

INTERACTIVE ALGORITHM FOR GEOMETRIC MODELLING DOUBLE-CURVATURE ARCH DAMS

INTERAKTIVNI ALGORITAM ZA GEOMETRIJSKO MODELIRANJE DVOJNO ZAKRIVLJENIH BRANA

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1 INTRODUCTION

In suitable terrain and geological conditions, arch dams consistently outperform other concrete dam types in terms of load capacity, safety and economic efficiency. Benefiting from the concrete compressive strength and the advantageous geometry, arch dams effectively transmit static and dynamic loads to the abutments and foundation. To further decrease the amount of construction material and push the financial savings to higher levels, arch dams structural design and construction techniques focus on variable geometry minimizing the thickness. The dam design process starts with the arch dam initial layout. The next phase consists of gradual adjustments of the dam complex geometry and comparison of results of structural analyses. The

analyses in the successive optimization steps consist of structural evaluation and sensitivity calculations of critical parameters, such as displacement and stresses developed in the dam body, foundation and abutments. In response to the results of the complex analyses, the engineer gradually updates the arch dam geometry model in the Euclidean three-dimensional space. The double-curved shape of an arch dam requires judicious evaluation and optimization of the design parameters yet, the most widespread arch dam design techniques are still dependent on engineering judgment and experience and involve recommendations given in the traditional technical documents.

With the rapid increase of computer capacity, the computer-aided engineering design became the standard technique for design and optimization modelling of arch dams. The optimization process of the dam geometry and structural parameters is carried out until the dam optimal design satisfies the allowable design criteria [1-4]. The software accuracy and capacity to carry out complex structural and sensitivity analyses and fine-tuning of the dam geometry contribute to the effectiveness of the final dam shape [3-7]. The existing numerical methods can be categorized into three broad groups: geometric and feature modelling [12-17], solid modelling [18-19] and surface modelling [20-22]. Wassermann (1983) [5], used eight-node isoparametric solid finite elements to model a double-curvature arch dam and to solve the optimization problem by the sequential linear programming method [1]. To achieve general 3D surface design optimization (Mortenson 1985) [4], the Bezier surface for shape design parameterization was applied [23-24]. Seyedpoor et al.

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[8] focused on soft computing techniques for optimal design of arch dams. The authors first simulated the dam-water–foundation rock system using the finite element method, and then conducted the optimization process. To further accelerate the optimization process, the generally time-consuming dynamic finite element analyses were replaced with the neuro-fuzzy inference system combined with the particle swarm optimization [8]. On the other hand, to create a solid model of an arch dam, the computer-aided design platform CATIA V5 [25-26] develops arch dam geometric characteristics applying geometric and feature modelling methods [17].

Although equipped to carry out sophisticated analyses, current computer-aided design models have a range of shortcomings. As indicated by Kirk Martini [27], the developed algorithms for geometric modelling are often not in full compliance with requirements for practical and applicable engineering drawings, i.e., while traditional engineering drawings apply a concise description of the dam geometry that can easily be modified and decomposed in a top-down manner, [17,27] the current computer models generally use a bottom-up approach [27]. The latter approach appears not well suited for design purposes, in particular for cases where an update of the dam geometry can be a demanding task. To overcome the above issues, considerable research was conducted on the effectiveness of computer-based geometric modelling techniques to capture practical design problems. A few algorithms exist in the literature for automatic generation of dam geometry based on mathematical description of the dam structural geometry considering top-down approach. For example, Goulas [23] developed a procedure for the preliminary design of double-curvature arch dams, compatible with the well-known DIANA software [24]. D. J.Vicente [28] presented an innovative software for preliminary geometric design of double-curvature arch dams FEM models based on the US standards [28]. Likewise, to optimize the dam geometry for static and dynamic loads, Jalal Akbari [5] suggested a practical computer algorithm applying Hermit cubic splines. It can be concluded from the above discussion that improvement and sophistication of the computer-based geometric modelling and visualization techniques are needed to capture the necessary practical design issues.

In this paper, an original algorithm for a user-friendly design of arch dams is presented that effectively combines the advantages of the traditional geometric-design methods with innovative graphical and computational capabilities [12,13]. The main objective is to further facilitate the decision-making in the dam design process. The generated design algorithm was implemented in and runs parallel with the ADAD-IZIIS software for structural analyses of concrete arch and gravity dams [29]. The implemented design process includes the following successive steps: (i) define topography and select potential dam micro location(s); (ii) design dam initial layout; (iii) generate finite element mesh of a single and double-curvature arch dam together with a portion of the foundation rock to account for dam-foundation interaction, (iv) generate boundary element mesh representing the boundaries of the fluid domain to account for the fluid-dam interaction, (v) introduce construction joints within the dam body and peripheral joints at the dam-foundation interface, (vi)

analyze the stress-strain state under static and dynamic loads, (vii) compare the analysis results, and (viii) return to step (ii) with the updated dam geometry (if necessary). To demonstrate the effectiveness of the proposed method for geometric design, an example is given of a 130 m high double-curvature arch dam located in a V-shape canyon.

2 TOPOGRAPHY AND OPTIMAL LOCATION

The proposed dam geometric design process starts with generation of a mathematical model of the terrain topography. The digital elevation model of the potential construction site(s) is created from elevation points from geodetic surveys (e.g., light detection and ranging LIDAR data) and/or existing numerical topographic maps. The coordinates of the point raster are defined in a fixed global Cartesian system (X_G - Z_G - Z_G), where the Z_G axis points vertically upward, Fig. 1a. Equally spaced contour lines are then mathematically presented with short straight-line segments or, in case of insufficient data density, with polynomials of a second order passing through three neighbouring points. In the vertical direction, further densification of the spacing between contour lines can be done where necessary.

The topography is defined in a global coordinate system, which remains unchanged throughout the design procedure. The geometry of the arch dam components, however, is determined in both the global coordinate system and in a changeable local Cartesian coordinate system (X_L - Y_L - Z_L - α). The local coordinate system facilitates generation and visualization of the crown cantilever and the horizontal arches and updating of their geometry. The origin of the local coordinate system, X_C - Y_C - Z_C , and the deflection angle α with respect to the global coordinate system, can change during the location selection process. In the presented example, the arch dam local coordinate system was rotated by 87° in the counter clockwise direction, Fig. 1.

The local coordinates of any point of the arch dam are transformed into global coordinates with the following equation,

$$\begin{Bmatrix} X_G \\ Y_G \\ Z_G \end{Bmatrix} = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} X_L \\ Y_L \\ Z_L \end{Bmatrix} + \begin{Bmatrix} X_C \\ Y_C \\ Z_C \end{Bmatrix} \quad (1)$$

The horizontal coordinates Y_C and X_C are different from zero, while the vertical coordinate Z_C could equal zero in case when the absolute global Z_G coordinates are used for definition of the vertical 2D model of the crown cantilever in the reference plane, Fig. 1b.

The algorithm allows the possibility to select among the multiple potential locations the one that offers at this stage the most cost-effective solution. The selection process is based on a comparative study, where the user defines a number of vertical cross sections in the studied narrow portion of the canyon with successively increasing dam heights. In general, canyons with complex topography and geometrical singularities require higher number of potential locations and dam elevations. In Fig. 2 is illustrated such an example of selection of the dam optimal location and height.

