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Composite Modeling of the Effect of Material Composition on Spatial Dam Breaching due to Overtopping

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Abstract

The overtopping of embankment dams and levees often causes erosion of embankment material, and can result in failure of the structure by breaching. The breaching process is affected by numerous characteristics of the embankment and reservoir system, including embankment geometry, material composition, and hydraulic conditions. The effects of these parameters are generally investigated by physical model experiments. The extent to which a parameter is investigated is often limited by the amount of time required for physical model setup, experimentation, and data post-processing. This study proposes a composite modeling strategy for more efficient modeling of embankment dam breaching due to overtopping. First, an embankment dam breach is modeled with physical experiments. Second, a corresponding numerical model is set up, with the same geometry, material composition, and hydraulic inputs as the physical model. Next, important findings from the physical modeling are implemented in the numerical model. Lastly, the numerical model is validated with results from the physical modeling. The composite modeling strategy was applied to an investigation of the effect of material grain size on dam breaching. The composite modeling strategy showed the ability to represent numerous effects of material grain size, including erosion rates and timing of peak outflow, as confirmed by separate physical modeling of the same system. Preliminary results indicate that the composite modeling strategy is a viable option for modeling dam breaching to investigate effects of various parameters on the breach process, allowing for greater efficiency and larger test series than with physical modeling by itself.

Keywords: Dam breach; Homogeneous embankment; Composite modeling; Physical modeling; Numerical modeling

1. INTRODUCTION

Earthen embankments are utilized as dams and levees throughout the world. Failure of these hydraulic structures poses a threat to lives and property wherever they exist, and better understanding of their failure processes can lead to improved management of their associated risks. Failure of embankment dams by overtopping typically begins with headcutting or surface erosion forming an initial breach at a vulnerable location on the downstream face. Flow through the initial breach continues the erosion of embankment material, lowering the breach profile towards the base of the structure. Sidewalls of the breach channel, steepened by the vertical erosion, eventually collapse through mass slope failures, resulting in lateral expansion of the breach. Numerous aspects of the breaching process, such as the rate of surface erosion, failure angles, and seepage, are dependent on the composition of embankment material.

Investigating the effects of embankment material composition on the dam breach process has been extensively performed through physical model experiments, such as the studies of Pickert et al. (2011), Schmocker and Hager (2012), Al-Riffai (2014), Schmocker et al. (2014), Wallner (2014), Frank (2016), and Dhiman and Patra (2020). However, physical model experiments are often time consuming, labor intensive, and space limited. Other options for dam breach investigations are available, depending on the desired accuracy, detail, and effort. Dimensionless equations developed from experimental data can be used to predict important parameters, such as the magnitude and timing of peak breach flow, volume of erosion, and embankment shape (Frank, 2016; Asghari Tabrizi et al., 2017; Boes et al., 2017; Dhiman & Patra, 2020). Parameter models, such as those of Macchione (2008), Wu (2013), and Peter et al. (2018), provide a computationally efficient means of numerical modeling when additional detail, such as a complete breach outflow hydrograph, is required. For greater accuracy, several detailed physically-based numerical codes have been developed that are designed for embankment dam breach modeling, including those of Wu et al. (2012), Volz et al. (2012; 2017), Begam et al. (2018), and Kang et al. (2020). These numerical models were generally validated by modeling a dam breach that was also represented by a physical model experiment, and producing comparable results.

This study used a composite modeling strategy to model embankment dam breaching due to overtopping. Laboratory physical model experiments were performed with a homogeneous dam made of uniform coarse sand. Detailed physically-based numerical modeling was performed by applying the hydrodynamic and morphodynamic modeling software BASEMENT (Vetsch et al., 2020), which incorporates the numerical approaches of Volz et al. (2017). The numerical model represents the same geometry, hydraulic conditions, and embankment material as the physical model, and some findings from the physical modeling were used as inputs in the numerical model. The numerical model results were validated based on the physical modeling. The numerical model was then tested for its ability to investigate the influence of material grain size on the breach process. Results were compared to physical modeling of the same material grain size investigation, and the viability of the composite modeling strategy for investigating the dam breach process was assessed.

