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Experimental study on the external and internal erosion behaviors of biopolymer-treated earthen levee structures assessed via open channel hydraulic flume apparatus

Étude expérimentale sur les comportements d'érosion externe et interne des structures de digues en terre traitées aux biopolymères évaluées via un appareil à canal hydraulique à canal ouvert

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ABSTRACT: Earthen levee structures have been generally constructed using compacted geomaterials. Geomaterial for earthen levee structures is recommended to be well graded soils with coarse aggregates consisting no more than 20%. Meantime, environmentally friendly biopolymer-based soil treatment (BPST) has been recently introduced for sustainable geotechnical engineering. Previous studies have found the effectiveness of BPST on enhancing inter-particle bonding between soil particles, which results to significant shear strength (especially cohesion) increase. Thus, this study investigates effect of BPST to improve the erosion resistance and stability of earthen levee structures under severe erosion generating conditions. The external (overtopping) and internal (piping) erosion behaviors of an earthen levee model with and without BPST have been assessed using a large-scale laboratory open-channel hydraulic flume apparatus. Experimental results show that BPST reduces both surface and internal erosion and improves the overall stability during continuous flood conditions.

RÉSUMÉ: Les structures de digues en terre ont été généralement construites à l'aide de géomatériaux compactés. Il est recommandé que les géomatériaux pour les structures de digues en terre soient des sols bien classés avec des agrégats grossiers ne dépassant pas 20%. Entre-temps, le traitement des sols à base de biopolymères respectueux de l'environnement (BPST) a été introduit pour l'ingénierie géotechnique durable de nos jours. Des études antérieures ont montré l'efficacité du BPST pour améliorer la liaison inter-particules entre les particules de sol, ce qui se traduit par une augmentation significative de la résistance au cisaillement (en particulier de la cohésion). Ainsi, cette étude vise à appliquer le BPST pour améliorer la résistance à l'érosion et la stabilité des structures de digues en terre dans des conditions génératrices d'érosion sévère. Dans les détails, les comportements d'érosion externe (débordement) et interne (tuyauterie) d'un modèle de digue en terre avec et sans BPST ont été évalués à l'aide d'un appareil à canal hydraulique à canal ouvert de laboratoire à grande échelle. Les résultats expérimentaux montrent l'effet optimiste du BPST sur la réduction de l'érosion de surface et interne et l'amélioration de la stabilité globale dans des conditions de crue continue.

KEYWORDS: Biopolymer; Biopolymer-based soil treatment (BPST); Hydraulic erosion; Earthen levee structure erosion; Hydraulic flume test; External erosion; Overtopping; Internal erosion; Piping.

1 INTRODUCTION

Earthen levees are important infrastructure in modern civilization. In practice, earthen levee structures are generally composed of fine-grained soils. In contrary, coarse grained particles are recommended to consist less than 20% of the entire soil composition to ensure stability of earthen levee structures(USSD 2011). However, the high fine particle content can lead to severe instability issues. For instance, suffusion or suffosion can occur in clayey soil. Both phenomenon are caused by removal of fine soils whereas suffusion does not render volume contraction (Fannin and Slangen 2014). This study aims to improve the overall stability of earthen levee structures by using microbial biopolymers as an inter-granular binder among coarse grains instead of using fine clay particles. Specifically, biopolymer aims to provide cohesion between cohesionless coarse particles as well as providing reinforcement among particle-particle aggregates.

Recently, biopolymer has been introduced as a new soil treatment binder in geotechnical engineering due to its competitive strengthening effect and environmentally friendly characteristics. Previous studies have demonstrated the technical feasibility of biopolymer-based soil treatment (BPST) through various approaches, including soil strengthening, soil-water retention increase, permeability reduction, and liquefaction potential reduction (Im, Tran et al. 2017, Chang and Cho 2019, Tran, Chang et al. 2019).

Additionally, BPST is regarded to be environmentally friendly due to its low carbon footprint along its production and low impact to nature.

Xanthan gum biopolymer has been considered in this study due to its economic feasibility and sufficient strengthening characteristics. Xanthan gum is a shear thinning biopolymer, that provides significant interparticle cohesion at rest state (Ong, O'Byrne et al. 2019). Thus, it is expected that xanthan gum treatment to a soil will increase the critical shear stress of the mix against hydraulic erosion circumstances due to the high interparticle cohesion and yield point (i.e. shear strength).

