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Breach Evolution in Sand-Silt Dams with a Surface Layer of Xanthan Gum-Treated Soil during overtopping: Laboratory Experiments

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ABSTRACT

Laboratory experiments on breach development in non-cohesive, compacted dams during overtopping show that adding a silt fraction to sand magnifies the effects of biopolymer-treatments that reduce dam breaching. Base case experiments conducted with untreated soil showed that differences in breach development in compacted sand and sand-silt (10% silt content) dams are not significant. Breaching in sand-silt-xanthan gum mixtures was significantly slower than in dams made of xanthan gum-treated sand in all the tested cases. The reduction of failure time in dams with a 5 cm thick top layer of xanthan gum-treated soil was less effective than when the entire dam was built with treated soil. Our results suggest that biopolymer treatments to non-cohesive soils may be more effective in presence of silt sized particles, which is more likely in real-world applications.

INTRODUCTION

Protection of dams and levees against breaching is often done with soil treatments designed to improve geotechnical properties or reduce surface erosion. Most of the breach-induced failures occur due to overtopping (Foster et al. 2000, ASCE task force 2011) with flow eroding the embankment surface. Typical soil improvements to reduce erosion include additions of cement, lime, or fly ash, which may cause toxicity in the soil and elevated carbon emissions of the cement industry (e.g. Mahedi et al. 2019). Such drawbacks have motivated exploration into eco-friendly alternatives such as the application of biopolymers as soil additives. Numerus studies have focused on the use of xanthan gum, a hydrophilic polysaccharide that absorbs water to form a hydrogel (Chang et al. 2020). This biopolymer has been investigated for soil strength (e.g. Chang et al. 2015), erodibility (Kwon et al. 2020), and in limited application to control breach development in dams (Ko and Kang, 2018, 2020).

The effectiveness of xanthan gum (XG) to improve soil strength or resistance to erosion depends on several factors, including concentration and soil gradation. Soil compressive strength increases with relatively small concentrations of XG relative to conventional methods (e.g. Chang et al. 2015, Dubey et al. 2024, Hamza et al. 2022). For example, a natural soil mixed with 1% XG had twice the measured strength than the same soil with a 10% concentration of Portland cement (Chang et al. 2015). Similarly, resistance to erosion caused by fluid shear increases as biopolymer concentration increases in non-cohesive sands (Kwon et al., 2020). Critical shear strength is increased with biopolymer concentration as well (Baas et al. 2019, Kwon et al. 2023). Finally, fine sediment content (percentage of particles smaller than 63 microns) also affects the relative effectiveness of biopolymer additions (Kwon et al. 2023).

An exhaustive campaign of laboratory experiments is in progress in the Hydraulics Laboratory at the University of South Carolina to understand if and how xanthan gum can be used as a soil additive to control breach development in non-cohesive, compacted dams and levees (e.g. Czapiga et al. 2024). In this paper results on the influence of silt content (10%), xanthan gum treatment and thickness of the biopolymer-treated layer on breach development are presented.

METHODOLOGY

Dam breach experiments were conducted in a 5 m long, 0.3 m deep, and 0.27 m wide flume with an upstream constant head reservoir and downstream free overfall (Fig. 1a). Model dams were 0.2 m tall with a 0.3 m long crest and 2:1 (H:V) side slopes. A 2 cm wide and 1.8 cm deep 'pilot channel' was cut into the dam crest to control breach location and initial geometry. Time zero in the experiments corresponded to water first entering the pilot channel. Experiments ended when the breach channel eroded into the upstream reservoir. Xanthan gum was added to the sand-silt mixture at a 0.15% concentration (relative to the dry soil mass) using the wet mixing method (Ko and Kang 2018, Czapiga et al. 2024), where XG is first hydrated in water and mixed into a homogeneous, viscous hydrogel, which is then mixed uniformly into the sediment.

