Geotechnical Engineering in the Face of Climate Change: Role of Multi-Physics Processes in Partially Saturated Soils

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Abstract

Climate change is expected to alter the statistics of extreme events including rainfall storms, floods, droughts, and heatwaves. Climate-adaptive geotechnical structures warrant a quantitative assessment of the impacts of emerging and projected extreme patterns on the short and long-term behaviors of earthen structures. Furthermore, long-term changes to soil carbon and moisture due to non-extreme climate events should also be considered. While several large-scale studies have been conducted to evaluate various aspects of climate change, there is a clear gap in the state of knowledge in terms of assessing the resilience of geotechnical structures to changes in climatic trends (e.g., warmer climate, protracted droughts, intensified extreme precipitations, and sea level rise). The majority of the aforementioned climatic trends pose multi-physics problems involving thermo-hydro-mechanical (THM) processes in partially saturated soils and earthen structures. This review paper discusses how soil-atmospheric interactions and extreme event patterns in a changing climate can alter soil properties and loading conditions, affecting the performance of partially saturated geotechnical structures. We speculate how changes in climatic trends may weaken partially saturated earthen structures through strength reduction, drying, soil desiccation cracking, shrinkage, microbial oxidation of soil organic matter, fluctuation in the ground water table, land and surface erosion, and highly dynamic pore pressure changes. Each of these weakening processes is primarily induced by variations in the soil moisture and temperature. Finally, we discuss potential modes of failure imposed on partially saturated earthen structures by climatic trends.

INTRODUCTION

Projected climate change trends indicated an increase in the frequency of extreme events related to precipitation and temperature (IPCC, 2013). Current models indicate temperature increases of 3° F to 5° F across the United States by the end of the century with prolonged periods of warm spells (Melillo et al. 2014; Cheng et al., 2015). Even historical observations indicate substantial increases in warm spells, short-term heatwaves, and concurrent drought and heat waves (Mazdiyasni and AghaKouchak, 2015; Shukla et al., 2015; Damberg et al., 2014). The first six months of 2017 are the second highest January-June period on record falling between the records set in 2015 and 2016 (NOAA National Centers for Environmental Information. 2017). These changes in global temperature trends have also been accompanied by increases in heavy downpour events, sea level rise, reduction of snow cover, sea ice and glaciers, and prolonged drought (Melillo et al. 2014). The exact changes are heavily dependent upon the region with some areas of the U.S., such as the north and southeast, experiencing an increase in extreme rainfall events, while others, such as the southwest, experience prolonged droughts (Melillo et al. 2014). However, both types of precipitation conditions (dry spells and heavy rainfall), temperature increases, and sea level rise result in damage to earthen infrastructure. Furthermore, it is likely that combinations of these events will occur concurrently or sequentially, posing a multi-hazard risk (Moftakhari et al., 2017; Hao et al., 2013; AghaKouchak et al., 2014a). Figure 1a shows the increase in heavy precipitation event occurrence from 1958 to 2012, and Figure 1b shows annual average air temperatures changes in the U.S. since the early 20th century (since 1901 for the contiguous 48 states and 1925 for Alaska). It should be noted that despite some regions having a decreased average temperature, every state has experienced record highs in the last decade. Assessment of existing earthen structures and design of climate-adaptive geotechnical systems requires a quantitative evaluation of new extreme patterns on the short and long-term behaviors. This is especially true for near surface materials such as slopes and road sub-grades which have been well documented to have significance changes in performance and strength due to seasonal changes it precipitation and temperature.

