Analysis of upper dam failure and cascade impacts in pumped-storage hydropower systems: a case study of Brava - Sfikia scheme, Aliakmon River, Greece

P. Dimas[1*], A. Lykou[1], A. Zarkadoulas[1], G.K. Sakki[1], A. Efstratiadis[1] and C. Makropoulos[1]
[1] *Dept. of Water Resources and Environmental Engineering, School of Civil Engineering, NTUA, Athens, Greece*
** e-mail: pdimas@mail.ntua.gr*

Introduction

The analysis of dam failure mechanisms and the subsequent propagation of flood waves is critical in understanding the risks associated with hydropower infrastructure. This also includes pumped hydropower storage (PHS) systems, which are, in fact, interconnected infrastructures, and they are pivotal for renewable energy integration. Given the growing significance of PHS, understanding the multidimensional impacts of potential failures on human activities and critical infrastructures downstream, is paramount.

This study focuses on the pumped-storage hydropower system at Sfikia Reservoir, located in the Aliakmon River basin in Greece, which incorporates a series of cascading reservoirs (Ilarionas, Polyfyto, Sfikia, Asomata, Ag. Varvara). The PHS project in hand includes a primary existing reservoir (Sfikia), a proposed upper reservoir at Brava, and associated hydraulic structures. Utilizing advanced simulation tools, combined with empirical approaches, this research examines the potential failure mechanisms, focusing on piping of the upper dam at Brava, and the resulting flood wave dynamics across the entire downstream path, down to the lower dam (Sfikia).

In particular, the study investigates multiple failure scenarios, assesses flood wave propagation through hydrodynamic simulation, and evaluates the impacts on downstream reservoir under the scope of hydrologic routing of the incoming hydrograph and the effects of large-scale wave generation (tsunami phenomenon). This concludes to effective risk mitigation measures, such as early warning systems and preventive interventions, ensuring the safety and sustainability of the integrated PHS system.

Materials and methods

This study integrates: *(a)* dam failure modelling, by using both HEC-RAS (Goodell, 2005) and BASEbreach (Macchione, 2008; Peter, 2017; Peter et al., 2018) in a Monte Carlo context, thus providing a range of potential outflow patterns (Fig. 1a); *(b)* hydrodynamic modelling via HEC-RAS 2D, to assess the impact of dam failure and flood wave propagation between the upper and the lower reservoir; *(c)* a dual approach to model tsunami generation and propagation in Sfikia reservoir, by assuming that the incoming hydrograph generated from the dam break is acting as a landslide, and *(d)* the routing of the hydrograph, combined with upstream inflows, through the control structures of Sfikia dam (turbines and spillway). This scheme ensures a comprehensive evaluation of the *cascade risks* and their potential impacts.

Flood modelling focuses on the propagation of flood waves from the Brava Reservoir to the downstream Sfikia Reservoir in the event of dam failure. Using HEC-RAS 2D, the study simulates flood wave dynamics, including velocity, depth, and timing. Key considerations include: *(i) Dam Breach Parameters*: A number of scenarios of piping failures are modelled using regression-based equations and empirical relationships (e.g., Froehlich, 2008), *(ii) Hydraulic Connectivity*: The hydrological and topographic linkages between the reservoirs are modelled to capture wave movement, *(iii) Flood Wave Transformation*: Flood wave characteristics, i.e. maximum depths, velocities (Fig. 1b) and arrival times, are assessed along the flow path for three specific scenarios (favorable, representative, adverse) accounting for attenuation due to natural and structural barriers. The Tsunami Generation Approaches (Fig. 1c) include: *(a) a Theoretical Approach*, and *(b) a Semi-Empirical Approach*. The first one employs physical principles to predict wave generation dynamics from landslides entering the reservoir. The key factors encapsulate: *(i) Landslide Volume*: total displaced material entering the water, *(ii) Entry Velocity*: speed of the landslide upon entering the reservoir, *(iii) Slope Angle*: Affects the energy transfer into wave generation. The initial wave height is estimated using the differential equation proposed by Di Risio and Sammarco (2008). Factors such as bottom friction, radial dispersion, and diffraction are included to refine wave height predictions over distance (Goda, 2010), while the last step calculates the run-up at the Sfikia dam crest. The Semi-Empirical approach follows the computational procedure developed by Evers et al. (2019), which utilizes empirical formulae that are calibrated against observations, thus enabling more realistic predictions of wave impact.

