Influence of the Valley Shape on the Earthquake Induced Response of a Dam

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Abstract

In a series of works by the authors, the problem of the earthquake-induced response of a dam was studied with respect to the topographical conditions of the site. It was proven that in some cases, these conditions can be especially unfavourable compared to widely used recommendations and code requirements. The current work studies the seismic response of a dam at the common conditions of river conjunction just upstream of the dam site with a convex slope opposite to the dam. A concrete gravity dam is studied because of the largest hydrodynamic pressure at the almost vertical upstream dam slope. Based on a particular case study, comparison of the usually implemented approach with transmitting opposite boundary of the fluid domain with the real 3D model of reservoir, respectively, is performed. Thus, by a realistic modelling of the system in the ANSYS environment, the influence of the real spatial geometry of the reservoir on the dynamic response of the dam is studied. After discussion of the obtained results, conclusions are drawn, and tasks for further research related to particular topographical configuration are formulated.

Keywords: convex opposite slope; earthquake excitation; gravity dam; valley shape layout.

Introduction

Dams, especially large ones, are essential components of the regional and national critical infrastructure. Their operational resilience is a problem of crucial importance in regions of higher seismicity. Moreover, they are facilities of large secondary risk directly related to their structural integrity itself, to the safety of downstream located population and infrastructure and to the operational conditions of the whole Hydraulic Engineering system where reservoirs always play the key role. At the same time, dams subjected to earthquake excitation represent complex physical phenomena where appropriate computational modelling is essential for the realistic assessment of the dynamic response of such facilities. In addition to the actual code requirements, maximum realistic dam response analysis is crucial for adequate assessment of the safety of both the dam itself and potentially affected territory.

For dams and their physical environment, earthquake ground motion causes physically complex dam-foundation-reservoir interactions. There are numerous models accounting for these interaction phenomena. A problem of particular importance is the dynamic dam-reservoir interaction because it transfers the additional hydrodynamic pressure on the upstream dam surface during seismic excitation. The intensive historical development in this field unfolds within about hundred

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years, presenting many qualitative breakthroughs. We cannot outline here this development in detail, only some of its milestones will be pointed out further below. One of the first deep theoretical analyses was the book by Shulman (1987). Many research works followed with important summaries of the applicable models and their features (USACE, 2003; Salamon, 2018). A recent and comprehensive synthesis analysis of the models for dynamic dam-reservoir interaction was performed by Chopra (2020).

Related to the attempt for possibly realistic modeling of the fluid domain and the dam-reservoir interaction in the seismic analysis of dams, respectively, the particular question arises about the topographical conditions of the reservoir, i.e. the valley form in layout and its development along the river flow. The problem of the impact of the topographical reservoir form on the seismic response of a dam is neither trivial nor a new one. Already in the 1980s, the problem of the influence of the reservoir form on the seismic response of a dam was thoroughly studied with the available at that time state-of-the-art approaches by Huang and Chwang (1985). A conclusion was that the pressure distribution on a dam is affected by the shape of the reservoir. Therefore, a spatial dam-reservoir analysis of the hydrodynamic response was recommended.

A related paper by Millán et al. (2007) thoroughly studied the effects of reservoir geometry on the seismic response of concrete gravity dams. Five typical forms of the reservoir adjacent to the dam with simplified geometry were studied under the El Centro excitation along the valley and vertical in both frequency and time domains. At the reservoir end far from the dam, a transparent boundary condition was introduced. The bottom absorption coefficient was found to be an important response parameter. Important conclusions were drawn related to all particular models and varied parameters. A typical characteristic feature of all studied models was the rectangular canyon cross section.

Special attention should be paid here to the paper by García et al. (2014). The paper focuses on the study of the influence of reservoir levels and the presence of bottom sediment layers in the reservoir on the dynamic behaviour of the dam. Two geometries were studied – one with an open transparent far end of the reservoir, and another one for comparison purposes with reservoir slope opposite the dam. Without describing the large research work done by the authors, it should be noted that in general, the closed reservoir by a slope opposite the dam delivers more intensive dam response than the open one subjected to an excitation parallel to the valley.

If the slope of the reservoir opposite the dam is located at a distance comparable to the dam height, or if the valley form layout has some special form, the problem is set about how realistic and safe would be the use of commonly accepted and implemented models in such cases, such as the added mass approach presented for example in the Bulgarian national seismic code for dams, Petkova et al. (2024a). This question also arises regarding the usually applied cylindrical form of the reservoir being geometrically extruded upstream of the dam with constant cross-section of the valley. This is a typical approach represented by numerous recent applications found for example in the special symposium proceedings edited by Fry and Matsumoto (2016). For particular topographical conditions of the reservoir in their immense possible variety, however, this approximation may lead to unrealistic results, moreover, not on the safety side, Petkova et al. (2024b).

