Development of a Multiscale Monitoring and Health Assessment Framework for Effective Management of Levee Infrastructure

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ABSTRACT: This paper presents an overview of a framework to assess the structural integrity and health of earthen levees. The framework is being developed through a project supported by NIST (National Institute of Standards and Technology) and relies on remote sensing and field monitoring data of levees during environmental loading conditions and natural processes of degradation. The monitoring data consists of levee displacements obtained using satellite-based interferometric synthetic aperture radar (InSAR), Global Position System (GPS) receivers, and Shape-Acceleration Pore Pressure (SAPP) Arrays. These measurements are used in an integrated fashion to localize internal zones of degradation within levees and quantify the corresponding level of weakening. The framework is demonstrated using test data of small scale centrifuge levee models.

INTRODUCTION

The integrity and reliability of levees and other earthen flood-control infrastructure are essential components of homeland safety. However, the national flood-control infrastructure is aging and its structural health is deteriorating. The ASCE's 2009 Report Card for America's Infrastructure gives the condition of our nation's dams a grade of D and levees a grade of D$^-$. The failure of such systems due to natural or man-made hazards such as hurricanes, floods, earthquakes, or deterioration may have monumental repercussions, sometimes with dramatic and unanticipated consequences on human life

and the country's economy. The failure of levees during hurricane Katrina in 2005, which led to the catastrophic flooding of New Orleans, is a highly illustrative example (Fig. 1).

The current consensus among engineers and decision-makers is that an effort must be urgently undertaken to upgrade and rehabilitate the national flood-control levee infrastructure. In numerous nationwide locations, we face significant consequences to people, property and economic activity if this infrastructure does not provide the expected protection during future flooding events. However, the specific locations and levee zones that have weakened, are degrading and require rehabilitation are generally unknown. The amount of flood-control infrastructure to inspect is considerable. In addition to the New Orleans area, major levee systems exist along the Mississippi and Sacramento Rivers. The Mississippi levee system represents one of the largest in the world. This system comprises over 5,600 km of levees. Furthermore, 43 percent of the U.S. population lives in counties with levees designed to provide some level of protection from flooding, some of which are as old as 150 years (CHC 2008).

FIG 1. Failure of the 17th Street Canal levee in New Orleans during Hurricane Katrina (Link et al. 2006).

Assessing the health of levees, identifying weakening zones and implementing countermeasures are challenging tasks in view of the complexity of the associated processes of long-term environmental degradation and wear. Furthermore, soils are inherently random media and information necessary for health assessment, such as material properties and in situ conditions, is always incomplete. For instance, it is practically impossible to amass all needed details on the foundation soil supporting a system of levees. To maintain this infrastructure, engineers have to rely on efficient

programs that continuously monitor, assess the health and adaptively manage these systems.

An accurate monitoring and health assessment of a sprawling system of levees, such as for instance the one protecting the city of New Orleans, using traditional sensors and sensing tools is expensive and technically demanding. Currently, there is still a prevalent lack of affordable, accurate and real-time health assessment tools for levees and other geo–structures. Current tools are based on antiquated approaches that rely on local site visits or limited surface sensing means. This current of state of affairs results in slow response, misinformed decisions and lengthy timeframes to initiate repair and rehabilitation.

This paper presents an overview of the elements of a health assessment framework to cost-effectively monitor, manage and ensure the safety of levees and other earthen systems of a flood-control infrastructure. This framework is being developed within the context of a NIST-TIP (National Institute of Standards and Technology-Technology Innovation Program) project.

VISION AND OVERVIEW

The main objective of the NIST-TIP project mentioned above is to develop a cost-effective *sensor-based model-aided* framework to: (1) continuously monitor a system of flood-control levees on global, intermediate and local scales, and (2) assess the health of levees on multiple scales, and provide early warning of distress and degradation. The framework integrates remote sensing field sensors data with realistic levee models to assess the evolution of health of levees. The project objectives will enable the development of an effective new paradigm where the fixed-interval visual inspections that are often used as the sole mean to assess the status of levees, are replaced by sustained cost effective monitoring and evaluation giving continuous information on levee health, safety and failure hazard.

The developed framework uses a *multi-scale (global, intermediate, and local)* approach to optimize the monitoring and health assessment of levees (Riedel and Walther, 2008) in view of the massive size of this infrastructure. A schematic illustrating the project vision and the associated multi-scale monitoring of flood control levees is shown in Fig. 2.