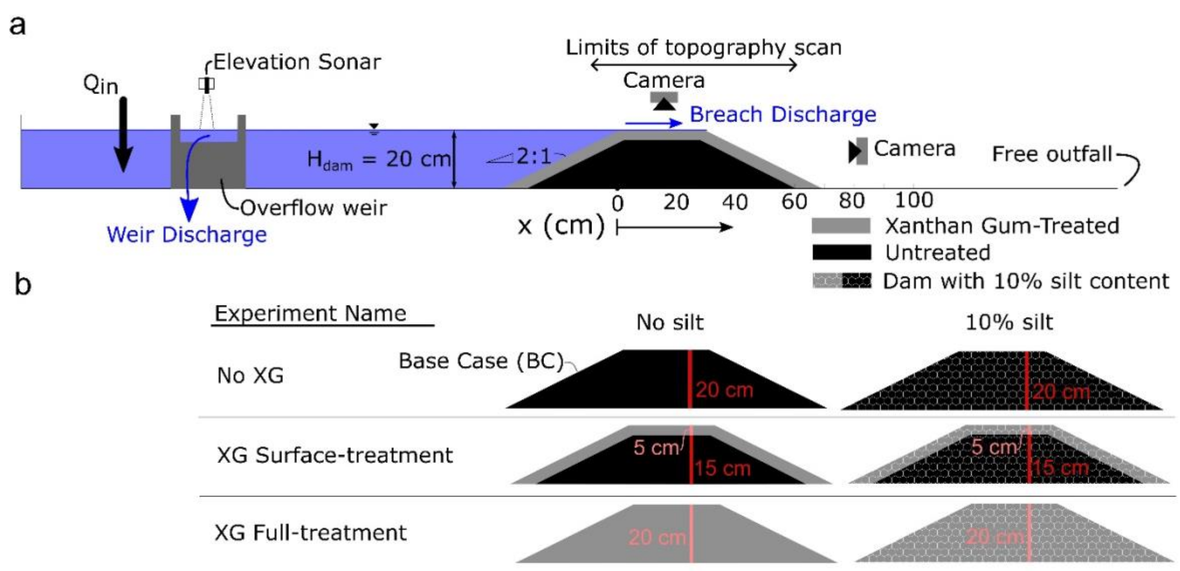

Figure 1. Experimental conditions for a) flume setup, and b) schematic cross-sections of the dam per each experiment.

Thickness of XG-treated layer and silt content in the soil were varied in the experiments. In particular, dams were built with untreated soil (base case), with a 5 cm top layer of XG-treated soil (surface-only treatment), and dams were also entirely built of XG-treated material (full-dam treatment) (Fig 1b). The non-cohesive soils consisted of sand (D_{50} = 0.3 mm) and a sand-silt mixture with 10% mass content of silica flour with D_{50} = 0.02 mm (silt) (Fig. 2). The sand-silt mixture has nearly identical median grainsize as the sand-only mixture (Fig. 2).

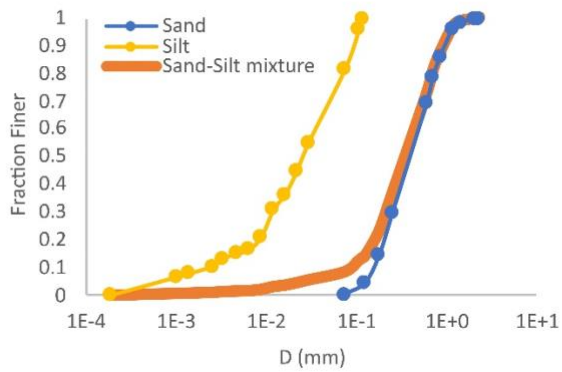

Figure 2. Grainsize distribution of sand, silt, and the 90% sand/10% silt mixture used in this study.