2. EXPERIMENTAL SETUP

2.1 Laboratory Experiment Setup

Five physical model experiments of embankment dam breaching were performed in a 1 meter (m) wide and 11.9 m long recirculating hydraulic flume in the Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich. Model dams were built on a 0.55 m deep elevated test section. All five model dams had the same size and shape: dam height w = 0.3 m, width b = 1.0 m, crest length L_K = 0.1 m, total streamwise length L_D = 1.3 m, and upstream S_u and downstream S_d face slopes of 2:1 (horizontal:vertical). All model dams consisted of a uniform coarse sand with a mean diameter d_m = 1.75 millimeters (mm), and a geometric standard deviation of grain size distribution $\sigma_g = (d_{84}/d_{16})^{0.5} = 1.2$, where d_x is the grain size diameter for which x% of material is finer. A half-model setup was used, in which the breach centerline was directed along the transparent left sidewall of the flume by a 0.1 m deep (w_p) and 0.2 m wide (b_p) triangular pilot breach, cut into the left side of the dam crest. This allowed for observation and recording of the breach centerline while representing only half of the dam in the experiment (Frank, 2016). A 0.21 m long and 1.0 m wide floor drain, located beneath the downstream face of the model dams, captured seepage flow and routed it to a collection tank. A sediment collection basket was located directly downstream of the test section. All experiments were run for at least 200 seconds (s). Experimental setup and procedures followed those of Frank (2016). A schematic representation of the model dam setup and parameter definitions is shown in Figure 1.

Inflow entered the flume upstream of the model dams, via a pump. Inflow was set at Q_o = 10 l/s for all experiments, and was measured by an inductive discharge measurement (MID) device. Water levels were measured by ultrasonic distance sensors (UDS) upstream of the model dam (h_o) and in the seepage collection tank (h_s), which allowed for calculation of changes to reservoir storage and the seepage flow rate. Breach discharge (Q_b) could be calculated based on these measurements, using a volumetric continuity approach also used by Coleman et al. (2002), Cestero et al. (2015), Frank and Hager (2015), and Frank (2016). Measurements of the seepage flow rate were unavailable for two runs of the physical model experiment, therefore the seepage flow hydrographs in those experiments were set as the average of the seepage flow hydrographs of the other three experiments.

The embankment surface was recorded throughout the experiments by a photogrammetric measurement system, described by Frank and Hager (2015). The photogrammetric system outputs the topography of the embankment surface, allowing for continuous estimation of the remaining embankment volume. The volume of eroded embankment material (V_e) was then calculated, by subtraction of the remaining embankment volume from the initial embankment volume. This photogrammetric volume-based method for calculating embankment material erosion was also applied by Frank (2016).

A system for continuous measurement of the embankment material erosion was utilized for one run of the physical model experiment. The sediment collection basket, located less than 0.2 m from the downstream toe of the dam, was suspended from a steel support structure by three metal chains. Each chain was connected to a force transducer, which allowed for weight measurement. The weight of material eroded from the dam was therefore continuously measured upon collection in the sediment basket. The water level at the sediment collection basket (h_{sed}) was measured by a UDS. The volume of eroded material was then calculated from this continuous mass measurement method, based on the material density and porosity. A similar method for quantifying embankment material erosion by a continuous mass measurement approach was applied by Pickert et al. (2011).