It has been widely reported that the main failure patterns of earthen levee structures are external erosion (overtopping) and internal erosion (piping), where external erosion takes 34% and internal erosion takes 28% of the entire failure modes (Chen, Zhong et al. 2019). This study aims to mitigate both external erosion (overtopping) and internal erosion (piping) of earthen levee models with xanthan gum BPST. Various xanthan gum BPST conditions were considered on small-scale earthen levee models where the erosion behaviors were simulated via a laboratory open-channel hydraulic flume apparatus.

2 MATERIALS AND METHOD

2.1 *Materials*

2.1.1 *Sand*

Sydney sand was used as the coarse granular soil in this study. It is defined as a poorly graded soil (SP) by the Unified Soil Classification System (USCS). The basic properties of Sydney sand are summarized in Table 1.

Table 1. Geotechnical properties of Sydney sand.

e_{max}	e_{min}	D_{50}	C_u	C_c
0.92	0.6	0.36	1.18	0.96

2.1.2 *Xanthan gum*

Xanthan gum is produced by *Xanthomonas campestris*, which forms viscous hydrogels in the presence of water. Xanthan gum is hetero-polysaccharide which consists of repeating units of beta-D-glucan main chains and trisaccharide side chains. The side chains of trisaccharide's are linkages of alpha-D-mannose, beta-D-glucuronic acid, and beta-D-mannose (García-Ochoa, Santos et al. 2000). In this study, research grade xanthan gum (Sigma aldrich; CAS number: 11138-66-2) in apowder form is used.

2.2 *Methods*

2.2.1 *Sample preparation*

Clean sand is dried in an oven at 100ºC for 24 hours. Xanthan gum powder is dissolved into deionized water to prepare xanthan gum hydrogel. Xanthan gum hydrogel is prepared to a concentration (i.e., biopolymer to water ratio in mass, m_{bp}/m_{water}) of 5%. The xanthan gum hydrogel is then thoroughly mixed with the dry sand to form a uniform xanthan gum-sand mixture using a pneumatic mixer. Moisture content and xanthan gum content (biopolymer to soil ratio in mass, m_{bp}/m_{soil}) of the xanthan gum-sand mixture was controlled at 20% and 1%, respectively.

Earthen levee structures are designed to have 2H:1V (horizontal:vertical) inclined slopes on both up and down stream sections. Untreated earthen structures are constructed using partially saturated sand without BPST, while biopolymer-treated earthen levee structures were fabricated with the xanthan gum-sand mixture.

For internal erosion simulation, a 10 mm diameter cylinder was placed along the bottom corner of the hydraulic flume prior to fabricating the earthen levee model over it. After completion of the earthen levee model, and once water level at the upstream reached the maximum height (i.e.levee model height), the embedded cylinder was carefully removed to initiate internal water flow through the earthen levee structure. For internal erosion, the untreated earthen levee model and 25% surface xanthan gum-treated conditions were considered. The 25% surface treatment indicates that 25% of the model surface consists of xanthan gum-treated sand whilst the underlying 75% remains clean sand in the cross-section view.

For external surface erosion, the untreated earthen levee model was assessed as a control case, compared to an earthen levee model entirely constructed using xanthan gum-sand mixtures.

2.2.2 *Test method*

The earthen levee models are placed in the middle of a laboratory open-channel hydraulic flume apparatus to minimize turbulence effect near the water inlet. Dimensions of hydraulic flume device are 10 m in length, 0.5 m in width, and 0.9 m in height. The configuration of hydraulic flume device is described in Figure 1.

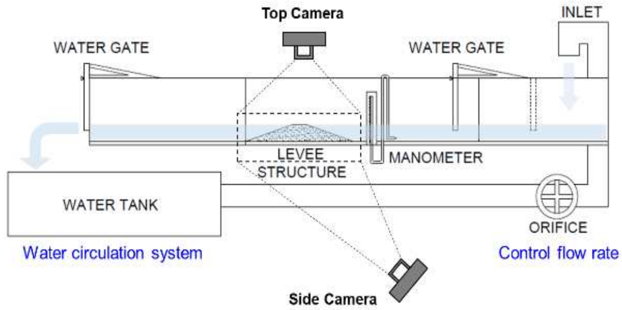

Figure 1. Hydraulic flume device.

