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## ABSTRACT

Earthen levees protecting coastal regions can be exposed to compound flooding induced by multiple drivers such as coastal water level, river discharge, and precipitation. However, the majority of flood hazard analyses consider only one flood driver at a time. This study numerically investigates the performance of an earthen levee in Sherman Island, Sacramento, CA under compound flooding induced by fluvial and pluvial flooding. A finite element model is built for fully coupled 3D stress- flow simulations of the levee. The finite element model is then used to simulate the hydro-mechanical response of the levee under different flood scenarios. Fluvial flood hydrographs for different scenarios are obtained using a bivariate extreme analysis of peak river discharge and peak ocean level while accounting for the significance of correlation between these two variables. Pluvial flooding is characterized using Intensity-Duration-Frequency (IDF) curves of extreme precipitations for the study area. The fluvial and pluvial flood patterns for different recurrence intervals are used in the finite element model to simulate the hydro-mechanical response of the levee. Results show that considering compound flooding leads to 8.7% and 18.6% reduction in the factor of safety for 2 and 50-year recurrence intervals, respectively.

## INTRODUCTION

Levees are one of the most critical infrastructures that play a major role in constraining and controlling the flood risks. Most of the extreme events that impact earthen levees lead to serious economic and social losses. According to the National Oceanic and Atmospheric Administration (NOAA), the flooding damages cost more than $7.6 billion annually over the last four decades. The observed increase in the impact of climate change on the severity of extreme events is expected to continue in the future; therefore, flooding damages are estimated to rise to around $1 trillion by 2050, if no appropriate protective measure is implemented (Hallegatte et al., 2013). Moreover, the extreme events affected by climate change are the major reasons of fundamental damages all around the world. From 1980 to July 2019, the United States has experienced over 250 weather and climate disasters with a total cost of over $1.7 trillion (NCEI, 2019). In this time period, inland floods have posed over $126 billion of CPI-adjusted losses to the nation (NCEI, 2019). The flood protection system in the United States consists of approximately 2,000 levee systems that serve in all 50 states, in addition to Washington D.C. These levees keep the dryland safe from flooding and in some areas, such as California, deliver the drinking water (Robinson and Vahedifard, 2016; Vahedifard et al., 2016). Additionally, the US Army Corps of Engineers' (USACE) National Levee Database (NLD) reported that levees serve nearly 35% of the nation's counties and approximately two thirds of the American population living in a county are protected by at least one earthen levee. Many of these levees are working under poor levels of service or critical conditions. Furthermore, considering the rapidly growing urbanization and developments in low lying areas exposed to flooding, levees' failures could cause even more damages in the future (USACE, 2018).

Extreme precipitation within a basin usually initiates massive pluvial floods, which are flood events resulting from direct precipitation. Additionally, controlling the pluvial floods, due to extreme precipitation, threatening urban areas relies mainly on drainage systems that play a major role in controlling excessive surface runoff, also known as fluvial flood. When the capacity of the main drainage system is insufficient to cope with the overflowing runoff due to pluvial events, the overland flood is likely to occur. Although, the essential flood risks are caused by fluvial flooding events, the recent studies considered the effect of pluvial flooding to highlight the impact of all expected flooding scenarios (Chen et al., 2010). Also, in most cases pluvial flooding is generated due to inadequate drainage systems in urban areas under impact of extreme rainfall. Indeed, pluvial and fluvial flooding are very likely to co-occur, which causes more serious consequences than the one due to a single mechanism of flooding (Ashley et al., 2005). Furthermore, coastal regions are threatened by multi flood drivers such as sea water level, wave action, discharge of the rivers, and extreme precipitation. However, the evaluation of flood hazard usually considers a single driver and discards possible composite effects (Moftakhari et al., 2017, 2019). Although the interdependent factors affect all risk drivers, one may not necessarily be an extreme event individually; dependence between two or more drivers can lead to serious extreme impacts (Leonard et al., 2014; Sadegh et al., 2018; Vahedifard et al., 2015; AghaKouchak et al., 2018). Furthermore, the extreme or non-extreme events happening simultaneously or sequentially can increase the failure probability of infrastructure systems such as levees subjected to such events.

