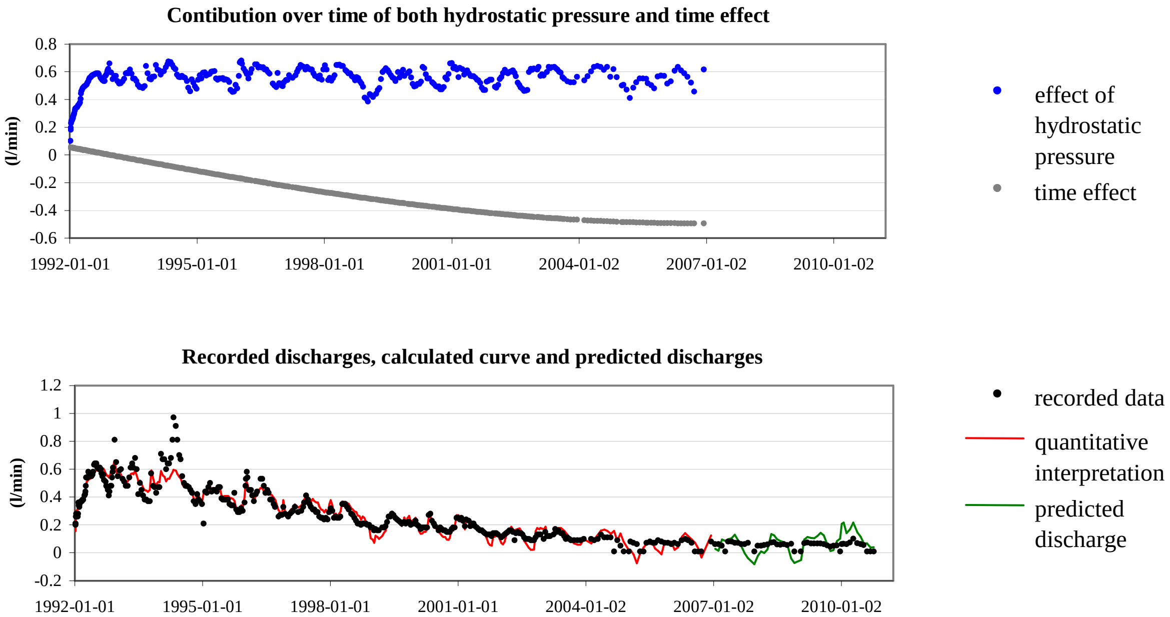


Figure 10: Interpretation of discharges recorded in drain D10/11.1, with the effect of the hydrostatic pressure represented by a function of $h^3 + h$ and the time effect by a cubic polynomial

