Computer-aided design and analysis of arch dams

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ABSTRACT: Double curvature arch dams feature geometrical complexity with a significant amount of parameters involved. Different criteria exist to assist in the design task, from simplified geometrical approaches to optimization procedures. However, most of them present a lack of flexibility and are not integrated in computer-aided design tools.
In this contribution, an interactive and flexible software tool is presented to support the complete design process: geometrical definition, FEM model generation (including the mesh, the loads and the boundary conditions) and thermo-mechanical analysis.
The design can be performed with different levels of detail to adapt to the information available in each stage of the project. The tool allows defining the shape of the reference cylinder, the excavation depth and slope along the foundation, the crown cantilever thickness and curvature, the shape and location of horizontal arcs; all these steps were described in former contributions. Here, special attention is paid to the introduction of additional features such as joints, spillways, abutments of varying shape and outlet works. All steps have been defined with a high degree of flexibility in the design process.
The tool is integrated with the pre and post process software GiD, which allows taking advantage of its functionalities, such as mesh generation and results analysis. It is also coupled with a specific application for thermo-mechanical analysis of dams, developed in Kratos Multiphysics – a framework for building parallel multi-disciplinary simulation software. The whole design process can be followed in a unique environment, because the structural response of preliminary designs can be computed and the results considered to refine the dam geometry.

1 Introduction

Arch dams are more efficient than other typologies in terms of structural behavior. Unlike gravity or rock fill dams, which resist the hydrostatic load mostly by means of their weight, arch dams distribute part of the load to the abutments, which allows reducing the necessary volume of concrete.

This higher efficiency implies a greater complexity: On the one hand, their structural verification requires three-dimensional models, and on the other, their design is more complicated. The development of the finite element method (FEM) allowed performing their structural analysis, which can be done with different software tools. However, design continues to be fundamentally based on rules of good practice and past experience, a process that is clearly susceptible to improvement.

Reference documents in engineering practice contain useful design criteria [1], [2], though they do not take advantage of the possibilities of computer-aided design. Recently, the United States Bureau of Reclamation (USBR) has published a design manual including a spreadsheet for a simplified design [3], but it can only be applied to dams with circular axe.

The topic aroused interest of the community: Goulas [4] presented an application to assist in the design of arch dams compatible with the FEM code DIANA [5].

In this context, we are working on a software tool for automatizing the whole process of design and verification of double-curvature arch dams. It includes functionalities for defining the geometry in an interactive way. It is integrated in the pre and post process software GID [6] and coupled to "DamApp", an in-house developed code for thermo-mechanical computation of dams. The latter is one of the applications of the open-source environment Kratos Multiphysics [7], [8], which has been previously employed for the structural analysis of arch dams [9], [10], [11]. Once the FEM model has been created and the calculation performed, the design can be modified in view of the results and the process repeated until the problem constraints are fulfilled.

The first version of the application was described in a previous work [12]. Here, we briefly describe the most relevant features and present some new functionalities implemented. They correspond to additional features such as monolithic joints, spillways, abutments of varying shape and outlet works.

2 Methods

2.1 Model geometry

As mentioned before, the tool is integrated in the software GID. Once the topography of the dam site has been loaded, the main steps to be followed are:

1. Definition of the elevation of (a) crest and (b) lowest point in the foundation.
2. Selection of the guideline curve for the reference cylinder. In the current version, it can be either a parabola or an ellipse. It should be noted that most circular arcs can be approximated with ellipses with enough accuracy, if necessary.
3. Introduction of the excavation depth, which can be different for different sectors of the foundation.
4. Generation of the reference cylinder and computation of its intersection with the ground topography
5. Definition of the crown cantilever. Initially, the preliminary design proposed by the USBR [3] is drawn; it can be modified afterwards.
6. Selection of lines of centers for the curves defining the upstream and downstream faces at ten equally spaced elevations between crest and foundation.
7. Generation of the arcs for each elevation and dam face (intrados and extrados).
8. Creation of the dam body in 3D.
9. Selection of the excavation slopes for each margin and for the river bed.
10. Adjustment of the overhanging, if appropriate.
11. Definition and generation of additional features, if applicable:
    - Monolith joints
    - Abutment blocks
    - Spillway
    - Outlet works
12. Mesh generation

The main window of the interface is depicted in Figure 1. The example corresponds to a parabolic fit. Schemes to assist to the definition of the excavation depth and the lines of centers can be activated by the user. In the example, the first is shown.

