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HYDRAULIC AND SEISMIC VULNERABILITY OF EARTHEN FLOOD PROTECTION STRUCTURES: A PROBABILISTIC ASSESSMENT

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Abstract

Flood protection systems play a critical role in reducing flood risk in many regions worldwide; however, their reliability may be compromised by extreme environmental conditions. Earthen flood protection structures such as levees, riverbanks and retention dams are particularly sensitive to hydraulic and seismic loading, which may significantly affect their stability. This paper presents a probabilistic vulnerability assessment of earthen flood protection structures exposed to hydraulic and seismic hazards. The study builds upon the results of three projects funded through the Union Civil Protection Mechanism, addressing different types of flood protection infrastructure. Hazard quantification was performed using downscaled climate scenarios, extreme rainfall analysis, hydraulic modelling and earthquake scenario simulations. These hazard scenarios were combined with detailed geometric and geotechnical characterization of the investigated structures to develop numerical probabilistic stability analyses. The results demonstrate that the governing hazard varies depending on the type of structure and local conditions. The probabilistic analyses enabled the development of fragility curves describing the relationship between hazard intensity and failure probability. The presented methodology provides a quantitative basis for vulnerability assessment of flood protection infrastructure and supports further risk analysis and decision-making in civil protection and infrastructure management.

Keywords

flood protection structures, floods, earthquakes, probabilistic analysis, Union Civil Protection Mechanism

1 Introduction

In recent decades, the frequency and severity of flooding events have increased in many regions worldwide, posing significant risks to communities, infrastructure and the environment. This trend is largely associated with climate change, which is manifested not necessarily through increased annual precipitation totals but through a higher occurrence of short-duration, high-intensity rainfall events. Such extreme precipitation events generate rapid hydrological responses, significantly increasing loads acting on flood protection systems. Despite continuous improvements in flood forecasting, monitoring, and structural resilience, recent catastrophic events demonstrate the vulnerability of existing protection systems. A notable example are the 2021 European floods (Lehmkuhl et al, 2022), which caused more than 240 fatalities and extensive economic losses across several countries. Failures of flood protection infrastructure were reported at multiple locations during these events, illustrating that the reliability of flood protection systems is often governed by their weakest components. Earthen flood protection structures, such as levees and dams, are particularly sensitive to extreme environmental conditions. Prolonged drought periods may induce desiccation and cracking in the soil body, altering its hydraulic and mechanical properties and increasing permeability (Vardon, 2015). When such conditions are followed by intense rainfall events or rapid increases in water levels, the infiltration of water through these cracks can accelerate internal erosion processes, reduce soil strength and initiate failure mechanisms such as slope instability or piping.

In addition to hydraulic loads, earthen flood protection structures may also be highly vulnerable to seismic actions. Earthquakes can induce rapid changes in stress conditions within soil bodies, leading to loss of shear strength, excess pore pressure generation, and potential liquefaction of susceptible materials. This vulnerability was clearly demonstrated during the Petrinja earthquake sequence in central Croatia. The strongest event, which occurred in December 2020 with a magnitude of M_w 6.4 caused widespread damage to buildings and infrastructure. Importantly, the earthquake also affected flood protection systems the county, where levee failures were recorded at many locations (Kovačević et al, 2025). These observations highlighted the potential for earthquakes to compromise the integrity of flood protection structures even in the absence of extreme hydraulic loading.

The growing complexity of flood protection systems introduces additional challenges for risk management. As more regulating structures are constructed to control water levels and flows, the number of potential failure points within the system increases. These structures are exposed to multiple hazards and often operate under uncertain environmental conditions, including extreme hydrological events, climate variability and seismic activity. Consequently, breaches and failures of flood protection systems continue to occur worldwide on a semi-regular basis. The interaction of hydraulic and seismic loads may significantly influence the stability and performance of earthen structures, making multi-hazard assessment approaches increasingly important.

The research presented in this paper builds upon the efforts of three projects funded through the Union Civil Protection Mechanism (UCPM) and coordinated by the Department of Geotechnics, Faculty of Civil Engineering, University of Zagreb. These projects address different aspects of the resilience of flood protection infrastructure exposed to multiple hazards, Figure 1.