Another most recent work of particular importance is the report by Mircevska and Nanevska (2024) on the influence of the direction of the seismic excitation on an arch dam-reservoir system and its dynamic interaction with the water in the reservoir with regular and complex configuration. The analysis was conducted applying a coupled BEM-FEM technique and the matrix of hydrodynamic interference. The considered direction of the seismic excitation was stream-wise, cross-stream and at 45 degrees with respect to the dam axis accompanied with a vertical component. Highest hydrodynamic pressures were obtained for a three-component seismic excitation in the stream-wise direction. The vibration of the arch dam and canyon walls with complex geometry

generated different fields of compressive and dilatational waves when compared to a reservoir with regular geometry. This resulted in considerably higher magnitudes and modified distribution pattern of the hydrodynamic pressures at the dam-fluid interface.

Most recently, some cutting-edge advances were reported in this field with respect to the use of real topographical conditions in both static and dynamic Dam Engineering problems. Chen and Hu (2025) applied a nonlinear seismic analysis method for high concrete dams with irregular terrain based on the finite element – scaled finite element method (FEM-SBFEM). They incorporated a special used defined element into the commercial software ABAQUS. Then, nonlinear seismic analysis was carried out on the dam-irregular terrain foundation system under earthquake action. The authors claimed this was an initial stage of their research work. Unfortunately, the model of the reservoir was not described. The report by Žvanut (2025) presented the complicated topographical environment of the Moste dam in Slovenia spatially modelled as part of the complete digital model of the system, however, without any details about the seismic response of the system. A spatial analysis of the Enguri dam in Georgia was performed by Andrian et al. (2025) including seismic response. The real topographical conditions in the vicinity of the dam were realistically modelled, and a transparent boundary condition was introduced at the far end of the reservoir model. Despite the comprehensive study, no details were presented of the model for the reservoir and for the dynamic dam-reservoir interaction during earthquake excitation. Gaftoi et al. (2025) reported on the development of a complex monitoring program of the Paltinu dam in Romania, including seismic analysis of the system of facilities with the real geometry of the dam site. Here, the dynamic response analysis of the system was performed by the use of the added mass approach according to Westergaard.

A related work also was presented by Petkova and Kisliakov (2025). There, four typical idealized valley layout forms were studied in terms of the earthquake induced hydrodynamic pressure on the upstream surface of a concrete gravity dam. These topographical forms were an idealized representation of a confluent configuration of two tributaries and were in fact different from the ones analysed by Millán et al. (2007). The excitation was represented by a real accelerogram. Besides the developed hydrodynamic pressures, the valley form influence was evaluated by the dam response in terms of equivalent von Mises stresses in the dam cross section. As expected, the maximum response in terms of both hydrodynamic pressure values and equivalent stress envelopes were observed with the T-form of the valley layout where the upstream slope of the reservoir was opposite the dam.

Xu et al. (2025) studied the infinite foundation radiation damping of the spatial dam system model of Yangfanggou arch dam in China by viscoelastic boundary absorbing scattered waves. The non-linear opening of transverse joints of the dam body was simulated by dynamic contact with Lagrange Discontinuous Deformation Analysis (LDDA). The dynamic dam structural finite element simulation was carried out for the Design basis earthquake (DBE). In this paper, no details were given on the reservoir model and the dynamic dam-reservoir interaction model.

The research activities and the remarkable increase of modelling capabilities of the modern multi-physics software platforms led recently to the possibility of much more realistic modelling of the earthquake-induced fluid-structure interaction in the dam-reservoir system. Consequently, there is an increasing number of research studies in this field. Modelling of the dam lake as fluid domain has become already a standard in the design practice of large dams. However, a comprehensive literature study on the spatial dam–reservoir–foundation interaction would far exceed the frame of this work and could be subject at least of a monograph. The most important results in this field are the procedures for more realistic computation of the dynamic dam-water and bottom-water interaction under different actual conditions as well as the comprehensive analyses of the applicability of these models. Currently, the related recommendations may be summarized as

presented by USACE (2003) and by Løkke and Chopra (2019) that the reservoir part adjacent to the dam should be considered with its real irregular form, and only the far fluid domain with the transparent boundary condition at the far end should be modelled with a cylindrical form.

In general, as it can be seen from the short literature survey above, despite the qualitative increase of the computational capabilities allowing for fully coupled multi-physics spatial modelling of dam systems, to our knowledge there are still relatively few research activities dedicated to the problem of the impact of actual reservoir topography on the seismic response of dams in terms of generated hydrodynamic pressures. While modern fluid-structure interaction and multi-physics models offer improved accuracy, the influence of seismic topography remains insufficiently addressed. Furthermore, the performed literature survey could highlight the sensitivity to modelling assumptions and the lack of experimental and field validation as the main problems currently in this field. The applied seismic input also remains as factor of crucial importance for the obtained results. Another particularly demanding field of special interest would be the development of spatial acoustic wave field in the reservoir. Such research should not end in itself. At the end, the real hydrodynamic pressure on the dam surface would be obtained. It should be noted that the wave field in the reservoir requires on the one hand modelling at least of its representative part. On the other hand, this problem crucially depends on the model of seismic excitation and the propagation of waves in the considered foundation continuum. It is well known that for a real topography, this seismological problem is still far from its solution. This is the main reason for the application of simplified excitation to our (although maximum sophisticated) computational models.

