Can Protracted Drought Undermine the Structural Integrity of California's Earthen Levees?

Farshid Vahedifard, M.ASCE

Assistant Professor, Dept. of Civil and Environmental Engineering, Mississippi State Univ., Mississippi State, MS 39762 (corresponding author). E-mail: farshid@cee.msstate.edu

Joe D. Robinson, S.M.ASCE

Geotechnical Engineer, Terracon Consultants, Inc., 51 Lost Mound Dr., Suite 135, Chattanooga, TN 37406; formerly, Graduate Student, Dept. of Civil and Environmental Engineering, Mississippi State Univ., Mississippi State, MS 39762. E-mail: Jody.Robinson@terracon.com

Amir AghaKouchak, M.ASCE

Assistant Professor, Dept. of Civil and Environmental Engineering, Univ. of California, Irvine, CA 92697. E-mail: amir.a@uci.edu

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Introduction

There is a crucial need to improve our understanding of the potential threats of extreme events, such as the ongoing California drought, on critical geotechnical infrastructure and take subsequent actions in a timely manner to adapt our infrastructure. The need is more pronounced for levees because their functionality to protect limited water resources and dry land is more critical during drought (Hanak and Lund 2012; Vahedifard et al. 2015a). The frequency and severity of California's drought are anticipated to worsen in a warming climate (Port and Hoover 2011). The Millennium Drought (1997–2009), that severely impacted the economy and environment in southeastern Australia (AghaKouchak et al. 2014a), is often considered as an archetype of an extreme event that California should prepare for. The Millennium Drought significantly affected critical infrastructure like river ecosystems, dry land and irrigated agriculture, and surface water storage in natural and engineered reservoirs (Van Dijk et al. 2013). The event led to significant reduction in production of water-intensive crops (e.g., rice and cotton) by up to 99%, resulting in over 4.5 billion Australian dollars in Federal Government drought assistance and investments in multibillion dollar water infrastructure for improving preparedness and response (e.g., Van Dijk et al. 2013; Howden et al. 2014).

The 2012–2015 California drought has been one of the most extreme on record, characterized by low precipitation and high temperatures (Shukla et al. 2015; AghaKouchak et al. 2015). Fig. 1(a) displays snapshots of drought conditions from 2012 to 2015 based on the standardized soil moisture index (SSI) (Hao et al. 2014). As Fig. 1(a) shows, the most severe drought on record occurred in May 2014, and it continues to remain in a critical condition. The severity of drought is in part a result of the lack of snow pack, which affects the overall exploitable water supply throughout the state. As Fig. 1(a) indicates, there is also a shortage of soil moisture, which comes in addition to the water shortages caused by lack of snow packs. Figs. 1(b and c) show the 4-year average precipitation and temperature, respectively. The concurrent extreme low precipitation [Fig. 1(b)] and high temperature [Fig. 1(c)] was estimated to be a 200-year extreme event (AghaKouchak et al. 2014b).

This paper intends to stimulate discussions among the geotechnical engineering community regarding the effects of California's prolonged drought on levees in the Central Valley and Sacramento–San Joaquin Delta (Delta). There is a clear gap in the state of our knowledge in terms of structural-scale assessment of levees under extreme drought (CACC 2015). We call for further investigations to quantitatively assess the impact of California's protracted drought on the short- and long-term behavior of levees and also for a timely action to strengthen and improve the resilience of California's levees to cope with drought. This paper discusses, from a geotechnical engineering perspective, how the current California drought might threaten the integrity of levee systems. Catastrophic levee failures and major damages that occurred in similar drought situations are shown and discussed to illustrate the devastating impacts that the California drought might impose on existing levees. Several drought-induced, thermo-hydro-mechanical weakening processes are also discussed. Although the focus of this paper is more on levees throughout the Delta, the drought-induced weakening processes discussed herein also threaten levees in similar conditions in Northern California.

