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Compound Effect of Flood-Earthquake Events on Performance of Earthen Levees

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Abstract **-** This paper investigates the performance of an earthen levee subjected to concurrent flooding and earthquake events with specific focus on soil liquefaction and slopes instability hazards. For this purpose, future water levels are determined for various return periods based on data provided by several piezometers positioned along the whole levee over a time period of 22 years. These water levels are used to simulate various floods scenarios. A hypothetical but plausible earthquake consistent with the seismicity of the study area is then applied at the base of the levee foundation. The numerical analyses involve several stages using GeoStudio software. The obtained results show that assuming single separate flooding or earthquake hazard events may not detect the levee's slopes instabilities even when a significant decrease of safety factors is noticeable at the upstream and/or downstream sides of the levee due to soil liquefaction hazard. Considering concurrent flooding and earthquake events scenario, even without accounting for possible interactions between them, leads however to further reduction of safety factors and reveals a slope's instability at the upstream side of the levee for a return period of 500 years.

Keywords**:** earthen levees - flooding - earthquake – soil liquefaction - slopes instability.

1. Introduction

Earthen levees are essential components of a nation's flood control system. Most of these levees around the world were built several decades ago in haphazard manner without accounting for either potential effects of climate change [1] or modern seismic design requirements [2]. Recently, prolonged periods of drought followed by incessant precipitation caused a levee failure on the Pajaro River in central California and resulted in mass evacuations and flooding [3]. In addition to extreme weather events, several other natural hazards can contribute to earthen levees breaches. Notably, earthquakes are recognized for having a higher damage potential than floods [4][5]. For instance, earthquake-induced ground shaking may cause cracks and fissures to form along the levee, create pathways for water to seep through the structure and lead to erosion, internal piping and levee saturation. Combined with high water levels, earthquakes may also result in liquefaction of saturated earthen levees [6][7]. Sasaki et al. [8] conducted a damage investigation for river levees following the 2011 Tohoku earthquake in Japan, confirming that soil liquefaction is one of the main causes of levees breaches in earthquake-prone areas.

Although several studies have investigated levees performance considering separate hazards, research accounting for multiple hazards has been very limited and still under-researched [9]. Recently, the rising frequency, intensity and duration of extreme events related to climate change have created an urgent need to expand existing failure prediction methodologies to include multi-hazard effects and combined failure modes. Abdollahi and Vahedifard [10] assessed the performance of Elkhorn levee in Sacramento, CA, under compound flood-earthquake hazards. Finite element analyses revealed that flooding increases levee susceptibility to liquefaction during earthquake-induced ground shaking, potentially leading to slopes instabilities. The same levee was analyzed by Vahedifard et al. [11] to evaluated its fragility against multiple failure modes that include slope stability, underseepage, and uplift. The results provided by a fully coupled finite element seepage-limit equilibrium slope stability model showed that future flood events could significantly increase the levee's probability of failure against both individual and combined modes.

The present paper presents a methodology to investigate the performance of an earthen levee subjected to successive flooding and earthquake hazards. Data provided by piezometers positioned along the whole levee over a time period from

1996 to 2018 allowed to determine future water levels that were used to simulate various flood scenarios. A fictional earthquake consistent with the study area were simulated and applied at the levee foundation base. The numerical modelling involved several stages using GeoStudio software. The effect of compound hazards on the levee performance was investigated through liquefied areas and then slopes instabilities.

2. Data and Methodology

This study analyzes an old earthen levee, depicted in Fig. 1, that was assessed in earlier research [12]. Geological and geotechnical investigations showed that the levee stratigraphy consists of 10 m backfill (soil 1) overlaying a thin 1-meter sandy layer (soil 2) and several meters of consolidated marl (soil 3) which constitutes the soft rock substratum. Table 1 summarizes some supplementary and relevant properties values of these levee layers.

Since no near-field seismic ground motion data is available for the study area so far, a hypothetical earthquake with a magnitude $M_w = 5.3$ and peak horizontal ground acceleration $a_{max} = 0.35\ g$ was simulated and used to apply seismic loading to the levee. M_w and a_{max} values were chosen to be both consistent with the seismicity of the investigated area and significant enough to highlight the liquefaction triggering within the sandy layer under ground shaking according to the previous study [12]. The acceleration time history of the earthquake applied at the base of the levee foundation, is shown in Fig. 2.