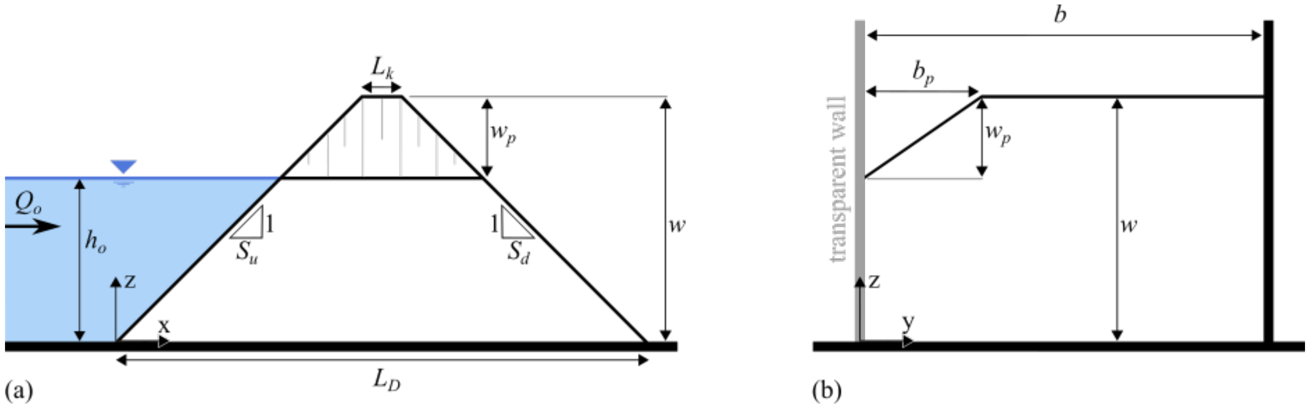

Figure 1. Schematic representation of model dam setup and parameter definitions with (a) longitudinal and (b) transverse sections of the model embankment dam.

2.2 Numerical Model Setup

Numerical modeling was performed by applying the hydrodynamic and morphodynamic software BASEMENT version 2.8.1 (Vetsch et al., 2020). The numerical model domain consisted of two sub-domains: a two-dimensional (2D) surface flow region and a three-dimensional (3D) subsurface flow region (Volz et al., 2017). The surface flow sub-domain represents the flume geometry and the continuously evolving dam surface. The finite volume method is used to solve the shallow water equations for hydraulic calculations. Morphodynamic processes are modeled with the Exner equation in combination with empirical sediment transport relations and a geometrical sidewall failure approach. The subsurface flow sub-domain represents the interior of the model dam. For modeling of seepage flow, the Richards equations are solved using the Lattice-Boltzmann method. The two sub-domains are coupled based on water depths and pore pressures. The numerical modeling was designed to replicate the physical model setup, with the same geometry, material composition, and hydraulic conditions. Determination of the inflow boundary condition is described in section 3.2.

The embankment material composition was represented with five grain sizes, each representing a portion of the grain size distribution. Bed load transport was applied based on the empirical relation of Meyer-Peter and Müller (1948), extended for multiple grain sizes (Ashida & Michiue, 1971) and incorporating the correction of Wong and Parker (2006). Hydraulic roughness was incorporated with a Strickler parameter, selected based on the grain size of embankment material. Similar strategies were employed by Volz et al. (2012; 2017).

3. RESULTS AND DISCUSSION

3.1 Physical Model Reliability and Repeatability

The physical model experiment performed in this study was designed to replicate an experiment that was performed previously at the VAW laboratory (Frank, 2016). That previous experiment, performed in the same hydraulic flume as the experiments of the present study, was part of a series of spatial dike breach experiments for investigating experimental repeatability and reliability, as well as the effects of various geometric, material, and hydraulic parameters. That experimental procedure was demonstrated to be repeatable and reliable, and were thus followed here. The physical model experiment performed in this study used the same dam size, shape, position, material composition, inflow, and seepage control as the experiment of Frank (2016).

The physical model experiment was performed five times in the present study, to ensure repeatable application of model setup, measurement techniques, and seepage control. Repeatability was assessed by comparison of hydraulic results of the five runs of the experiment, as well as by comparison of embankment surface profiles. The comparisons showed acceptable similarity of results between the five runs of the experiment, thus demonstrating repeatability of the experimental procedure.

Reliability of the physical modeling was assessed by comparison with the experiment of Frank (2016), to confirm that experimental results were unaffected by the model operator or by minor modifications made to the flume. Hydraulic and morphodynamic results were compared using one run of the experiment to represent the present study. Those results are compared in Figure 2 with temporal output of (a) upstream water level, (b) breach discharge, and (c) eroded material volume. Profiles of the embankment surface are compared in Figure 3 at times t = 0, 20, 60, and 200 s at (a) a cross section through the center of the dam crest and (b) a longitudinal profile through the breach centerline. Embankment surface profiles are compared using compilations and averaging from multiple runs of the physical model experiment to represent the present study. This was necessary due to gaps in the embankment surface outputs, which left no single experiment run with enough data to cover the entirety of the comparison profiles. The temporal results and dam surface profiles of the present study were similar to those of the experiment by Frank (2016), thus demonstrating reliable application of the experimental procedure.

In one run of the physical model experiment, material erosion was measured continuously using the mass measurement approach, as described in section 2.1. Figure 2(c) includes the results of this measurement, showing a similar erosion rate to that calculated from the photogrammetric volume-based method. This similarity demonstrates the reliability of measuring embankment material erosion by either method.

