BENNETT, RPI

DHS Coastal Resilience Center

Research Project:

Annual Project Performance Report

Covers reporting period July 1, 2016 – June 30, 2017

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;
   - Cathleen Jones, NASA/Jet Propulsion Laboratory;
   - Joel Dudas, Department of Water Resources, Sacramento, CA;
   - USACE, Vicksburg, MS

4. **Short Project Description ("elevator speech"):**

   As climate change progresses in the form of continuous land subsidence and rising sea water level, the integrity and reliability of flood-control infrastructure has become ever more essential components to homeland safety. This project employs 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. An artificial neural network tool labeled Risk Estimator for Earth Structures (REES) is developed for the transition of the research findings to the end users.

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 coupled with analyses to place the monitored data in context of performance parameters will be used to assess the health of this spatially distributed system. This innovative approach serves to identify weak sections and impending failures and 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. An artificial neural network tool labeled Risk Estimator for Earth Structures (REES) is developed for the transition of the research findings to the end users.

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.

DWR is engaged in this project by default because they own the section of levee containing the in situ instruments. They have been available for on-site support during the initial instrument installation and subsequent maintenance visits. They have provided boring locations and layouts, in addition to access to historic inclinometer readings of the Sherman Island setback levee test site. Joel Dudas, Senior Engineer with California's DWR FloodSAFE Environmental Stewardship and Statewide Resources Office, Technical Director of USACE Engineer Research and Development Center (ERDC), and a 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 Governor's Office of Emergency Services (CalOES) (http://www.caloes.ca.gov/). Brian Banning (ASIS Certified Protection Professional) and Mark Johnson at CalOES are interested in receiving monitored data and incorporating into the Flood Emergency Response Information Exchange (FERIX) data management system (http://ferix.water.ca.gov/webapp/home.jsp). Kent Zenobia in the Flood Maintenance Office of DWR will facilitate the data sharing to the FERIX system. 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). Acting Technical Director of USACE ERDC, and Research Geologist for USACE ERDC, are funding a pilot project at RPI, 'Historic InSAR Case History Study of New Orleans Risk Reduction Infrastructure, Louisiana.' Transition efforts will be enhanced by leveraging both projects.

7. Unanticipated Problems:

An artificial neural network (ANN) tool, Risk Estimator for Earth Structures (REES), is a product of this research project that will be provided to the end users. We have determined that the parameter to be used for training this tool should be the shear strain at critical locations within the earth structure rather than using the probabilities of exceedance. A scaled conjugate gradient backpropagation training function is implemented in MATLAB to train the ANN tool and we believe that the modified approach will lead to a lower mean square error.

8. Project Impact:

The work conducted so far includes the integration of a validated remote-sensing monitoring program and numerical modeling towards the development of protocol for assessing the integrity of levees. The Sherman Island levee section, within the California Sacramento Delta area, is used as a testbed for the development of the proposed technology. The Sacramento Delta levee system provides significant agricultural value to the State of California and economic value to the Nation in terms of protecting the freshwater aqueduct system and maintaining the freshwater head in the surrounding rivers.

Sherman Island levees were originally constructed around the 1870s. This implies around 147 years of peat layer decomposition for these levees (~50,000 days). Data (from literature) show the Sherman Island site to be underlain by highly fibrous peat. Satellite images and in-ground GPS sensors are used to collect displacement measurements at the study levee section. Three stand-alone, continuously monitoring GPS stations were installed on the setback levee on Sherman Island at locations shown in Figure 1a. Concrete pedestal foundations were used to anchor the station to the levee surface, Fig. 1b. Each station contains a Novatel ProPak 6 receiver and a dual-frequency GPS plus GLONASS pinwheel antenna (Fig. 1c). The ProPak 6 is a high performance Global Navigation Satellite System (GNSS) receiver capable of receiving and tracking different combinations of GNSS signal and integrated L-Band on 240 channels. The receivers have a built-in cellular modem and are connected to the AT&T network for remote data transmission.

The results from the three GPS stations are shown in Figure 2. Data shown herein was collected from April 2015 to January 2017. The data includes North, East, and Height measurements from top to bottom. North and East represent lateral movement of the levee surface and the height component is measuring settlement. The settlement accumulates to approximately 12 cm over a one year monitoring period. The data from August 2015 to April 2016 can be compared to satellite data collected in this area during that time period. Vertical lines have been added to Fig. 3 to indicate this time span. The displacement rates to be compared with satellite measurements are included on the right-hand side of the plots.