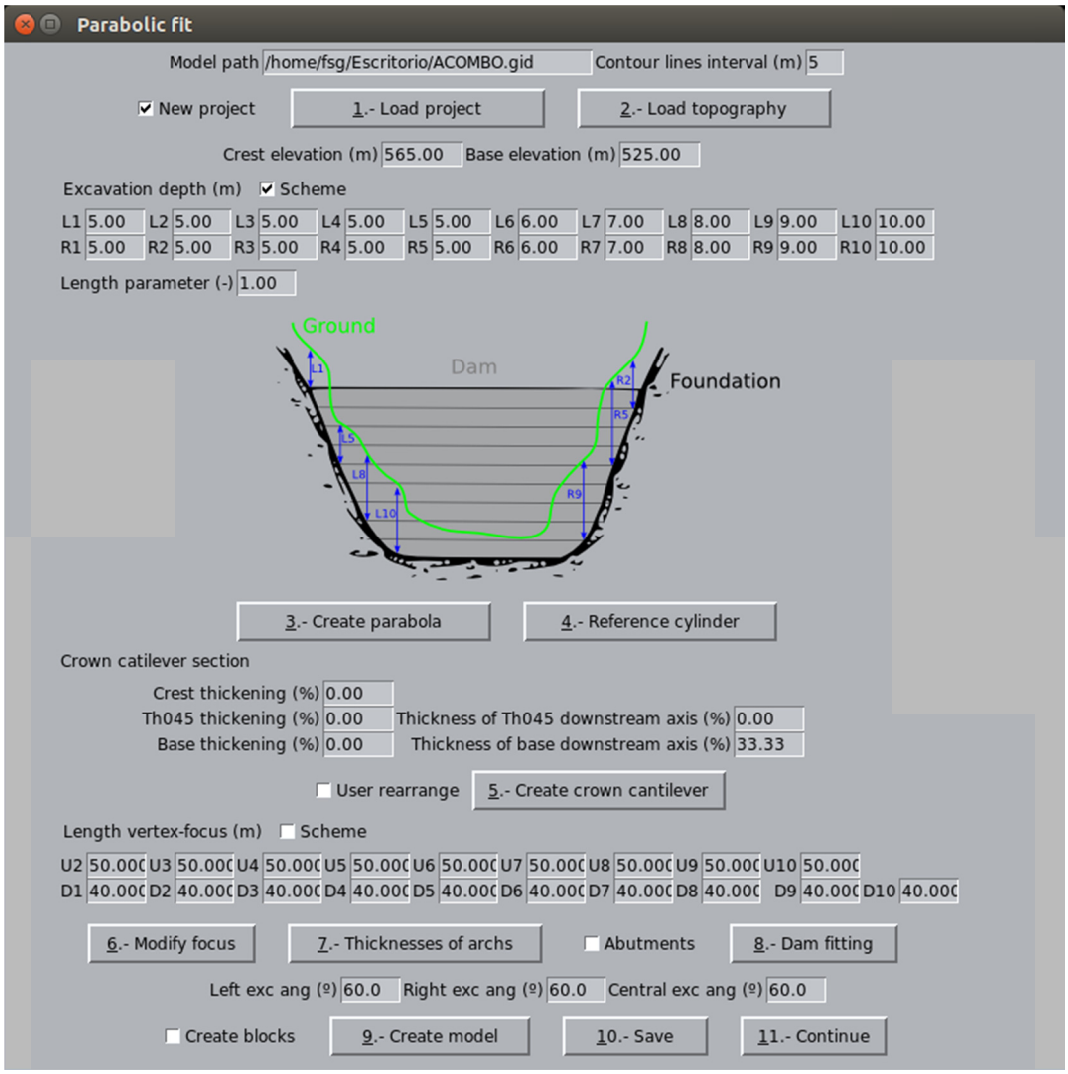

Figure1: Interface of the application. Main window.

At the end of the process, a 3D finite element model is generated, which can be used in a thermo-mechanical analysis. Figure 2 shows an example, where the spillway, abutments and excavation can be observed.