Lessons from Previous Cases of Levee Performance in Drought

An example of a similar extreme event is the Millennium Drought in southeastern Australia that impacted the performance of riverbanks along the Murray River (Hubble and De Carli 2015). Analogous to levee construction, anthropogenic modifications have been made to several sections along the Murray riverbanks to enhance their usability for farming and recreational purposes (Hubble and De Carli 2015). At the peak of the Millennium Drought (i.e., 2008–2009), cracking, strain softening, slumping, scouring, and eventually widespread mass failures occurred along sections of the riverbanks as a result of heavy rainfall. Hubble and De Carli (2015) stated that several of the observed cracks extended as much as 1.5 m deep and 0.6 m wide. The heavy rainfall events following the Millennium Drought also threatened the integrity of more than 300 km of levees throughout southeastern Australia (Todd 2010). Fig. 2 depicts several of the failures that occurred along the Murray riverbanks after the drought was superseded by heavy rainfall (Hubble and De Carli 2015). Fig. 2 depicts several of the failures that occurred along the lower Murray's riverbanks in 2009 during the peak of the Millennium Drought. The failure was a consequence of drawdown effects induced by lowered river levels (Hubble and De Carli 2015). Fig. 2(a) is indicative of a riverbank section near the Murray Bridge before the collapse, and Fig. 2(b) shows the riverbank after the collapse. The multibeam bathymetry map in Fig. 2(c) depicts the failed riverbanks along a 150-m section

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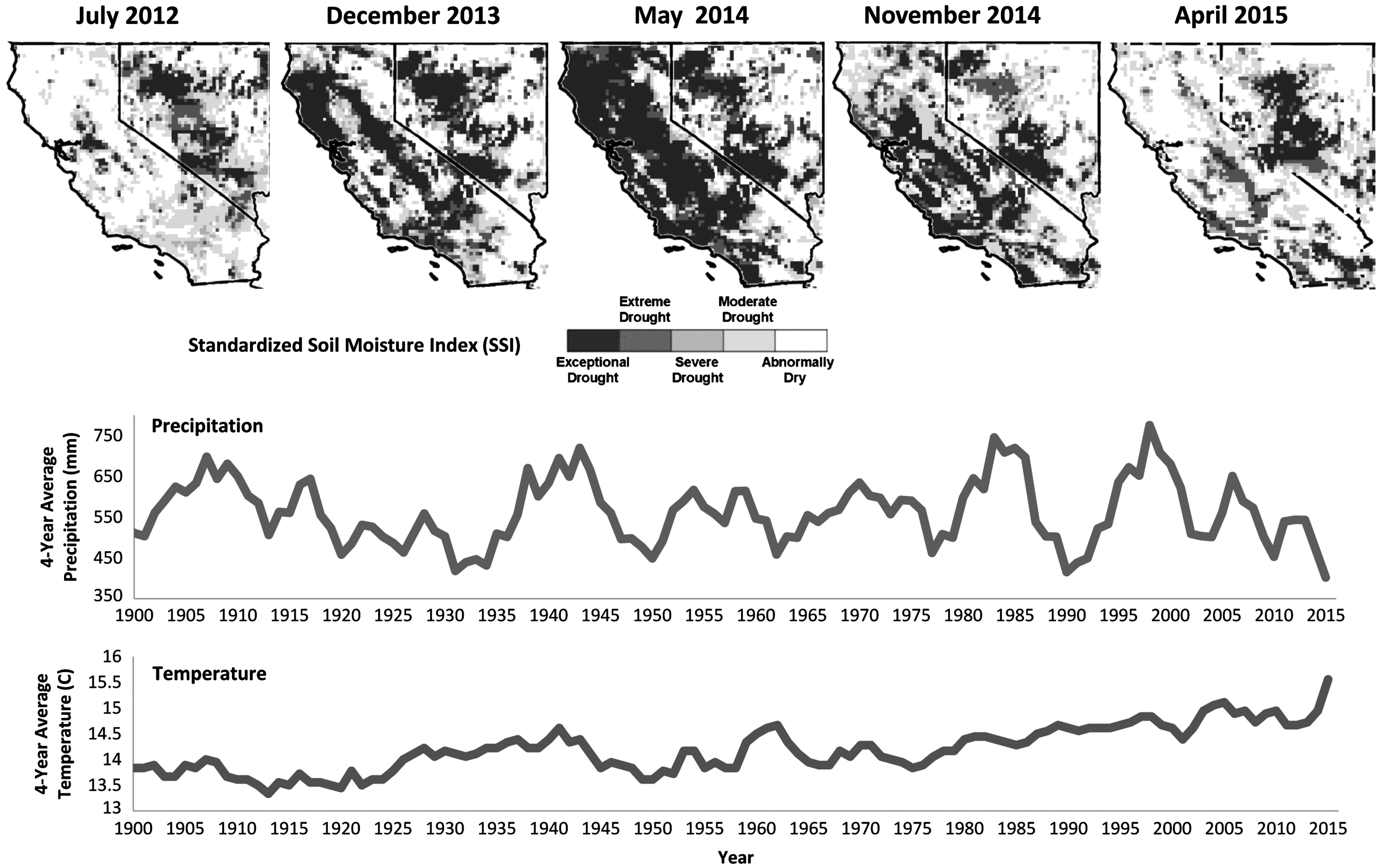