Satellite data was also collected over the levee test site in the same time period of the GPS data by the Japan Aerospace Exploration Agency. The Advanced Land Observing Satellite-2 (ALOS-2) uses L-band Synthetic Aperture Radar with a 1.2 GHz frequency range (22.9 cm wavelength). The Short Baseline Subset (SBAS) analysis technique was used with nine ALOS images of the setback levee on Sherman Island. The results of this analysis are shown in Figure 3. Time series plots for two points in the vicinity of the GPS station GNSS-2 are included. The cumulative settlement measurement is approximately 3.5 cm from August 2015 to April 2016 in the line of sight (LOS) of the satellite. This value could be roughly compared to 8 cm of settlement measured from GNSS-2 from August 2015 to April 2016. This favorable initial comparison will be improved by projecting the GPS measurement on to the LOS of the satellite (incidence angle of 32-35$_{o}$). In this projection, GNSS-2 measures 4.8 cm of displacement.

The GPS measurements are used for the calibration of a numerical model, using the finite element program PLAXIS 2D, with large deformation mesh updating. A fine 15-nodel element mesh was used with the domain having 1961 elements and 15,975 nodes. Locations of Global Navigation Satellite System (GNSS) in situ recordings of displacement (GNSS-1, 2 and 3) are shown in Figure 4. Points A and B along the levee landslide side slope are used to compare the data from the numerical model with monitored GNSS records. Flow and deformations boundary conditions were assigned appropriately.

The data from the model are used to establish fragility curves providing the probability of exceeding performance limit states including the influence of peat layer decomposition/aging with time. Peats with three degrees of decomposition, from fibrous (H1-H3) to hemic (H4-H7) to amorphous (H8-H10), are modeled and the corresponding deformation aspects are shown in Figure 5 at 10,000 days for the presumed three-peat decomposition cases.

Figure 5 shows higher deformation especially at the toe location for fibrous (H1-H3) peat compared to hemic and amorphous peats. As peat decomposition level increases, the deformation values decrease as the peat layer experiences less compression with time. Figure 6 shows the fragility curves for the three modeled peat layers. In this case, fragility is defined as the probability of exceeding a given limit state, given the decomposition rate of the peat layer with time. It should be noted that LSIII corresponds to a critical condition, defined as exceeding shear strain of 5% or higher at the landside toe area.

As shown in Figure 6, for fibrous (H1-H3) peat, shear strain exceeds a value of 1% (corresponding to LSI) at approximately 270 days. Probability of exceeding LSII increases around 9100 days when shear strain reaches 2.6% and the probability of exceedance keeps increasing to reach 95% at 50,000 days. For hemic (H4-H7) peat, it takes 10,000 days to reach 100% probability of exceeding LSI as the shear strain trend for this case does not exceed 1% until 1800 days. The use of amorphous peat (H8-H10) properties requires more time (around 300,000 days) to yield an indication of 100% probability of exceedance. The probability of exceeding LSII for both hemic and amorphous peat is very low, as the shear strain values did not reach close to 3% (LSII) by 50,000 days.

Within the context of modeling, the use of fibrous (H1-H3) peat yielded a shear strain value around 3.2% at 50,000 days, which corresponds to the approximate lifetime of the Sherman Island levee (Figure 3). This value of shear strain corresponds to 100% probability of exceeding LSI. As peat ages with time, more shear strain will be developed causing the probability of exceeding LSII to increase as well and therefore increases the vulnerability of the levee and its susceptibility to failure (reaching LSIII) under extreme flood events. However, it is important to note that several factors still need to be investigated, such as the time needed in the field for peat to decompose, as the decomposition rate is influenced by temperature, aerobic and anaerobic activity, pH, etc. These analyses nonetheless demonstrate the value of condition assessment of levee health to place its vitality in the context of impending severe weather events.