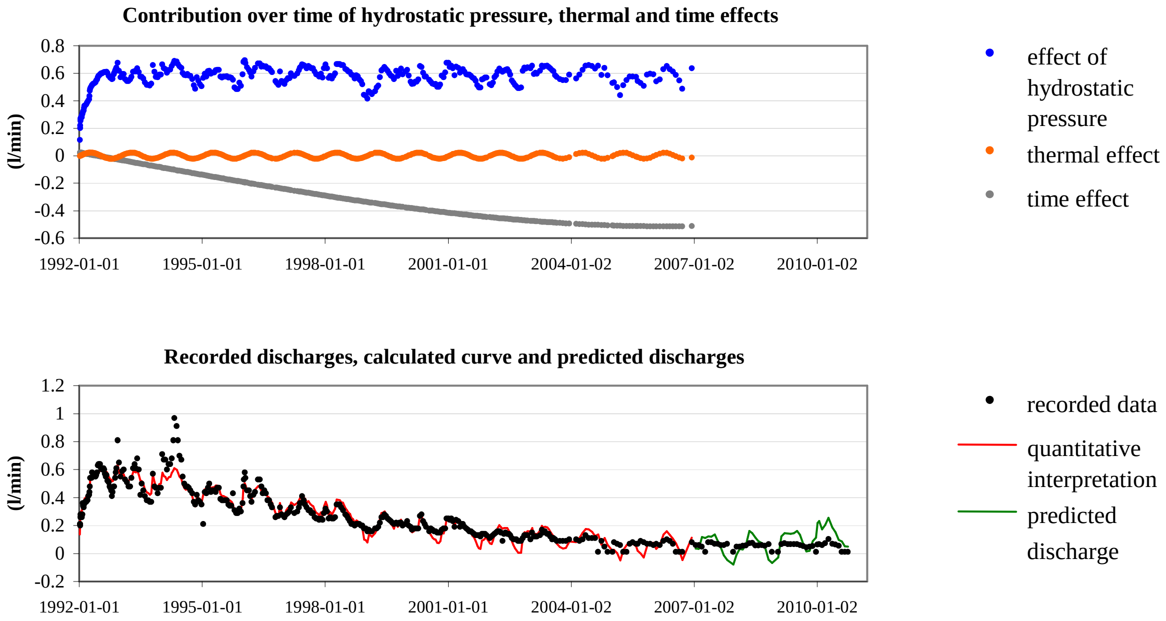


Figure 11: Interpretation of discharges recorded in drain D10/11.1, with the effect of the hydrostatic pressure represented by a function of $h^3 + h$, the thermal effect by a sinusoidal curve and the time effect by a cubic polynomial

4.4 Quantitative interpretation of discharges recorded in seepage measuring weirs

As the results of quantitative interpretations of discharges recorded in single drains were not satisfactory, an attempt was made to interpret the total discharge, recorded in seepage measuring weir 3. Figure 12 shows the results of an interpretation in which the effect of the hydrostatic pressure was represented by a function of h^3 and the time effect by a cubic polynomial. In this case the effect of hydrostatic pressure becomes significant, unlike what was observed in analysis of discharges in a single drain, in which it was close to the time effect. However, the time effect is not well fitted and calculated discharges in a period subsequent to that used to establish the quantitative interpretation curve were not close to those measured. An exponential curve was then used to simulate the time effect and the results were much better (Figure 13). However, for the highest and lowest discharges, the calculated flows are higher than those recorded (the calculated curve exaggerates the peaks), which means that the calculated effect of the hydrostatic pressure is higher than it should be.

Other interpretations were carried out by adding a linear term to simulate the time effect and by taking into account the thermal effect. It was concluded that when a linear term in h is used the curve which represents the effect of the hydrostatic pressure does not make sense, due to the lack of recorded discharges for water heights in the reservoir lower than 72 m (Figure 14). In this case, quantitative interpretations are better carried out with the effect of the hydrostatic pressure represented by a function of h^3. As in the analysis of seepage in a single drain, the thermal effect is very low.

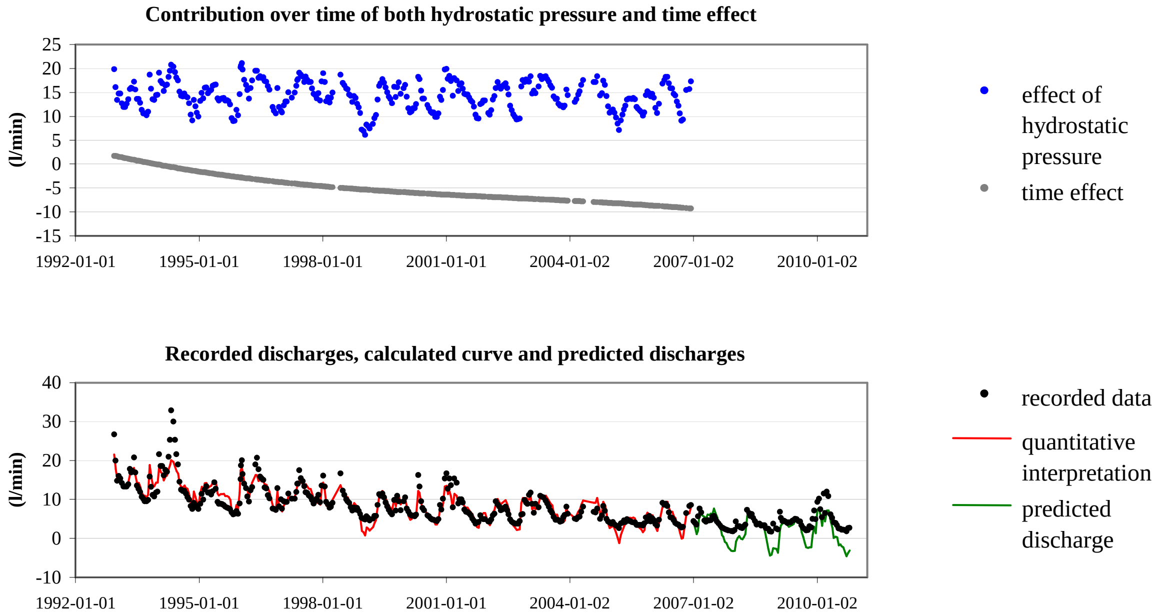


Figure 12: Interpretation of discharges recorded in seepage measuring weir 3, with the effect of the hydrostatic pressure represented by a function of h^3 and the time effect by a cubic polynomial