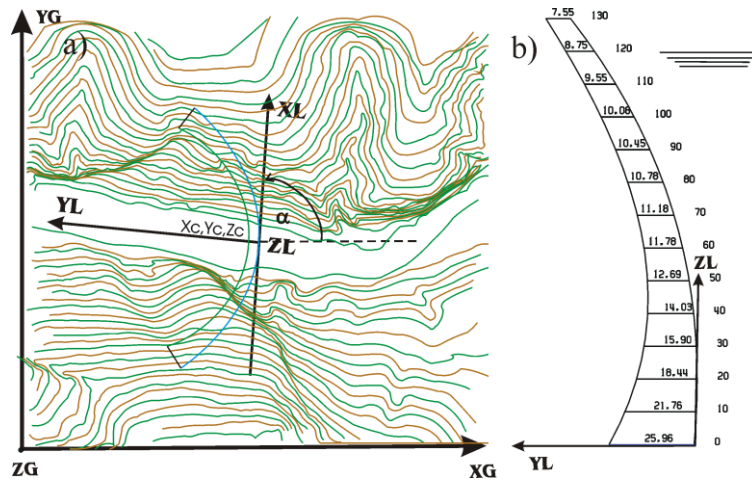


Figure 1. Global (G) and in local (L) coordinate systems for: a) Location of the crown arch of the dam, and b) Cross section of the crown cantilever representing the reference plane in the local coordinate system. The origin of the local coordinate system is indicated with X_c - Y_c - Z_c .

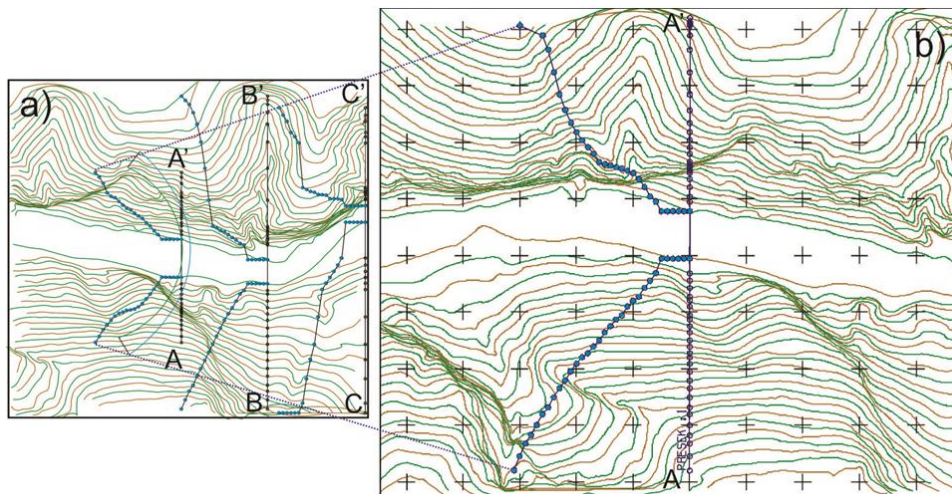


Figure 2. Selection of optimal dam location: a) potential locations (straight lines) and respective cross section profiles (overturned projections) of the dam foundation, and b) final location of the dam (cross section A-A').

Three locations with different dam heights are explored in Fig. 2a. In the selection process the dam height was gradually increased with successive height increments of 10m. The optimal location, cross section A-A' in this case, was selected in the narrowest portion of the canyon up to the extent of the steepest portion of the sidewalls and with respective shortest crest length. Any increase of the dam height beyond the final 130 m, could have resulted in unattractive solution from an economic viewpoint due to the progressively increased length of the dam crest.

3 GEOMETRY OF CROWN CANTILEVER AND ELEVATION ARCHES

Following the selection of the dam location, the arch dam geometrical model is built in a form of circular segments assigned to each incremental height. The curved shape results from the combination of both the

crown cantilever geometry and the curvature of the composite arches. As the geometry of a double curvature dam curves horizontally towards the abutments and vertically towards the crest, the design of the arches is conducted in parallel to the definition of the crown cantilever.

3.1 Crown cantilever geometry

The initial dimensions of the crown cantilever depend on the shape of the selected topographic profile, mainly characterized by the vertical distance from the dam crest to the foundation rock, referred to as structural height (H), and straight line distances between the abutments at the dam crest and at $0.15H$ including assumed excavation to the solid rock. The crown cantilever is with vertical curvature to counter the development of tensile stresses in the structure and has two curved surfaces on the upstream and downstream face of the dam.

The crown cantilever is defined in the Y_L-Z_L reference plane with the following local coordinates, Fig 1b:

- Y_{LEn}, Z_{LEn} - coordinates of the extrados points with respect to the local reference system $X_L-Y_L-Z_L$, where: $X_{LE}=0$ and $Y_{LEn} \neq 0, Z_{LEn} \neq 0$ for $n=1, K$, where K represents the number of selected elevations for the dam design;
- Y_{Lin}, Z_{Lin} - coordinates of the intrados points with respect to the local reference system $X_L-Y_L-Z_L$, where: $X_{Li}=0$ and $Y_{Lin} \neq 0, Z_{Lin} \neq 0$ for $n=1, K$.

The reference plane Y_L-Z_L and $X_L=0$ is the imaginary upstream to downstream vertical cross section through the crown cantilever and the line-of-centres related to the central segment of the dam, Fig 1b. In the given example, the crown cantilever was divided in a number of superimposed substructures corresponding to each 10m incremental dam height. In this way, the thickness of the crown cantilever becomes a design variable as function of the geometrical features of the selected topographic profile, Fig. 1b. To mathematically determine the shape of the crown cantilever, curve fitting was applied through the coordinates of nodes representing its upstream and downstream faces. Among the tested functions, a third order polynomial was found to reasonably simulate the curved shape of the crown cantilever. The adopted shape of the crown cantilever indicates a thin arch dam as the base thickness to height ratio is $26m/130m=0.2$.

3.2 Shape of individual arches

In the horizontal direction, the arches consist of one central and two peripheral segments. Three pairs of lines-of-centres are therefore needed to generate the circular segments. One pair of lines-of-centres defines the central segment, whereas the other two pairs delineate symmetrical or asymmetrical peripheral segments. Together they approximate an elliptical shape of a composite arch that reproduces the line of thrust for U or V-shaped canyons.

The number of lines-of-centres relative to the extrados and intrados arcs determines whether the arches are of uniform or of variable thickness in the horizontal direction. Uniform thickness of the segment corresponds to a single line-of-centre and variable thickness is obtained for a pair of spatially different lines-of-centres. On the other hand, variable centres of curvature along the dam height contribute to the vertical curvature of the dam. The dam curvature is highest in the upper central part and decreases towards the abutments and the base of the dam accompanied with a gradual increase of the thickness. An output of the algorithm for a horizontal cross section together with relevant design parameters is given in Fig. 3. They describe the arch geometry with increasing thickness from the reference plane toward the abutments.