Risk Estimator for Embankment Structures (REES) Tool Development

REES uses an Artificial Neural Network (ANN) model to assess the probability of exceeding a limit state without the need to conduct advanced numerical modeling. A graphical user interface (GUI) tool is developed to implement the ANN model and allows for a user-friendly approach for estimating the probabilities of exceeding a given limit state. ***REES*** provides risk in terms of failure consequence as a function of fatality rates with distance away from the embankment structure using peak breach discharge (cubic feet per second) and 10-year discharge (cubic feet per second) values from the FEMA loss of life risk sheet (FEMA risk tool, 2008). However, the risk can be estimated in terms of economic impact and loss of functionality of critical infrastructure if the “impact” data are available. A user manual is developed to guide the user through operating the tool with examples.

9. Research Activity and Milestone Progress:

Research Activities and Milestones: Progress to Date

Reporting Period 7/1/2016 – 6/30/2017			
Research Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not reached, and when completion is expected
Task a. Site Data Collection	6/30/2016	100%	
Task b. Model Calibration	6/30/2017	100%	
Task c. Baseline Case	6/30/2017	100%	
Task d. Probability of Exceeding Limit State and Uncertainty	6/30/2017	70%	*We had to revise the approach implemented in the Artificial Neural Network (ANN) REES software, which we use for estimating the probability of exceeding a limit state, and therefore the risk. The approach that was previously implemented in the ANN module was based on machine learning through training with data on "probability of exceedance." We discovered that these probability values are clustered at two extreme ends; in the low range (1 in 100,000) or in the high range (1-5 in 10; under very severe conditions). While performing the extensive parametric studies on levees that is currently undergoing, we have discovered that a better parameter to use for training ANN is the shear strains within the embankment as these emerge as a function of flood loading. These values are well distributed in the range of .01% to 5% and therefore the training of REES software is more robust. We will then link the output of the ANN to an Excel worksheet for estimating probability of exceedance and the corresponding risk using REES. This "linking" process will be performed in the background, and the user interface will remain simple. We anticipate the software*

			will be delivered by the end of the year for beta testing.
Task e. Field Comparison	12/31/2017	70%	
Research Milestone			
Characterization of the subsurface properties and possible constitutive relationship to use in the modeling effort	6/30/2016	100%	
Establishment of Levee Section fragility in terms of probability of exceedance versus flood cycle and level	6/30/2017	70%	See explanation for Task d above.
Establish the coupled model-monitored data approach as a means to identify vulnerabilities of the levee section studied herein.	12/31/2017	20%	

10. Transition Activity and Milestone Progress:

Transition Activities and Milestones: Progress to Date

Reporting Period 7/1/2016 – 6/30/2017			
Transition Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not reached, and when completion is expected
Present preliminary findings of Task 1 at the CRC annual meeting	6/30/2016	100%	
Present modeling approach, and model results at the Geo-Frontiers annual meeting	3/12/2017	100%	
Present paper at Geo-risk 2017	6/4/2017	100%	
Submit a Journal paper documenting the findings of the 2-year study	12/31/2017	10%	
Transition Milestone			
Report on subsurface properties of the Sherman Island Levee section to be studied reviewed by DWR	6/30/2016	100%	
Calibrated model of the levee section with accurate description of section response	6/30/2017	50%	See explanation for Task d above.

Establishment of the levee section condition in terms of probability of exceedance the predefined limit states	6/30/2017	100%	
Successful demonstration of the coupled model-monitored data for identifying vulnerabilities of the levee section with variation in reservoir level and number of flood cycles	12/31/2017	20%	

11. Interactions with education projects:

The PIs engaged some CRC MSI education partners at the CRC Annual Meeting in February 2017. Unfortunately this did not result in a summer intern. 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 be happy to work with Tom Richardson to identify some domestic students that will be placed at RPI or NCSU in the future, if possible. 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. We have also identified an additional opportunity to leverage an existing educational project at Rensselaer Polytechnic Institute.

Professors Abdoun and Bennett are currently developing a mixed reality and mobile (MR&M) game that will be integrated with traditional geotechnical engineering education but will provide an opportunity for students to experience the field work and testing necessary to instill practical skills. In order to educate a professional workforce who is properly trained in STEM, able to identify warning signs in advance of system failures, and capable of making the right decisions, undergraduate engineering education must be transformed to include the development of sense-making capabilities - the skills to recognize, report, diagnose, and assess risks.