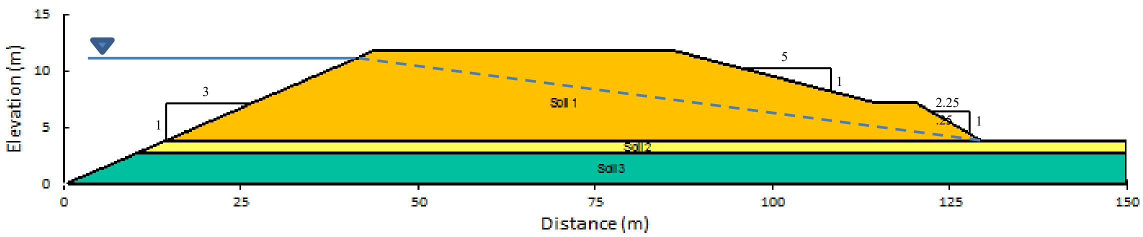


Fig. 1: Cross-section of the earthen levee.

Table 1. Geotechnical properties of levee layers.

Soil	Thickness (m)	$\gamma\ (kN/m^3)$	$c\ (kPa)^*$	$\varphi(°)^{**}$	$k(m/s)^{***}$
Soil 1	10	22	25	28	10^{-6}
Soil 2	1	19	0	35	10^{-5}
Soil 3	3	20	0	38	10^{-4}

*Soil cohesion; ** Soil friction angle; *** Soil hydraulic conductivity.

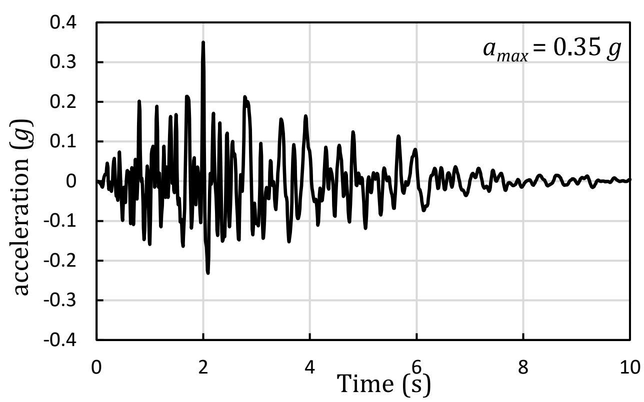


Fig. 2: Acceleration time history of the hypothetical earthquake.

Several piezometers, positioned along the whole levee over a time period of 22 years from 1996 to 2018, showed that the highest and lowest water levels were at 7.3 m and 9.5 m below the crest level. Based on the provided data, future water levels for various return periods were determined through a frequency analysis using the Annual Maxima/Generalized Extreme Value (AM/GEV) approach. Table 2 summarizes the extremely high and low water levels provided by the 95% confidence interval (CI) for return periods of 10, 50, 100 and 500 years. These water levels were used to simulate various floods scenarios.

For each return period, single flooding or earthquake events are first considered separately. The water behind the levee (i.e. canal side) is assumed to be at the lowest level provided by the 95% CI, while it is set at the ground surface in the land side. To simulate a potential flooding event that may result in extreme precipitation, the canal water level is raised gradually until reaching the highest level of the 95% CI. Assuming a single earthquake hazard involves applying only a ground shaking according to the simulated hypothetical earthquake at levee foundation base. The levee performance is subsequently investigated under concurrent flooding and earthquake events without interaction between them.

Table 2. Extremely high and low water levels for the 95% CI*.

	Return period (years)			
	10	50	100	500
Low level	-7.97	-7.61	-7.52	-7.40
High level	-6.92	-5.01	-3.89	-0.36

* These values are measured with respect to the crest level.

3. Numerical Analysis

GeoStudio software [13] was used to investigate the performance of the levee under flooding and/or earthquake events. The numerical analyses involved several stages using Seep/W and Sigma/W for steady-state and transient flows respectively, Quake/W for seismic loading, Sigma/W for initial static stress state and stress redistribution before and after earthquake respectively, and Slope/W for downstream and upstream slopes stability assessment.