Experiments were conducted with constant reservoir head, i.e. the water level in the upstream reservoir was held constant with a calibrated overflow weir. An inflow pump discharged Q_{in} = 2.25 L/s into the reservoir. Water level in the reservoir was monitored throughout the experiment with an ultrasonic sonar. Discharge through the breach Q_{br} was computed via mass balance as:

$$Q_{br} = Q_{in} - Q_{weir} - \frac{dV_{res}}{dt} \qquad (1)$$

where Q_{weir} is the discharge over the weir and V_{res} is the reservoir volume directly computed algebraically from reservoir geometry and water level.

Breach elevation was monitored with a 2D laser-profiler attached to a sliding cart, allowing collection of 3D breach topography every 20 seconds (Czapiga et al. 2024). Two cameras recorded the changes to the downstream slope and dam crest, respectively.

Altogether, breach discharge and breach topography were monitored for all experiments and this information were used to assess how XG-treated sand and the sand-silt mixture behave during overtopping. The experiment on breaching of a compacted sand dam was used as the base case.

RESULTS

Dam breaching often ends with an abrupt release of water from the upstream reservoir. Thus, breach discharge can be used to understand breach development. Measured breach discharge (Eq 1) for all six experiments is presented in Fig. 3. Experiments with untreated sand and sand-silt soil are represented with red lines, experiments with a surface layer of XG-treated soil are in blue and experiments with the entire dam made of XG-treated soil are in black. Dashed lines represent experiments with sand-silt mixtures.

All experiments began with a breach discharge between 0.1 and 0.3 L/s. Most experiments showed an abrupt increase in discharge, indicating a rapid release of water when the breach channel eroded into the upstream reservoir. The experiment with dam entirely made of the XG-treated sand-silt mixture (dashed black line) ended after 12 hours and the breach channel never reached the upstream reservoir. Breach discharge in all experiments increased throughout the experiment at a rate of 0.1 L/hr/hr until failure occurs (Fig. 3).

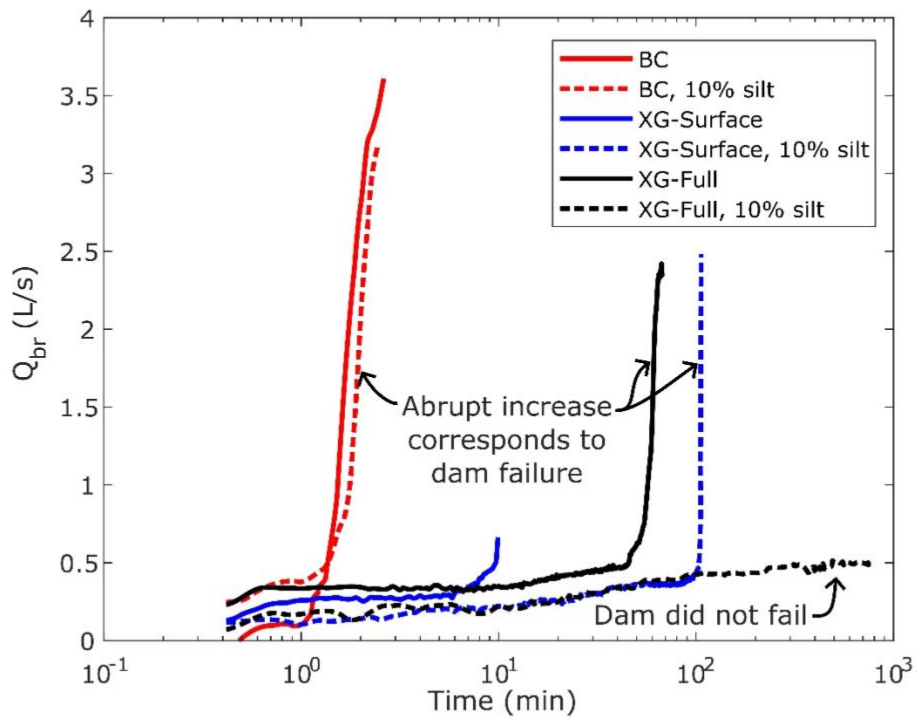

Figure 3. Discharge through the breach Q_{br} (Eq. 1) of all experiments. Time is started when water initially enters the pilot channel on the dam crest.

