BENNETT, RPI

DHS Coastal Resilience Center

Research Project

Annual Project Performance Report

Covers reporting period January 1, 2016 – June 30, 2016

1. **Project Title:** Establishment of a Remote Sensing Based Monitoring Program for Performance Health Assessment of the Sacramento Delta

2. **Principal Investigator / Institution:** Victoria Bennett, Rensselaer Polytechnic Institute

3. **Other Research Participants/Partners:**
   - Tarek Abdoun, RPI
   - Mourad Zeghal, RPI
   - Mohammed Gabr, NCSU
   - Brina Montoya, NCSU;
   - NASA/Jet Propulsion Laboratory;
   - Joel Dudas, Department of Water Resources, Sacramento, CA;
   - USACE, Vicksburg, MS

4. **Short Project Description:**

   As climate change progresses in the form of continuous land subsidence and rising sea water level, the integrity and reliability of flood-control infrastructure become ever more essential components to homeland safety. This project will employ a sensor-based (remote sensing with in-ground instrumentation for validation) and model-aided approach to provide engineers and decision makers with systematic tools to assess the health and provide early warning of deteriorating levees in the Sacramento Delta. The modeling tool integrates the use of measured data with the concept of performance limit states to effectively achieve a performance-based, network-level health assessment of the levee system.

5. **Abstract:**

   As climate change progresses in the form of continuous land subsidence and rising sea water level, the integrity and reliability of earthen dams and levees become increasingly essential components of homeland security. The failure of levees during Hurricane Katrina in 2005 is a highly illustrative example of the criticality of these systems. But this distributed system of national flood-control infrastructure is aging and its structural health is deteriorating. Assessing the health, predicting the failure and implementing countermeasures are challenging tasks for any civil infrastructure in view of the complexity of the associated processes of long-term environmental degradation and

wear. To efficiently maintain this infrastructure, managing engineers should have access to fully automated programs to continuously monitor, assess the health and adaptively upgrade these systems. *A **validated** remote sensing-based (i.e., satellite or airborne radar) approach will be used to assess the health of this spatially distributed system in order to identify weak sections and impending failures that can be used to help prioritize maintenance and upgrade efforts.* This project highlights the potential of a remote sensing-based monitoring system and health assessment tools that will enable early identification and warning of vulnerable levee or dam sections enabling prioritized repair work. This project will validate the use of satellite imagery to detect rate of deformation of a levee section on Sherman Island. Such data will be used and implemented in a numerical model for estimating the probability of exceeding a performance limit state. This probability will provide an indication of the likelihood of failure and the extent of damage from such failure.

6. End users:

The work in this project is focused on developing an innovative platform for monitoring and condition assessment of the California Delta levees. A levee on Sherman Island is used for this purpose. The proposed approach couples the concept of deformation-based limit states (LS) with data collection from frequently employed remote sensing efforts to identify the levees' weak sections and possible impending failure modes. The modeling of the levee sections will provide condition assessment of their current state and will provide the context through which the monitoring data will be viewed to discern gradual and abrupt condition changes. The end users include the following:

i. California's Department of Water Resources (DWR);
ii. US Army Corps of Engineers (USACE);
iii. Federal Emergency Management Agency (FEMA);
iv. US Bureau of Reclamation (USBR); and
v. Levee Safety Boards.

Joel Dudas, Senior Engineer with California's DWR FloodSAFE Environmental Stewardship and Statewide Resources Office, Mike Sharp, Technical Director of USACE Engineer Research and Development Center (ERDC), and Rich Varuso, Senior Program Manager at USACE – Risk Management Center, will consult with the research team throughout the two-year project and will serve as ambassadors for the transition to practice. Joel Dudas is also an incident responder with DWR. Joel McElroy, Superintendent with Reclamation District #341, is responsible for bimonthly levee inspections and is a first responder for levee breaches on Sherman Island. John Paasch, Program Manager for the Delta Flood Emergency Preparedness, Response and Recovery Program, will link our project to others in DWR Emergency Management and California Emergency Management Agency (CalEMA) (http://www.water.ca.gov/floodmgmt/hafoo/fob/dfeprrp/). Jim Murphy, Head of Levee Condition Assessment Division of Risk Assessment, Mapping and Planning Partners (RAMPP), will help bring the project outcomes from FEMA Region IX to other critical coastal areas such as Louisiana (Region VI) and New York / New Jersey (Region II).