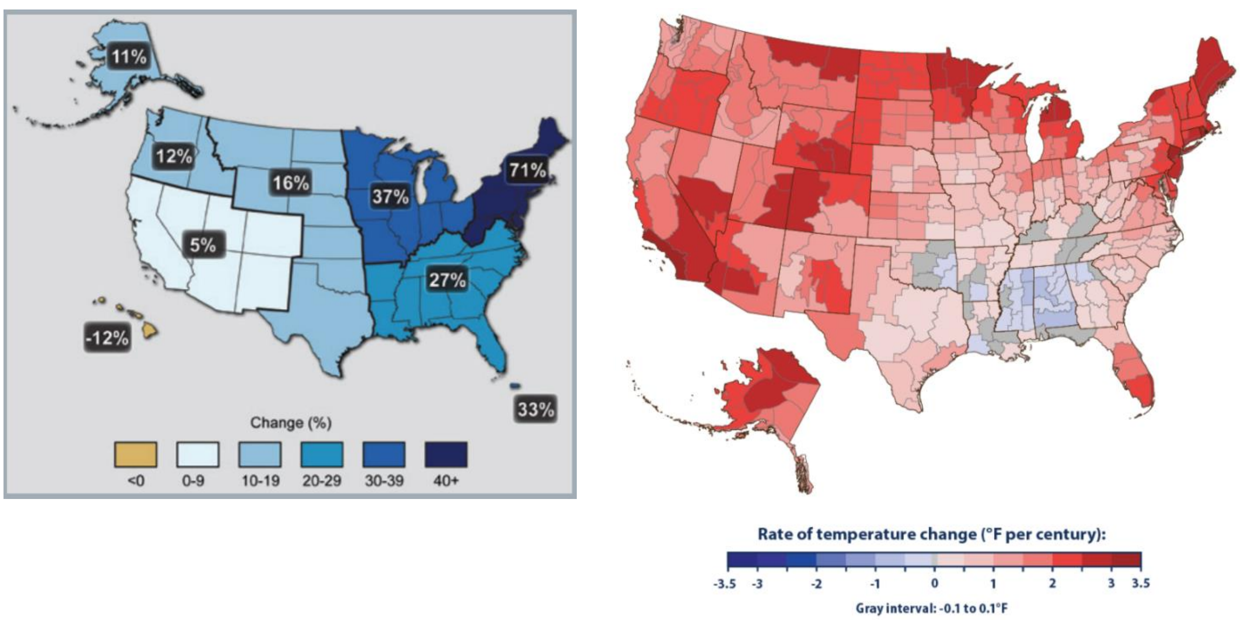

Figure 1. (a) Increases in Heavy Rainfall Events in the U.S. (updated from Karl et al. 2009); (b) Rate of Temperature Change in the U.S. (EPA 2016)

The impacts of these events on earthen infrastructure and natural slopes have been assessed and summarized by a number of previous works (i.e., Vardon 2015; Turnbull 2016). However, previous assessments often focused on potential failure modes involved and a discussion of the impacts at a system scale. It is equally important to understand the multi-physics processes involved. Additionally, examination of multi-hazard risks posed by these events is also necessary. A summary of atmospheric-soil interactions is provided in Figure 2. This review paper explores how changes in climatic trends, particularly extreme events, may weaken partially saturated earthen structures through strength reduction, drying, soil desiccation cracking, shrinkage, microbial oxidation of soil organic matter, fluctuation in the ground water table, land and surface erosion, and highly dynamic pore pressure changes. Each of these weakening processes is primarily induced by variations in the soil moisture and temperature as a multi-physics process and possible multi-hazard scenarios are identified. Potential modes of failure imposed on partially saturated earthen structures by climatic trends are also discussed. The goal of this work is to provide a summarized review of the thermo-hydro-mechanical (THM) processes of unsaturated soil systems exposed to extreme weather events under a changing climate.