Earthen levees protecting coastal regions can be exposed to compound flooding induced by multiple drivers such as coastal water level, river discharge, and precipitation. However, the majority of flood hazard analyses consider only one flood driver at a time. The main objective of this study is to numerically investigate the performance of an earthen levee in Sherman Island, Sacramento, CA under compound flooding induced by fluvial and pluvial flooding. A finite element (FE) model is built for fully coupled 3D stress-flow simulations of the levee. The FE model is used to simulate the hydro-mechanical response of the levee under different flood scenarios. Fluvial flood hydrographs for different scenarios are obtained using a bivariate extreme analysis of peak river discharge and peak ocean level while accounting for the significance of correlation between these two variables. Pluvial flooding is characterized using Intensity-Duration-Frequency (IDF) curves of extreme precipitations for the study area. The fluvial and pluvial flood patterns for different recurrence interval (RIs) are used in the finite element model to simulate the hydro-mechanical response of the levee.

## FLUVIAL AND PLUVIAL SCENARIOS

Hydrodynamic models are used to characterize various flood scenarios for different recurrent periods. In this study, the statistic hybrid hydrodynamic is simulated by using a bivariate extreme analysis of peak river discharge and peak ocean level (Moftakahri et al., 2017). First, the significance of correlation structure between the two main variables (i.e., river flux and ocean water level) are evaluated. Then, the copula functions within joint likelihood domain is used to characterize the correlation structure. Finally, various combinations of peak river inflow and peak ocean level are chosen for simulating three hydrodynamic modeling scenarios, which are they "Most Likely" (the most likely event which is associated with the highest joint probability density function), "Q Dominated" (simulated flood water level by considering the peak river discharge) and "T Dominated" (simulated the flood water level scenario corresponding to peak coastal water level) (Moftakahri et al., 2019).

For appropriate representation of flooding dynamics near Sherman Island, we need to characterize extreme surface water level. This water level is a result of three main components in freshwater-influenced coastal systems (including Sacramento-San Joaquin Delta). Extreme water level in these systems is the sum of three components: the mean water level (that is influenced by mean sea level and freshwater influx), astronomic tides (driven by gravitational forces), and non-tidal residuals (including wind-driven surge and waves). In this study, we use the sum of daily discharge from three USGS gauges at Sacramento River near Verona, CA (11425500), American River at Fair Oaks, CA (11446500), and San Joaquin River near Vernalis, CA (11303500) as representative of the upstream river flux. This flux is a major contributor to fluvial flooding dynamics near Sherman Island. We also consider water level record at the NOAA tide gauge in Port Chicago, CA (Station ID: 9415144) as downstream boundary condition that represents coastal processes (e.g. tides) contribution to flooding dynamics near Sherman Island. For appropriate characterization of extreme water surface elevation (WSE) adjacent to the levee of interest, we take the record water level at the USGS gauge at Threemile Slough near Rio Vista, CA (11337080) between 2007 and 2017 to fit a linear multivariate function that relates upstream (UB) and downstream (DB) boundary conditions to the WSE. We can then simulate the extreme WSE near the levee for given compound scenarios of boundary conditions. Our analyses suggest coefficients of: $a_1$ = -0.0143, $a_2$ = 9.1577e-05, and $a_3$ = 0.8842 for the multivariate linear regression with equation: $WSE = a_1 + a_2\,UB + a_3\,DB$; with Nash–Sutcliffe model efficiency coefficient = 0.9623 and RMSE = 9.9920e-17.

To generate the WSE scenarios used in the FE model, we need to do a comprehensive joint frequency analysis of boundary conditions (UB and DB) to reflect upon the likelihood that coastal processes (i.e., mean sea level variability and tides) and fluvial process (i.e., hydrologic runoff from rainfall and snowmelt) coincide to produce hazardous situations. We limit the analysis to RIs less than 50 years, as per the probability theory, extrapolation greater than 2-4 times length of record yields in large uncertainties and so unreliable compound hazard scenarios. Figure 1 shows the flood level hydrographs versus duration simulated for three hydromechanics models in five RIs.