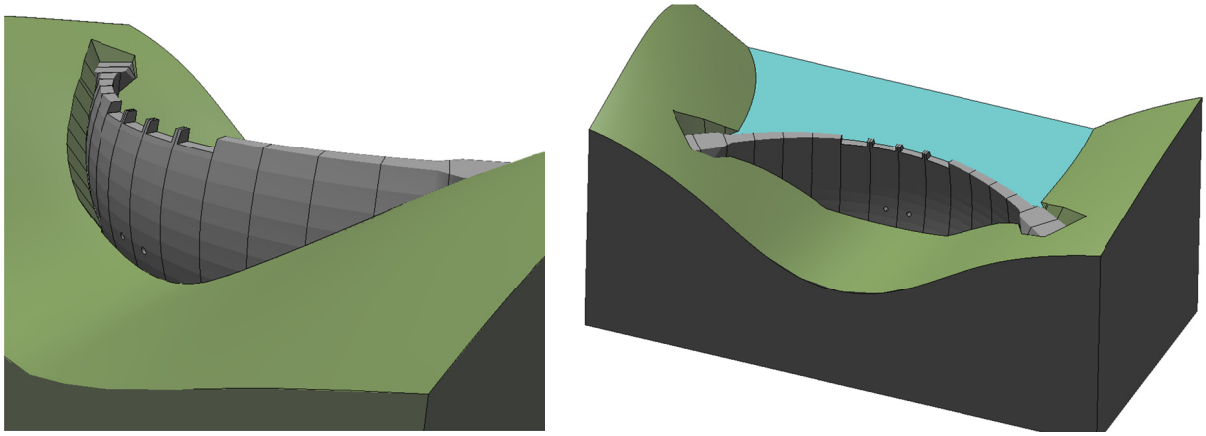

Figure 2: Example of 3D model generated with the tool.

Some features such as spillways or bottom outlets works, whose influence in the structural response is typically minor, are optional and can be neglected in preliminary studies.

It is worth noting that the final FEM model can be modified from the GID interface, as an ordinary model. Each element of the model geometry can be tuned, as well as the mesh properties, domain dimensions, etc. Nonetheless, a preliminary fit can be done and computed by users unfamiliar with GID or any other pre-process software.

2.2 Thermo-mechanical analysis

The tool is also integrated into "DamApp", an application for thermo-mechanical analysis that includes specific features for dam engineering:

1. Seismic analysis can be performed, including hydrodynamic effects, which can be considered by means of the Westergaard formula [13] or by fluid-structure interaction (FSI) [14].
2. Modal analysis is available to obtain the natural frequencies.
3. Joints between cantilevers (or blocks in gravity dams) can be accounted for via joint elements, which can reproduce their nonlinear behavior. They are governed by a cohesive bilinear law [15], [16].
4. Nonlinear constitutive models can be used to account for damage.
5. Transient loads and boundary conditions can be applied
6. Sub-pressure and uplift can be considered, together with the effect of drainage.
7. Variable water temperature, both in time and depth, can be accounted for, including the variation in the water surface elevation along time. Both the Bofang formula [17] and a user-defined one can be employed.
8. The construction process can be reproduced by activating layers along the transient calculation.
9. Stresses in global coordinates can be transformed into principal stresses (tensile/compressive) for a more intuitive interpretation of the results.
10. The results of the numerical model and the monitoring data can be jointly analyzed: the user can define the location and nature of the monitoring devices, which results are written into specific files.

2.3 New functionalities in the geometry generation process

As mentioned before, the main aspects of the geometry generation process were described in depth in a previous work [12]. In this section, we focus on the new functionalities implemented, which allow including additional elements such as joints, abutment blocks, spillways and outlets works. The parameters involved in the definition of these elements are listed in Table 1.

Table 1: Geometrical parameters of dam elements

Element	Parameter	Id	Element	Parameter	Id
Monolith joints	Cantilever thickness	J_{th}	Spillways	Location-Right sidewall	S_{rs}
	Location	J_x		Location-Left sidewall	S_{ls}
Abutment blocks	Location	A_x		Ogee crest elevation	S_h
	Transition length	A_{tl}	Outlet works	Location	O_x
	Downstream thickness	A_{th}		Elevation	O_e
	Downstream slope	A_{ds}		Diameter	O_d

The location of each element is defined in terms of the distance along dam axis to the vertex of the guideline curve of the reference cylinder (O), as depicted in Figure 3.

Joints

The position of the vertical joints is determined by the width of the cantilevers (J_{th}), which is frequently constant along the dam axis. This value can be introduced in the corresponding window. With this procedure, a joint coincides with the vertex O, and the remaining ones are evenly spaced towards both abutments.