Global scale

Satellite-based remote sensing is employed to effectively monitor the displacement of a whole system of levees protecting a certain region or area. Such a sensing approach provides a cost-effective solution to obtain global-scale monitoring data of a sprawling network of levees on a continuous basis (with a frequency of the order of few days or weeks). A sample of subsidence rate of a levee in the New Orleans area is shown in Fig. 3. These rates were obtained using 23 TerraSAR-X (2012) remote-sensing images collected between March 2009 and October 2011 and processed using InSAR (Interferometric Synthetic Aperture Radar) techniques (Lv et al. 2013). TerraSAR-X is a German Earth observation satellite capable of acquiring high resolution images (about 3 m per pixel) with a return period of 11 days (over a given location on earth).

The remote sensing data is employed along with geotechnical, topographical and other a-priori information to assess the health of levees and identify zones that are degrading and have a higher probability of failure in the event of a future large environmental loading event (e.g., flooding or hurricane). The assessment is conducted on a global scale using data with a spatial resolution of the order of 10 m (on the ground surface).

Intermediate scale

An intermediate-scale analysis is undertaken if warranted by the outcome of the global-scale analysis (e.g., the global analysis shows evidence or possibility of a weak levee zone). The weakening or degrading zones identified based on the global scale analysis are reassessed on an intermediate scale using remote sensing data with a higher resolution (of order of 6 m on the ground surface). Additional details of this analysis are provided below.

Local scale

The weakening or degrading levee zones would be densely monitored using a new class of minimally invasive field sensors if the intermediate scale analysis confirms the outcome of the global analysis and shows that additional information is needed to conclusively characterize the nature and extent of degradation. These sensors include cost effective Global Position System (GPS) receivers and Shape-Acceleration Pore Pressure (SAPP) arrays. These GPS receivers cost less than $2000 per unit and measure three-dimensional ground (surface) displacement with a high-accuracy (±1-2 mm). The SAPP array consists of an integrated suite of digital MEMS (Microelectromechanical systems) sensors that economically measure soil deformation, vibration, and pore pressure with a spacing of 1 m or less and up to a depth of about 30 m (Abdoun et al. 2009, Bennett et al. 2007). This array costs about $5000 per 10 m of length. The GPS and SAPP arrays will be installed with a judicious topology within the weakening zone to provide high-resolution (few meters in space and few hours to few minutes in time) measurements. The main goal of such topology is to enable effective levee health assessment.

The sensor measurement and remote sensing data will be used in an integrated fashion to effectively assess the health of levee on a local scale and systematically evaluate the nature, extent and level of degradation within any weakening zone. A model-based approach capable of idealizing the mechanisms of degradation will be employed to evaluate the level of degradation. This approach incorporates our knowledge about soils into the assessment of levee conditions and extraction of information about possible zones of levee degradation. Alternative approaches such as data-driven ones would not be as effective since they require a substantial amount of data for training to become accurate.

INTERMEDIATE SCALE HEALTH ASSESSMENT

Assessment of the health of a system of levees presents a significant challenge, not only because of the sheer size of these earth structures but also because they are constructed of complex geological materials which are intrinsically random in composition and with intricate degradation mechanisms. As described above, such an

assessment is advantageously tackled a multi-scale (global, intermediate and local) approach. Because of space limitation, this paper focuses on the intermediate-scale of levee health assessment (the full health assessment framework will be published elsewhere).

The global scale analysis may indicate accelerated levee degradation or weakening. An intermediate analysis is consequently used to estimate the level and extent of degradation before implementation (if necessary) a more intrusive, and potentially costly local scale analysis. The intermediate-scale health assessment uses solely surface displacements provided by remote sensing and GPS receivers to identify the location and level of degradation of a zone within a levee that is experiencing weakening (regardless of the reason for this weakening), as summarized conceptually in Fig. 4.