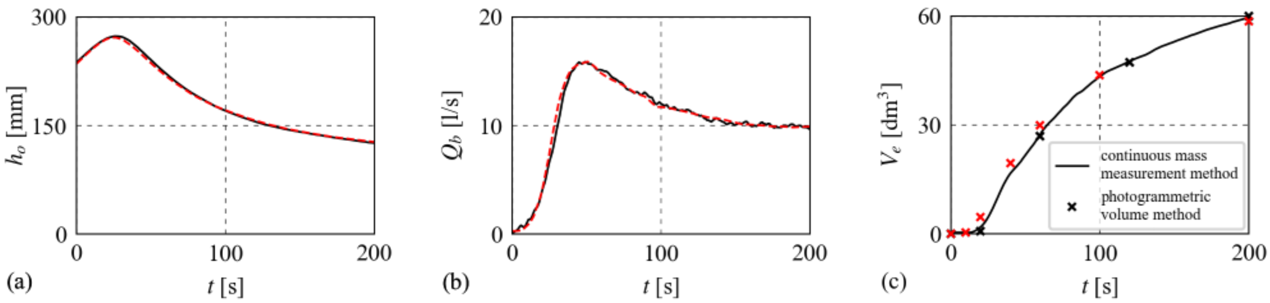

Figure 2. Temporal output of (a) headwater level h_o, (b) breach discharge Q_b, and (c) volume of eroded dam material V_e, from physical modeling of (—,×) the present study and (– –,×) Frank (2016).

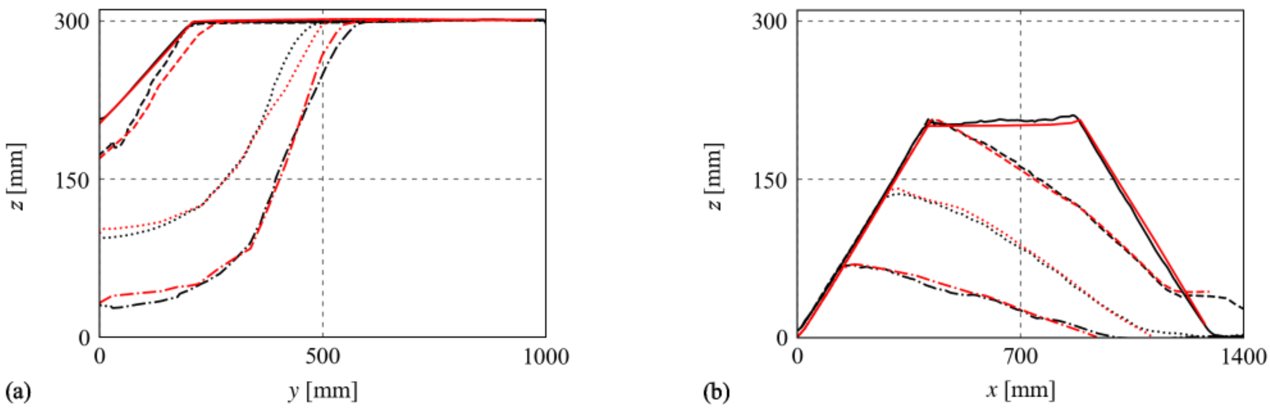

Figure 3. Dam surface profiles at (a) a cross section through the dam center and (b) a longitudinal profile at the breach centerline at t [s] = 0 (—), 20 (– –), 60 (···), and 200 (–·–), from physical modeling of (—) the present study and (—) Frank (2016).

3.2 Inputs to Numerical Model from Physical Modeling

Inflow to the numerical model domain was set with a source boundary condition, using an inflow hydrograph. The numerical model's inflow hydrograph was designed to make the same amount of flow available to the overtopping breach as was available in the physical modeling. This required some adjustment from a simple constant inflow. Inflow for the physical modeling was set to Q_o = 10 l/s, but the inflow measured by the MID ranged between 9.5 and 10.2 l/s. The measured pump inflow, averaged between multiple physical model experiments, was applied to the numerical model inflow hydrograph. In the physical modeling, water seeps into the model dam and is collected by the drainage system. In the numerical model, hydrostatic pressure on the dam face leads to infiltration, represented by increased saturation. But this infiltration does not transfer water volume from the surface flow region to the subsurface flow region. Therefore, water in the reservoir is not lost to seepage in the numerical modeling. To account for seepage flow, a hydrograph of flow lost to seepage, averaged between multiple physical model experiments, was subtracted from the inflow hydrograph.

