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ESSAY

Weakening mechanisms imposed on California's levees under multiyear extreme drought

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Abstract California is currently suffering from a multiyear extreme drought and the impacts of the drought are anticipated to worsen with climate change. The resilience of California's critical infrastructure such as earthen levees under drought conditions is a major concern that is poorly understood. California maintains more than 21,000 km of urban and nonurban levees which protect dry land from floods and deliver two-thirds of the state's drinking water. Many of these levees are currently operating under a high failure risk condition. This essay argues that California's protracted drought can further threaten the integrity of these already at-risk levee systems through the imposition of several thermo-hydro-mechanical weakening processes. Pertinent facts and statistics regarding California's drought and current status of its levees are presented. Lessons from previous catastrophic levee failures and major damages which occurred under similar events are discussed. Weakening processes such as soil-strength reduction, soil desiccation cracking, land subsidence and surface erosion, and microbial oxidation of soil organic carbon are comprehensively evaluated to illustrate the adverse impacts that the ongoing California drought can have on levees. This essay calls for further research in light of these potential drought-induced weakening mechanisms to support adaptation and mitigation strategies to possibly avert future levee failures. These weakening processes can threaten any drought-stricken infrastructure interfacing with soil, including embankments, roads, bridges, building foundations, and pipelines.

1 Introduction

The United States has over 160,000 km of earthen embankments (referred to as earthen levees) that protect dryland from flooding and water resources (CRS 2011). A significant amount of

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these levees are operating under rather poor reliability (e.g., NRC 2012; Sehat et al. 2014). The United States Army Corps of Engineers (USACE) conducted a field study on the status of more than 740 levee systems throughout the United States and rendered over 90 % of these systems as being “minimally acceptable” or “unacceptable”, indicating that the levee has minor deficiencies or is not resilient enough to protect water resources and dryland from flooding (Maciag 2011). Many of these marginal levees are over 70 years old (NRC 2012). This indicates that the resilience of these systems is a primary concern without even considering for extreme weather events under a changing climate.

Catastrophic levee failures such as those occurring in August 2005 in New Orleans, Louisiana due to extreme events have led to severe societal and economical losses. During the peak storm surge of Hurricane Katrina, several kilometers of earthen levees breached along the Mississippi River-Gulf Outlet Canal in New Orleans, ranking among the worst engineering disasters of all time (e.g., Briaud et al. 2008). The levee failures resulted in flooding throughout 80 % of New Orleans, leading to more than 1300 deaths and over $100 billion worth of economic loss (Briaud et al. 2008). Following this catastrophic disaster, roughly $14 billion was put forward to reconstruct New Orleans’ levee system. However, the USACE recently stated that the resilience of these rehabilitated levees may not be enough to withstand observed and projected climate extremes (Reid 2013).

There is a clear gap in the state of our knowledge in terms of characterizing and quantifying the impacts of extreme events under a changing climate on the resilience of critical infrastructure such as earthen levees. California is suffering from a record-setting extreme drought (2012–2015) (Diffenbaugh et al. 2015). Australia’s Millennium Drought (i.e., 1997–2009), that led to substantial societal and ecological impacts, is often labeled as the type of event that California should prepare for. California’s record-setting drought is categorized by low precipitation and corresponding high temperatures (Shukla et al. 2015). Figure 1a and b illustrate the four-year average precipitation and temperature throughout California, respectively. The synchronized extreme low precipitation and high temperature was predicted to be a 200-year extremity (AghaKouchak et al. 2014). These extreme conditions have led to substantial decreases in soil moisture, placing most of California in severe to exceptional drought over the past four years (Vahedifard et al. 2016a). The intensity of the drought is a consequence of the snow pack reduction resulting from elevated temperatures and soil moisture scarcities, which affect the overall available water supply (Diffenbaugh et al. 2015).

There is a vital need to improve the current knowledge on the possible threats that protracted drought can impose on infrastructure and take subsequent actions in a timely manner to mitigate these threats and adapt our infrastructure to climate change. The need is more time sensitive for earthen levees since their functionality to protect limited water resources and dryland is more critical during extreme drought conditions (Vahedifard et al. 2016a). In California, over 21,000 km of urban and non-urban levees deliver approximately two-thirds of potable water to more than 23 million Californians and protect over $47 billion worth of homes and businesses from flooding (CDWR 2011; Taylor 2015). Levees throughout the Sacramento-San Joaquin Delta (Delta) are non-urban in that they protect dryland that is at or below sea level (Vahedifard et al. 2016a). In contrast, levees located in Central and Northern California are primarily urban as they defend heavily populated areas from floods (CDWR 2011). California’s levees were originally constructed out of low-compacted, non-engineered mixtures of sandy, clayey, and peaty soils, in an