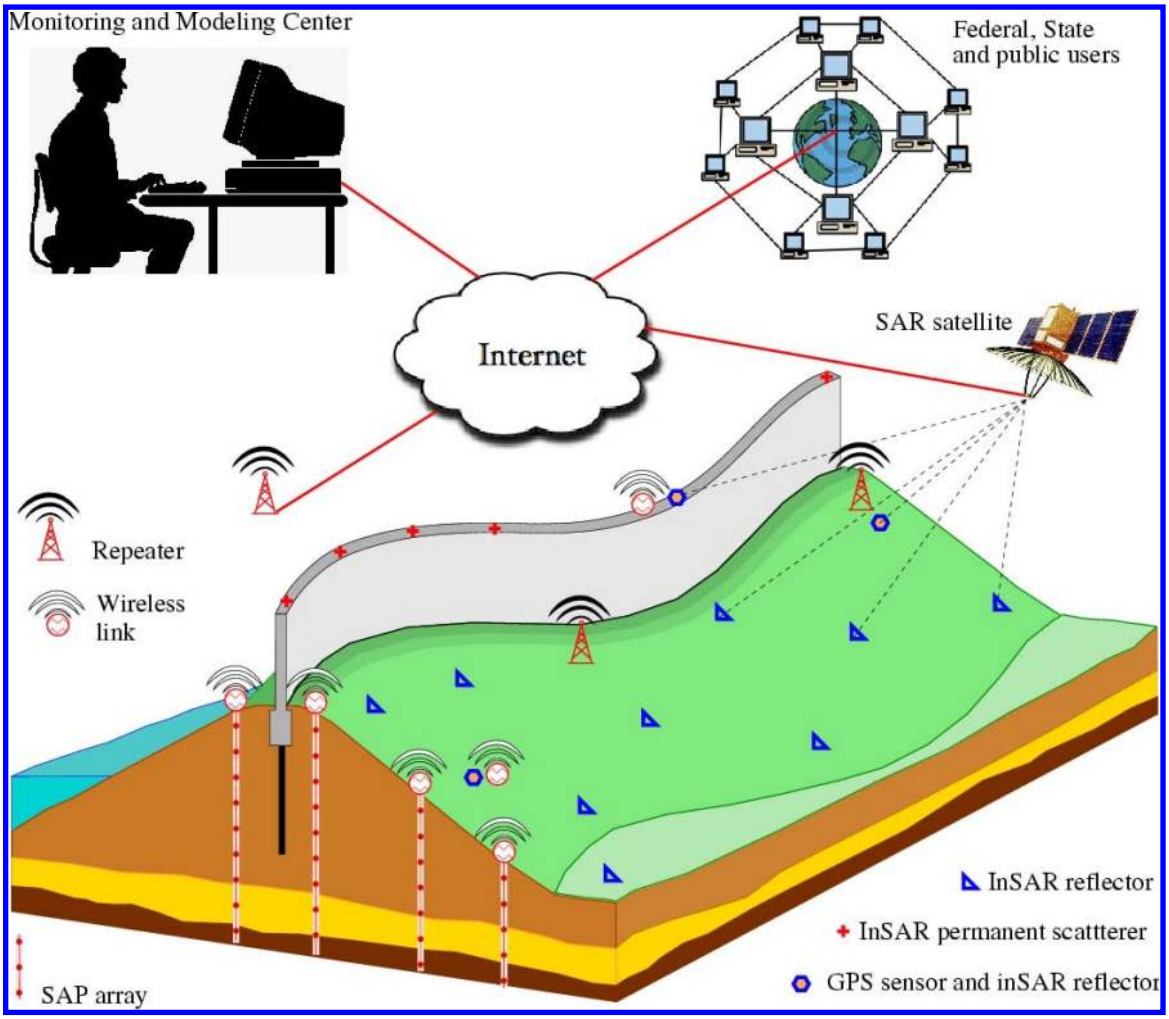

FIG. 2. Sketch rendering the vision of sensors aided model based assessment of a levee system health using InSAR, GPS and SAPP monitoring.

FIG 3. Rate of subsidence of a levee in New Orleans between March 2009 and October 2011 based on remote sensing data obtained using TerraSAR-X (Lv et al. 2013).

