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Application to oliana dam

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ANALYSIS OF THE DISCHARGE CAPACITY OF RADIAL-GATED SPILLWAYS USING NUMERICAL MODELING. APPLICATION TO OLIANA DAM.

F. Salazar, R. Morán, R. Rossi and E. Oñate

ABSTRACT

Current paper focuses on the analysis of radial gated spillways, which are analyzed by the solution of a numerical model. The Oliana Dam study case is considered and the discharge capacity is predicted both by the application of a level-set based free-surface solver and by the use of traditional empirical formulations The results of the analysis are then used in training an Artificial Neural Network so to allow real-time predictions of the discharge in any situation of energy head and gate opening within the operation range of the reservoir. The comparison of the results obtained with the different methods shows that numerical models can be useful as a predictive tool for the analysis of the hydraulic performance of radial-gated spillways, and highlights some drawbacks regarding the application of the empirical formulas.

KEYWORDS

hydraulics, spillways, radial gates, discharge coefficient, side contractions, CFD, Kratos, numerical,

1. Introduction and objectives

Hydraulic design of spillways has been traditionally carried out on the basis of empirical formulations which were developed from the results of experimental tests. The most accepted methodologies date from the middle of the 20th century, and were produced by north-American institutions, such as the US Bureau of Reclamation (USBR 1987) and the US Army Corps of Engineers (USACE 1992). As a general rule, these methods offer a good approximation for each particular case, useful for the definition of a preliminary design, which most of the times is specifically tested in laboratory afterwards. The final design is obtained after a trial-and-error process, taking into account the results of the tests. This procedure requires a great economic effort, and a long time for the construction of the models, the run of the tests, and the analysis of the results.

The performance of spillways with free ogee crests has been deeply studied (USBR 1987), so that it is possible to calculate the relation between energy head and discharge, taking into account the shape of the abutments, the aspect ratio of the bays or the downstream water depth, among other features.

On the contrary, research on orifice flow under gated spillways is more uncommon. The main reason is that in general, gated spillways work under free flow conditions during extreme floods (the gates are totally opened), and these are the relevant events in terms of dam safety. Spillways only work in orifice flow conditions during normal operation. As a consequence, the influence of side contractions, upstream and downstream conditions, shape of the piles and abutments, etc. is not well known for such configurations.

The problem has been widely analyzed for irrigation canals (Wahl 2004), because in these structures gates are used for flow measurement, apart from their obvious function of water level control. However, upstream and downstream boundary conditions in canals are highly different from those presented in spillways, so that these studies cannot be applied to the latter.

In the recent years, numerical methods have achieved a great advance, which, together with the improvement in the performance of computers, make them be capable of simulating complex problems with a high level of detail. Numerical methods have substituted physical tests in some fields of dam engineering, such as structural calculation. Although the design of hydraulic structures is still based on laboratory experiments, some of the latest works in this field already combine numerical and experimental tests (USBR 2009), or even do without experiments (Ackers et al. 2011).

The objective of the current work is the description of a methodology for the calculation of the discharge curves in gated spillways combining the predictive capabilities of the Finite Element Method (FEM) and the fast response times guaranteed by Artificial Neural Networks (ANN's).

2. Background

2.1. Empirical formulations

As mentioned above, the formulas which are commonly used for the calculation of the discharge in spillways where developed from the results of experimental tests. Discharge over a free ogee spillway can be computed by Eq. 1:

$$Q_L = C \cdot L \cdot {H_e}^{1,5} \qquad (1)$$

where Q_L is the discharge (m^3/s), C is the discharge coefficient for free flow, L is the effective length of the spillway (m), and H_e is the total energy head on the crest (m).

The discharge coefficient is influenced by a number of factors, such as (1) the depth of approach, (2) the energy head on the crest, (3) the upstream face slope, and (4) the downstream conditions (USBR 1987). Experimental campaigns were undertaken to analyze the influence of these factors so that corresponding design charts were developed, which allow correcting the value of the discharge coefficient for a specific geometry.

Effective length can be computed by Eq. 2 (USBR 1987):

$$L = L' - 2 \cdot (N \cdot K_p + K_e) \cdot H_e \qquad (2)$$

where L' is the net length of the crest, N is the number of piles, K_p is the pier contraction coefficient, K_e is the abutment contraction coefficient, and H_e is the energy head on the crest.

Both contraction coefficients depend upon the geometry of the piles and abutments, respectively.

This formulation takes into account the effect of the side contractions, which in practice is equivalent to a reduction of the discharge capacity proportional to the energy head.

USACE (1992) suggests Eq. 3 to compute the discharge over gated spillways:

$$Q = C_g \cdot A \cdot \sqrt{2 \cdot g \cdot H} \qquad (3)$$

where:

Q is the discharge (m^3/s)

C_C is the discharge coefficient for orifice flow, computed from Fig. 1.

A is the area of orifice opening (m^2)

H is the energy head to the center of the orifice (m)

The same formula is recommended by USBR (1987) and different institutions, such as the Spanish Committee on Large Dams (SPANCOLD 1997).

This formulation assumes that the discharge coefficient is mainly dependent upon the shape of the stream lines both upstream and downstream the gate (USACE 1992). Thus, the discharge coefficient is obtained from the angle θ formed by the tangent to the gate lip and the tangent to the crest curve at the nearest point of the latter (USACE 1992), using Fig. 1.

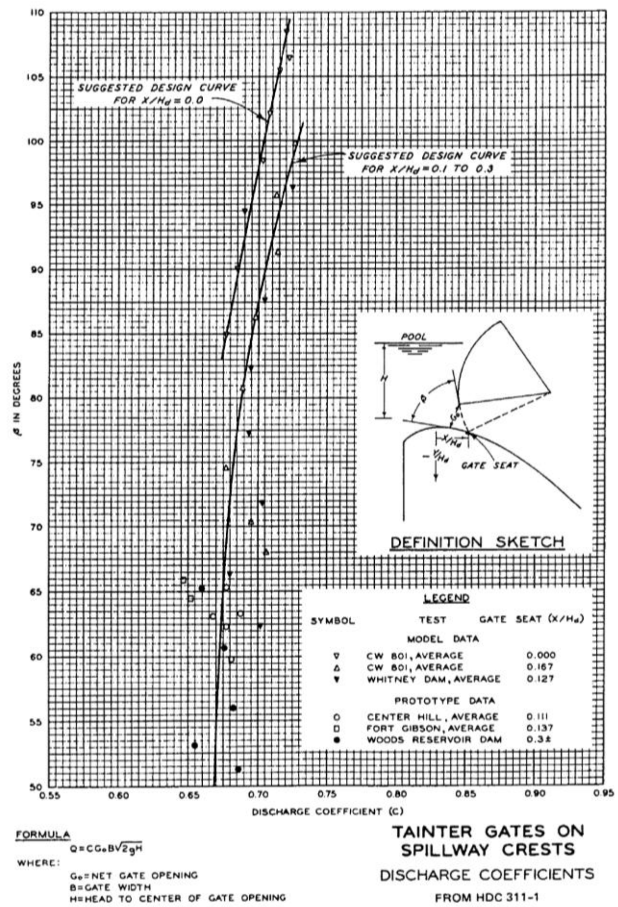

Figure 1. Proposed curve for the calculation of the discharge coefficient as a function of θ. Points represent the results of the tests which were used for the definition of the suggested curves (USACE 1992).

