Use of remote-sensing deformation monitoring for the assessment of levee section performance limit state

Utilisation de la télédétection pour l'évaluation de l'état limite de la performance de la section des digues

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ABSTRACT: Performance monitoring of the Sacramento Delta levee system on the network level and the assessment of exceeding potential limit states are needed for the maintenance and rehabilitation of this system. In this case, deformation needs to be assessed especially in view of the levees age, sea level rise, and ongoing subsidence due to the decomposition of the peat foundation layer. The work presented herein describes the remote sensing of a levee section deformation with time, which will ultimately be used for levee condition assessment. The levee section is located on Sherman Island, California and monitoring was conducted in situ by GPS, in addition to remote sensing by airborne synthetic aperture radar. Coupled deformation/seepage numerical analysis of the levee section is performed using finite element modeling software. The numerical model included characterization of the unsaturated-saturated zones and the peat foundation layer. The numerical analyses were also used to assess the probability of exceeding a prescribed deformation limit state while varying the loading conditions in terms of rate of rising and duration of high water level in the reservoir.

RÉSUMÉ: La surveillance de la performance du système de digues du delta de Sacramento au niveau du réseau et l'évaluation du dépassement des états limites potentiels sont nécessaires pour l'entretien et la réhabilitation de ce système. Dans ce cas, la déformation doit être évaluée en particulier compte tenu de l'âge des digues, de l'élévation du niveau de la mer et de l'affaissement en cours dû à la décomposition de la couche de fondation de la tourbe. Les travaux présentés ici décrivent la télédétection d'une déformation de la section de levée avec le temps, qui sera finalement utilisée pour l'évaluation de l'état des digues. La section des digues est située sur l'île de Sherman, en Californie, et la surveillance a été effectuée in situ par GPS, en plus de la télédétection par le radar d'ouverture synthétique aéroporté. L'analyse numérique des déformations / infiltrations couplées de la section des digues est réalisée à l'aide d'un logiciel de modélisation par éléments finis. Le modèle numérique comprenait la caractérisation des zones saturées insaturées et de la couche de fond de tourbe. Les analyses numériques ont également été utilisées pour évaluer la probabilité de dépasser un état limite de déformation prescrit, tout en faisant varier les conditions de chargement en termes de vitesse de montée et de durée du niveau d'eau élevé dans le réservoir.

KEYWORDS: Monitoring, Remote Sensing, Levees.

1 INTRODUCTION

The consensus among engineers and decision-makers in the United States is that a substantial effort must be urgently undertaken to upgrade and rehabilitate the national flood-control infrastructure. We face significant consequences to people, property, and economic activity if this infrastructure does not provide the expected protection during future flooding and earthquake events. Major levee systems exist along the Mississippi and Sacramento Rivers, i.e., the Sacramento-San Joaquin Delta, which comprises over 1700 km of levees. The levees in this system are not only at high risk of failure due to flooding and have failed previously, but are also located in an area of high seismic activity. It is also the heart of a massive north-to-south freshwater delivery system (USGS 2000). Preliminary risk assessment demonstrated a 40% chance that at least 30 islands in the Delta would be flooded by simultaneous levee failures in a major earthquake in the next 25 years (Mount and Twiss 2005). Concern about the Delta levees also exists from ongoing land subsidence due to the peat layer decomposition. Amorphous peat has particles that are mainly colloidal and the majority of porewater is adsorbed around the grain structure. Fibrous peat has an open structure with interstices filled with a secondary structural arrangement of non-woody, fine fibrous material. In the case of fibrous peat, most of the water occurs as free water in the soil fabric (Kazemian et al. 2011). Amorphous peat is the product of biochemical decomposition and breakdown of fibrous components and other plant remains. It includes a significant amount of inorganic matter. Mesri and Ajlouni (2007) mentioned that there is not a significant difference between the biochemical composition of amorphous and fibrous peat particles although the organic grains for amorphous peat are smaller and more or less equi-dimensional (Ng and Eischens 1983).

Given the hundreds of miles of levees with potential subsidence issues, the use of a remote sensing-based health assessment can quantitatively identify weak sections and impending failures. Continuous remote sensing technology, such as satellite and airborne monitoring, can serve as an accurate early warning system, as well as a valuable resource for assessing gradual and abrupt ground subsidence. The use of such monitored data within the context of performance limit states, as for example those presented by Khalilzad and Gabr (2011) and Khalilzad et al. (2014), allows for assessment of functionality levels as well as the fragility (in terms of probability of exceedance versus flood level).