Educational games have the transformative potential to overcome the societal challenge associated with the deteriorating infrastructure, while also utilizing a technology that is familiar to today's students. The proposed game-based module is flexible and variations of the game can be scaled with little difficulty, depending on the targeted audience. The developed MR&M game can be made available to geotechnical engineering programs throughout the United States as well as used by practitioners, such as the Department of Water Resources in California and the US Army Corps of Engineers. CA DWR has expressed interest in using the developed game to train its levee inspection personnel.

12. Publications:

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

- ***"Deformation Monitoring for the Assessment of Sacramento Delta Levee Performance"*** Victoria Bennett, Cathleen Jones, David Bekaert, Jason Bond, Amr Helal, Joel Dudas, Mohammed Gabr, Tarek Abdoun. Geo-Risk 2017 (Geotechnical risk from theory to practice), Denver, Colorado.
- ***"Use of remote-sensing deformation monitoring for the assessment of levee section performance limit state"*** Victoria Bennett, Chung Nguyen, Tarek Abdoun, Amr Helal, Mohammed Gabr, Cathleen Jones, David Bekaert, Joel Dudas. Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul 2017.

13. Tables:

Table 1: 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	December 2017	Federal Agencies looking for an expedient means to assess performance of levees and earth dams

Table 2: 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	$61,595	US Army Engineer Research Development Center
New Faculty Startup Funds	Victoria Bennett	$241,500	Rensselaer Polytechnic Institute
10% of annual year salary and associated fringe benefits	Victoria Bennett	$11,780	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
Field instrumentation recovered from V-Line Levee site in New Orleans	$25,000

14. Metrics:

Metric	**Year 1** (1/1/16 – 6/30/16)	**Year 2** (7/1/16 – 6/30/17)
HS-related internships (number)		
Undergraduates provided tuition/fee support (number)		
Undergraduate students provided stipends (number)		
Graduate students provided tuition/fee support (number)	2	3
Graduate students provided stipends (number)	2	3
Undergraduates who received HS-related degrees (number)		
Graduate students who received HS-related degrees (number)		2
Graduates who obtained HS-related employment (number)		
SUMREX program students hosted (number)		
Lectures/presentations/seminars at Center partners (number)	1	1
DHS MSI Summer Research Teams hosted (number)		
Journal articles submitted (number)		0
Journal articles published (number)		
Conference presentations made (number)	2	3
Other presentations, interviews, etc. (number)	1	3
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 agencies or governments (number)	4	2
Total milestones for reporting period (number)	3	3
Accomplished fully (number)	3	2 (REES being updated)
Accomplished partially (number)		1
Not Accomplished (number)	0	0

