SOLUTION OF DAM-FLUID INTERACTION USING ADAD-IZIIS SOFTWARE

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ABSTRACT

Fluid dam interaction has a remarkable impact on the dynamic response of dams and could play an important role in assessment of their dynamic stability. This is particularly emphasized when dams are subjected to strong seismic excitations. The phenomenon has been for the first time physically explained and mathematically solved by Westargaard. The very first dynamic analysis based on application of "Added Mass Concept"; underestimated the random earthquake nature in assessment of the hydrodynamic effects. In the recent years, various BEM-FEM and FEM-FEM techniques have been developed to account for many significant parameters that influence the accuracy of calculated hydrodynamic effects. This paper presents a BEM-FEM orientated solution based on the use of the matrix of hydrodynamic influence as a very effective tool for analyses of extensive domains of fluid-dam-foundation rock systems for two major reasons: the computation time is far more effective than that in direct or iterative coupling methods and stability of the solution. The presented analyses are based on the use of genuine software originally written for static and dynamic analysis and design of arch dams.

1. Introduction

The ADAD-ver.3 computer program [1], originally written for static and dynamic analysis and design of arch dams, is under development for the last several years. It implements an analytical procedure for the three-dimensional dynamic analysis of arch dams including the effects of dam-water interaction (water incompressibility), soil-structure interaction and the nonlinear behavior of the of contraction joint manifested by partial joint opening and closing as well as tangential displacement. The process of generation of mathematical model runs parallel and interactively with the process of design of the particular dam. The program gives an option for computer design of the dam body [2, 3], whose embedment is in accordance with topology of the terrain. Program offers automatic pre-processing for generation of finite element mesh of dam and part of the foundation mass to account for the dam-foundation interaction phenomenon, as well as effective way of generation of boundary element mesh, sufficiently accurate in following the topology of the terrain to account for the fluid structure interaction.

The program use sensitivity search analysis to detect the "most adequate" location of the truncation surface [4], where non-reflecting truncation boundary conditions should be imposed. The truncation surface should be located in a way to define the required completeness of the wave field where expansion of P compressive and dilatational waves takes place followed by scattering and radiational effects. Its further displacement away from the dam should have a negligible impact on the calculated magnitude of the hydrodynamic effects.

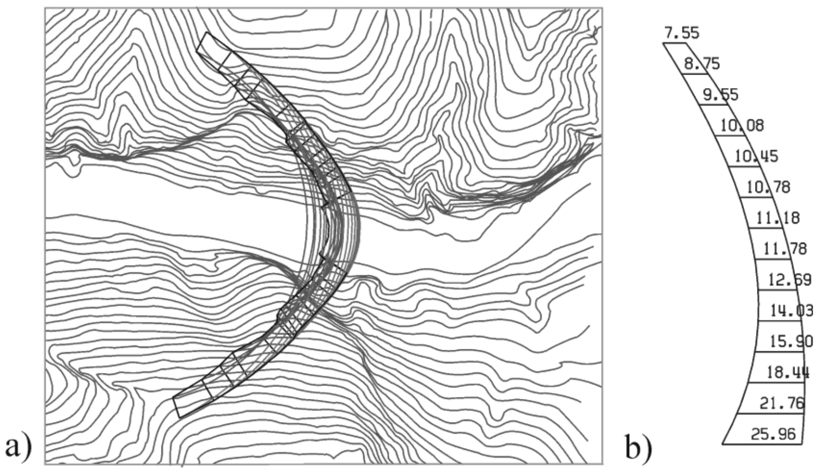
The conducted analyses are based on an original and simple FEM–BEM fluid–structure interaction solution embedded in the ADAD–IZIIS software. This solution eliminates the difficulties of "direct" and "iterative" coupling methods by analyzing independently the two physically coupled sub-domains. The interaction effect is obtained in an uncoupled way computing the matrix of hydrodynamic influence by applying the concept of virtual work of "unit accelerations". The suggested method does not belong to direct coupling or to iterative coupling methods, yet with its computational steps it offers a two-way coupling by transferring the fluid forces to the structure and the structural accelerations back to the fluid.

The paper presents BEM-FEM oriented solution of the fluid-dam interaction along with the boundary element discretization of the reservoir domain. The dam was subjected to El Centro earthquake excitation with duration of 7 sec., scaled to the pick acceleration of 0.3 g. The dam properties are the following: Dam height H=130 m; Young's modulus E = 31.5 GPa; mass density ρ = 2450 kg/m^3; Poisson's ratio ν = 0.2; the acoustic wave velocity in water c = 1440 m/s.