For external erosion tests, the initial flow velocity and flow rate are controlled as 0.31 m/s and 3.5 L/s, respectively. These values are then increased up to 0.34 m/s and 16.1 L/s to facilitate erosion on xanthan gum treated earthen levee structures. For internal erosion tests, hydraulic head at the upstream reservoir is maintained at 150 mm (same as the levee model crest height)

3 RESULTS

3.1 *Xanthan gum treatment effect on external erosion*

Figure 2 shows that xanthan gum delays structure failure from external erosion.

For the control group (untreated earthen levee models), crest breaching leads to rapid severe failure of the overall structure as shown in Figure 2b and 2c. The test results indicate that the levee virtually collapses within 4 minutes. This rapid failure is due to the lack of cohesion within the coarse-grained soil structure between soil particles.

Moreover, it was observed that the coarse-grained soil particles detached from slope surface and flocculated even before crest opening (extreme water flow) occurred. However, soil detachment was not observed on the earthen levee structure treated with xanthan gum as described in Figure 2e. It is postulated that xanthan gum induces cohesion between soil particles as shown in Figure 2f, 2g, and Figure 2h. Despite the higher flow velocity and flow rate, xanthan gum treated earthen structure shows structural retention even after 330 mins (Figure 3).

3.2 *Xanthan gum treatment effect on internal erosion*

Internal erosion on control group (untreated earthen levee structure) is described in Figure 4. Immediately after the water flow initiation through the predetermined internal piping hole, untreated coarse-grained soil was rapidly eroded. In fact, pipe roof failure occurs after only 1 minute due to the driving force (self-weight of soil over pipe) being higher than the resisting force (cohesion of soil on side walls of the pipe). In other words, seepage occurs rapidly through the soil matrix on the earthen levee structure, resulting in roof failure, crest height decrease and overtopping. Additionally, it is observed that seepage through the soil matrix induces a decrease in downstream slope angle which is convergent to the internal friction angle.

For surface treated earthen levee structures, the internal erosion of the untreated part of the levee is severe while the xanthan gum treated part retains its structure. This proves that xanthan gum induced cohesion substantially enhances the structural stability of the levees, even though turbulent flow did occur within the untreated part. In detail, the turbulent flow occurred following interface between the treated part and untreated part as shown in Figure 4f. Continuous hydraulic water flow following the upstream slope leads to structure instability. Consequently, while the downstream slope structure is retained, the upstream slope is mostly failed as it loses stability. On the untreated earthen levee structure, downstream slope failure occurs first, while upstream failure is more prominent in the xanthan gum treated earthen levee structure.

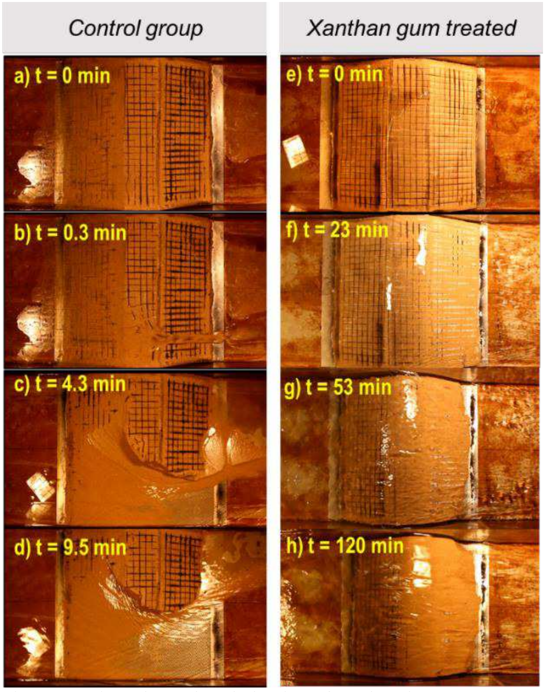

Figure 2. Time dependent behavior of earthen levee structure – erosion against external erosion (overtopping).

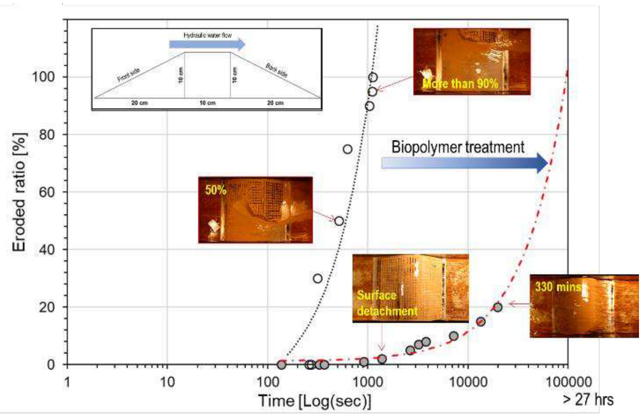

Figure 3. Reinforcing effect of earthen levee structure using xanthan gum biopolymer – focusing on external erosion (overtopping).