Multiple meetings between the PI, Joel Dudas, and Joel McElroy have occurred in the first period of this project. The outcomes of these meetings included a review of GPS station locations by Joel Dudas and Joel McElroy, sharing of DWR's prior site investigation documents, e.g., boring logs and soil profiles along monitored section, and a DWR review of soil profile geometry incorporated into finite element model. The importance of this project to these individuals and agencies has escalated due to the appearance of surface cracks in the setback levee section on Sherman Island. These cracks appeared in March 2016. The California Department of Water Resources and Reclamation District #341 is tasked with identifying improvement projects to the Sherman Island levee system that will protect public facilities and provide public benefits. Improved levees minimize the threat of levee failure, protect the Sacramento Delta water quality and protect the reliability of the State Water Project, Contra Costa Canal, and Central Valley Project. Due to the public benefit provided by Sherman Island levees and the valuable assets they protect, the Reclamation District and DWR gather a variety of technical information for analysis and use in assessing the status of the levee system, i.e., levee crown surveys, visual inspections, inclinometer monitoring, settlement plate monitoring, etc. All of these techniques require technical personnel to visit the site and manually collect data. The proposed UAVSAR and GPS/SAA monitoring of the Sherman Island levees will provide continuous deformation information that can be collected remotely. Currently, these agencies do not have a framework to prioritize their levee rehabilitation efforts. The outcomes of this project will be of direct benefit to Reclamation District #341, California's DWR, the Army Corps of Engineers, and FEMA. The end users will be the professional staff at these agencies that are in charge of monitoring and maintaining the Delta Levee system. The components of the monitoring/modeling framework in this project will be transferred to these agencies through Joel Dudas and our USACE stakeholder. This will be in the form of the instrumentation layout, frequency of data collection, algorithms to process the monitored data, and the numerical analyses model and the coupling of the monitoring and modeling to perform condition assessment of the levee section being investigated.

7. **Explanation of Changes:** Nothing to report.

8. **Unanticipated Problems:**

An unexpected policy from NASA's Jet Propulsion Lab resulted in a delay in establishing the subcontract. The contracts and grants office at JPL will not process paperwork for projects totaling less than $50,000. This has not resulted in any milestone delays in the first performance period because remote sensing validation was scheduled for the second performance period. Our plan to address this problem is to increase the JPL subcontract to $50,000 for performance periods 2 and 3. The money will come out of the equipment line item. The instrumentation equipment was purchased through other external funds (included in External Funding and Leveraged Support Table).

9. Project Outcomes:

The work in this project presents results of integrated and validated remote-sensing program and finite element modeling for a Sherman Island levee section. At this location, satellite images and in-ground GPS sensors are collecting displacement measurements. These measurements are used for the calibration of a numerical model using the finite element program PLAXIS 2D with mesh updating. The model is used to establish a deterministic performance response under rising water level loading and investigates the effect of the peat decomposition on the deformation response of the levee section.

The large deformation option in the finite element program PLAXIS 2D 2015 is used to model a levee section on Sherman Island, within the California Delta area. The section geometry was selected on the basis of the information presented by Jafari et al. (2016) as shown in Figure 1. The locations of Global Navigation Satellite System (GNSS) remote sensing recordings of displacement (GNSS-1, 2 and 3) are shown in Figure 1. Points A and B along the levee landslide side slope are used to compare the numerical model displacement with monitored GNSS records. Different finite element mesh resolutions are investigated from coarse to fine to very fine mesh showed a slight increase in the displacement. A fine 15-node element mesh was used with the domain having 1961 elements and 15975 nodes. Flow and deformation boundary conditions were assigned appropriately.