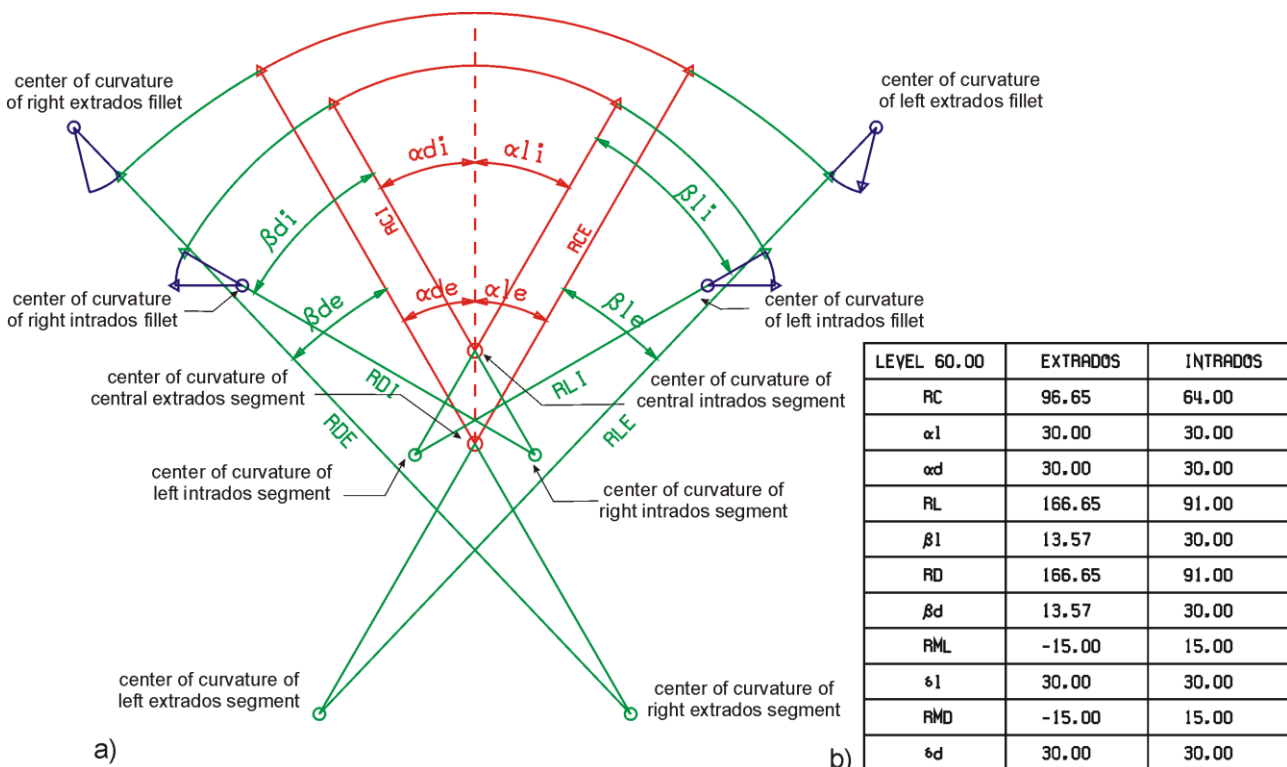


Figure 3. Output of arch parameters at structural height of 60m (elevation 395m): a) arch designed with one central (red colour) and two peripheral segments (green colour) and b) quantification of the arch parameters. The dam fillets are indicated with dark blue colour.

In the horizontal direction, the arches are determined with the central and peripheral radii of extrados and intrados and by the corresponding central and peripheral angles, Fig. 3a. They are determined with respect to the local coordinate system XL-YL-ZL, as follows:

- R_{CI} - radius of the central segment of intrados arc and R_{CE} - radius of the central segment of extrados arc;
- α_{LI} - left angle of the central segment of intrados arc and α_{LE} - left angle of the central segment of extrados arc;
- R_{LI} - radius of the left peripheral segment of the intrados arc and R_{LE} - radius of the left peripheral segment of the extrados arc;
- β_{LI} - angle of the left peripheral segment of the intrados arc and β_{LE} - angle of the left peripheral segment of the extrados arc;
- R_{DI} - radius of the right peripheral segment of the intrados arc and R_{DE} - radius of the right peripheral segment of the extrados arc
- β_{DI} - angle of the right peripheral segment of the intrados arc and β_{DE} - angle of the right peripheral segment of the extrados arc;

To reduce the accumulation of stresses in the horizontal direction, the arch dam structure may require increase of the thickness at the abutments. Hence, for a smoother distribution of lateral loads to the foundation rock, the adopted procedure pays particular attention to the design of the fillets along the abutments, Fig. 3a. The parameters needed for the design of the fillets are:

- R_{ME} and δ_{LE} - radius and angle at the end of the extrados at the left dam side;
- R_{MI} and δ_{LI} - radius and angle at the end of the intrados at the left dam side;
- R_{ME} and δ_{DE} - radius and angle at the end of the extrados at the right dam side;
- R_{MI} and δ_{DI} - radius and angle at the end of the intrados at the right dam side;

The local coordinates of the centres of curvatures for the central segment correspond to the sum of the extrados and intrados radii and the already defined local coordinates of the extrados and intrados of the cantilever. Likewise, the local coordinates of the centres of curvature for the peripheral segments are calculated by adding-up the length of the extrados and intrados radii to the coordinates of the points at compound curvature of the respective central and peripheral segments. In this respect, the radii of right and left extrados fillets are negative. The values are presented on the screen in a table format and can be easily modified by the user, Fig. 3b.

4 GRAPHICAL OPTIONS

Throughout the design process, the algorithm allows for visual assessment of the dam horizontal and vertical cross sections and their position with respect to the canyon topography. In addition, the relevant design parameters for the geometry of extrados and intrados curvatures are shown on the screen in a table format.

This extremely useful option gives not only a detailed insight into the dam geometry and dimensions, but also facilitates eventual corrections in the optimization process of the desired design parameter(s). In average, following the initial dam layout, an update of the dam geometry takes only several minutes.

4.1 Arches with one central and two peripheral segments

With the exception of the bottom arch, all other arches are designed as composite arches with one central and two peripheral segments. In Figs. 4 are given composite arches at elevation of 385m (structural height of 50m) and 465m (130m high crown arch), respectively. These figures show that the central and peripheral segments have different centres of curvature of the extrados and intrados arcs, indicating arch segments of variable thicknesses. As mentioned earlier, the arch thickness is the lowest at the reference plane and increases toward the abutments, whereas the cantilever thickness decreases with dam height and is lowest at the dam crest.

4.2 Full-radial arch abutments

Accurate design of the full-radial arch abutments perpendicular to the central axis of the arc provides solid resting and stress distribution in the foundation rock. The algorithm gives the possibility to observe to which extent the arch abutments satisfy the full-radial design, and enables effective correction of the arch resting when necessary. For a better stability, the abutments should extend radially from the extrados centre of the peripheral segment. To satisfy this requirement, the initial shape of the abutments shown in Fig 5a was corrected for the one depicted in Fig 5b. Figs. 5 also shows a central segment of uniform thickness obtained assigning the same centre of curvature for the extrados and the intrados arcs.