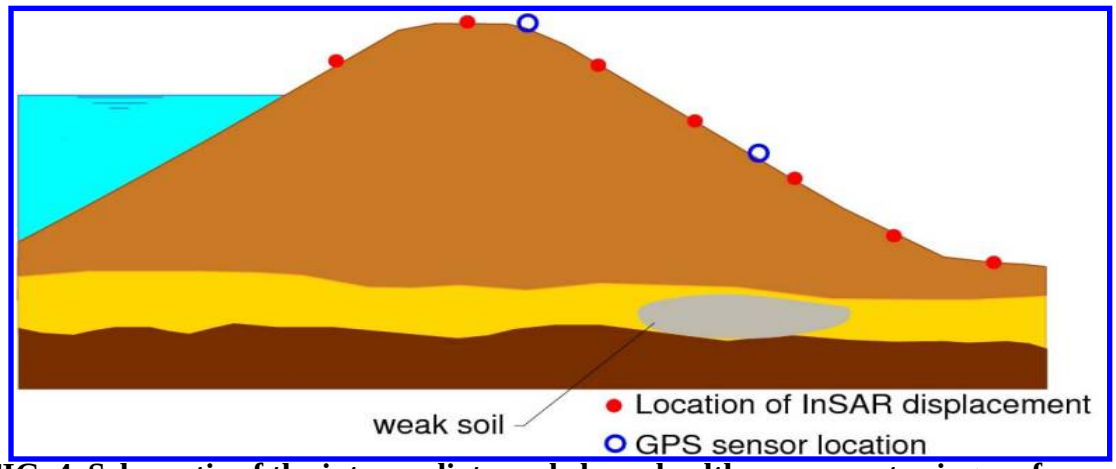

FIG. 4. Schematic of the intermediate-scale levee health assessment using surface displacements (involving identification of location and level of degradation of an evolving weak zone).

For every newly acquired data set, the (intermediate) health assessment algorithm includes (Mercado 2012): (1) a localization of the evolving weak zone within a levee section (previously recognized as possibly problematic based on the cruder global analysis), (2) quantification of the level and magnitude of degradation (e.g., in terms of stiffness, strength and other mechanical parameters), and (3) estimation of associated level of reduction in levee health.

Localization of an evolving weak zone in a levee is performed using a Neural Networks technique (Mercado 2012). Identification and inverse problem tools are used thereafter to quantify the extent and level of internal weakening and associated changes

in strain energy. The localization analysis provides information that enables a reduction of the identification problem indeterminacy. The health of the levees is quantified in terms of a factor which is a function of the estimated state of strain energy and the ultimate energy capacity (Hsu 1991, Mercado 2012). The algorithm was verified extensively using numerical simulations. This paper presents some validation results on the basis of centrifuge tests of a small-scale levee.

Centrifuge tests and validation

A number of small-scale centrifuge tests were conducted to generate realistic data of a levee experiencing soil weakening (Exton 2012, Fig. 5). Each of the tested levees consisted of a sandy soil and had an internal weak zone that was constructed using low permeability clayey soil and varied in size and location. The levees were submitted to an increasing gravitational centrifuge level. During this increase, the sandy soil experiences a rise in strength associated with larger effective confining stresses. In contrast, the clayey soil experiences an undrained response with no changes in effective confining stresses and strength. Thus, the levees practically undergo a relative weakening within the clayey soil during the increase of gravitational field (more details are provided by Exton 2012). This weakening induces displacement and deformation within the levee and ultimately failure at large gravitational levels.

Laser sensors were used to measure surface displacements of the centrifuge levee model (during the increase in gravitational level) in a fashion that mimics the type of data obtained from satellite remote sensing (Exton 2012). A generic section layout of the tested levees and locations of the employed laser sensors are presented in Fig. 6. The levee displacements were used along with the developed health assessment algorithm to identify the evolution of levee structural health with changes in gravitational level.

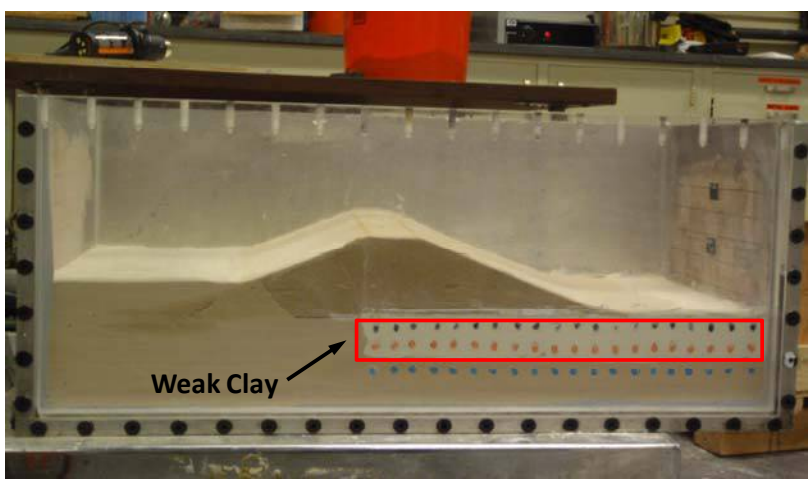

FIG. 5. Small-scale centrifuge test of a levee with a layer of weak clay designed to lead to structural health deterioration with increase in (centrifuge) gravitational level.