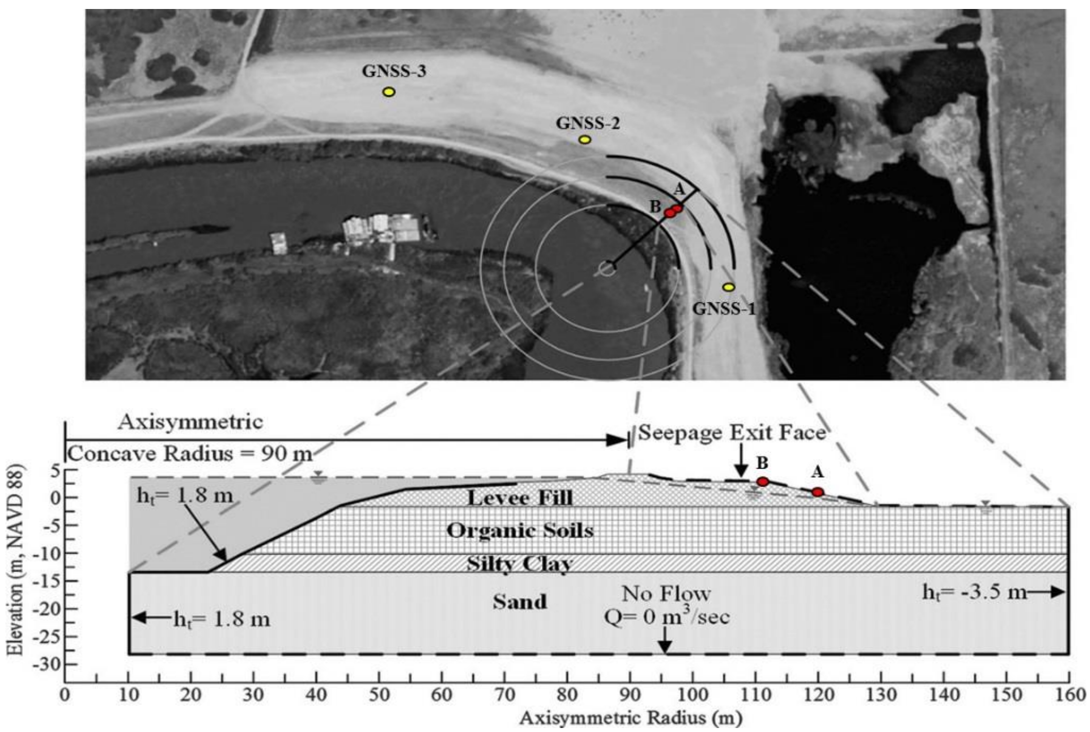

Figure 1.Model of Sherman Island proposed by Jafari et al. (2016).

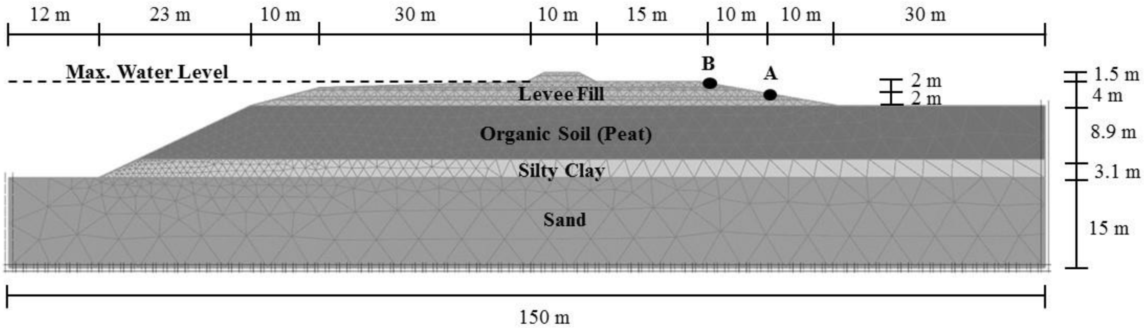

Figure 2. Finite element PLAXIS 2D levee mesh and boundary conditions

Soft Soil Creep Model (SSC) in PLAXIS is used to model to the peat layer to account for the viscous effects including creep and stress relaxation. This model takes into account secondary (time-dependent) compression (creep) and utilizes stress-dependent stiffness with the failure behavior conforming to the Mohr-Coulomb criterion. The input parameters for the soil model were assumed from the literature as limited data is available for the Sherman Island site. The levee is modeled using staged construction in 7 layers. Direct generation of initial effective stresses, and pore pressures and state parameters in the foundation layers is performed before construction of the embankment. The initial groundwater level was assumed at the boundary between the fill layer and the peat layer.