4.3 Bottom arch consisting of one central segment

The function of the bottom arch is to provide embedment of the dam foundation into solid rock. Fig. 6a depicts the initial layout of the bottom arch at elevation of 335m consisting of one central segment. As can be seen in plan this design fails to enable full contact with the foundation rock. Following a slight shift of the bottom arch in downstream direction, a rapid correction was made by broadening the left and right angles of the intrados from the initial 4° to 65° , and left and right angles of the extrados from the initial 5° to 50° degrees. As well, the curvature of the intrados was subsequently slightly decreased by enlarging the radius of intrados by 3 meters, Fig. 6b. These interactive corrections enabled a solid contact between the arch and foundation rock at both banks.

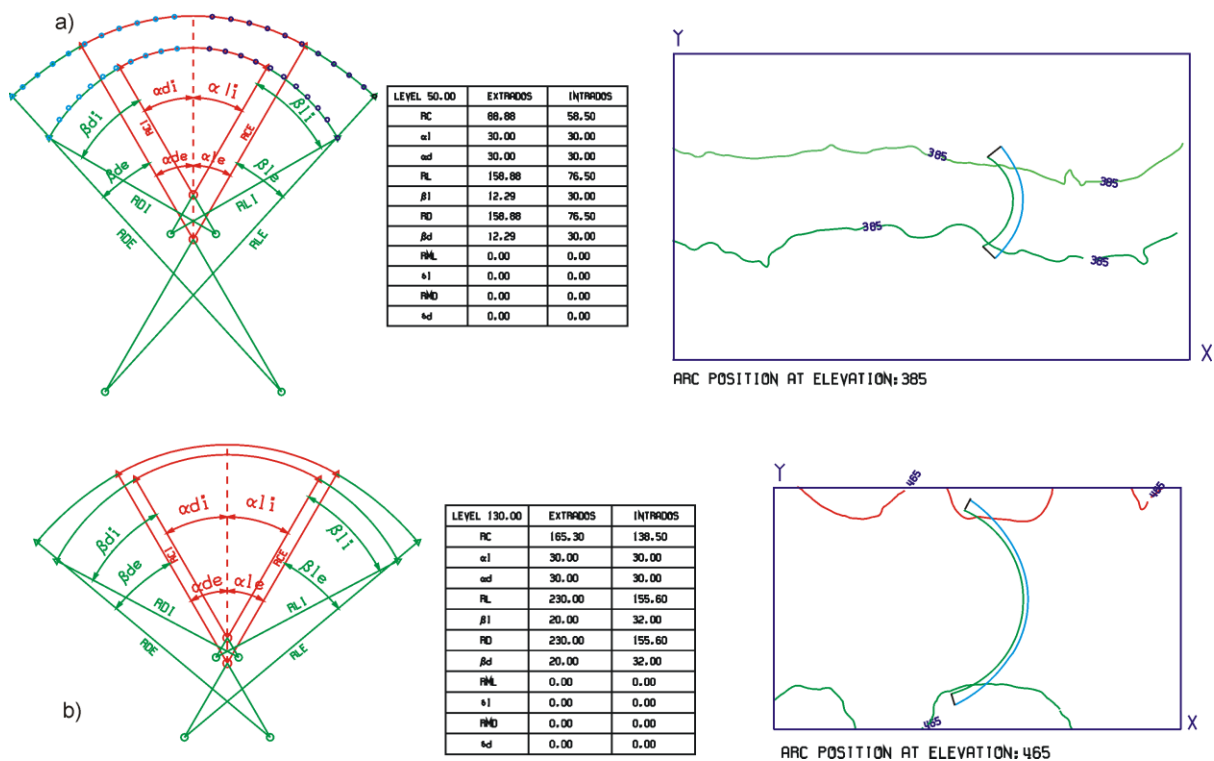


Figure 4. Arch geometry designed with one central and two peripheral segments supported at the abutments: a) dam height of 50m (elevation 385m) and b) dam crest with height of 130m (elevation 465m). The blue nodes on the arcs indicate the location of the nodes describing the substructures.

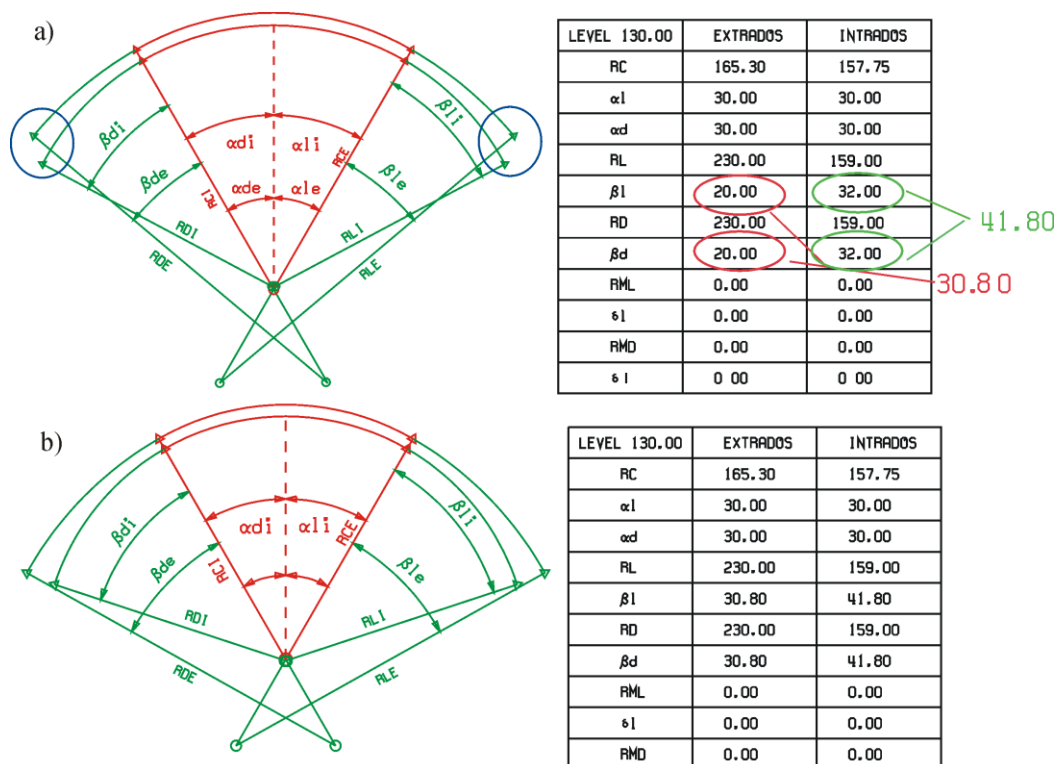


Figure 5. Geometry of the crown arch (elevation 465m) designed with one central segment with constant thickness and two peripheral segments with variable thickness: a) initial embedment of the arch, and b) corrected embedment providing better resting and stress distribution.