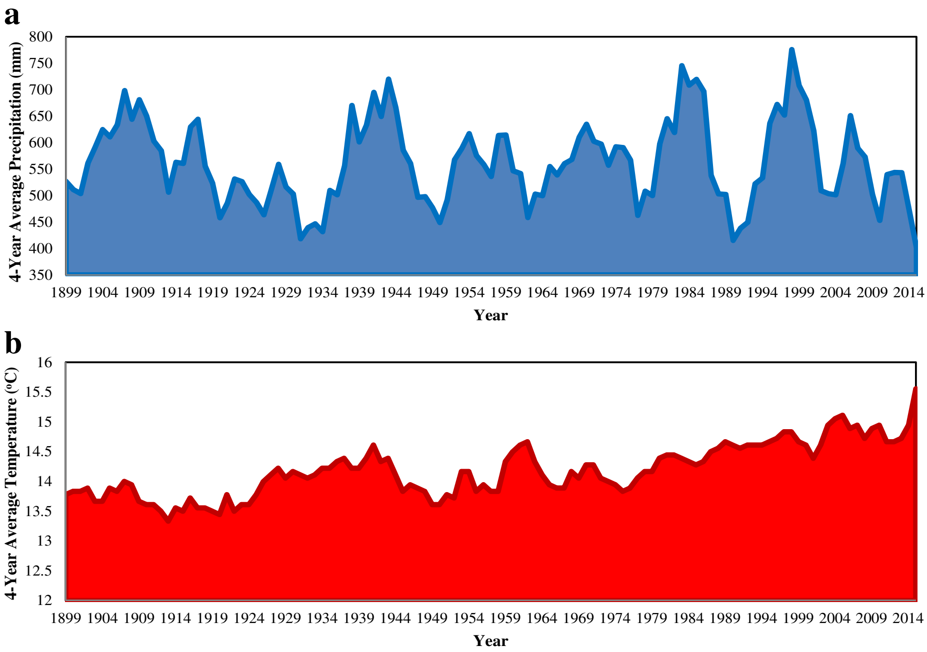

Fig. 1 **a** Four-year average precipitation (mm) and **b** Four-year average temperature (°C) throughout California from 1899 to 2014. The data presented in Fig. 1a and 1b comes from Hao et al. 2014; NOAA 2015. The synchronized extreme low precipitation and high temperature was predicted to be a 200-year extremity (AghaKouchak et al. 2014)

effort to protect agricultural lands from flooding. As indicated by Table 1, about 56 % of California's levees are rated as "*high hazard*", meaning that they are in serious danger of failing during an earthquake or a flood event (CDWR 2011).

Table 1 Summary of overall hazard categorization for California's urban and non-urban levees (data from CDWR 2011)

Levee type	Flood Control System	Levee hazard rating				
		Low hazard (kilometers)	Medium hazard (kilometers)	High hazard (kilometers)	Lacking sufficient Data (kilometers)	Total (kilometers)
Urban levees						
Sacramento and San Joaquin river watersheds	SPFC	209	14	243	11	478
Non-urban levees						
Sacramento river watershed	SPFC	48	462	689	143	1342
	NSPFC	23	51	43	34	151
San Joaquin river watershed	SPFC	63	105	468	5	640
	NSPFC	6	15	120	111	252
Total:	-	140	633	1320	293	2386

SPFC State Plan of Flood Control, *NSPFC* Non- State Plan of Flood Control

Vahedifard et al. (2015a, 2016a) note that protracted drought can undermine the structural integrity of California's earthen levees. This essay aims to comprehensively discuss potential thermo-hydro-mechanical (THM) weakening mechanisms that prolonged drought can impose on California's *high hazard* levees. We argue that California's protracted drought could be a critical threshold, 'last straw' event that could trigger widespread failure or degradation of the levees. While there have been several large-scale studies on the impacts of other climate trends such as increased rain intensity, progressive land subsidence, and global sea-level rise on levee systems (e.g., Dixon et al. 2006; Vicuña et al. 2006), the impacts of drought on the integrity of California's levees remain uncertain. Potential drought-induced weakening processes such as soil-strength reduction, desiccation cracking, land subsidence and erosion, and soil organic carbon (SOC) decomposition are discussed to illustrate the devastating impacts that the ongoing California drought might impose on existing levees. We call for further research in light of these potential weakening mechanisms to support adaptation and mitigation strategies to possibly avert future catastrophic levee failures. While the focus of this essay is on the effects of the ongoing extreme drought, it is prudent to consider the resilience of levees under a multi-hazard scenario to better prioritize adaptation and mitigation strategies. It is almost inevitable that extreme drought is ensued by other extreme climate events, notably extended periods of high temperatures, major flooding, storm surges, sea level rise, and extreme precipitations; all of which can further threaten the structural integrity of levee systems.