Further below, another analysis of the valley shape impact on the earthquake-induced response of a concrete gravity dam is presented as a particular case study following the recent works on this problem by Petkova et al. (2024a, 2024b), Petkova and Kisliakov (2025). The dam type corresponds to the real one, and it is located immediately downstream of the confluence of two small rivers with steep side slopes. Thus, a convex slope is formed opposite the closely located upstream dam surface. These topographical conditions correspond to some extent in idealized form to the Y-form of the valley layout studied in Petkova & Kisliakov (2025). The main idea here was to ascertain whether such convex opposite slope could act as the hump at the bottom of a champagne bottle affecting the seismic response of the dam.

The problem of a piston with a convex head in a cylinder is well known. The shape of the piston head has a significant impact on internal flows, turbulence and impulse distribution in the cylinder (Ferguson & Kirkpatrick, 2016). Experimental and numerical CFD studies have shown that different piston head geometries (flat, spherical, concave) lead to significant differences in the intensity of vortex structures and turbulent kinetic energy, which changes the dynamic effect of pressure on the fluid.

In the developed model of the spatial system, the real convex opposite slope of the reservoir close to the dam was modelled, moreover, representing the natural asymmetric topographical conditions. For comparison purposes relevant to the contemporary design practice, two other models were developed, too. The system also was studied with a prismatic model of the upstream valley with transmitting boundary condition at the far end of the reservoir. In the third model, the reservoir slope opposite the dam was modelled as a homogeneous ramp. A comparison of practical relevance was made between the obtained results by these three computational approaches. All models of the dam-reservoir system were developed in the ANSYS computational environment, ANSYS (2022-2024).

Methodology

In the following, a slightly simplified model of the Chaira concrete gravity dam in Bulgaria, Fig. 1, with the real topography of the dam site is presented as a case study of the shared idea about the convex piston of a “champagne bottle”. The height of the dam is 80 m, its crest length is 300 m, and

the layout of the site is presented in Fig. 2. This is a particular case study but it should be noted that building a dam downstream of a confluence of two tributaries is a common concept in Dam Engineering. These tributaries may flow almost in a straight-line opposite each other like Punt dal Gal dam in Switzerland and Soyanggang dam in Republic of Korea – the studied T-form in Petkova and Kisliakov (2025), or flow together under some angle like the example herewith – the idealized Y-form in the same report. The real topographies of such confluences are in general not symmetric – Pyasachnik dam, Kamenets dam in Bulgaria; moreover, the dam may be located at a certain angle to the axis of the convex terrain form – Ticha dam in Bulgaria. Thus, the present case study presents a topographical configuration not rarely observed at mountainous dam sites.



Fig. 1
Aerial view of Chaira dam (authors' archive)

From the digital topographical map of the real dam site, the computational boundary of the model was developed.

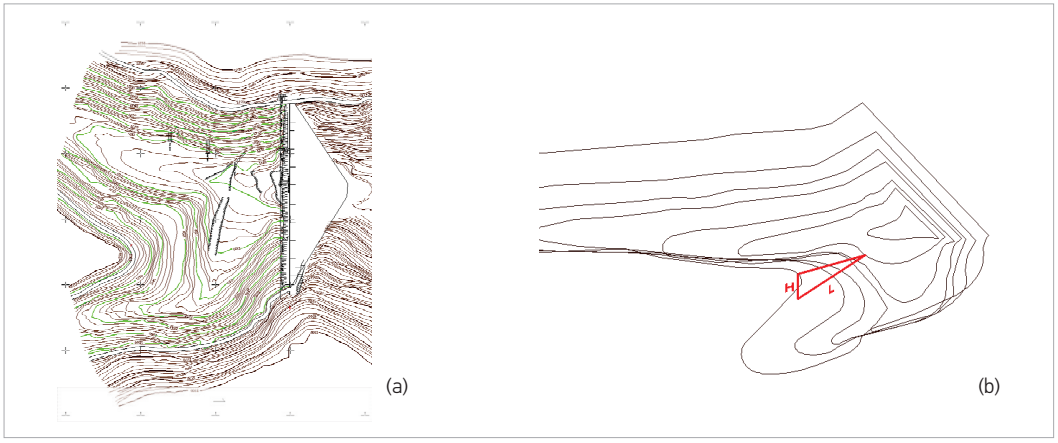


Fig. 2
Topographical model of the dam site:
a Terrain of dam and reservoir;
b Computational model with the ratio obtained from the terrain slope H:L ≈ 1:2