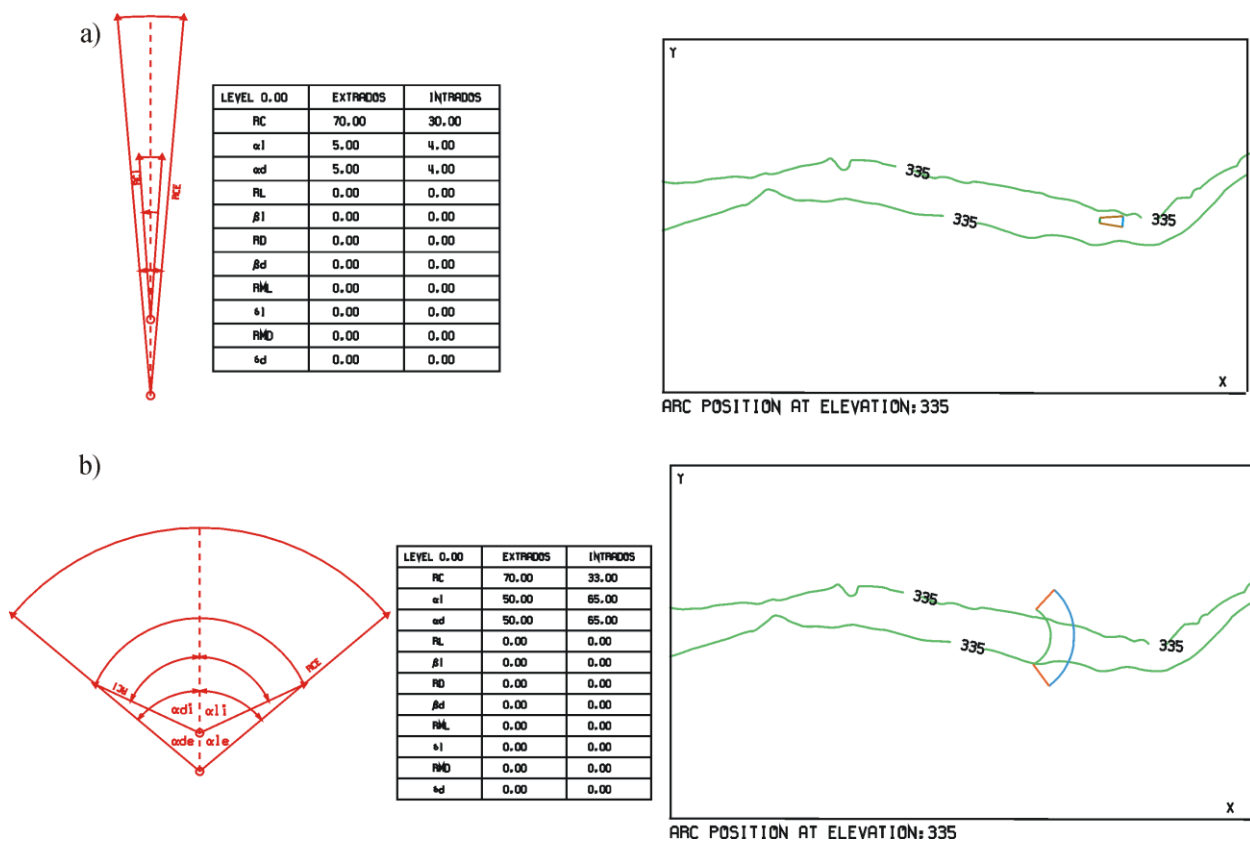


Figure 6. Arch geometry at the dam bottom (elevation of 335m) designed with one central segment for: a) improper partial support at the abutments, and b) final appropriate support at the abutments obtained by broadening after displacing the segment in downstream direction.

4.4 Dam continuity in the vertical direction

The geometry of double curvature arch dams is characterized with downstream overhanging near the crest and with upstream undercutting of the heel. Overhanging of the upper arches occurs typically at the crown cantilever and gradually diminishes towards the abutments. In the arches near the dam crest, this condition contributes to the development of low tensile stresses on the upstream face, and counterbalances the development of tension on the downstream face. Severe overhanging, however, can develop unacceptable tension at the upper upstream face causing closure of contraction joints and preventing appropriate grouting. On the other hand, the contact between the concrete and foundation rock undercuts the upper concrete portions at the upstream dam face. The moment generated by the weight of the upper dam portions compresses the concrete and outweighs the occurrence of tension from the reservoir pressure. In extreme cases, undercutting may cause instability during construction with potential overturning in the upstream direction.

During the geometrical design and structural analyses of arch dams, a special attention must be given to achieve smooth transition of dam faces taking into account the overhanging and undercutting effects. In this respect, the algorithm allows for an efficient observation and assessment of the continuity of the system of independent arches in plan. This helps to detect eventual shape deviation among neighbouring arches in

horizontal cutting planes. The user can also select the option to display the overhanging and undercutting zones along the cantilevers in vertical cross sections. Figs. 7 give the mutual position of two 10m high adjacent arches with a contact at elevation of 375m and along the structural heights between 30-40m and 40-50m. Gradual changes of the dam shape can be observed with a slight overhanging effect of the upper arch.

At this stage of the design process, the user can intervene to adjust the position of individual arches to improve the continuity of the dam faces and/or the embedment of the abutments. This is achieved by a slight shift or rotation of individual arches or even of the entire dam with respect to the canyon axis. The coordinates of the updated dam shape and location are automatically modified and stored in conformity to the amended local coordinate system.

4.5 Lines-of-centres

The lines-of-centres represent the loci of centres of circular arc segments applied to determine the extrados and intrados faces of the dam. To avoid presence of excessive tensile stresses in the lower part of the dam, they are positioned closer to the crown cantilever resulting in shorter radii, higher curvature and stiffer arches as shown in, Fig. 8.

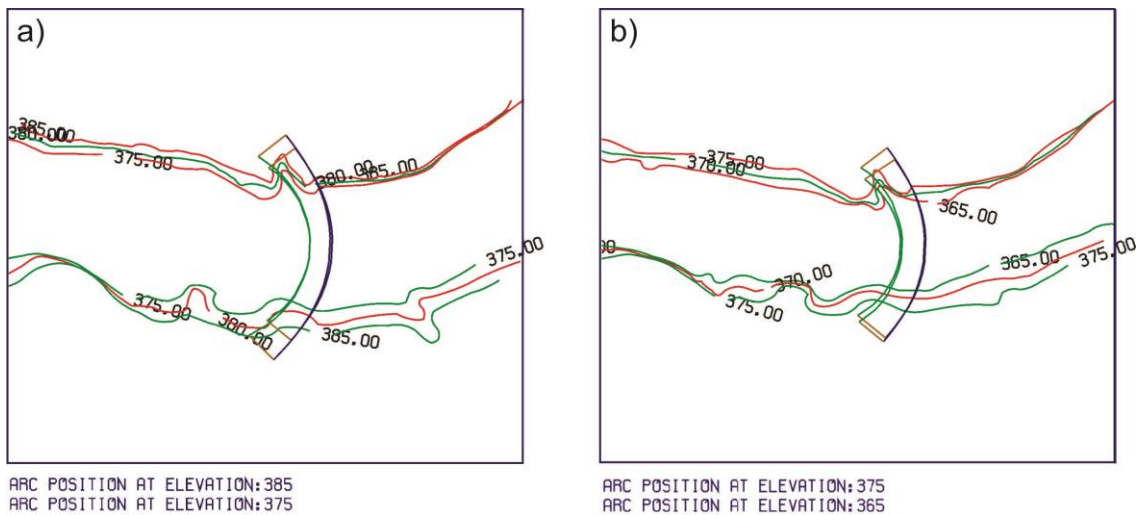


Figure 7. Plan view of the mutual positions of two 10m high arches with contact at 375m: a) horizontal cutting plane at elevation of 385m, and b) horizontal cutting plane at elevation of 365m