The suggested design curve is based upon the results of model and prototype data. Besides, it is stated that "*data shown are based principally on tests with three or more bays in operation. Discharge coefficients for one single bay would be lower because of side contractions, although data are not presently available to evaluate this factor*" (USACE 1992).

The analysis of this formulation provides some important ideas which should be kept in mind before its application:

- The discharge coefficient plotted in Fig. 1 implicitly considers the effect of both side contractions and adjacent bays, because it is based upon three-dimensional tests with several bays in operation.

- No information is available on how discharge coefficient is influenced by factors such as the energy head, the shape of the piles and abutments, the bay aspect ratio or the number of bays in operation.

- Suggested curves present up to a 5% deviation from the experimental data, especially for angles between 50 and 75^{o}.

Folsom Dam is one of the most recent and well documented cases regarding radial gated spillways discharge curves (USBR 2009). The report produced by USBR contains the results of the discharge capacity studies on a gated spillway, using both numerical and experimental modeling. In Folsom dam, spillway releases are controlled using five 12.80-ft-long by 15.24-ft-tall radial gates for the service spillway and three 12.80-ft-long by 16.15-ft-tall radial gates for the adjacent emergency spillway. The details can be consulted in the reference, but it is important to remark that both experimental and numerical models produced similar results, which were used for the definition of the discharge curves.

Given that the details of the geometry of the gates is not provided in the report, it is not possible to compare the discharge coefficients with those given by Fig. 1 (angle θ is not known). So, an inverse process has been followed, i.e. the value of the discharge coefficient has been calculated as:

$$C_C = \frac{Q}{A \cdot \sqrt{2 \cdot g \cdot H}} \qquad (4)$$

where the variables have the same meaning than in Eq. 3. In this case, the values of *A*, *Q* and *H* have been taken from USBR (2009).

It has been found that the discharge coefficient is mainly dependent upon the gate opening, being the influence of the energy head negligible in this case. Table 1 shows the values for the different gate openings.

Gate opening (ft)	**C_C**
5	0,700
10	0,720
15	0,740
20	0,755
25	0,770
30	0,780
35	0,800

Table 1. Discharge coefficients for Folsom dam spillway.

The relation between the discharge coefficient and the gate opening-design head ratio has been computed via curve fitting, obtaining a second order polynomial:

$$C_g = -0.0784 \cdot \left({}^{D}/_{H}\right)^2 + 0.2433 \cdot \left({}^{D}/_{H}\right) + 0.68 \qquad (5)$$

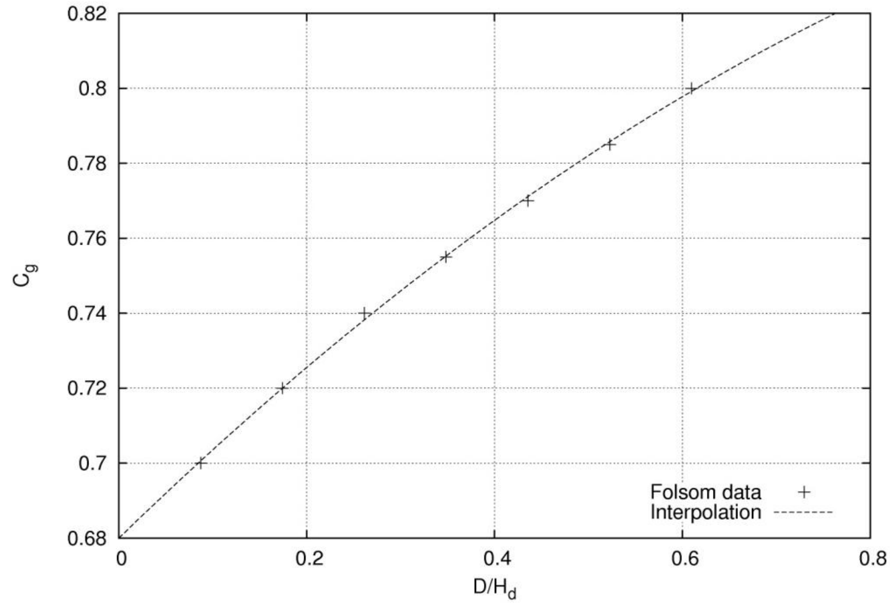

Figure 2. Discharge coefficient in terms of gate opening-design head ratio for Folsom Dam

The expression fits with test data with a root mean square error of 0.001. This formula has been applied to Oliana Dam spillway, as described later.

The analysis of the discharge curves for Folsom dam leads to the following conclusions:

- Although a strict correlation between Folsom dam discharge coefficients and those given by Fig. 1 cannot be made with the published data, it can be point out that the former are higher. They are up to 0.8, whereas the higher value in Fig. 1 is around 0.74.
- Discharge coefficient is higher with greater gate openings. This agrees with USACE chart.
- Discharge curves for Folsom Dam are accurately reproduced using a constant discharge coefficient for each value of the gate opening. Thus the influence of energy head seems to be negligible in this case.

2.2. Numerical modeling

Despite the success of numerical models in the structural design of dams, the application of such techniques for the assessment of the hydraulic behaviour of spillways is still rather infrequent. This situation roots in the complexity and cost of the solution of the Navier Stokes equations as well as in the need of dealing with an unknown free-surface position. The increasing maturity of computer methods makes however available an increasing number of numerical techniques capable of running full 3D calculations. USACE (2001) produced a report on the analysis of the accuracy and capacity of the available numerical codes for dam hydraulics.

Three-dimensional numerical codes follow two basic tendencies: one uses a Lagrangian formulation and meshless techniques, and the other applies an Eulerian approach complemented by specific methods for an accurate definition of the position of the free surface. Most of the numerical codes can be classified in one of these categories, so that they can be labeled as Lagrangian or Eulerian codes.

In Eulerian approaches, the analysis domain is discretized into a finite element mesh which remains constant during the simulation. Since the position of the free-surface varies on the top of such mesh, specific algorithms are required for tracking the free surface, that is, to follow its position within the domain. Common choices are the Volume of Fluid (VOF) technique (Hirt and Nichols 1981) or the use of a level-set function (Osher and Fedkiw 2001).

Lagrangian methods are gaining users in recent years. The most popular ones use the Smooth Particle Hydrodynamics (SPH) approach (Liu and Liu 2010). One of the most recent applications of this technique in dam hydraulics was carried out by Eun-Sug (2010), who used one of these codes to analyze the discharge capacity of Goulours Dam spillway.

An alternative to them both, having some of the features of each, is based in the Particle Finite Element Method (PFEM). This method has been successfully applied to solve a wide number of engineering problems concerning fluid-structure interaction, as well as dam hydraulics (Larese et al. 2008), some of which are otherwise hard to assess (Oñate et al. 2004, 2008, 2011, Salazar et al. 2011).