Figure 3 shows how xanthan gum treatments extended dam failure time, and the effectiveness is boosted by the presence of 10% silt content. Both untreated (no XG) dams failed within 2 minutes from the beginning of the experiment (red lines in Fig. 3). Failure time of the sand-silt dam was about 35% longer than for the sand dam (from 1.5 minutes to 2 minutes), as previously observed by O'Donal (2023), who conducted experiments on breaching of sand compacted, non-cohesive dams with the same soil and with a constant head reservoir. Biopolymer treatments to sand dams extended failure time by up to 50 times (from ~2 minutes to up to 100 minutes; Fig. 3). XG treatments to sand-silt dams were even more effective, as the full-dam XG treatment did not fail after over 700 minutes (~12 hours). The longer failure time of the XG-treated sand-silt dam compared to a sand dam agrees with previous erosion tests by Kwon et al. (2023).

Increasing the thickness of XG-treated soil layer, as well as silt content, helped increasing failure time. The addition of 10% silt content to XG-treated sand, however, was most effective. Dams with a surface layer of XG-treated soil failed earlier than dam entirely made of XG-treated soil regardless of silt content. In our experiments, the dam made of XG-treated sand failed sooner

(60 minutes) than the sand-silt dam with a surface layer of XG-treated material (100 minutes). This observation, however, cannot be generalized and more experiments are needed to determine the relative impact of silt content and thickness of biopolymer-treated layer on dam failure time.

Biopolymer treatments to sand-silt dams increased failure time by inhibiting channelization on the dam slope with water flowing as sheet flow. High resolution dam topography is presented in Figure 4 for the experiments with dams entirely made of XG-treated soil (sand-silt-XG dam on the left and sand-XG dam on the right) at times equal to 25, 100, and 300 minutes, respectively. Elevation is presented with a color shift from red (dam top, 20 cm above flume bottom) to blue (at flume bottom). After 25 minutes, the XG-treated sand-silt dam eroded with local scours forming on the downstream slope, while a narrow and deep breach channel with upstream-migrating headcuts formed on the XG-treated sand dam. The approximate extent of breach flow width in Figure 4a,b is marked with dashed white lines, clearly showing the different flow on the downstream slope of XG-treated sand and sand-silt dams.