Fig. 1. (a) Snapshots of drought condition based on the standardized soil moisture index (SSI); (b) 4-year average precipitation (mm); (c) 4-year average temperature (°C) from 1899 to 2015 [(a)–(c) data from Hao et al. 2014; NOAA 2015]

near the Murray Bridge. The contours in Fig. 2(c) are representative of the depths of the Murray River after the riverbank failures, with the smallest depths indicated by red (gray in the black-and-white figure) and the largest by dark blue (black in the black-and-white figure).

Another example of the impacts of extreme drought on earthen structures is the failure of the Wilnis Dike in the Netherlands (Van Baars 2005). The Wilnis Dike serves as a secondary dike, and the surficial soil layers in the vicinity of the Wilnis Dike failure consisted mostly of a highly anisotropic deposit of peat overlying a thick layer of dense sand. During one of the driest summers in more than 50 years, the Wilnis Dike failed in August 2003. Field inspections revealed small and large desiccation cracks in the peat material. Fig. 3 shows the largest failure occurring in the Wilnis Dike. The failure consisted of a 10-m horizontal translation that was triggered by the drought-induced cracks and other factors, namely, reduction in soil unit weight and shrinkage (Van Baars 2005). The horizontal translation of the dike led to rapid dissipation of water in the Wilnis Canal, displacing approximately 2,000 residents in the Wilnis Village from their homes and placing roughly 600 houses under about half a meter of water (Van Baars 2004). Reduction in self-weight, shrinkage, and desiccation cracking of the peat material were identified to be the principal contributing factors to the failures of the Wilnis Dike during the unusually dry season in 2003 (Van Baars 2005).

Additional studies have been conducted in the United States regarding the impact of drought stress on levees. In November 2004, the United States Army Engineering Research and Development Center conducted ponding tests on a section of the Retamal levee in the Lower Rio Grande Valley, Texas (Dunbar et al. 2007). The body and foundation of the Retamal levee comprises predominately of high plasticity clay (Dunbar et al. 2007). The ultimate goal of the study was to delineate potential weakening and failure mechanisms in levees under extreme drought stress (Dunbar et al. 2007). Several areas along the Retamal levee showed signs of extensive surface cracks, soil drying, and internal erosion. It was noted that surface cracks extended into the core of the levee to a depth of about 2.7 m (Dunbar et al. 2007).

Status of California Levees

In California, more than 21,000 km of urban and nonurban levees protect dry land from floods, deliver two-thirds of the drinking water, and protect homes, businesses, and agriculture in the Central Valley, Delta, and Northern California from flooding (CDWR 2011; Taylor 2015). The levees throughout most of the Delta downstream of Sacramento are primarily nonurban levees that protect land that is at or below sea level and often continuously hold back water. On the contrary, a majority of levees throughout the Central Valley and Northern California are urban because they protect densely populated areas from flooding (CDWR 2011). The later levees are intermittently loaded and are designed to function only during flooding or high water levels. Drought-induced weakening mechanisms can also threaten the structural integrity of urban flood control levees throughout Sacramento, Stockton, and other cities in northern California.

Resilience of California's levees, regardless of extreme drought, is a primary concern by considering the fact that a majority of California's levee systems are operating under rather poor reliability