Eulerian codes are more frequent in the analysis of dam hydraulics. Ansys is one of the most popular commercial CFD codes, which has been recently used by Andersson et al. (2010), for the hydraulic analysis of Höljes Dan spillway, and by Ackers et al. (2011) for the design of Lake Holiday dam spillway.

Flow-3D is also becoming popular in dam hydraulics. Sung-Duk et al. (2010) have used it for the design of the approach guide walls of Karian Dam spillway, in Korea, as well as Johnson and Savage (2006) to study the pressure distribution over an ogee spillway.

In the recent years, Flow-3D is being widely applied in Électricité de France (EDF) for the analysis of the discharge capacity of labyrinth and piano-key weirs. Most of this work has been published in the proceedings of the International Conference on Labyrinth and Piano Key Weirs (PKW 2011) by Pralong el al. (2011), Blancher et al. (2011) and Laugier et al. (2011).

The same software was used for the analysis of the discharge capacity of gated spillways in Canada (Chanel 2008, Chanel and Doering 2008, Gazek 2007). In these works, the results of numerical models are compared with experimental data. However, no correlation between them and empirical formulations has been made, and the effect of side contractions has not been analyzed.

Given that the performance of free ogee spillways is well known, these structures have been often used as benchmarks for the validation of several innovative numerical codes, such as Castro-Orgaz and Hager (2010), Olsen and Kjellesvig (1998), Bhajantri et al. (2007), or Kirkgoz et al. (2009).

A common feature of all of the methods reported is however the need of large computational resources, particularly in terms of CPU time needed to obtain results. While such computational effort may be accepted at some stage of the design, faster response times are needed in other contexts.

The approach followed in the current work was consequently to use two models with different level of accuracy. The predictions obtained by the FEM are consequently used in training a simplified reduced-order model, designed to provide fast response times at the expense of the accuracy.

While different techniques exist for the construction of such low order model, in current work the choice was made to use an Artificial Neural Networks model, as described in the next section.

2.3. Artificial Neural Networks (ANN's)

As briefly commented in the previous chapter, Artificial Neural Networks are techniques that allow the construction of effective black-box meta models for a wide variety of problems.

Conceptually, ANN's allow to "predict" the output of a system (discharge in our case) as a results of a number of given inputs (energy head and gate opening). The fundamental difference with respect to fully predictive models (as the FEM) is that Neural Networks are not aware of the underlying physics, but rather allow "interpolating" existing knowledge by providing a systematic way to build a relation between inputs and outputs.

The construction of a ANN model is thus typically based on a "training" phase in which the model is fed with inputs and the corresponding outputs. The model's results are then verified by comparing its predictions for cases that do not coincide exactly with the cases used in the training phase.

Among the many different types of ANN's (López, 2008) which exist in the literature, the Multilayer Perceptron (MLP) has been used in this work. It is formed by a number of single units, called perceptrons, organized in different layers.

A perceptron is an application which provides an output (scalar) from one or more inputs. It is obtained via simple mathematical operations. Figure. 3 shows a scheme of a perceptron, which has n input data (xi). Each one is multiplied by a constant (weight) wi. The sum of the results is added to another constant (b) called the bias, thus obtaining c, which, in turn, is the input of the activation function (a), which provides the output of the peceptron (y). Mathematically:

$$c = \sum x_i \cdot w_i + b\,; y = a(c) \tag{6}$$

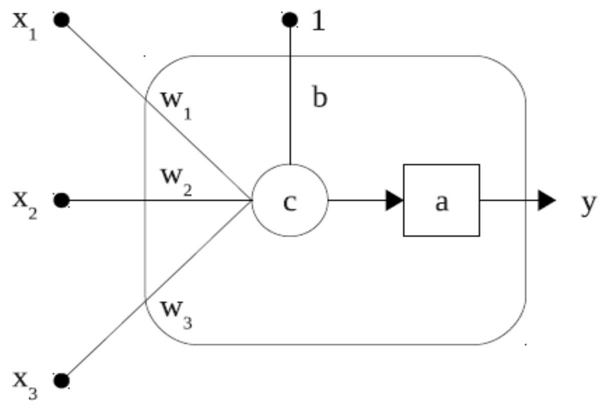

Figure 3. Perceptron example (López 2008)

Weights and bias are different for each perceptron in the ANN. Their values are randomly initialized, and further modified during the training process. Activation function can be selected from several types, being the most frequent the threshold function, the linear function and the sigmoid function. In this simple case the latter has been used.

The simplest architecture of an MLP is formed by three layers: input, hidden and output. In general, the most appropriate architecture of a MLP for a particular case is obtained by means of successive iterations. Sometimes, a good approximation can be achieved based on experience, as well as on the number and characteristics of inputs and outputs. Our case is one of the simplest that can be posed, with just two inputs and one output. So, no iterations were needed, and one single layer having three neurons has turned out to be appropriate.

As mentioned above, the free parameters of each perceptron (weights and bias) are calculated as a result of a procedure called training. During this task, a set of both input and their correspondent output data is supplied to the ANN. The values of the free parameters of the ANN are modified following previously defined criteria, whose objective is to minimize the discrepancy between the already-known outputs and those predicted by the ANN. In our case, the training has been carried out using the *Quasi-Newton Method* (López, 2008).

3. Methodology

3.1. Numerical FEM model

The examples presented in the current work were run using the code Kratoss (Dadvand et al. 2010, Rossi et al. 2011), developed at CIMNE.

The solution module used is designed for the resolution of the Navier-Stokes equations in three dimensions, using the FEM. Specifically a level-set approach is used for the simulation of the free-surface problem. The main features of the solver (described in Rossi et al. (2011)) are:

1. Discretization of the Navier-Stokes equations for incompressible fluid using the standard Finite Element approach
2. Use of low order elements: triangles in 2D and tetrahedra in 3D.
3. Time integration using a semi-explicit version of the fractional-step approach.
4. Improvement in mass conservation via an "error recovering" technique that allows correcting the solution taking into account the errors made in the previous time steps.
5. Level-Set Method (Osher and Fedkiw 2001) for tracking the free surface.
6. An extrapolation function which allows computing the values of velocity, pressure and pressure gradient on the nodes in the non-fluid area close to the free surface.

The algorithm follows the following steps:

1. Extrapolate velocity, pressure and pressure gradient on the extrapolation domain.
2. Convect the level-set function defining the new free surface on the basis of the velocity field both on fluid and extrapolation domains.
3. Re-initialize the distance function on the whole domain starting from the zero of the level-set function obtained at step 2.
4. Solve the momentum equations.
5. Set the pressure boundary condition so that pressure is (approximately) zero at the position indicated by the zero of the level-set function.
6. Solve the pressure equation
7. Solve the correction equation
8. Back to step 1.

The code is currently suitable for parallel processing for Shared Memory Machines (SMMs) using OpenMP. The algorithm is also adequate for Distributed Memory Machines (DMMs) parallelization, nevertheless at the current stage only SMM version is available.

3.2. ANN

The high computational cost is one of the drawbacks of numerical modeling of 3D hydraulic problems. The ideal objective is the real-time computation, which would allow the dam owner to compute actual discharge in the current situation (energy head, gate opening).