2 Performance of earthen levees under extreme drought conditions

To better understand the implications of extreme drought on levees, it is prudent to study previous cases that document the performance of similar earthen structures under drought conditions. During the peak of the Australian Millennium Drought (i.e., 2008–2009), extreme drought conditions prompted a myriad of catastrophic failures in the riverbanks of the Murray River (Hubble and De Carli 2015). Hubble and Rutherford (2010) reported another Australian example of widespread failures in anthropogenically modified banks of the Nepean River, southeastern Australia, which occurred in response to large floods that followed the breaking of a long-term drought.

Most of the riverbanks along the Murray River have been anthropogenically modified for recreational purposes, dairy farming, or marinas (Liang et al. 2015; Hubble et al. 2014). This is typically done by placing an embankment of soil over the top of natural riverbanks, which is analogous to levee construction. The failures that occurred along the Murray riverbanks were attributed to the unprecedented and abnormal below sea-level position of the river pool (Hubble et al. 2014; Hubble and De Carli 2015). This situation created what is described to be a 'slow-motion' rapid-drawdown slump failure, which is a very apt example of leveed river bank failure during a drought. Slump failures of more than 150 m long were identified at the Murray Bridge adjacent the Long Island Marina (LIM) (Hubble et al. 2014). The river margin slope where the failures occurred is developed on a 12- to 15-m-thick layer of low-permeability, soft clay. Figure 2a displays the 150-m failure section near the LIM. As can be seen in Fig. 2a, the remarkably low pool level of the Murray River prompted extensive desiccation cracks along the crest of the sloped riverbanks. The extensive cracks served as the primary weakening mechanisms, causing significant soil-strength reduction. The multi-beam

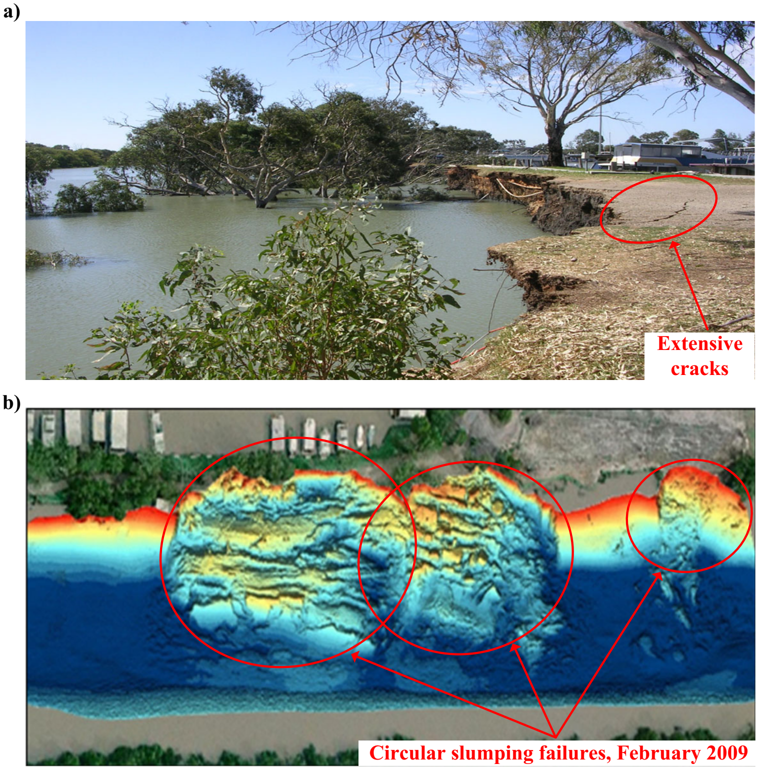

Fig. 2 **a** Slumping failures at the peak of Australia's Millennium Drought in the Murray Riverbanks and **b** Multi-beam bathymetry map of slumping failures. In Fig. 2a, the suppressed pool level of the Murray River induced desiccation cracks along the crest of the riverbanks. These cracks were the primary weakening mechanisms that led to significant reductions in soil strength. The multi-beam bathymetry map in Fig. 2b displays the post-failure topography of the riverbanks. The smallest depths are shown in *red* and the largest in *dark blue* (courtesy of Prof. Tom Hubble and Elyssa De Carli)

bathymetry map in Fig. 2b depicts the change in topography of the riverbanks after the failures. The smallest depths are indicated by red and the largest by dark blue, representing about 1 and 13 m changes in topography of the riverbanks, respectively.