For the performed comparative study, three finite element method (FEM) models were developed in the program ANSYS (2022-2024). The solid domain of each of the system models was built applying the element SOLID186 – a 3D 20-node structural solid element. The domain of inviscid, irrotational and compressible fluid was modelled using the element FLUID221 – a 3D acoustic 10-node element. and as infinite acoustic element, FLUID130 was used. It realizes a second-order absorbing boundary condition so that an outgoing pressure wave reaching the "transparent"

boundary of the model is “absorbed”, (i.e. transmitted) with minimal reflections back into the fluid domain. Thus, by introducing such absorbing boundary condition, radiation damping was applied at the fluid boundaries far from the dam as damping mechanism for the fluid.

The dam body consists of concrete with density of 2500 kg/m^3, elastic modulus of 30 GPa and Poisson’s ratio 0.2. Rayleigh damping was introduced in the transient analysis whereas the global damping matrix was defined as a linear combination of the mass and stiffness matrices with the mass-proportional damping coefficient and the stiffness-proportional damping coefficient . The structural behaviour of the dam was assumed to be linear elastic.

A rigid foundation domain and no absorbing sediment layer on the reservoir bottom were assumed. In the particular case, the latter corresponds well to the real conditions of this mountainous reservoir. These simplifying assumptions as well as the ones related to the seismic input further below were made because the emphasis in this study was on the comparison of the introduced models with respect to the earthquake induced hydrodynamic pressures on the dam surface. Thus, on the one hand, in a more “purely” formulated numerical experiment, the influence of the particular topography could be clearer estimated for the performed comparisons. On the other hand, the computational effort needed was considerably smaller without the loss of qualitative features of the dynamic response.

The computational model of the system with real topography is presented in **Fig. 3** together with the corresponding finite element mesh. All computational models developed have total length of about 7.5 times the dam height, total height 2 times the dam height and total width 5 to 7.5 times the dam height.

Fig. 3

Computational model of the real topography: **a** geometry of the model; **b** generated finite element mesh of both solid and fluid domains

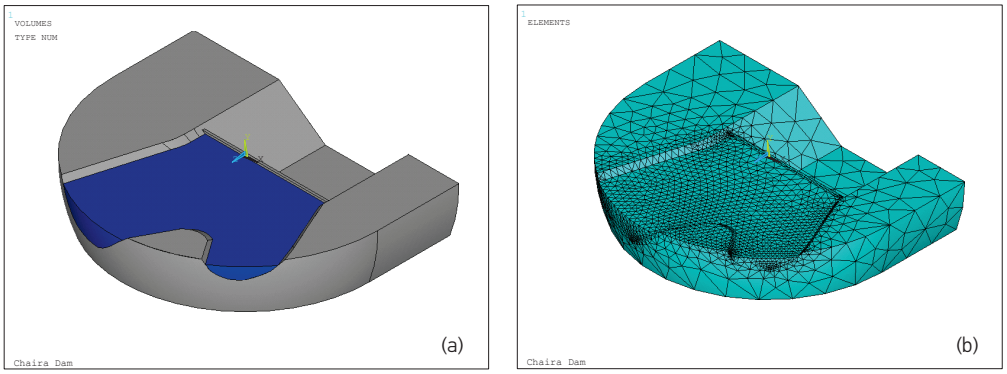
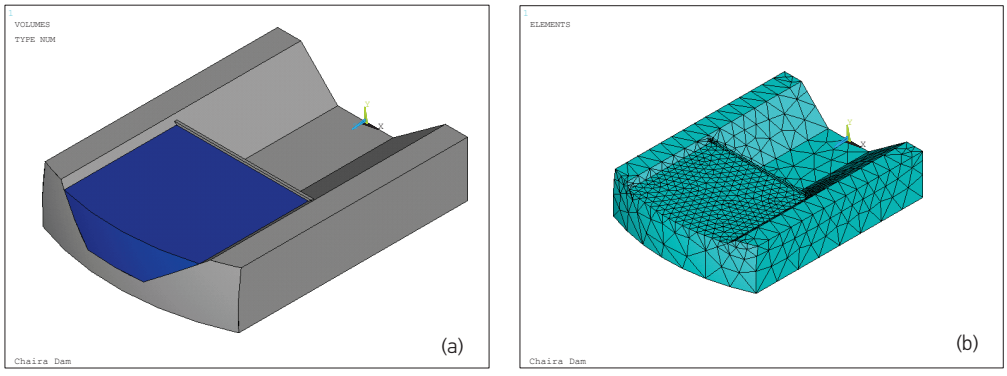


Fig. 4

Computational model of the system with cylindrical reservoir: **a** geometry of the model; **b** generated finite element mesh of both solid and fluid domains



As it can be seen from Fig. 3, the spatial topography of the dam-reservoir system is truncated by a spherical surface. This is related to the fluid domain containing both river tributaries coming together immediately upstream of the dam. The spherical surface enables introduction of the absorbing acoustic boundary condition at the upper ends of these two river valleys.

