Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY
© 2024 the Authors
ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-266
Open Access: www.taylorfrancis.com, CC BY-NC-ND 4.0 license

Spatial vulnerability of levees to cascading hazards

Vulnérabilité spatiale des digues aux aléas en cascade

M. Bačić, N. Rossi*, L. Librić, M.S. Kovačević
University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia
*nicola.rossi@grad.unizg.hr

ABSTRACT: Levees are vulnerable to a multitude of hazards which may cause their partial or complete failure, thus leading to loss of their main purpose of protection against floods. As earthen structures, levees are also highly susceptible to earthquakes. A major concern arises in the unlikely case that these two events occur at the same time with extreme magnitudes. A similar situation occurs when an earthquake damages upstream components of the same flood protection network, such as dams, causing water waves to propagate downstream. The loads are not simultaneous, but within the short delay the damage to the levees would not have yet been identified/repaired to prevent flooding of the surrounding area. This paper analyses cascading scenarios of strong earthquakes followed by water waves resulting from damaged dams, acting upon the downstream levees. The levees in the cross-border area of Croatia and Slovenia, sharing the seismic and flooding hazards, are selected for validation of the vulnerability assessment methodology. The vulnerability of levees was modelled considering the influence of earthquakes on both the levee network and the upstream hydropower plant. Probabilities of failure are derived, enabling the categorization of the levee network, and giving valuable information to infrastructure managers and first responders on the criticality of the network whose overall efficiency is controlled by the weakest link.

RÉSUMÉ: Les digues sont vulnérables à une multitude d'aléas qui peuvent provoquer leur rupture partielle ou totale, entraînant ainsi la perte de leur fonction principale de protection contre les inondations. En tant que struct. en terre, les digues sont également très sensibles aux tremblements de terre. Une préoccupation majeure surgit dans le cas peu probable où ces deux événements se produiraient en même temps avec des ampleurs extrêmes. Une situation similaire se produit lorsqu'un tremblement de terre endommage les composants en amont du même réseau de protection contre les inondations, tels que les barrages, provoquant la propagation des vagues d'eau en aval. Les charges ne sont pas simultanées, mais dans un court laps de temps, les dommages causés aux digues n'auraient pas encore été identifiés/réparés pour éviter l'inondation des zones environnantes. Cet article analyse des scénarios en cascade de forts tremblements de terre suivis de vagues d'eau résultant de barrages endommagés, agissant sur les digues en aval. Les digues de la zone transfrontalière de la Croatie et de la Slovénie, partageant les risques sismiques et d'inondation, sont sélectionnées pour la validation de la méthodologie d'évaluation de la vulnérabilité. La vulnérabilité des digues a été modélisée en tenant compte de l'influence des tremblements de terre à la fois sur le réseau de digues et sur la centrale hydroélectrique en amont. Les probabilités de défaillance sont dérivées, permettant la catégorisation du réseau de digues et fournissant des informations précieuses aux gestionnaires d'infrastructure et aux premiers intervenants sur la criticité du réseau dont l'efficacité globale est contrôlée par le maillon le plus faible.

Keywords: Probability of failure; cascading effect; levees; point estimate; categorization.

1 INTRODUCTION

Throughout history, humans have been continuously trying to establish control over rivers, both for resources and for containing and regulating damaging floods. This is done by altering the watercourse by constructing hydraulic structures such as dams, levees, weirs, culverts, etc., at which point the river loses its natural flow regime. The more regulating structures are constructed, the more potential failure points there are, which are subject to many uncontrollable conditions which may deteriorate their stability, resulting with a lot of variability and uncertainty in risk management. Such uncertainty is usually addressed by conducting probabilistic analyses where probabilities of failure or unwanted behaviour are calculated, which serve as a basis for conducting maintenance works. The considered loads can be diverse, mostly high river discharges, rainfall, and earthquakes, or a combination of loads such as the one analysed in this study.

2 PROBLEM DESCRIPTION

This paper presents a case study pertaining to the categorization of a stretch of levees along the river Sava, between the hydropower plant (HPP) in Brežice (Slovenia) and the Jankomir bridge in Zagreb (Croatia), an area of mutual interest for flood protection (Figure 1). At the same time, this cross-border area is extremely prone to earthquakes due to its position in a seismically active area.

The categorization also includes levees along the 6 tributary rivers, for a total length of 51 km. It consists of determining the probability of failure of the levees, induced by the cascading effect of high river discharges due to partial failure of the HPP Brežice dam caused by an earthquake. Two earthquakes are considered, one occurring near Brežice, and the other near Zagreb, both with 2475-year return periods. As a starting assumption, we take it that both earthquakes will surely lead to a partial failure of the dam, which is defined through 5 scenarios that generate different hydrographs (Rak et al., 2023). Due to the relatively large area of interest, a simplified methodology is used to efficiently assess the stability of the levees.