In our days, however, the way in which discharge curves are calculated using numerical models is the same as for experimental tests: a number of relevant cases are selected, and the results are used to obtain general expressions via curve fitting.

In order to optimize the work, the numerical test campaign has been planned so to obtain the discharge curves by extrapolation of the results of 2D models (which computational cost is significantly lower than 3D runs). A few 3D models have been run so to validate the extrapolation. The steps of this methodology are the following:

1. 2D numerical modeling of situations corresponding to integer values of the gate opening. For each one of them, at least three values of the inflow have been computed.

2. Extrapolation of the results to actual spillway geometry (3D), taking into consideration side contractions. In our work, the expression developed to calculate effective length in free ogee crests has been used.

3. Numerical modeling of a few representative cases in 3D. The goal is to check the accuracy of the extrapolation defined in step 2.

4. Creation and training of an ANN based on previous results, which allows the user to calculate the outflow in any possible situation (upstream head, gate opening) within the operation range of the spillway.

The ANN has been generated and trained using the Flood software (López et al. 2008), an open-source software implementation of the multilayer perceptron developed at CIMNE. It allows the user to solve a learning problem, i.e., to find a multilayer perceptron which optimizes an objective functional by means of a training algorithm (López, 2008).

3.3. Oliana Dam case study

The Oliana Dam spillway has been chosen as the test case for the application of Kratos. Oliana Dam is located on the Segre River, between Oliana and Peramola municipalities, in Lleida (Spain). Its spillway is comprised by two bays, both controlled by radial 17-m long by 9-m tall gates. The operation range goes from crest elevation (509.3 m.a.s.l.) to a design head (H_0) of 9.0 m (518.3 m.a.s.l.).

3.3.1. Inflow boundary condition

In 2D models, inflow discharge is imposed by setting the velocity of the fluid in the boundary of the domain opposite the spillway, so that:

$$q = v \cdot l \qquad (7)$$

Where q is the unit flow, in m^2/s, v is the velocity in the boundary, in m/s, and l is the length of the boundary line.

An analogous condition has been applied for 3D calculations:

$$\mathrm{Q} = \mathrm{v} \cdot \mathrm{A} \qquad (8)$$

Where Q is flow, in m^3/s, v is the velocity in the boundary, in m/s, and A is the area of the boundary surface.

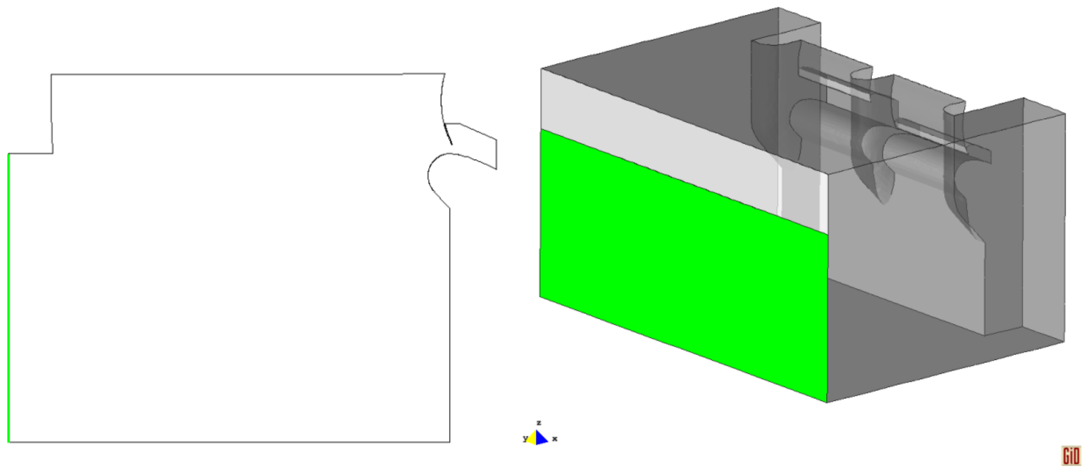

Figure 4. Fixed-velocity boundary condition both for 2D (left) and 3D (right) models.

3.3.2. Domain dimensions

One of the parameters which may influence the value of the discharge coefficient is the depth of approach (P), i.e., the vertical distance from the crest to the bottom of the domain. According to USBR (1987), the discharge coefficient for free flow is independent of this factor when the ratio P/H_0 is greater than 3.

Given that the design head is 9.0 m, and that the depth of approach in Oliana Dam is above 30 m, it can be concluded that actual discharge coefficient in Oliana Dam spillway does not depend on this factor. Thus, the vertical distance from spillway crest to the bottom of the domain has been set to 30 m in all the numerical models, so that they reproduce this effect.

The domain in the downstream side of the gate has been restricted to the topmost part of the chute. It has been checked that supercritical regime has been reached, so that the downstream condition does not affect the discharge coefficient.

A sensitivity study on the influence of the horizontal dimensions has been carried out both for two and three dimensional models. The objective is to define the limits of the domain, so that boundary conditions do not affect the results.

A 3-m opening case has been selected in 2D, with 750 m^3/s inflow (22.06 m^2/s unit inflow). It has been run for three different domains having 50, 75 and 100 m measured from the spillway face to the inlet.

Results show that the difference in terms of energy head between the three models is below 1 cm, representing around 0.15%. As a result, it can be concluded that the smaller domain is large enough so to make sure that the inlet boundary condition does not affect the results.

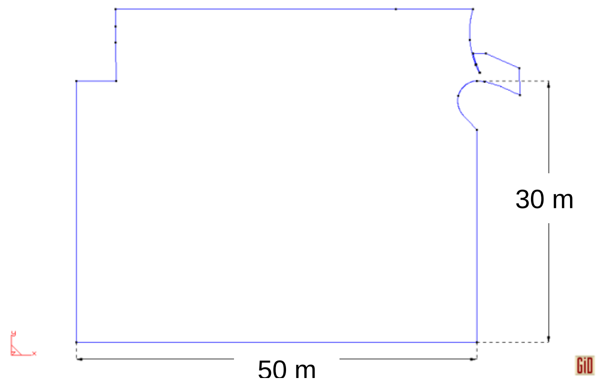

Figure 5. Model geometry for 2D simulations.

A similar analysis has been carried out for 3D models, in order to determine the third dimension of the domain. Obviously, it will have to be large enough to model the whole bay, as well as the pile and the abutment. Taking advantage of the symmetry of the domain, Oliana dam spillway has been modeled in 3D with one single bay.

Three different domains, having 10, 20 and 30 m measured from the abutment to the boundary have been used to calculate the case with free flow and 500m^3/s. Figure 6 shows the geometries of them all.