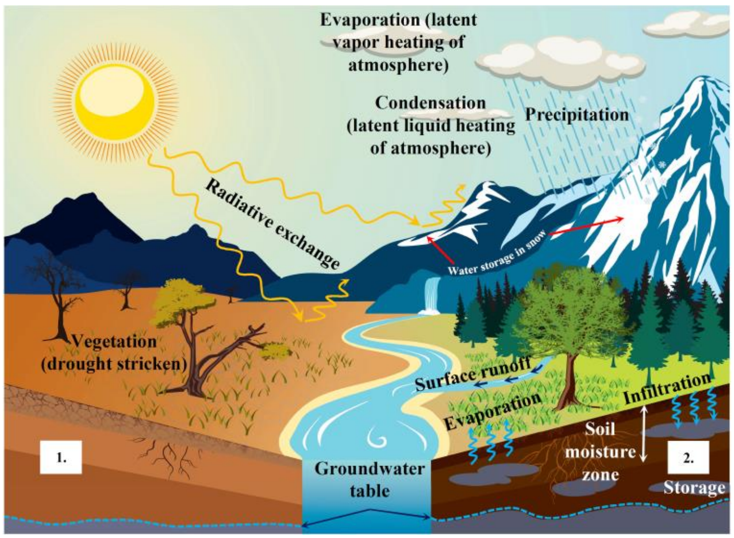

Figure 2. Soil-Atmosphere Interaction Mechanisms

DROUGHT

Dry and warm spells are coupled and have feedbacks on each other through land-surface processes (Seneviratne et al., 2006). Dry spells can potentially trigger or intensify droughts and below average precipitation can increase the likelihood of heatwaves. Recent examples of such droughts and warm spells have occurred in Australia, Europe, Texas, Oklahoma, and California (Vahedifard et al. 2015; Seneviratne et al., 2006; AghaKouchak et al., 2014b).

Drought induced weakening processes include strength reduction, desiccation cracking, land subsidence, and organic carbon decomposition (Robinson and Vahedifard 2016). A summary of these weakening processes is illustrated in Figure 3. Strength reduction due to drought can be caused by instability due to desiccation cracking or reduction in soil suction due to reduction in the air-water interface (Lu and Likos 2006, Robinson and Vahedifard 2016). The reduction in shear strength due to a decrease in the suction stress is largely governed by the pore size with narrow ranges retaining strength noticeably longer than soils with larger particles for similar decreases in saturation (Lu and Likos 2006; Robinson and Vahedifard 2016). Furthermore, these reductions in shear strength can be worsened by elevated soil temperatures (Uchaipichat and Khalili 2009; Alsherif and McCartney 2015). The development of desiccation cracks is also due to soil drying and is largely governed by the soil's plastic properties, temperature, and number of volume change cycles experienced (Péron et al. 2009; Tang et al. 2011).

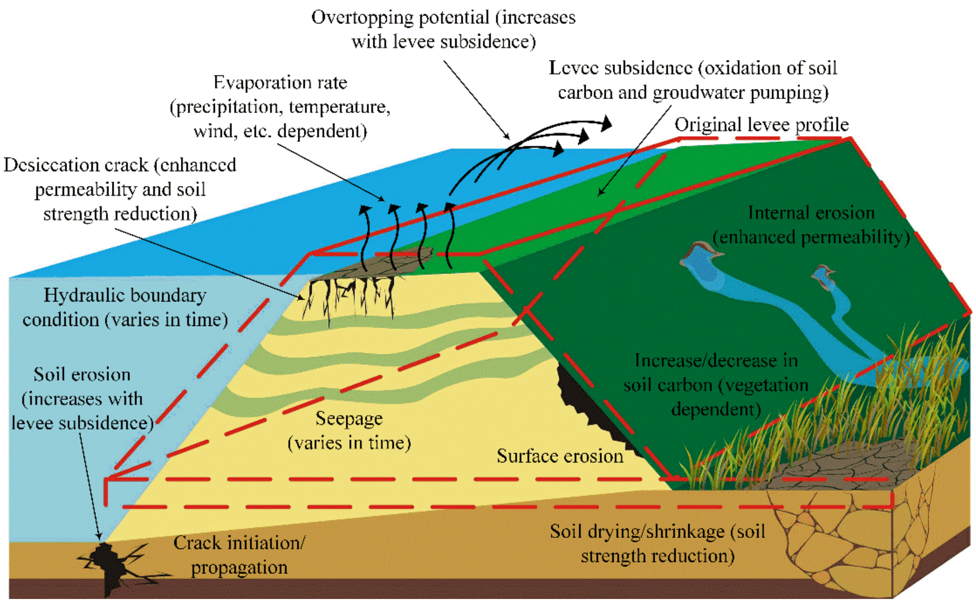

Figure 3. Weakening Processes Due to Drought (from Vahedifard et al. 2016)

In addition to weakening and cracking, drought conditions may also increase the rate of land subsidence and organic carbon decomposition. Land subsidence may occur due to increased ground water consumption and rate of evapotranspiration during drought conditions. Groundwater usage is controlled by human and societal factors and therefore not within the scope of this work. However, water table reduction due to evapotranspiration is controlled by the soil's THM properties and atmospheric conditions. Subsidence occurs as previously saturated soils dry out allowing the soil to collapse and fill void space. This behavior is worsened by the decomposition of organic soil that becomes exposed to oxygen under the dry conditions (Robinson and Vahedifard 2016; Lopez et al. 2016). The rate of decomposition is heavily affected by temperature and moisture content with hot dry conditions yielding rapid loss of organic carbon (Conant et al. 2011).