If some cantilever features different width, the location of the corresponding joints can be introduced manually defining their distance to the vertex O (J_x). Figure 3 shows the interface for defining the joints with the 'automatic' or 'manual' options.

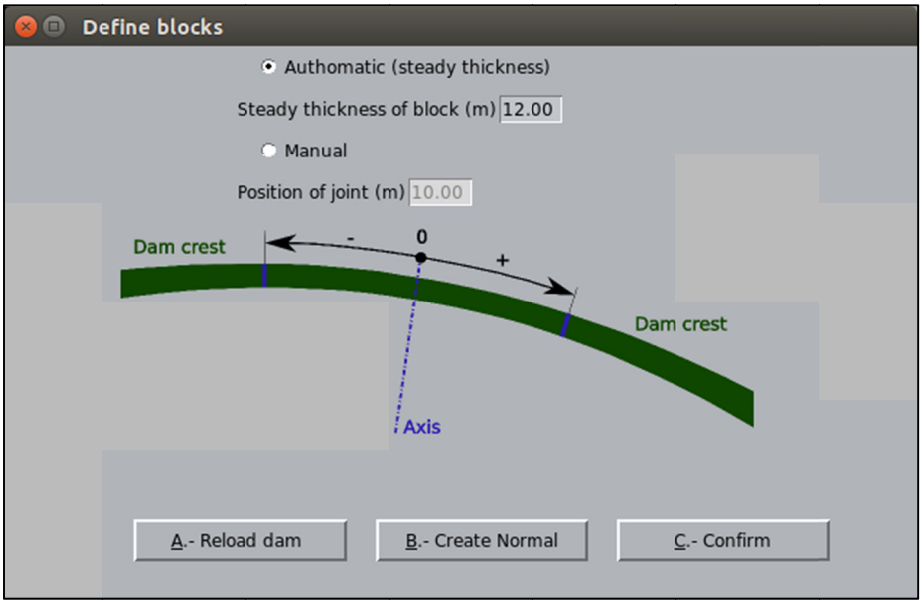

Figure 3. User interface to introduce the location of the monolith joints. They are defined in terms of their distance to the vertex along the axis of the reference cylinder.

Abutment blocks

Many arch dams transmit part of the loads to the margins through a special structure, with higher width, also termed "artificial abutment". This reduces the maximum stress applied to the foundation, hence favors a smooth distribution of stress. A procedure to define these elements is also implemented in the design tool. In this version, four parameters need to be defined: (a) distance to the vertex (A_x) (which defines the start of the block), (b) transitions length (A_{tl}), (c) downstream thickness (A_{th}) and (d) downstream slope (A_{ds}).

The geometrical construction follows the following process (see Figure 4):

1. The point A in the upstream face of the dam, where the abutment starts, is fixed with the distance A_x.
2. The segment AB is defined by placing the transition length A_{tl} along a perpendicular to the axis of symmetry of the reference cylinder through A.
3. The symmetrical segment to AB with respect to the tangent to the extrados at A is drawn and moved from A to C, turning into $\overline{CD}$.
4. BE and DF are perpendicular to the original end of the abutment.

5. The thickness can be incremented by turning DF toward downstream an angle A_{th} obtaining the point G.
6. The downstream slope can be modified with the parameter A_{ds}.

Each abutment block can be defined separately. Figure 5 shows the interface of the tool for introducing the parameters of the abutment blocks.