High variability in extreme precipitations and river discharge regime of California have shown a large number of random floods. Furthermore, due to extreme rainfall events, the

Sacramento-San Joaquin Delta has experienced numerous severe flood events during its lifetime. On the other hand, the variability in the intensity, duration, and frequency of extreme precipitations are key factors impacting the risk of flash floods. The design and analysis procedures of hydraulic structures are commonly relying on the use of IDF curves of precipitations (e.g., Ragno et al., 2018). IDF curves provide information on the intensity of a rainfall event given its average RI and duration (DePoto and Gindi 1991). IDF curves are commonly used tools for simulating hydrology and modeling flood events.  Also, IDF curves can be used to estimate pluvial flooding scenarios under extreme precipitation events.  Changes in intensity, as well as duration and frequency of extreme rainfall events change the fragility state of the geotechnical structures such as levees (e.g., Jasim et al., 2017; Robinson et al., 2017; Vahedifard et al., 2017). The stationary framework similar to the procedure proposed in Bonnin et al. (2006) is used to simulate IDF curves (Figure 2). Furthermore, NOAA Atlas 14 is used to assess the historical rainfall data.

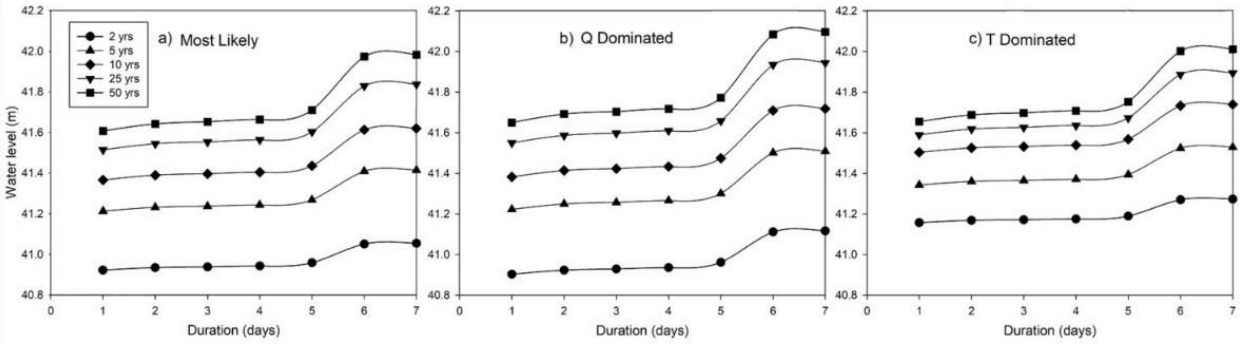

**Figure 1. Flood level hydrographs versus duration simulated for three hydromechanics models for Sherman Island levee with five recurrence intervals: 2, 5, 10, 25, and 50 years.**

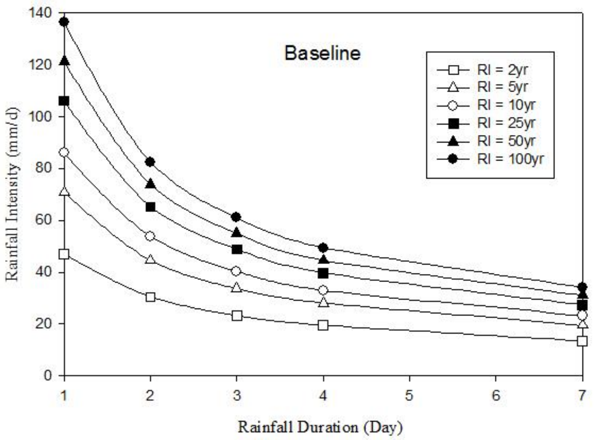

**Figure 2. IDF curves for Sherman Island levee.**

## NUMERICAL MODELING

A fully coupled 3D stress-variably saturated flow numerical model is built using the 3D FE program, RS3 V2.0, to examine the performance of levees under various floods scenarios. Sherman Island levee (Figure 3) is used for numerical modeling purposes. The same levee section was previously employed by Jafari et al. (2016) for different numerical modeling purposes. The Sherman Island levee (Figure 3) is located at the western end of the California Delta, where the Sacramento and San Joaquin rivers converge to the north-east of the Three Mile Slough lines. The FE model is used to compare the safety factor against slope instability, evaluated by the strength reduction technique from the FE model, of the modeled levee under three different hydrodynamic scenarios of Most Likely, Q Dominated and T Dominated (Figure 1). In addition to the impact of fluvial flooding on the performance of levees, this paper studies the effect of pluvial flooding, which is the water level resulting from extreme precipitation. This study uses the IDF curves (Figure 2) for each RI corresponding to the three different hydrodynamic scenarios by adding the rainfall-induced water level (i.e., rain intensity times rain duration) to both riverside and landsides of the simulated model.