Another seminal example of drought impacts on levees is the failure of the Wilnis Levee in the Netherlands (Van Baars 2005). The Wilnis levee comprises predominately of Holland peat, which is very susceptible to desiccation cracks, deformation, and reductions in soil strength (Van Baars 2005). In August 2003, the Wilnis Levee failed after a prolonged drought season. A rigorous field evaluation conducted after the failure unveiled signs of extensive desiccation cracks in the peaty soil. The largest of the cracks were observed in the longitudinal direction (i.e., parallel to the levee) at the crest of the levee. Figure 3 depicts the largest failure event, which was a 10-m horizontal translation (Van Baars 2005). The drought-induced soil unit weight reduction, soil shrinkage and cracking were identified as the primary weakening mechanisms that prompted the horizontal translation failure. This failure lead to catastrophic flooding in the new housing quadrant depicted just north of the levee in Fig. 3.

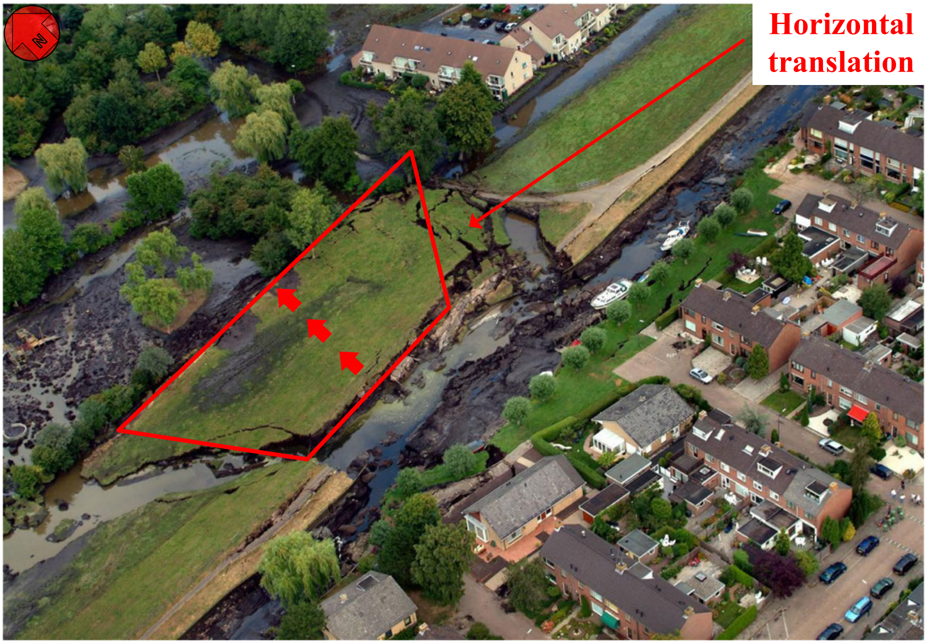

Fig. 3 Horizontal Failure of the Wilnis Levee in the Netherlands, occurring in August 26, 2003 after an overnight flooding superseded a drought season (image courtesy of Koen Suyk,EPA/Newscom). The failure was identified to be a consequence of self-weight reduction, shrinkage, and desiccation cracking of the earthen levee material

3 Imposition of weakening mechanisms on California's levees under severe drought

We argue that California's levees are at their most vulnerable state as the record-setting drought further threatens their already-marginal stability through an ensemble of THM weakening processes. The increased force and frequency of extreme drought has stimulated research initiatives over recent years regarding the impacts of these processes on earthen structures. However, as noted, information on the implications of these weakening processes on California's earthen levees is relatively incomplete. Figure 4 illustrates some of the adverse effects of drought on levees. Potential weakening mechanisms and their threats on levee stability are discussed in the subsequent sections.

3.1 Influence on soil strength

Soil strength is the primary stabilizing factor maintaining the stability of any earthen structure. The imposition of drought-induced weakening mechanisms such as desiccation cracks can lead to levee instabilities by reducing soil strength (i.e., soil shear and tensile strength). Soil shear and tensile strengths are an indication of a soil's capability to resist external compressive and tensile stresses, respectively, without failing (e.g., Lu and Likos 2006; Lu et al. 2009). Most of the soils that make up the structure of a levee are under a variably saturated condition. Soil strength is not constant for soils under variably saturated, non-isothermal conditions (e.g., Vahedifard and Robinson 2015; Alsherif and McCartney 2015).