Previous cases of drought occurrence have demonstrated that many of the described processes can result in the weakening or failure of earthen structures. The Australian Millennium drought (AghaKouchak et al., 2014b) provided examples including slump failure of levees and extensive desiccation cracking (Robinson and Vahedifard 2016). Systems of desiccation cracks weaken levee systems and contribute to multi-hazard failure at the end of the drought. Further discussion of the multi-hazard behavior is provided in a later section of this paper. The occurrence of land subsidence can be found in areas across the U.S. (Galloway et al 1999), and several studies have shown increased levels in recent years for drought exposed regions such as California (Faunt et al. 2016, Vahedifard et al. 2016a).

HEAVY PRECIPITATION

The intensity and frequency of heavy rainfall events are expected to increase in many regions under a warming climate (see Figure 1a for a historical perspective on the observed changes). These changes in event occurrence pose a particular risk to existing infrastructure, which was designed using historically based rainfall data (e.g. Bonnin et al. 2006). Under a changing climate using a nonstationary approach for frequency analysis may be more appropriate for future designs (Cheng and AghaKouchak 2014; Robinson et al. 2017; Vahedifard et al. 2017a). Natural and man-made slopes are particularly affected by heavy rainfall events.

Heavy rainfall events may cause fluctuation of the groundwater table, erosion, and dynamic pore pressure changes resulting in the failure of earthen slopes. For unsaturated soils, the sudden changes in pore pressures may cause instability of the system due to loss of suction with increasing saturation (Clarke et al. 2006; Lee and Jones 2004). Such behavior is explained using unsaturated soil mechanics and easily observed. Harder to define is the risk of erosion to slopes during high intensity rainfall events which depends on the soil's composition and vegetative cover. Both erosion and the reduction of suction stress cause weakening and softening of slopes and embankments. Figure 4 illustrates these effects on a typical slope. Shallow failures of such slopes are largely controlled by extreme rainfall events, or other extreme wetting phenomena such as snowmelt (Melchiorre and Frattini 2012). However, deep-seated landslide behavior is not typically affected by single events, and are controlled by long-term hydraulic behavior. Regions that experience a mean decease in rainfall will likely experience a decrease in deep-seated landslides due to long-term water table lowering, and vice-versa (Coe and Godt 2012, Gariano and Guzzetti 2016). Overall, it is clear that the performance of earthen material under extreme precipitation is reduced due to loss of suction due to fluctuation in the saturation of the material and the depth to the water table which such effects being most prevalent for slopes.

In addition to the risk posed by the rainfall itself, heavy precipitation events may result in flooding (Sorooshian et al. 2011; Nguyen et al., 2016). Flooding continues to impose reduced suction due to wetting, inundation and erosion similar to rainfall (Nguyen et al., 2015). However, there is an additional risk posed to water retention structures due to increased pore pressure differences between the up and down-stream sides. This difference increases the probability of various modes of failure including piping (Vardon 2015, Jasim et al. 2017). A similar long-term risk is posed by sea level rise. However, this change poses different challenges due to its gradual, but constant nature. Unlike floodwaters, sea level rise will not recede leading to permanent changes in pore pressures.