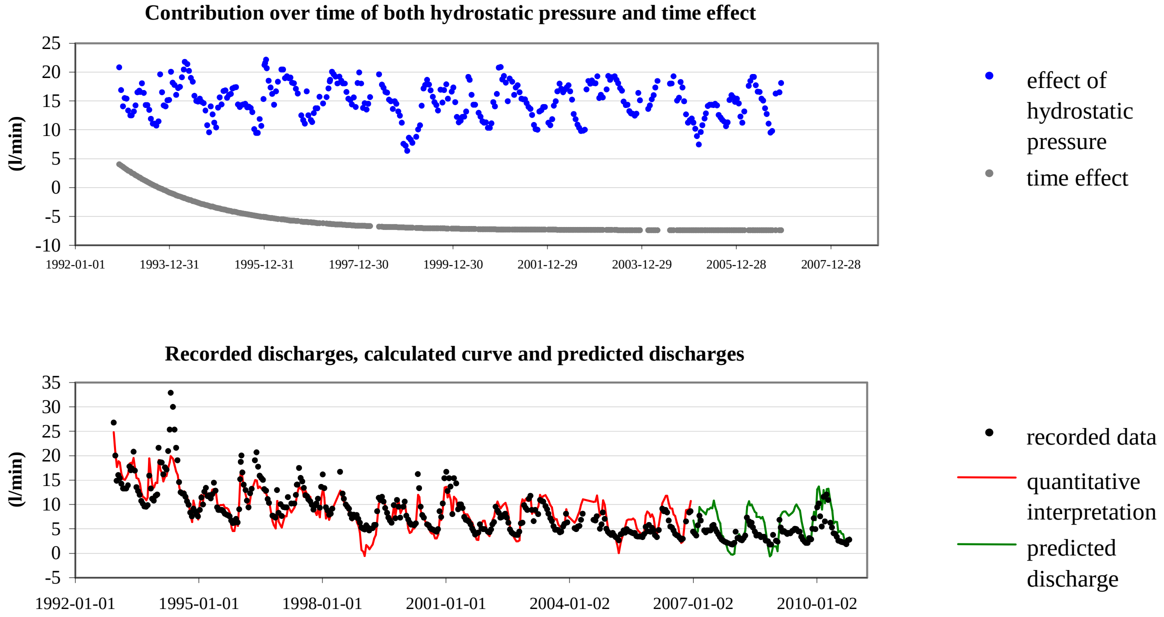


Figure 13: Interpretation of discharges recorded in seepage measuring weir 3, with the effect of the hydrostatic pressure represented by a function of h^3 and the time effect by an exponential curve

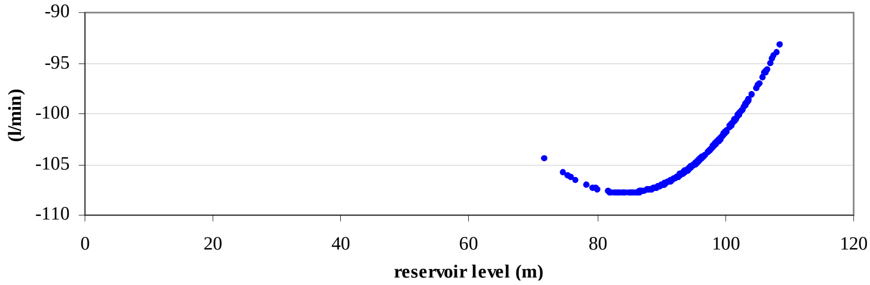


Figure 14: Effect of the hydrostatic pressure represented by a function of $h^3 + h$

4.5 Analysis of the possible time gap between variations in the main loads and in the measurement data

The analysis was based on the assumption that discharges vary instantaneously with variations in the main loads. The comparison between readings of discharges in Alto Lindoso dam, taken with an automated system, and the part due to variations in hydrostatic pressure obtained in a quantitative interpretation (Figure 15) shows that there is a sudden increase in discharges, although not as high as calculated, when there is a sudden increase in the reservoir level, like that observed from 6 to 15 February 2007. However, the same figure also shows that discharges do not decrease when the water level in the reservoir slowly decreases from around 324 m to 313. Part of the variations in discharges is due to non-linear effects, which possibly include time lags.