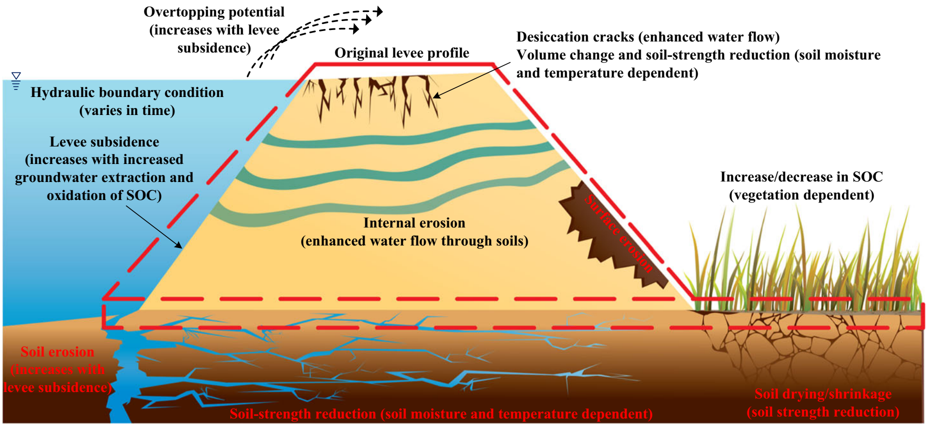

Fig. 4 Conceptual model of thermo-hydro-mechanical weakening mechanisms imposed on levees during extreme drought conditions (after Vahedifard et al. 2016a)

California's levees are primarily built out of sandy-clayey soils. For three representative sand types with different particle ranges, Figs. 5 and 6 illustrate the influence of the effective degree of saturation (i.e., normalized moisture content) on the magnitude and variation of shear strength and suction stress, and tensile strength and matric suction, respectively. Matric suction represents the difference between pore-air pressure and pore-water pressure. Suction stress collectively represents all active forces concentrated at or near the interparticle contacts. These forces for unsaturated soils include physico-chemical forces, surface tension forces, and forces arising from negative pore water pressure (Lu and Likos 2006; Vahedifard et al. 2016b).

For sands, as demonstrated in Fig. 5, if conditions are too wet (e.g., extreme rainfall events), or inversely, too dry (e.g., drought) the air-water interface areas in soil will diminish, resulting in very small to zero suction stress, and smaller shear stress than as seen between $0\ \% < S_e < 100\ \%$. Such changes in suction stress and shear strength can significantly impact the stability of natural and man-made earthen structures such as levees (e.g., Lu and Likos 2006; Vahedifard et al. 2015b, 2016c). Figure 6 displays the interrelationship between the

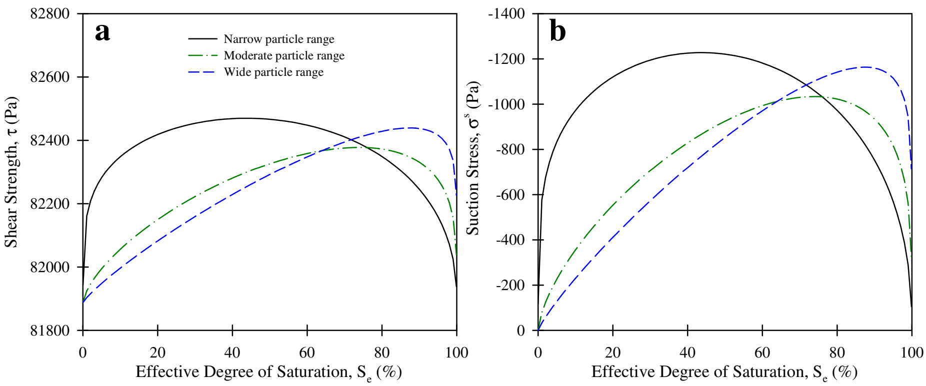

Fig. 5 **a** Shear strength and **b** Suction stress characteristic curves (SSCCs) for three fine sands with different particle-size distributions. Input soil properties were selected based on values reported after Reinert et al. (2014) for a California levee sand. The SSCCs were computed here for a depth (z) of 9 m, which is a practical height for the body of an earthen levee

