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Slope Stability of an Earthen Levee Strengthened by HPTRM under Turbulent Overtopping Conditions

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Abstract**—**High performance turf reinforcement mat (HPTRM) is one of the most advanced flexible armoring technologies for severe erosion challenges. The effect of turbulence on the slope stability of an earthen levee strengthened by high performance turf reinforcement mat (HPTRM) is investigated in this study for combined storm surge and wave overtopping conditions. The results show that turbulence has strong influence on the slope stability during the combined storm surge and wave overtopping conditions. Among the surge height, peak wave force and turbulent force. The turbulent force has the ability to stabilize the earthen levee at the large wave force the turbulent force has strongest effect on the FS. The surge storm acts as an independent force on the slope stability of the earthen levee. It just adds to the effects of the turbulent force and wave force on the slope stability of HPTRM strengthened levee.

Keywords**—**Slope stability, strength reduction method, HPTRM, levee, overtopping.

I. Introduction

High performance turf reinforcement mat (HPTRM) is one of the most advanced flexible armoring technologies for severe erosion challenges. It has been studied for earthen levees protection in overtopping conditions [1]. Surge and wave overtopping of an earthen levee usually occurs during the extreme conditions, such as hurricane. The overtopping of an earthen levee produces fast-flowing, turbulent water velocities on the landside levee that can damage the protective grass covering and expose the underlying soil to erosion [2]. One of levee failure modes is rapid erosion of the landside levee soil during overtopping conditions. For example, during Hurricane Katrina, the earthen levees that surrounded the New Orleans experienced catastrophic overtopping and extensive damage during the hurricane [3]. After Hurricane Katrina, field investigations showed that most earthen levee damage occurred on the levee crest and landside slopes by overtopping [4]. Besides overtopping erosion, slope failures of levee occurred at different magnitudes of the overtopping forces during the hurricane that can result in the catastrophic failure of the levee system [5].

HPTRM is a combination of nylon filaments matrix and polyester geogrid reinforcement at low strains to lock soil in place, and provides permanent reinforcement to prevent soil loss during storm events [6]. As shown in Fig. 1, nearly 95% of space is open in this material. As the grass roots grow through the open space of HPTRM, roots become entwined within the turf reinforced mat. The interlocking between roots and HPTRM can enhance the roots resistance against hydraulic life and shear forces created by high water flow hydraulic erosion. HPTRM can be used as a vegetated slope reinforcement system that consists of a rolled-out geosynthetic composite material integrated with natural grass [7]. It has been tested in full-scale overtopping conditions for levee crest and landside slope during surge overflow, wave-only overtopping and combined wave and surge overtopping [1].

(a)

(b)

Fig. 1 (a) Three-dimensional structure of HPTRM mat, and (b) vegetated HPTRM system

Xu et al. [8] conducted a slope stability analysis in the surge-only, wave-only, and combination of surge and wave overtopping conditions for the HPTRM strengthened levee. It was found that HPTRM significantly improve the stability of levee during wave only overtopping, and during combined storm surge and wave overtopping conditions. However, the influence of turbulence on the stability of an earthen levee is not considered in these studies. The turbulent water velocities at the overtopping condition can produce a shear stress on the crest and landside slope of the earthen levee [9]. In addition to

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eroding the soil of the crest and landside slope of an earthen levee, the shear stress also affects the stability of the levee. Thus, the impact of turbulence and shear stress should be included in the slope stability analysis for the HPTRM strengthened levee during the overtopping conditions. This study includes the turbulence effect on the slope stability of an earthen levee strengthened by HPTRM under the condition of surge, wave and turbulence overtopping. The turbulent force is treated as a random force starting from the front of the crest and moving through the crest and landward side of the earthen levee. To simplify this study, erosion and scour caused by the turbulence is not included, and other robust levee strengthening methods are not considered.