As mentioned above, the second model developed for comparison represents a strong simplification of the real terrain by extrusion of the valley cross-section geometry at the dam profile upstream, Fig. 4. This is a commonly applied approach in many seismic dam analyses. Thus, a cylindrical form of the reservoir was formed. At the far end of the reservoir, an absorbing boundary condition was introduced.

The third computational model also is a relatively rough approximation of the real reservoir form near the dam. It was obtained by assuming a ramp with a slope angle equal to the one of the convex slope opposite the dam, Fig. 2b. Thus, instead of an acoustic boundary condition at the far end of the reservoir, a "tank" model for the fluid domain was introduced with an extremely unfavourable upper boundary condition, Fig. 5.

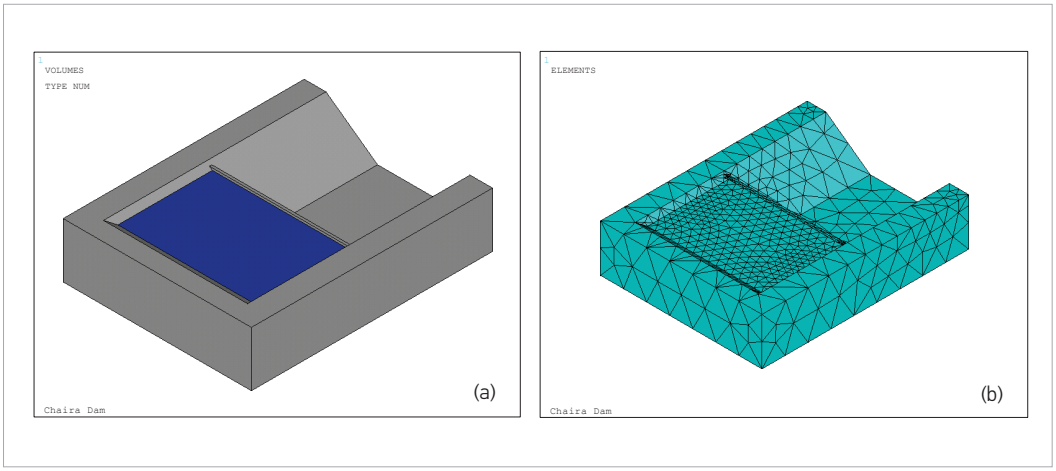


Fig. 5

Computational model of the system with plane slope opposite to the dam: **a** geometry of the model; **b** generated finite element mesh of both solid and fluid domains

The seismic analysis of all three above presented models was performed in the time domain with a short real accelerogram, Fig. 6. This kinematic support excitation was applied synchronously at the support points of the whole model, respectively, along the valley, i.e. transverse to the dam axis.

The applied seismic input corresponds to an extracted part from a real acceleration record. A part of the real record was used due to the needed computational resources. It has a total duration of 1.3 s and a constant sampling interval of 0.002 s, providing a sufficiently fine time discretization for accurate transient analysis. The record was scaled to a peak ground acceleration (PGA) of approximately 1.05 m/s² which corresponds to 0.1g and represents a typical strong motion

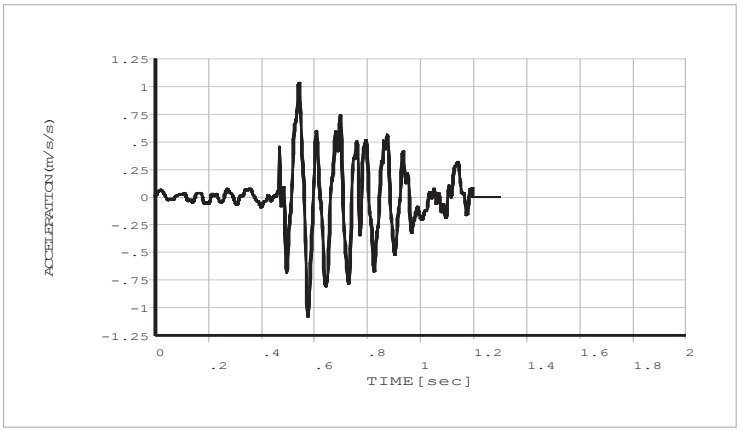


Fig. 6

Acceleration time history for the performed seismic analysis.

