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Influence of irregular canyon shape on location of truncation surface

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ABSTRACT

Fluid–structure interaction phenomenon, by its nature, is three-dimensional and consequently dependant on the shape of a dam and canyon that in-fact defines the spatial domain where the generated acoustic waves are spread. The complex topography of the terrain in general requires sufficiently large extent of reservoir to be included in the model, which is undoubtedly feasible if BEM technique is used. This paper shows that the irregular canyon shape dictates "the most adequate" location of the truncation surface that gives the smallest negative impact on calculation accuracy. The derived conclusions are based on various 3D analyses of a rigid dam–reservoir system with different shapes and lengths of the fluid domain, where the fluid is treated as incompressible and inviscid. The presented work contributes towards disclosure of the topographic site effects and towards promotion of simple and effective procedure for generation of BE mesh, which is quite accurate in following the topology of the terrain.

1. Introduction

Fluid–structure interaction is a three-dimensional phenomenon. The expansion of generated acoustic waves and the way of their propagation as compressive or dilatation waves depends not only on the specified boundary conditions but also on the shape of the reservoir boundaries in respect to the direction of the seismic excitation. The complex topographical conditions of the canyons, where the dams are built, require a large extent of practically unbounded fluid domain to be included in the models. However, if the concept of unbounded fluid domain is not used [1,20], then it is necessary to truncate the reservoir at a certain distance from the dam. In order to have correct analyses, special attention should be paid on the selection of the fictitious position of the truncation surface (TS), when modeling the dam–reservoir system with highly complex shape of the canyon. The topographic site effect has so far been unfairly ignored in BE and FE modeling of the reservoir despite its impact on the accuracy of the calculated hydrodynamic pressure (HDP). In 1986, Liu was the first who studied the effect of the complex geometry and showed the influence of the dam shape over the solution [38]. Porter and Chopra have successfully applied the 2D finite element technique for modeling an arch–dam–reservoir system of regular geometry [35,36]. Hall and Chopra's work has been the trigger for pioneer promotion of the three-dimensional analysis that solves interaction effect between the dam and the reservoir of regular shape [37]. The presented work given in this paper contributes toward the recently published 3D fluid–dam interaction analyses based on either FEM–FEM formulation or BEM–FEM formulation [2,5,14,24–30]. The above 3D analyses are mostly devoted for improvement of the numerical methods and computational techniques of FSI solutions as well as their implementation in the existing software. Pointing out the complexity of the FSI phenomenon focus was placed on improvement of the solutions concerning energy dissipation at the far upstream end, and absorption of the energy of hydrodynamic pressure waves by the bottom sediments. However, in their solution, the reservoir is mostly treated as regular or irregular but with constant cross-section and simplified shape of the canyon walls. Namely, Chuhan and Wang Jinting [27] has made a 3D study of the influence of the seismic input mechanism and the damping effect over dynamic response of 210 m high arch dam. FE discretization of the fluid–dam–foundation continuum has been used, treating semi-cylindrical canyon and massless foundation model with viscous spring boundaries. Mirzabozorg et al. [25] have made a 3D FE analysis considering the arch–dam–reservoir foundation interaction. They investigated the influence of a non-uniform seismic excitation at the reservoir bottom over the seismic response of the whole system. The analyzed fluid domain is with a regular shape whose side walls are parallel to the assumed upstream

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Abbreviations: TS, truncation surface; TBC, truncation boundary condition; HDP, hydro-dynamic pressure; BC, boundary condition

