Reply to the comments of the Reviewer #1

A: We thank the Reviewer for a comprehensive review of the manuscript, his/her valuable comments and an overall positive evaluation. We respond hereafter to the specific comments of the Reviewer and point out, how we would tackle the raised issues in the revised manuscript.

R: The Authors have studied fluvial dikes along the river Rhine nearby Cologne (Germany) under combined seismic and flooding loads. The manuscript contains: multi-hazard fragility analysis and damage risk (failure probability) analysis. It represents an interesting interdisciplinary research, which perfectly fits in with the scope of NHESS. The topic is timely and innovative.
Although the text is generally very well written (it is virtually word-perfect), the style is slightly verbose. There is room for considerably shortening the manuscript by focusing more strictly on the key messages and avoiding redundancy. For instance, the text on P7 (comments of Figs. 3; 4 and 5) is unnecessary long, …

A: We have revised the manuscript in this regard, shortened the figure captions and removed redundancies. In particular, we strongly reformulated the text to address the verbose and ornate writing style and make it more concise and pointed.

The literature review is comprehensive.
It seems that the Authors focus solely on "liquefaction" of the dike (based on Seed and Idriss, 1971), while worldwide dike overtopping is by far the most frequent mode of dike failure. A discussion is needed in this regard.

A: The reviewer is right that the overtopping seems to be most frequent dike failure mechanisms, as statistics collected by Vorogushyn et al. (2009) shows. However, the methodology for development of fragility curves for overtopping has been already presented by Apel et al. (2004) and to our knowledge is still based on the best available process knowledge considering data availability. Vorogushyn et al. (2009) developed methods for piping and micro-instability failure mechanisms. Though liquefaction is not very common, this is a likely breach mechanism under multi-hazard load by floods and earthquakes. Such fragility curves would thus be required for multi-hazard assessment of dikes in earthquake-prone areas. We have pointed out in the manuscript more clearly to the previous developments in the field and the purpose of the presented methodology. L69-78, L118-126.

Wording "damage risk" sounds a bit odd. If I understand well, the authors use the word "risk" for "probability", since they mean actually the "probability that some damage occurs" (elsewhere, they use "damage probability", e.g. in Sect. 3, in title 15 of Sect. 4 …). In science and engineering, risk is a broader concept than just "probability". It would be wiser to consistently use the wording "failure probability" throughout the manuscript, instead of "damage risk".

A: We agree with the reviewer that the term "damage risk" can be misleading and substitutes it with the term "damage or failure probability". This is actually what we mean in the presented context.

Clarifications are necessary regarding the derivation and characteristics of the fragility surface displayed in Fig. 3. Why does the failure probability not reach 1 for the highest values of water level (e.g. overtopping or nearly overtopping conditions) when PGA is low or zero? The same applies for Fig. 4. The reason relates probably to the liquefaction mechanism which is considered by the Authors; but still the results seem a bit puzzling.

A: Yes, the reviewer is right. The probability of dike failure/damage does not reach 1 even for water levels reaching the dike crest at low values of peak ground acceleration (PGA). At the first glance it looks odd, but if we recall that under probability we mean solely the probability of failure due to liquefaction and not the overall probability of dike failure then this result appears meaningful. We shall briefly explain this in the revised manuscript.

2 Specific comments

In the Introduction, mention the different failure mechanisms of dikes (incl. overtopping, seepage …) and briefly discuss their relative importance.

A: This has been shortly discussed, L69ff

Make clear which are the differences between *embankments* (frontal / normal to the flow direction) and *dikes* (parallel to the flow direction), and which are the consequences in for risk analysis (different designs, presence of a core …)?

A: It seems that the term 'embankments' is sometimes used as a synonym for dikes/levees. However, "embankment dams" are meant indeed as structures frontal/normal to the flow direction. In the manuscript we refer at some occasions to the literature on "embankment dams". We checked the use of this term. We now consistently use the term "dikes" for the structures parallel to the flow direction and "embankment dams" for structures normal to the flow direction.