Figure 4 Slope Failure after Heavy Rainfall (from Orense 2004)

Extreme precipitation events cause numerous landslides across the globe and result in significant damage and loss of life each year (Schuster and Highland 2001). The trend of increasing extreme event frequency has been noted to be the cause of several instabilities in recent years (NRC 2013). Due to the widespread and localized nature of landslides, no specific examples are provided herein. Possible effects of changes to precipitation intensity and frequency have been explored models to compare performance under historic intensity-duration-frequency curves and projections. Such studies have considered the effects of extreme precipitation on slope stability (Robinson et al. 2017), levee stability (Jasim et al. 2017), and mechanically stabilized earth walls (Vahedifard et al. 2017a). Each study indicated that the use of historic data will likely lead to underestimations in the hydro-mechanical behavior of the soil structure. Furthermore, the threat posed by heavy rainfall and flooding was highlighted by extensive flooding of Louisiana in 2016 (Vahedifard et al. 2016b).

MULTI-HAZARD SCENARIOS

While the risk posed by individual extreme events have been presented thus far, the greater risk posed by climate change effects is largely due to compounding of these events in multi-hazard scenarios. In the case of extreme events, multi-hazard considers the occurrence of events at the same time or in sequence such that the net increase in risk of failure is greatly increased. This concept has been identified for a number of event combinations (Vardon 2015; Moftakhari et al. 2017a; 2017b). It should be noted that the concept of cumulative hazards means that the accumulation of frequent event costs may exceed a single extreme event which planning is usually based on (Moftakhari et al. 2017b). The individual processes of any multi-hazard event are a combination of the weakening processes described in the previous sections. Interactions between such processes can often lead to the failure of earthen structures. Several key examples related to climate change include: drought followed by rainfall, flooding, or sea-level rise; and rainfall combined with flooding or sea level rise.

The sequential occurrence of drought and rainfall is typical of precipitation patterns in many regions. Often the rainfall at the end of a prolonged drought occurs as extreme heavy rainfall event. Because of the crack systems developed during a drought, the soil is exposed to rapid infiltration and pore pressure increases, which may cause the soil to reach its limit state (Vardon 2015; Robinson and Vahedifard 2016). Flow through these cracks can also assist in internal and external erosion (Vardon 2015). Some types of earthen slopes have also been noted to fail more easily due to the onset of rapid pressure changes and surface erosion due to overland flow caused by heavy precipitation (Robinson et al 2017). The development of piping systems due to high pore pressures due to flooding and sea level rise can also be exacerbated by these crack systems. Furthermore, land subsidence due to soil drying and decomposition of organic materials during prolonged drought can lower the height of levees increasing the risk of overtopping.

The second type of multi-hazard event considered is the concurrent action of rainfall with flooding and flooding with sea level rise. The effect of these simultaneous events on earthen structures is large increases in soil saturation resulting in decreased suction along with erosion. Overtopping also becomes more likely as rainfall continues to raise the water level. However, there is an additional component of concurrent inland flooding and sea-level rise for coastal communities. Such an event is likely, but outside of the common flood risk assessment practice. The use of models to evaluate this compound effect found that the consideration of a single variable is not sufficient in many cases (Moftakhari et al. 2017a).

There have been a number of multi-hazard failures over the past two decades. Two clear examples related to extreme precipitation superseded by drought conditions are riverbank failures along the Nepean River after the Millennium drought and the excessive damage to the Oroville Dam. Riverbanks along the Nepean River experienced widespread failures following a heavy rainfall event during the long-term drought. These failures have largely been attributed to the crack systems and soil softening that occurred during the drought (Robinson and Vahedifard 2016). A possible more recent example is the series of events that occurred at the end of California's record setting 5-year drought. The large hole that developed in the primary spillway and erosion of the emergency spillway of the Oroville dam may have been the cumulative effect of the proceeding drought and rainfall event itself (Vahedifard et al. 2017b). The events are similar to those described by Robinson and Vahedifard (2016) in which the soil may be weakened and given increased permeability by the development of crack systems. However, further investigation of the dam failure will be needed to verify that this sequence of events did affect the performance of the dam. The final case considered in this paper is the occurrence of heavy rainfall with existing flood conditions. During August of 2016, Louisiana experienced extensive flooding (Vahedifard et al. 2016b). The flooding was the compounding of multiple local floods as precipitation continued to occur (Vahedifard et al. 2016b).