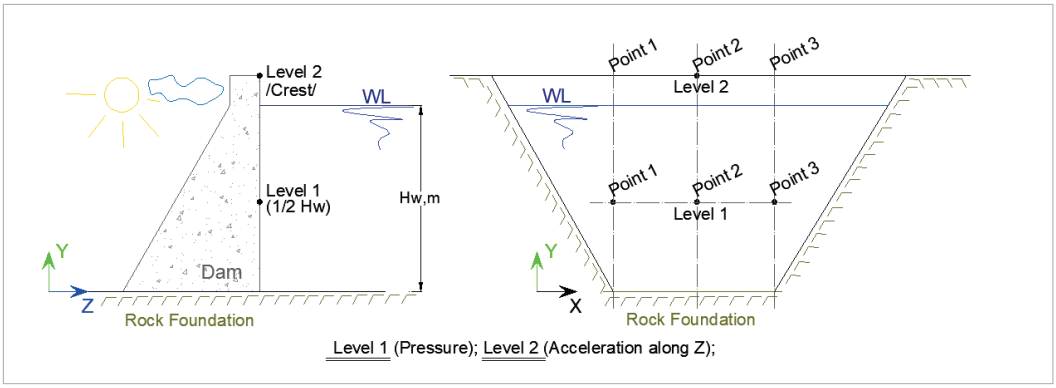
intensity level for Bulgaria. Furthermore, it features rapidly varying amplitudes, typical of shallow short-duration earthquakes. This input motion was selected to provide a physically realistic dynamic excitation and, although not being a result of site-specific seismic hazard study, it was considered adequate for capturing the essential characteristics of the analysed fluid–structure interaction under seismic loading.

Results and discussion

For a systematic comparison of the results of the performed seismic time history analysis of all three dam-reservoir system models, the dam response was recorded in two sets of control points, Fig. 7. They were set in three vertical sections of the dam – in the middle of the dam axis at the crest and in the middle of each half, respectively. In every one of these vertical sections, two control points were set – one at the dam crest and one in the middle of the maximum range of operational water level changes. At the points on the dam crest, the seismic response of the dam was recorded in terms of nodal acceleration. At the points on the dam upstream surface in the reservoir, the obtained nodal pressure was recorded. This set of control points was formulated in the presented form also because of the non-symmetric form of the dam lake.

Fig. 7

Control points on the upstream dam surface where the response parameters were recorded

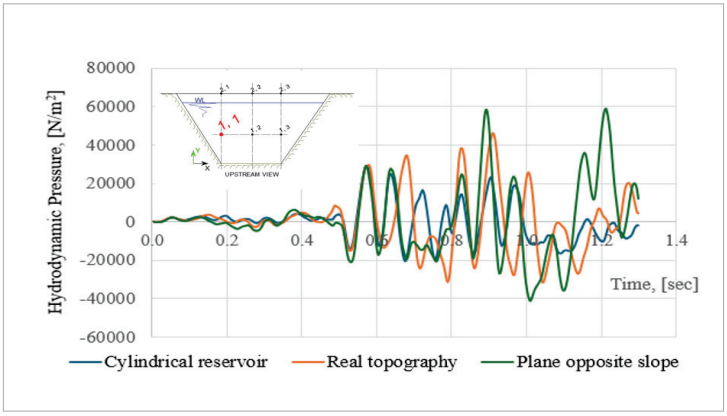


Thus, by means of the recorded response parameters, some general conclusions could be drawn on both the simplified structural response of the dam and the earthquake induced hydrodynamic impact of the reservoir. Further below, the time histories of these response parameters in the control points are shortly presented. The signature of the control points used is according to Fig. 7, looking downstream to the dam at the longitudinal dam section.

On Fig. 8 to Fig. 10 further below, the corresponding response pressure time histories at the control points on Level 1, Fig. 7, i.e. in the middle of the maximum operational water depth of the reservoir are presented. For every one of these control points, response pressure time histories are graphically shown for all three dam-reservoir system models: the one with the real geometry, Fig. 3, the cylindrically extruded reservoir, Fig. 4, and the reservoir with plane slope opposite to the dam, Fig. 5. For better orientation, the reference scheme of the points also is provided again.

Fig. 8

Response pressure time histories at control point 1, 1.



In general, the generated hydrodynamic pressure registered in the control nodes remains lower than the hydrostatic one, as expected, for the applied intensity of the ground motion signal. Regarding the response time histories of the earthquake induced hydrodynamic pressure shown in Fig. 8 to Fig. 10, the following remarks can be made with respect to the obtained results.

The use of the real system geometry led to higher hydrodynamic pressure values compared to the cylindrical reservoir obtained by geometric extrusion of the valley profile at the dam. It should be reminded here that the latter model is most widely used together with the added mass approach. In our opinion, this result was due to the influence of the convex non-symmetric geometry of the slope opposite the dam, i.e. similar to the one of a convex piston head (Ferguson & Kirkpatrick, 2016). However, the obtained quantitative differences in terms of generated hydrodynamic pressures on the dam upstream surface compared to the ones in the model with cylindrical reservoir were not of a magnitude which would lead to formulation of general recommendations. About the dam dynamic response in terms of crest accelerations at the selected pints, no decisive conclusion could be drawn, Fig. 11 to Fig. 13.