2. Numerical model of arch dam and fluid domain

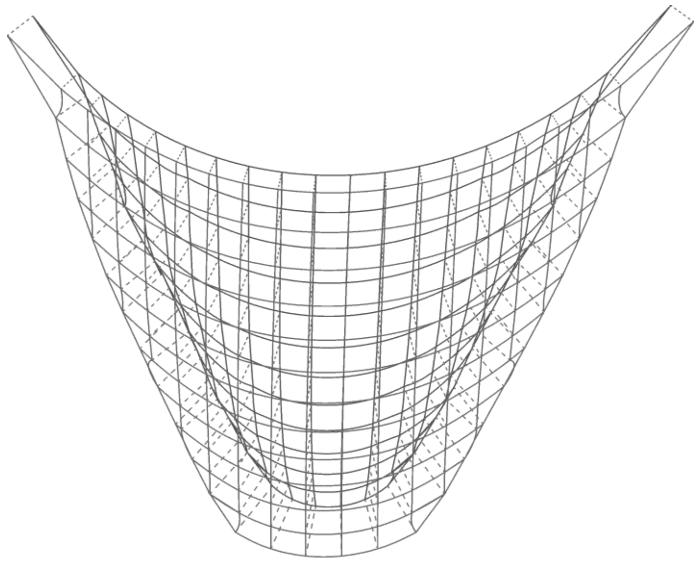
The process of generation of the discrete mathematical model of the arch dam and the fluid domain runs parallel with the process of design of the dam body. This process starts by digitization of topographic data of the terrain and the shape of the main central cantilever, Picture 1. The developed pre-processing within the ADAD–IZIIS software enables each topographic isoline to be mathematically presented by a set of equations of a second order, i.e., curves passing through three neighboring digitalized points on it. Each isoline is stored in the computer by means of a certain number of polynomials. The program gives an option for computer design of the dam body [2, 3], whose embedment is in accordance with topology of the terrain. Arch dam body can be modeled in a form of few circular segments as well as in the form of a parabola. During modeling, it is possible to observe the shape of the arches at all elevations along with the corresponding tables containing their geometrical parameters and to observe their mutual position in order to control overlapping. Picture 2, presents the mathematical model of the dam generated automatically, using adopted shapes of the arcs at all selected elevations in accordance with the topology of terrain. The model is formed by 199 substructures. The substructures are automatically digitized into a certain number of finite elements that are not presented in the picture. The model contains 6294 finite elements and 11170 external nodes. The bend of the system is 3111. The model posses 2013 contact elements that are involved at the connections between substructure's blocks. The contact elements are generated automatically and the contact element mesh refinement is in accordance of the model analyst request.

ADAD-IZIIS software offers a very efficient and accurate modeling of the 3D fluid boundaries according to the downstream topology of the canyon terrain. The boundary elements at the extrados of the arch dam are directly extracted from the general FE model while the boundary element mesh that represents the boundaries of the reservoir, i.e., both banks, the reservoir bottom, the water mirror and the reservoir end, very accurately follows the shape of the topographic isolines. Generation is simply by giving the number of planes that intersect the terrain along with their distances from the uppermost point of the crown cantilever. In case of highly irregular and twisted terrain, more section planes and a more refined mesh should be used in order to model the complexity of the terrain in the most accurate way, which is undoubtedly easily feasible and with shorter computational time if BEM technique is engaged. However, for the concrete configuration of the terrain and detected "most adequate" location of the truncation surface situated at the downstream distance of 210 m from the dam, the number of boundary elements used in the model for accurate modeling of the 3D fluid boundaries is 1600, Pic. 3.