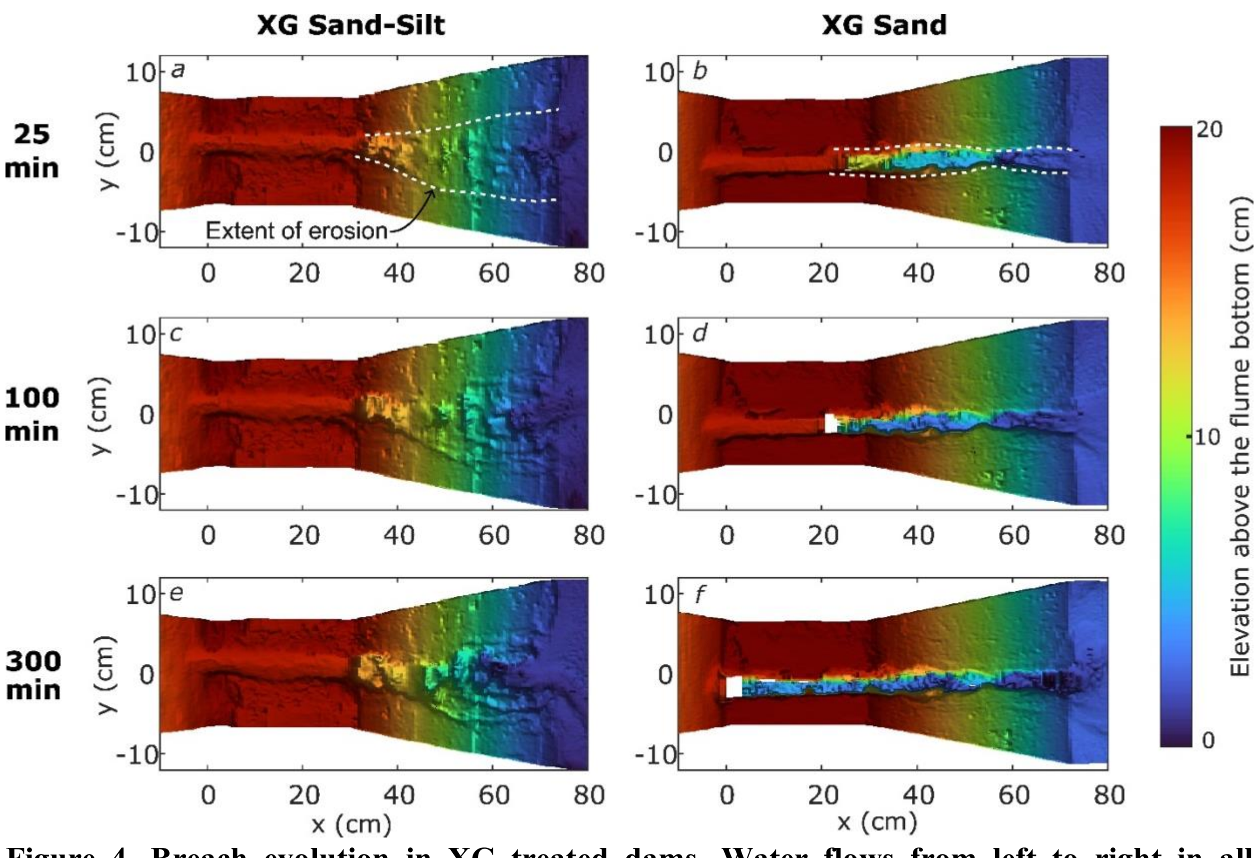

Figure 4. Breach evolution in XG treated dams. Water flows from left to right in all subfigures, showing dam topography at 25 minutes (subfigures a,b), 100 minutes (c,d) and at 300 minutes (e,f). Results are shown for both the sand-silt dam (subfigures a,c,e) and sand dam (subfigures b,d).

As the breach channel grows, the erosional headcut steadily migrates upstream in the breach channel of the XG-treated sand dam. When the headcut reaches the upstream reservoir, breach discharge increases causing dam failure (Fig. 4d,f). Breach channel width hardily varies from that of the initial pilot channel and breach channel banks maintain nearly vertical slopes. The XG-treated sand-silt dam (Fig. 4a,c,e) gradually erodes into the downstream slope, but there is significantly less incision than observed in the sand-XG dam.

CONCLUSION

Laboratory experiments were conducted to evaluate how silt content and xanthan gum treatment (5 cm layer vs full dam) impact breach development in compacted, non-cohesive dams during overtopping. Adding 10% silt content alone yielded very little reduction of dam failure time compared to the case of a sand dam. The experiments indicate that XG treatments extend failure time by 50 times and the presence of silt-size sediment strongly exacerbates this effect. Silt content is apparently more influential than the thickness of the XG-treated layer for the conditions tested in this study. More experiments must be conducted, however, at larger scale to verify the relationship between fines concentration and xanthan gum and assess the applicability of XG treatments in the real world.

