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Editorial

Dam Safety-Overtopping and Geostructural Risks

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There is a growing concern about the safety of dams and dikes in modern society. The new regulations demand an increasing level of safety. Therefore, the technical community related to dams is making an effort to understand the failure mechanisms that threaten dam safety, prioritize actions with informed criteria, and develop more efficient solutions to heighten the safety of new and existing dams with the limited resources available.

The safety of dams and dikes involves multiple issues such as the understanding of the behavior, even in extreme conditions near failure; proper design, construction, and exploitation; and also logical and efficient management and assignment of available economical and personal resources.

The overtopping of embankment dams has been the main cause of dam failure in the last decades. Consequently, the main challenge related to dam safety is to find efficient solutions to quantify risk and avoid the failure of new and existing dams due to overtopping. Hydrological safety is one of the most active areas in dam engineering research, involving a considerable technical community all over the world.

The rest of the failure mechanisms (internal erosion, sliding, concrete cracking, etc.), related to dam behavior and geostructural safety usually affect parameters such as seepage, movements, or interstitial pressures that can be controlled by means of visual inspection and the analysis of the data provided by the monitoring system.

Predictive models are developed with the purpose of detecting anomalous dam behavior that could potentially be a symptom of the onset of an incident or dam failure. Physically based models, such as finite element models, or data models are useful for that. Both types of models have experienced enormous development in the last years and today a huge effort is being made to enhance their prediction accuracy.

Data models were traditionally based on multiple linear regression (HST model and a long list of models derived from that). Machine learning and artificial intelligence techniques are now being investigated to develop models that more closely adapt to the complexity of the dam-foundation system. Better accuracy and more profound understanding is being achieved by these methods, previously developed in different complex areas of knowledge such as sociology or the Internet.

In the field of dam safety management, risk analysis has also experienced a rapid dissemination. A lot of effort is concentrated on developing fragility curves for the different types of failure mechanisms, which are essential for a rigorous application of risk analysis.

A deep understanding of the physical processes involved in dam failure mechanisms is essential for modeling the behavior of dams and dikes in extreme situations, close to catastrophic failure, and the definition of reliable fragility curves.

The Special Issue *Dam Safety. Overtopping and Geostructural Risks* covers recent advances in the understanding and improvement of hydrological and geostructural dam safety related to the abovementioned subjects. It includes eleven papers (10 research papers and 1 review paper; 2 of them are Feature papers and 1 is Editor's Choice).

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The reader will find five papers related to overtopping; two of them are about understanding of dam failure and related actions, and three papers are about the protection of embankment and concrete dams. Three papers deal with geostructural safety, two of them about the use of data and physically based models, and one more related to sky jumps. Estimation of failure probability and development of fragility curves correspondent to overtopping and different geostructural risks is the subject of another three papers.

Understanding the failure process is the necessary first step for the assessment of the safety of dams against overtopping. This process strongly depends on the type of dam and its particular characteristics. Most of the research effort has been dedicated in the past to understanding of the failure of clayey homogeneous embankment dams, and several codes with empirical basis were developed to model the failure process of this type of dam.

Based on extensive experimental work, Monteiro-Alves et al. [1] analyzed the failure process of rockfill dams in the case that the rockfill of the shoulders is highly permeable. They provided a description of the failure process and a formula for the estimation of the unit overtopping discharge that causes the complete failure of the shoulder, which can be expected to be quite similar to the one that leads to the catastrophic dam failure.

In this type of rockfill dam, the failure process and the critical unit discharge of the overtopping highly depend on the permeability of the rockfill. Therefore, the correct assessment of the permeability is relevant for modeling the failure. In coarse granular materials, the relation between seepage velocity and hydraulic gradient, the resistance formula of the flow, is not linear, as is usual in fine materials, but parabolic. López et al. [2] collected a wide variety of resistance formulas available and compiled them under a unified view in such a way that every formula is a particular case of the general formulation.