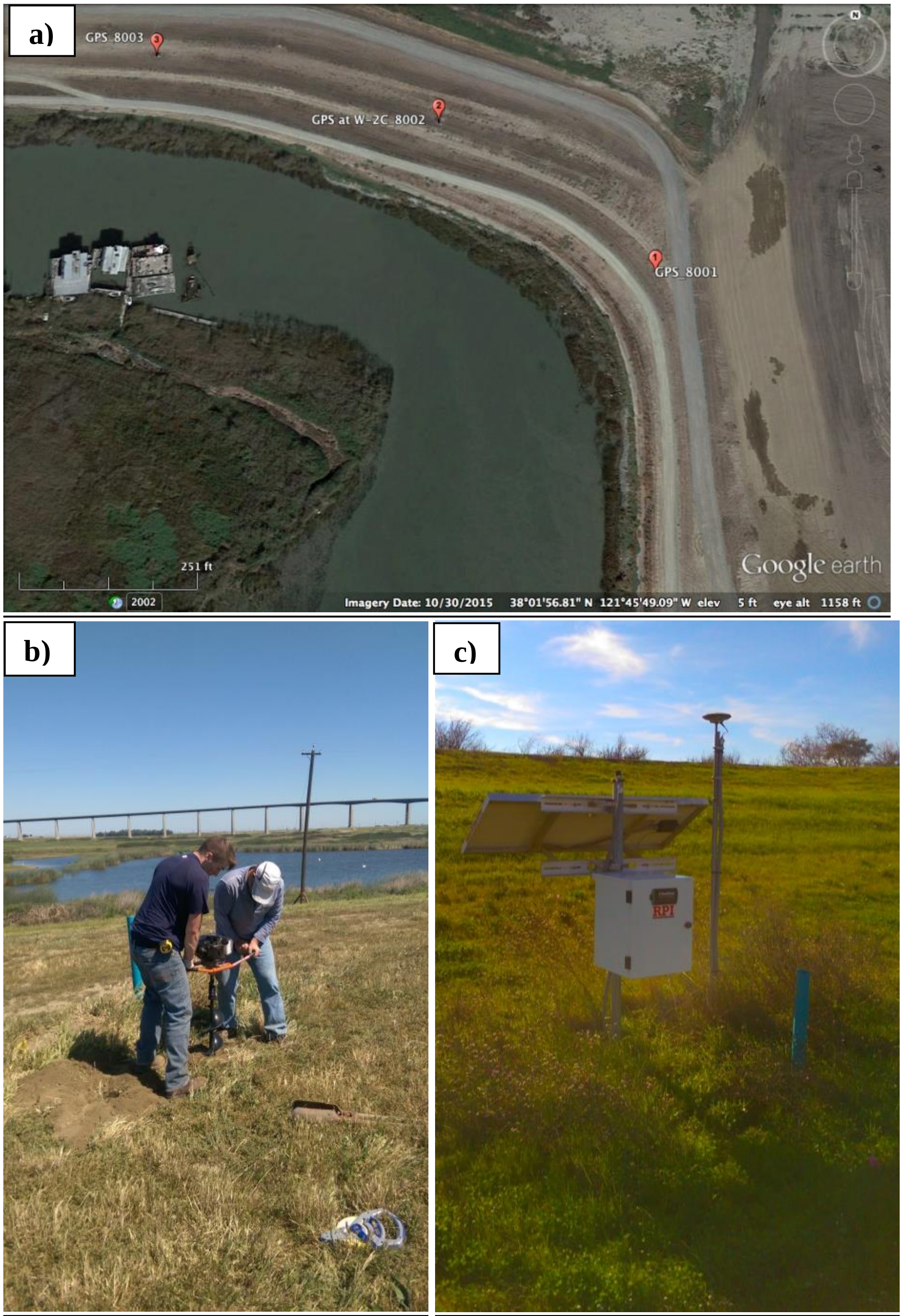


Figure 1. a) Location of in situ GPS stations (approximate coordinates: 38_{o}01’56.81” N, 121_{o}45’49.09” W); b) Installation of pedestal foundation for GPS station; c) completed autonomous GPS station (8003).

