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Composite Modeling to Detect Scale Effects in Embankment Dam Breaching due to Overtopping

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Abstract: *The failure of a dam can have catastrophic consequences for populations and infrastructure downstream. The processes of dam failure are typically studied with small to medium scale laboratory physical model investigations. Findings from laboratory scale studies should inform decision making for prototype scale dams, but upscaling introduces uncertainties and complexity. Detailed numerical models can simulate complex breach processes and depict larger dams, allowing for investigations at larger scale. But with increasing detail and numerical refinement comes increasing computational cost, making modeling of prototype systems potentially prohibitive. Parametric numerical models allow for efficient simulation at prototype scale, but with simplified geometries and limited erosion processes. These numerical options could connect findings from smaller scale studies to prototype scale, if the effect of scale in each method is accounted for. In this study, the effect of scale is investigated with medium laboratory scale (dam height = 0.5 m) and large laboratory scale (dam height = 1.0 m) breach modeling. Laboratory experiments, detailed numerical modeling, and parametric numerical modeling (with the* Macchione *and* Peter *methods) are performed at both scales. During initial breach formation (while reservoir head was constant), the laboratory experiments showed no effect of scale. Later, as the reservoir head fell, a faster increase in breach discharge occurred at large scale, leading to an earlier peak discharge. Detailed numerical modeling showed the effect of scale on breach growth, but with limited reproduction of the effect on breach discharge. Both parametric methods replicated the discharge hydrographs well, but only the* Peter *model adequately reproduced the effect of scale on timing of peak discharge.*

Keywords: *Dam breach, composite modeling, overtopping, laboratory experiments, numerical modeling, parametric numerical modeling.*

1. Introduction

Dams and dikes face the threat of overtopping due to a variety of natural hazards, including river floods, storm surge, and impulse waves. Risk from these hazards is increasing in many parts of the world due to climate change and aging infrastructure. Overtopping of a homogeneous earthen embankment dam can result in the formation of a progressive dam breach. This can lead to the uncontrolled release of impounded water, threatening downstream settlements and environment. The breaching of a homogeneous earthen embankment dam is a complex hydrodynamic and morphodynamic process that has been the focus of much research over the past several decades, as summarized by ASCE/EWRI (2011) and Amaral et al. (2020). Despite extensive study of the topic, predicting the rate at which a specific prototype dam will fail remains a major challenge, making risk assessments and emergency planning difficult and uncertain.

Dam breaching is typically studied with laboratory scale physical model experiments, as summarized by Frank (2016) and Amaral et al. (2020). Laboratory experiments typically use dam heights up to 1 meter (m). Larger experiments have generally been performed as field experiments (with field scale dam heights of approximately 1 to 6 m), such as the European IMPACT project (Vaskinn et al., 2004; Morris et al., 2007; Zech & Soares-Frazão, 2007) and the experiments of Visser (2000), Kakinuma and Shimizu (2014), and Peeters et al. (2014). Breach experiments with prototype scale dams (dam heights typically greater than 5 m) are generally unfeasible.

Dam breaching has also been studied with detailed numerical modeling. Several codes for detailed numerical modeling of homogeneous earthen embankment dam breaching have been developed in recent years. Detailed numerical modeling can be used to model a prototype scale dam breach, such as in the case of Begam et al. (2018). However, the computational demand of modeling at prototype scale is generally prohibitive, and most detailed numerical modeling has been carried out for laboratory scale (Volz et al., 2012; 2017) or field scale dams (Kang et al., 2020). Like most physical experiments, detailed numerical modeling of dam breaching has typically modeled a generic embankment dam and reservoir setup, rather than a scaled version of a specific prototype dam.

A specific prototype dam can be more efficiently modeled with parametric numerical modeling. A parametric numerical model depicts an embankment dam breach with a simplified representation, generally using a single cross section of the dam across the breach (Macchione, 2008; Peter, 2017). Setup and computation of parametric numerical models is far simpler than for detailed numerical models, requiring minutes rather than hours or days. A parametric numerical model can be utilized by practitioners, including dam and flood protection engineers, to estimate the breach outflow hydrograph of a specific prototype dam, without needing advanced knowledge of the dam breach process or numerical methods.

Improved knowledge of dam breaching is typically achieved through physical model experiments and detailed numerical modeling at laboratory or field scale. Findings from these dam breach studies must be applied to larger scale, but there are major challenges and limitations in scaling up results to prototype scale, as scale factors can be easily over 100 if comparing a small scale laboratory experiment to a prototype scale dam. Parametric numerical modeling can be performed at prototype scale, but the complex processes of dam breaching are not depicted in parametric numerical modeling. To avoid major uncertainties, parametric numerical modeling should not be used by itself to study the dam breach process.

Better understanding of dam breaching at prototype scale can be achieved through composite modeling, in which processes are studied at laboratory or field scale through physical experiments or detailed numerical modeling. Findings can be applied to prototype scale through a parametric model, in which the effect of studied processes on relevant results can be calibrated in the parametric model at model scale and then upscaled to prototype scale. To reliably relate results to prototype scale, the effect of scale in each modeling method should be assessed.