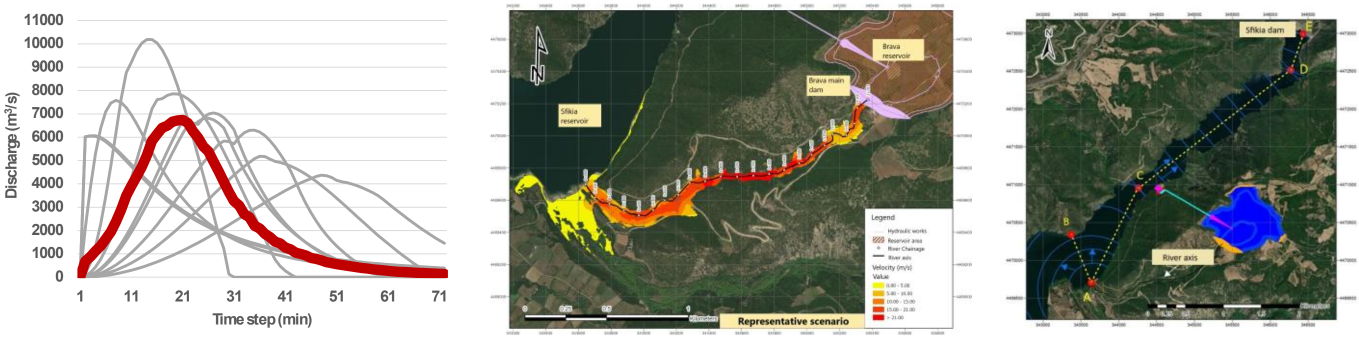

Figure 1. Characteristic elements of the modelling approach (a) outflow hydrographs due to upper dam break (bold line refers to the representative scenario); (b) maximum velocity for the area between Brava and Sfikia reservoirs, and (c) tsunami propagation route.

Results and concluding remarks

The analysis of potential impacts due to upper dam failure highlights significant risks across the PHS system. The modelled flood waves showed peak discharges exceeding 6,500 m³/s at the Sfikia Reservoir under the representative scenario. Flood propagation analyses revealed potential inundation of downstream areas, stressing the importance of integrated risk management. Tsunami modelling demonstrated that landslide-triggered waves could substantially amplify localized water levels within the reservoirs. The semi-empirical approach produced wave heights exceeding 6 m near the landslide impact zone, with attenuation observed downstream due to bottom friction and reservoir geometry. The run-up at the Sfikia dam location is calculated ~1.4 m. The theoretical approach, on the contrary, is producing run-up heights ranging from 1.4 to 3.7 m. Overall, the results highlight the need for enhanced mitigation strategies, including early warning systems, adaptive structural reinforcements, and coordinated reservoir operation plans to strengthen system resilience.

References

Di Risio, M., Sammarco, P., 2008. Analytical modeling of landslide-generated waves. Journal of waterway, port, coastal, and ocean engineering 134, 53–60.

Evers, F., Heller, V., Fuchs, H., Hager, W., Boes, R., 2019. Landslide-generated impulse waves in reservoirs. Basics and Computations. Swiss Federal Office of Energy SFOE. Bern, Switzerland. Laboratory of Hydraulics, Hydrology and Glaciology VAW. ETH Zurich. Zurich, Switzerland.

Froehlich, D.C., 2008. Embankment Dam Breach Parameters and Their Uncertainties. Journal of Hydraulic Engineering 134, 1708–1721. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:12(1708)

Goda, Y., 2010. Random seas and design of maritime structures. World scientific.

Goodell, C.R., 2005. Dam Break Modeling for Tandem Reservoirs — A Case Study Using HEC-RAS and HEC-HMS, in: Impacts of Global Climate Change. Presented at the World Water and Environmental Resources Congress 2005, American Society of Civil Engineers, Anchorage, Alaska, United States, pp. 1–11. https://doi.org/10.1061/40792(173)402

Macchione, F., 2008. Model for Predicting Floods due to Earthen Dam Breaching. I: Formulation and Evaluation. Journal of Hydraulic Engineering 134, 1688–1696. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:12(1688)

Peter, S.J., 2017. Dam break analysis under uncertainy 241. https://doi.org/10.3929/ethz-b-000484484

Peter, S.J., Siviglia, A., Nagel, J., Marelli, S., Boes, R.M., Vetsch, D., Sudret, B., 2018. Development of Probabilistic Dam Breach Model Using Bayesian Inference. Water Resources Research 54, 4376–4400. https://doi.org/10.1029/2017WR021176