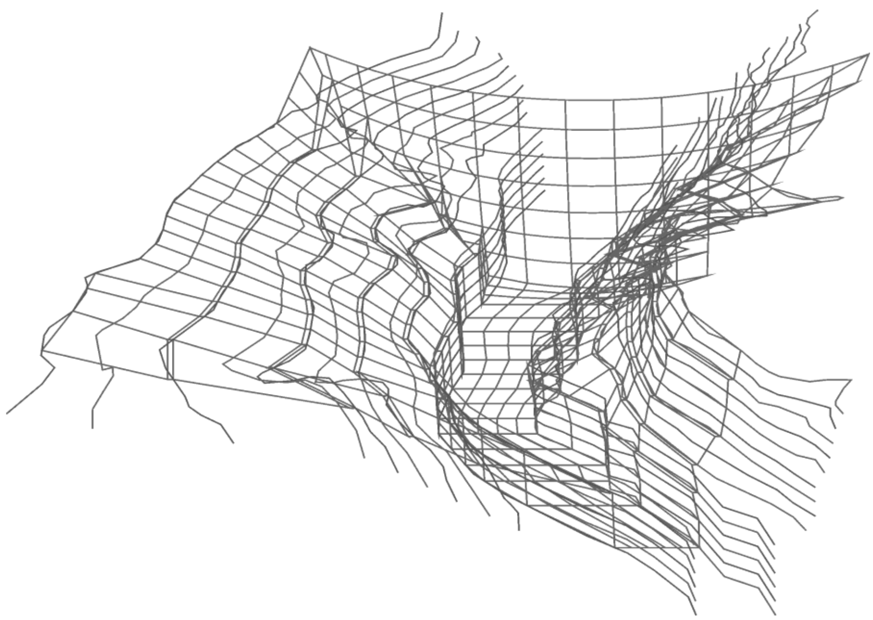


Picture 1 a) Topology of the terrain b) Shape of the central cantilever

Fluid-structure interaction (FSI) is affected by the irregularity of the terrain in the near surrounding of the dam-fluid interface. The topology of the terrain dictates the "most adequate" location of the truncation surface where non-reflecting truncation boundary conditions (TBC) should be imposed. The detection of the "most adequate" location of the truncation surface (TS) is an important task in development of a reservoir model due to the fact that the hydro-dynamic pressure (HDP) intensities on the dam-fluid interface are sensitive to the extent and type of waves generated by the boundaries. The truncation surface should be located in a way that its further displacement away from the dam has a negligible impact on the calculated HDP intensities.

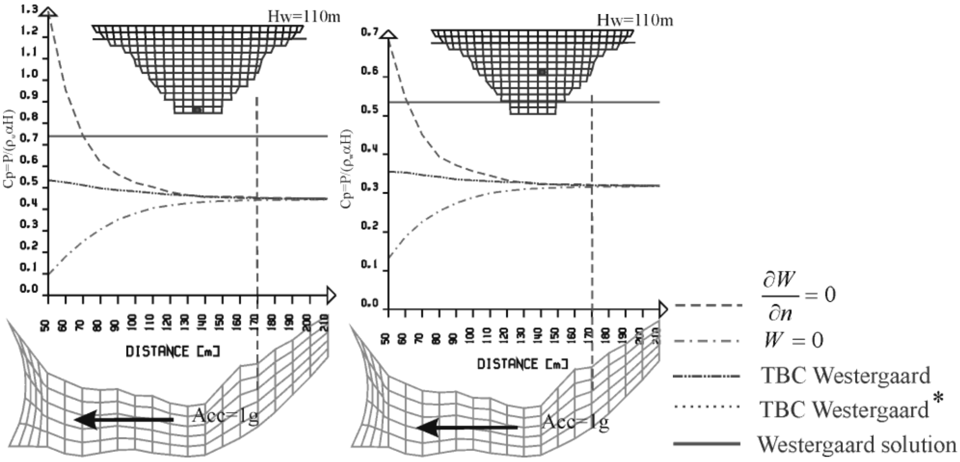


Picture 2 Mathematical model of a dam (substructures and construction joints)