In this study, the effect of scale was studied in the three methods of dam breach investigation: physical model experiments, detailed numerical modeling, and parametric numerical modeling. First, the laboratory physical model experiments were performed. Then the detailed numerical modeling was performed using the software BASEMENT (Vetsch et al., 2020), which incorporates the code of Volz et al. (2012; 2017). Finally, parametric numerical modeling was performed, using the models of Macchione (2008) and Peter (2017).

2. Methods

2.1. Dimensions and Scaling

Laboratory experiments and numerical modeling of dam breaching were carried out for embankment dams with two different heights: 0.5 m and 1.0 m. These dam heights lie in the range of laboratory scale dams (0.1-1.0 m), with the 0.5 m dam considered to be *medium laboratory scale* and the 1.0 m dam considered to be *large laboratory scale*. All dams were trapezoidal in profile, with upstream and downstream face slopes of 2:1 (horizontal:vertical). Along the centerline of each dam, a triangular pilot channel was cut through the crest in the streamwise direction. Scaling was performed using Froude similarity, in which the Froude number should be the same at all scales. In Froude similarity, linear dimensions are scaled according to the length scale factor λ. Dimensions of each scale dam are listed in Table 1.

Table 1. Dimensions of dams.

	Medium scale	Large scale
Scale factor λ	0.5	1.0
Dam height	0.5 m	1.0 m
Dam streamwise base length (toe to toe)	2.15 m	4.3 m
Dam transverse length (along crest)	2.0 m	3.0 m
Crest width	0.15 m	0.3 m
Pilot channel invert elevation	0.45 m	0.9 m
Pilot channel top width	0.2 m	0.4 m
Pilot channel invert length	0.35 m	0.7 m
Initial water level	0.475 m	0.95 m
Mean grain size	1.75 mm	3.1 mm

Morphodynamic processes, including sediment transport, sediment entrainment, and sediment deposition, are controlled by drag and turbulence. These processes are related to the grain Reynolds number. The grain Reynolds number may not be scaled correctly through Froude similarity, and therefore morphodynamic processes may not be the same at different scales. To compensate for this, an adjustment to the scaling of sediment grain size (which would otherwise be scaled by λ) can be applied (Amaral et al., 2020). The method of Pugh (1985) was applied in this work. This method, which adjusts sediment grain size based on settling velocity to ensure similarity of the sediment deposition process, was applied to the entire grain size distribution (GSD), as in the work of Halso et al. (2023). The medium scale dam was made of a mixture of sand and gravel with a mean grain size d_m = 1.75 mm and a GSD standard deviation $\sigma_g = (d_{84}/d_{16})^{0.5} = 3.0$, where d_x is the grain size for which x % of sediment is finer. Scaling the medium scale GSD by λ would have produced a large scale GSD with d_m = 3.5 mm and σ_g = 3.0, but the adjustment based on settling velocity resulted in a large scale GSD with d_m = 3.1 mm and σ_g = 3.5.

2.2. Laboratory Physical Model Experiments

2.2.1. Large Scale Experimental Setup

The large scale laboratory physical model experiment (EL) was carried out in a 30 m long, 1.18 m deep, and 1.5 m wide hydraulic flume (Flume 1). The experimental dam was constructed on a 6.3 m long and 1.05 m deep raised test section in the middle portion of the flume. Beneath the test section was a seepage-collection system, which routed water to a separate outflow channel. Along the left side of the flume was a transparent glass wall (Fig. 1).

Flume 1 was filled from a supply tank with a head of 8 m. Water was routed to the flume inlet basin, which formed the upstream portion of the model reservoir. The inflow was regulated by a valve and measured by an inductive discharge measurement device (IDM), the reservoir water level was measured by a ultrasonic distance sensor (UDS), and the water level in the seepage outflow channel was measured at two locations with UDSs. Measurement of sediment erosion was not possible in Flume 1. The seepage flow rate was calculated with the measurements in the seepage outflow channel, using the Manning equation. Discharge through the breach was then calculated from the measurements and the calculated seepage flow rate, using a volumetric continuity approach. The valve was manually-controlled during experimentation, with adjustments made based on instantaneous water level and inflow measurements. The large scale physical model experiment was performed first, and the reservoir water level was recorded for use in the medium scale experiment.

2.2.2. Medium Scale Experimental Setup

The medium scale laboratory physical model experiment (EM) was carried out in a 11.3 m long, 1 m deep, and 1 m wide recirculating hydraulic flume (Flume 2). The experimental dam was constructed on a 5.15 m long and 0.53 m deep raised test section in the upstream portion of the flume. Downstream of the test section was a sediment-collection basket, for measuring the rate of sediment erosion from the dam. Beneath the test section was a seepage-collection system, for controlling the seepage line. Along the left side of the flume was a transparent glass wall, through which the experiment was recorded to measure the evolution of the dam profile along the breach centerline (Fig. 1).