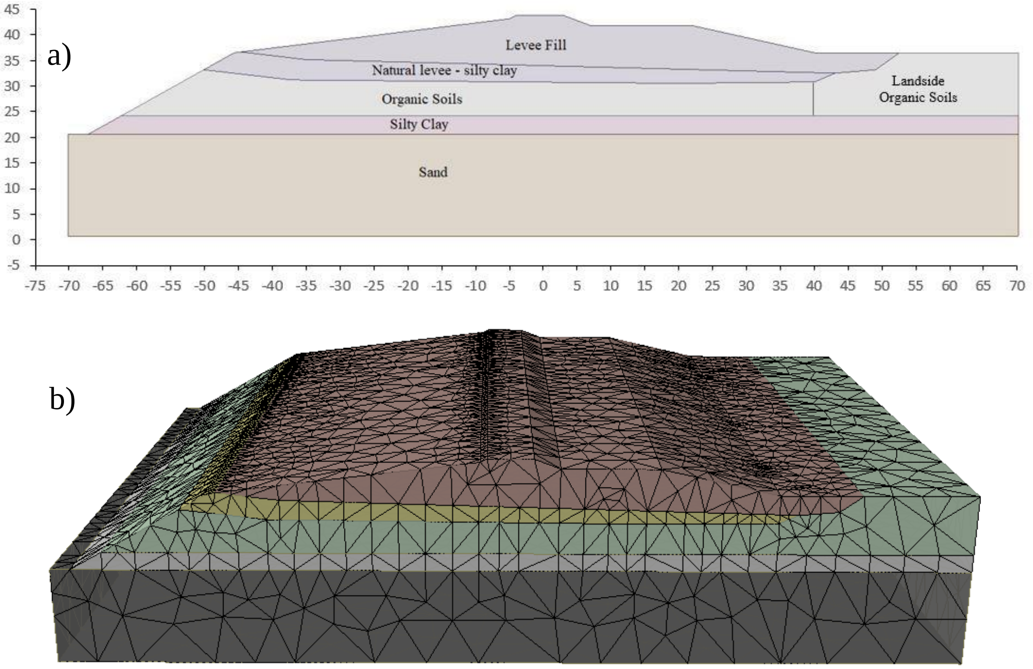

**Figure 3. Geometry of the Sherman Island levee model used in simulations: a) 2D cross section, and b) 3D finite element model.**

The foundation soils are mainly composed of a mixture of coarse-grained sediments, including gravel and loose clean sands, and silty sands. The soil profile begins at the bottom with a fine sand layer beneath 15 m (the NAVD88 vertical datum), as shown in Figure 3a. Over the sand, there is a silty clay layer, which is also known as Bay Mud, deposited due to the sea level that has risen after the last ice age. The thickness of this clay layer is 3.1 m and there is an organic soil layer over it that extends to the ground level. The main materials composing the Sherman Island levee embankment are dredged loose to medium sand and silt. Due to the weight of embankment layers, the organic soil layer has undergone excessive settlements, leading to a decrease in the horizontal hydraulic conductivity. The levee is built up directly on the natural barriers of San Joaquin River, which are mostly a layer of clay and colored clay. Figure 3a presents the geometry and soil layers of the FE model. Table 1 shows the soil properties used for different soil types in the FE simulations. The parameters are obtained from those reported in Hamedifar et al. (2014) and Jafari et al. (2016).