Explain the complementarity between "large scale" studies such as the present one and more detailed small-scale studies (e.g. Rifai et al. 2017, WRR). While the latter are interested in the fine details of the failure mechanisms, studies such as the present one provide valuable insights on the effects on dike failure at a much broader spatial level (regional).

A: Thanks for this comment. We "bridge the scale" by linking small scale process studies to the attempts of applying the knowledge at a larger scale. This is actually what the presented manuscript tries to do: use the detailed geotechnical process knowledge to derive fragility curves which can be used for large scale risk assessment and modelling studies.

☐Define "hazard curve".

A: Done

☐Is the wording "impoundment of the dike" standard in the field? It sounds a bit odd compared to more standard terminology such as "overtopping" or "overflowing" of the dike …

A: The literature in the field is not very numerous. So, it is hard to say what is standard though the term was already previously used. "Impoundment of a dam" would be more obvious. With a dike the situation is different, since the flow is usually parallel to the dike. But we still believe, the term "impoundment" would be appropriate since we explicitly do not mean "overtopping" or "overflow" of a dike, but also consider the situations, where a dike is only partially "impounded" by water, i.e. the water level does not reach the crest by far.

☐Explain shortly "overburden stresses", as the readership of NHESS is multidisciplinary.

A: This has been reformulated

☐Is "phreatic surface" a standard terminology in English? Does it stand for "water table"?

A: "phreatic surface" is often used in this content. Water table is typically meant to be horizontal, whereas "phreatic surface" can be inclined and develops gradually in the dike core

☐Table 1: explain "N-values", "blows/foot".

A: This is a standard number associated with the standard penetration test (SPT) and is explained in any textbook on soil mechanics. The explanation here would be too lengthy.

☐Acronym PGA must be clearly defined when it is first used.

A: Done

☐P6 L28: is the word "proportional" (i.e. a purely linear relationship) appropriate?

A: This sentence has been reformulated

☐Fig. 3 and Fig. 4 seem redundant … They display the same information, don't they?

A: In fact, yes. Figure 4 represents the contour plots in the PGA-Water level 2D space of Figure 3. This is because 3D plots are sometimes difficult to interpret, but they nicely show the 3D nature of the fragility surface. We thus prefer to keep both and shortly discuss the features of both plots.

☐P8 L9: why disregard more frequent floods than the 100-year flood?

A: Yes, in fact, one can consider also smaller floods as soon as the dikes become impounded. This comment refers, however, to the future modelling study building upon the presented manuscript. This is made clear in the revised manuscript. This is a valuable comment by the Reviewer. We shortly discuss the implication of multi-hazard analysis for scenarios with flood return period below design level and expected impact on flood risk curves, L283-294.

☐P8 L15: explain briefly “S-wave velocity” for he multidisciplinary readership of NHESS.

A: Thanks. “S-wave velocity” is now explained, L300ff

☐P8 L33: is the word “risk” appropriate there?

A: This has been revised.

☐P9 L13: replace “term of the equation” by “factor in the integral”.

A: Done

☐P9 L17-19: remove this paragraph as it sounds trivial.

A: revised

☐P10 L17: “at” instead of “it”

☐P10 L23: “uppermost” instead of “most upper”

A: The minor issues above are revised.

☐Fig. 6 : the caption must explain that each curve corresponds to a different dike section. Using a grey scale (or colors) for the different curves would make the graph more informative by suggesting which curves correspond to more upstream (resp. downstream) dike sections.

A: Thanks, the explanation is added. The distribution of earthquake hazard is indicated in Figure 1. The different colors for curves would not enhance readability.

☐Conclusion: please shorten. There are some repetitions, particularly in the second half of the Conclusion.
A: Yes, conclusions have been made more concise.

3 Formal issues, typos …

A: We addressed the minor issues listed below

☐P5 L9: “there are different methods exist” … Rephrase.