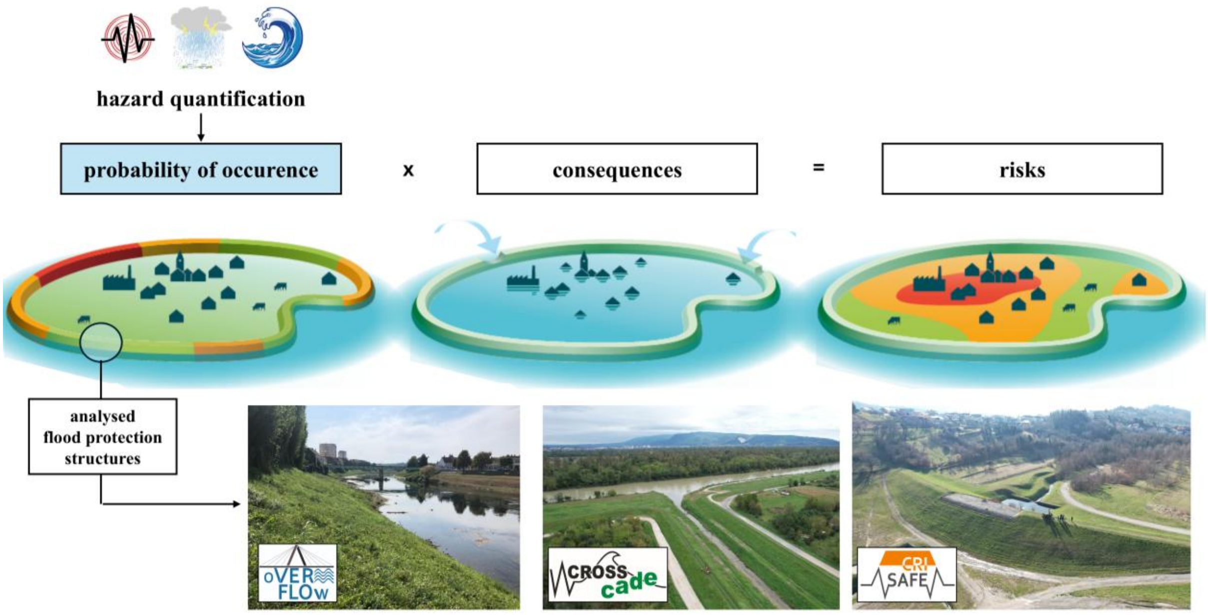


Figure 1. The framework of analysed UCPM project with presentation of case study areas, visual adapted from Vergouwe et al. (2016)

The oVERFLOw (Vulnerability assessment of embankments and bridges exposed to flooding hazards) project investigates the vulnerability of flood protection structures along the Kupa River in the city of Karlovac (Bačić et al, 2022). Karlovac is located at the confluence of four rivers and has historically experienced numerous flooding events that affected settlements, transportation infrastructure, and urban areas. The analysed assets include approximately 1.5 km of riverbanks and levees on each side of the river within the city centre. The project analyses the vulnerability of riverbank structures and levees to seismic loading and water levels derived from downscaled climate change scenarios. The CROSScade (Cross-border Risk Assessment of Cascading

Events Along the Sava River Basin) project focuses on the categorization and vulnerability assessment of levee systems along the Sava River between the Brežice hydropower plant in Slovenia and the Jankomir bridge in Zagreb, Croatia (Bačić et al., 2024; Gašper et al., 2025). This area represents a transboundary flood protection zone that has experienced numerous flooding events in the past and is located within a seismically active region. The analysis includes levees along the main river reach and six tributaries, covering a total length of approximately 51 km. Within the project, the cascading effects of earthquakes and high-water events are analysed through numerical simulations of two earthquake scenarios combined with five identified hydraulic scenarios associated with potential operational or structural issues at the Brežice hydropower plant. The CRISAFE (Critical infrastructure early warning system and population awareness for multi hazard cascading events) project addresses flash flood protection infrastructure in the city of Zagreb, which is protected by a system of 19 retention dams located on the slopes of the Medvednica mountain. Within this study, three retention structures, Črnomerec, Pusti Dol, and Jazbina, are analysed to demonstrate the developed methodology. The research investigates the response of these structures to extreme rainfall events and seismic loading.

The work presented in this paper focuses on the quantification of hazards and the assessment of vulnerability of earthen flood protection structures, including extensive efforts in collecting the necessary input parameters for probabilistic analyses. While the aforementioned projects address a broader range of objectives, including risk assessment and operational planning, the vulnerability analyses presented here provide the fundamental basis for further risk evaluation related to protected infrastructure and assets located on the defended side of flood protection systems. These results support the development of practical outputs for civil protection authorities and infrastructure managers, including implementation guidelines (oVERFLOw), action plans (CROSScade) and early warning systems (CRISAFE). The central methodological component of this paper is the assessment of flood protection assets through the development of fragility curves, which describe the conditional probability of reaching or exceeding a specific damage state for a given hazard intensity.

2 Quantification of hydraulic and seismic hazards

A reliable assessment of the vulnerability of earthen flood protection structures requires a consistent quantification of the hazards that may act on them. Hydraulic and seismic loads represent major sources of stress for such systems, particularly in regions exposed to both extreme hydrological events and seismic activity. The magnitude, frequency and spatial distribution of these hazards determine the intensity of loads acting on levees and retention dams, and therefore strongly influence their stability and potential failure mechanisms.