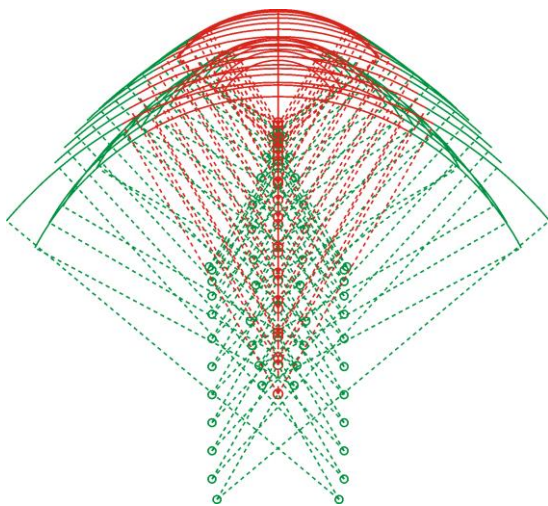


Figure 8. Line of centres, radii and angles of three segment arches with variable-thickness.

Arch segments with uniform thickness are determined by a single line-of-centres, whereas arches with variable-thickness require additional lines-of-centres.

Fig. 9 depicts the lines-of-centres for a three centred arch dam. The central segment of the dam is defined by the coupled lines-of-centres LOC-1/LOC-2 and LOC-3/LOC-4, where the former designs the crown arch with constant thickness (Fig. 9b and Fig. 5b) and the latter with variable thickness (Fig. 9c and Fig. 4b). These loci of the centres are coplanar with the crown cantilever and defined in the reference plane. Likewise, the coupled line-of-centres LOC-5/LOC-6 and LOC-7/LOC-8 define the shape of the arches at the left and right outer segments, respectively. The central and the peripheral segments of the dam are coplanar at an angle of compound curvature as measured from the reference plane.

Since the line-of-centres LOC-5/LOC-6 and LOC-7/LOC-8 are more distant from the base of the crown cantilever than the line-of-centres LOC-1/LOC-2 and LOC-3/LOC-4, the radii of arches of the peripheral segments are larger than the radii of arches of the central segment, resulting to a smaller curvature of the outer segments comparing to the central segment of the dam (Figs. 8 and 9). As can be observed in Fig. 9, the centres of the curvatures and the respective radii are positioned in a way that provides smooth transitions, hence avoiding abrupt changes in the geometry and stress concentrations.

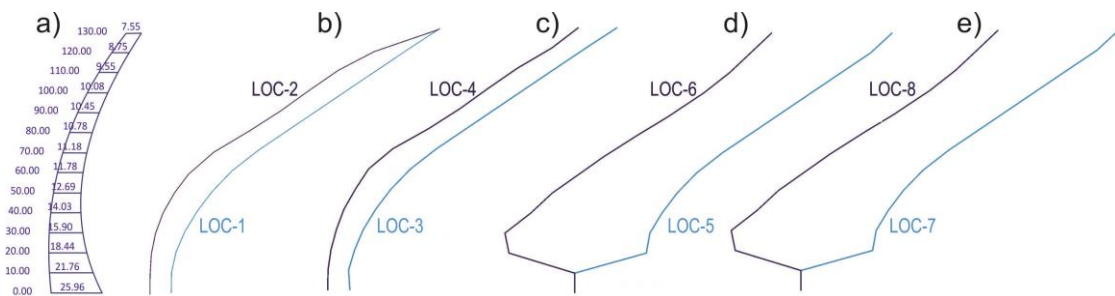


Figure 9. Lines-of-centres for a three-centred arch dam with a) crown cantilever, b) constant thickness of the central segment LOC-1/LOC-2, c) variable thickness of the central segment LOC-3/LOC-4, d) left outer segment LOC-5/LOC-6, e) right outer segment LOC-7/LOC-8.

4.6 Foundation Rock and Abutments

Dam abutments extend into the solid rock. As it was the case with the dam gradually changing geometry, the excavation for the abutments has also to provide smooth transition zones with depth. To meet this requirement, the user can verify in plan and in cross section the lateral extent of the arches, their position with respect to the topography and the embedment depth in the canyon walls. In Fig. 10 is given the interface between the intrados and extrados arcs and the foundation rock at elevation of 385m that describes this option. The layout of the selected foundation profile in Fig. 10 considers removing

the weak soil and altered rock up to the solid rock. In the given example it was assumed that the foundation rock is approximately 7-10m below the ground surface, where the top 3-5m are related to the surficial soils and regolith and as much is excavated into the underlying solid rock. On the other hand, Fig. 11 illustrates the computed contacts of the dam intrados and extrados abutments with the ground surface and the excavation depth into the solid rock layer. This information helps to obtain accurate estimate of the volume of excavation needed for proper embedment of the dam abutments.

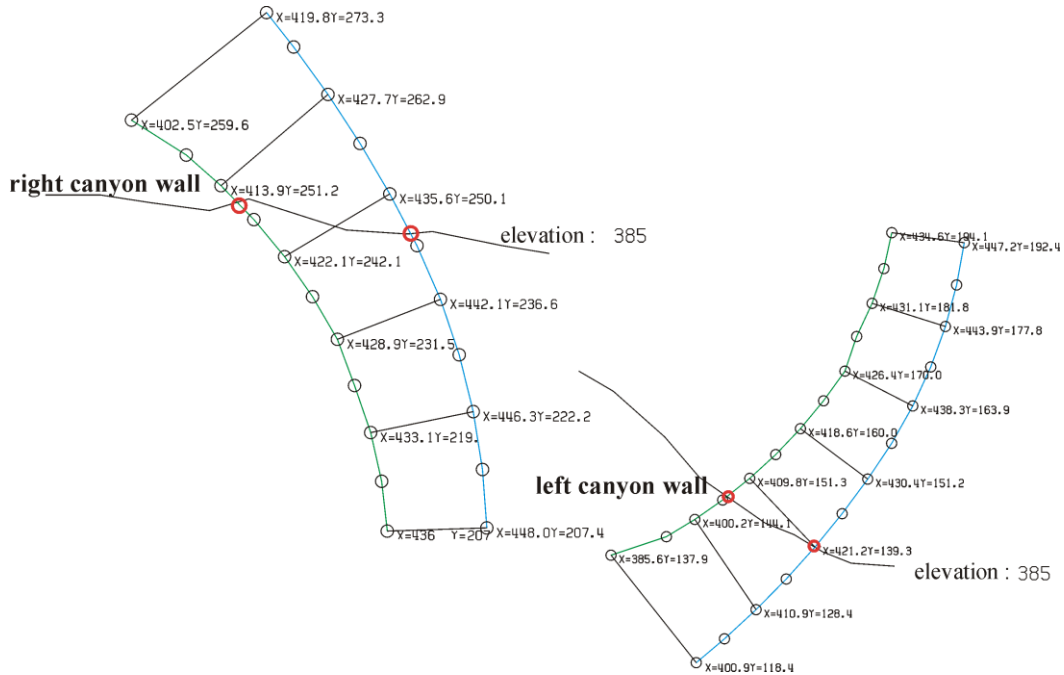


Figure 10. Interface between the intrados and extrados arcs and the foundation rock at elevation of 385m: a) right abutment, and b) left abutment. Points of intersection of the arcs with the terrain contour lines are indicated with red hollow circles.