☐P5 L11: remove “engineering”

☐P5 L25: remove “to be”

☐P6 L20: “in three-dimensional form”, instead of “in the three-dimensional form”

4 Conclusion

I strongly recommend that the Authors are invited to submit a revised version of the manuscript for publication in NHESS. I believe that substantially shortening the text, by focusing on the main points, would enhance the potential impact of the paper. If necessary, I am available to review the revised manuscript.

Reply to the comments of the Reviewer #2

A: We thank the Reviewer for a positive review of the manuscript, his/her valuable comments. We respond hereafter to the specific comments of the Reviewer and point out, how we tackled the raised issues in the revised manuscript.

General comments:

[*] I suggest you include a model uncertainty factor in the MCS

A: This is not quite clear to us what sort of the model uncertainty factor is meant here to be used in the Monte Carlo simulation. So far, we have considered the uncertainty in the geometrical and geotechnical dike parameters by taking into account their moments and typical probability distributions available in the literature. Considering the model (structure) uncertainty requires alternative model formulations i.e. different equations, which are not available in our case. Thus, we do not see, how we can consider model structure uncertainty unless the reviewer means something different under model uncertainty factor.

[*] I think you need to consider more frequently occurring water levels, not just the ones with very high return periods. The more frequent occurring water levels have higher likelihood of occurring in combination with an earthquake event.

A: Thanks for this comment, which goes in the same direction with the Reviewer #1. Indeed, smaller flood events are more likely, thus the probability of the coincidence with earthquakes would be higher. In terms of risk (probability x damage), the damage from small floods is however smaller. In any case, this is a valid comment, but the probabilities of floods/flood scenarios will be considered in a subsequent analysis, where we plan to integrate the entire flood and earthquake risk in a Monte Carlo analysis. In this subsequent study, the here developed fragility curves will be used for assessment of dike failures and subsequent inundation using hydrodynamic modelling. This goes, however, beyond the scope of the presented study. We shall consider also scenarios with smaller return periods than 100. We shortly discuss the implication of multi-hazard analysis for scenarios with flood return period below design level and expected impact on flood risk curves, L283-294.

[*] Please write out in more detail how you get to failure probabilities. I get the feeling you multiply annual flood probabilities (T=200 means p=0.005) with annual PGA probabilities. This is not allowed, which can be seen from the fact that the product has the unit year^-2, which has no meaning.

If that is the case, the method is incorrect. You need to take into account that if in year Y both a flood event and an earthquake event occur, it is more likely that they occur at different times in the year than that they happen at the same time. This needs to be taken into account in the computation. This strongly decreases the failure probability.

Additionally, you need to take into account the recovery (repair) time of the dike after an earthquake. This increases the failure probability.

It appears you did not take these factors into account. Apologies if you have, but in that case I propose you elaborate more on this

[*] I feel this paper should at least do one complete risk computation. Suggesting that it is "reasobale to think that the combination leads to higher risks", as you do near the end of the paper, is not doing the rest of the paper justice. And it should not be that much extra worrk.

Furthermore, your whole introduction is about how important it is to consider the combination of the two hazards (which I agree with). Then the least I expect is a comparison of failure probabilities of [a] a flood risk analysis, [b] an earthquake risk analysis and [c] a combined risk analysis