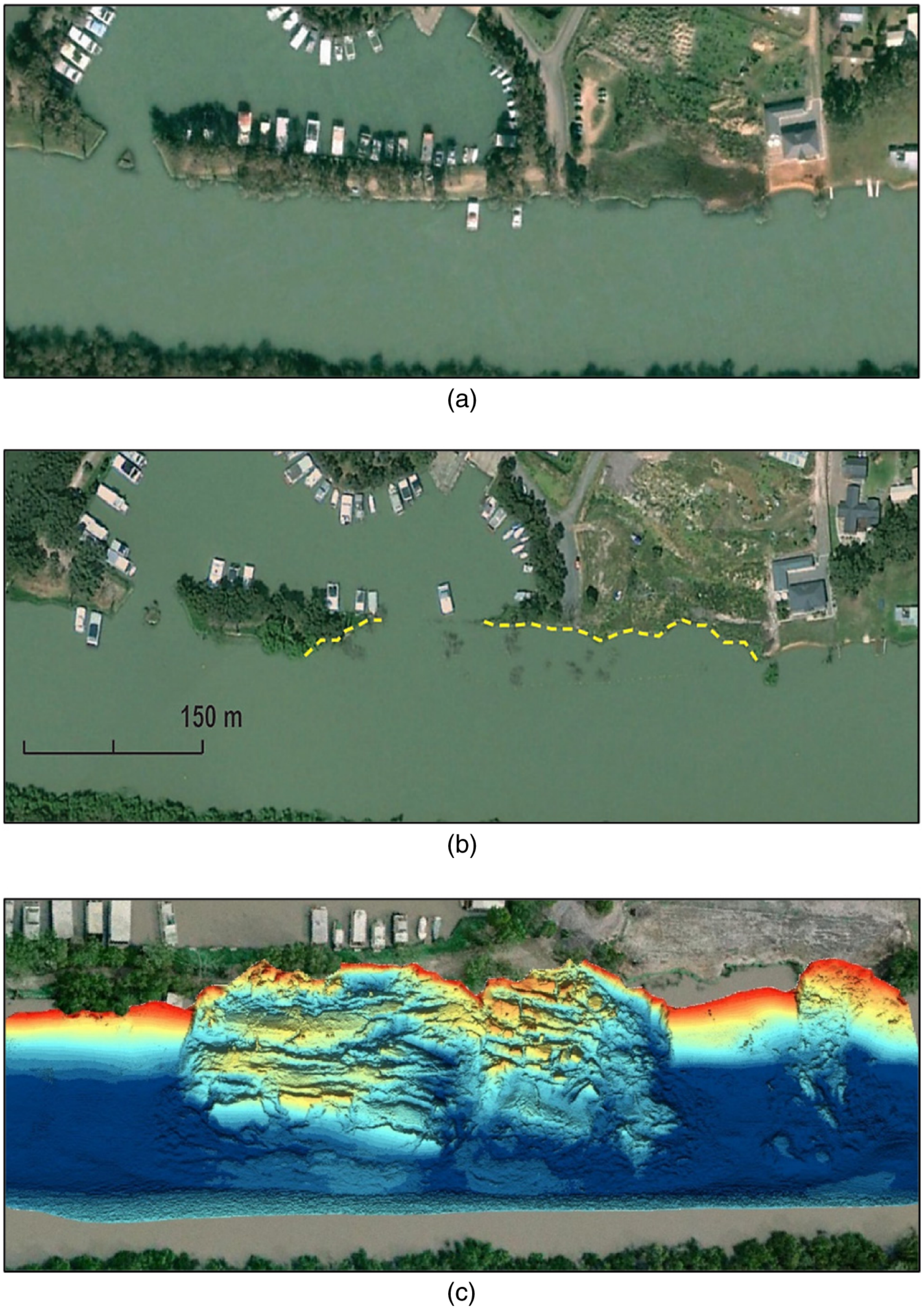

Fig. 2. Failures at the peak of Australia's Millennium Drought in Murray Riverbank: (a) before-collapse; (b) after-collapse; (c) multibeam bathymetry map of riverbank after-collapse [(a) and (b) map data: Google, DigitalGlobe; (c) courtesy of Professor Tom Hubble and Elyssa De Carli]

(Taylor 2015). A high percentage of the levee systems in the Delta were constructed by settlers in the mid- to late-eighteenth-century to protect agricultural lands from flooding. These levees comprised predominately of poorly compacted, unengineered mixtures of sandy, clayey, and organic soils. In addition, a vast majority of these marginal levee systems were built directly above deep layers of highly organic peaty soils (Reinert et al. 2014). Notably, the original function for the Delta levees was to protect rich farmland that often flooded on a 2- to 5-year basis and not to restrict saltwater from intruding into the freshwater system. However, their role has changed within time, and the Delta levees are currently critical for California in that agriculture and movement of water for the State Water Project and the federal Central Valley Project depend heavily on these levees (Taylor 2015). This change in the Delta levees' role is primarily due to the major land subsidence that the Delta has been historically undergoing. Failure of the Delta levees would inundate land that has subsided below sea level, drawing in seawater, and consequently, contaminating the water supply.