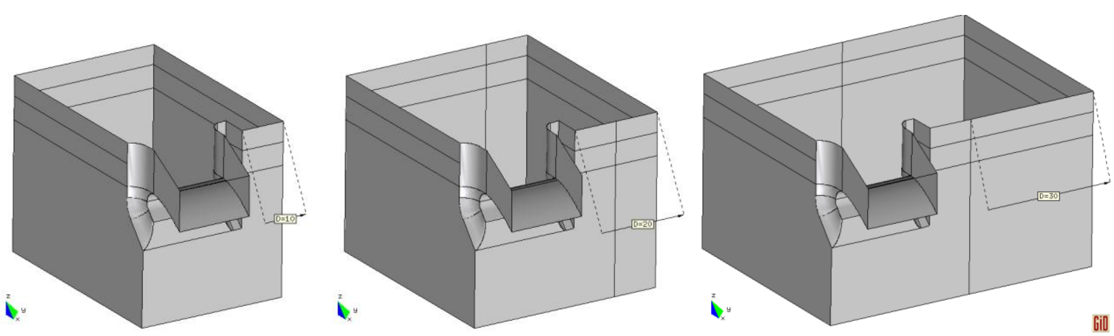

Figure 6. Geometry of the models for the sensitivity analysis of the width of the domain

Energy head has been computed as the average of the water surface elevation in the area which is outside the acceleration zone (where velocity head is negligible), and the results are shown in table 1.

Width	10 m	20 m	30 m
Average W.S.E.	515,32	515,34	515,34

Table 2. Energy head in the three domains for the selected case

The results show that the effect of the width increment on the approach head losses is negligible for 20 m. Thus, the intermediate domain has been selected for 3D models.

3.3.3. Energy head measurement and outflow stability

All the models start from an initial situation in which the domain is full of water up to the spillway crest. From that moment on, inflow makes the free surface rise, and outflow begins and increases, until the steady-state is achieved (i.e, inflow equals outflow, and the free surface remains stable). Certain fluctuations have been recorded in terms of outflow, which have been analyzed in order to assess their relevance. Outflow discharge is measured by means of defining a control section under the gate lip, as outlined in Fig. 7.

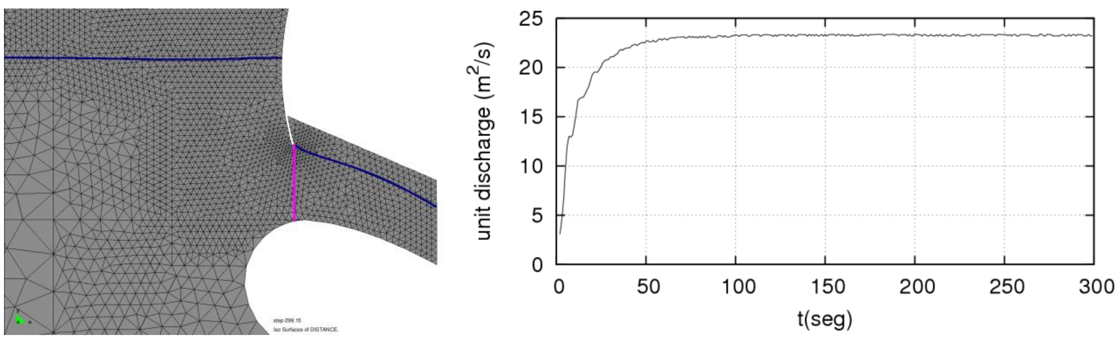

Figure 7. Left: Detail of the mesh, showing the position of the free surface and the cut under the gate lip. Right: Evolution of the discharge

As Fig. 7 shows, the outflow discharge gets stable after around 60 seconds of simulation. The magnitude of the fluctuations is below 0.15 m^2/s (<1%). So, it can be considered that equilibrium has been reached.

A similar procedure has been followed in 3D cases, where the outflow discharge is measured over a surface limited by the gate lip, the spillway crest, the pile and the abutment. Energy head has been measured in a time step in which it has been checked that outflow variations are within a 1% from the average.

3.3.4. Mesh size

Mesh size is one of the key aspects of each calculation using the FEM. It must be fine enough so as to accurately reproduce the phenomenon. On the contrary, the amount of elements must be moderate, so that the computational cost is affordable. The latter is equivalent to a lower limit of the mesh size.

When running a fluid dynamics calculation with free surface, it is essential to set a fine mesh in the area where the free surface is expected to be. This way, its position can be accurately computed, and its possible irregularities can be accounted for. On the contrary, the area which will be far from the free surface during the whole simulation can be meshed using a bigger size.

It is also convenient to set a fine mesh in the part of the domain where significant gradients of the variables (pressure, velocity) are expected to occur. In our work, this happens in the environment of the gate and the crest, as well as in the chute.

The mesh size has been defined following the above-mentioned criteria. Thus, 2D models have been meshed with 0.25-m-edge triangles for the fine mesh, and with 3-m-triangles for the coarse mesh. For 3D models, 0.5-m and 3-m edge tetrahedra have been used.

3.3.5. Roughness

The numerical code used allows the user to model the effect of boundary roughness, which is taken into account as a wall law. The value of the wall law input parameter has to be set so that it matches the magnitude of the absolute roughness of the actual boundary.

In our work, given that the velocity does not reach high values (only the reservoir and the topmost reach of the chute are modeled) this effect is expected to have little influence on the results. However, it has been accounted for, setting the input parameter of the wall law to 1 mm.

3.4. Extrapolation of the results of 2D models

As mentioned above, the discharge coefficients suggested by empirical formulation (Fig. 1) were obtained from tridimensional experimental tests, so that they implicitly consider the effect of side contractions. Therefore, total length of the spillway has to be considered when computing discharge flow this way.

On the contrary, bidimensional numerical models reproduce unit discharge, without side contractions at all. In order to apply their results to an actual spillway, an effective length has to be considered, lower than total length, which accounts for side contractions which actually occur. Given that there is not a specific expression for calculating effective length in gated spillways, the empirical formulation which is commonly used for free ogee crests (Eq. 2) has been used in our work. Thus, discharge flow can be computed as:

$$\mathrm{Q} = \mathrm{q_{2D}} \cdot \mathrm{L} = \mathrm{q_{2D}} \cdot \left[\mathrm{L'} - 2 \cdot (\mathrm{N} \cdot \mathrm{K_p} + \mathrm{K_e}) \cdot \mathrm{H_e}\right] \qquad (9)$$

where Q is total discharge (m^3/s), q_{2D} is unit discharge from 2D models (m^2/s), L is effective length calculated using Eq. 2, in m, and H_e is energy head on spillway crest (m). This procedure provides an extrapolation of the results of 2D models, which can be applied to obtaining discharge curves for an actual gated spillway.

3.5. Calculation of the underflow discharge using ANN

Discharge curves for gated spillways are commonly presented on a chart showing discharge-head relation for several gate openings. They can be obtained via numerical modelling, from the results of several runs. For Oliana Dam spillway, at least three values of the inflow (covering the whole operation range) have been computed for every integer value of the gate opening, from 1 to 5 m using Kratos. However, during reservoir operation, the dam owner needs to know this relation for any value of the energy head and gate opening.

One option to do that is to obtain a mathematical expression for calculating the discharge coefficient for any given value of both head and gate opening, using (Eq. 3). There is not a general rule which allows this procedure. It has already been shown that empirical formulation does not take into account some of the factors which may influence the discharge curves, such as side contractions or energy head.

An obvious alternative would be to run the numerical simulation of the specific situation of interest at any moment. This would require the availability of the numerical code, and certain time for the run, so that it is not practical.