At the central point, the resulting accelerations were

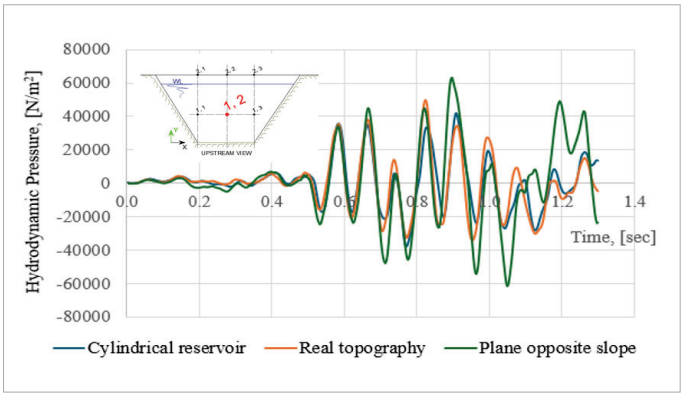


Fig. 9

Response pressure time histories at control point 1, 2.

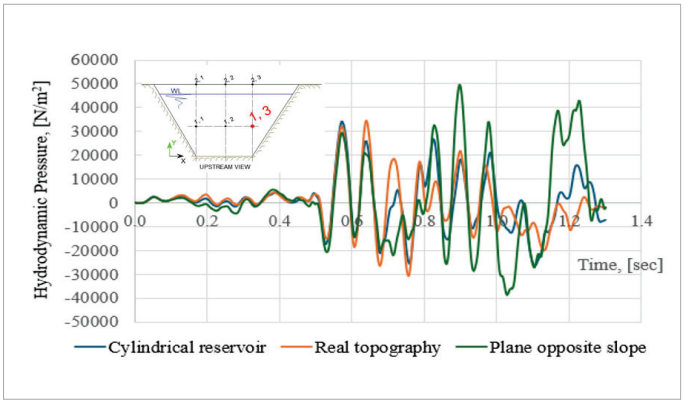


Fig. 10

Response pressure time histories at control point 1, 3.

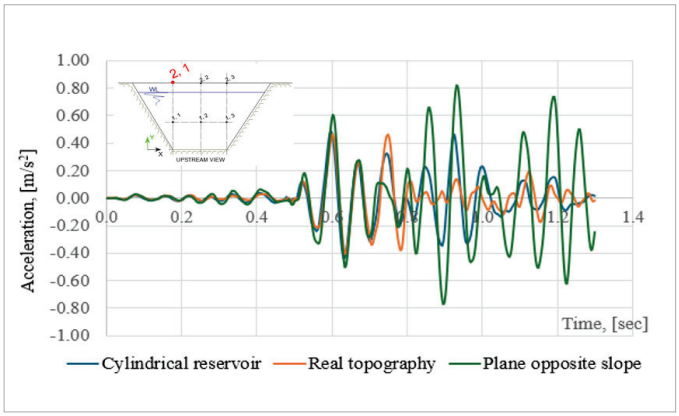


Fig. 11

Floor response acceleration time histories at control point 2, 1.

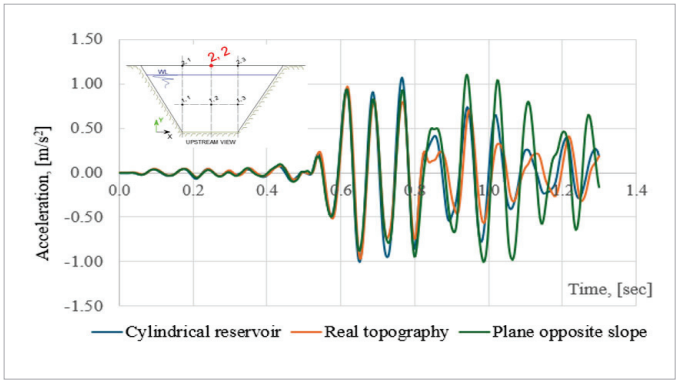
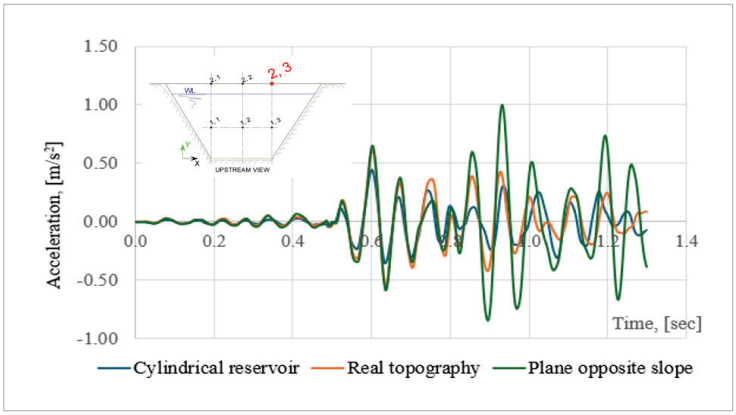


Fig. 12

Floor response acceleration time histories at control point 2, 2.