A: We thank the reviewer for pointing to these two issues. We would prefer to address them together as they partly relate to each other. In fact, we envisage a subsequent study doing a full-scale multi-risk assessment of "simultaneous" occurrence of floods and earthquakes by running a coupled 1D-2D hydrodynamic model for the Rhine and considering dike breaches (by the way not only due to liquefaction, but also due to overtopping and piping). As partly proposed by the reviewer we intend to compare the marginal change in flood risk due to multi-hazard load in relation to single-flood risk curve. This is, however, much more work contrary to the expectation of the Reviewer since the hydrodynamic and dike breach simulations are complex, run also probabilistically in Monte Carlo simulation and the variety of results need to be evaluated from various perspectives (see e.g. Vorogushyn et al., 2010). We therefore abstain from merging this research with the here proposed methodological development on the derivation of fragility curves for liquefaction in one manuscript. In the analysis we consider the "simultaneous" occurrence of floods and earthquakes if the latter occurs within 30 days period – a typical duration of a flood wave on the Rhine. For the subsequent analysis, we have developed synthetic flood hydrographs of 30 days duration. We shall modify the equation (3) to make this point clear. Yes, the Reviewer is right that multiplying the annual probabilities of earthquake and floods is wrong. Indeed, we mistakenly used annual earthquake probability in combination with annual flood probabilities. We recomputed the failure probabilities for an exemplary dike section using earthquake probability within 30 days window. Assuming the time window of 30 days, we undertake several assumptions. First, the probability of liquefaction depends on the development of the water table within a dike during the onset of the flood event. We treat this probability as uniform for the sake of brevity. Otherwise, we would need to carry out the dynamic modelling of water front propagation, which is an additional serious complication. Second, during the flood event no dike repair actions are taken into account, which might reduce the overall flood risk. This effect is however very difficult to estimate. The assumption of "no repair" during an entire year would be very unrealistic as mentioned by the reviewer. Such an assumption for the 30 days period might be reasonable, but in any case, this represents the conservative risk assessment. These limitations are discussed in the revised manuscript.

Minor and editorial remarks: the Reviewer #2 proposed several editing changes in the text using the change track mode in the pdf file. We shall carefully address them all in the revised manuscript, but we do not summarize them here in this reply letter.

References:

Vorogushyn, S., Merz, B., Lindenschmidt, K.-E., and Apel H. (2010): A new methodology for flood hazard assessment considering dike breaches, Water Resources Research, 46 (8), 2010, doi:10.1029/2009WR008475

Multi-hazard fragility analysis for fluvial ~~earthen~~ dikes in earthquake and flood prone areas

Sergey Tyagunov~~ (~~1~~)~~, Sergiy Vorogushyn~~ (~~2~~)~~, Cristina Muñoz Jimenez~~ (~~1~~)~~, Stefano Parolai ~~(~~1*~~)~~, Kevin Fleming~~ (~~1~~)~~

(1) GFZ German Research Centre for Geosciences, Centre for Early Warning, Helmholtzstrasse 7, D-14467, Potsdam, Germany.

~~-~~(2) GFZ German Research Centre for Geosciences, Section 5.4 Hydrology, Telegrafenberg, D-14473, Potsdam, Germany.

*now at: Seismological Research Centre of the OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante 42/C, 34010 Sgonico, Italy.

Correspondence to: Sergey Tyagunov, sergey.tyagunov@gmail.com

Keywords: multi-hazard; fragility; ~~earthen dike;~~ liquefaction; dike failure probability; earthquake; flood; Rhine; Cologne

Abstract

The paper presents a methodology for multi-hazard fragility analysis ~~and damage risk analyses~~ for fluvial earthen dikes in earthquake and flood prone areas due to liquefaction. The methodology ~~and results are an integral part of the multi-hazard (earthquake-flood) risk study implemented within the framework of the EU FP7 project MATRIX (New Multi-Hazard and Multi-Risk Assessment Methods for Europe)~~has been applied for the area~~ around~~ ~~-Cologne, Germany. The study area covers~~along the Rhine River reach and adjacent floodplains between the gauges Andernach and Düsseldorf. Along this domain, the urban areas are partly protected by ~~earthen~~ dikes, which may be prone to ~~damage (~~failure~~)~~ during exceptional floods and/or earthquakes. ~~The main focus of the study is to consider the damage potential of the dikes within the context of the possible interaction between the two hazards.~~ The fragility of the earthen dikes is analyzed in terms of liquefaction potential characterized by the factor of safety estimated with the use of the procedure of Seed and Idriss (1971). Uncertainties in the geometrical and geotechnical dike parameters are considered ~~by using~~in a Monte Carlo simulation (MCS). ~~The damage potential~~Failure probability of the earthen structures is presented in the form of a fragility surface s~~howing the damage probability~~ as a function of both seismic hazard and ~~water level~~hydrological/hydraulic load.~~ The presented results can be used for multi-hazard risk assessment in earthquake and flood prone areas.~~