Sidewall slope failures are numerically modeled with a geometrical approach (Volz et al., 2012; 2017). When sidewall slope becomes steeper than a user-defined critical angle, slope failure occurs. The critical angle is dependent on material type and level of saturation. Fully saturated and completely dry material both have failure angles in the range of the angle of repose. Partially saturated material can experience apparent cohesion, which increases soil shear strength and thus increases the failure angle. Deposited material (material that has been eroded and then deposited in a new location) has a failure angle in the range of half of the angle of repose, but is also dependent on saturation (Volz et al., 2017). Predicting the effect of apparent cohesion is complex, but thanks to the physical modeling, some important parameters could be measured. The steepest angle measured during the physical model experiments was 70°. The steepest angle of fully saturated material was measured at 30°. These angles were applied to the numerical model as critical failure angles, with γ_{max} = 70° applied as the maximum failure angle, and γ_{rep} = 30° applied as the angle of repose.

3.3 Comparison of Numerical and Physical Model Results

The ability of the numerical model to accurately represent the physical model is evaluated through comparison of hydraulic and morphodynamic results, shown in Figure 4. Comparisons of embankment surface profiles are shown in Figure 5. During the first phase of the breach process (t < 20 s), surface erosion lowers the downstream face and shortens the pilot channel length. This process was well matched by the numerical model, as shown by the t = 20 s centerline profile and the similar rates of eroded material volume.

In the second phase of breaching (20 s < t < 60 s), after surface erosion has propagated through the upstream end of the pilot channel, lowering of the upstream face occurs, and rapid horizontal expansion by sidewall failures of the breach begins. The numerical model successfully represented the occurrence of both of those processes, albeit at slower rates. The more rapid upstream face lowering and initial horizontal expansion in the physical modeling is shown by its higher volume of eroded material during this phase, as well as in the t = 60 s centerline profile and cross section. The breach cross section grew less rapidly in the numerical modeling during this phase, resulting in the slower increase in breach discharge, and thus an extended upstream water level rise. The peak water level was reached 10 s later in the numerical modeling, and it peaked approximately 3% (9 mm) higher. The peak breach discharge was reached 19 s later, and the peak flow was within 0.5% (0.1 l/s) of the physical modeling. The rate of breach expansion was difficult to match during this phase, possibly due to the application of the empirical bed load transport model that was designed for uniform flow and equilibrium sedimentation conditions, conditions that do not prevail in dam breach processes. Nevertheless, the numerical model was successful at reproducing the important parameter of peak breach flow rate.

After the upstream water levels and breach discharges began coming down from their peaks (t > 60 s), breach growth slowed in both models. Lowering of the breach centerline appears slightly faster in the numerical modeling, possibly due to the still higher upstream water level and higher breach discharge causing a greater shear stress as breach flow passed over the dam surface. Despite this difference, the erosion rate of dam material is matched well in this phase. Additionally, the falling limbs of the upstream water level and breach discharge hydrographs have similar shapes and approach similar steady values.

The numerical model demonstrated a reasonable ability to reproduce the dam breaching observed in the physical model experiments. The dominant morphodynamic processes of centerline profile lowering by surface erosion and lateral expansion by sidewall failures were represented by the numerical model, albeit sometimes at different rates than in the physical modeling. Importantly, the numerical model was successful at reproducing the peak breach flow rate and the erosion rate of embankment material. Based on these results, the numerical model is considered validated.