In order to solve this drawback, ANN's have been used to obtain a mathematical expression which computes the discharge flow in any given situation (energy head and gate opening) from the results of the numerical tests.

In Oliana Dam spillway analysis, 20 different situations of gate controlled discharge have been calculated using FEM, comprising 1, 2, 3, 4 and 5 m gate openings. Given that these data seemed to be too scarce to be used as training data, a greater input data set has been generated. It has been found that an interpolating polynomial can be obtained for computing the head-discharge relation for each gate opening (with a root mean square error below 1%). So, these expressions have been used to generate the input data set. One hundred trios of data have been generated this way (20 for each integer value of the gate opening), covering the whole operating range of the spillway (from 0 to 9.0 m energy head).

The training process has been performed using the so-called *supervised learning*. In this kind of training algorithm, both the inputs and the correspondent right outputs are supplied to the ANN. The initial values of the free parameters are randomly defined. Then, the ANN takes the input values (energy head and gate opening), modifies the free parameters, obtains a result, and compares it with the right one (discharge) which has been supplied. This process is repeated until the error becomes lower than the desired tolerance.

Once the training process has been successfully completed, the ANN can be used to calculate the discharge for any given gate opening within the range of the training data (i.e., between 1 and 5 m). If a gate opening lower than 1 m or greater than 5 m is used, the ANN provides an output (extrapolation) which in general will be wrong. If the input value is close to the limits, the output may be used as an approximation, but as a general rule, the ANN should not be applied outside the range of the training data set.

4. Results and discussion

4.1. Empirical formulations

Discharge curves for Oliana Dam spillway have been computed using the empirical formulation suggested by USACE (1992), as described above. The values of the discharge coefficients have been calculated two ways: a) from Fig. 1, and b) by extrapolation of Folsom Dam spillway discharge coefficients using (Eq. 5). The results are shown in Fig. 8.

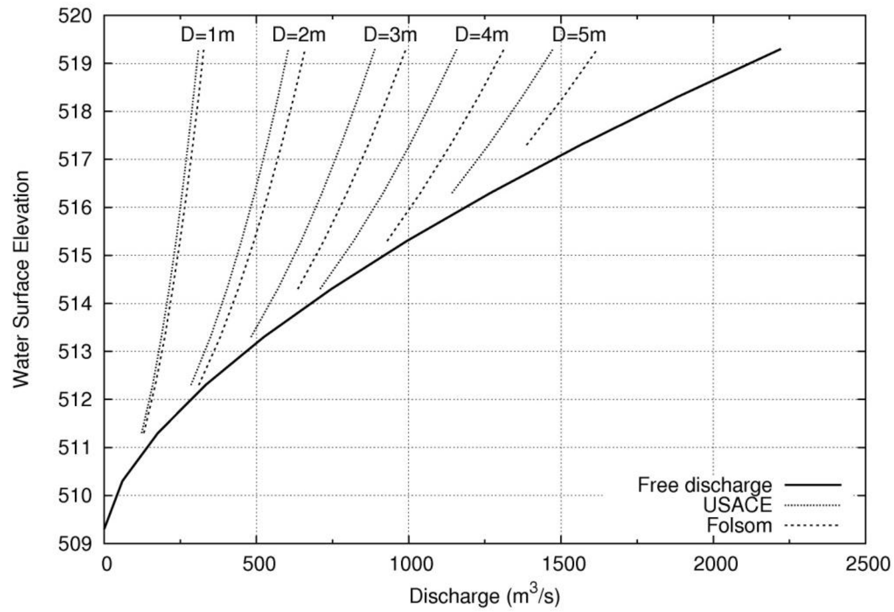

Figure 8. Discharge curves for Oliana Dam spillway computed using empirical formulation. Discharge coefficients have been computed: a) using the suggested curve by USACE and b) by extrapolation of Folsom Dam spillway discharge coefficients.

The discharge coefficient from USACE is lower than Folsom Dam for every given energy head and gate opening, so the discharge is lower as well. The discrepancy between both methods is greater for greater gate openings, up to a 13%.

4.2. Numerical modeling

No information is available regarding neither experimental models nor on-site measurements for Oliana Dam spillway. Thus, the validation of the numerical results cannot be made quantitatively. However, some qualitative aspects of the numerical results have been analyzed for validation purposes.

The shape of the velocity field on the upstream side of the crest for free discharge is well known from experimental tests. Figure 9 shows the expected shape of the velocity isolines according to SPANCOLD (1997), in comparison with numerical results obtained using Kratos.

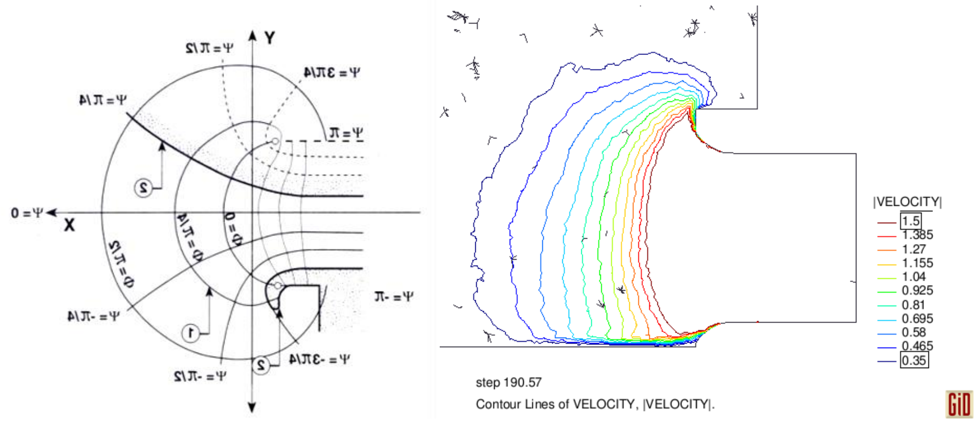

Figure 9. Velocty isolines on the free surface. Left: observed (SPANCOLD 1997). Right: numerical model results.

The shape of the free surface at the beginning of the chute is also a qualitative indicator of the accuracy of the results. It is concave in free flow, having a greater depth in the center of the bay. Some pictures of actual Oliana Dam spillway during a small spill are available, and have been compared to numerical results for a similar case. Although the latter corresponds to a higher flow, the concavity of the free surface can be observed.