Khalilzad and Gabr (2011) defined earth embankment limit states by correlating shear strain values to the horizontal deformation at the embankment toe location. They presented definitions for the limit states (LS) as follows - LS(I): minor deformations, no discernible shear zones (max deviatoric strain less than 1%), low gradients (i.e., $i < 0.3$) throughout the embankment dam and foundation; LS(II): medium (repairable) deformations, limited piping problems (i.e., $i > 0.6$ within a shallow depth at the location of toe), dispersed plastic zones with moderate strain values (maximum deviatoric strain less than 3%), tolerable gradients less than critical; LS(III): major deformations, breaches and critical gradients at key locations (i.e., $i > 1$, boiling and fine material washing at the location of toe), high strain plastic zones (maximum deviatoric strain > 6%).

This paper presents some results of integrated remote-sensing monitoring and modeling to assess the performance-based response of a levee section. The modeled levee is part of the Whale's Mouth section on Sherman Island where satellite images and in-ground GPS sensors are used for displacement measurements. The Whale's Mouth levee is modeled using the large deformation option of a finite element modeling program The model is used to establish a deterministic performance response under maximum water level loading and to investigate the effect of peat decomposition on the deformation response of the levee section. The remote sensing data are used to calibrate the numerical model.

2 FINITE ELEMENT AND DOMAIN MODEL

The finite element program was used to model the Sherman Island levee section. The section geometry was selected on the basis of the information presented by Jafari et al. (2016), as shown in Figure 1b. Global Navigation Satellite System (GNSS) displacement recording locations (GNSS-1, 2 and 3) are shown in Figure 1a. Measured displacements at Points A and B along the levee landside slope will be compared to those predicted by the numerical model. The modeled soil profile consists of 4 layers, which include a levee fill underlain by approximately 8 m of organic soil (peat). This organic layer is underlain by a silty clay over a thick layer of sand. Soil properties are extracted from data by Jafari et al. (2016) with some of the parameters assumed based on information from borehole logs performed on the Sherman Island setback levee project. Complete parameter selection can be found in Helal et al. (2017). The borehole logs suggested that the peat soil is highly fibrous, so the initial model utilized fibrous peat data.

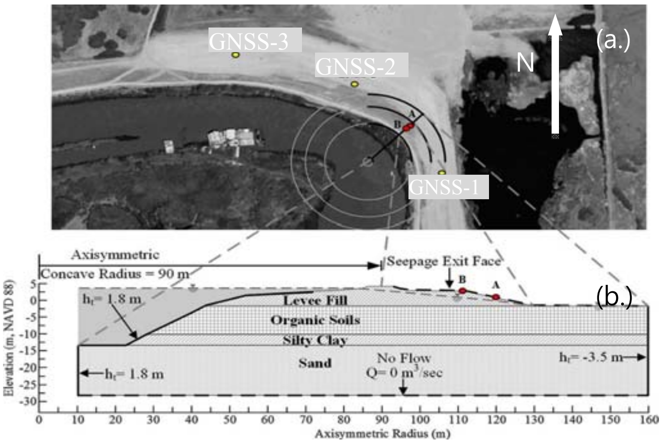

Figure 1. (a) Layout of three stand-alone GPS stations installed in Sherman Island setback levee. (b) Model of Sherman Island proposed by Jafari et al. (2016).

Different finite element mesh resolutions were investigated from coarse to fine to very fine mesh. Changing the mesh from coarse to fine, caused a 5% increase in displacement at point A, for example. No significant change was observed when using a very fine mesh in comparison to a fine mesh, thus a fine mesh with 15-node elements was used with the domain having 1961 elements and 15,975 nodes. Horizontal and vertical deformations were restricted at the bottom boundary of the sand layer. Only the horizontal deformations are restricted at the lateral boundaries of the model. Flow boundary conditions included a no-flow boundary at the lower boundary of the model (boundary of sand layer) and a free-flow boundary at the downstream slope of the embankment. The upstream face of the levee was defined as steady state seepage. The modeled embankment is shown in Figure 2.

3 MODELING PHASES AND CALIBRATION

The levee was modeled using staged construction in 7 layers. Direct generation of initial effective stresses, and pore pressures and state parameters in the foundation layers were 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 2 days and the consolidation phase time was estimated using trial runs. In these phases, the displacements and strains are reset to zero before placement of the next layer. To simulate the extreme loading condition, the water level was raised to the max elevation (1 m below crest elevation) and allowed to reach a steady state condition over 1,000 days. In the final phase, a consolidation analysis was performed to capture secondary compression settlement (creep effect) for 20,000 days (over 50 years).