Introduction

~~The problem of r~~Risk assessment in areas affected by several natural perils can be ~~discussed~~ carried out in two possible ways: on the one hand, one can consider ~~the~~ different types of hazards and risks independently, while on the other, ~~the~~ possible interactions between ~~the~~ hazards ~~may~~ can be taken into account. The former approach is based on traditional methods of single-type hazard and risk assessment and represents a common practice~~and presently is most commonly used by researchers and practitioners worldwide~~. The latter is used much more rarely, ~~perhaps because~~as it involves scenarios with obviously lower occurrence probabilities, which might, therefore, be underrated and sometimes unreasonably neglected. At the same time, the tragic lessons of past disasters show that in multi-hazard prone areas the risk of losses from single hazardous events can dramatically increase due to possible interactions between different types of hazards and the occurrence of cascading effects. For instance, the devastating experience of the Katrina Hurricane, 2005, and the Tohoku earthquake, 2011, sorely demonstrated that low occurrence probability events may result in extremely high consequences. Therefore, the possible interactions between hazards in multi-hazard prone areas should not be ignored in decision making.

~~A steadily increasing number of studies devoted to different aspects of multi-hazard risk assessment emphasize the raising awareness and interest of scientists and practitioners to quantifying multi-hazard scenarios, their effects and occurrence probabilities.~~ The earlier multi-hazard studies were solely based on the comparison of single-type hazard and risk assessments without considering interactions and potential cascading effects (e.g., HAZUS-MH, 2003, KATARISK, 2003, Grünthal et al., 2006, Fleming et al., 2016). In the recent years, frameworks for the assessment of the interactions of multiple hazards have been developed ~~for comprehensive risk assessment~~ (e.g., Marzocchi et al., 2012, Selva, 2013, Mignan et al., 2014).

The present research work, which was undertaken as part of the multi-hazard (earthquake-flood) risk study implemented in the frame of the EU FP7 project MATRIX (New Multi-Hazard and Multi-Risk Assessment Methods for Europe) focuses on the problem of multi-hazard fragility analysis of fluvial earthen levee.~~dikes representing the flood protection system in the area around Cologne, Germany.~~ We ~~assess~~ develop the methodology for assessment of ~~the~~ fragility ~~of those structures~~due to liquefaction by taking into account potential flood and earthquake impacts on dikes at the Rhine reach around Cologne.

The ~~areas around Cologne as well as the city itself are~~middle Rhine is regularly affected by flooding ~~from the Rhine River~~ (e.g., Fink et al., 1996) and vast floodplains are protected by dikes. ~~Therefore, within the framework of the regional flood risk management program, the urban areas along the river are partly protected by a system of earthen embankments (dikes or levees).~~ The areas not protected by ~~earthen dikes~~dikes are typically behind concrete walls, protected by mobile flood protection walls or are located on elevated banks~~ and hence are not subject to extensive inundation~~.

Besides ~~the ~~flood hazard, the areas around Cologne are exposed to other types of natural hazards, in particular windstorms (e.g., Hofherr and Kunz, 2010) and earthquakes (~~e.g., ~~Grünthal et al., 2009, Fleming et al., 2016). Although rarer than floods or windstorms, earthquakes have a higher damage~~ing~~ potential (Grünthal et al., 2006, Fleming et al., 2016). In combination with high water levels, earthquake may lead to liquefaction of saturated earthen dikes.~~ and would be able to cause considerable direct and indirect losses in the affected area~~ ~~. Such conclusion is made from a comparison of the single hazards and risks in the area (Grünthal et al., 2006).~~

~~In the MATRIX project, for the first time to the author's knowledge the possible effects of the temporal-coincidence and interaction of flood and earthquake hazards in the area are considered. The problem of temporal and spatial interaction between earthquakes and floods is dual: on the one hand, one should consider how the existing earthquake hazard may influence the level of flood risk and on the other, how the presence of flood hazard may change the level of seismic risk. Generally, earthquake and floods can aggravate their impacts in a number of ways, for instance, through damage to the flood protection infrastructure by the earthquakes, through the increasing severity of local effects of ground shaking by the presence of inundated areas or by influencing the vulnerability (fragility) of the built environment. In the present work, the interaction of the earthquake and flood hazards is accounted for only in terms of potential joint influence of earthquake ground shaking and flooding on the flood protection system of earthen dikes.~~