For this reason, the development of representative hazard scenarios is a critical step in vulnerability assessment. Scenario-based analyses allow the consideration of both historical observations and projected future conditions, including climate change impacts and extreme events with low probability but potentially severe consequences. Within the scope of the projects presented in this paper, different methodological approaches were applied to quantify hydraulic and seismic hazards for selected flood protection systems. These approaches include downscaled climate projections, extreme rainfall analysis and earthquake scenario modelling. The resulting hazard scenarios provide the input parameters for the subsequent stability and vulnerability analyses of the investigated earthen structures.

2.1 Downscaled climate scenarios within the oVERFLOw project

Within the oVERFLOw project, historical and projected climatological and hydrological parameters were analysed for a one-hundred-year period spanning from 1970 to 2070 for the Karlovac case study area in Croatia (Burić & Grgurić, 2020). The objective of the analysis was to evaluate potential future changes in river discharge and water levels of the Kupa River. Future hydrological conditions were estimated using a machine learning approach that integrates temperature and precipitation data obtained from the regional climate model

RegCM4. The RegCM4 simulations were performed using four different global climate models developed within the framework of the Croatian Climate Change Adaptation Strategy. Two representative climate scenarios were considered: a moderate emissions scenario (RCP 4.5) and an extreme emissions scenario (RCP 8.5). Model projections indicate that changes in annual precipitation totals remain relatively small, with a slight decrease predicted for both scenarios by the end of the analysed period, between 2041 and 2070. Hydrological simulations indicate that climate change may influence seasonal river flow patterns. While the projected changes in annual average flows and water levels are relatively small, significant seasonal variations are expected. The models predict an increase in flow and water levels during winter months and a decrease during summer months for both scenarios. These changes are more pronounced in the extreme scenario, particularly in the period between 2041 and 2070. Additionally, a notable decrease in flows during autumn months is expected under the extreme scenario.

Regarding flood frequency, the moderate scenario does not indicate a significant increase in flood occurrence. However, under the extreme scenario, there is an indication of an increased frequency of small and moderate flood events, while the frequency of very large floods with return periods between 100 and 1000 years may decrease. Figure 2 presents historical and projected daily water levels at the Karlovac measurement station for the RCP 8.5 scenario, which was subsequently used as the reference scenario in the vulnerability analyses of the investigated flood protection structures.

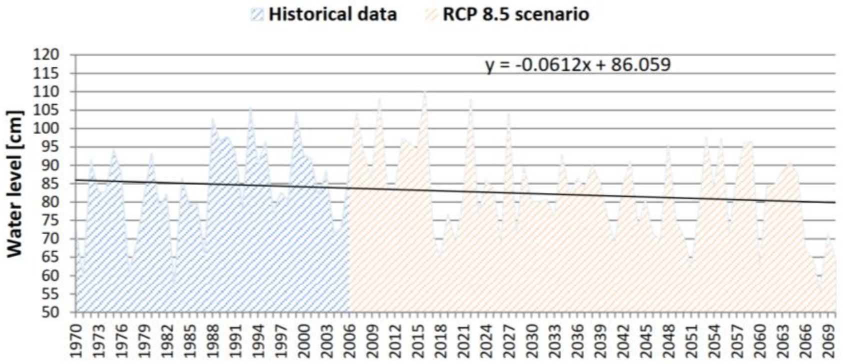
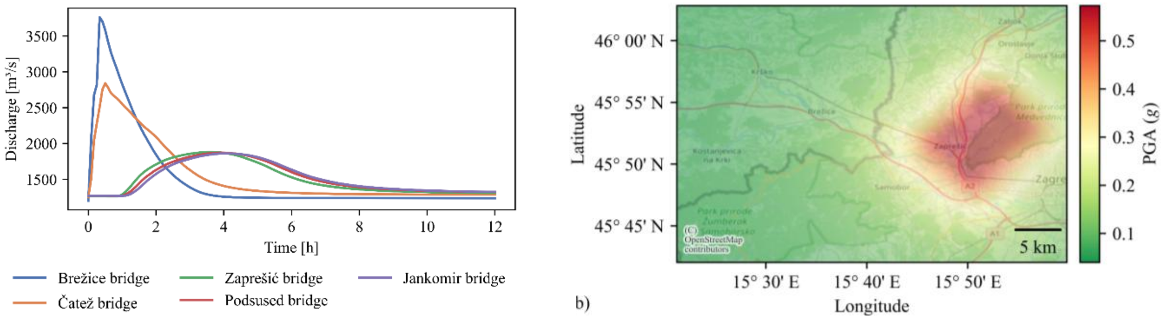


Figure 2. Historical data (1970 - 2005) and future data (2006 - 2070) of mean annual water level for station Karlovac generated by model ensemble with a corresponding trend for the entire analysed period according to RCP 8.5 scenario (Burić & Grgurić, 2020)