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REFERENCES

ASCE/EWRI Task Committee on Dam/Levee Breaching. (2011). Earthen Embankment Breaching. *Journal of Hydraulic Engineering*, *137*(12), 1549–1564. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000498

Baas, J. H., Baker, M. L., Malarkey, J., Bass, S. J., Manning, A. J., Hope, J. A., Peakall, J., Lichtman, I. D., Ye, L., Davies, A. G., Parsons, D. R., Paterson, D. M., & Thorne, P. D. (2019). Integrating field and laboratory approaches for ripple development in mixed sand–clay–EPS. *Sedimentology*, *66*(7), 2749–2768. https://doi.org/10.1111/sed.12611

Chang, I., Im, J., Prasidhi, A. K., & Cho, G.-C. (2015). Effects of Xanthan gum biopolymer on soil strengthening. *Construction and Building Materials*, *74*, 65–72. https://doi.org/10.1016/j.conbuildmat.2014.10.026

Chang, I., Lee, M., Tran, A. T. P., Lee, S., Kwon, Y.-M., Im, J., & Cho, G.-C. (2020). Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices. *Transportation Geotechnics*, *24*, 100385. https://doi.org/10.1016/j.trgeo.2020.100385

Czapiga, M.J., Kotey, E., Elalfy, E., Viparelli, E., and Chaudhry, M.H. (2024). Laboratory experiments of breaching with xanthan gum biopolymer. Proceedings of the American Society of Civil Engineers, Environmental & Water Resources Institute Conference, Milwaukee, WI, May 2024

Dubey, A. A., Machale, J., Ravi, K., Dhami, N. K., & Mukherjee, A. (2024). Rheological Properties of Xanthan-Gum Solutions and Their Role in Improving River Embankments. *Geotechnical and Geological Engineering*, *42*(4), 2387–2401. https://doi.org/10.1007/s10706-023-02678-0

Foster, M., Fell, R., & Spannagle, M. (2000). The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal*, *37*(5), 1000–1024. https://doi.org/10.1139/t00-030

Hamza, M., Nie, Z., Aziz, M., Ijaz, N., Ijaz, Z., & Rehman, Z. ur. (2022). Strengthening potential of xanthan gum biopolymer in stabilizing weak subgrade soil. *Clean Technologies and Environmental Policy*, *24*(9), 2719–2738. https://doi.org/10.1007/s10098-022-02347-5

Ko, D., & Kang, J. (2018). Experimental Studies on the Stability Assessment of a Levee Using Reinforced Soil Based on a Biopolymer. *Water*, *10*(8), Article 8. https://doi.org/10.3390/w10081059

Ko, D., & Kang, J. (2020). Biopolymer-Reinforced Levee for Breach Development Retardation and Enhanced Erosion Control. *Water*, *12*(4), Article 4. https://doi.org/10.3390/w12041070

Kwon, Y.-M., Ham, S.-M., Kwon, T.-H., Cho, G.-C., & Chang, I. (2020). Surface-erosion behaviour of biopolymer-treated soils assessed by EFA. *Géotechnique Letters*, *10*(2), 106–112. https://doi.org/10.1680/jgele.19.00106

Kwon, Y.-M., Moon, J.-H., Cho, G.-C., Kim, Y.-U., & Chang, I. (2023). Xanthan gum biopolymer-based soil treatment as a construction material to mitigate internal erosion of earthen embankment: A field-scale. *Construction and Building Materials*, *389*, 131716. https://doi.org/10.1016/j.conbuildmat.2023.131716

Mahedi, M., Cetin, B., & Dayioglu, A. Y. (2019). Leaching behavior of aluminum, copper, iron and zinc from cement activated fly ash and slag stabilized soils. *Waste Management*, *95*, 334–355. https://doi.org/10.1016/j.wasman.2019.06.018

O'Donal, H. (2023). Impact of Dam Height and Grain Size Distribution on Breaching of Non-cohesive Dams Due to Overtopping, MSc Thesis, University of South Carolina, 2023

Pickert, G., Weitbrecht, V., & Bieberstein, A. (2011). Breaching of overtopped river embankments controlled by apparent cohesion. *Journal of Hydraulic Research*, *49*(2), 143–156. https://doi.org/10.1080/00221686.2011.552468