Investigation of erosion behavior of biopolymer treated soil using laboratory hydraulic flume testing

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ABSTRACT

As the failure of earthen dam structures have been mostly caused by overflow or piping events, numbers of research have tried to mitigate surface erosion against severe overflow. Recently, many studies suggested microbial biopolymer as a new environmentally friendly material to enhance the strength and erosion resistance of geotechnical engineering structures, but also to reduce the usage of cement. Microbial biopolymer has significant potential to improve the erosion resistance of soils due to its aimed coagulating characteristic with sustainable feature. In this study, the feasibility of microbial biopolymer treatment to improve waterfront earthen structures including dam, levee, and dike, is investigated via laboratory hydraulic flume erosion test. The results showed that the microbial biopolymer enhanced hydraulic erosion resistance at the surface of earthen levee models.

Keywords: Hydraulic erosion; Hydraulic flume testing; Surface erosion; Biopolymer; Soil.

1 INTRODUCTION

Biopolymer has been recently introduced as a new alternative for sustainable geotechnical engineering according to its competitive strengthening effect with environmentally friendly feature which does not contribute to global climate change relate to greenhouse gas emissions (Aguilar et al. 2016; Ayeldeen et al. 2016; Cabalar et al. 2017; Chang et al. 2016; Chang et al. 2018; Kulshreshtha et al. 2017; Latifi et al. 2016). Biopolymers show proper functions in geotechnical engineering in terms of shear strength increase, vegetation growth promotion, and hydraulic conductivity reduction (Ayeldeen et al. 2016; Badiane et al. 2001; Fatehi et al. 2018). Moreover, previous studies show the promising potential of biopolymers to enhance erosion resistance of soils via laboratory precipitation simulation (Chang et al. 2015) and Erosion Function Apparatus (EFA) approaches (Ham et al. 2016).

Despite previous studies have shown the feasibility of biopolymer treatment to mitigate soil erosion, pre-exiting attempts have several limitations. In detail, precipitation testing method cannot present laminar flow on soil surfaces. In other words, the flow can become a turbulent flow along the surface. Thus, the testing results cannot be precisely analyzed. Meanwhile, EFA method only considers particle detachment on water-soil interfaces, with the lack of considering water infiltration and accompanying soil pore pressure variation which also becomes a critical factor on soil destabilization. As a result, the experimental results can be distorted, and the erodibility of biopolymer treated soil cannot be accurately evaluated.

To evaluate surface erosion behavior of biopolymer treated soil, the laboratory hydraulic flume test was performed in this study. The target application model was decided to be a levee structure. Therefore, small-scale levee structure was made using biopolymer treated sand mixtures. Consequently, the surface erosion behavior at the levee structure was characterized, and the feasibility of biopolymer treatment on levee structure for practical implementation was verified in this study.

2 MATERIALS AND METHOD

2.1 Materials

Sand: Sydney sand is used in this study. It is classified as poorly graded soil (SP) by Unified Soil Classification System (USCS). It has the geotechnical properties as the maximum void ratio (e_{max}) of 0.92, the minimum void ratio (e_{min}) of 0.6, D_{50} of 0.36, coefficient of uniformity (C_u) of 1.18, coefficient of curvature (C_c) of 0.96, and specific gravity of 2.6 g/cm^3 (Payan et al. 2016). The particle size distribution curve is shown in Fig. 1.

Xanthan gum: Xanthan gum is anionic polysaccharide produced by the plant-pathogenic bacterium Xanthomonas campestris (Chang et al. 2015). Xanthan gum is a hetero-polysaccharide which has a primary structure consisted of two glucose units, two mannose

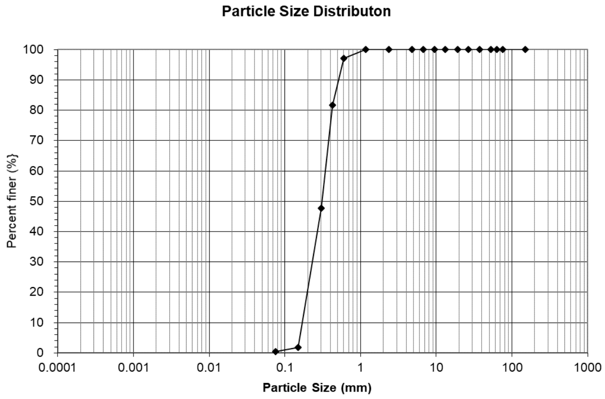

Fig. 1. Particle size distribution of Sydney sand

units, and one glucuronic acid unit (Becker et al. 1998).