~~The designated purpose of fluvial dikes (representing earthen embankments running along the river banks) is to confine the water flow up to a certain level and protect the built-up or arable areas against flooding. The physical (and functional) reliability of the dikes plays an important role in the reliable performance of the whole flood protection system. Therefore, a comprehensive risk assessment should include the reliability analysis of the dikes, taking into consideration all the processes leading to possible breaching.~~

Dikes~~-~~ may fail due to various ~~damage ~~failure mechanisms induced either by high water levels~~, moisture content in the dike core, intense rainfall influence ~~ and/or earthquake impact (~~e.g., ~~Armbruster-Veneti, 1999, Foster et al., 2000, Apel et al., 2004, Allsop et al., 2007, Briaud et al., 2008, Wolff, 2008, Van Baars and Van Kempen, 2009, Vorogushyn et al., 2009, Nagy, 2012, Huang et al., 2014). When considering solely hydrologic/hydraulic load, overtopping is the most common failure mechanism followed by piping and slope instability (see Vorogushyn et al., 2009 and references therein). For these breach mechanisms, approaches for fragility analyses has been proposed (Apel et al., 2004, Vorogushyn et al., 2009). ~~Correspondingly, a variety of approaches to account for different damage (failure) modes are being~~

~~developed and used for performance and reliability analyses of earthen structures (dikes, levees, embankments, dams) under different hazard conditions. As has been already indicated, the focus of our research interest lies on earthquake and flood hazards.~~

Under earthquake load, the liquefaction phenomenon is indicated as the most important cause of embankment dam failure (Ozkan, 1998).~~Regarding the earthquake hazard considerations, one can refer to the review article of~~

Marcuson et al. (2007), ~~which traces~~reviewed the development of the state of practice in seismic design and analysis of embankment dams, starting from the fundamental publications of Newmark (1965) and Seed and Idriss (1971). ~~Another overview of different approaches to seismic safety assessment of earthen embankments and dams can be found in Ozkan (1998), where the liquefaction phenomenon is indicated as the most important cause of the damage occurrence in earthquake prone areas.~~

Sasaki et al. (2004) described empirical and analytical methods used in Japan for estimating the settlement of ~~river~~ dikes due to liquefaction, considering both the probable subsidence of the bottom boundary and deformation of the dikes. ~~With respect to empirical methods, we can also mention the paper of~~ Singh and Roy (2009) ~~,~~proposed a correlation relationship for the earthquake-induced deformation of earthen embankments ~~where,~~ based on the examination of 156 published case histories and using the ratio of the peak horizontal ground acceleration and the yield acceleration as ~~the~~ an estimator~~, the authors proposed a correlation relationship for the earthquake-induced deformation of earthen embankments~~.

In recent years, more sophisticated computer-based linear or non-linear methods for seismic analyses of embankments have been developed, using one-, two- (~~e.g.,~~ Kishida et al., 2009, Athanasopoulos-Zekkos and Seed, 2013) or three-dimensional (~~e.g.,~~ Wang et al., 2013) models. At the same time, Kishida et al. (2009) concluded that simplified models based on equivalent-linear analyses can provide reasonably accurate results up to moderate ground shaking levels, while nonlinear analyses should be used to evaluate ~~levee~~ dike responses at stronger shaking levels. We therefore ~~employ~~ focus on a simplified approach, since we are concerned with the study on a regional spatial scale in the areas of low to moderate seismicity.

Rosidi (2007) presented ~~A~~a seismic risk assessment procedure for earthen embankment dams~~s~~ and ~~levees~~dikes~~ is presented in the paper of Rosidi (2007)~~, where ~~the levee~~ dike fragility was expressed as a function of earthquake-induced slope deformations. Considering different strengthening scenarios, Rosidi (2007) estimated levee failure probabilities ~~in~~ depen~~den~~ding~~ce~~ on earthquake ground motion return period.~~,~~ ~~h~~However, possible fragility changes due to flood water elevation and dike core soil saturation was not taken into account in that study.