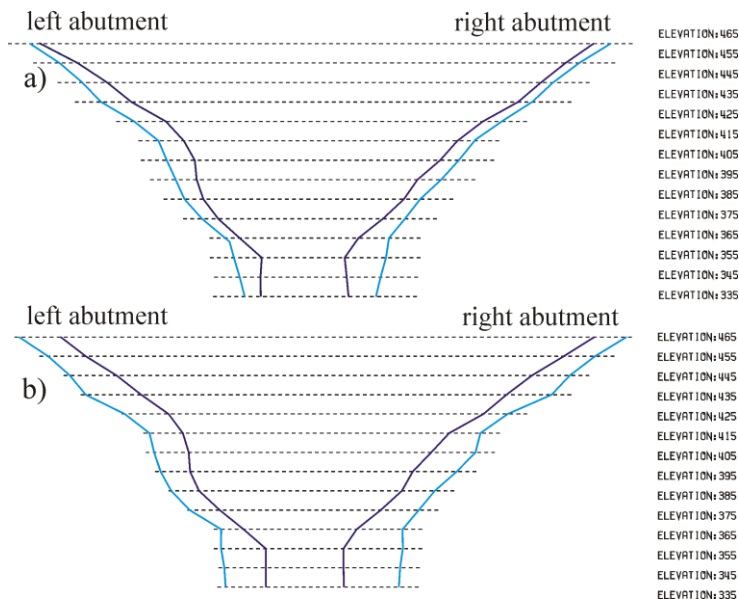


Figure 11. Longitudinal section of the planned contacts with ground surface (dark blue line) and with solid rock (light blue line): a) intrados face, and b) extrados face.

5 GENERATION OF FE MODEL OF THE DAM AND BE MODEL OF THE FLUID DOMAIN

Static and dynamic structural analyses are conducted in parallel to the design of the geometric layout of the dam. To this end, a FEM-BEM numerical model of the example double-curved arch dam was built in a format compatible with the ADAD-IZIIS software, which runs the analyses. The dam model consists of substructures with 15 and 20-nodes, further divided in a number of 15 and 20-node finite elements of Serendipity type. Each substructure represents part of a monolithic block, situated between two adjacent elevations spaced evenly at 10m and between two construction joints distanced 15m horizontally along the arches. Construction joints are placed at the lateral contact of two adjacent monolithic blocks. Within each substructure, two different types of nodes describing the substructures and the finite elements are required to generate the mathematical FE model. To fully determine the substructures, respective coordinates are automatically generated for i) basic nodes describing the construction joints between the monoliths and ii) nodes interpolated between the basic nodes along the arcs. The position of the basic nodes along the arcs and the nodes interpolated in-between are presented in Figs. 4a and 12, respectively. In order to define all nodes used for generation of 15 and 20 noded substructures, additional interpolation of nodes is required between two superimposed arcs. Fig. 12 depicts interpolated nodes along the arcs at elevations of 395 and 405 together with vertically interpolated nodes.

The FE model of the example double-curved arch dam together with the construction joints is given in Fig. 13. It was generated automatically using the predefined shapes of the arcs and the coordinates for the basic nodes at all design elevations. In this case, the final FE model contains 11,170 external nodes connecting 199 substructures discretized into 6,294 finite

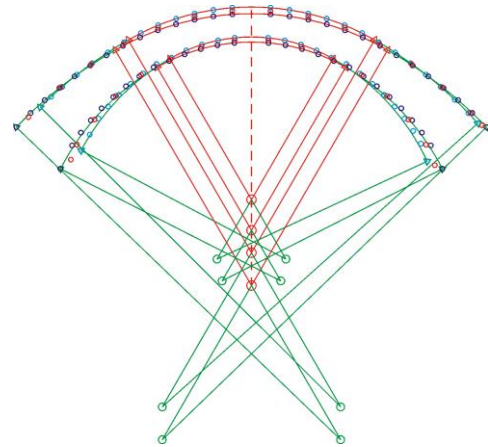


Figure 12. Interpolated nodes: horizontally along the arcs at elevations 405 (dark blue circles) and 395 (light blue circles) and vertically between these two elevations (red circles)

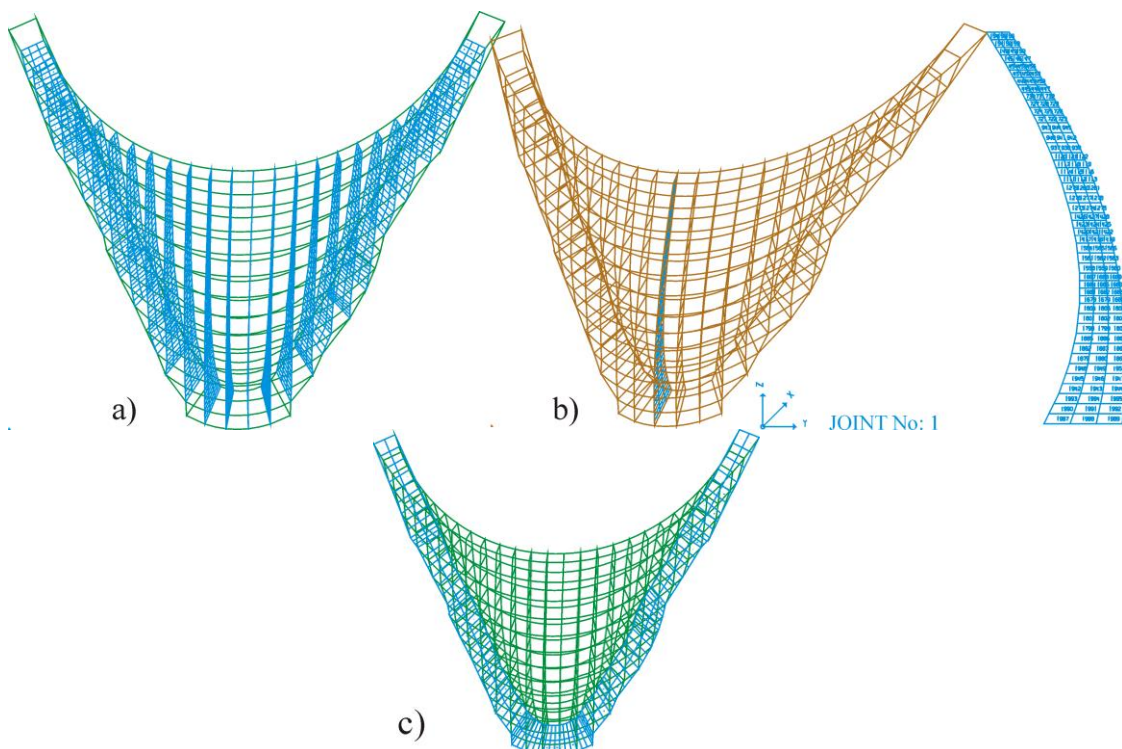


Figure 13. Perspective view of the mathematical model of the arch dam: a) construction joints at the vertical contacts between the monolith blocks, and b) construction joints discretized by contact elements. c) contact elements between the dam abutments and the foundation rock