The beta-D-glucose units in a primary structure has connection at 1 and 4 positions, therefore, it consists main chain. Two mannose units and one glucuronic acid unit are linked to the main chain by the connection toward glucose at O-3 position (García-Ochoa et al. 2000).

2.2 Method

<u>Sample preparation:</u> Clean and dried sand was mixed with xanthan gum hydrogel solution thoroughly. Xanthan gum hydrogel solution was prepared by mixing xanthan gum powder to deionized water with a laboratory rotary mixer resulting a solution having 5% xanthan gum concentration. Xanthan gum solution was then mixed with dry sand with 20% solution to soil content in mass which results to xanthan gum-sand mixture having 1% biopolymer to soil content in mass (m_{bp}/m_s = 1.0%).

Xanthan gum-sand mixture was molded to a levee model on a portable steel plate, having a 2:1 inclined slopes on both sides as shown in Fig.2. Non-cohesive (untreated) levee model has been prepared accordingly except xanthan gum biopolymer treatment.

<u>Test method:</u> Levee models were placed in a hydraulic flume apparatus (length 10 m; width 0.6 m; height 0.9 m) as shown in Fig.3. The flow rate has been controlled by monitoring feedback from manometer measurements.

For the noncohesive (untreated) levee model, the initial flow velocity and the flow rate were controlled as 0.31 m/s and 3.5 L/s, respectively. For xanthan gum-treated levee model, the flow velocity

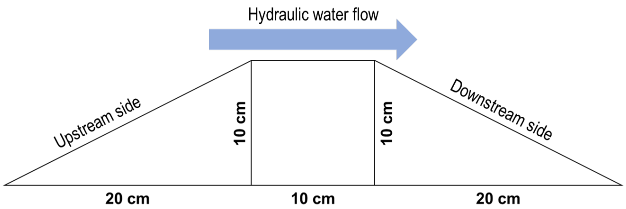

Fig. 2. Cross-sectional view of model levee.

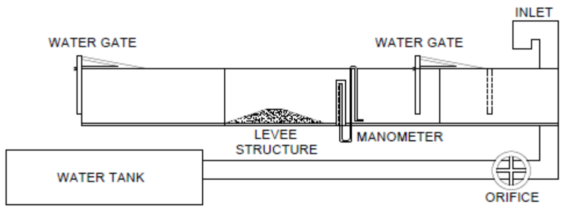

Fig. 3. Schematic diagram of the hydraulic flume testing device.

and flow rate were increased with time where the final flow velocity and flow rate marked 0.34 m/s and 16.1 L/s, respectively.

The erosion processes were monitored by optical cameras.

3 TEST RESULTS

The initiation time is defined as t = t_0, which the water flows from the reservoir to flume channel. For the noncohesive (untreated) levee model, the surface detachment of the upstream slope was firstly observed at initial phase of the experiment. The levee erosion was begun by upstream slope surface detachment as shown in Fig.4(a). Once overflow was initiated, the levee breaching was immediately started as shown in Fig.4(b). As levee breaching was progressed, breach opening was mostly widened along eroded parts of the levee model, which leads to severe failure of the levee structure as Fig.4(c) and 4(d). Severe erosion had collapsed the entire levee structure shown in Fig.4(e) and 4(f). The levee structure was thoroughly collapsed at t = *15.3* mins.

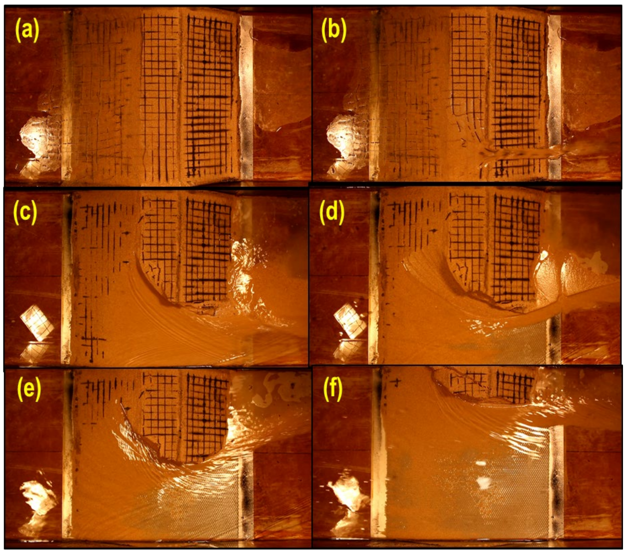

Fig. 4. The erosion behavior of levee structure using untreated sand. (a) upstream slope surface detachment during water level increase (t = *4.3* mins); (b) breach opening immediately after overflow (t = *4.6* mins); (c) 30% of erosion (t = *5.2* mins); (d) 50% of erosion (t = *8.6* mins); (e) 75% erosion (t = *10.4* mins); (f) more than 90% erosion (t = *15.3* mins).