Table 1. Summary of Climate Change Impacts on Geotechnical Infrastructure

Climate Change Feature	Fundamental Impact	Practical Impact
Increased Temperature	Higher evaporation rate/Soil drying, Soil organic carbon (SOC) oxidation Changes in vegetation amount; Snow, ice and permafrost melting	Increased suction, desiccation cracking, shrinkage; Land subsidence; Varied effect depending on type of vegetation; Reduced strength of arctic soils, release of entrapped carbon, increased risk of mass wasting at higher elevations
Decreased Mean Precipitation	Soil drying and water table lowering, Vegetation reduction	Possible desiccation cracking and shrinkage, increase in suction; Loss of cover and increased risk of erosion
Increased Mean Precipitation	Soil wetting and water table rise	Decreasing suction leading to reduced shear strength
Drought	Soil drying and water table lowering	Significant desiccation cracking and shrinkage, increased susceptibility to intense precipitation due to increased permeability from cracking and shrinkage
Intense Precipitation	Rapid soil wetting Overland flow	Sudden changes in suction possible leading to heightened failure risk; Possible erosion and mass wasting
Flood/Sea Level Rise	Large pore pressure increases, Soil wetting, soil erosion	Lowered suction within flood protection infrastructure due to wetting, increased risk of multiple failure mechanisms such as piping and overtopping, erosion, costal landslides

SUMMARY OF IMPACTS AND INDUCED MODES OF FAILURE

Primary processes related to atmospheric-soil interactions have been identified in the context of likely climate change scenarios. A summary of predicted climate change trends and their resultant effect on geotechnical infrastructure is provided in Table 1 and Table 2.

Table 2. Potential Failure Modes Induced by Climate Change (after Vardon 2015)

Climate Change Feature	Impact on Earthen Structures/Slopes	Potential Failure Modes Affected
Increased Temperature	Drying Ice and snow melt at higher elevations	Uplift Slope instability
Decreased Mean Precipitation	Possible desiccation cracking; Shrinkage Loss of vegetation cover	Piping, internal erosion, slope instability; Piping Piping, slope instability
Increased Mean Precipitation	Soil wetting and water table rise	Erosion, slope instability, piping;
Drought	Elevated risk of impacts given for decrease in mean precipitation	See decreased mean precipitation;
Increased Extreme Precipitation	Rapid soil wetting Overland flow	Piping, slope instability, Slope stability, erosion
Flood/Sea Level Rise	Large pore pressure increases, Soil wetting	Piping, internal erosion, slope instability, erosion, costal erosion and landslides

CONCLUSION

In recent years, climate change impacts on earthen infrastructure have gained a great deal of attention. In this review paper, we discuss the underlying unsaturated soil processes that are fundamental to the expected climate change impacts. Example cases of climate change events from case studies and modeling attempts are provided from different regions. The authors also highlight the importance of considering a multi-hazard (e.g., combined floods and sea level rise, droughts and heatwaves) mindset in the light of climate change. A multi-hazard approach is more important when an event has multiple interdependent drivers leading to compounding effects on the impact.

Historical observations and future projections indicate that we should prepare for more intense and frequent extremes including rainfall storms, warm spells and floods, along with higher sea levels. Furthermore, it is well known that extreme events often have multiple drivers (e.g., wind, surge, precipitation leading to coastal flooding) that interact with earthen infrastructure and natural slopes. Historically, design of man-made infrastructure has relied on individual extremes ignoring the interdependence between drivers. While multiple individual events can pose their own challenges, the compounding effect of multiple drivers can be even more significant. We argue that a multi-hazard process involving earthen infrastructure and natural slopes can be summarized as a series of multi-physics processes related the soil moisture, temperature, and pore pressure.

By considering multi-physics processes, it is possible to understand and quantify the effects of compound extreme events. While this review has focused on the THM behavior of soil systems under extreme events, a fully realized multi-hazard analysis will require consideration of long-term changes in soil moisture and carbon content to climate change as an additional driver to extreme event occurrence. Through such considerations, existing infrastructure systems can be evaluated for their performance under a changing climate and be even integrated into future designs accounting for projected changes in atmospheric conditions and ocean levels. These changes in evaluation and design are necessary to move toward climate adaptive infrastructure systems.

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