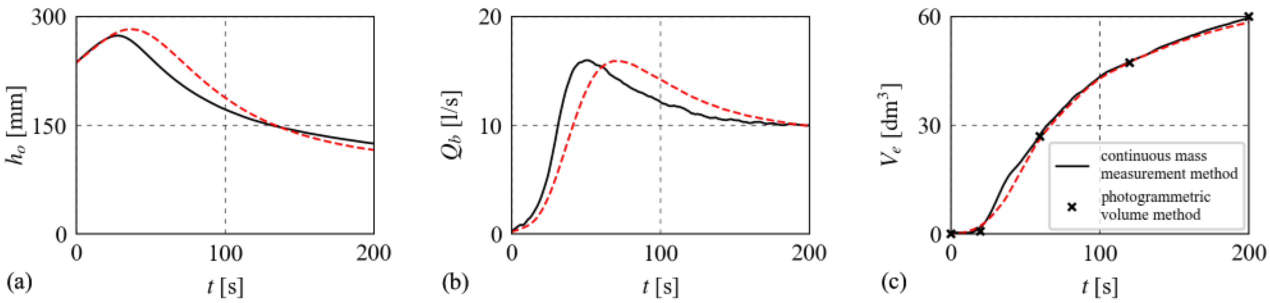

Figure 4. Temporal output of (a) headwater level h_o, (b) breach discharge Q_b, and (c) volume of eroded dam material V_e, from (—,×) physical modeling and (– –) numerical modeling.

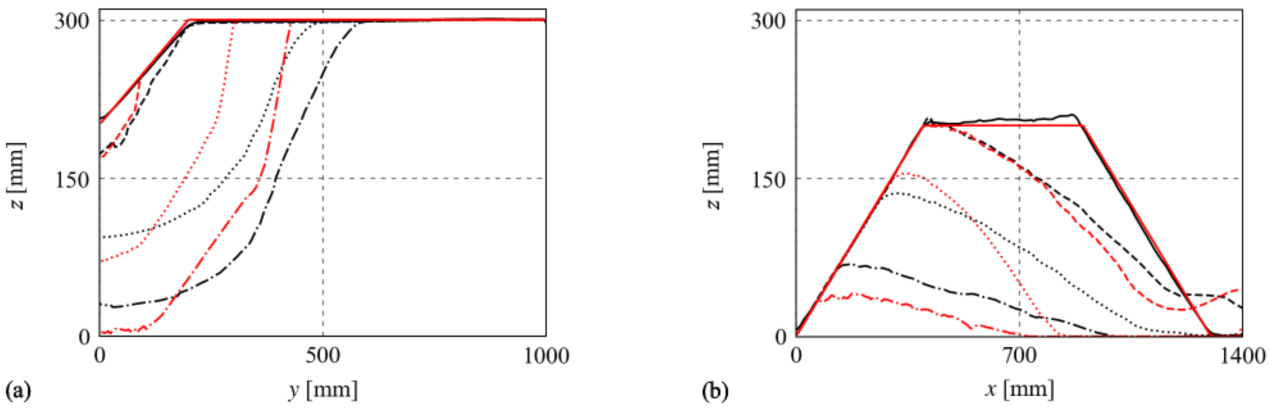

Figure 5. Dam surface profiles at (a) a cross section through the dam center and (b) a longitudinal profile at the breach centerline at time t [s] = 0 (—), 20 (– –), 60 (···), and 200 (−·−), from (—) physical modeling and (—) numerical modeling.

3.4 Composite Modeling Strategy

The physical experiments and numerical modeling described in the preceding sections form a composite modeling strategy for modeling of embankment dam breaching. The strategy is summarized with the following steps:

i. Setup of a laboratory physical model experiment for breaching of a homogeneous embankment by overtopping.
ii. Perform physical model experiments to confirm experimental repeatability and reliability.
iii. Setup of a numerical model that matches geometry, hydraulic conditions, and material composition of the physical model experiment.
iv. Incorporate select parameters from physical modeling results as inputs to the numerical model.
v. Validate reliability of the numerical model by comparing numerical results with results of the physical model experiments.
vi. Perform extended experimental investigations by using the validated numerical model to expand on the setup and parameter ranges of the physical model experiments.

4. APPLICATION OF COMPOSITE MODELING STRATEGY: EFFECT OF MATERIAL PROPERTIES

The composite modeling strategy was evaluated for potential application to investigating the effects of embankment material parameters on dam breaching. The numerical model developed herein with the composite modeling strategy was based on a dam made of uniform (σ_g = 1.2) coarse sand with mean grain size d_m = 1.75 mm. The numerical model was then used to model breaching of dams made of uniform material with mean grain sizes d_m = 0.86 and 3.78 mm. This numerical modeling is referred to in this section as “composite modeling.”

Results of the composite modeling were compared to physical model experiments of dam breaching with these same parameters, performed previously at the VAW laboratory by Frank (2016). Figure 6 shows comparisons of hydraulic results from the composite modeling and corresponding physical model experiments. Comparisons of breach development are shown with profiles of the embankment surface in Figure 7.