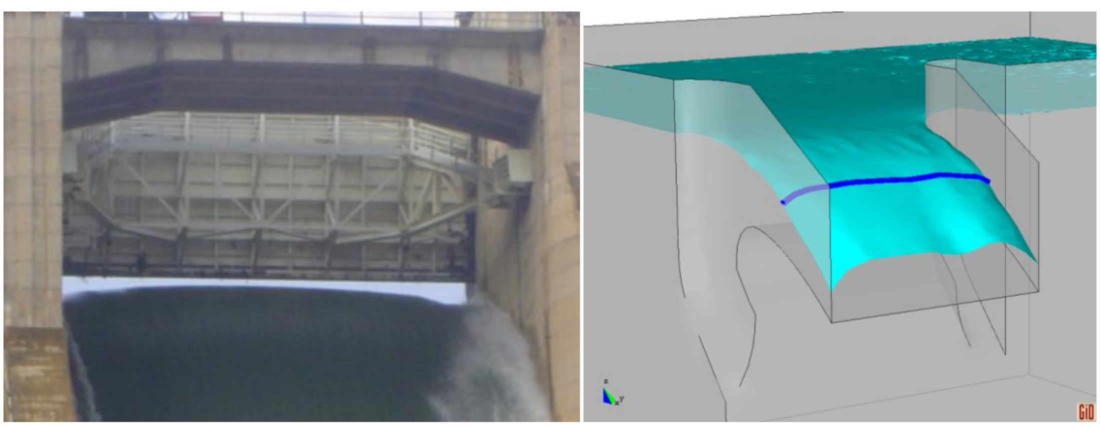

Figure 10. Shape of the free surface for free flow. Left: Actual Oliana Dam spillway. Right: Numerical model

Bidimensional numerical models have been carried out for 20 different situations having gate openings from 1 to 5 m, and covering the whole range of energy head of the spillway for underflow discharge. These models do not consider side contractions. Figure 11 shows the results.

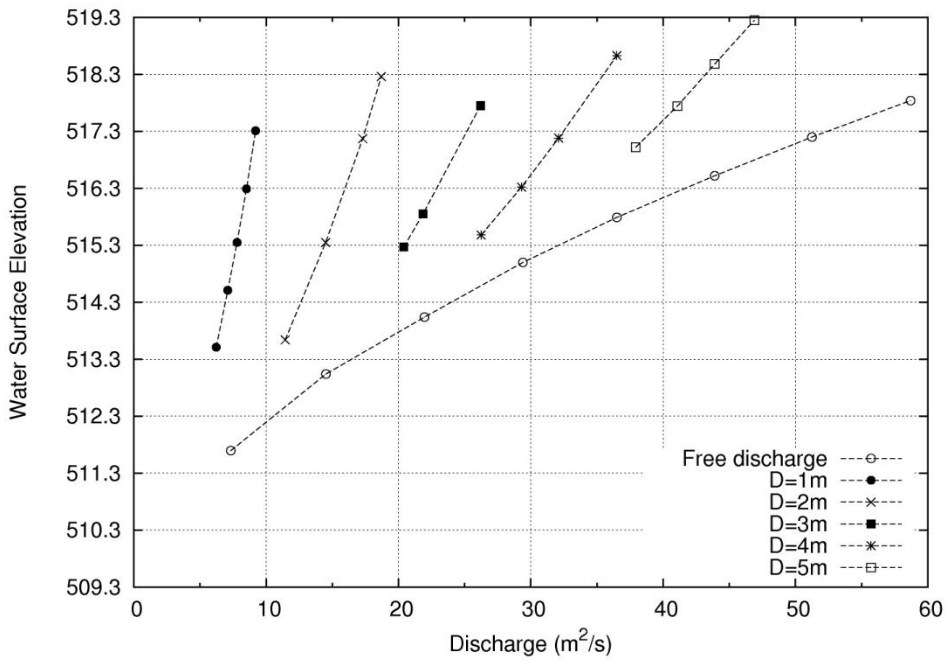

Figure 11. Results of 2D models. Unit discharge.

It can be seen that the curves joining the output points have an analogous shape to those predicted by the formulas, being quasi-vertical for 1-m gate opening, and tending to horizontal for larger openings.

These results have been extrapolated to Oliana Dam spillway multiplying the computed unit discharge by the effective length calculated using Eq. 2. The result is a family of curves of similar shape, which has been compared to the results of 3D models. Figure 12 shows this comparison.

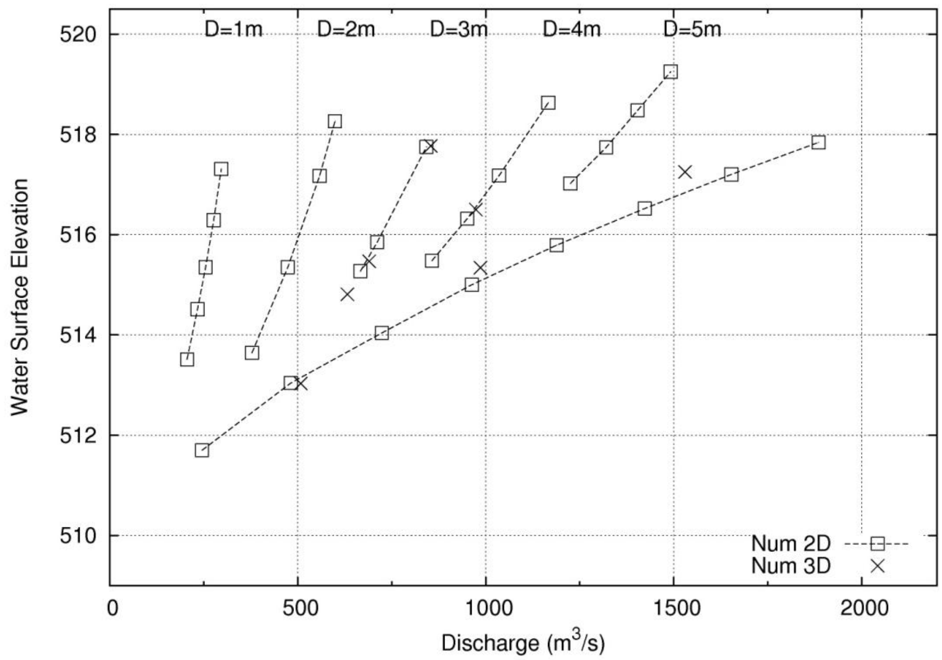

Figure 12. Comparison between extrapolation of 2D results and 3D models.

The results of the 3D models for underflow discharge match the predictions of the extrapolations of 2D models with a discrepancy around 1%. This strongly suggest that the formula for calculating the effective length which was developed for free ogee crests can be a good approximation to account for the side contractions in underflow discharge.

4.3. Artificial Neural Network

The test of the accuracy of the ANN is performed during the training stage, when the free parameters are adjusted until the root mean square error gets lower than the tolerance. However, a further test can be made by comparing its results to those given by the numerical simulations. It has been checked that the discrepancy between them is below 1%.

Figure 13 shows the outputs of the ANN both for 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5 and 5 m gate openings in comparison with the results of the numerical modeling. The latter show the polynomials fitting with the extrapolation of the 2D results.