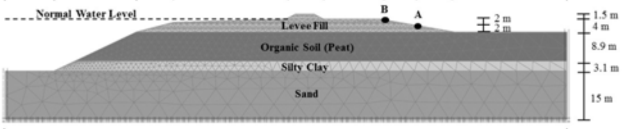

Figure 2. Finite element levee mesh.

Several points along the landside slope were chosen to investigate the displacement response given the change in the peat properties and to place such a response within the context of the defined limit states. Results for vertical displacement (negative sign means settlement) 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 GPS records available near these locations on 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 rate of deformation with time shows a relatively close trend to the model results, and falls 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 m per year computed for point A. The rates predicted by the model and measured for point B were not in good agreement, but the monitored points are located on the protected side of the levee; a location consistent with “point A” as shown in Figure 1. Day 2000 (Fig 3) represents the time needed for achieving a steady state condition after levee construction and water level rise in the numerical model. The measured data is assumed to be taking representative of the consolidation phase of the embankment.

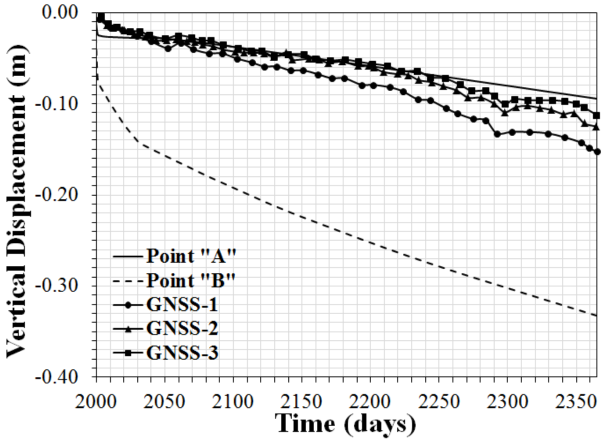

Figure 3. Displacement with time for fibrous peat versus measured data.

4 REMOTE SENSING TECHNOLOGY AND PROCESSING TECHNIQUES

Synthetic Aperture Radar (SAR) satellite imagery is a cost effective tool to monitor the global response of a sprawling flood-control levee system. A number of sources of SAR data will be used in this project. Numerous satellites were launched over the last two decades explicitly to conduct ground-surveying operations. Some of these satellites have interferometry capabilities, and have collected and archived tremendous amounts of valuable data. These satellite data used in this paper was collected by the Japan Aerospace Exploration Agency’s (JAXA) Advanced Land Observing Satellite-2 (ALOS-2). The specified spatial resolution of this data is 1x3m per pixel. The orbit period or repeat cycle is 14 days for ALOS-2 and 11 days for TerraSAR-X. TerraSAR-X uses a frequency of 10 GHz (X-band), corresponding to a wavelength of 3.1 cm. The shorter wavelength allows for high-resolution imagery, which improves our ability to monitor levee displacements with greater accuracy. This higher resolution comes with the compromise of limited penetration in areas of long grass. L-band (1.2 GHz, 23 cm wavelength) SAR images of the Sacramento Delta, obtained using ALOS-2 between 2015 and 2016, are used in this study. A significant challenge in InSAR measurement is to decide which combinations of raw data acquisitions are to be used for a particular radar system. The optimal combination of pass (descending and/or ascending), beam mode and look angle is required. This requires some previous knowledge of ground topography and previous land movement data (Mei et al. 2008). This project uses the Short Baseline Subset Analysis technique and ALOS data of the Sacramento Delta to produce surface deformation measurements comparable to the in situ GNSS measurements.

5 SHERMAN ISLAND FIELD INSTRUMENTATION

The monitoring utilized herein will be combined with the aforementioned modeling efforts as a step towards establishing a platform for a long-term assessment of the levee system health based on local measurement of deformation (Bennett et al. 2011) due to natural cycles of water elevation loading and unloading associated with rain storms, flood cycles, tides, tremors, and traffic loads, as well as aging, consolidation and creep. Thus, federal and local governments will be able to prioritize and implement repairs and rehabilitation, as well as assess the effectiveness of these repairs before major events. This approach attempts to reduce the risk of a catastrophic failure of a flood-control system similar to that of Hurricane Katrina and Superstorm Sandy. The levee test site is located on Sherman Island in Sacramento County, California. Sherman Island is at the confluence of the Sacramento and San Joaquin Rivers, approximately two kilometers northeast of Antioch, CA. The instrumented levee section is known as the setback levee and is owned by California Department of Water Resources.