The effects of mean grain size on the breaching process are partially represented by the composite modeling. During the early and middle stages of the experiments (t < 60 s), initial surface erosion and horizontal expansion appear faster with increasing mean grain size. This is clear from both the composite modeling and physical modeling in the comparisons of material erosion, as well in the cross sections and centerline profiles for t = 20 s and t = 60 s. The initial faster erosion with increasing mean grain size leads to faster rises in breach flow, and thus earlier peaking of breach flow and upstream water level. This is also observed in both the composite modeling and physical modeling, along with a decrease in peak upstream water level with increasing mean grain size. The decreasing peak breach flow with increasing mean grain size that is observed in the physical modeling is, however, not represented in the composite modeling.

Later in the experiments (t > 60 s), the rate of erosion appears faster with decreasing grain size. The relative rates of erosion, a reversal from earlier in the experiments, can be seen in both the composite modeling and physical experiments, in the comparisons of material erosion and the cross sections and centerline profiles for t = 60 s and t = 200 s. However, there are some differences in the magnitudes of both vertical and horizontal breach expansion, with expansion generally underpredicted by the composite modeling, particularly at t = 60 s. At t = 200 s, the composite modeling shows that lateral breach expansion is equivalent between the three experiments. The physical modeling similarly shows nearly equivalent lateral expansion up to an elevation of approximately 100 mm, but above that elevation the side slopes differ, with sidewalls appearing stable at steeper angles with decreasing mean grain size. Vertical breach expansion appears overpredicted by the composite modeling, particularly at t = 200 s. However, the overall rates of erosion appear similar, and the profile slopes at t = 200 s are nearly identical for all experiments, at approximately 0.08 m/m.

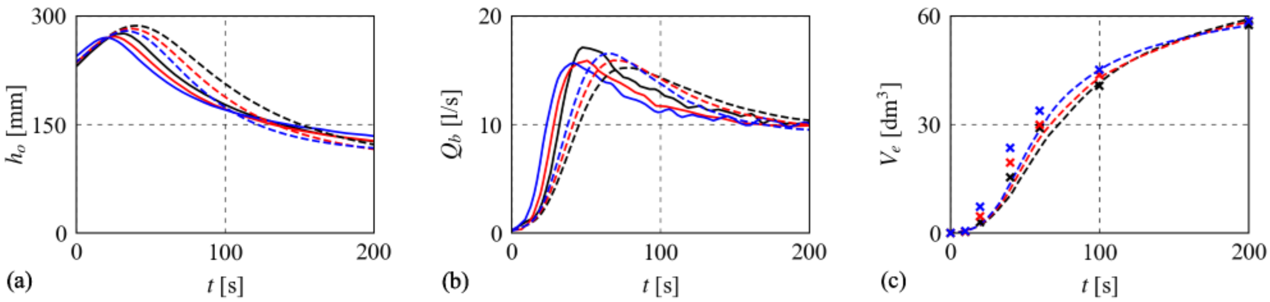

Figure 6. Temporal output of (a) headwater level h_o, (b) breach discharge Q_b, and (c) volume of eroded dam material V_e, from (—,×) physical modeling and (– –) composite modeling with mean grain size d_m [mm] = 0.86 (—), 1.75 (—), and 3.78 (—) mm.