Figure 3b shows the 3D FE model used to simulate the hydro-mechanical response of the Sherman Island levee under transient variably saturated seepage. The bottom boundary is fixed in all three directions, whereas the other boundaries are fixed in the horizontal and vertical directions. In order to assign the initial flow boundary conditions, the bottom, front, back, left and right boundaries are set as impermeable boundaries. Ten-node tetrahedra elements are used to create the FE mesh (Figure 3b). The flow is simulated by specifying various flood water level boundary conditions to the upstream (according to the hydrodynamic scenario), and downstream sides of the levee. Figures 1 and 2 show the flood level hydrographs and IDF curves, respectively, which were used to represent various flood events in the FE simulations. The simulation for each model consists of two stages:

- Stage 1: Steady-state seepage using the normal water level (41 m) on the riverside to generate initial hydraulic conditions (at t = 0);
- Stage 2: Transient seepage for two scenarios:
  a) Only fluvial flooding, by applying the fluvial flood hydrographs (most likely, Q Dominated, and T Dominated) on the riverside
  b) Fluvial plus pluvial flooding, by applying the fluvial flood hydrographs (most likely, Q Dominated, and T Dominated) on the riverside and imposing the pluvial flooding determined from the IDF curves on the landside.

**Table 1. Soil properties of Sherman Island levee.**

| Soil type | Bulk Unit Weight $\gamma$ (kN/m$^3$) | *Cohesion* $c$ (kPa) | Friction angle $\phi$ (deg.) | *Hydraulic Conductivity* $K_h$ (m/s) | $K_h/K_v$ | *Modulus of Elasticity* $E_{ur}$ (kPa) |
|---|---|---|---|---|---|---|
| Levee Fill | 17.7 | 9.6 | 0 | $1 \times 10^{-3}$ | 4 | $7.6 \times 10^{4}$ |
| Organic Soil Under Levee | 11.6 | 9 | 0 | $3 \times 10^{-5}$ | 10 | $2.1 \times 10^{5}$ |
| Landside Organic Soil | 10.5 | 3.2 | 0 | $3 \times 10^{-4}$ | 3 | $2.6 \times 10^{4}$ |
| Silty Clay | 16.7 | 4.5 | 0 | $1 \times 10^{-6}$ | 10 | $5.0 \times 10^{6}$ |
| Sand | 19.5 | 0 | 31 | $1 \times 10^{-2}$ | 10 | $1.0 \times 10^{5}$ |

## RESULTS

Figure 4 shows the factor of safety versus the duration under the effect of three fluvial flooding scenarios (most likely, Q Dominated, and T Dominated) for five RIs. As can be seen, the factor of safety decreases with increases in the duration due to the corresponding increase in the flood water level. Also, the RI plays a major role in the decreasing in factor of safety due to increase in flood severity recorded with higher RIs. These results (Figure 4) show that the most likely scenario has the highest factor of safety while the T Dominated has the lowest factor of safety. This trend is because the T Dominated has the highest water level compared to the two other fluvial flood scenarios for most points. Furthermore, the trends of factor of safety under the effect of 50-year event decreases at a higher rate than events with shorter RIs for all durations, and the factor of safety considering 50- years is the lowest for all durations compared with the other RIs.