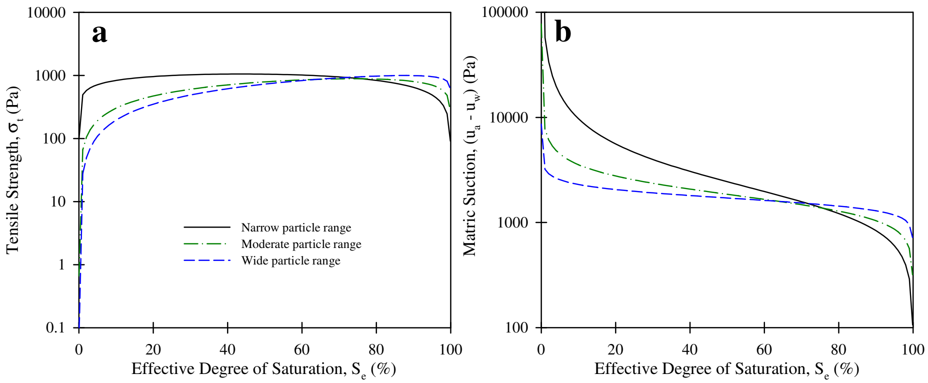

Fig. 6 **a** Tensile strength characteristic curve (TSCC) and **b** Soil water characteristic curve (SWCC) for three fine sands with different particle-size distributions. Input soil properties were selected based on values reported after Reinert et al. (2014) and Lu et al. (2009) for a California levee sand and analogous sandy material, respectively

tensile strength characteristic curve (*TSCC*) and the soil water characteristic curve (*SWCC*) for the same three representative sands. The *TSCC* and *SWCC* represent changes in tensile strength and matric suction, respectively, at various effective degrees of saturation. As shown, the tensile strength of sand exhibits a non-monotonic trend with variations in S_e. Too dry or too wet conditions will lead to reductions in the tensile strength. As it can be seen, sands with a smaller pore size distribution sustain greater inter-particle isotropic tensile stress and matric suction, resulting in larger tensile strength. However, between $0\ \% \leq S_e \leq 20\ \%$, it can be seen that sands with a wide particle-size range and pore size distribution can undergo larger reductions in tensile strength. This degradation in the tensile strength reinforces the need for its consideration under extreme drought conditions.

The current California drought imposes non-isothermal conditions to the levees, inducing concurrent changes in soil moisture and temperature. However, knowledge of soil strength response to concurrent moisture and temperature changes is incomplete (e.g., Alsherif and McCartney 2015). 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 physico-chemical forces in such soils. Elevated soil temperatures and low soil moisture levels during a drought can lead to reductions in the effective stress and corresponding soil strength (e.g., Uchaipichat and Khalili 2009; Alsherif and McCartney 2015).

3.2 Desiccation cracking and soil softening

Extreme drought can adversely impact the stability of earthen levees by softening the soil and inducing desiccation cracks in their body and foundation (e.g., Dunbar et al. 2007; ASCE 2015). Desiccation cracking behavior is governed by a large number of factors, namely, mineral composition, temperature, relative humidity, layer thickness and layer size (e.g., Péron et al. 2009; Tang et al. 2011). Sandy and peaty soils contain a significant amount of large pores and may be more sensitive to water loss during an extreme drought event. Conversely, clayey soils have very few macro-pores and therefore, are more likely to retain water. However, clayey soils (i.e., fine-grained soils) are extremely susceptible to desiccation cracking. Several studies (e.g., Skempton et al. 1969; Van Baars 2005; and Dyer et al. 2009) have investigated the adverse effects of clay desiccation fissuring and softening on earthen structures. Fissures refer to narrow openings or cracks whose dimensions are largely governed by soil moisture and plasticity (Dyer et al. 2009). Tang et al. (2011) noted that an overall increase in temperature and prolonged periods of no precipitation (i.e., drought) can lead to long-term soil drying, which eventually leads to shrinkage and corresponding desiccation cracking. Hudacsek et al. (2009) used centrifuge tests to show how soil softening and irreversible creep due to pore-pressure cycling induced swelling and shrinking in clayey soils, consequently desiccation cracking, leading to serviceability failure in earthen structures. Such behavior in the fine-grained soils of levees can lead to more significant structural instabilities such as slides, flows, or falls (Tang et al. 2011). For example, a material with a dry density below its average dry density may increase the risk of sliding in earthen levees (Vardon 2015).