2.2 Cross-border earthquake and high water scenarios in the CROSScade project

The CROSScade project addresses the potential cascading effects of seismic events and hydraulic disturbances in the transboundary section of the Sava River basin between Slovenia and Croatia. Along this river section, Slovenia has constructed a cascade of five run-of-river hydropower plants (HPPs) along approximately 40 km of the Sava River, from Vrhovo to Brežice. Over the past two decades, numerous hydraulic studies have been conducted to analyse different operational conditions of these hydropower facilities. Based on the results of these studies, five representative scenarios of exceptional malfunction of Brežice HPP were identified as the most relevant for analysing potential cascade events. These scenarios include malfunction of spillway gates, structural damage to the gates, and breaching of the embankment structure of the Brežice HPP. The scenario development followed the recommendations of the International Commission on Large Dams (ICOLD), combined with operational experience and previously recorded hydraulic events in the region. The hydraulic modelling was performed in two stages to capture the complexity of flood propagation in the Sava River basin (Gašper et al., 2025). The first stage analysed the river section from Krško to the Slovenian–Croatian border, including the Brežice HPP, where the modelling considered both plant operation and potential dam or spillway failures. The second stage covered the downstream reach from the border to Zagreb, where a dynamically coupled 1D–2D model was used to simulate river flow and floodplain inundation, allowing detailed analysis of water levels, flow velocities, and flood extent. Figure 3a shows one of the scenario results - a case with all 5 gates of Brežice HPP opened simultaneously at maximum speed, with dischagre over time along the characteristical locations along the project case study.

In addition to hydraulic disturbances, the region is characterized by significant seismic activity. The seismic hazard in the study area is primarily associated with two active reverse faults: the Artiče fault near Brežice and the North Medvednica fault near Zagreb. These faults have generated several historically significant earthquakes, including the 1917 Brežice earthquake (M_w 5.7) and the 1880 Zagreb earthquake (M_w 6.0). To evaluate potential earthquake impacts on flood protection infrastructure, two representative seismic scenarios were developed within the project. Ground motion fields were simulated using advanced numerical modelling based on ground motion prediction equations (GMPEs) combined with stochastic simulation techniques. This methodology enabled the generation of spatial distributions of peak ground acceleration (PGA) across the study area with a grid resolution of 0.5 km². The resulting seismic hazard maps, such as the one for Zagreb earthquake on Figure 3b, were subsequently used as input for vulnerability analyses of levee systems located along the Sava River and its tributaries.



(b)

Figure 3. Hydrograph transformation along the Sava River between the Brežice HPP and the city of Zagreb for Scenario 2 (a); mean PGA fields on rock for Croatian seismic scenario (b), from Gašper et al. (2025)

2.3 Extreme rainfall and earthquake scenarios for flash-flood dams in the CRISAFE project

The city of Zagreb is protected from flash floods originating from the Medvednica mountain slopes by a system of retention dams. To evaluate the potential hydraulic loads acting on these structures, extreme rainfall scenarios and corresponding water waves were determined for three selected retention dams: Črnomerec, Pusti Dol, and Jazbina.

Precipitation data from four meteorological stations, Mikulići, Puntijarka, Šestine, and Maksimir, were obtained from the Croatian Meteorological and Hydrological Service (DHMZ) for the period 25 years The dataset includes daily measurements from manual stations and hourly measurements from automatic stations. Analysis of the precipitation time series revealed a highly localized spatial distribution of intense rainfall events (Rossi et al, 2025). Considering that the catchment areas of the analysed retention dams are located on the slopes of Medvednica, the automatic meteorological station Puntijarka was selected as the most representative source of precipitation data for further analyses. To estimate the peak runoff and associated water volumes from the precipitation data within the respective basins, generated by intense rainfall events, the Rational Method was applied (Žugaj, 2010). The resulting inflow hydrographs represent the combined contribution of runoff generated within the catchment and direct rainfall falling onto the reservoir surface. The maximum water levels reached in the reservoirs depend on the total water volume stored behind the dam. These relationships were defined using volume–elevation curves developed for each retention basin based on high-resolution LiDAR terrain data. In order to generate water waves with different probabilities of occurrence, both rainfall duration and rainfall intensity were considered. A joint probability distribution of rainfall duration and intensity was derived from the analysed dataset (Rossi et al, 2025). For each dam, three rainfall durations were chosen, 25.4 minutes, 60 minutes, and 147.8 minutes, corresponding to the 0.0015, 0.5, and 0.9985 fractiles of the duration distribution. For each duration, three rainfall intensities corresponding to the same fractiles were selected, resulting in nine possible rainfall combinations and corresponding reservoir water level scenarios for each dam. One graph of water wave volume- and elevation-vs-time for 0.5 fractile of the duration and rainfaill intensity distribution, at the Črnomerec dam basin, is shown in Figure 4a.