Figure 1. Medium (left) and large scale (right) laboratory experiments (after breaching). Blue arrows show flow direction.

Flume 2 was equipped with a pump with a discharge capacity of 120 l/s. The flume pump brought water from the outlet basin, located on the downstream side of the flume, to the inlet basin, located on the upstream side of the flume. The inlet basin formed the upstream portion of the model reservoir. The water levels in the reservoir and in the seepage collection tank were measured with UDSs, and the pump discharge was measured by an IDM.

Discharge through the breach was calculated from these measurements using a volumetric continuity approach. The experimental setup of Halso et al. (2022) was used, with some alterations. One such change was the use of a proportional-integral-derivative (PID) control system, which utilized the measurements of reservoir water level and pump discharge to adjust the pump frequency, in order to more closely match the actual reservoir water level to the desired water level (Frank et al., 2020). The desired water level for experiment EM was determined by scaling the measured reservoir water level hydrograph from experiment EL. This scaled hydrograph was used as the upstream boundary condition for EM.

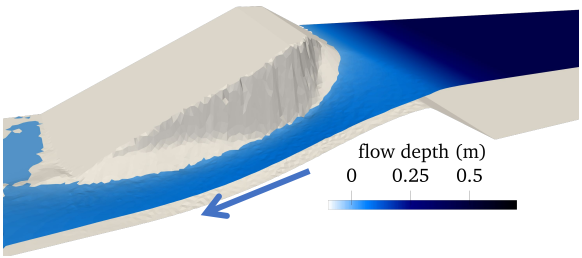
2.2.3. Dam Construction

Model dams were built using mixtures of sand and gravel (Fig. 1). Prior to construction, the sediment was mixed to ensure a consistent mixture, and the GSDs were controlled by sieve analysis. For construction, sediment was placed in 10 cm thick layers that were evenly compacted with a metal tamper. Construction of the desired final embankment shape was guided by a trapezoidal wooden template. Dams were constructed as "half-models," meaning that the dam on only one side of the breach centerline was modeled. This was accomplished by positioning the pilot channel invert along the transparent glass sidewall of each flume. The sidewall was thus the centerline of the breach channel. Breach formation was then assumed to be symmetrical across the breach channel centerline. According to Frank (2016), this assumption of symmetrical dam breaching is valid in laboratory experiments of homogeneous embankment dams, and the glass wall has negligible effect on breach formation.

2.3. Detailed Numerical Modeling

Detailed numerical modeling was performed with the hydro- and morphodynamic modeling software BASEMENT Version 2.8.2 (Vetsch et al., 2020). The numerical models simulated surface-flow hydrodynamics and morphodynamics on a two-dimensional (2D) unstructured mesh of triangular elements. Hydrodynamics were calculated with the 2D shallow water equations using a finite volume approach combined with a Riemann solver. Morphodynamics were calculated using the Hirano-Exner model with the mixed-size sediment transport relation of Hunziker (1995) and a slope-collapse approach implemented by Volz et al. (2012). The bed topography due to morphological changes was updated with the Exner-equation. Seepage flow through the dam body was simulated on a three-dimensional (3D) structured grid of cubic cells using the 3D Richard's equation (Volz et al., 2017).

Numerical models were made to represent the laboratory flumes. The numerical model of the large scale dam (NL) represents Flume 1, and the numerical model of the medium scale dam (NM) represents Flume 2 (Fig. 2). The model domain upstream of the dam, representing the inlet basin and model reservoir, had a fixed bed. Reservoir inflow was applied with a source term distributed throughout this fixed-bed region. The region representing the dam and further downstream had an erodible bed. At the downstream end of the model domain, water and sediment exited the model through a downstream boundary condition. At the interface of the surface flow and seepage flow regions, the domains were coupled based on hydrostatic pressure and pore pressures. Like the laboratory physical model experiments, the numerical models were "half models," representing the dam on just one side of the beach centerline, with a symmetrical breach development assumed across the breach centerline.



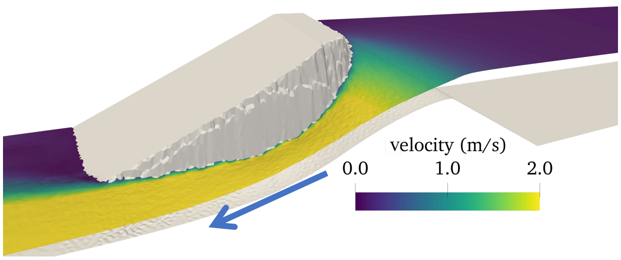


Figure 2. Medium scale (left) and large scale (right) detailed numerical models. Blue arrows show flow direction.