Picture 3 Boundary element mesh of the fluid domain

The program offers sensitivity search analysis to detect the most adequate location of the TS. For the presented BE model in figure 3., the elapsed CPU time for performing such analysis is approximately 15 min. The numerical procedure is based on the conventional BEM. Laplace differential equation that governs the incompressible and inviscid fluid motion is used. The procedure is conducted over a rigid dam-canyon-walls assemble. It follows a horizontal acceleration of 1 g applied in downstream direction. The acoustic elastic P waves were generated as a result of the vibration of the considered upstream dam face and the rigid canyon's walls. The expansion of generated waves and the way of their propagation as compressive or dilatation waves depends not only on the specified boundary conditions but on the shape of the reservoir boundaries in respect to the direction of the seismic excitation. Three different types of truncation boundary conditions (TBC) were considered: a) stationary type of truncated boundary conditions, i.e., perpendicular acceleration at all the points on the truncation surface is set to zero; b) hydrodynamic pressure at all points on the truncation surface set to zero; and c) non-reflecting boundary condition. Sixteen different location of the truncation surface were considered and analyzed. The curve associated with the TBC that allows dissipation of the outgoing waves shows mostly decreasing trend until reaching the meeting point of the curves of TBC type (a) and TBC type (b), at distance of L=180 m (L=1.6-1.7 Hw) away from the dam. Further on, this curve remains almost horizontal, indicating unaltered value of HDP. This means that it is irrelevant whether TS is positioned at a greater distance than L=180 m, since the effect of the amount and type of generated waves is negligible with further increase of the model length. However, this effect is remarkable along length L<180 m, wherefore placing TS closer to the dam means overestimation of the HDP. In accordance with the applied direction of ground acceleration and due to the irregular configuration of the terrain in the vicinity of the dam, the right bank generates mostly dilatation waves while the left bank generates compressive waves. For the concrete topological conditions, the considered depth of impounded water, according the results presented in [4], the "most adequate" location of the truncation is selected at a distance of L=1.9 Hw=210 m.



Picture 4 Variation of the normalized hydrodynamic pressure magnitudes as a function of the considered 16 locations of the truncated surface and different truncation boundary conditions (selected node at the bottom and at the middle of the crown cantilever)

3. BEM-FEM solution of fluid-dam interaction

FSI is an interaction of a moveable and/or deformable structure that is immersed in a fluid and/or contains a fluid. A model that captures such an interaction must use two-way coupling model, where the fluid motion affects the structure's motion and the structure's motion affects the fluid's motion. Coupling should provide compatible link of both media which means equilibrium and correct transition of the physical variables at the interface. There exist various algorithms for coupling the merits of both BEM and FEM numerical methods, direct [5-8] and iterative coupling methods [9-12]. ADAD-IZIIS software [1] is based on BEM-FEM oriented solution of the coupled structure and the incompressible and inviscid fluid. The solution of the coupled system is accomplished by calculating in advance the matrix of hydrodynamic influence utilizing the concept of virtual work of "unit accelerations". This matrix is stored in the system and recalled in any time step of the dynamic response of the dam. Hence the solution of the coupled systems is actually separated and mutually independent. Hydrodynamic forces are obtained as a product of the matrix of hydrodynamic influence and the vector of manifested total accelerations along the normal at any interface node. The interaction effect at the fluid–solid interface is enforced by adding the matrix of hydrodynamic forces to the classic equation of dynamic motion of the dam, eq. (3). The governing equation for solving the small amplitude irrotational motion of the impounded incompressible and inviscid fluid is governed by the three-dimensional Laplace's equation as follows:

$$\frac{\partial^2 W}{\partial x^2}+\frac{\partial^2 W}{\partial y^2}+\frac{\partial^2 W}{\partial z^2}=0 \tag{1}$$

where *W(x,y,z)* is a function of the potential in the fluid domain. The equation (1) has to be amended by the specified "essential" and "natural" type of boundary conditions that exists at the boundaries of the analyzed fluid domain. Applying BEM technique, Brebbia [13], the discretization of boundary surfaces is made by assemble of eight nodded quadratic "Serendipity" type of boundary elements as follows:

$$\frac{1}{2}W_i+\sum_{nel=1}^{NEL}\int_{\Gamma 1}\left(\frac{\partial W}{\partial n}p-\overline{W}\frac{\partial p}{\partial n}\right)d\Gamma_1+\sum_{nel=1}^{NEL}\int_{\Gamma 2}\left(\frac{\partial \overline{W}}{\partial n}p-W\frac{\partial p}{\partial n}\right)d\Gamma_2=0 \tag{2}$$

where: i=1,NBE; NBE is a number of nodes in the boundary ele ment model.

The differential equation of motion of a discrete system written in an incremental form for the "i"-th time increment is the following:

$$M_i\hat{\Delta}\ddot{U}+C_i\hat{\Delta}\dot{U}+K_i\hat{\Delta}U=\hat{\Delta}P_i+\hat{\Delta}F_{HDi} \tag{3}$$

where: $\hat{\Delta}F_{HDi}$ is a vector of hydrodynamic force increment and $\hat{\Delta}P_i$ is a vector of seismic force increment.