Fig. 4 illustrates the hazard ratings for urban [Fig. 4(a)] and nonurban [Fig. 4(b)] levees throughout the Sacramento and San Joaquin River Watersheds, reported by the California Department of Water Resources (CDWR 2011). The evaluation considered 478 and 2,386 km of urban and nonurban levees, respectively. As can be seen, 51 and 55% of urban and nonurban levees evaluated were classified as high hazard, indicating that they are in danger of failing during an earthquake or flood event. Importantly, these classifications were

Fig. 3. Aerial view of the failure of the Wilnis levee in the Netherlands, early Tuesday, August 26, 2003, following overnight flooding superseded a drought season; a 100-m-long section of the levee collapsed, causing the evacuation of around 2,000 inhabitants (courtesy of Koen Suyk, EPA/Newscom)

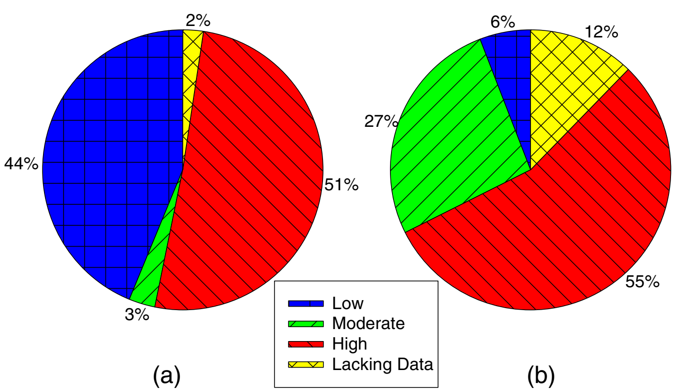

Fig. 4. Hazard classifications of (a) urban; (b) nonurban levees in the Sacramento and San Joaquin River Watersheds (data from CDWR 2011)

performed before the ongoing extreme drought commenced. This implies that the functionality of the aging levees will continue to decrease unless strategic actions are taken to implement some level of maintenance and rehabilitation approaches (NRC 2012).

A risk analysis was conducted in 2006 to compare consequences of California levee failure before and after drought (Vicuña et al. 2006). The analysis indicated that levee failure in the postdrought scenario resulted in land fallowing of approximately 1 million acres in the San Joaquin Valley, in addition to a farm productivity loss of roughly \$250 million. Levee failure in the before-drought scenario was estimated to result in land fallowing of approximately 700,000 acres and a decline in farm profits of about \$100 million (Vicuña et al. 2006). These figures and economic impacts are anticipated to rise at the current time given inflation and worsened drought conditions.

Potential Weakening Mechanisms in Levees due to Drought Stress

To properly investigate adverse impacts of the ongoing drought on the structural integrity of California's levees, the effects of drought on stabilizing and destabilizing factors contributing to the stability of levees should be quantified. As schematically shown in Fig. 5, several drought-induced weakening mechanisms can adversely impact the integrity of earthen structures such as levees. The mechanisms include, but are not limited to, soil strength reduction, desiccation cracking, land subsidence and erosion, fissuring and soil softening, and soil organic carbon oxidation (e.g., Dunbar et al. 2007; Vicuña et al. 2006; Port and Hoover 2011; Brooks et al. 2012; Vardon 2015; CACC 2015; Vahedifard et al. 2015a).

The impact of drought on the stability of earthen levees can be quantified by its influence on the non-isothermal shear strength of soil. Shear strength is not constant for soils under non-isothermal partially saturated conditions and therefore, is highly dependent on soil saturation, matric suction, and soil temperature. California's levees are primarily built out of sandy-clayey soils. For sands, it is shown that the shear strength typically exhibits a non-monotonic trend versus saturation (e.g., Lu and Godt 2011). That is, the shear strength of sand significantly decreases under too dry (i.e., drought) or too wet (e.g., heavy rainfall) conditions, which can adversely impact the stability of levees. For fine-grained soils (e.g., clay and silt), the impact of soil temperature is more pronounced, which is attributed to the existence of intermolecular physicochemical forces in such soils. Elevated soil temperatures and low soil moisture levels due to the drought can lead to reductions in the effective stress and corresponding shear strength (e.g., Uchaipichat and Khalili 2009; Alsherif and McCartney 2015). Furthermore, a decrease in the effective stress can adversely impact the stability of slopes (e.g., Vahedifard et al. 2015b, c) and bearing capacity (e.g., Vahedifard and Robinson 2015) in partially saturated soils.