II. NUMERICAL METHODS

A. Strength Reduction Finite Element Analysis of HPTRM Strengthened Levee

Finite element program, ANSYS, is used to conduct the slope stability analysis of HPTRM strengthened levee under the turbulent wave and surge overtopping. Strength reduction technique is applied to FEM to obtain slope stability safety factor [10]. This method initiates a systematic reduction sequence for the original effective shear strength parameters c' and ϕ', to find the factor of safety (FS) of a slope. The reduction values of shear strength parameters c_f' and ϕ_f', are defined as:

$$c_f' = c' / SRF \tag{1}$$

$$\phi_f' = \tan^{-1}\left(\frac{\tan\phi'}{SRF}\right) \tag{2}$$

where SRF is the Strength Reduction Factor. Same strength reduction factors corresponding to the c' and ϕ' terms were applied. The non-convergence method [11] was used as a suitable indicator of failure in this study. The failure criterion is the SRF that causes a sudden increase in dimensionless displacement, and the lack of convergence even when reaching the iteration ceiling. The factor of safety is the value of SRF to cause the slope to fail.

B. Conceptual Model for HPTRM Strengthened Levee

A clay-core levee embankment with HPTRM strengthened along the crest and landside slope is shown in Fig. 2. The geometry of the levee section has been chosen based on the same size as the full-scale overtopping tests recently performed [1]. The full-scale overtopping tests included surge only overflow, wave only overtopping, and combined storm surge and wave overtopping conditions. The levee crest is 3.25 m high, with a slope of 4.25H: 1V on the flood side and 3H:1V on the landside (protected) slope. A vegetated HPTRM system including grass, HPTRM, and soil was developed in Mississippi for six months. Clay soil was selected and compacted beneath the HPTRM system. As the grass roots grow through the open space of HPTRM, roots become entwined within the turf reinforced mat. The shear strength of vegetated soil in the HPTRM system was obtained from the large-scale direct shear tests [8]. Material properties of HPTRM system and soils used in this study are summarized in Table I.

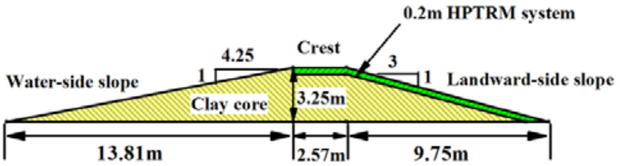


Fig. 2 Cross-section profile of levee embankment strengthened by HPTRM in crest and landside slope

TABLE I
PARAMETERS USED FOR SLOPE STABILITY ANALYSIS OF HPTRM STRENGTHENED LEVEE

Material	Friction angle ϕ' (^{0})	Cohesion c' (kPa)	Unit weight γ(kN/m^3)	Poisson's ratio ν	Young's modulus E' (MPa)
Clay (CL)	7.0	4.0	18.1	0.3	30
HPTRM system	42.0*	5.9*	13.0	0.26	50

Note: *interfacial shear strength parameters between clay and HPTRM.

Similar to the conceptual method in [8], the HPTRM strengthened levee was simplified to be a two-dimensional plane strain problem. The clay-core of earthen levee was assumed as elastic-perfect plastic material, satisfying elastic-perfect plastic strain-stress relationship. The Drucker-Prager elastic-perfect plastic model was used for the levee in this study. There is no relative movement between the HPTRM system and underlain clay core based on experimental observation [1]. Therefore, no interface element is used between the HTPRM and clay core.

C. Force Boundary Conditions

Gravity loads were applied to the 8-node quadrilateral or 6-node triangular elements mesh for the soil body and HPTRM strengthened system. Storm surge, wave, and turbulence with varying velocities and intensities are applied on the surface of the levee during hurricanes. The surge and wave can induce normal and shear stresses on the plane of the slope. Since turbulent flows are highly dissipative, and viscous shear stresses perform deformation work at the expense of the kinetic energy of turbulence, the turbulence is considered to induce a shear stress in this study. Surge forces over the crest are simplified to be constant shear stress and normal stress as shown in Fig. 3. Displacement boundary conditions were given as vertical rollers on side boundaries, and fixed at the base.