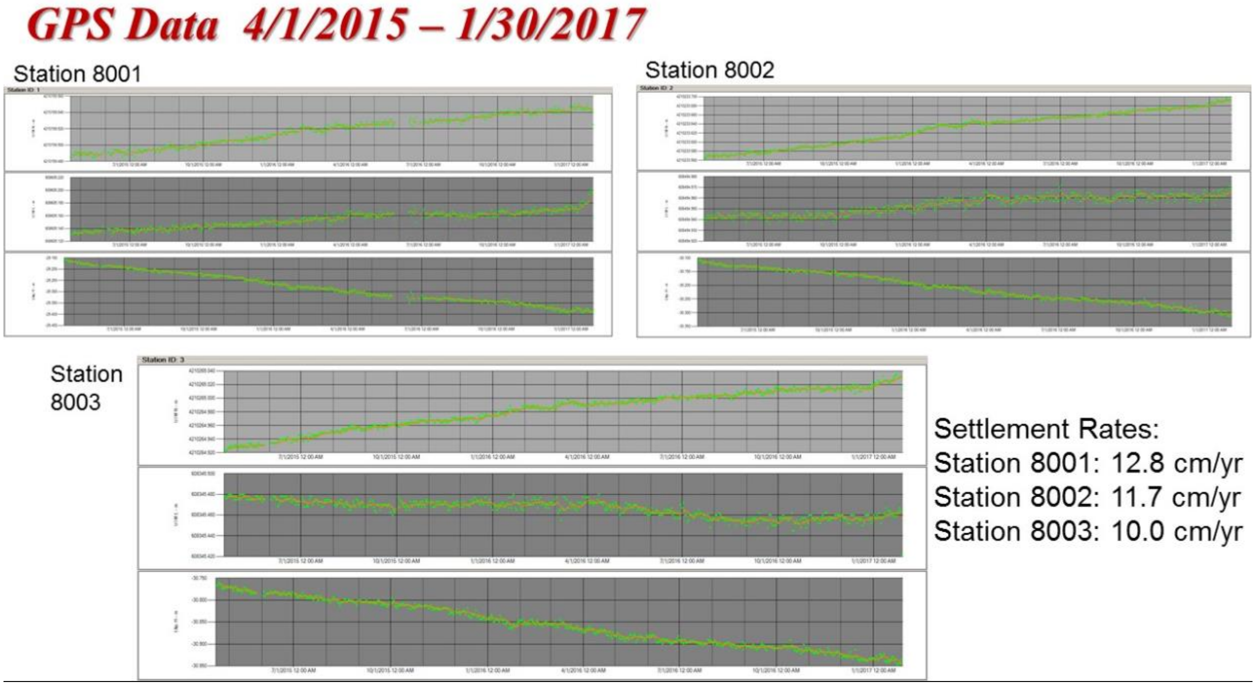


Figure 2. GPS time series at setback levee from April 2015 to January 2017.

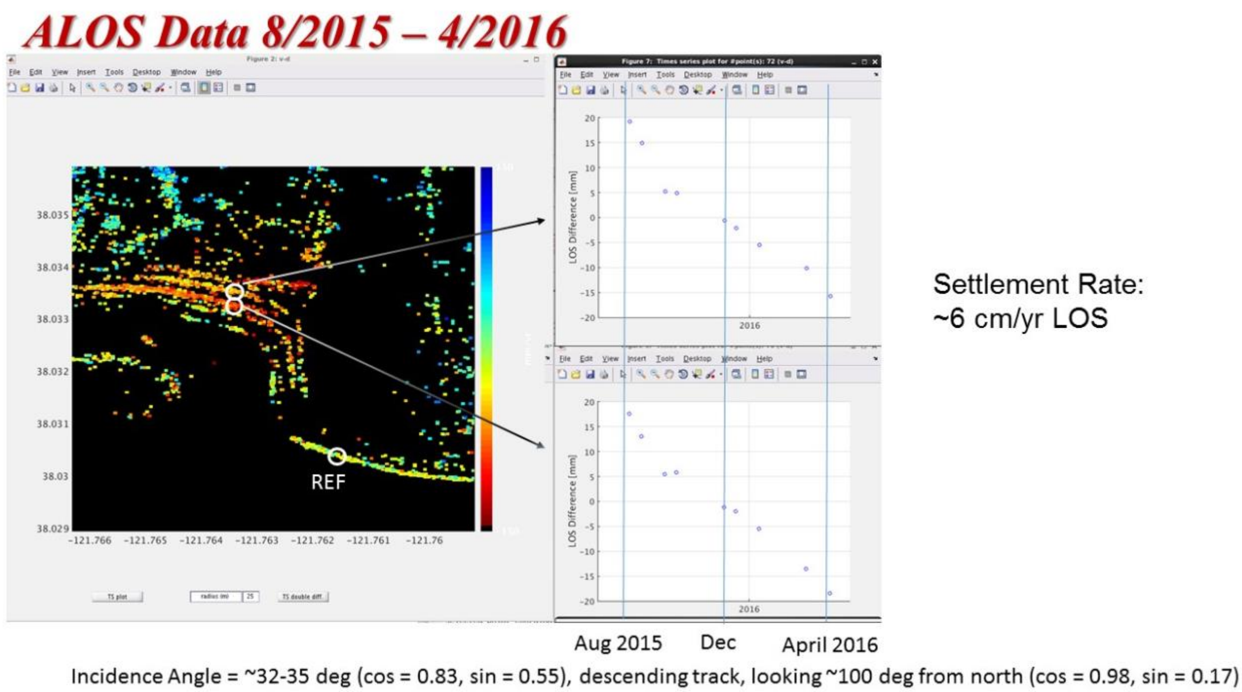


Figure 3. ALOS time series of setback levee from August 2015 to April 2016.