Several points along the landslide side slope were chosen to investigate the displacement response given the change in the peat properties and place such a response within the context of limit states. Results for vertical displacement (Negative sign means settlement downwards) versus time for fibrous peat are shown in Figure 3 for points A and B (designated on Figure 1). These points were chosen to allow for the model calibration with the GNSS-1 and GNSS-2 remote sensing records available near these locations in the Sherman Island levee. These GNSS data are for a one-year period from 4/1/2015 up to 4/1/2016. In this case, the rates of deformation with time show a relatively close trend as the model results fall between the range of measured deformation at points A and B. The GNSS data showed an average of 0.13 m of deformation per year compared to the 0.095 per year computed for points A. The rates between the model results and point B were not in agreement but the monitored points are located on the landside side slope in locations consistent with “point A” as shown in Figure 1.

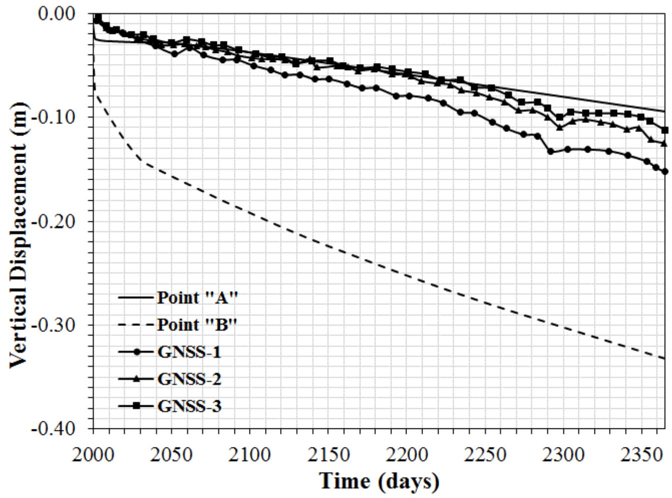

Figure 3. Displacement with time for fibrous peat versus measured data

Similar to the approach for model calibration, the levee is modeled using staged construction in 7 layers. Direct generation of initial effective stresses, and pore pressures and state parameters in the foundation layers is performed before construction of the embankment. The groundwater level was assumed at the boundary between the fill layer and the peat layer. The time interval for placing each layer was set to 1 day. In these phases, the displacement and strains are reset to zero before placement of the next layer and undrained behavior was ignored. Large deformation option was used (updated mesh technique) in all phases.

Water level was raised on two stages; first to reach its normal elevation (sunny day) of 1.5 m below crest. Second, a transit analysis is preformed where water level is raised with a rate of 0.08 m/hr to reach its max elevation (1 m below crest), then leaving it there for a week (7 days) while performing a consolidation analysis. Water level was then lowered with the same rate of 0.08 m/hr to the sunny day level of 1.5 m below crest. At such point, consolidation analysis of 1000 days was performed to capture the deformation profile with time. After the end of consolidation stage, another cycle of raising and lowering water level was performed with the exact same rate and stages as before. Then, a consolidation phase of another 1000 days was carried out. The results of such analyses are shown in Figure 4. The displacement profiles at points A and B showed that the effect of the transient high water level loading on the displacement magnitude is insignificant compared to the secondary compression due to the presence of the peat layer. The assumption of having an amorphous peat layer leads to a lower settlement with time of the levee section compared to fibrous peat. The rate of deformation in the case of the amorphous peat increases with time, as shown in Figure 4, due to the smaller change in void ratio as compared to the amorphous peat, and therefore a larger secondary compressibility rate with time. As peat properties transition with time from fibrous to amorphous case, the vertical deformation will be bounded by the trend shown in Figure 4. Figure 5 shows the change in the deviatoric strain with time and the associated limit states on the basis of using the mean value of C_α/C_c=0.06 for assessment of deformation.

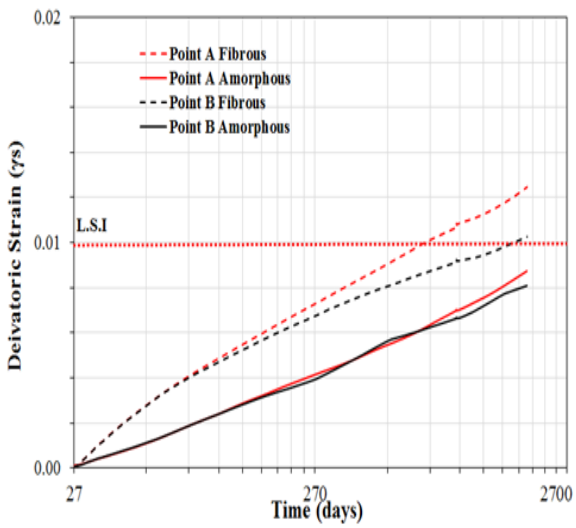

Figure 4. Vertical Displacement with time for fibrous and amorphous peat.