Fig. 13
Floor response acceleration time histories at control point 2, 3.



the highest in all models - in our opinion, due to the deformability of the elastic dam body assumed as a monolith without being separated in structural blocks.

As expected, the maximum pressure values at the dam surface and accelerations at the crest were generated by the use of the "tank" model with plane slope opposite the dam. This is a relatively rare configuration but in some particular cases it should be accounted for, e.g. Punt dal Gal dam in Switzerland – the studied T-form in Petkova and Kisliakov (2025), Luda Yana dam in Bulgaria, Petkova et al. (2024b).

On Fig. 11 to Fig. 13 below, the corresponding response acceleration time histories at the control points on Level 2, Fig. 7, i.e. on the dam crest are graphically presented. For every one of these control points, the floor response accelerograms are shown again for all three dam-reservoir system models. Here, the respective reference schemes are provided again.

No sensitivity analysis was performed with respect to the configuration parameters of the different models or to those of the input signal. All these describing parameters are too many for a systematic sensitivity study, this would far exceed the frames of this sole work. However, the accompanying tests carried out show that, as always in Earthquake Engineering problems, the seismic input has the crucial impact on the system response. Here, simulations with two other signals with different frequency content and PGA were performed, but the obtained results showed no qualitative difference between the used models. Furthermore, since the problem formulation was linear and no particular eigenmodes of the systems were activated in the performed tests, the duration of the seismic excitation had no impact on the response.

Unfortunately, although the herewith studied topographical configuration in its idealized form is not so rare, as shown in the presented literature survey, no comparison could be made with results of similar performed analysis or experimental field study, since to our knowledge, no such study has been carried out. The above presented works on influence of differently represented topographical conditions have used substantially different computational models.

It can be seen, Fig. 11 to Fig. 13, that the dam structural response in terms of floor acceleration time histories at the control points on the crest is almost the same for the models with real topography and with a cylindrical reservoir. The model with plane slope opposite the dam generates considerably higher floor response accelerations at the crest at all thee control points. This could be explained with the much higher load, i.e. hydrodynamic pressure on the dam upstream surface in this model.

Conclusions

In general, the conclusions on the impact of the opposite slope of the dam drawn in Petkova et al. (2024b) and in Petkova and Kisliakov (2025) could be confirmed here. For small mountainous reservoirs and ones with relatively steep slopes opposite the dam, considering the real topography of the valley at the dam site in a spatial model should be mandatory in seismic analyses. However, the suggestion about possible substantial amplification of the hydrodynamic pressure due to a convex slope opposite the dam which powered the motivation for this research could not be confirmed to an extent that certain recommendations for practical used could be formulated. The performed additional simulations related to this work showed that in general, if the reservoir

slope opposite the dam is at a distance larger than 4 times the dam height, and the bottom in this range is with a negligible slope, a cylindrical reservoir model with absorbing boundary at the far end will be a realistic approximating model despite the irregularity in the real topography of this opposite slope.

A further conclusion is that a reservoir model with a plane opposite slope should be implemented only where it realistically corresponds to the actual topographical conditions since it delivers, as expected, much higher response in terms of hydrodynamic pressures on the upstream surface of the dam. Although not explicitly discussed in most of the national seismic codes, this conclusion is of crucial importance for the seismic resilience of the dams as major components of the national critical infrastructure.

In general, in the herewith mentioned series of works by the authors, the influence of the most commonly observed topographical forms of dam sites on the earthquake induced hydrodynamic pressures was investigated in more or less idealized form. Yet as a task for related future research, a parameter study of the problem with particular topographical parameters of the dam site – for example the distance of the opposite slope to the dam, as well as this slope angle, could be formulated. The development of such topography dependent pressure values during seismic excitation for arch dams also would be of particular interest due to the spatial character of the upstream dam surface.

Furthermore, seismic input signals of different type, intensity and frequency content, respectively, could be applied. The possible variety of the geological parameters of the foundations also is large, and incorporating the dynamic dam-foundation interaction into the model would be another wide field of research activities.

Also, each one of the mentioned problems would require large research resources, but a parameter study in any of these fields would substantially increase the knowledge about the actual seismic response of a certain type of dam in the actual natural conditions which, as already mentioned, could essentially differ from the prescriptions of the design codes and usually implemented approaches.

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