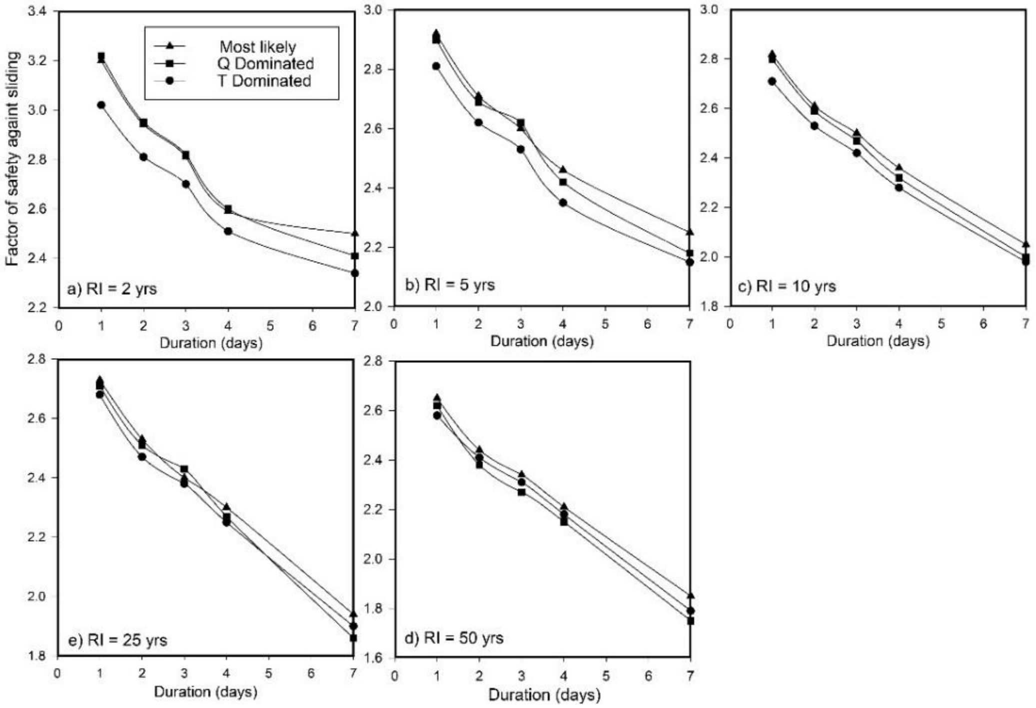

**Figure 4. Factor of safety against slope instability for a 7-days flood event comparing three fluvial hydromechanics flood scenarios in five recurrence intervals: 2, 5, 10, 25, and 50 years.**

Figures 5 shows the factor of safety versus duration under the effect of fluvial and pluvial flood scenarios for five RIs. As can be seen, the factor of safety decreases with longer durations due to the increase in the flood water level corresponding to each duration. Also, the trends of decreasing the factor of safety goes down slightly faster after four days due to the significant increase of flood water level after 4 day. As has been noted, the flood water level and duration are the key points of decreasing the factor of safety, but the flood water level has significant impact on the performance of levees.

Figure 6 shows the percentage change in the factor of safety obtained from the fluvial flood model compared to the fluvial plus fluvial flood model for 7-day flood events considering five RIs: 2, 5, 10, 25, and 50 years. The relative changes in the factor of safety considerably fluctuate in the period of 2-5 days that highlight pluvial flooding has a significant impact on the factor of safety in various durations. The factor of safety decreased non-uniformly between 2.3-18.6%, which shows the added risk of failure due to the impact of extreme precipitation-induced flooding.

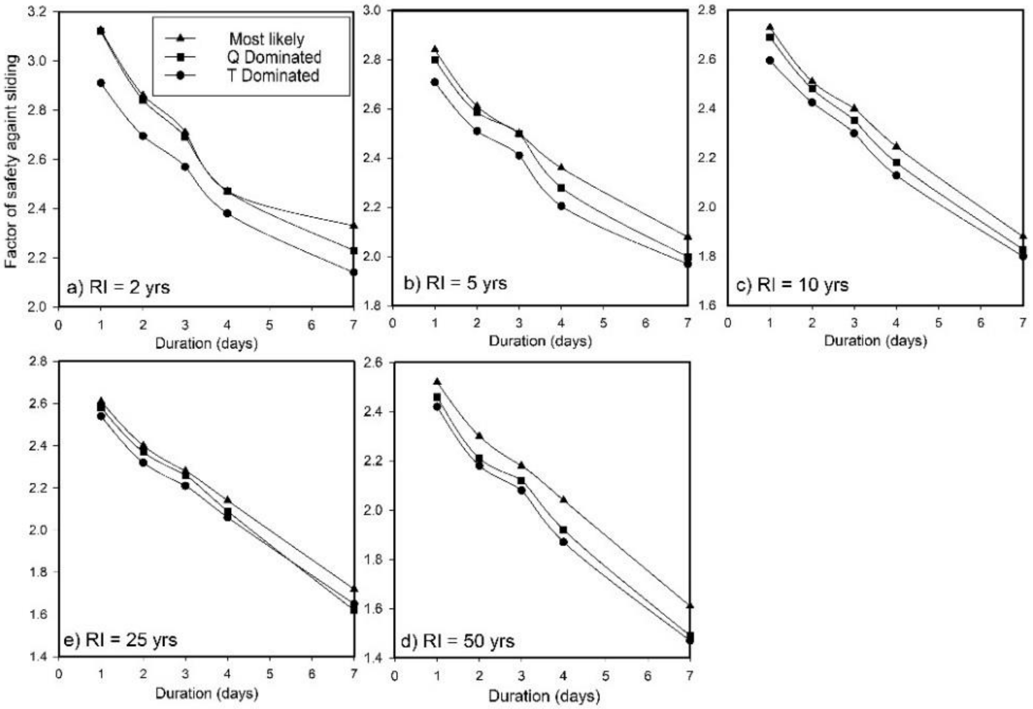

Figure 5. Factor of safety against slope instability for a 7-days flood event comparing pluvial and three fluvial hydromechanics flood scenarios in five recurrence intervals: 2, 5, 10, 25, and 50 years.