2.4. Parametric Numerical Modeling

Parametric numerical modeling was performed with the software BASEbreach (Vetsch et al., 2023). BASEbreach is a software tool that provides multiple dam breach models for estimating the outflow of a progressive overtopping dam breach. In this work, the *Macchione* (Macchione, 2008) and *Peter* (Peter, 2017; Peter et al., 2018) dam breach models were utilized. Both of these models use a system of two ordinary differential equations (ODEs) – one for continuity of water and one for continuity of sediment – to calculate the progressive erosion of a dam and the emptying of the impoundment. The system of ODEs was solved in the model using the 4$^{\text{th}}$ order Runge-Kutta method. Unlike the laboratory experiments and the detailed numerical modeling (which are "half models"), the parametric numerical models are "full models," representing the dam on both sides of the breach centerline. Breach development is symmetrical across the breach centerline, allowing for straightforward comparison to the laboratory experiments and detailed numerical modeling. The medium and large scale dams were each modeled with both the *Macchione* model (PM-M and PL-M) and the *Peter* model (PM-P and PL-P).

2.4.1. *Macchione* Model

The *Macchione* model (Macchione, 2008) represents the breach channel with a triangular shape (Fig. 3), until the breach reaches a non-erodible elevation, at which point it stops becoming deeper and transitions to a trapezoidal shape. The *Macchione* model uses the bedload transport relation of Meyer-Peter and Müller (1948) for modeling the erosion of embankment sediment. The rate of breach deepening is represented by the erosion velocity dY/dt, which is related to embankment sediment through the characteristic velocity v_e. The characteristic velocity is a calibration parameter that is based on a roughness coefficient k_s and a coefficient related to material properties and breaching conditions k_0:

$$\frac{dY}{dt} \propto v_e \propto \frac{k_0}{{k_s}^3} \tag{1}$$

In this modeling, v_e was defined based on a relationship from Knüsel (2023). In that work, a calibration of the Macchione model was performed for small scale (dam height = 0.3 m) laboratory overtopping dam breach experiments, and a relationship was derived between k_0/k_s^3 and the sediment grain size distribution:

$$\frac{k_0}{{k_s}^3} = 3.28 \cdot 10^{-7} \frac{d_{90}}{\sigma_g} \tag{2}$$

2.4.2. *Peter* Model

The *Peter* model (Peter, 2017; Peter et al., 2018) represents the breach with a parabolic shape (Fig. 3). The rate of embankment sediment erosion q_s is calculated based on the critical flow velocity through the breach v, the hydraulic radius at the critical flow cross section r_h, and a global scaling coefficient γ:

$$q_s = \gamma v^{\nu} {r_h}^{\eta} \tag{3}$$

where ν and η are exponents that can be used to apply different bedload transport relations. In this work, the relation of Meyer-Peter and Müller (1948) was applied by setting $\nu = 3.0$ and $\eta = -0.5$. In the research of Knüsel (2023), parametric numerical modeling of experiments EM and EL was performed with the *Peter* model using a range of values for γ. In this study, γ was set for each scale according to recommendations from that research.

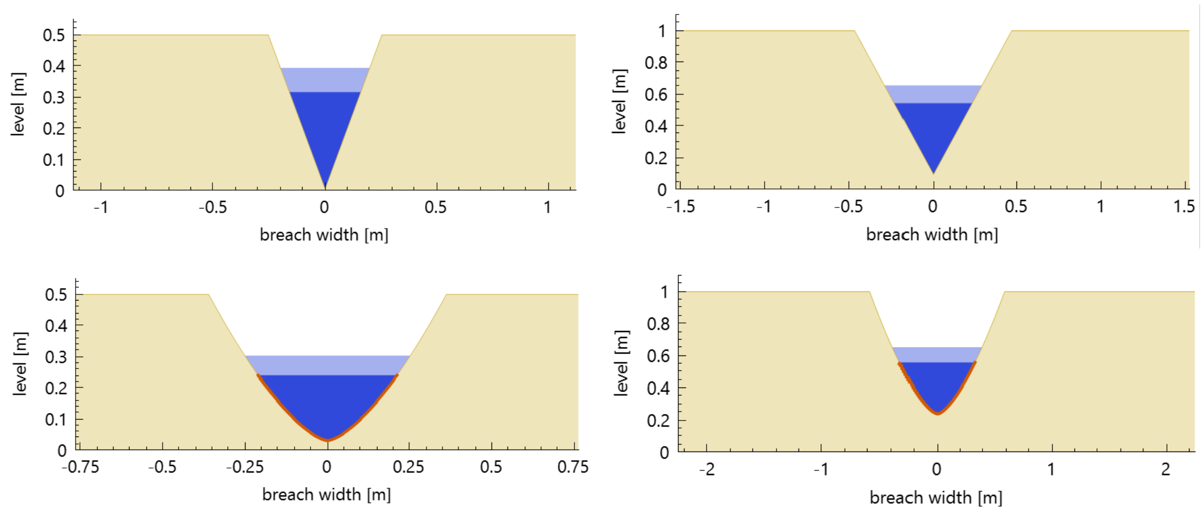


Figure 3. Cross sections from parametric dam breach numerical modeling with *Macchione* model (medium scale: upper left; large scale: upper right) and *Peter* model (medium scale: lower left; large scale: lower right).