In Eq. (3), the vector of hydrodynamic force increment is calculated by use of previously defined matrix of hydrodynamic influence and directly added to the vector of seismic force increment.

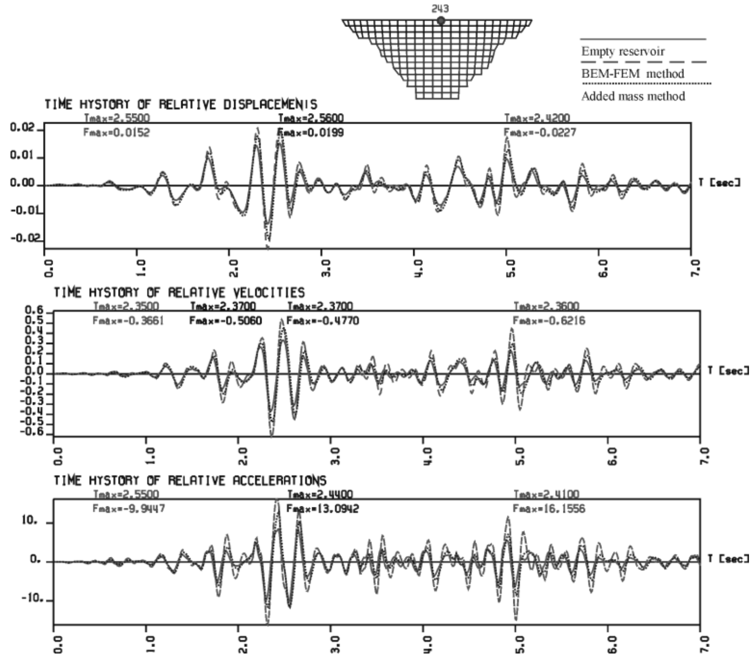
$$\hat{\Delta}F_{HDi}=\left[W_{ij}\right]\Delta a_{nj}^{tot} \qquad i,j=1,NPT \tag{4}$$

where: $\left[W_{ij}\right]$ is a matrix of hydrodynamic influence; Δa_{nj}^{tot} is the absolute acceleration along the boundary element normal; NPT is the total number of nodes at dam-fluid, bottom-fluid and banks-fluid interfaces, where the natural type of boundary condition exists

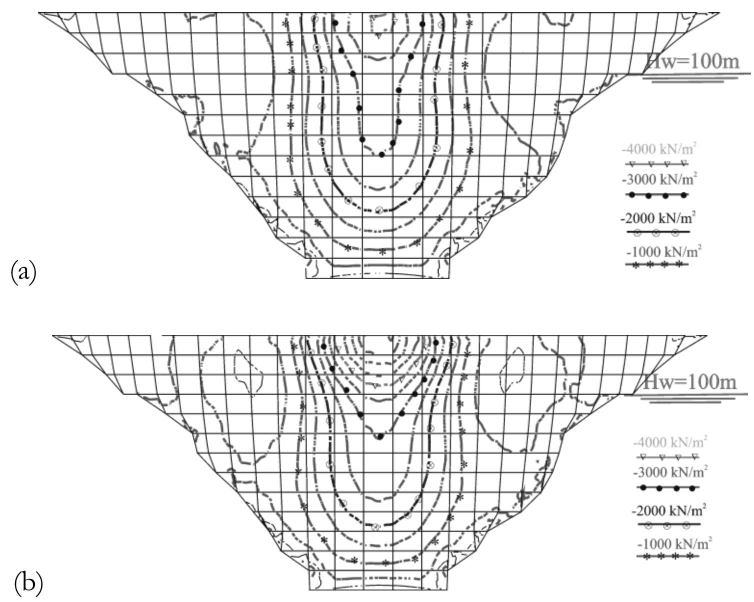
Pic. 5, presents the time history response of relative displacement velocity and acceleration for the selected node at the dam crest, top of the crown cantilever, where the extremes of the response occurred. Obviously, fluid structure interaction based on BEM-FEM numerical solution modifies the extreme of the response acceleration at the dam crest by 38 % in respect to the dam responce with empty reservoir. Additionally calculated are hydrodunamic effects by use Westergaard added mass concept. It gives lower modification of the dam responce, i.e, the exterem of the relative responce acceleration at the dam crest is modified by 31 % Nothe that, the time of extreme occurance is not coinside. Westergaard added mass concept do not give recogition to the impact of the dam flexibility on the amount of generated energy in the fluid domain and therefore on the intensity of the manifested FSI effects. The flexibility property of the dam and the influence of the reservoir domain alter the behavior of the fluid significantly and consequently the coupled system has a stronger response.