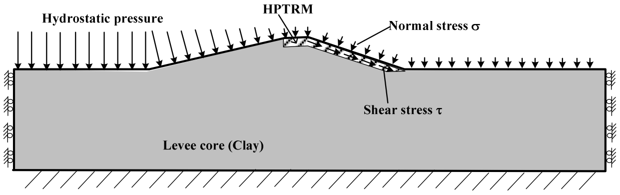


Fig. 3 Distribution of hydrostatic pressure on the levee caused by surge-only overflow

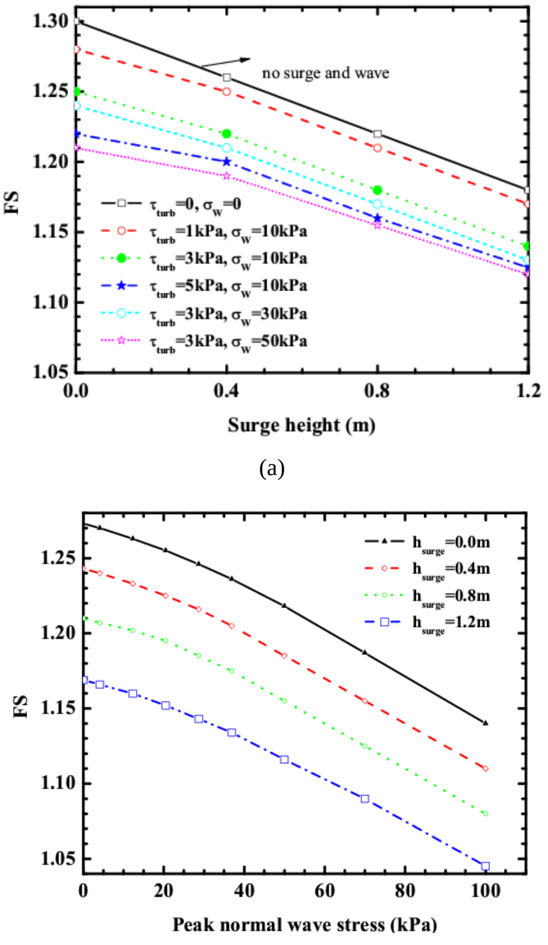
Wave force is assumed to be a random wave applied on the middle point of crest. The normal stress and shear stress developed in the wave force are defined as:

$$\sigma_w(t) = 0.5 * A_N\left[\left|f(t)\right| + f(t)\right], \qquad \tau_w(t) = A_S f(t) \qquad (3)$$

where σ_w is the normal stress, τ_w is the shear stress, $f(t)$ is random wave force function, A_N is the amplitude of the normal stress, and A_S is the amplitude of the shear stress. The effect of the turbulence is represented by a shear force acting on the crest and landside of the earthen levee. The turbulent shear force is a random force with certain amplitude, and moves from the left end of the crest all the way to the toe of the landside.

III. RESULTS AND DISCUSSION

In the combined storm surge and wave overtopping condition, the slope stability of the earthen levee is determined by the three loading parameters: surge height, peak wave forces, and peak turbulent force.



(a)

(b)

Fig. 4 FS as a function of: (a) surge height for different turbulent and wave forces, and (b) wave force for different surge height with turbulence stress of 2.0 kPa in combined wave and surge overtopping

A. Effect of Surge Height

Fig. 4 (a) shows the factor of safety (FS) as a function of surge height for the following condition: surge only without turbulence considered, peak turbulent force ranging from 1 kPa to 5 kPa with peak wave force of 10 kPa, and the peak wave force ranging from 30 kPa to 50 kPa while the peak turbulent force at 3 kPa. The FS decreases monotonically as the surge height increases. The surge only without turbulence condition has the largest FS. The turbulence has the tendency to reduce the FS. The FS decreases about 5% as the peak turbulent force increases from 1 kPa to 5 kPa.