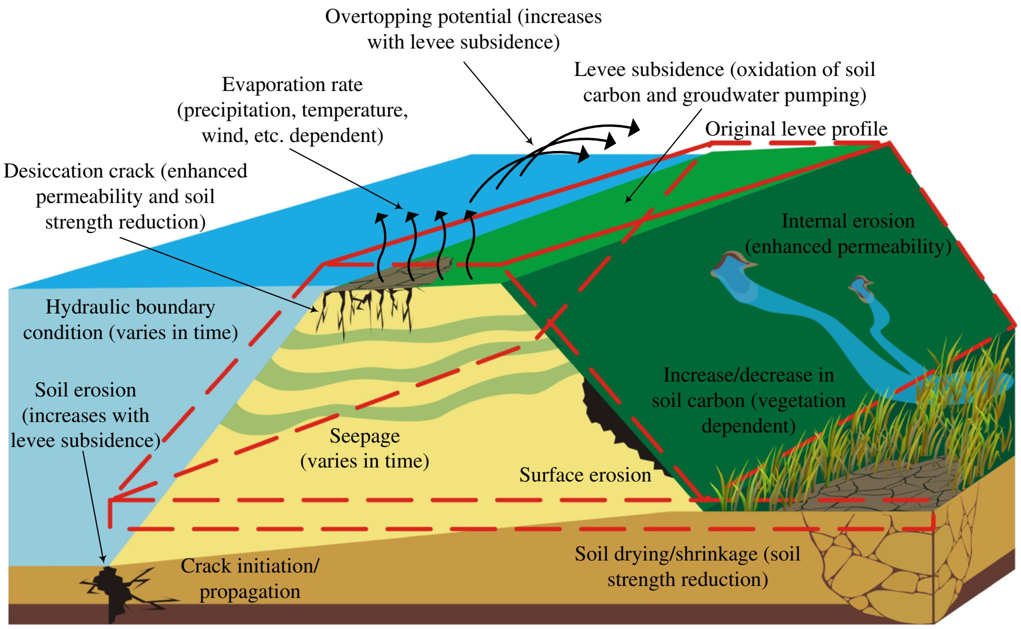

Fig. 5. Potential weakening mechanisms imposed on earthen levees due to drought

Drought can lead to further weakening mechanisms such as soil desiccation cracking, drying, shrinkage, and softening (e.g., Vardon 2015). Desiccation cracks expose the soil to rapid infiltration leading to large increases in pore pressures with depth (Tang et al. 2011; Baram et al. 2013). Some levees throughout California, such as those in the Delta, continuously hold water behind them. The depths of desiccation cracks in these levees are presumably limited by the position of the phreatic surface within the levee. As opposed to Delta's levees, urban levees in the Central Valley and Northern California are intermittently loaded. Drought-induced desiccation cracking can be of greater consequence for the integrity of these intermittently loaded levees that may become completely dry during drought. A number of studies (e.g., Van Baars 2005; Dyer et al. 2009) have investigated the impact of clay fissuring and softening and suggested possible hydromechanical failure mechanisms due to cracks. Tang et al. (2011) noted that an overall increase in temperature and prolonged drought can lead to long-term soil drying, eventually leading to shrinkage ensued by desiccation cracking. Such behavior can lead to more significant structural instabilities such as slides, flows, or falls in levees.

The Delta has been undergoing land subsidence primarily due to microbial oxidation and compaction of organic-rich soils (Mount and Twiss 2005; Brooks et al. 2012). Extreme drought will increase the demand for groundwater extraction as well as the rate of soil organic carbon (SOC) decomposition. Both of the aforementioned factors will accelerate land subsidence (Deverel and Leighton 2010), which can directly threaten levee structures by reducing lateral support, making the systems more susceptible to instabilities and overtopping failures. Recent results from a long-term remote sensing–based monitoring study showed that land subsidence in parts of the Delta has reached historical rates of approximately 5 cm per month (Farr et al. 2015), several times larger than pre-drought subsidence rates (i.e., as much as 3.4 cm per year) estimated for the same area (Deverel and Leighton 2010). Regarding the impact of land subsidence on levees, an important lesson can be learned from the 2005 levee failures in New Orleans, Louisiana, during Hurricane Katrina. The failures resulted in more than 1,300 deaths and greater than $100 billion worth of economic loss (Briaud et al. 2008). Dixon et al. (2006) found that a land subsidence period from 2002 to 2005 prompted overtopping levee failures during the peak storm surge of Hurricane Katrina.

