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Numerical Simulation of Earth Dam Erosion due to Overtopping Using a One-dimensional Model

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Abstract

The increasing frequency of extreme weather events, driven by climate change, poses significant challenges to hydraulic structures such as earth dams. These structures are increasingly exposed to sudden inflows of large water volumes, which can exceed their discharge capacities. When overtopping occurs, the resulting erosion of the earth dam can lead to catastrophic releases of retained water, endangering downstream areas. In Poland, two such disasters have taken place in recent years: in 2010 in Niedów and in 2024 in Stronie Śląskie. These events emphasize the critical need for advanced computational tools to model erosion processes and enhance the safety of areas located downstream. This study presents the application of a one-dimensional numerical model based on the physics of erosion phenomena. The simulation results were validated through experimental studies conducted at Wrocław University of Science and Technology, where physical models of earth embankment erosion were tested. The comparative analysis demonstrates the robustness of numerical approaches in a predicting erosion dynamics. The findings underscore the vital role of integrating numerical simulations and laboratory experiments to improve the predictive capabilities of dam safety assessments in the context of a changing climate.

1. INTRODUCTION

The increasing frequency of extreme weather events driven by climate change has intensified the risk of catastrophic failures in hydraulic structures such as earth dams. Events like the overtopping of the Niedów Dam in 2010 and the washout of the Stronie Śląskie Dam in 2024 highlight the vulnerability of these structures to intense rainfall and the devastating consequences for downstream areas. These incidents emphasize the critical need for advanced tools to predict and mitigate the risks associated with dam breaches.

This study applies a one-dimensional numerical model calibrated against laboratory experiments. The model captures the breach development and resulting outflow hydrograph during overtopping scenarios. By combining experimental data with numerical simulations, this study provides a practical framework for enhancing dam safety amidst increasingly frequent extreme weather events.

2. LABORATORY EXPERIMENTS CARRIED OUT

Laboratory experiments were conducted at the Wrocław University of Science and Technology to investigate the erosion mechanisms of a homogeneous earth embankment under overtopping conditions. The embankment, constructed from noncohesive sand with a height of 0.50 m, was tested in a controlled setting using a reservoir with a capacity of 14.4 m³. The experiments aimed to simulate real-world overtopping scenarios and analyze the breach development process. Four distinct phases of erosion were identified: the initiation phase, vertical erosion, lateral erosion, and reservoir emptying. These phases were consistently observed across three trials, with lateral erosion showing the highest variability (Urbaniak et al. 2024).

3. CALCULATIONS ACCORDING TO NUMERICL MODEL

The model described by Macchione (2008) offers a physically-based numerical framework for predicting dam breaches caused by overtopping. It captures both the temporal evolution of the breach geometry and the resulting outflow hydrograph. According to this approach, the breach initially develops in a vertical direction with a triangular cross-section until its base reaches the foundation level. Subsequent lateral erosion causes the breach to expand, eventually forming a trapezoidal shape. This process aligns with breach morphologies observed in both experimental