In situ instrumentation was installed along the setback levee on Sherman Island in April 2015. Three stand-alone, continuously monitoring GPS stations were anchored to the ground surface. Locations of GPS stations compared to the modeled cross-section are shown in Figure 1b. Each station contains a Novatel ProPak 6 receiver and a dual-frequency GPS plus GLONASS pinwheel antenna. 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 stand-alone GPS station located at GNSS-2 in Figure 1a are shown in Figure 4. Data was collected from April 2015 to April 2016. The data collected includes North, East, and Height measurements. North and East represent lateral movement of the levee surface and the height component is measuring settlement. Only the height (vertical settlement) measurement is shown here. The settlement accumulates to approximately 12 cm over the one year monitoring period.

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 (Jones et al., 2014) was used with nine ALOS images of the setback levee on Sherman Island. The results of this analysis are shown in Figure 5. 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°). In this projection, GNSS-2 measures 4.8 cm of displacement. The middle slope location shown in Fig. 5(a) is representative of the GNSS-2 location.

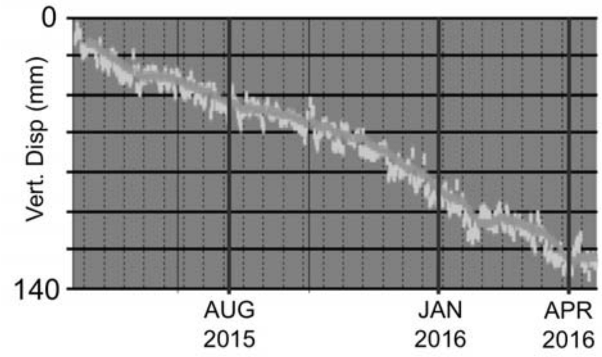

Figure 4. GPS time series at setback levee from April 2015 to April 2016.

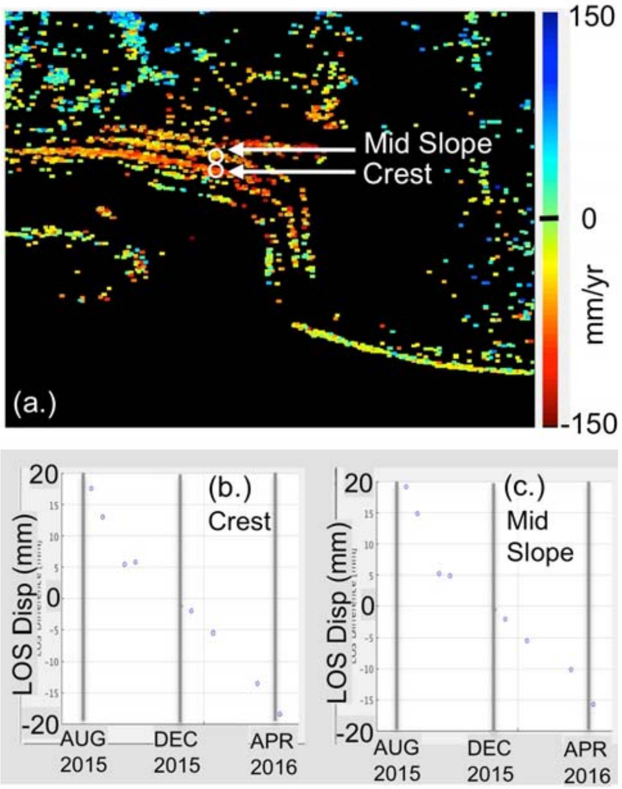

Figure 5. (a.) ALOS displacement rate map of setback levee from August 2015 to April 2016; (b.) time series of point on crest of levee; (c.) times series of point on the middle of levee slope.

6 CONCLUSION

This paper presents a preliminary comparison between displacement monitoring with locally installed Global Positioning System (GPS) equipment and remotely sensed satellite imagery. Displacement measurements were collected from a levee section on Sherman Island, CA. Sherman Island is at the confluence of the Sacramento and San Joaquin Rivers and is part of the critical north-to-south freshwater delivery system in California. The site will continue to be monitored and more local sensor installations will follow. Ultimately, data collected from the in-ground instrumentation will be used to improve the surface displacement readings from the satellite-based InSAR analysis. The use of both types of monitoring enables the use of global-local health assessment of the distributed levee system. The combination of modeling and measurements will provide significantly more accurate information about the health state of levees than either modeling or measurements alone.

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