Three contributions to this special issue refer to different solutions to protect dams against overtopping [3–5]. A rockfill toe can be added to the downstream shoulder of a rockfill dam to increase the resistance in the event of overflow. Several geometrical configurations are possible for that toe, from completely external to completely internal to the dam shoulder. Smith et al. [3] analyzed, by a combination of physical and numerical modeling, the effect of the rockfill toe configuration on the throughflow. It is quite relevant for the safety of the dam, considering that the failure strongly depends on the position of the water surface inside the dam. They conclude that "the internal and combined toe configurations are effective in lowering the phreatic line within the dam, for enhanced slope stability compared to the cases without a toe or an external toe" [3] (p. 18).

Different techniques are available to protect the downstream surface of an earth or rockfill dam to avoid erosion or unraveling in an overtopping scenario. Wedge-Shaped Blocks (WSBs) have a long history of development in different countries. Using a testing facility specifically designed for this purpose, Caballero et al. [4] presented a new enhanced WSB and provide a considerable quantity of data on the pressures on the faces of the blocks, also the base and the riser, the hydrodynamic forces and percolation through the block contacts. Remarkable conclusions are obtained about the hydrodynamic performance of the new WSB, like the suctions registered at the base that attract the block towards the dam body, or the position of the highest negative pressures in the upper part of the riser, where the aeration holes are located.

Concrete dams are far less vulnerable to overtopping than embankment dams. However, the overflow can cause significant and dangerous erosion in the rock mass in the area of contact with the dam. The challenge is to evacuate the flood in a safe way, and an effective solution for that is to use Highly Convergent Chutes that gather water flowing over the dam in the lateral areas, outside of the spillway. This type of solution was investigated by Moran et al. [5] by means of a singular testing facility that allows modeling spillways with Highly Converging Chutes of different slope and position. The research is focused on the behavior of the stilling basin and its ability to dissipate the water energy. Especially relevant is the conclusion that an existing hydraulic jump stilling basin may serve to accommodate a flood greater than the one considered during the design phase if a part of the extra flow is introduced through highly converging chutes. This makes this type of solution very attractive for solving the improvement of safety against overtopping of gravity dams and even arch dams.

Research work related to geostructural safety involves a wide variety of techniques and failure mechanisms. The application of machine learning and artificial intelligence to monitoring data for the assessment of geostructural dam safety is one of the most active research areas today. Different algorithms like Artificial Neural Networks, Support Vector Machines or Random Forest, among others, have successfully been applied for detecting behavior anomalies. It is well known that the most appropriate algorithm depends on the particular features of the data set. Alocén et al. [6] improved the precision and robustness of the data models by using several machine learning techniques (experts). They compared the Stacking and Blending strategies for combining algorithms and conclude that Stacking provides more accurate predictions than Blending. A complete methodology is proposed to combine experts.

Many dams are being built in locations with high seismic hazards. Although dams are structures with considerable resistance to seismic action, compared with other types of structures, such as buildings or bridges, it is necessary to confidently assess the risk of failure in such cases. Due to the difficulty in performing physical models that reproduce the effect of earthquakes, numerical models are used to evaluate dam behavior. These models are quite complex, and a considerable number of assumptions must be made. Based on extensive numerical experimentation, Wang et al. [7] analyzed the influence of some of the most significant assumptions. They conclude that the dam-foundation interaction has a significant effect in the dam response, and also that the method used to model the water-dam interaction significantly influences dam stresses, although the effect on displacements is negligible. They proposed a reservoir length three times the dam height for the numerical model.

The risk associated with rock scour downstream of ski jump spillways has drawn attention during the last years. Assessment of the impact area is required for the later evaluation of that risk. The impact area corresponding to high discharge flow rates is easy to determine because it is clear that the water jumps in the direction determined by the angle of the ski jump. Pellegrino et al. [8] presented an experimentally verified formula and a complete method to estimate the minimum discharge that causes the jump to occur. For a discharge under that minimum value, water falls at the ski jump toe, which must be protected. With the calculation of that minimum value and the maximum corresponding to the design flood, the impact area can be assessed and proceed to estimate the risk associated with the rock scour using one of the methodologies available.

Three papers are directly related to the development of fragility curves that are necessary for the risk assessment [9–11]. The fragility curves represent the probability of failure, or a certain level of damage, depending on a parameter that defines the intensity of the main action that might cause the failure. Fragility curves corresponding to the different potential failure mechanisms are needed to quantify the global risk of a dam.