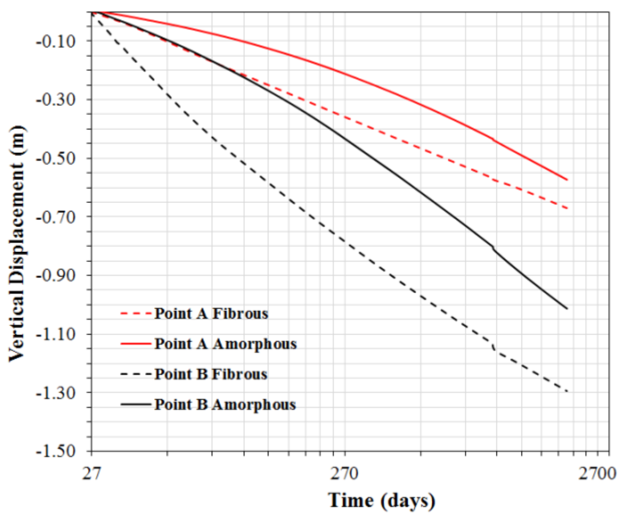

Figure 5. Total Deviatoric Strain (γ_s) with time and limit state criteria for mean value of C_α/C_c=0.06.

Based on the results in this work, the following conclusions are advanced:

1- Amorphous peat shows stiffer response and lower compressibility than fibrous peat, which agrees with literature (Mesri and Ajlouni, 2007). The assumption of amorphous peat led to lower computed displacements overall that ranged from 10 to 30% depending on the location within the domain.

2- The analyses indicated a relatively small mechanistic deformation induced by "extreme" water level under transient conditions. This is in comparison to the continuous and large deformation induced by the compression of the peat layer. The high-water level will however affect the exit hydraulic gradients and may lead to critical conditions as was discussed by Jafari et al (2016).

3- The variability in the reported values for compression coefficients (C_c and C_α) for fibrous and amorphous peat suggests these values need to be better defined as a function of fiber contents, state of decomposition, and water content. A parameter in terms of cellulose and lignin content can provide insight as to the chemical composition of the materials and the related shear strength with aging for more accurate performance assessment of the levee.

The analyses results indicated the exceedance of LS I in terms of deviatoric strain, with main driving factor being the compressibility of the peat layer. The deformation of the embankment levee is non-uniform due to stress variability with location. The continuous large deformation can lead to compromising the levee hydraulic performance function and transitional sliding of the embankment as presented by Duncan and Houston (1983).

10. Research Activity and Milestone Progress:

Research Activities and Milestones: Progress to Date

Reporting Period 1/1/2016 – 6/30/2016			
Research Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not reached, and when completion is expected
Task a. Appropriate sensor selection and layout	2/15/2016	100%	
Task b. Deployment of field sensors in Sherman Island	6/30/2016	100%	
Task i. Site Data Collection	6/30/2016	100%	
Research Milestone			
Report on instrumented test site on Sherman Island	6/30/2016	100%	Upon completion of field instrumentation installation, Joel Dudas and Joel McElroy were briefed on setup and technology. Instrumentation cabinet access keys were provided to Bryan Brock of DWR (liaison between field site and Sacramento office).
Characterization of the subsurface properties and possible constitutive relationship to use in the modeling effort	6/30/2016	100%	Site investigations and boring logs provided by DWR were used by NCSU as input geometry for finite element model. Literature review and previous work by NCSU (as part of UNC-CH's Center of Excellence) used to evaluate available constitutive models for peat soils.

Transition Activity and Milestone Progress:

Transition Activities and Milestones: Progress to Date

Reporting Period 1/1/2016 – 6/30/2016			
Transition Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not reached, and when completion is expected
Present preliminary findings of Outcomes 1 and 3 at the CRC annual meeting	6/30/2016	100%	
Transition Milestone			
Report on subsurface properties of the Sherman Island Levee section to be studied reviewed by DWR	6/30/2016	100%	During a face-to-face meeting in June 2016, Joel Dudas of DWR provided previous site investigations and boring logs to PI Bennett. These documents were used to select input parameters and geometry for finite element model. Appropriateness of resulting model was reviewed and accepted by Joel Dudas.