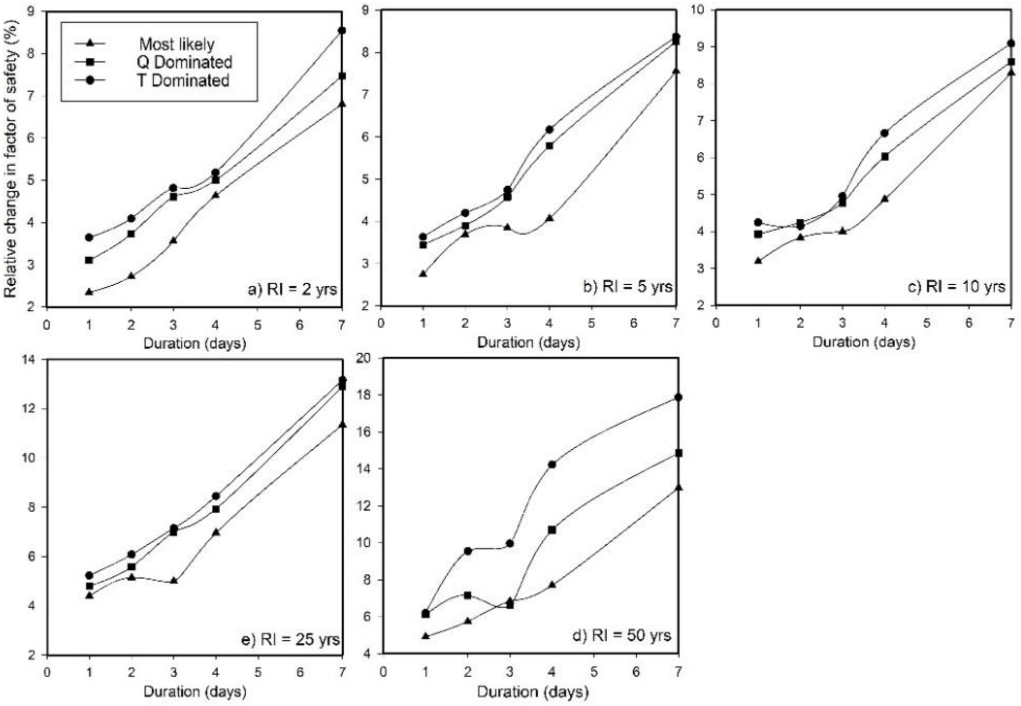

Figure 6. Percentage change in factor of safety obtained from the fluvial flood model compared to the fluvial plus fluvial flood model for 7-days flood.

## CONCLUSIONS

The current study aimed to evaluate the performance of earthen levees under impact of fluvial and pluvial flood scenarios. The behavior of the Sherman Island levee in California was numerically simulated under impacts of fluvial and pluvial flood scenarios for the study area. A fully coupled 3D stress-flow finite element model was developed to simulate the levee's behavior under three different hydrodynamic scenarios (most likely, Q Dominated, and T Dominated) combined with pluvial flood scenario. Incorporating pluvial flood events with fluvial flooding into the levee failure analysis led to 8.7 and 18.6% reductions in the factor of safety for 2 and 50-year recurrence intervals, respectively.

The results showed significant impacts of considering the fluvial and pluvial flooding events on the stability of levee. Costal levees coastal regions can be exposed to compound flooding induced by multiple drivers such as coastal water level, river discharge, and precipitation. However, the majority of flood hazard analyses consider only one flood driver at a time. Findings of this study highlight the importance of considering the effect of compound flooding for risks assessment and analysis of earthen levees protecting. This need will become only more pronounced under a changing climate, which is projected to worsen severity and frequency of extreme events in several regions.

## ACKNOWLEDGMENT

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