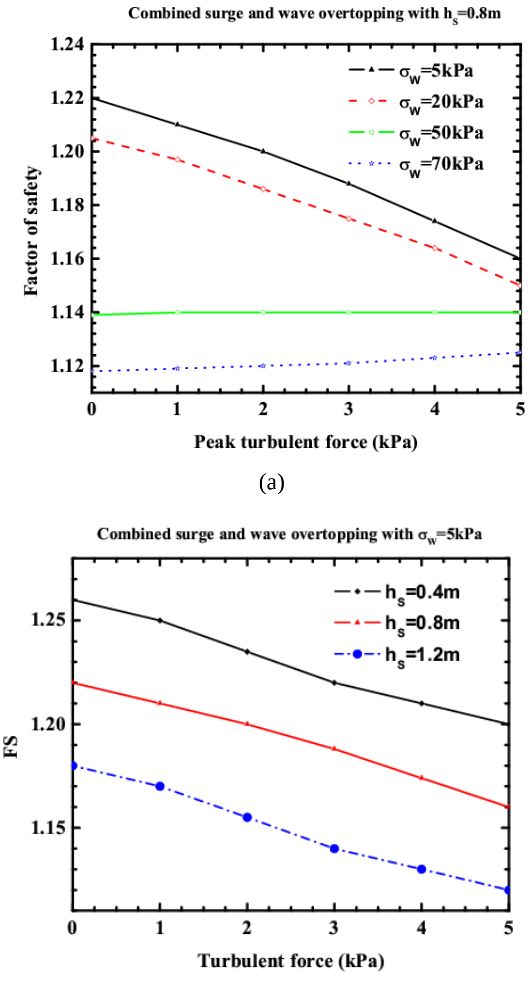
B. Effect of Peak Wave Force

The FS as a function of peak wave force is shown in Fig. 4 (b) for different surge heights and fixed peak turbulent force (2 kPa). The FS decreases slowly as the peak wave force increases from 0 kPa to 40 kPa. It drops quickly as the peak wave force increases from 40 kPa to 100 kPa. The FS decreases about 3% as the peak wave force increases from 0 to 40 kPa. It drops about 26% as the peak wave increases from 40 kPa to 100 kPa. The parallel curves of the FS on the peak wave forces for different surge heights indicate that the surge and wave independently affects the slope stability. This is different from the relationship of FS on the wave and turbulence in the wave only overtopping conditions.

C. Effect of Peak Turbulent Force

The dependence of the FS on the turbulent force is shown in Fig. 5 for different surge heights and peak wave forces. Fig. 5 (a) shows that the FS as a function of the peak turbulent force for surge height of 0.8 m, and peak wave forces being 5, 20, 50 and 70 kPa. The dependence of factor of safety on the peak turbulent force is similar to the wave only overtopping condition. For small peak wave force, the FS monotonically decreases as the turbulent force increases. It decreases about 5% as the peak turbulent force increases from 0 kPa to 5 kPa for a 5 kPa peak wave forces. As the peak wave force increases to 20 kPa, the FS decreases slower as the peak turbulent force increases compared to the 5 kPa peak wave force. When the peak wave force increases further to 50 kPa, the FS almost remains constant as the peak turbulent force changes. The FS increases slightly as the peak turbulent force increases for the case of 70 kPa peak wave force. This indicates that for large peak wave force, the turbulent force tends to stabilize the earthen levee.

The FS as a function of the peak turbulent force is shown in Fig. 5 (b) with different surge heights for a peak wave force of 5 kPa. With the small peak wave force (5 kPa), the FS decreases monotonically as the peak turbulent force increases for all the surge heights. The FS decreases about 5% as the peak turbulent force increases from 0 kPa to 5 kPa. The relation between the FS and the peak turbulent force is similar to that of surge only overflowing condition.