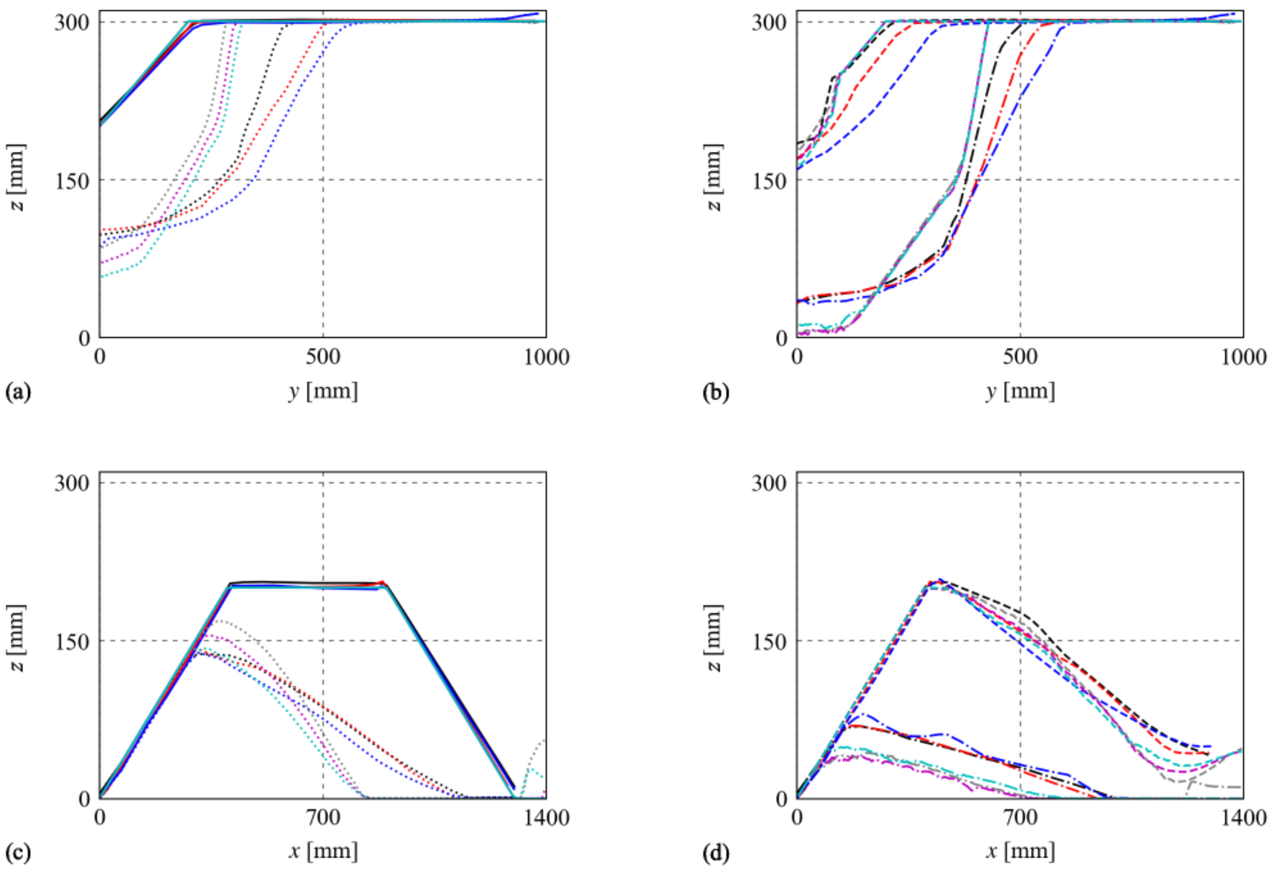

Figure 7. Dam surface profiles at (a, b) a cross section through the dam center and (c, d) a longitudinal profile at the breach centerline at t [s] = 0 (—), 20 (– –), 60 (···), and 200 (–·–), from physical modeling and composite modeling with mean grain size d_m [mm] = 0.86 (—,—), 1.75 (—,—), and 3.78 (—,—).

5. CONCLUSIONS AND OUTLOOK

A composite approach to modeling of embankment breaching due to overtopping was utilized by performing both physical and numerical modeling. The composite modeling approach was applied to an investigation of the effects of material grain size on the breaching process. Comparison of the results of the composite approach with physical modeling of the same investigation showed that some effects of material grain size can be represented by the composite approach, including effects on the rate of erosion, peak upstream water level, and timing of peak breach flow. Future work will be undertaken to improve the ability of the numerical model to imitate the physical model. Various bed load relations and critical shear stress applications will be considered to improve surface erosion rates, with the consideration that most sediment transport relations have been developed under uniform flow and equilibrium sedimentation conditions, conditions that are generally violated in dam breach processes.

The results of this research suggest that a composite approach can be a viable option for experimental investigations of the effects of embankment material properties on the breaching of homogeneous embankment dams. This will be evaluated in future research by comparing parameter investigations by composite modeling to the same investigations by physical modeling, as was done in this study for mean grain size d_m. Further, the composite modeling approach will be applied to investigating the effects of other types of characteristics on the dam breach process, such as geometric parameters, hydraulic parameters, and zonation.

6. ACKNOWLEDGEMENTS

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