Van Bergeijk et al. [9] developed fragility curves for dikes covered with grass subject to wave overtopping. The dike is considered failed when erosion reaches a depth of 20 cm, which is approximately the length of grass roots. They observed a very significant influence of grass cover, as compared with a clayey surface, and also its quality, on the probability of failure. They included the effect of transitions and damages.

Fragility curves for river levees reinforced with geogrid, related to slope stability, were developed by Rossi et al. [10]. They concluded that the global uncertainty is much more conditioned by the uncertainty of the friction angle value of the dam material than that associated with the geogrid material. However, the contribution of the geogrid layer located at the highest level is greater than that of the rest layers. Based on a probabilistic characterization of soil properties and the use of numerical modeling, the same authors [11] developed fragility curves for piping and slope stability of river levees and applied them to the river Drava levee. Probability of failure depends on the water level in the river, including overflow scenarios.

An idea is common to the three papers dealing with fragility curves: conservative assumptions were made to cover the lack of knowledge that led to a conservative estimation of failure probability. Therefore, it is expected that the increase of basic knowledge in relation to the different failure mechanisms will permit us in the future to develop more accurate fragility curves. It will have the consequence of lowering the cost of corrective measures adopted to improve the safety level when needed.

As highlighted here, research is very active to understand overtopping and develop efficient solutions for protecting dams and levees against overtopping, and also to understand and evaluate the geostructural risks associated with different failure mechanisms. This research will support informed decisions to efficiently assess and guarantee the demanded safety of our dams.

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References

1. Monteiro-Alves, R.; Toledo, M.Á.; Moran, R.; Balairón, L. Failure of the downstream shoulder of Rockfill Dams Due to Overtopping or throughflow. *Water* **2022**, *14*, 1624. [CrossRef]
2. López, J.C.; Toledo, M.Á.; Moran, R. A Unified View of Nonlinear Resistance Formulas for Seepage Flow in Coarse Granular Media. *Water* **2021**, *13*, 1967. [CrossRef]
3. Smith, N.S.; Ravindra, G.H.R.; Sigtryggsdóttir, F.G. Numerical Modeling of the Effects of Toe Configuration on Throughflow in Rockfill Dams. *Water* **2021**, *13*, 1726. [CrossRef]
4. Caballero, F.J.; Toledo, M.Á.; Moran, R.; San Mauro, J. Hydrodynamic Performance and Design Evolution of Wedge-Shaped Blocks for Dam Protection against Overtopping. *Water* **2021**, *13*, 1665. [CrossRef]
5. Moran, R.; Toledo, M.Á.; Peraita, J.; Pellegrino, R. Energy dissipation in Stilling Basins with Side Jets from highly convergent cites. *Water* **2021**, *13*, 1343. [CrossRef]
6. Alocén, P.; Fernández-Centeno, M.; Toledo, M.Á. Prediction of concrete dam deformation through the Combination of machine learning models. *Water* **2022**, *14*, 1133. [CrossRef]
7. Wang, C.; Zhang, H.; Zhang, Y.; Guo, L.; Wang, Y.; Htun, T.T.T. Influences on the Seismic Response of a Gravity Dam with Different Foundation and Reservoir Modeling Assumptions. *Water* **2021**, *13*, 3072. [CrossRef]
8. Pellegrino, R.; Toledo, M.; Aragoncillo, V. Discharge flow rate for the Initiation of Jet Flow in Sky-Jump Spillways. *Water* **2020**, *12*, 1814. [CrossRef]
9. van Bergeijk, V.M.; Verdonk, V.A.; Warmink, J.J.; Hulscher, S.J.M.H. The Probability of Cross-Dike Failure by Wave Overtopping over Grass-Covered and Damaged Dikes. *Water* **2021**, *13*, 690. [CrossRef]
10. Rossi, N.; Bai, M.; Kovačević, M.S.; Librić, L. Fragility Curves for Slope Stability of Geogrid Reinforced River Levees. *Water* **2021**, *13*, 2615. [CrossRef]
11. Rossi, N.; Bačić, M.; Kovačević, M.S.; Librić, L. Development of Fragility Curves for Piping and Slope Stability of River Levees. *Water* **2021**, *13*, 738. [CrossRef]