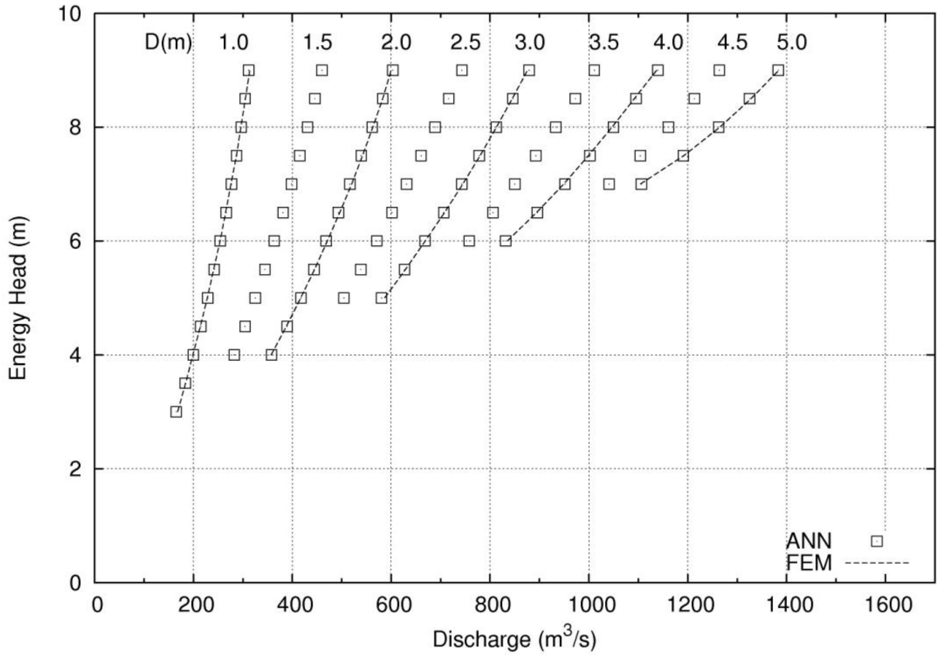

Figure 13. ANN vs. numerical results

4.4. Empirical vs. numerical results

Figure 14 shows the comparison of the discharge curves for Oliana Dam spillway computed using the different methodologies described:

1. Empirical formulation (Eq. 3)

    1.1 Discharge coefficients suggested by USACE

    2.1 Discharge coefficients from Folsom Dam spillway

2. Numerical modeling

    2.1 Extrapolation of 2D numerical models

    3.1 3D models

Free flow discharge curve (both empirically and numerically computed) has been inserted so to use as a reference, as well as to point out the accuracy of the numerical results for this situation.

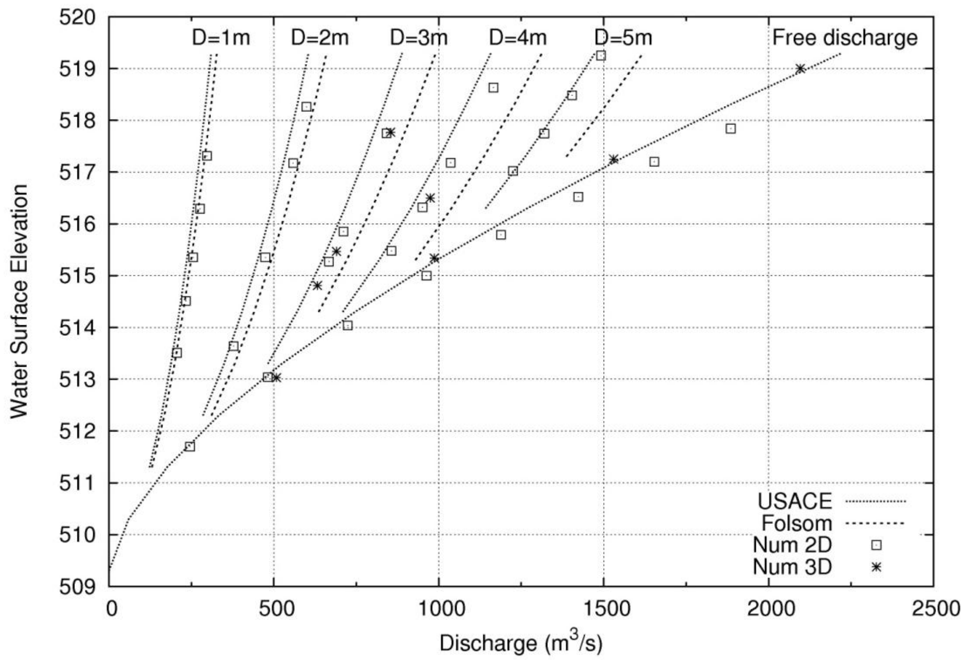

Figure 14. Discharge curves for Oliana Dam spillway: a) using Eq. 3 and Cg suggested by USACE (1992); b) the same, using Folsom Dam spillway C_g (USBR 1987); c) extrapolating 2D numerical models; d) from 3D numerical models.

In general, the results of numerical modeling are closer to the predictions of USACE, especially for large gate openings. However, the discrepancy between discharge coefficients for Folsom Dam spillway and those proposed by USACE suggests that this parameter is influenced not only by theta, but by further features of the spillway, such as side contractions or bay aspect ratio. The role of these variables on underflow discharge seems to be worthy of analysis.

5. Summary and conclusions

Discharge curves for Oliana Dam spillway have been calculated both for free and underflow discharge via numerical simulation. An Eulerian Finite Element code has been used. The relation between head and unit discharge for 1, 2, 3, 4 and 5 m gate openings has been obtained from the results of 2D models. These results have been extrapolated to actual geometry of Oliana Dam spillway multiplying the unit discharge by an effective length. The latter has been computed using the empirical formulation developed for free ogee crests (Eq. 2).

Then, four different situations of inflow-gate opening have been computed in 3D, so to analyze the accuracy of the former extrapolation. The results differ in around 1% from those extrapolated from 2D models.

Conclusion 1. The formulation for computing the effective length in free flow spillways can be a good approximation for calculating underflow discharge curves based on the results of 2D numerical models.

Empirical formulation developed by USACE and recommended by USBR and SPANCOLD has been analyzed. It has been observed that the results of the experiments which constitute the basement of the definition of the discharge coefficient differ in up to 5 % from the suggested curve. Discharge curves for Oliana Dam spillway have been computed using this methodology.

Furthermore, discharge curves for Folsom Dam spillway have been revised. An expression for the calculation of the discharge coefficient in terms of the gate opening has been produced and applied to Oliana Dam spillway case. Results differ from USACE methodology in up to 13%.

Conclusion 2. The results of the application of empirical formulas to the calculation of underflow discharge curves for a gated spillway may lead to significant errors, because they do not take into account aspects such as side contractions.

Conclusion 3. Discharge coefficient for underflow discharge in gated spillways may be significantly influenced by side contractions, geometry of piles and abutments, gate geometry, gate lip shape, etc. A deep analysis of these effects seems to be convenient.

The results given by numerical simulations differ in up to 8% from both empirical formulations. Further aspects of the results, such as the shape of the free surface, or the velocity field have been analyzed and found to be as observed in reality.

Conclusion 4. Kratos numerical code can be useful in the calculation of discharge capacity of spillways, both for free and underflow discharge. In order to get more confidence in the results, information on either experimental or on site data for Oliana Dam spillway would be needed.

An Artificial Neural Network has been developed and trained on the basis of the results of numerical models. It reproduces numerical models results with an accuracy of 1%, and produces reasonable approximations to the discharge curves for intermediate openings.

Conclusion 5. Artificial Neural Networks can be a useful tool for the real-time calculation of the response of a system on the basis of discrete data given by numerical (or experimental) tests.

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