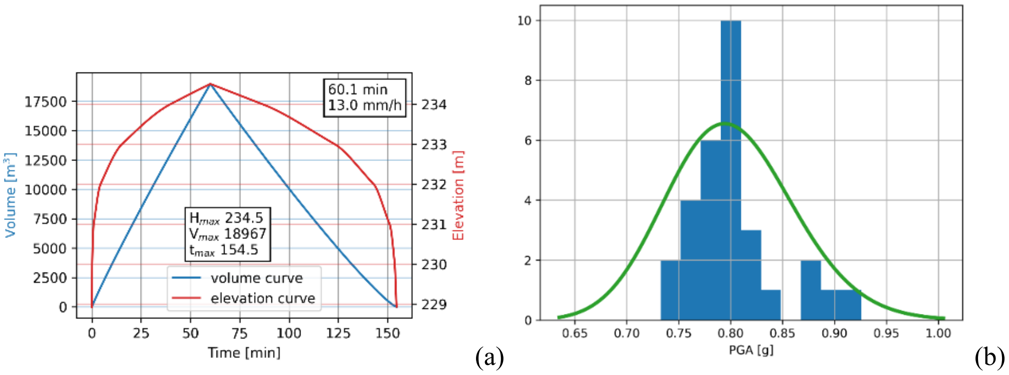


Figure 4. Graphs of water wave volume- and elevation-vs-time for 0.5 fractile of the duration and rainfaill intensity distribution, Črnomerec dam basin (a); example PGA distribution from the acceleration spectrum (b), from Rossi et al. (2025)

To account for seismic loading in the stability analyses, a set of artificial earthquake records was generated. According to Eurocode 8 (2004), the generated accelerograms must be compatible with the nationally defined design response spectra. The design spectra depend on the soil type, damping ratio, and importance class of the structure. In this study, a damping ratio of 5% and an importance class II were adopted.. The soil type was determined based on geophysical investigations - soil type B was assigned for the Črnomerec and Jazbina dams, while soil type A was assigned for the Pusti Dol dam. Accordingly, two design response spectra were constructed. A total of 30 artificial seismic records were generated and subsequently fitted to these spectra (Rossi et al., 2025). For the probabilistic stability analysis, PGA will be sampled from a distribution corresponding to each dam's fundamental period. The PGA distribution is calculated from the response spectra of all the time histories. Figure 4b presents the example distribution at an arbitrary period.

3 Geometric and geotechnical characterization of flood protection structures

The development of reliable numerical models for the assessment of flood protection structures requires detailed and accurate information on the geometry of the structures and their surrounding terrain, as well as on the geotechnical and hydraulic properties of the materials forming both the structures and their foundation soils. Consequently, a significant effort was invested in the acquisition, compilation and processing of input data necessary for the analyses presented in this study.

Regarding the geometric characterization of the analysed structures and terrain, several remote sensing and surveying techniques were employed within the different projects. In the oVERFLOw project, terrain topography along the analysed riverbanks in the city of Karlovac was obtained using an Unmanned Aerial Vehicle (UAV) combined with photogrammetric processing (Bačić et al, 2022). UAV-based photogrammetry provides a highly advantageous aerial perspective, which is particularly suitable for surveying linear flood protection systems such as levees and riverbanks. The method enables the generation of a high-resolution three-dimensional georeferenced point cloud, Figure 5, allowing semi-automatic extraction of terrain cross-sections and detailed representation of the geometry of the analysed assets. These data were subsequently used as input for the numerical probabilistic models.

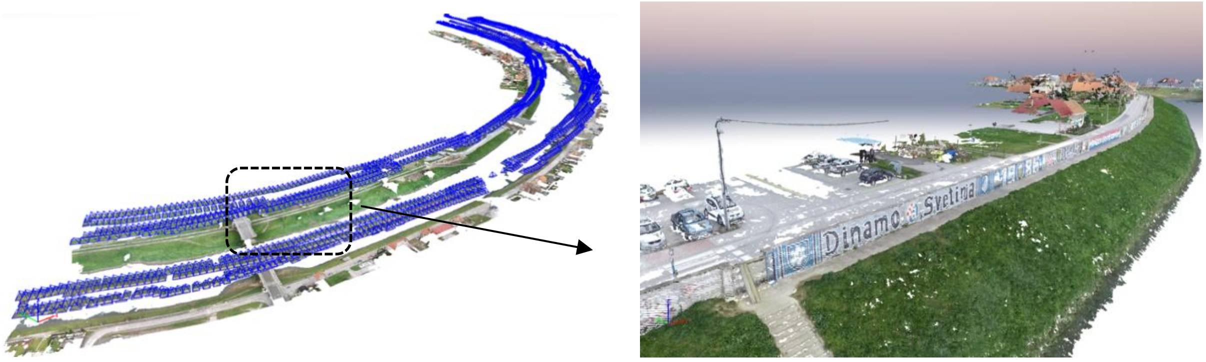


Figure 5. A 3D point cloud of the riverbanks next to the Kupa river (Bačić & Kovačević, 2021)