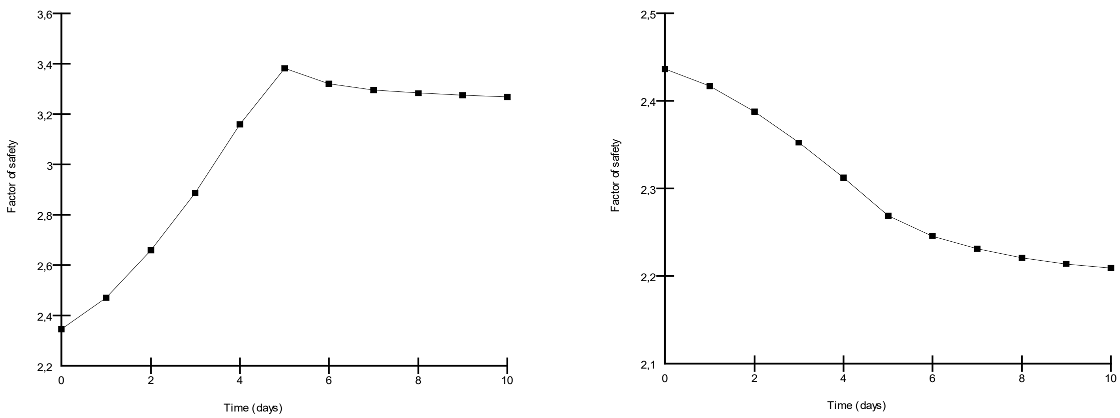
For each return period, a total head equal to the lowest level of the 95% CI was first assigned to the canal side. The canal water level was then raised at a constant rate (for example 6 cm/hour for a return period of 500 years) until reaching the highest level of the 95% CI. For the sake of convenience, the flood peak was subsequently kept for few days until a steady-state condition was reached. For these two stages, the downstream slope was defined as potential seepage surface, and soil layers above the water level are assumed to be unsaturated with typical soil water retention curves available in GeoStudio library. A static stress state was then derived based on the obtained pore-water pressure and used as initial condition for the subsequent seismic analysis. The simulated acceleration time history was then applied at the levee base which was fixed in both vertical and horizontal directions but with a vertical boundary of the levee that can move in the horizontal direction. Stress redistribution after seismic loading was calculated to determine the corresponding deformations. Downstream and upstream slopes stability was assessed both before and after the ground shaking.

4. Results and Discussion

Table 3 summarizes the safety factor F_S values provided by upstream and downstream slopes stability assessments before earthquake (i.e. single flooding event) and after earthquake (i.e. concurrent flooding and earthquake events) for different return periods. As can be noticed, assuming a single flooding event does not reveal any slopes instabilities neither in the downstream nor in the upstream sides of the levee. Significantly high $F_S$values are provided at the end of flooding event for all return periods. Moreover, the increase of water level at the upstream side of the levee acted as a resisting force improving further the slope stability while it slightly reduces it at its downstream side. Fig. 3 shows the F_S variations during flooding event at upstream and downstream levee's sides for a return period of 500 years.

Table 3. F_S values before and after earthquake.

	Return period (years)			
	10	50	100	500
	Before earthquake			
Downstream	2.424	2.366	2.331	2.209
Upstream	2.372	2.549	2.703	3.269
	After earthquake			
Downstream	1.642	1.601	1.483	1.476
Upstream	1.154	1.108	1.050	0.987



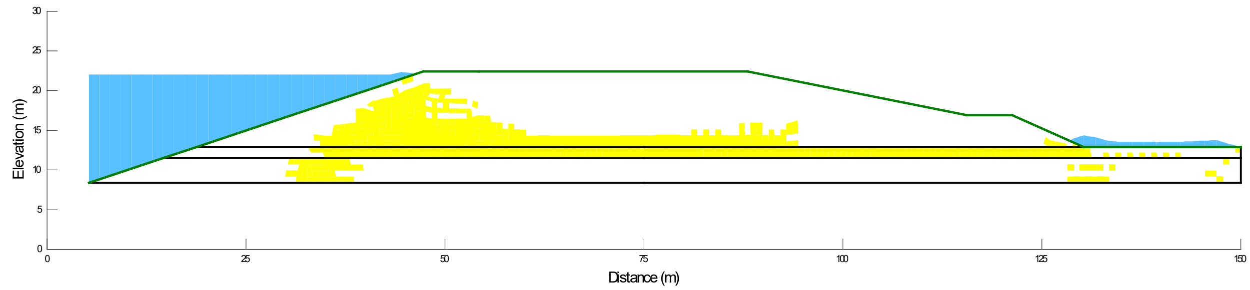
(a) Upstream side (b) Downstream side

Fig. 3. Variations of F_s during flooding event for a return period=500 years.