Each or a combination of the aforementioned drought-induced weakening processes can be important factors threatening the integrity of California's levees. However, the impacts of these mechanisms on levees have not been well understood and deserve greater attention in a timely manner to properly mitigate any drought-induced failure.

Resilience of California Levees under a Multihazard Scenario

Although the focus of this paper is about the effects of drought, it is prudent to consider a multihazard scenario when assessing the performance of California's levees during drought. It is almost inevitable that drought is superimposed or followed by other climatic conditions, such as severe flooding, storm surges, high temperatures, sea level rise, and extreme rainfall events, which can further threaten the structural integrity of levees. El Niño is also anticipated to hit California in 2016 with high temperatures, heavy rainfall, and storm surges, all resulting from changes in the distribution of warm water in the Pacific Ocean (Prigg 2015). During the 1997 El Niño events, California experienced a 200% increase in rainfall compared with preceding annual averages. These heavy rains (i.e., approximately 760 mm of rain in 2 months) prompted overtopping levee failures as well as avalanches throughout the Sacramento River Basin, displacing more than 120,000 individuals and resulting in approximately $35 million (1997 dollars) in economic loss (CERT.io 2015).

Additionally, the high seismicity level of California poses yet another challenge to the resilience of California's levees (e.g., Port and Hoover 2011; Reinert et al. 2014). There is a 67% chance that a 6.7 or greater magnitude earthquake will occur in the Delta Region in the next 20 years; an earthquake of this magnitude could induce more than 140 levee failures as well as flood several islands instantaneously, leading to repair costs of greater than $2.3 billion (Port and Hoover 2011).

In terms of flood hazard, the current warming trend will likely induce a 30-cm sea level rise in the next 25 years (Port and Hoover 2011). Such a threat is anticipated to increase the frequency of a 100-year peak tide to only a 10-year event, resulting in flooding of at least 27 islands in the Delta (Port and Hoover 2011). Sea level rise near the Delta's western end can also induce increases in seawater intrusion, which could slowly disrupt water supply systems for several months to several years (Hanak and Lund 2012).

Concluding Remarks

The purpose of this paper was to stimulate discussion and to highlight the critical need for quantitatively assessing the resilience of California's earthen levees to the ongoing extreme drought. A vast majority of the California levees are currently at a high risk condition. Drought can further threaten the structural integrity of California's levees by inducing weakening mechanisms resulting from soil desiccation cracking, temperature rise, drying shrinkage, clay fissuring and softening, and land erosion/subsidence.

Assessing the impacts of climate change on levees could be conducive in answering critical questions, including the following: (1) How does drought influence the factors of safety in the current and future states of levees? (2) How does the rate and variability of drought affect the short and long term behavior of California's levees? (3) What are the constraints in existing levee design, maintenance, and monitoring guidelines for extreme loads caused by drought, flooding, increased rainfall-intensity, earthquake, and temperature rise? and (4) What are the adaptation and mitigation strategies for reducing drought impacts on the performance of levee systems throughout California? The geotechnical engineering community can take a proactive role to properly answer the preceding questions and protect the health and welfare of the general public.

In the current hydrologic and geotechnical design guidelines, drought risk and the impacts of potential future climate changes have not been considered (Vahedifard et al. 2015a). Given the significance of projected changes, there is a need to develop a framework for integrating drought and climate change risks in engineering design. Assuring the resilience of the California's levees in a prolonged drought involves many authoritative and complex technical aspects and necessitates the development of appropriate strategies and measures that are effective and efficient on both the short and long term.

In March 2015, Governor Jerry Brown of California proposed to accelerate more than \$1 billion in water resource spending. More than 65% of the proposed budget is anticipated to go toward rehabilitating flood control structures (e.g., levees) with hopes of increasing their resilience under an extreme condition such as drought. This is an example of forward looking strategy to be more prepared for the future. Further, different authorities are constantly monitoring the Delta levees to address and repair distressed levee sections. However, more in-depth scientific research is needed to understand how drought can threaten the integrity of critical infrastructure, such as levees, especially under a multihazard scenario.

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