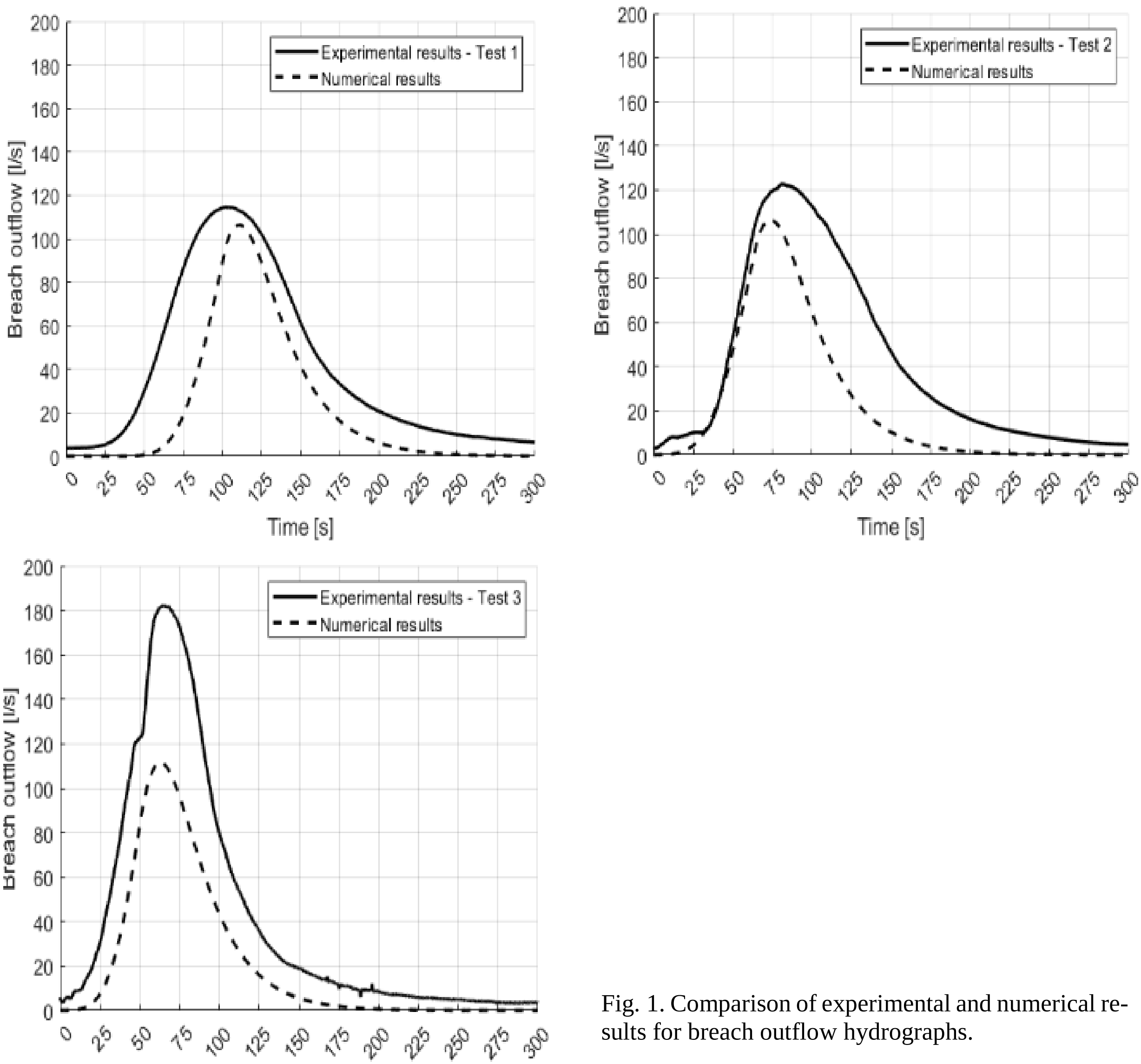

Fig. 1. Comparison of experimental and numerical results for breach outflow hydrographs.

and real-world scenarios. The model incorporates critical flow conditions through the breach to calculate discharge, using formulations specific to triangular and trapezoidal cross-sections. The volumetric sediment load per unit width is determined using the Meyer-Peter Müller formula, assuming that critical shear stress is negligible compared to the mean shear stress.

The model relies on system of coupled differential equations describing breach growth and the corresponding outflow hydrograph. The evolution of breach width and depth is governed by sediment transport equations, which depend on hydraulic shear forces acting on the erodible material.

The implementation of the model produced a hydrograph illustrating the temporal evolution of discharge during a breach event (Fig. 1). The results captured the rapid rise to peak discharge, followed by a gradual decline, reflecting the progressive widening and deepening of the breach. These numerical simulations were calibrated against laboratory test results conducted earlier in this study, ensuring that the model accurately represents observed erosion processes. Hydrographs that best correspond to the results of the laboratory tests are presented in Fig. 1.

4. SUMMARY AND CONCLUSION

The comparison between experimental and numerical results, as summarized in Table 1, highlights the strengths and limitations of the numerical model in predicting key breach characteristics. The peak discharge values (Q_p) from the numerical model closely align with experimental results in Tests 1 and 2, with errors of –7.20% and –13.27%, respectively. However, in Test 3, the model significantly underestimates Q_p by –37.94%. This discrepancy may be attributed to the increased variability observed in the lateral erosion phase during the experiments, which is challenging to capture with the current one-dimensional framework.

In terms of the time to peak discharge (T_p), the numerical model demonstrates reasonable accuracy, with errors ranging from +8.80% in Test 1 to –13.95% in Test 2. For Test 3, the predicted T_p is slightly higher than the experimental value +6.25%, indicating the model's capacity to approximate the temporal progression of the breach despite inherent simplifications.

Table 1

Comparison of experimental (Exp.) and numerical (Num.) results for peak discharge Q_p and time to peak discharge T_p across three tests

	Test 1		Test 2		Test 3	
	Exp.	Num.	Exp.	Num.	Exp.	Num.
Q_p [ls^{-1}]	114.65	106.39	122.67	106.39	182.17	113.05
T_p [s]	102	111	86	74	64	68

Overall, the results underscore the importance of calibrating numerical models with experimental data to improve their predictive accuracy. The discrepancies observed in Test 3 suggest the need for further refinement, particularly in representing the dynamic interactions of hydraulic forces and erosion processes during the lateral erosion phase. Nonetheless, the close agreement in Tests 1 and 2 validates the robustness of the model and its utility in assessing dam breach scenarios under varying conditions. These findings highlight the necessity for continued advancement of numerical methodologies to better capture complex erosion mechanisms and enhance predictive capabilities. Furthermore, additional experimental studies are crucial for providing high-quality data to support model calibration and validation, ultimately ensuring the reliability of such tools in real-world applications.

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