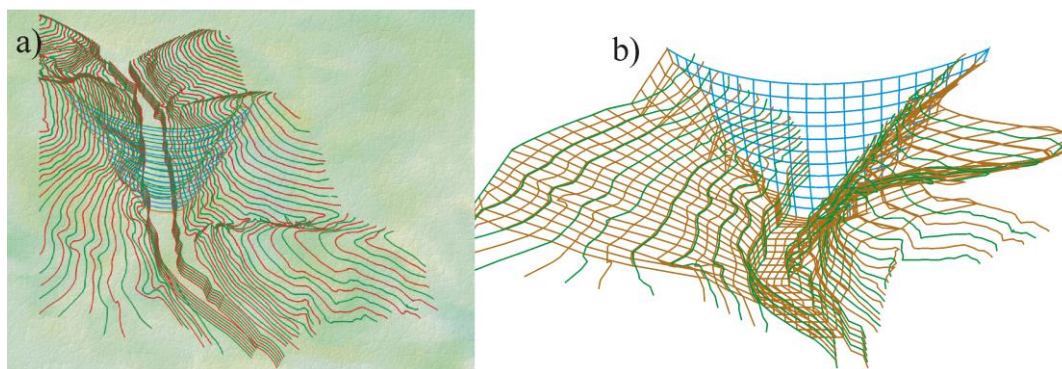


Figure 14. 3D perspective view: a) canyon topography and dam geometry, and b) generated BE mesh of the dam-fluid-foundation system bounded by the dam-fluid interface, canyon walls, river bed, (boundary elements at the water mirror and the upstream truncation surface are not presented).

elements. The band of the system of matrices is 3,111. The model also contains 2,013 contact elements at the interface between monolithic structural blocks, which simulate the effect of the construction joints, Fig. 13b. If needed, automatic refinement of the contact element mesh can be further conducted upon user provided mesh parameters. Fig. 13c. presents the contact elements generated between the dam abutments and the foundation rock. For cases when the solid rock mass is not included in the analysis, these contact elements act as spring elements with such mechanical properties that simulate a non-rigid support at the foundation base.

The next step consists of discretization of a BE model of the dam-fluid-foundation system taking into account the complex topographical conditions of the canyon [30-31]. The mesh generation process of the fluid domain is simple requiring that the user specifies the number of vertical planes intersecting the terrain together with respective distances from the top of the crown cantilever. Evidently, complex highly irregular terrain conditions will require increased number of vertical planes and a more refined mesh [30-31]. In this respect, the proposed algorithm offers a 3D perspective view of the canyon and the dam, Fig. 14a. It is also possible to extract the boundary elements at the extrados directly from the upstream face of the FE model, Fig 14b. This option allows the user to confirm that adequate distribution of the hydrodynamic pressure is attained along the dam-fluid interface.

6 CONCLUSION

An original algorithm for geometric modelling and effective design of double-curvature arch dams is presented. It was developed and implemented to run in parallel to the ADAD-IZIIS program for structural analyses of arch dams. Combining FEM-BEM modelling, the algorithm enables accurate FE modelling for the dam and BE modelling of the reservoir domain adjusted to the terrain configuration. The proposed interactive design starts with the generation of a mathematical model of the terrain topography. The next step consists in selection of the optimal dam location based on comparisons of the dam heights and extents.

The arch dam geometrical model is built in a form of circular segments assigned to each incremental height. A variety of different graphical presentations of the dam structural geometry and terrain topography are displayed on the screen including cross-sections, plan views, contacts at the dam abutments, and 3D views of the dam mathematical model. Correction of the parameters is possible at each step of the design. The practical engineering drawings and descriptions of the dam geometry are automatically modified following the introduced changes. Thus, they provide competent insight in the design and the design possess itself with abundant range of details and clarity.

The presented example of geometric design of a 130m high double curved arch dam in a V-shape canyon demonstrated the above capabilities. Compared to the existing commercial software, the developed algorithm showed a few significant advantages: the dam-reservoir design is directly dependant on the configuration of the site, the number of graphical options available at the push of a button offer an intuitive and user-friendly environment.

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ABSTRACT

INTERACTIVE ALGORITHM FOR GEOMETRIC MODELLING DOUBLE-CURVATURE ARCH DAMS

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A rapid and efficient algorithm for interactive geometric modelling of arch dams is presented. It combines the advantages of the traditional geometric-design with innovative computational capabilities offering simple procedures for otherwise complex process of laying out double-curvature arch dam-reservoir coupled systems. The key parameters taken into account are: terrain topography, shape and thickness of crown cantilever, reference cylinder, thickness and curvature of individual arches, excavation depth, concrete volume, vertical and peripheral construction joints and automatic generation of finite element and boundary element models. The proposed algorithm was implemented in and runs parallel to the ADAD-IZIIS FEM-BEM, a finite element-boundary element software for structural analyses of concrete arch dams. To demonstrate the performances of the proposed algorithm, an example of a 130m high double-curvature arch dam was considered in a narrow V-shape canyon. The number of graphical options available at the push of a button, such as vertical and horizontal cross sections and 3D perspectives, allows the user to rapidly conduct the dam design within the optimization process.

Keywords: arch dam; geometric modelling; FEM-BEM numerical modelling; terrain topology; ADAD-IZIIS software

REZIME

INTERAKTIVNI ALGORITAM ZA GEOMETRIJSKO MODELIRANJE DVOJNO ZAKRIVLJENIH BRANA

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Ovaj članak se odnosi na efikasno formulisani algoritam za interaktivno geometrijsko modeliranje lučnih brana. Algoritam predstavlja kombinaciju tradicionalne metode za dimenzionisanje kombinovan sa inovativnim kompjuterskim veštinama koje pružaju mogućnost jednostavnog procesuiranja kompleksnog projektovanja fleksibilno spregnutog sistema dvojno zakrivljene lučne brane – rezervoara. Ključni parametri koji se uvode u predmetni algoritam su topologija terena, oblik i debljina glavne centralne konzole, referentni cilindar, debljina i zakrivljenost pojedinih lukova, dubina iskopa za temelje u terenu, vertikalne konstruktivne razdelnice (fuge), perimetralna (obimna) fuga i automatsko generisanje numeričkih modela od konačnih i graničnih elemenata. Algoritam je ugrađen u kompjuterski program ADAD:IZIIS namenjen statičkoj i dinamičkoj analizi lučnih brana. Program je orijentisan na primenu metoda konačnih i graničnih elemenata. Da bi se demonstrirala primena algoritma odabran je primer lučne dvojno zakrivljene brane visoke 130m koja je postavljena u tesni kanjon oblika V-tipa. Prikazan je veći broj grafičkih priloga koji se dobija jednostavno selekcijom tražene opcije. Jasna prezentacija značajnih inženjerskih crteža na ekranu omogućuje brzo optimalno dimenzionisanje i formiranje matematičkih modela lučnih brana.

Ključne reči: lučna brana, geometrijsko modeliranje, MKE-MGE numeričko modeliranje, topologija terena, ADAD-IZIIS softver