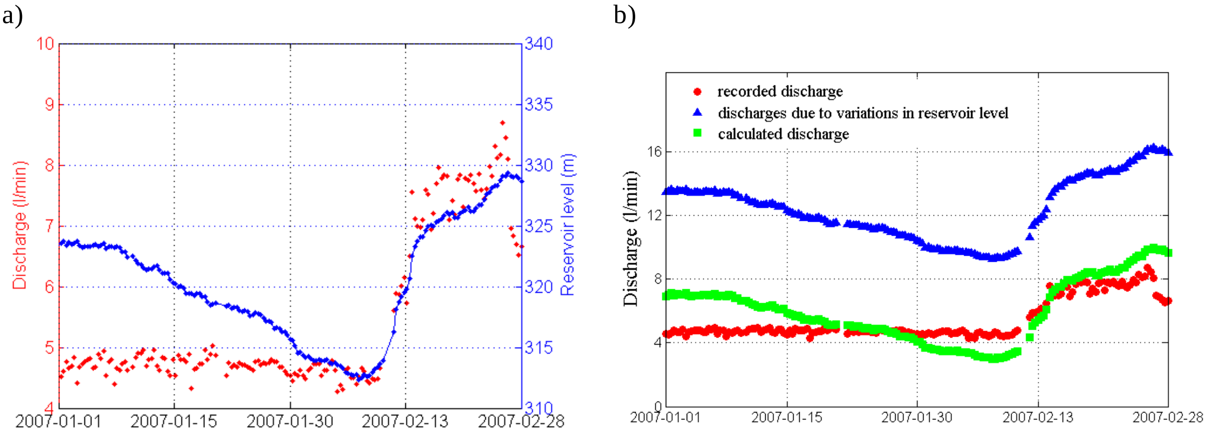


Figure 15: (a) Variations in both reservoir level and total discharges recorded with an automated system; and (b) comparison of the total discharges with the part due to variations in hydrostatic pressure obtained in a quantitative interpretation

5 QUANTITATIVE INTERPRETATION OF DISCHARGES RECORDED IN ALQUEVA DAM

5.1 Main characteristics of Alqueva dam

Alqueva dam (Figure 16), owned by Empresa de Desenvolvimento e Infra-Estruturas do Alqueva (EDIA) and designed by EDP, 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 first filling of the reservoir began in February 2002 and was recently concluded, in the beginning of January 2010.

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.

For foundation seepage control, grout and drainage curtains were installed from the foundation gallery of the dam. There are five drains per dam block, located 3 m apart. The total discharge is around 100 to 150 l/min, of which around 20 l/min are from the valley bottom. To evaluate the efficiency of the relief system a network of piezometers was installed.

Figure 16: Downstream view of Alqueva dam

5.2 Quantitative interpretation of discharges

The study carried out included quantitative interpretations of discharges recorded in the drain of the valley bottom that collects the highest quantity of water (drain D25 D) and of discharges collected in the drainage gallery in an area which encompasses the bottom of the valley. Recorded discharges are shown in Figure 17, where it can be seen that there are large variations in discharges which are not justified by variations in the reservoir level. In the case of Alto Lindoso dam the time effect is well approximated by a cubic polynomial because there are no significant variations in recorded discharges. In the case of Alqueva dam, however, a simpler function, such as a logarithm or an exponential, is more adequate to simulate the time effect.

The study was carried out in a similar manner to that in Alto Lindoso dam. Quantitative analysis was done with data recorded until the end of 2008, and the calculated curve was used to calculate discharges from then until mid-October 2010. These calculated discharges were compared with discharges measured over the subsequent period of time.

Figure 18 shows the results of quantitative interpretation and calculated discharges over the subsequent period of time in drain D25 D. In this case, the time effect is around half of that due to hydrostatic pressure and, although the calculated curve follows a pattern close to that defined by recorded discharges, the calculated discharges are not close to those measured. More accurate results can be obtained with discharges recorded in the valley bottom, as shown in Figure 19. As in the case of discharges recorded in seepage measuring weir 3 in Alto Lindoso dam, the linear term in h can not be used. As expected, the thermal effect is very low.