2.5. Overtopping Flow

Overtopping was initiated in all models by raising the reservoir water level above the invert of the pilot channel, which caused water to flow through the pilot channel. The reservoir water level was held constant at this elevation (medium scale: 0.475 m, large scale: 0.95 m) through formation of the initial breach channel and for the first few seconds of breach expansion. Keeping a constant reservoir water level required a gradual increase in inflow to the reservoir, to match the seepage flow and the gradual increase in breach discharge.

The initial constant water level was managed in the large scale laboratory physical model experiment (the first experiment performed) by gradually increasing the opening of the control valve. This continued until the inflow reached 20.3 l/s. From this point, the valve opening was kept constant for the remainder of the experiment, and the inflow was thus constant. As the breach continued to grow and breach discharge increased, the reservoir water level fell. The reservoir water level was falling for the majority of each model run.

3. Results and Discussion

Laboratory experiments, detailed numerical modeling, and parametric numerical modeling of dam breaching due to overtopping have been performed at two scales: *medium laboratory scale* (dam height = 0.5 m) and *large laboratory scale* (dam height = 1.0 m). For comparison of results at different scales, the large scale results have been scaled down to the medium scale, through Froude similarity. According to Froude similitude, lengths and elevations scale by λ, and breach discharge and sediment discharge scale by $\lambda^{2.5}$. Additionally, all discharge results from laboratory experiments and numerical modeling have been converted to "full model" results (meaning they represent the dam on both sides of the breach centerline), for comparison with the parametric numerical modeling. This means that breach discharge and sediment discharge results have been doubled. Breach discharge (Q_b) and sediment discharge (shown as the volume of eroded embankment material V_e) for each experiment and numerical model simulation are shown in the following sections. Embankment profiles are also shown for each experiment and detailed numerical model simulation.

3.1. Laboratory experiments

Throughout the entirety of the laboratory experiments, the reservoir water level was consistent between EL and EM (Fig. 4a). For the first 20 seconds of the experiments, when the constant water level was maintained during initial breach formation, the breach discharges (Fig. 4b) at the two scales are similar. This corresponds with the experimental breach profiles, which for t = 20 s (Fig. 5a) are nearly identical. But for the remainder of the breach discharge increase, while the reservoir water level is falling, the rising limb of the hydrograph is slightly steeper for EL than for EM. At t = 40 s, the breach discharge is greater for EL than for EM. This is inconsistent with the experimental breach profiles at t = 40 s (Fig. 5b), where the EM profile is lower than the EL profile, indicating a larger breach channel in the large scale experiment. The peak breach discharge is reached earlier for EL (t = 53 s) than for EM (t = 62 s), but with a similar magnitude for the two scales (EL: 40.8 l/s, EM: 41.7 l/s). After the peak discharges are reached, the discharge for EL fell much more rapidly than the discharge for EM. This is consistent with the breach profiles observed at t = 60 (Fig. 5a) and 90 s (Fig. 5b), where the breach crest – the maximum elevation of the breach profile, which controls the rate of discharge through the breach – is higher for EL than for EM. A higher rate of discharge should flow through the larger breach that formed in EM.

From the laboratory experiments, the effect of scale on dam breaching can be summarized as follows: during initial breach formation, while the reservoir head was constant, breach formation occurred at similar rates, and no effect of scale was observed. As the reservoir level began to fall and breach growth continued, the breach discharge increased slightly faster at larger scale, despite the breach profile lowering slightly faster at medium scale. This led to an earlier peak discharge at large scale. After the peak discharges, the breach remained larger at medium scale, allowing for the breach discharge to remain high, while the breach discharge at large scale fell more rapidly.

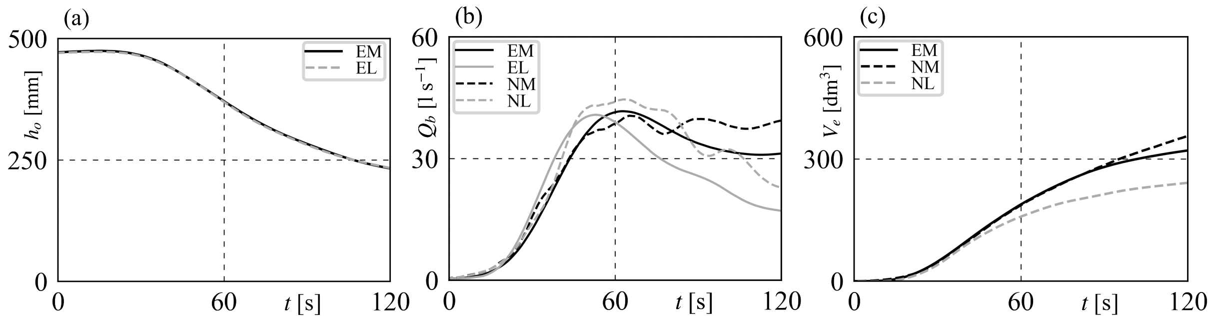


Figure 4. Reservoir water level (a), breach discharge (b), and embankment erosion (c) of dam breach medium scale and large scale laboratory experiments (EM and EL) and detailed medium scale and large scale numerical modeling (NM and NL). Reservoir water level only shown for EM and EL. Embankment erosion was not measured in EL.