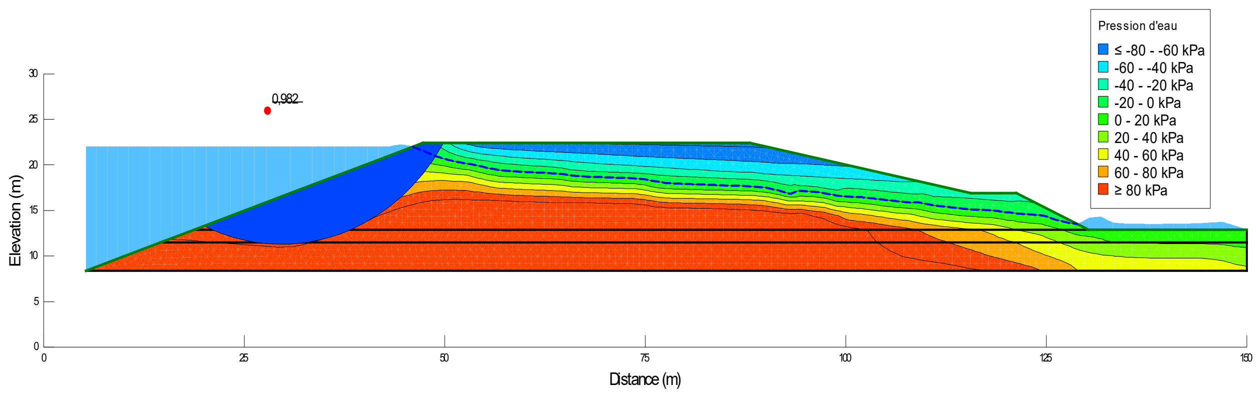
Considering an earthquake following the flooding event, leads to important decrease of F_s values as shown in Table 3 above. This F_s drop is more significant at the upstream side of the levee revealing therefore a slope instability risk for a return period of 500 years for which F_s drops below 1.0 ($F_s = 0.982$). This slope instability is mainly caused by liquefaction triggering within the sandy layer and some areas within soils 1 and 3 under ground shaking as can be seen in Fig. 4 (a). It is important to note that nonlinear dynamic analysis in Quake/W is conducted based on the concept of collapse surface; that means a stress state point is marked as liquefied when any amount of static or dynamic disturbance could move it onto the collapse surface, as a result of excess pore pressure build-up or grain structure collapse. A slip surface developing over these liquefied areas as can be observed in Fig. 4 (b), leads to considerably smaller F_s values.

The reduction in F_s values is mainly attributed here to the build-up of excess pore water pressure and concomitant loss of soil strength due to the ground motion and earthquake-induced liquefaction. This drop is further intensified by the water level rise due to flooding event. Indeed, the assumption of a single earthquake hazard (i.e. without flooding) gives rise to liquefied zones displayed in Fig. 5 for a return period equal to 500 years and the upstream stability assessment after earthquake provides F_s=1.203, as summarized in Table 4, which implies a safety state. Flooding event saturates further soils areas within the levee, increasing hence their susceptibility to liquefy when subjected to seismic loading and result in F_s decrease of about 18% at upstream side.

These obtained results highlight the importance of multi-hazard risk assessments of earthen levees. Indeed, risk assessment analyses assuming single flooding or earthquake hazards do not reveal any slopes instabilities neither in downstream nor in upstream sides of the levee. Conversely, the simultaneous consideration of flooding and earthquake events highlights a slope instability at upstream side of the levee for a return period of 500 years.



(a)



(b)

Fig. 4. A conjunction of flooding and earthquake events: (a) Liquefied areas and (b) Slip surface at upstream side of the levee.

Fig. 5. Liquefied areas within the levee under single earthquake event.

Table 4. F_s values under single and compound hazards for a return period=500 years.

	Single hazard		Compound hazard
	Flooding	Earthquake	Flooding-earthquake
Downstream	2.209	1.695	1.476
Upstream	3.269	1.203	0.982

5. Conclusion

The compound effect of flooding and earthquake events is considered in this study to assess the performance of an earthen levee with specific focus on soil liquefaction and slopes instability risks. Significantly high safety factors are obtained at both upstream and downstream slopes of the levee when assuming only a flooding event. Considering a single earthquake hazard results in a considerable drop of slopes safety factors for all return periods but without causing slopes instabilities neither at upstream nor at downstream sides of the levee. This decrease is mainly attributed to soil liquefaction triggering within the sandy layer during the earthquake-induced ground shaking. Assuming concurrent flooding and earthquake events leads to further decrease of safety factors revealing therefore slope instability at upstream slope for a return period equal to 500 years with a safety factor dropping below 1.0. In this case, the water level rise due to flooding appears to further saturate it and consequently, leading to increased occurrences of soil liquefaction during the earthquake. Although the study remains fairly simplified in some respects (e.g. constant flood peak for several days, overlook of interaction between flooding and earthquakes, more reliable climate and hydrologic models for future flood simulations), it nonetheless emphasizes the crucial importance of multi-hazard assessments of earthen levees which can appear stable under single hazard scenario but which can reveal a major failure risk when concomitant risk scenarios are considered.

Soil liquefaction consequence (slope failure) depends not only on this phenomenon triggering but also on the earthquake duration (number of cycles); a distant seismic event of long duration can in fact produce a large number of cycles with low acceleration on the site, which can be critical for soil liquefaction triggering and the severity of its consequences. A sensitivity analysis could therefore be led considering the durations of both events.

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