6 CONCLUSIONS

This paper presents a study carried out to experiment applying methods customarily employed in the analysis of mechanical factors in the analysis of discharges. The study shows that statistical models based on the simplified methods of quantitative interpretation, which can be an accurate and powerful tool in the analysis of concrete dam displacements, merit still further study in order to be properly used in the analysis of the hydraulic behaviour. Although more limited when used in the analysis of discharges, this type of method may be useful to approximately predict discharges over short periods of time in which it can be assumed that the trend of the time effect will remain the same.

The most significant conclusions were that the effect that variations in reservoir level have on discharges is adequately simulated by polynomials of the type $h^3 + h$ or $h^4 + h$, and that it is not possible to predict discharges recorded in single drains, as they are largely due to local effects and do not represent the permeability of the rock mass. This means that discharges recorded in seepage weirs, collected in relatively large areas, rather than discharges in single drains should be analysed. Quantitative interpretations were only carried out for discharges, as these are more useful for the evaluation of foundation performance than water pressures taken in the low number of installed piezometers, which give only local information[16].

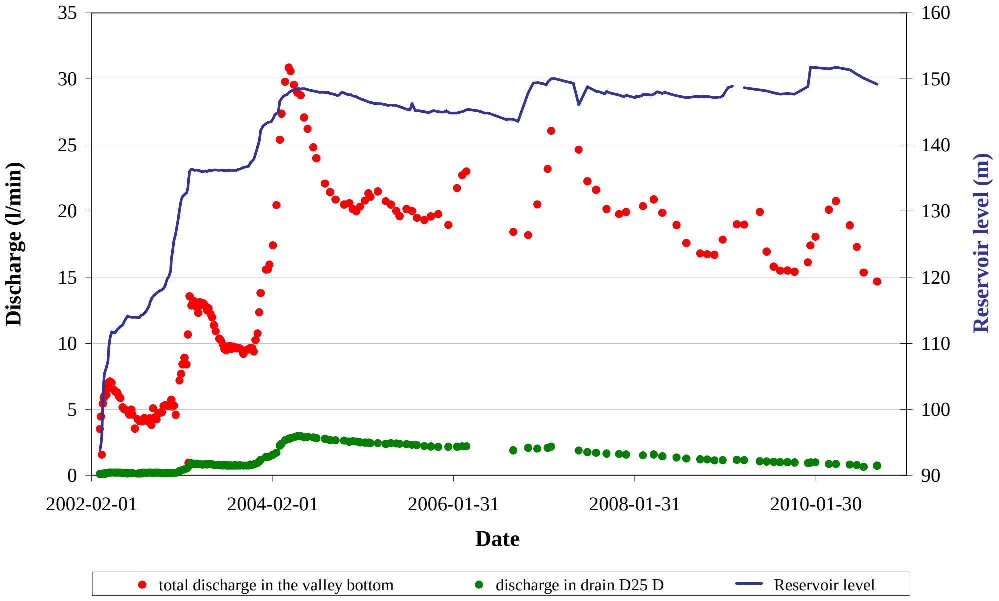


Figure 17: Recorded discharges in the bottom of the valley and in drain D25 D

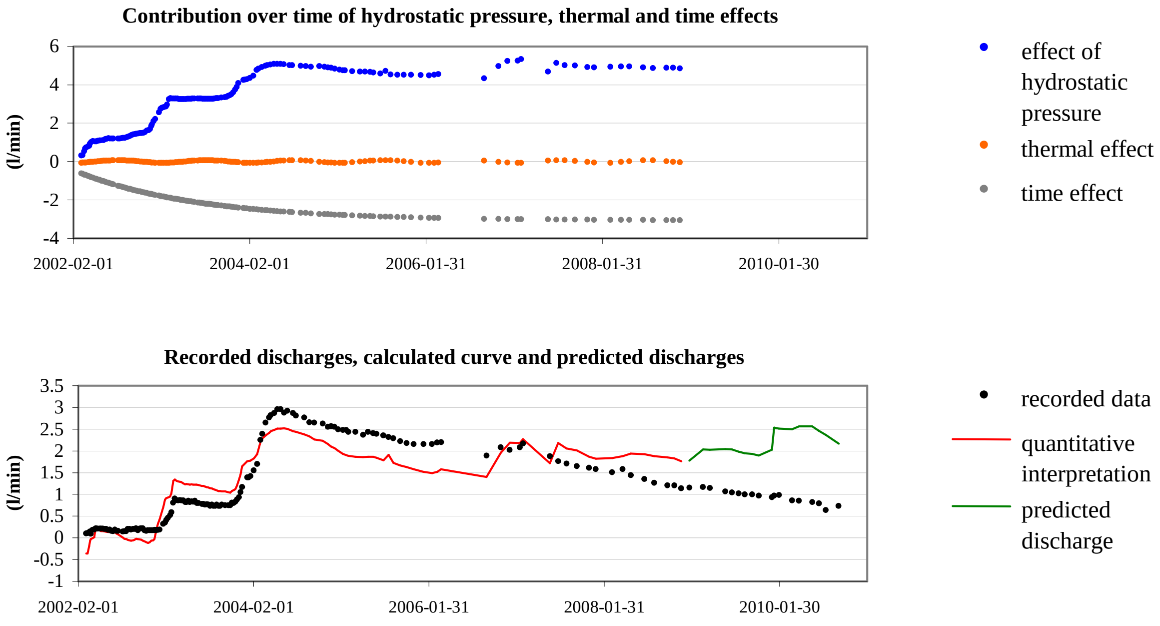


Figure 18: Interpretation of discharges recorded in drain D25 D, with the effect of the hydrostatic pressure represented by a function of h^3 and the time effect by an exponential curve

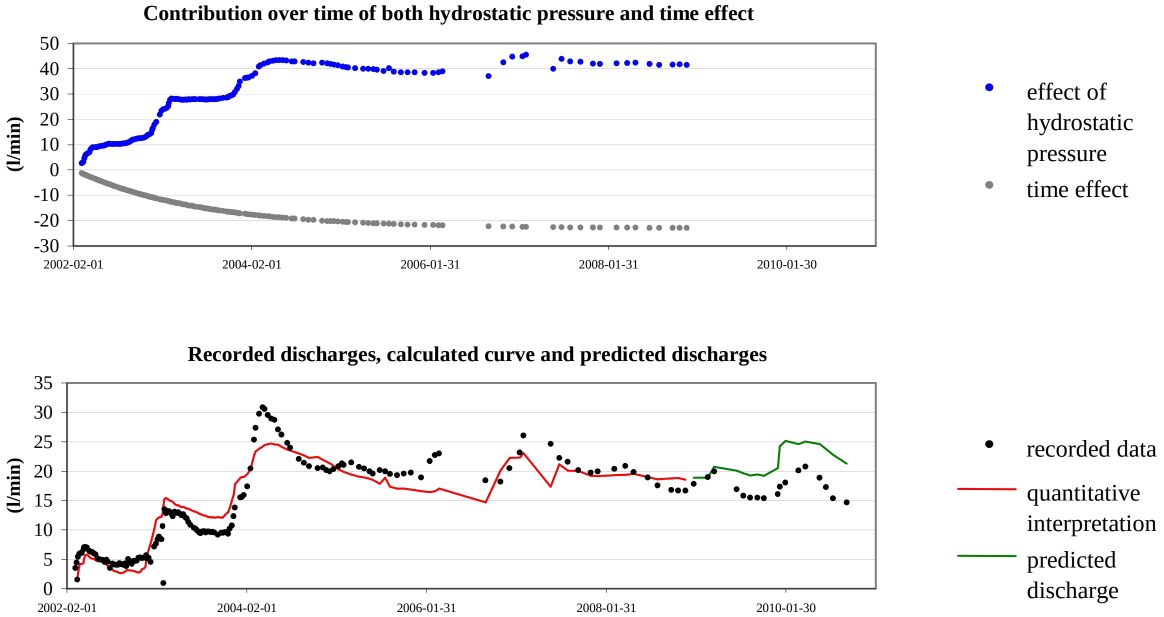


Figure 19: Interpretation of discharges recorded in the valley bottom, with the effect of the hydrostatic pressure represented by a function of h^3 and the time effect by an exponential curve

Recently, other techniques have been proposed to support the assessment of the field data and results of quantitative interpretation of dam displacements have been compared with those obtained using both the neural network approach, in which the model "learns" from the information contained in a training set of data provided by the user[17,18], and with algorithms which combine a model selection procedure based on the minimization of the simulation error and a pruning mechanism for the elimination of redundant terms[19]. These methods may be an alternative, or an additional means, to analyse dam behaviour and particularly discharges.

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