In the case of desiccation cracking, prolonged rainfall events during and following drought have shown to influence partially saturated soil zones by up to 12 m below the ground surface (Baram et al. 2012). Desiccation cracks expose the soil to rapid infiltration leading to large increases in pore pressures at uncharacteristic depths (Tang et al. 2011). Large increases in pore pressures, in addition to water infiltrating into open cracks, can lead to significant decreases in the effective stress and corresponding soil strength, which can drive an earthen structure to its limit state. It is important to note that limit state may not necessarily denote instability in the form of immediate catastrophic failure. Continual motion can lead to catastrophic failure if that motion causes a reduction in shear strength. For instance, the 1963 Vaiont dam failure in Northern Italy occurred after a prolonged period of creep leading to strain softening. In time, the small increases in load led to disproportional increases in velocity (i.e., creep) and the driving force (i.e., weight of the structure) increased due to losses in shear resistance along the failure surface.

3.3 Land erosion and subsidence

Drought-induced land subsidence and erosion can threaten the integrity of levee systems in California by reducing lateral support and shear resistance, making the systems more susceptible to structural instabilities (Mount and Twiss 2005). Levees constructed in the Delta are founded on thick layers of peat and the unique macro-structure of peat poses a critical challenge in evaluating subsidence (Reinert et al. 2014; Cappa et al. 2015). Progressive land subsidence can directly threaten levee structures by exacerbating the risks of water rising over the tops of levees (referred to as overtopping). For the New Orleans levee failures, Dixon et al. (2006) stated that the rapid 2002–2005 subsidence period prompted the failures as the height of the levees was most likely not great enough to sustain the storm surge.

Land erosion can provide potential pathways for cracking, leading to enhanced permeability and reduction in the stability of an earthen structure (Vardon 2015). Cutting off the land from flood waters in the Delta has barred replacement of sediments. This has led to dramatic land subsidence and erosion as previously flooded, low-oxygen soils have been drained and aerated, losing significant amounts of organic carbon in the process (Mount and Twiss 2005). Certain parts of the central and western Delta currently sit more than 3 m below sea level (Lund et al. 2007). Sea level rise is projected to be a consequence of climate change, leading to an increased risk of coastal flooding. Together, land subsidence and rising sea levels have rendered the region behind the levees increasingly vulnerable to flooding (Zhu et al. 2007), with particular susceptibility noted for the western and central Delta (Lund et al. 2007).

Land subsidence, and subsequent erosion, further increases when groundwater is being consumed at a rate faster than it is being replenished by groundwater recharge. Significant land subsidence due to excessive groundwater pumping has been recorded in the Delta over the past few years. Brooks et al. (2012) used Interferometric Synthetic Aperture Radar (InSAR) measurements to project future land subsidence and potential levee overtopping. They predicted that, with the current global estimated sea-level rise, small isolated regions in the Delta will have subsided by approximately 0.5 m by the year 2025. By 2050, their predictions showed estimates of widespread subsidence of more than 0.5 m. Brooks et al. (2012) predicted that all Delta levees will have subsided below the 0.5-m threshold by the year 2100, which could eventually lead to potential levee overtopping ensued by very high risk flooding throughout the Delta. A recent remote sensing study showed that land subsidence in parts of the Delta has already reached historical rates of around 5 cm per month (Farr et al. 2015). This is several times larger than the rates predicted for similar regions throughout the Delta.

3.4 Soil organic carbon decomposition

California's extreme drought is impacting the decomposition reactions and rates of microbial SOC by increasing soil temperature and reducing soil moisture. Land subsidence in the Delta is primarily caused by aerobic microbial oxidation of SOC, coupled with sea level rise, and compaction of organic soils resulting from groundwater extraction and agricultural practice (Mount and Twiss 2005; Brooks et al. 2012; Reinert et al. 2014). In fact, microbial oxidation of SOC accounts for approximately 75 % of the elevation loss due to peat subsidence (Mount and Twiss 2005). Consequently, the risk of overtopping failures in California's earthen levee further increases with increasing land subsidence.

As noted, many of the Delta levees are founded on peaty soils (Reinert et al. 2014). A significant amount of carbon around the globe is stored in organic soils (e.g., peat) and changes in soil temperature and moisture due to the current warming trend significantly influence SOC dynamics. Peaty soils have decomposition reactants with high activation energies (i.e., slow rates), meaning that these soils will experience greater proportional increases in decomposition with increasing global temperature (Davidson and Janssens 2006; Conant et al. 2011). In fact, 25 % of the estimated global SOC stock in peat is subject to loss due to the current warming trend (Davidson and Janssens 2006).