3 METHODOLOGY

3.1 Cross-section selection

To categorize a large stretch of levees with limited resources, optimizing the number of considered cross-sections is necessary. To discretize the levees, they are divided into reaches, which ideally would not only be defined by similar geometrical, physical, and mechanical properties, but also by equal consequences (flooded area) in the case of failure of any of the sections along the reach. However, to simplify the selection of relevant sections in accordance with the available data, both sides of each tributary river's levees are deemed one reach (6 reaches), and the river Sava's levees are divided into reaches where breaks in their continuity occur on each side of the river, such as bridges, tributaries, etc., resulting in 7 reaches. One of the seven Sava reaches was further divided due to geometrical differences, which finally resulted in 14 reaches total. Each reach is defined by one section, whose positions are shown in Figure 1. For a division into reaches, however detailed it is, the safety of the whole reach is defined by its most critical section (the weakest link). The sections' geometries are assessed through LiDAR data shown in Figure 1, provided by courtesy of the International Sava River Basin Commission (ISRBC), as well as from the respective projects of the levees not covered by the LiDAR.

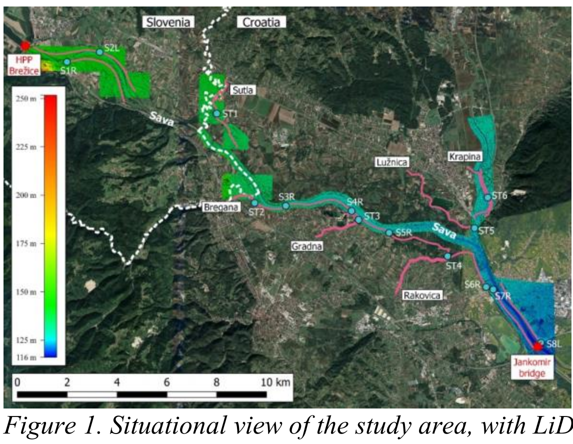

Figure 1. Situational view of the study area, with LiDAR.

3.2 Site characterization

The soil profiles and the geotechnical parameters are determined from existing borehole logs with SPTs, used to check the validity of the division into reaches, and supplementary CPTu data on the exact section locations. The necessary parameters for the analyses $(c, \varphi, \gamma, k, n)$ are thus determined separately for each selected cross-section. The foundation soil throughout the whole area is relatively similar, due to all the levees being constructed on the Sava river-terraces and floodplain, which consist predominantly of gravels and sands, with some clay content. Local differences are found mostly in thin, fine-grained, surface layers.

3.3 Conducted analyses

The analyses need to consider the previously described cascading effect. However, when an earthquake occurs, it will not only damage the dam but also the levees. To consider this effect, we would first need to quantify the earthquake-damage on the levees, before moving on to the stability during the water waves from the five scenarios. This type of damage includes soil liquefaction, subsidence, slope failures, longitudinal and perpendicular cracks, as seen in (Sasaki et al., 2012), and is unfeasible to quantify as an effect on the mechanical properties of soil. Thus, we need to introduce some assumptions and disregard all earthquake effects except slope failure. That way, we can compare the damage caused by earthquakes with the damage expected from high-water events. This is done in two stages. The first is analysing the slope stability during the earthquake, and if the levee fails at this stage, then further analyses are irrelevant, i.e., stability is determined by the earthquake alone. This means that the earthquake would give us a lower bound for the stability measure. If the levee holds (i.e., has satisfactory stability during the earthquake), then the oncoming water wave might bring it to failure. As we did not consider the effect of the damage on mechanical properties, the next stage consists of a simultaneous occurrence of the earthquake and the high-water, which is not realistic is this situation due to the source of the water wave but can give us a higher bound to the stability measure. Thus, the true stability measure should be found in between the two analysed cases. GeoStudio is used, with finite-element and limit equilibrium (Morgenstern-Price) methods for transient seepage and stability analyses, respectively.

An example of a model is shown in Figure 2, for the ST2 cross-section. The initial water table in each model is set to the corresponding hydrograph's starting elevation and is modelled as dependent of the water wave. After creating the models for each section, and assigning the five corresponding hydrographs, it is found that many hydrographs do not raise the water levels enough to even reach the levees' toes. In cases where the water does rise over the toe, the relatively short durations of the water waves (about 12 hours) are not enough to generate any meaningful seepage through the bodies. For this reason, only the water side stability is considered (during drawdown).