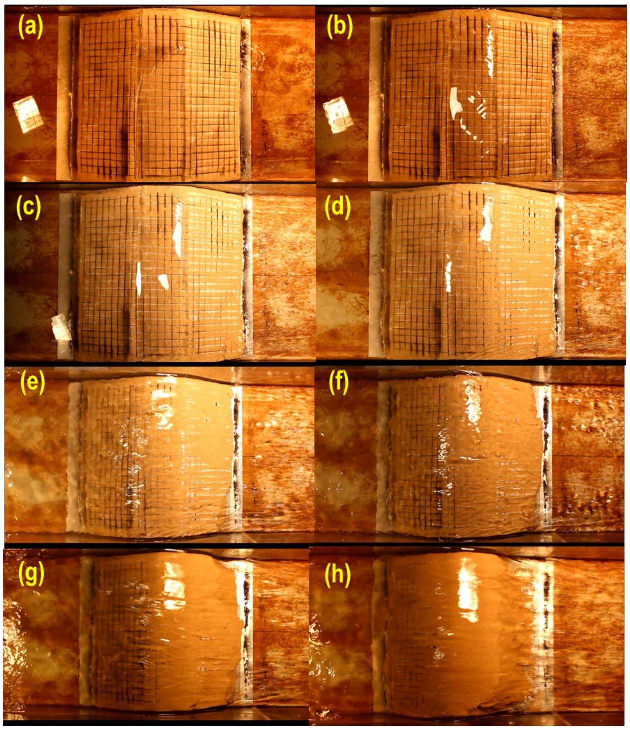

Fig. 5. The erosion behavior of levee structure using biopolymer treated sand. (a) intact surface before overflow; (b) at the onset of overflow; (c) no sign of erosion at *t = 15 mins*; (d) downstream slope surface detachment with increased flow rate (*t = 23* mins); (e) toe of levee being eroded off (*t = 44 mins*); (f) structure retention with slight toe erosion (*t = 53 mins*); (g) progressed downstream toe erosion (*t = 120 mins*); (f) levee structure maintaining itself with no piping effect (*t = 330* mins).

For the biopolymer treated levee model, the surface soil detachment at downstream slope and levee structure retention on erosion had been mainly observed as Fig.5. Unlike the noncohesive model, there was no surface detachment at the upstream slope immediately after overflow occurred (Fig.5a and 5b). This can be explained by the conglomeration of soil particles by biopolymer treatment (Chang and Cho 2018). With flow rate increase, the surface soil detachment was observed along the downstream slope of the levee structure, as shown in Fig.5(c) and 5(d). Despite the noncohesive levee model showed complete destruction at *t = 15 mins*, no sign of erosion at the levee structure was monitored at the same time frame (Fig.5c).

At maximum flow rate (16.1 L/sec), the downstream side of the levee structure started to show recognizable erosion along the downstream slope surface since 44 minutes (Fig.5e) and 53 minutes (Fig.5f) of testing. At *t = 120 mins* (Fig.5g) and *t = 330 mins* (Fig.5h), despite the front toe part has been eroded, more than 50% of the entire levee structure remains stable without any piping effect observed.

Thus, xanthan gum biopolymer treatment can be concluded to have positive effects on improving the stability of levee structures against severe flood

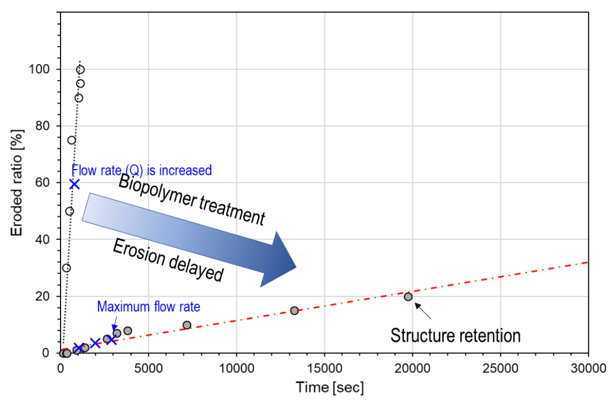

Fig. 6. The effectiveness of biopolymer treatment on levee structure.

conditions as: 1) Preventing immediate infiltration and excess pore pressure generation in the levee structure; 2) enhanced shear strength properties which provides higher surface erosion resistance; and 3) prevention of severe damage / failure of the entire levee structure even though partial failure occurs (Fig.6).