Figures 4f&h show the importance of the interface interaction between xanthan gum-sand and untreated sand, where most of the internal erosion is observed inside the untreated sand layer beneath the xanthan gum-sand surface crust.

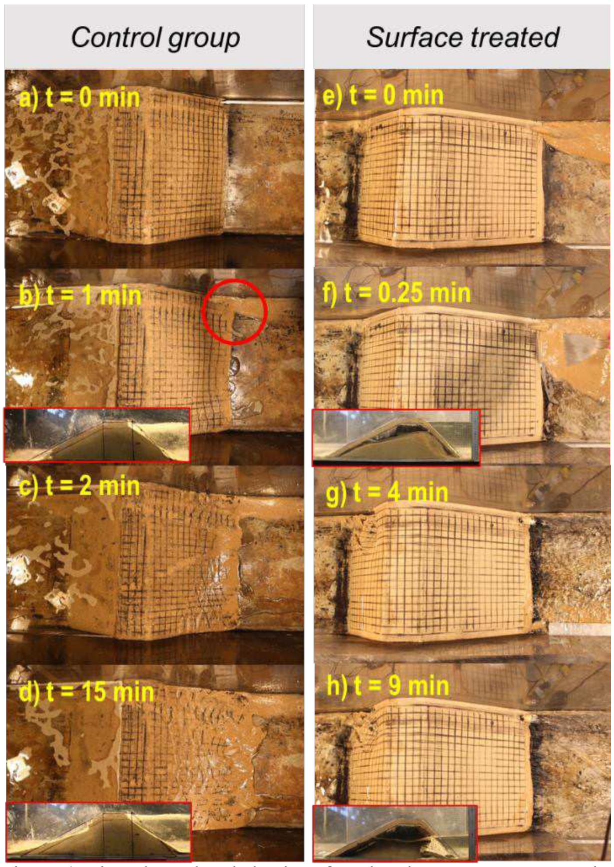

Figure 4. Time dependent behavior of earthen levee structure – erosion resistance against internal erosion (piping).

3.3 *Discussion*

Even though xanthan gum treated sand clearly shows the potential to delay earthen levee structure failure by overtopping, one needs to consider the economic efficiency for further practical implementation. The price of xanthan gum is gradually decreasing in the market, however it is still more expensive than conventional construction materials currently used to enhance the stability of earthen levee structures. Further work is required to fully understand the economic implications of using xanthan gum in this manner.

For internal erosion, the control group (untreated earthen levee structure) and xanthan gum treated earthen levee structure showed totally different outcomes on pipe failure, although both shared similar pipe failure mechanisms when the driving force (self-weight of soil over pipe) is bigger than the resisting force (cohesion of soil on side walls of pipe).

A further study on reinforcing design is required to achieve both effective strengthening effect and economic efficiency since this study focuses on exploring erosion reduction effect by BPST on surface of earthen levee structures.

4 CONCLUSIONS

This study aims to assess effect of biopolymer-based soil treatment (BPST) on earthen levee structures to reduce the most frequent failure hazards including overtopping and internal erosion. It is evaluated by laboratory experimental testing under steady state flow and findings from test are following below:

- For overtopping, it is shown that xanthan gum treatment delays structure failure by inducing cohesion between soil particles. The xanthan gum treated structure resists crest breach and just shows little surface detachment on downslope. It retains most of its structure after testing.
- For internal erosion, control group and xanthan gum treated structure show totally different progresses of internal erosion. It is likely that seepage is dominant after pipe failure on the untreated control group levee structure. However, on the xanthan gum treated earthen levee structure the erosion followed the interface between the untreated and treated parts of the levee leading to severe structure failure.
- Further study is required to better understand the economic implications of using BPST. A future study into the practical implementation of xanthan gum treated granular material levees is also recommended Additionally, particulate level analysis for internal erosion will be beneficial to better understand progressive internal erosion.

5 ACKNOWLEDGEMENTS

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