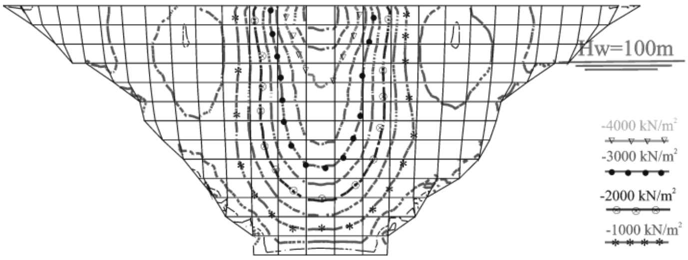
Pic. 6 shows the izolines of distribution of the principal stress G3 that acts along the arches with and without included hydrodynamic effects, whereat hydrodynamic effects are calculated according to added mass method and coupled BE-FE method. The stress extreme is increased by 15 % if added mass method is used and 49 % if coupled BE-FE method is used.

Despite the influence of the terrain irregularities on the amount of energy transferred to the fluid domain this effect has not been analyzed in detail applying boundary element model (BEM) or finite element model (FEM). ADAD-IZZIS software gives an opption for including the terrain irregularities into account. Pic. 7., presents a snapshot of hydrodynamic pressure distribution over the interface, at time T=4.95 s. It is obtained under the assumptions that the topology of the canyon has a regular shape as indicated in the drawing.



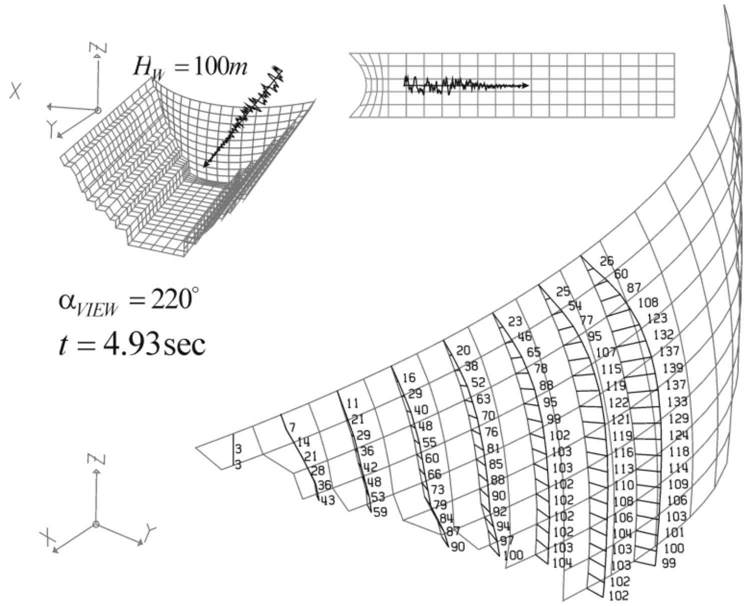
Picture 5 Modification of the dam response at the dam crest, relative displacement in (m) ; relative velocity in (m/sec) and relative acceleration in (m/sec2). FSI effects defined by use of BEM-FEM solution and Westergaard added mass method





(c)

Picture 6 Distribution of principal stress G3 at the extrados face at t=2.42 s
a) empty reservoir b) FSI using BEM-FEM regular terrain c) FSI using added mass method



Picture 7 Snapshot of hydrodynamic pressure distribution at time T=4.95 sec

4. Summary

ADAD-IZIIS software is based on BEM-FEM oriented solution of the coupled structure and incompressible and inviscid fluid domain. The process of generation of the mathematical model runs parallel and interactively with the process of design of the arch dam body. Automatically are generated the finite element mesh of the dam and part of the foundation mass for accounting the phenomena of dam-foundation interaction, and boundary element mesh that presents the boundaries of the fluid domain for accounting the fluid structure interaction. The solution of the coupled system is accomplished by use of matrix of hydrodynamic influence utilizing the concept of virtual work of “unit accelerations”.

5. References

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