4 CONCLUSIONS

In this study, the resistivity of levee surface treated with biopolymer was evaluated via laboratory hydraulic flume testing. The experimental results showed that the biopolymer treated levee structure was merely incurring the upstream slope surface detachment with levee structure retention at *t = 330* mins, whereas the noncohesive levee structure caused to thorough structure failure with initiation of breach opening at *t = 15.4* mins. In detail, the biopolymer treated levee structure presented detachment of toe part followed by surface detachment, with maximum flow rate (16.1L/s). The biopolymer treated levee structure was maintained without piping phenomenon until *t = 330* mins. The significant reinforcing effect that resistant time was risen more than 20 times can be explained by conglomeration of soil particles by cohesion induced by biopolymer.

Consequently, the biopolymer treated levee structure shows significant potential to enhance hydraulic erosion resistance (strength properties) by preventing infiltration and excess pore water pressure build up. It is deduced that the ultimate goal of biopolymer treatment on levee structures can be achieved by raising endurance time with prevention of breach opening (piping) leading to critical failure. However, the economic feasibility should be investigated for effective biopolymer application in the geotechnical engineering field.

ACKNOWLEDGEMENTS

This research was supported by a grant (19AWMP-B114119-04) from the Water Management Research Program funded by the Ministry of Land, Infrastructure, and Transport (MOLIT) of the Korean government; and a grant (19SCIP- B105148-05) from the Construction Technology Research Program funded by the Ministry of Land, Infrastructure, and Transport of the Korean government.

REFERENCES

Aguilar, R., Nakamatsu, J., Ramírez, E., Elgegren, M., Ayarza, J., Kim, S., Pando, M. A., and Ortega-San-Martin, L. (2016). "The potential use of chitosan as a biopolymer additive for enhanced mechanical properties and water resistance of earthen construction." *Construction and Building Materials*, 114, 625-637.

Ayeldeen, M. K., Negm, A. M., and El Sawwaf, M. A. (2016). "Evaluating the physical characteristics of biopolymer/soil mixtures." *Arabian Journal of Geosciences*, 9(5), 1-13.

Badiane, N. N. Y., Chotte, J. L., Pate, E., Masse, D., and Rouland, C. (2001). "Use of soil enzyme activities to monitor soil quality in natural and improved fallows in semi-arid tropical regions." *Applied Soil Ecology*, 18(3), 229-238.

Cabalar, A. F., Wiszniewski, M., and Skutnik, Z. (2017). "Effects of Xanthan Gum Biopolymer on the Permeability, Odometer, Unconfined Compressive and Triaxial Shear Behavior of a Sand." *Soil Mechanics and Foundation Engineering*, 54(5), 356-361.

Chang, I., and Cho, G.-C. (2018). "Shear strength behavior and parameters of microbial gellan gum-treated soils: from sand to clay." *Acta Geotechnica*, 1-15.

Chang, I., Im, J., and Cho, G. C. (2016). "Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering." *Sustainability*, 8(3), 251.

Chang, I., Im, J., Chung, M.-K., and Cho, G.-C. (2018). "Bovine casein as a new soil strengthening binder from diary wastes." *Construction and Building Materials*, 160, 1-9.

Chang, I., Im, J., Prasidhi, A. K., and Cho, G.-C. (2015). "Effects of Xanthan gum biopolymer on soil strengthening." *Construction and Building Materials*, 74(0), 65-72.

Chang, I., Prasidhi, A. K., Im, J., Shin, H.-D., and Cho, G.-C. (2015). "Soil treatment using microbial biopolymers for anti-desertification purposes." *Geoderma*, 253–254(0), 39-47.

Fatehi, H., Abtahi, S. M., Hashemolhosseini, H., and Hejazi, S. M. (2018). "A novel study on using protein based biopolymers in soil strengthening." *Construction and Building Materials*, 167, 813-821.

García-Ochoa, F., Santos, V. E., Casas, J. A., and Gómez, E. (2000). "Xanthan gum: production, recovery, and properties." *Biotechnology Advances*, 18(7), 549-579.

Ham, S., Kwon, T., Chang, I., and Chung, M. (2016). "Ultrasonic P-Wave Reflection Monitoring of Soil Erosion for Erosion Function Apparatus." *Geotechnical Testing Journal*, 39(2), 301-314.

Kulshreshtha, Y., Schlangen, E., Jonkers, H., Vardon, P., and Van Paassen, L. (2017). "CoRncrete: A corn starch based building material." *Construction and Building Materials*, 154, 411-423.

Latifi, N., Horpibulsuk, S., Meehan, C. L., Abd Majid, M. Z., Tahir, M. M., and Mohamad, E. T. (2016). "Improvement of problematic soils with biopolymer—an environmentally friendly soil stabilizer." *Journal of Materials in Civil Engineering*, 29(2), 04016204.