3.2. Detailed numerical modeling

During initial breach formation, when the reservoir water level was constant ($t < 20$ s), the breach formation rate in the detailed numerical modeling was similar for medium (NM) and large scales (NL), as can be seen in the embankment profiles for $t = 20$ s (Fig. 5a). The breach discharge (Fig. 4b) and sediment erosion rates (Fig. 4c) were also similar during initial breach formation. This is consistent with the laboratory experiments, for which breach discharge and embankment profiles were similar for medium (EM) and large scales (EL) during this period.

As the reservoir level fell ($t > 20$ s), the modeled breach discharges at the different scales deviated (Fig. 4a). NL saw a 12% higher peak discharge (45 l/s) than NM (40 l/s). This is inconsistent with the laboratory experiments, which had similar peaks discharges. NL and NM did however reach peak discharge at similar times (approximately $t = 63$ s). Development of the modeled embankment profiles during this time ($t = 40$ and 90 s, Fig. 5b; $t = 60$ s, Fig. 5a) are consistent with the experimental profiles, with both methods showing a faster breach development at medium scale, although with the experimental profiles eroding faster than the modeled profiles in the breach crest region. This is compatible with the material erosion, as V_e increases faster in NM than in NL (Fig. 4c). Additionally, the modeled erosion rate at medium scale is similar to the experimental erosion rate.

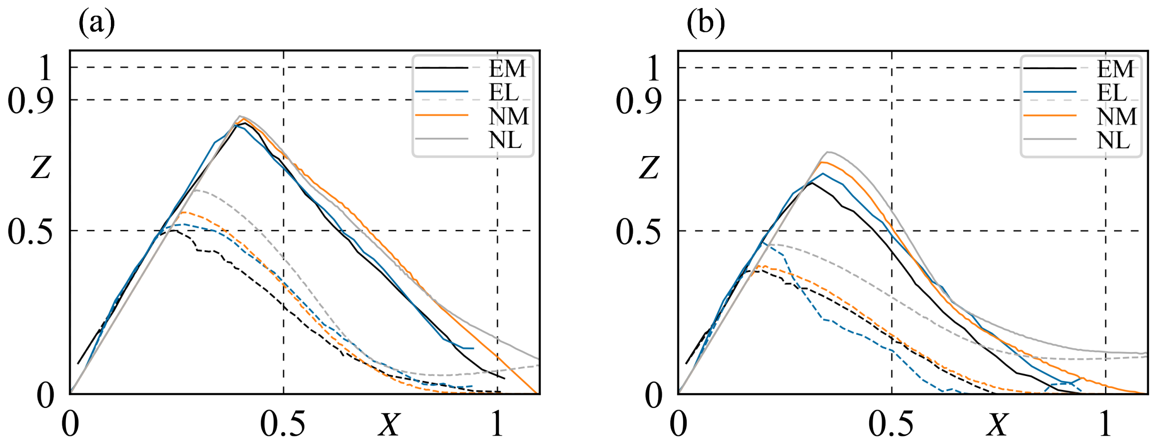


Figure 5. Embankment profiles along breach centerline at (a) $t = 20$ (–) and 60 s (--) and (b) $t = 40$ (–) and 90 s (--) from medium scale and large scale laboratory experiments (EM and EL) and medium scale and large scale detailed numerical modeling (NM and NL). X is the streamwise coordinate normalized by the dam base length. Z is the elevation coordinate normalized by the dam height.

This detailed numerical modeling showed that the effect of scale on breach development – the embankment profile eroding at similar rates during constant head, and then slightly faster at medium scale during falling head (Fig. 5) – could be reproduced with numerical modeling. This indicates that breach formation was slightly faster at medium scale, which is supported in the numerical modeling by the higher rate of material erosion at medium scale (Fig. 4c). For the period of constant reservoir head during initial breach formation, the modeled medium and large scale breach discharge (Fig. 4b) were also consistent with the experimental results. However, for the period of falling head during breach expansion and discharge increase, the numerical model did not reproduce the same effect of scale as in the experiments. A higher peak was seen in NL than in NM, while in the experiments the peaks in EL and EM were similar. This may be due in part to the challenge of morphodynamic modeling in rapidly evolving hydrodynamic conditions at different scales and with different material sizes. The relation for bedload transport and the selection of hydraulic roughness may be accurate for a certain phase of the breach process, but may become increasingly unreliable as the system becomes increasingly unsteady and supercritical.