The analysed levees vary in sizes, and thus not all are vulnerable to slope failures of the same magnitude (depth, volume). To account for that, the slip surfaces are limited to a minimal depth which varies depending on the geometry of each section. For very small levees the limit is 0.5 m, for most sections the limit is 1 m, and for one section (S6R) the limit is set to 3 m.

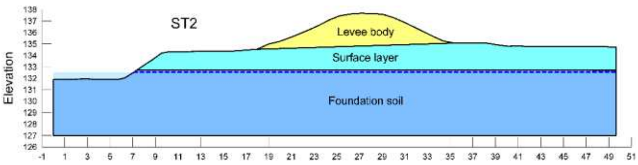

Figure 2. Example of a calculation model.

3.3.1 Probability of failure

The results of the described analyses are deterministic factors of safety (FS). To calculate the stability measure as the probability of failure (p_f), multiple LE analyses are required, and to optimize the required number of calculations on each section Rosenblueth's Point Estimate Method (PEM) (Christian and Baecher, 1999) is employed. It is assumed that the factors of safety are functions of only one random variable, the PGA, while all the others are deterministically known. In such case, this method requires only three analyses to estimate the distribution of the FS, assumed to be normal. The PGA follow a lognormal distribution, meaning that in the logarithmic space it is symmetric and approximately Gaussian. By evaluating the FS at the mean PGA and at two more values symmetrically spaced around the mean ($\mu_x \pm \sqrt{3}\sigma_x$), we can estimate the mean and standard deviation of the FS from its expected value raised to the power of m (Eq. 1).

$$E[Y^m] \approx P_-(y_-)^m + P(y_\mu)^m + P_+(y_+)^m \quad (1)$$

where y are the FS estimates, and P are weights at the corresponding points ($2/3$ for the mean, and $1/6$ for the rest). From this we estimate the mean and standard deviation as in Equations 2 and 3.

$$\mu \equiv E[Y] \quad (2)$$

$$\sigma \equiv \sqrt{E[Y^2] - (E[Y])^2} \quad (3)$$

Considering failures occur at FS equal to unity, the reliability index (β) can be calculated, and from it the p_f. This procedure is performed twice, first for the Zagreb earthquake, then for the Brežice earthquake.

4 RESULTS

The results are shown in Table 1. Along the scenarios 1-5 defined by 5 hydrographs resulting from different partial failure modes of the dam, an additional scenario designated 0 is introduced to indicate the earthquake acting on the levee alone. The blank cells show the scenarios where the water level did not rise over the levee toe. The scenarios which yield the highest increase in p_f are highlighted in red for each section. The increase might be interpreted as the maxium effect that the high water corresponding to the specific scenario has on increasing the probability of failure, after the slope being damaged by an earthquake, where the slope failure caused by the earthquake is further propagated by the water wave.

According to USACE (1997), the probability of slope failure deemed hazardous corresponds to 16%, which is far exceeded by many sections. However, two aspects are to note. First, the calculated probabilities relate to slope failure, and do not equal the probability of breaching, i.e., failure of the whole section. Thus, these calculated probabilities may be interpreted as total damage instead of failure. Global failure may be eventually achieved by propagation of the developed failure surface during future hazards, if not mended in the meantime. Second, in most cases the p_f values stem from the earthquake, with only a small percentage added due to the water wave, while only in a handful of cases the water wave has a major effect on increasing the p_f. This is because the analysed scenarios luckily generate such hydrographs that raise the water level not much over the toe, so even if complete failure would occur, the consequences are not expected to be great, other than the damaged levees. More so for the fact that failure is calculated during the receeding period of the water wave (RDD). Finally, a categorization is conducted based on the probabilities, shown in Figure 3. The reaches are divided into 5 categories, where the first two correspond to the values reported by USACE (1997) for „high" to „above average" behaviour ($p_f \leq 0.1\%$) and „above average" to „hazardous" behaviour ($p_f \leq 16\%$), while the rest all fall into the „hazardous" category, but are still arbitrarily divided into three groups. Even if whole reaches are categorized by one section, this does not mean that whole levees will fail, due to the variations in local conditions.

Table 1. Probability of failure (%) for all analysed sections.