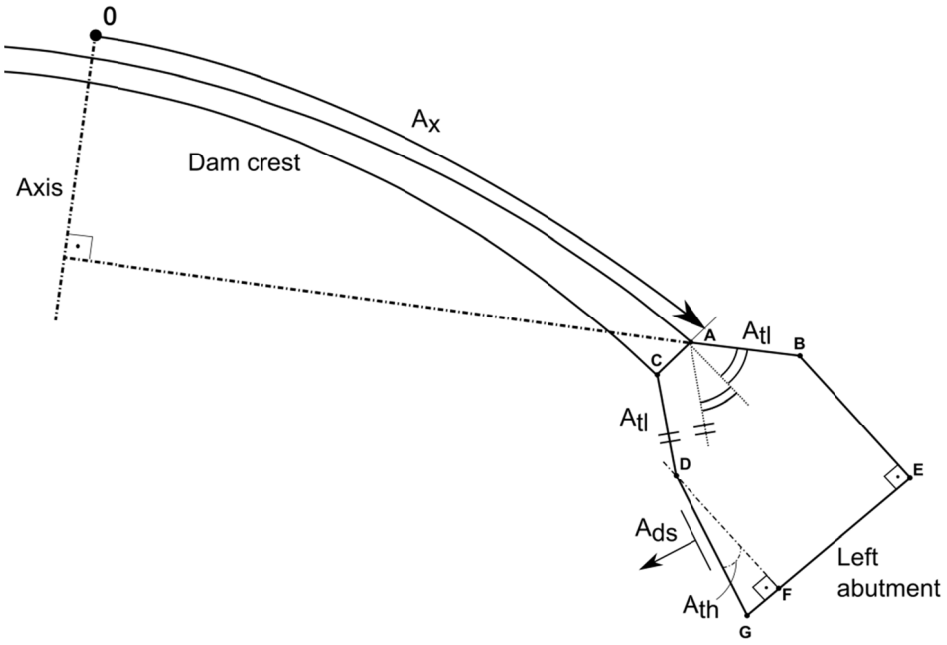

Figure 4. Elements involved in the definition of the abutment blocks.

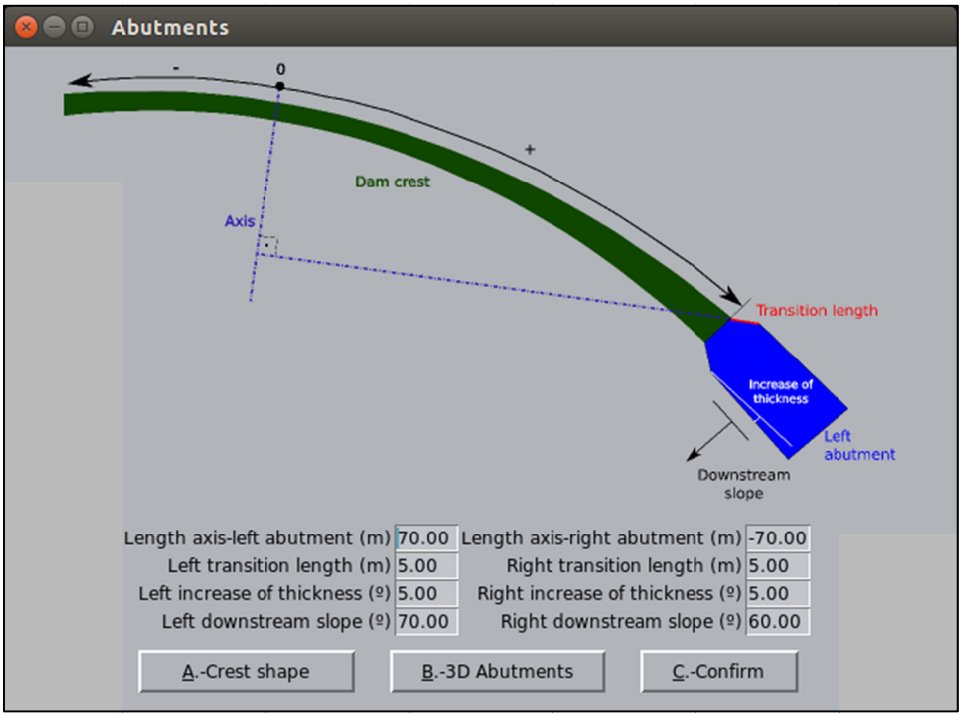

Figure 5. Interface of the tool to define the abutment blocks.

Spillways and outlet works

The application allows designing a 'spillway crest' located, as its name suggest, at the crest of the dam. As the elements described in the previous sections, it is defined taking the vertex of the guideline curve as a reference. Hence, the distances to the left (S_{ls}) and right (S_{rs}) sidewalls of each spillways bay need to be introduced, as well as the height (S_h) – difference between dam crest elevation and that of the spillway crest (Figure 6). The process can be repeated to introduce several spillway bays.