(a)

(b)

Fig. 5 The FS as a function of peak turbulent force: (a) for different peak wave force, and (b) for different surge heights in combined wave and surge overtopping

Comparing all these three parameters on the FS, the peak turbulent force has the strongest effect for small peak wave force in the combined wave and surge overtopping. The 5% change in the FS is induced by 5 kPa change in peak turbulent force. As the peak wave force exceeds 5 kPa, the wave becomes more important than turbulence. The turbulent force has the ability to stabilize the earthen levee at the large wave force. The surge storm acts as an independent force on the slope stability of the earthen levee. It just adds to it just adds to the effects of the turbulent force and the effect of the turbulent force and wave force on the slope stability.

IV. CONCLUSIONS

Influence of turbulence on the slope stability of an earthen levee strengthened by high performance turf reinforcement mat under overtopping conditions has been studied. In the combined surge and wave overtopping condition, the turbulent force has the strongest effect on the FS among the surge height, peak wave force and turbulent force. As the peak wave force exceeds 5 kPa, the wave becomes more important than turbulence. The turbulent force has the ability to stabilize the earthen levee at the large wave force. The surge storm acts as an independent force on the slope stability of the earthen levee. It just adds to the effects of the turbulent force and wave force on the slope stability.

Effects of erosion and scour are not included in the study although these are important components that trigger the instability of the slopes on the exterior side. In addition, the impact of the slope geometry and steepness of the slopes on the slope stability are not considered in this paper.

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REFERENCES

[1] Y. Pan, L. Li, F. Amini, and C. P. Kuang, “Full scale HPTRM strengthened levee testing under combined wave and surge overtopping conditions: overtopping hydraulics, shear stress and erosion analysis,” *Journal of Coastal Research*, vol. 29, pp. 182-200, 2013.

[2] G. L. Sills, N. D. Vroman, R. E. Wahl, and N. T. Schwanz, “Overview of New Orleans levee failures: Lessons learned and their impact on national levee design and assessment,” *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, vol. 134, pp. 556-565, 2008.

[3] J. Ubilla, T. Abdoun, I. Sasanakul, M. Sharp, S. Steedman, W. Vanadit-Ellis, and T. Zimmie, “New Orleans levee system performance during Hurricane Katrina: London avenue and Orleans canal south,” *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, vol. 134, pp. 668-680, 2008.

[4] ASCE Hurricane Katrina External Review Panel, *The New Orleans Hurricane Protection System: What Went Wrong and Why*. American Society of Civil Engineers, Reston, Virginia, 2007, pp. 1-70.

[5] J. Chatterjee, and F. Amini, “Slope stability analysis of T-wall subjected to Hurricanes loading,” *International Journal of Geotechnical Engineering*, vol. 5, pp. 103-112, 2011.

[6] D. Kelley, and R. Thompson, “Comprehensive hurricane levee design: Development of the controlled Overtopping levee design logic,” *SAME Technology Transfer Conference and Lower Mississippi Regional Conference*, Vicksburg, MS, pp. 70-81, 2008.

[7] R. Goodrum, “A comparison of sustainability for three levee armoring alternatives,” in *Optimizing Sustainability Using Geosynthetics*, the 24th Annual GRI conference Proceedings, Dallas, TX, USA, 2011, pp. 40-47.

[8] Y. Xu, L. Li, and F. Amini, “Slope stability analysis of earthen levee strengthened by high performance turf reinforcement mat under hurricane overtopping flow conditions,” *Journal of Geotechnical and Geological Engineering*, vol. 30, pp. 893-905, 2012.

[9] S. A. Hughes, J. M. Shaw, and I. L. Howard, “Earthen levee shear stress estimates for combined wave overtopping and surge overflow,” *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE, vo;. 138, pp. 267-273, 2012.

[10] D. V. Griffiths, and N. Lu, “Unsaturated slope stability analysis with steady infiltration or evaporation using elasto-plastic finite elements,” *International Journal of Numerical Analytical Method in Geomechanics*, vol. 29, pp. 249–267, 2005.

[11] D. V. Griffiths, and P. A. Lane, “Slope stability analysis by finite elements,” *Geotechnique*, vol. 49, pp. 387-403, 1999.