	S0		S1		S2		S3		S4		S5	
	Z	B	Z	B	Z	B	Z	B	Z	B	Z	B
S1R	72.7	99.1	73.1	99.1	76.5	99.1	74.1	99.1	71.0	98.9	89.9	99.7
S2L	1.80	69.7	-	-	3.90	77.1	-	-	-	-	10.2	87.3
S3R	98.0	94.1	98.8	94.2	98.5	96.0	97.8	94.4	98.9	94.5	99.0	96.8
S4R	40.7	1.61	59.0	6.62	58.6	6.24	64.0	9.80	58.9	6.39	59.0	6.76
S5R	34.7	0.30	35.7	0.51	35.0	0.50	-	-	-	-	35.6	0.40
S6R	58.5	0.05	-	-	-	-	-	-	-	-	-	-
S7R	43.1	<0.01	-	-	-	-	-	-	-	-	-	-
S8L	55.5	0.05	-	-	-	-	-	-	-	-	67.5	0.33
ST1	1.51	8.14	-	-	-	-	-	-	1.51	8.14	3.67	15.7
ST2	24.9	19.1	-	-	-	-	-	-	-	-	27.6	21.5
ST3	82.2	19.5	83.6	21.3	84.3	23.3	-	-	-	-	87.0	26.8
ST4	71.8	0.71	-	-	77.5	1.07	-	-	-	-	78.3	1.17
ST5	27.2	≪0.01	-	-	-	-	-	-	-	-	45.9	<0.01
ST6	77.7	0.51	-	-	-	-	-	-	-	-	77.7	0.51

Z – Zagreb, B – Brežice

5 CONCLUSIONS

The categorization of levees in the cross-border area of Croatia and Slovenia, resulting from the presented methodology, shows very high probabilities of slope failure (or damage), which are mostly attributed to the effect of the earthquake, and not so much to the water discharge scenarios, with the exception for a handul of scenarios. This means that even if slope failures do occur at certain sections, they may not propagate much further to cause a breach, and if they do, the water level is mostly too low to cause substantial consequences. For the damaged levees to breach and cause consequential floods, future hazards should occur. Finallly, it is more likely that the Brežice earthquake, closer to the HPP, will cause the partial failure of the dam, in which case the reported probabilities are much more acceptable. If the Croatian earthquake does indeed not fail the dam, then the high p_f still remains, but with no fear of flooding.

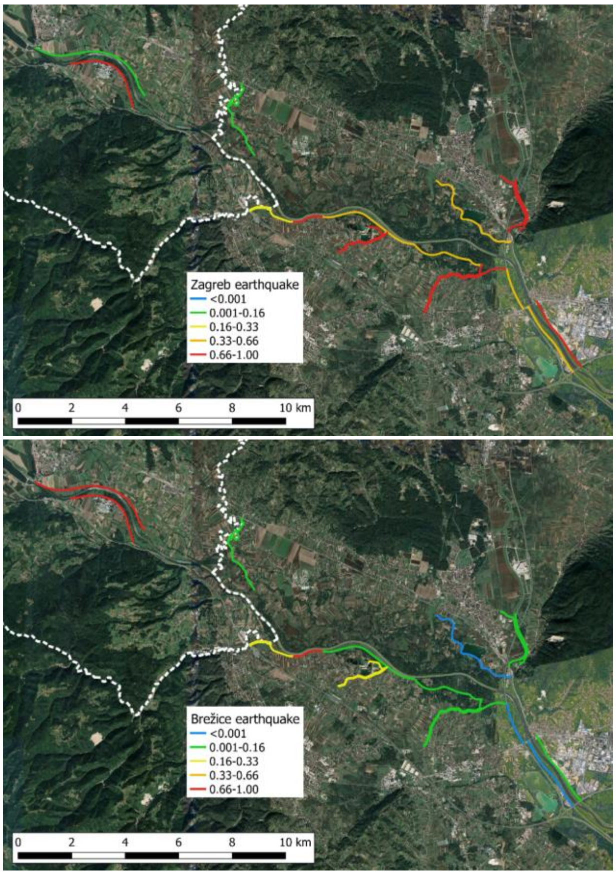

Figure 3. Levee categorization for both earthquakes.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by European Union Civil Protection Mechanism, GA no. 101048395, CROSScade project.

REFERENCES

Christian, J.T., Baecher, G.B., 1999. Point-Estimate Method as Numerical Quadrature. J. Geotech. Geoenviron. Eng. 125, 779–786. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:9(779).

Rak, G. et al., 2023. CROSScade Deliverable 3.2 - Cross-border cascading hazard events and scenarios (Deliverable No. D3.2.).

Sasaki, Y. et al., 2012. Reconnaissance report on damage in and around river levees caused by the 2011 off the Pacific coast of Tohoku earthquake. Soils and Foundations, 52(5), 1016–1032. https://doi.org/10.1016/j.sandf.2012.11.018.

USACE, 1997. Introduction to probability and reliability methods for use in geotechnical engineering (No. 1110-2-547), Engineering and Design. USACE, Washington, D.C.

INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 18th European Conference on Soil Mechanics and Geotechnical Engineering and was edited by Nuno Guerra. The conference was held from August 26th to August 30th 2024 in Lisbon, Portugal.