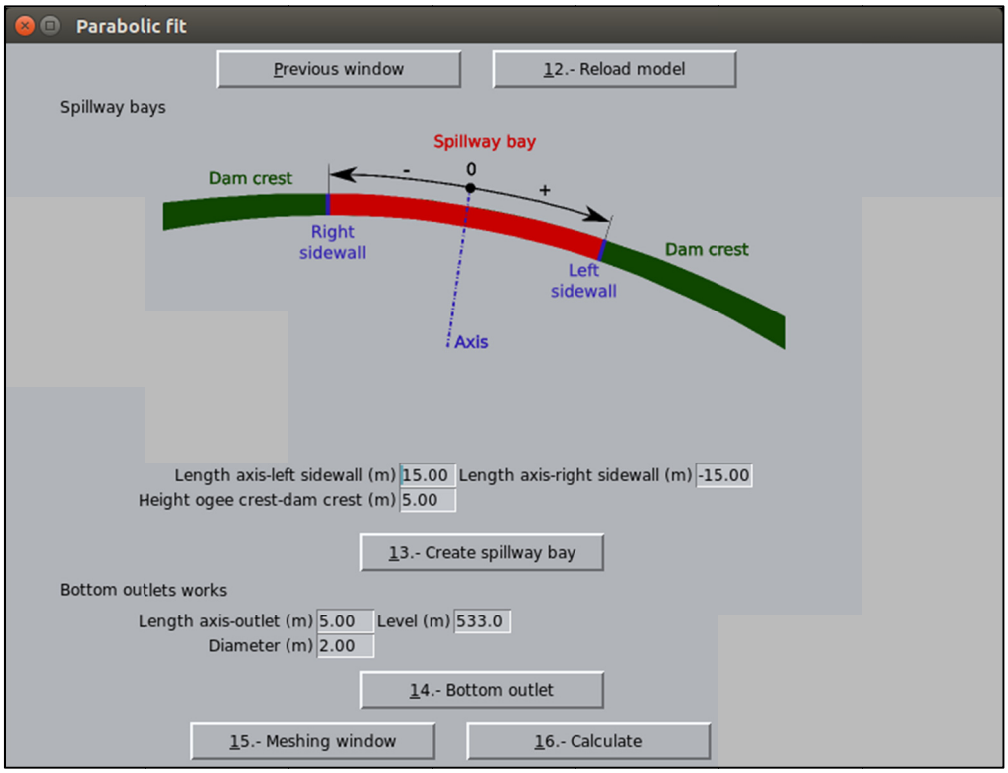

Figure 6. Definition of crest spillway and bottom outlets.

Outlet works can be defined in a similar way, i.e., as many elements as necessary can be introduced by means of 3 geometrical parameters: the location of the axis with respect to O (O_x), its elevation (O_e) and diameter (O_d) (Figure 6).

3 Example of application

The application has already been used to generate several 3D models of Spanish arch dams [12]. In engineering practice, 3D numerical models of existing dams need to be created with certain frequency, to make additional studies (in case of dam heightening, updated regulations, change in dam operation rules [18], etc.). In these cases, the geometry needs to be constructed in 3D from 2D drawings (top, side and front views). The conventional procedure consists in digitizing each cross section, putting them in their corresponding location in 3D, and generating volumes for each cantilever. This task is cumbersome and can be automated.

In this work, the new functionalities presented were applied to build a 3D model of La Baells dam. It is a 102-m height arch dam located in the Llobregat River, in Barcelona, Spain. It has been used as case study in previous works ([19], [20]), which include descriptions of the structure and its performance.

Figure 7 shows several views of the resulting model, highlighting the monolith joints, abutment blocks, outlet works and mesh.