Within the CROSScade project, the geometry of the analysed levee sections along the Sava River was primarily determined using LiDAR datasets provided by the International Sava River Basin Commission (Bačić et al, 2024). The LiDAR data enabled detailed representation of terrain elevations and levee geometries along large river sections. For those segments where LiDAR data were not available, the geometrical information was complemented using historical project documentation and previous engineering surveys. In certain locations where gaps in the available data were identified, additional LiDAR surveys were carried out in order to obtain a continuous and consistent representation of the terrain. For the flash-flood retention dams analysed in the CRISAFE project in the city of Zagreb, LiDAR data obtained within the national project "Multi-sensor Aerial Survey of the Republic of Croatia" were used. This large-scale survey covered the entire territory of Croatia with a spatial resolution of approximately four points per square meter, while flood protection embankments were surveyed with an even higher resolution of approximately nine points per square meter. These datasets enabled highly detailed terrain models, which were used to derive reservoir volume–elevation relationships and structural geometries required for the hydraulic and stability analyses (Gavin et al., 2025).

In addition to geometric data, reliable information on geotechnical, hydraulic, and seismic parameters of the structures and their foundation soils was required for the numerical modelling. As a first step in each project, an extensive review and compilation of existing documentation was conducted. This included original design documentation, previously conducted geotechnical investigations, historical reports, and other available engineering records related to the analysed flood protection assets. However, in most cases the available data proved insufficient for detailed numerical analyses. Many of the existing datasets were incomplete, outdated, or difficult to access due to the absence of a centralized and systematically maintained database of geotechnical and infrastructure information. Consequently, additional field investigations were required to obtain the necessary parameters for the analyses.

Within the oVERFLOw project, additional geotechnical investigations were carried out, including cone penetration tests with pore pressure measurement (CPTU), borehole drilling, and laboratory testing of soil samples (Bačić & Kovačević, 2021). These investigations were performed in order to determine the stratigraphy of the soil layers and to identify the mechanical properties of both the riverbank materials and the underlying foundation soils. Similarly, within the CROSScade project, CPTU investigations were conducted at each analysed levee cross-section along the Sava River in order to characterize the soil profile and mechanical properties of the embankment structures and their foundations (Bačić et al, 2024). The same type of in-situ investigation was also performed at the locations of the retention dams analysed within the CRISAFE project (Gavin et al, 2025). These additional field investigations provided the necessary geotechnical parameters required for the subsequent probabilistic analyses of the investigated flood protection structures.

4 Numerical probabilistic vulnerability assessment

The quantification of hydraulic and seismic hazards, together with the acquisition of geometric, geotechnical, hydraulic and seismic data, provided the basis for the numerical probabilistic vulnerability assessment of the analysed flood protection structures. Due to differences in spatial scale and structural complexity among the investigated assets, modelling approaches of different levels of detail were adopted within the three projects. For the oVERFLOw and CROSScade projects, simplified numerical methodologies were applied because the analysed levee systems extend over large river sections. Such approaches allow efficient evaluation of stability conditions along long stretches of flood protection infrastructure while maintaining an adequate level of reliability for vulnerability assessment. In contrast, the CRISAFE project focuses on a limited number of retention dams, which enabled the use of more advanced numerical models for detailed analysis of structural response under extreme loading conditions.

In all cases, the primary failure mechanism considered was the global slope instability of earthen structures. Stability was analysed under both static and dynamic loading conditions. Static analyses considered hydraulic loads associated with different water levels and water waves derived from hydraulic modelling scenarios, while dynamic analyses considered seismic loading represented through the peak ground acceleration (PGA). The following sections present the key results of the probabilistic vulnerability analyses conducted within the three projects.

4.1 Probabilistic vulnerability assessment within the oVERFLOw project

The vulnerability of riverbank slopes along the Kupa River in Karlovac was evaluated through probabilistic stability analyses of representative cross-sections (Bačić et al, 2022). The analyses focused on global slope stability as the governing failure mechanism, considering two independent loading conditions: rapid drawdown and seismic loading. The probabilistic assessment accounts for uncertainty in the identified soil parameters by varying them according to their respective coefficients of variation in both drained and undrained conditions.

Rapid drawdown scenarios represent conditions where the external river water level rapidly decreases following a high-water event, while elevated pore pressures remain within the riverbank body. For each analysed section, the external water level was reduced to a predefined low-water level, while residual water levels within the riverbank remained elevated. These analyses were performed using drained soil parameters. The second set of analyses considered seismic loading through a pseudo-static approach. A PGA of 0.15 g was adopted, corresponding to a seismic event with a return period of 475 years for the Karlovac region. Seismic stability analyses were conducted using both drained soil parameters and undrained parameters for the upper clay layers.