The health assessment was started by a localization analysis. This analysis was conducted to identify the position of the weak clay zone in the centrifuge models. A selection of

vertical displacements recorded (by the laser sensors) on the surface of the centrifuge levee models were used along with the developed Neural Networks algorithm to assess the ability of this algorithm identify the location of an evolving weak zone within the levee section. The Neural Networks were "trained" using a bank of levee degradation scenarios obtained using computational finite element simulations (representing a broad range of conditions in terms of material properties, dimensions and location of the weak clay zone). The conducted analysis showed that the localization algorithm provided reasonable results when the spacing between the employed displacements does not exceed 8 to 10 m. The analysis accuracy was found to improve with increasing amplitude of levee surface displacements (associated with larger levels of degradation). The algorithm produced reasonable results for displacements of the order of 5 mm or larger. These findings provide broad measures for the needed remote sensing resolution and accuracy (research is underway to achieve these measures).

An identification analysis was conducted (following the localization one) to assess the level of (relative) degradation with increasing gravitational level. The recorded levee vertical displacements were used along with identification algorithms to estimate the geometrical and mechanical parameters defining the zone of weak clay. Figure 7 shows the identified state of plastic strains for different stages of gravitational loading. The conducted analyses showed that the employed algorithm is capable of detecting the development of weakening zones in the levee well before the displacements became large or showed any visible signs of levee instability. Such an early detection will enable timely rehabilitation and remediation programs to improve levee safety.

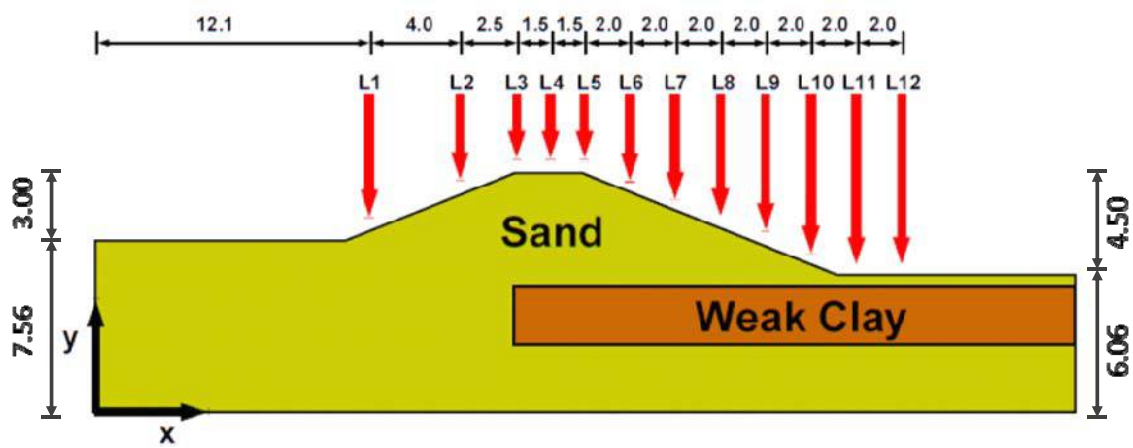

FIG. 6. Layout of a generic section of the tested levees and laser sensor measuring locations (dimensions are in meters and scaled for a 50 gravitational level).

CONCLUSIONS

This paper presented a *model-based sensor-aided* framework to continuously monitor and assess the health of a sprawling network of flood-control levees. This framework relies on satellite InSAR imagery and new cost-effective field sensors to monitor levees on local, intermediate and global scales. A model-based analysis is used along with data

provided by satellite images and sensors to assess the health of a system of levees and identify degrading zones on multi-scales (global, intermediate and local). A number of small-scale centrifuge tests were conduct to validate the intermediate scale analysis. This analysis showed that reasonable results are obtained when sensor (surface) spacing does not exceed 8 to 10 m and measured (surface) displacements are the order of 5 mm or larger. The proposed monitoring and health assessment framework will enable a long-term efficient assessment of the health of a levee system and provide tools to avoid the guesswork that is inherent to health assessments that are based on visual inspections.