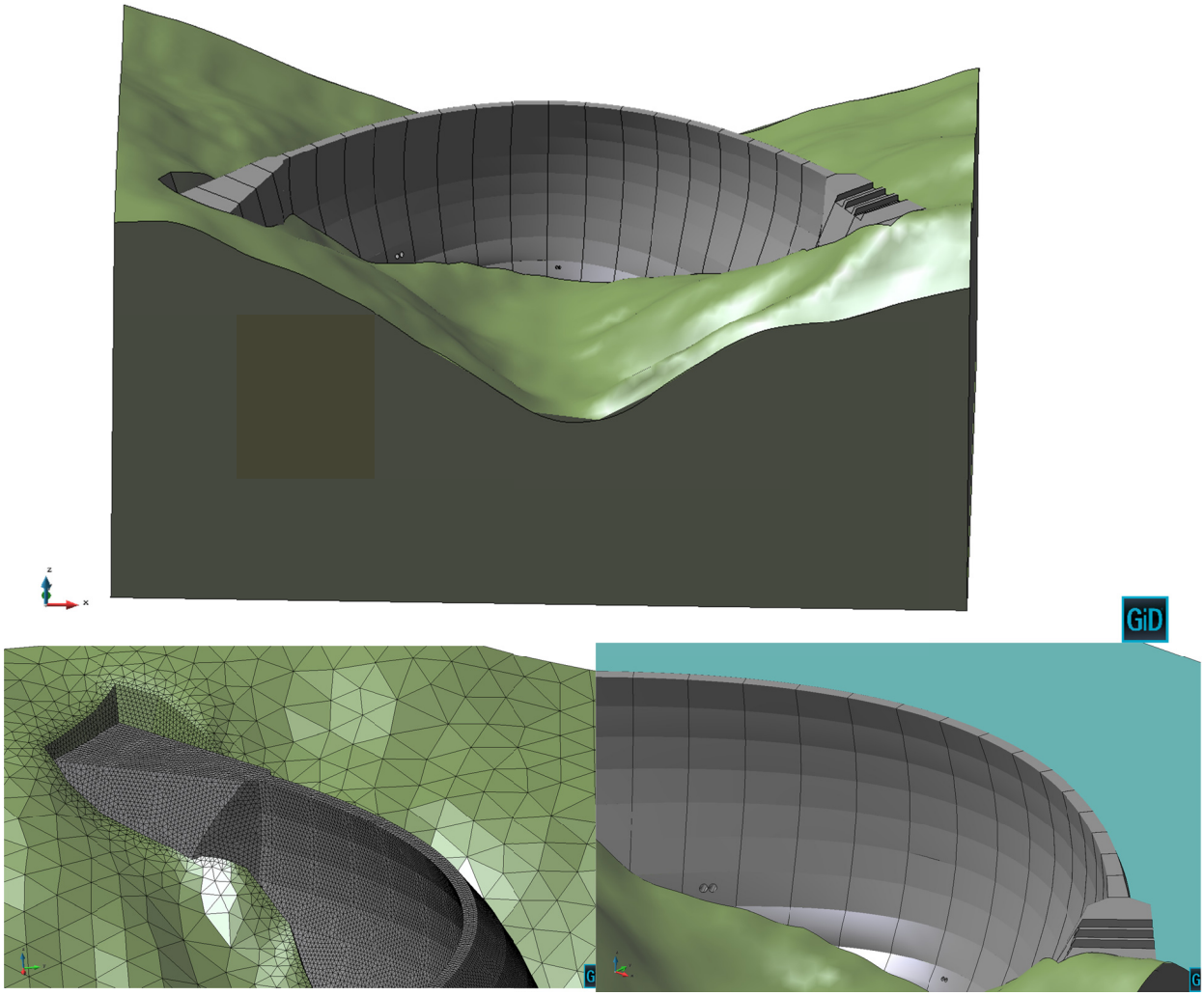

Figure 7. Resulting FEM model for La Baells dam. Top: view from downstream. Bottom left: detailed view of the right abutment, where the excavation can be observed, as well as the finite element mesh. Bottom right: View from the left abutment, showing the spillway and the outlet works.

4 Summary, conclusions and current work

An application has been presented to assist in the design process and structural verification of arch dams. The user can define the geometry of the model according to the rules of good practice, previous experience and the geometry of the canyon.

A finite element mesh can be directly generated from the resulting geometry, which in turn can be employed to run thermo-mechanical analyses. In view of the results, the design can be modified, if necessary. The FEM computation is performed by means of "Dam App", one of the applications developed in the Kratos environment, a framework for building parallel multi-disciplinary simulation software. Nonetheless, the model could also be analyzed with other solvers, thanks to the flexibility of GiD [6].

The parametric definition of specific elements of arch dams, such as joints, abutments spillways and outlet works, will help to create FEM detailed models in a straightforward way. It can also reduce the possibility of introducing mistakes in the design, or while building a FEM model of an existing dam.

Some of the processes were developed following determined design criteria, such as the shape of the abutment blocks or the geometry of the dam faces. We are currently working in the implementation of additional options, to increase the flexibility of the design process. Nonetheless, it should be noted that the resulting model can be fully modified by the user by means of the pre-process tools included in GiD.

The Dam App is also under development. The upcoming functionalities include the detailed consideration of the construction process and the boundary conditions, among others.

5 Acknowledgements

We acknowledge the financial support to CIMNE via the CERCA Programme/Generalitat de Catalunya. The research was also supported by the Spanish Ministry of Economy and Competitiveness (Ministerio de Economía y Competitividad, MINECO) through the projects ACOMBO (RTC-2015-3794-5) and NUMA (RTC-2016-4859-5).

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