Since riverbanks are typically designed for rare events with low probabilities of occurrence, rapid drawdown and seismic loading were considered independent hazard scenarios. While the seismic analyses were associated with specific river water levels, rapid drawdown scenarios represent post-flood conditions occurring after the peak water levels recede. The resulting probabilistic analyses enabled the development of fragility curves relating the probability of failure to the considered loading conditions. Figure 6a presents an example of fragility curves for one representative riverbank section, illustrating the relationship between the probability of failure and the analysed seismic loading conditions. Overall, the results indicate that, on average, seismic loading produced higher probabilities of failure than rapid drawdown conditions. However, several riverbank sections exhibited increased sensitivity to rapid drawdown due to local soil conditions and slope geometry. Based on the calculated probabilities of failure, the analysed riverbank sections were subsequently classified according to their vulnerability levels. Figure 6b shows such classification for the medium probability of flood occurrence (return period 100 years).

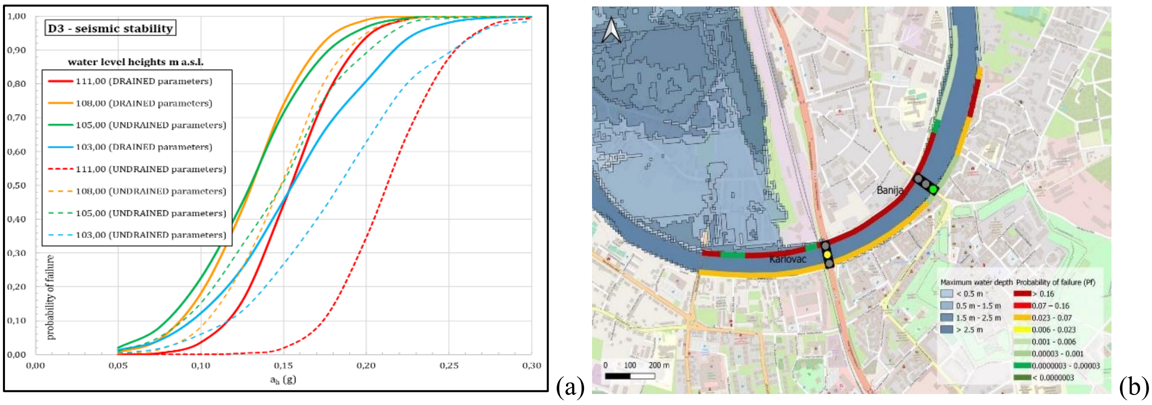
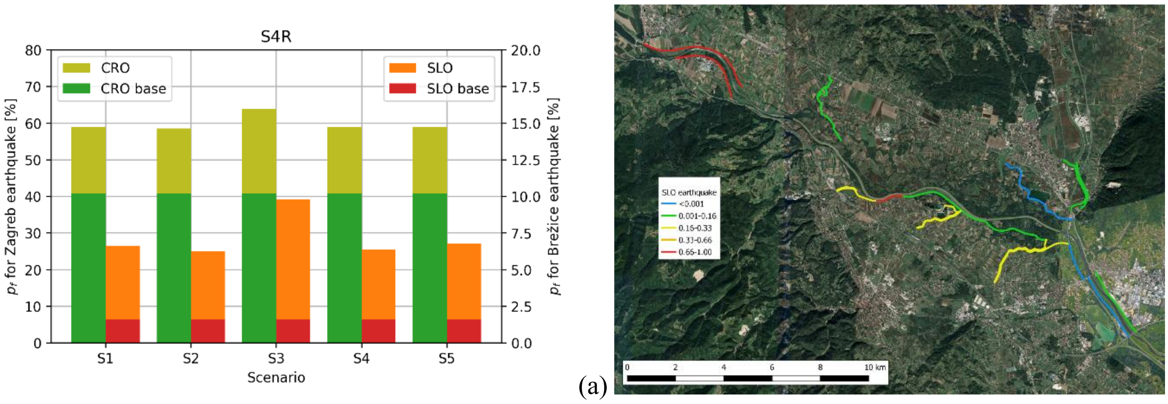


Figure 6. Fragility curves of seismic response of a riverbank (a), from Gavin and Reale (2021); results of the vulnerability analysis for riverbanks for medium probability of flood occurrence (b), from Skaric Palic & Stipanovic, 2022

4.2 Project probabilistic vulnerability assessment within the CROSScade project

Within the CROSScade project, probabilistic stability analyses were performed for levee sections along the transboundary reach of the Sava River (Bačić et al., 2024). The analyses considered cascading multi-hazard scenarios in which seismic loading could weaken levee structures, followed by the arrival of water waves generated by potential operational or structural failures at the Brežice HPP. The results revealed considerable spatial variability in the calculated probabilities of failure among different levee sections. In most analysed cases, seismic loading represented the dominant factor influencing slope instability, while hydraulic loading associated with water waves had a comparatively smaller impact. For the analysed earthquake scenarios, the calculated probabilities of failure varied significantly depending on soil composition, levee geometry, surrounding terrain morphology and the proximity of the levee sections to active fault zones. For the hydraulic loading phase, the results refer to the probability of failure of the water-side slope during the receding phase of the water waves. In several cases, the calculated probabilities approached values close to 100%. However, these probabilities represent the likelihood of slope instability and do not necessarily imply immediate breaching of the levee system. Breach formation could occur only as a consequence of progressive damage if the levee were not repaired prior to subsequent loading events.