3.3. Parametric numerical modeling

3.3.1. *Macchione* Model

Parametric numerical modeling of the large scale (PL-M) and medium scale (PM-M) dams with the *Macchione* model resulted in nearly identical timing of peak discharge (Fig. 6a). The peak discharge was slightly higher with the medium scale dam, matching the experimental results which also had a slightly higher peak discharge at medium scale. After the peak discharge, the PM-M discharge fell at a similar rate as in the medium scale experiment, and then remained relatively high throughout the duration of the experiment, similarly to in EM. The PL-M discharge fell rapidly for approximately 40 seconds, at a similar rate to the large scale experiment. The breach discharge slowly decreased to a similar level as in EL.

While the reservoir head remained constant, the rate of material erosion was similar in PL-M and PM-M (Fig. 6b). Once the reservoir head began to fall, the material erosion in PL-M became greater than in PM-M, and this difference continued for the duration of the experiment. Since eroded material was not measured in the large scale experiment, it cannot be determined if this is consistent with the effect of scale in the laboratory experiments. However, it is clear that the rate of material erosion in PM-M was lower than in EM for the entire experiment. This may have been due to the breach shape of the *Macchione* model, which assumes a constant elevation along the entire streamwise length of the dam. In the experiments, the profile shape slopes down from the breach crest elevation to the downstream toe of the dam, meaning that material has eroded from the downstream side of the dam, below the elevation of the breach crest. Erosion of material below the breach crest elevation is not simulated in the *Macchione* model.

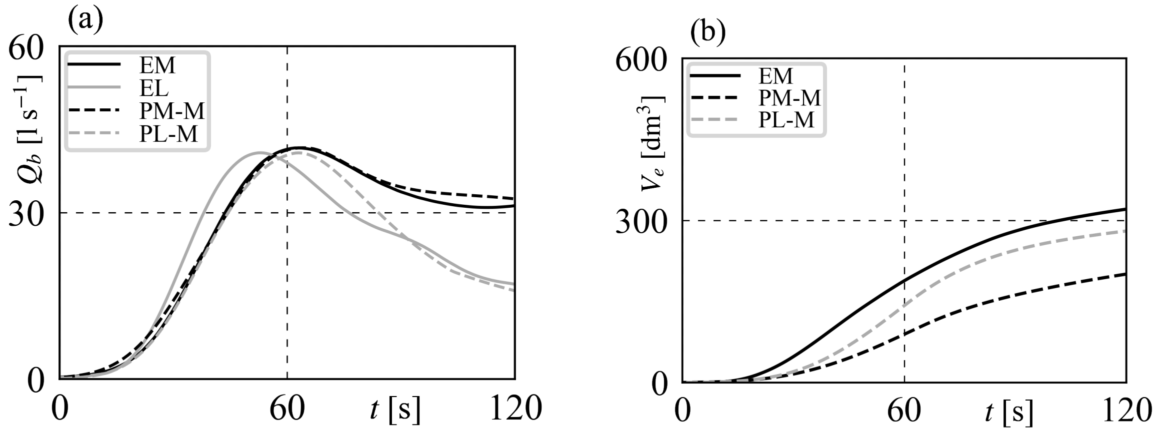


Figure 6. Breach discharge (a) and embankment erosion (b) of dam breach medium scale and large scale laboratory experiments (EM and EL) and medium scale and large scale parametric modeling with the *Macchione* model (PM-M and PL-M). Embankment erosion was not measured in EL.

3.3.2. *Peter* Model

Parametric numerical modeling with the *Peter* model resulted in a earlier peak discharge (Fig. 7a) with the large scale dam (PL-P). An earlier peak discharge for the large scale dam was also seen in the laboratory experiments. A higher peak breach discharge was achieved for the medium scale dam with the *Peter* model (PM-P). After the peaks, the discharges lowered with similar effect of scale as in the experiments: the PM-P discharge remained high, but with a slower decrease than in EM; and the PL-P discharge fell quickly and with a similar slope as EL.

The rate of material erosion (Fig. 7b) was not at all similar at medium and large scales with the *Peter* model. Material erosion initially increased much quicker for PL-P, and continued increasing at a higher rate for the entire experiment. The PM-P material erosion began much slower than in EM. But after the peak discharge the rates were similar for PM-P and EM until nearly the end of the experiment, at which point the material erosion rate in EM slowed down ($t > 85$ s), and the PM-P erosion became greater than the EM erosion ($t > 110$ s).

3.3.3. Effect of scale in parametric numerical modeling

This parametric numerical modeling of dam breaching showed that both the *Macchione* model and the *Peter* model can show some effects of scale in dam breaching due to overtopping. For the Macchione model, the medium scale experimental breach hydrograph was almost exactly replicated (Fig. 6a), including the rising limb, the peak, and the slowly-reducing falling limb. The modeled breach hydrograph at large scale also accurately matched the peak and initial lowering rate of the experimental large scale breach hydrograph.