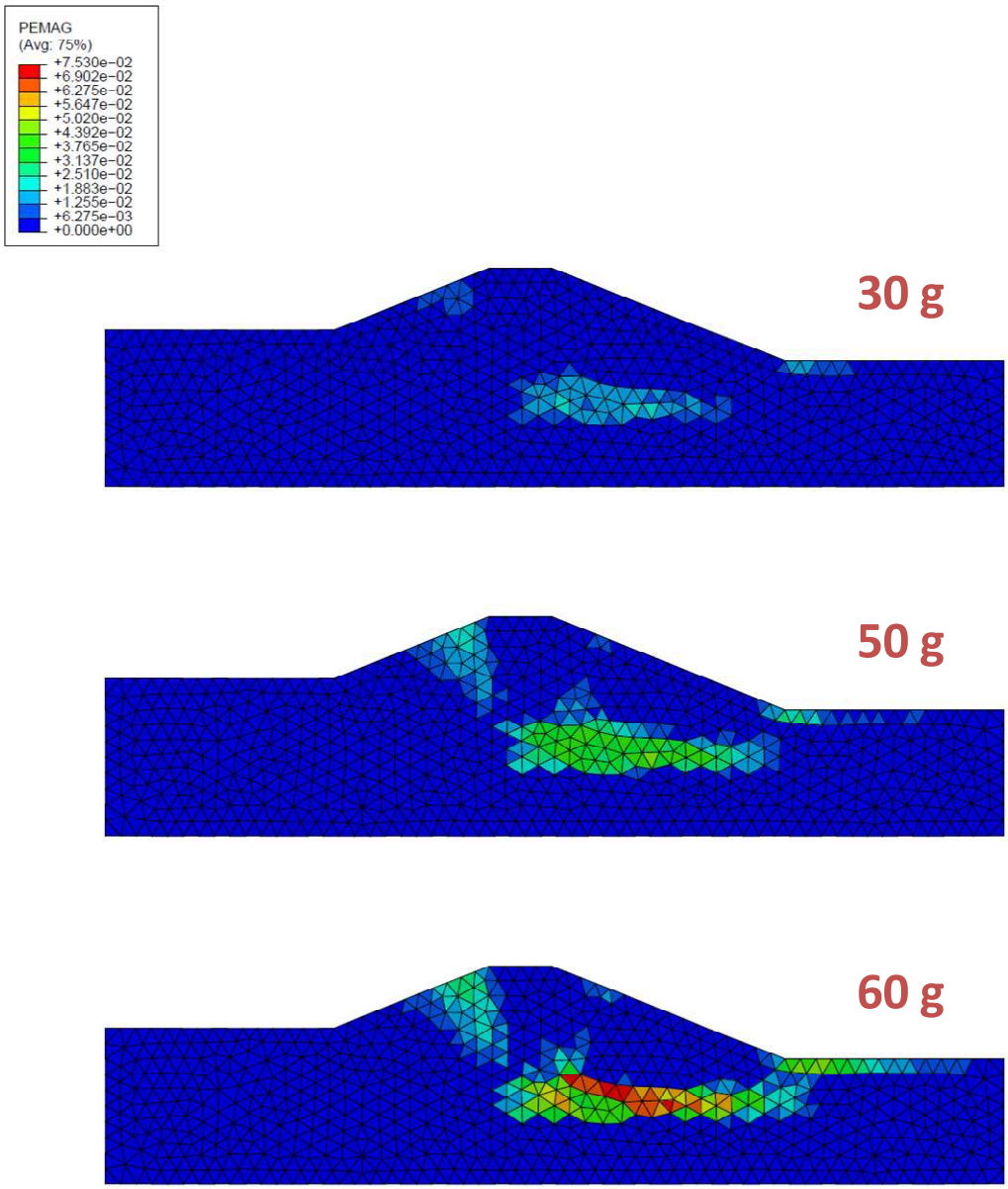

FIG. 7. Plastic strain magnitudes in the tested levee section identified using the developed health assessment algorithm for different stages of the gravitational loading (at 30, 50 and 60 g-levels).

ACKNOWLEDGMENTS

This article is based upon work supported by the National Institute of Standards and Technology within the Technology Innovation Program (Cooperative Agreement Number: 70NANB10H018, Project Manager: Dr. H. Felix Wu). This support is gratefully acknowledged.

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