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direction of the seismic excitation. Accordingly, the analysis that is based on application of the finite element oriented software NSAD-DRI [34], has neglected the effect of the canyon shape and the boundary conditions at the sides. Wang [5] has performed a study where the dam–water–foundation rock system is subjected to three-componential excitation. FE discrtization has been used for the fluid domain while the dam–rock interface has been discretized into a set of boundary elements. The fluid domain has been idealized as a finite region of irregular geometry adjacent to the dam, connected to an infinitely-long channel with a uniform cross-section. Bayraktar et al. [26] has also developed a 3D finite element model for solving a non-linear seismic response of an arch dam, using the ANSYS software [32]. Although the dam is built in a canyon with a highly complex topology, the performed analysis has been based on a semi-cylindrical shape of the fluid domain. Akköse et al. [24] has done a very sophisticated elasto-plastic 3D analysis of an arch dam using the NONSAP software [31]. Fluid–structure interaction has been solved by the Lagrangian approach. The applied fluid element supports the effect of a compressible wave propagation and surface sloshing motion. However, the analysis has been performed considering simple and regular shape of the reservoir with constant transversal cross-section. Birk and Ruge [2], have performed a 3D study of radiational dumping whereat the reservoir is split into a finite domain with simplified arbitrary geometry and constant cross-section enclosed by rigid canyon walls and a semi-infinite fluid-channel domain with regular shape. Bouaanani and Lu [3] have preformed a 2D fluid–structure interaction study based on FEM–FEM formulation in frequency domain applying the ADINA software [33], while treating the effects of water compressibility, dam flexibility and wave absorption from the bottom sediments. They have adopted an irregular shape of the reservoir bottom and have concluded that the analyzed effects are restrained by the simplified rectangular geometry of the impounded water. Software ADINA [33] offers advanced capabilities in meshing the irregular geometries of the dam–reservoir system. In publication [28], Aznarez at al., present a 3D BEM technique for dynamic analysis of a coupled dam–fluid system when the reservoir bottom is covered with fluid-filled poroelastic sediments with variable depth. Since the target of the analysis has been only to assess the importance of absorption of the pressure waves, the generated BEM is with a regular shape while the bottom of the reservoir is assumed to have an irregular shape, i.e., variable depth in the vicinity of the dam. Obviously, there is a demand for 3D analysis that takes into consideration the influence of the irregularity of the canyon. The presented work contributes towards the disclosure of the topographic site effects and also gives contribution towards effective and automatic way of generation of boundary element mesh, sufficiently accurate in following the topology of the terrain. Namely, when choosing the method for discretization of the complex canyon shape, in order to have a manageable computational time, advantage is given to BEM over FEM due to its merits [40,41]. Medina and Domínguez [8] have pointed out that BEM permits a good representation of the coupled dam–fluid–foundation system and is particularly convenient in the case of a curved dam shape and complicated topography of the terrain. Giving recognition to the coupling FEM–BEM approach, Tsai et al. have done extensive research in further development of 3D models [14,29,30]. The specification of the far-boundary condition is one of the most important duties in the development of a reservoir model regardless whether BEM or FEM formulation is used since it has a great impact on the solution. So far, various far-boundary conditions concerning both FEM and BEM numerical techniques in time or frequency domain have been reported in literature. Sharan [13,22], Coskun [7], Tsai and Lee [14], Maity and Bhattacharyya [15] and Birk and Ruge [2] have developed methods for energy dissipation in time domain. Since the disadvantage of time domain solutions is their inherent inability to consider the excitation frequency and the frequency dependence of energy dissipation, Humar and Roufaiel [9], Sharan [10,11] and Li et al. [12] have developed effective methods for imposing the boundary condition along the truncation surface, in frequency domain. Using BEM, it is also possible to leave the domain open, omitting the truncation surface from the model [16], or to couple FE with other type of discretization such as “infinite elements” [17], “boundary elements” [18,19] or “continuum” solutions [20,1]. In order to achieve the goal of the research presented in this paper, namely, prove the influence of topographic site effects, some of the performed analyses account for energy dissipation of the outgoing waves. It has simply been done by coupling BEM with continuum solution [1]. Classic Westergaard’s solution has been used for pressure distribution along the reservoir length, modified by the factor of reservoir irregularity. This factor is a correction of the classic Westergaard’s solution since the irregular reservoir shape presents a substantial deviation from the assumptions of the Westergaard’s solution. Despite its simplicity, the modified Westergaard’s TBC has shown the effectiveness of its application, fulfilling the requirements within the performed analyses, regardless the shape of the dam and the fluid domain. On the other hand, the TBC proposed by Kucukarslan has been reported to be suitable for analyses of dam–reservoir systems with a vertical upstream face [21]. Also, Sharan [13] and Coskun [7] have stated that their suggestion of exact truncation boundary condition for incompressible inviscid fluid allows the truncation boundary to be in close vicinity to the dam only if the reservoir is uniform in the near field. Bouaanania and Paultre [6] have performed 2D parametric study to prove the effectiveness and accuracy of the proposed boundary conditions. Their solution allows the TS to be placed near the dam upstream face but under the condition of regular rectangular shape of the reservoir. Aviles and Sanchez-Sesma [23] derived an analytical solution based on the Trefftz–Mikhlin method. Their TBC could be applied on dam–reservoir systems with non-vertical interface.

The paper is organized as follows. In Section 2, governing equations of fluid are described which have been used in the software ADAD-IZIIS, [51]. Section 3 describes a novel and very effective pre-processing procedure in generation of the BE mesh associated with the canyon configuration and based on the geodetic survey data. Section 4 presents the imposed TBC in the models and also gives some useful reflections on enhancement of the already developed sophisticated non-reflecting TBC in order to become applicable for curved dam shapes and irregular canyons. Section 5 presents the boundary conditions assigned at the remaining boundaries of the BE models as well as the results of the performed investigation. Conclusions are given in Section 6.

2. Governing equation and boundary element integral formulation

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 pressure in the fluid domain. Eq. (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.