11. Interactions with education projects:

The PIs engaged some CRC MSI education partners at the CRC Annual Meeting in March 2016. Unfortunately this was too late to make arrangements for the summer of 2016. We will start planning for the summer of 2017 now. While we have links to the University of Puerto Rico, Mayaguez through RPI graduate Ricardo Ramos, we do not have enough budget to fully host an intern from Puerto Rico for the summer. We will work with Robert Whalin to identify some domestic students that will be placed at RPI or NCSU in the summer of 2017 within an appropriate budget. If the intern is placed at RPI, undergraduate student activities in the Center for Earthquake Engineering Simulation (CEES) will be leveraged for this CRC intern as well.

12. Publications:

- "***Monitoring and Modeling of Peat Decomposition in Sacramento Delta Levees***" Amr Helal, Victoria Bennett, Mo Gabr, Roy Borden and Tarek Abdoun. Submitted to the Proceedings of Geotechnical Frontiers 2017, Orlando, Florida, March 12-17.

- ***"Deformation Monitoring for the Assessment of Sacramento Delta Levee Performance"*** Victoria Bennett, Mo Gabr, Amr Helal, Cathleen Jones, and Tarek Abdoun. Accepted abstract for Geo-Risk 2017 (Geotechnical risk from theory to practice), Denver, Colorado, June 4-7.

13. CRC Performance Metrics:

CRC Performance Metrics			
Metric	**Research**	**Education**	**Center**
Courses/certificates developed, taught, and/or modified		See Table	
Enrollments in Center-supported courses/certificates			
HS-related internships (number)			
Undergraduates provided tuition/fee support (number)			
Undergraduate students provided stipends (number)			
Graduate students provided tuition/fee support (number)	2		
Graduate students provided stipends (number)	2		
Undergraduates who received HS-related degrees (number)			
Graduate students who received HS-related degrees (number)			
Certificates awarded (number)			
Graduates who obtained HS-related employment (number)			
SUMREX program students hosted (number)			
Lectures/presentations/seminars at Center partners (number)			
DHS MSI Summer Research Teams hosted (number)			
Journal articles submitted (number)			
Journal articles published (number)			
Conference presentations made (number)	2		
Other presentations, interviews, etc. (number)	1		
Patent applications filed (number)			
Patents awarded (number)			
Trademarks/copyrights filed (number)			
Requests for assistance/advice from DHS agencies (number)			
Requests for assistance/advice from other Federal agencies or	4		
Total milestones for reporting period (number)	3		
Accomplished fully (number)	3		
Accomplished partially (number)			
Not accomplished (number)			
Product/s delivered to end-user/s (description and recipients)	See Table		
External funding received	See Table		
Leveraged support			
Articles on Center-related work published on website			
Coverage in media, blogs (number)			
Social media followers (number)			
Posts to social media accounts (number)			
Events hosted (number)			

Website hits (number)			

Table for Documenting CRC Research Project Product Delivery

Product Name	Product Type	Approx. Delivery Date	Recipient or Anticipated End Users
REES "Risk Estimator for Embankment Structures"	Software	June 2017	Federal Agencies looking for an expedient means to assess performance of levees and earth dams

Table for Documenting External Funding and Leveraged Support

External Funding			
Title	PI	Total Amount	Source
Establishment of Sensor Driven and Model Based Health Assessment for Flood Control Systems	Tarek Abdoun	$60,000	US Army Engineer Research Development Center
New Faculty Startup Funds	Victoria Bennett	$241,500	Rensselaer Polytechnic Institute

Leveraged Support	
Description	Estimated Annual Value
Spare GPS equipment available from JPL to maintain instrumentation installed in Sherman Island setback levee.	$34,500

References

Duncan, J. M., and Houston, W. N., (1983). "Estimating failure probabilities for California levees." *Journal of Geotechnical Engineering*, 109 (2): 260-268.

Jafari, N. H., Stark, T. D., Leopold, A. L., and Merry, S. M., (2016). "Three-dimensional levee and floodwall underseepage." *Canadian Geotechnical Journal*, 53:72-84, 10.1139/cgj-2014-0343.

Mesri, G. and Ajlouni, M. (2007). "Engineering Properties of Fibrous Peats." *J. Geotech. Geoenviron. Eng*., 10.1061/ (ASCE) 1090-0241(2007)133:7(850), 850-866.