For the *Peter* model, the ability to reproduce the effect of scale on the breach hydrograph was better than the *Macchione* model. The later timing of peak discharge at medium scale was seen in both the experiments and the *Peter* model, as was the slightly higher peak discharge at medium scale (Fig. 7a). Prior to the peaks, discharge was higher at large scale. After the peaks, this effect of scale reverses: the discharge hydrograph is higher for medium scale than for large scale. This reversal is reproduced by the *Peter* model, although with slightly higher discharges than in the experiments.

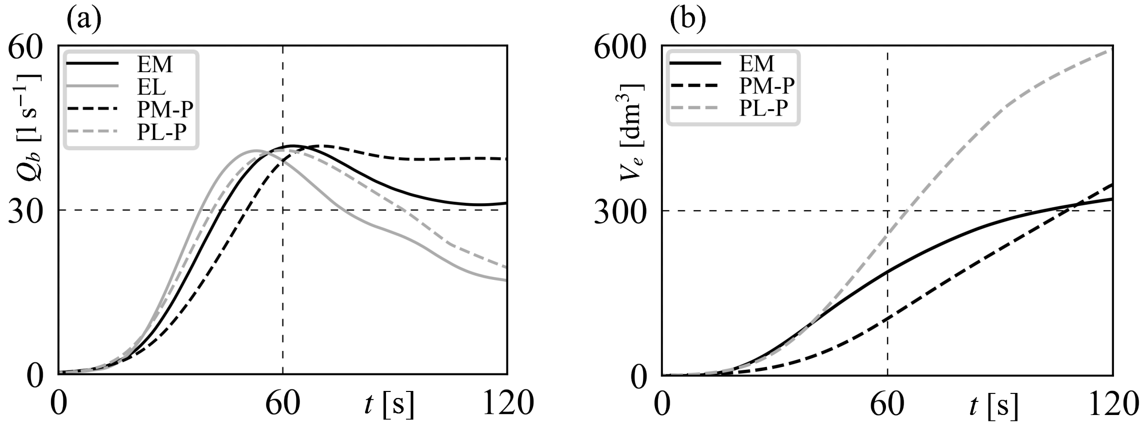


Figure 7. Breach discharge (a) and embankment erosion (b) of dam breach medium scale and large scale laboratory experiments (EM and EL) and medium scale and large scale parametric numerical modeling with the *Peter* model (PM-P and PL-P). Embankment erosion was not measured in EL.

4. Conclusions

A composite model investigation of embankment dam breaching due to overtopping has been performed with four methods: laboratory physical model experiments, detailed numerical modeling, parametric numerical modeling with the *Macchione* model, and parametric numerical modeling with the *Peter* model. The effect of scale on breach formation and breach discharge development was investigated by performing the laboratory experiments at two scales: *medium laboratory scale* (0.5 m tall dams) and *large laboratory scale* (1.0 m tall dams). The numerical models were also used to model the dam breach at both scales, and the ability of each numerical model to detect the effect of scale was assessed.

During the initial formation of the breach, while the water level was held constant, no effect of scale was observed in the laboratory experiments. After the period of constant water level, as the reservoir water level fell and the breach continued to expand, the breach grew slightly faster at medium scale, although the breach discharge increased slightly faster at large scale until the peak. After the peak discharge, the discharge at medium scale remained high, while the discharge at large scale lowered more quickly.

The detailed numerical model was able to reproduce the effect of scale on breach expansion rate, with similar rates during initial breach formation, and faster expansion at medium scale during falling reservoir head. The detailed numerical model also captured the effect of scale at the end of the breach hydrographs, with higher discharge at medium scale. But it did not fully capture the magnitudes of peak breach discharge, which is an important output in dam breach investigations. Due to the constantly evolving conditions of breach expansion and falling reservoir head, a more detailed calibration of the morphodynamic parameters for application to different model scales and different material sizes should be performed to improve reproduction of peak discharges.

The *Macchione* model was able to reproduce the medium scale breach discharge, and the effect of scale after the peak discharge – that discharge remained high at medium scale, but fell quickly at large scale – was accurately modeled. But the *Macchione* model did not reproduce the effect of scale on the timing of peak discharge. However, that effect – that peak discharge occurred sooner at large scale – was reproduced with the *Peter* model. The effect of scale after the peak was also shown with the *Peter* model. Accurate reproduction of some effects of scale on breach discharge is promising for interpretation of how findings at model scale apply to prototype scale dams.

Results suggest that model type and scale may have only a small effect on the peak breach discharge estimated by a model, with a much greater effect on the hydrograph of breach discharge (likely due to the erosive processes being simplified by numerical modeling or affected by Froude similarity). Temporal results such as timing of peak discharge and reservoir depletion rate are thus affected by model type and scale, and upscaling of such temporal results to prototype scale is therefore highly uncertain. This can lead to impacts in other stages of dam breach risk management, such as estimation of flood arrival times and development of emergency management protocols. To reduce uncertainty in upscaling results to prototype scale, upscaled results should be validated to known prototype dam failures. This would allow for greater confidence in related flood impact estimates and risk assessments.

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