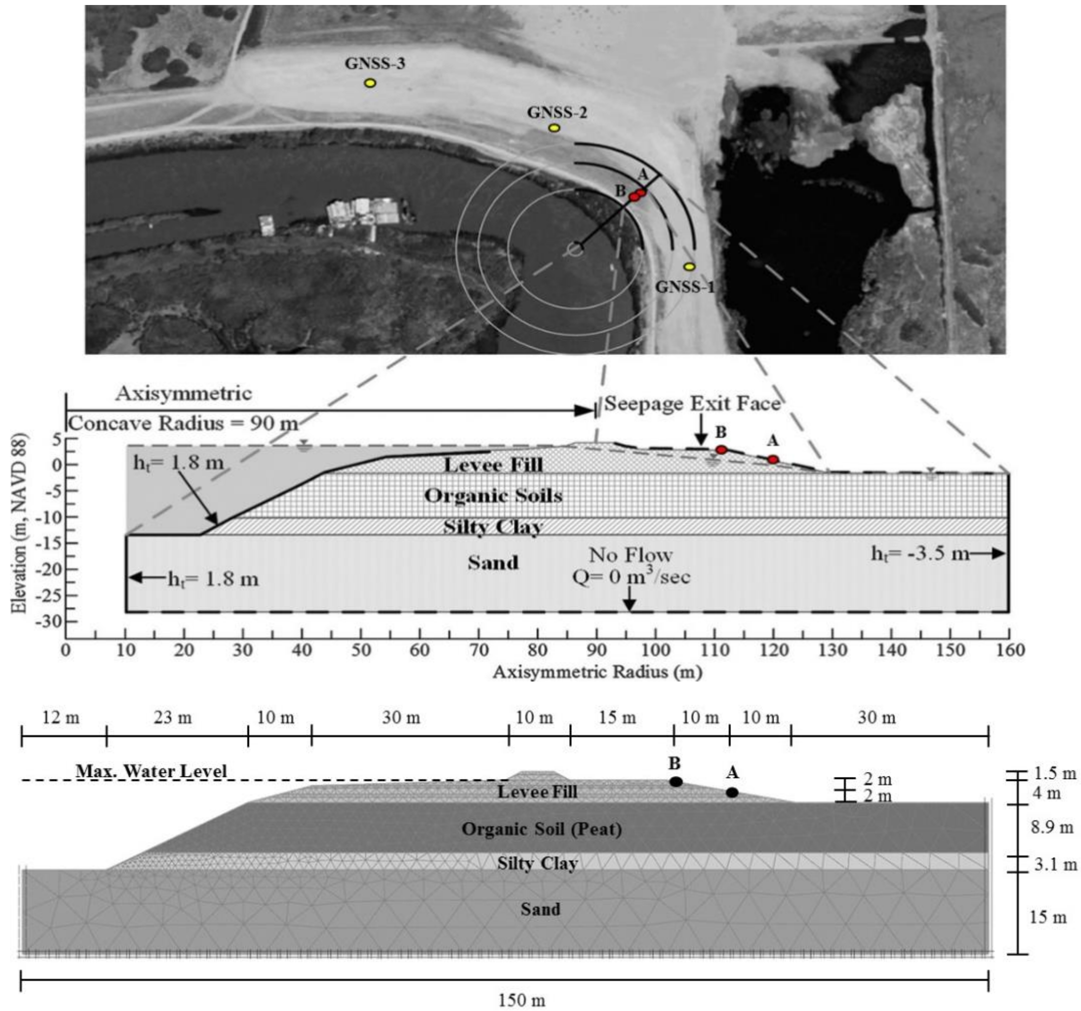


Figure 4. Finite element PLAXIS 2D levee mesh and boundary conditions.