The effects of temperature rise due to climate change on the decomposability and response rates of SOC still remain highly uncertain. Conant et al. (2011) developed a conceptual model which unravels the effects of a changing climate on SOC dynamics under a variety of circumstances. Figure 7 displays the component processes which govern the decomposability and response rates of SOC. These processes include depolymerization of complex compounds, production and conformation of microbial enzyme production, and adsorption/desorption and aggregate turnover limiting the availability of SOC. The red lines in Fig. 7 indicate that a process accelerates with temperature increases. Conversely, the blue lines indicate that a process is slowed with increasing temperature while the black lines indicate that the influence of temperature on a given process remains largely unquantified. As can be seen, physico-chemical protection slows the depolymerization and exchange of organic compounds, but its response to temperature rise is not well understood (Conant et al. 2011). However, the temperature response of physico-chemical protection varies as a function of the type of binding and bonding affinity. Specifically, the temperature effects on dispersion processes dominate for low-affinity SOC while desorption dynamics dominate for high-affinity SOC (Conant et al. 2011).

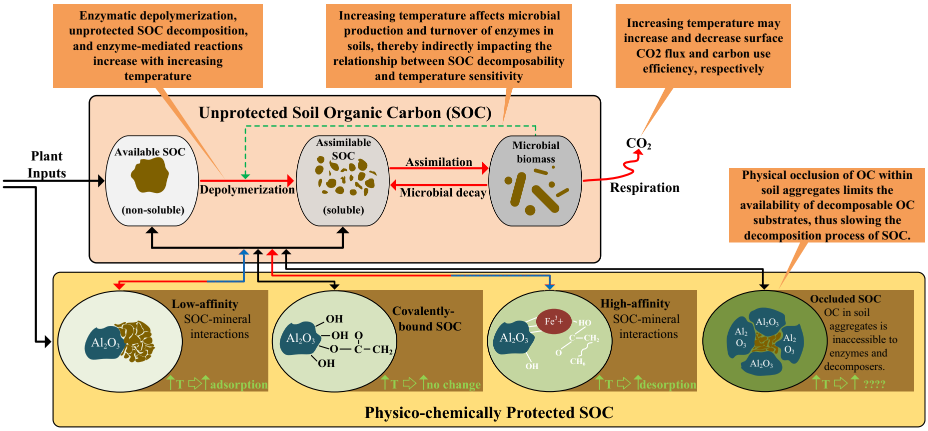

Fig. 7 Conceptual model of the impacts of temperature rise on soil organic carbon (SOC) dynamics (after Conant et al. 2011). The *red lines* indicate that a process accelerates with temperature increases. In contrast, the *blue lines* indicate that a process is slowed with increasing temperature, whereas the *black lines* indicate that the influence of temperature on a given process remains uncertain. As illustrated, the physico-chemical protection slows depolymerization and exchange of organic compounds. However, its response to temperature rise is largely unquantified (Conant et al. 2011)

While it may seem inconsequential, drought-induced SOC oxidation can be an important weakening mechanism in levees. To improve our understanding towards the effects of drought, there is a need to quantitatively investigate possible relationships between SOC decomposition, soil temperature and moisture, reductions in soil strength and consequently, subsidence in earthen levees.

4 Conclusions

This essay comprehensively discussed the thermo-hydro-mechanical weakening processes that California's multiyear extreme drought can impose on its levee systems. California's drought could be a critical threshold, 'last straw' event for its already at-risk levee system, especially if it is followed by heavy rainfall-induced flooding, as seen in several previous drought events. Drought-induced weakening mechanisms such as soil-strength reduction, desiccation cracking and soil softening, land erosion and subsidence, and soil organic carbon decomposition can add even more complexity to an already challenging problem. As demonstrated by previous failures that occurred under similar drought events, these processes can prompt several modes of earthen levee failures such as overtopping, slumping, and sliding. So, there is a serious need to improve our current state of knowledge about the drought-induced threats and take subsequent actions in a timely manner to strengthen our levee systems. Assuring the resilience of levees under a prolonged drought requires the development of innovative strategies and measures that are equally effective and efficient on both the short and long term.

Based on the afore-mentioned facts and discussions, we argue there is an urgent need to invest in research on the effects of drought-induced weakening processes on the short and long term behavior of earthen levees. It is noted that these weakening processes can threaten any drought-stricken infrastructure interfacing with soil, including embankments, roads, bridges, building foundations, and pipelines. An improved understanding of the resilience of

California's levees under a prolonged drought indisputably involves many authoritative and complex technical aspects. It also requires close collaboration between decision makers, engineers, and scientists from other fields including climate science, social science, economics, and disaster science. Community engagement and public risk education are also key to enhancing the resilience of levees to extreme droughts.

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