The results for selected section of a levee network is shown on Figure 7a representing two probabilities of failure. The first corresponds to scenarios in which hydraulic loading occurs simultaneously with the earthquake, while the second represents the earthquake-only case (labelled "base" in the graphs). The difference between these values can be interpreted as the maximum additional effect of the high-water wave associated with each scenario on the probability of failure, assuming that the slope has already been weakened by seismic damage. Note that "CRO" and "SLO" denote the locations of the earthquake source, while S1–S5 represent cascading scenarios associated with hydraulic loading resulting from a malfunction of the Brežice HPP. Figure 7b further presents an example of the spatial classification of levee sections according to their calculated probabilities of failure for the Slovenian earthquake event.



(a) (b)

Figure 7. Probabilities of failures for selected section of a levee network (a); levee classification for the Slovenian earthquake event and associated hydraulic loadings (b), from Bačić et al (2024)

4.3 Project probabilistic vulnerability assessment within the CRISAFE project

For the Zagreb case study, probabilistic stability analyses were conducted for three retention dams located on the slopes of the Medvednica mountain: Črnomerec, Pusti Dol and Jazbina. Advanced finite element modelling and limit equilibrium modelling were applied to simulate the behaviour of the dams under both hydraulic (static) and seismic (dynamic) loading conditions (Gavin et al, 2025).

Static analyses considered hydraulic loading generated by extreme rainfall events. Nine representative water levels were defined for each dam based on the joint probability distribution of rainfall duration and intensity derived from the analysed precipitation records. Transient finite element seepage analyses were first performed to determine pore-pressure conditions during both the peak water levels and the receding phase of the water waves, resulting in eighteen pore-pressure states for each dam. These pore-pressure distributions were subsequently used in limit equilibrium stability analyses of the upstream and downstream slopes. The results showed that variations in the factor of safety associated with hydraulic loading were relatively small, resulting in negligible probabilities of failure. This behaviour is primarily attributed to the relatively short duration of extreme rainfall events, which does not allow sufficient time for significant pore pressure development within the dam body. The dynamic finite element analyses were used to estimate permanent displacements of the dams as well as accelerations at the base and crest of the structures. The calculated permanent displacements were generally small, ranging from approximately 1 to 7 cm. These results were subsequently used in limit equilibrium stability analyses through a spectral pseudo-static approach that accounts for the variation of seismic acceleration along the height of the dam. Unlike the static analyses, the dynamic simulations produced a wider distribution of factors of safety, resulting in non-negligible probabilities of failure. The calculated probabilities ranged from very small values (10^{-8}) to approximately 0.85 depending on the considered seismic intensity and structural characteristics of the dams. By repeating the analyses for different values of peak ground acceleration, fragility curves were derived for each analysed dam, describing the probability of failure as a function of seismic loading intensity.

5 Conclusions

The research presented in this paper demonstrates the importance of integrated multi-hazard assessment for evaluating the stability and vulnerability of earthen flood protection structures. By combining hydraulic and seismic hazard quantification with detailed geometric and geotechnical characterization, probabilistic stability analyses were performed for different types of flood protection assets including riverbanks, levees and retention dams. The results obtained within the three analysed projects show that the relative importance of hydraulic and seismic loads strongly depends on the type of structure and local geotechnical and loading conditions. For the riverbank structures analysed in the oVERFLOw project, both rapid drawdown and seismic loading represent relevant stability conditions, although the probabilistic analyses indicate that seismic loading generally produces higher probabilities of failure. The analyses conducted within the CROSScade project highlight the potential significance of cascading multi-hazard scenarios in transboundary river systems, where seismic damage may increase the vulnerability of levee systems exposed to hydraulic disturbances. In contrast, the results obtained for the flash-flood retention dams in the CRISAFE project indicate that extreme rainfall events alone pose limited stability risk, while seismic loading may become the governing factor influencing structural response. The probabilistic framework applied in this study enabled the development of fragility curves describing the relationship between hazard intensity and the probability of structural failure. Such results provide a valuable basis for further risk assessments, prioritization of infrastructure maintenance, and the development of practical decision-support tools for civil protection authorities and infrastructure managers responsible for flood protection systems.

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