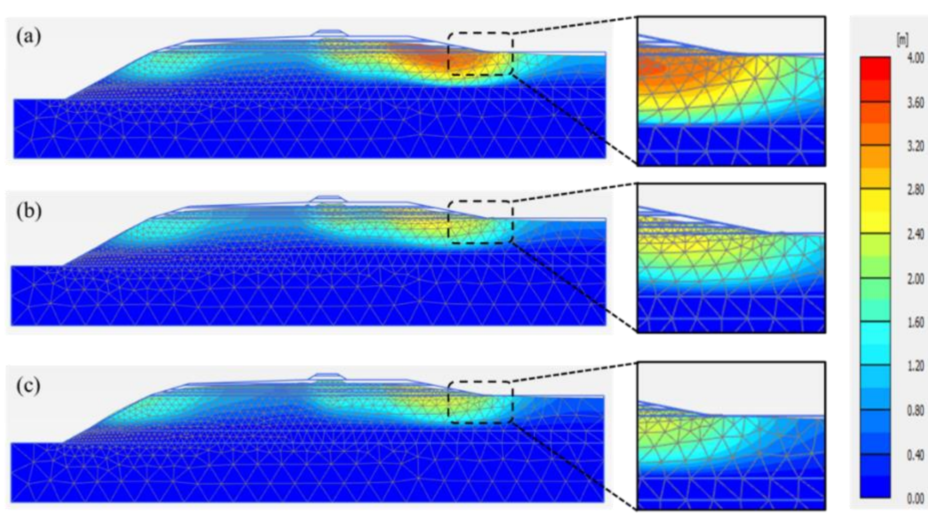
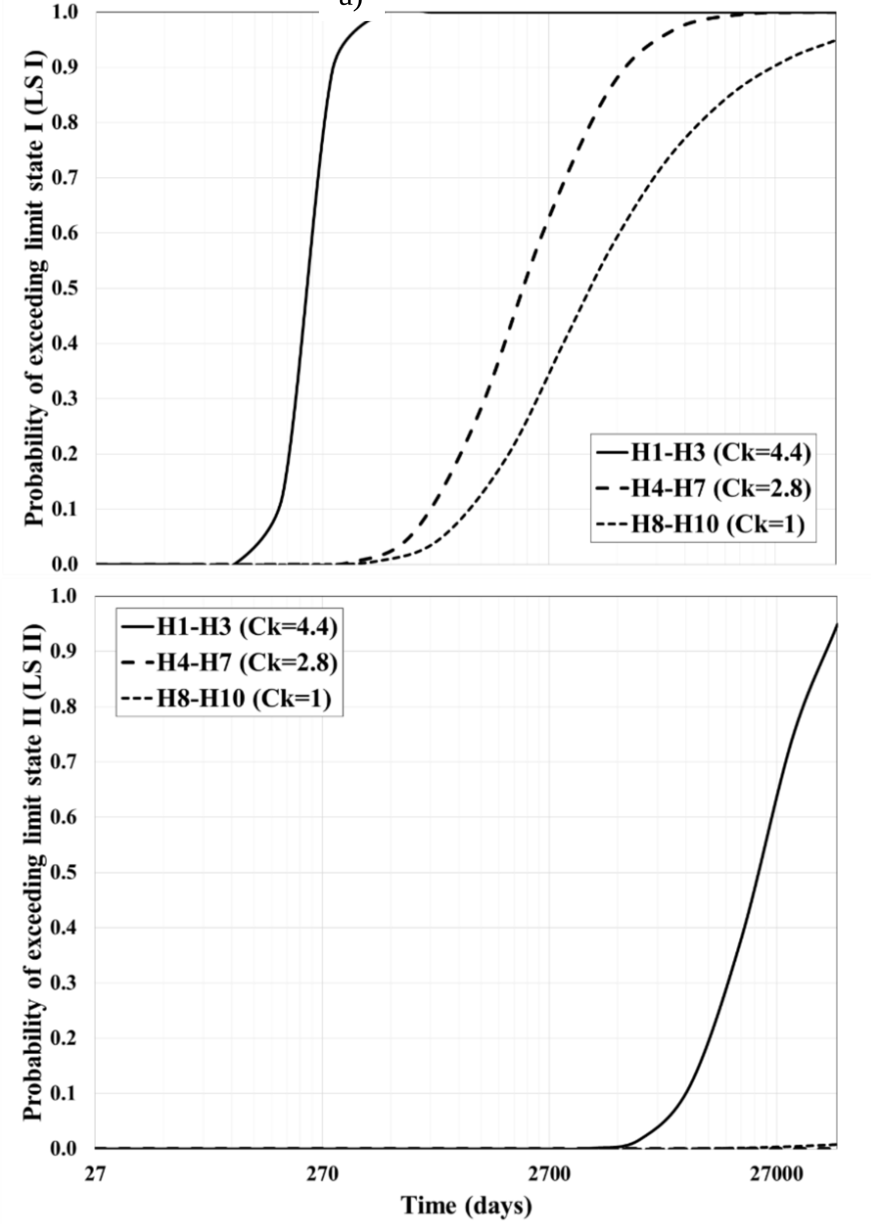


Figure 5. Deformation of levee for a) H1-H3 peat, b) H4-H7 peat, and c) H8-H10 peat at 10,000 days.

a)



b)

Figure 6. Probability of exceedance: a) LS I and b) LSII for shear strain for peat with different degree of decomposition.