~~In the matter of the flood hazard considerations,~~ For the purpose of single-type flood risk assessment, Apel et al. (2004) developed fragility curves for ~~the assessment of the~~ overtopping failure ~~probabilities~~ based on Monte Carlo simulations. Vorogushyn et al. (2009) extended this approach for piping and micro-instability breach mechanisms based on the formulations of Sellmeijer (1989) and Vrouwenvelder & Wubs (1985), respectively.

Recently, Schweckendiek et al. (2014) presented an approach to include field observations in the Bayesian updating of piping failure probabilities of dikes in the Netherlands. Krzhizhanovskaya et al. (2011) reported an integration of reliability analysis for various breach mechanisms into a prototype flood early warning system, including dike failure and associated inundation modelling. A summary of research and practical methods for reliability assessment of levee systems~~,~~ considering different failure mechanisms~~,~~ can be found in Wolff (2008).

The reviewed studies, however, used a single-hazard approach focusing on either earthquake or flood impacts on ~~the~~ infrastructure. The present study aims at filling the existing methodological gap~~,~~ considering both hazards together.

The main goal~~s~~ of the study ~~include (1)~~is the development~~ing~~ of a methodological approach for multi-hazard fragility ~~and damage risk~~ analyses ~~of earthen dikes in earthquake and flood prone areas, and (2)~~ and construction of~~ing~~ multi-hazard fragility functions for ~~the~~ dikes in the earthquake and flood prone areas along the Rhine River. These functions are meant to be incorporated into the regional flood hazard and risk assessment models ~~and to be used for further risk assessments in the area around Cologne~~. In this way, small-scale breaching process knowledge can be integrated into regional-scale risk analyses.

The existing regional Inundation Hazard Assessment Model IHAM (Vorogushyn et al., 2010) considers three breach mechanisms: overtopping, piping and micro-instability of the dike slope. More details on the parameterization of these breach mechanisms and the development of respective fragility functions are given in Apel et al. (2004) and Vorogushyn et al. (2009). Here we consider another possible failure mechanism – earthquake-triggered physical damage to earthen dikes due to liquefaction. This type of phenomena may occur in earthquake prone areas, where water-saturated sandy soils have the potential to liquefy when subjected to seismic vibrations. During liquefaction, when as a consequence of increased pore water pressure the strength of bonds between soil particles is drastically reduced to essentially zero, soil deposits may lose their bearing capacity and behave as fluids (~~e.g.,~~ Kramer, 1996, Idriss and Boulanger, 2008). ~~Other conditions being equal, water-saturation and vibration are major causes of this phenomenon. Therefore, the occurrence probability of liquefaction can predictably increase in multi-hazard (earthquake and flood) prone areas.~~ In our study, we assume that the liquefaction occurrence in the dike body may result in the subsidence of the ~~dike~~ core as well as in large slope deformations. The subsequent breach of the affected dike section is the~~refore assumed~~ resulting consequence.

The area under study, along with the communities at risk and location of dikes along the Rhine River, is presented in Fig. 1, where the ~~series of~~ points correspond to the geometric centres of the ~~existing~~ dike sections of about 500-600m length. ~~Also, for the purposes of illustration and general characterization of the area,~~ Fig.1 shows the ~~grid of~~ administrative boundaries (communities) as well as the general zonation of the seismic hazard. The shown hazard estimates are based on the earlier ~~D-A-CH~~ map by ~~(~~Grünthal et al.~~,~~ (1998)~~,~~ in terms of EMS intensities for an exceedance probability of 10% in 50 years, and are referred to the centres of communities (Tyagunov et al., 2006a). ~~For this study, however, we will calculate more a~~The accurate seismic hazard estimates for all ~~the~~ dikes locations will be calculated below.~~, as will be shown below.~~

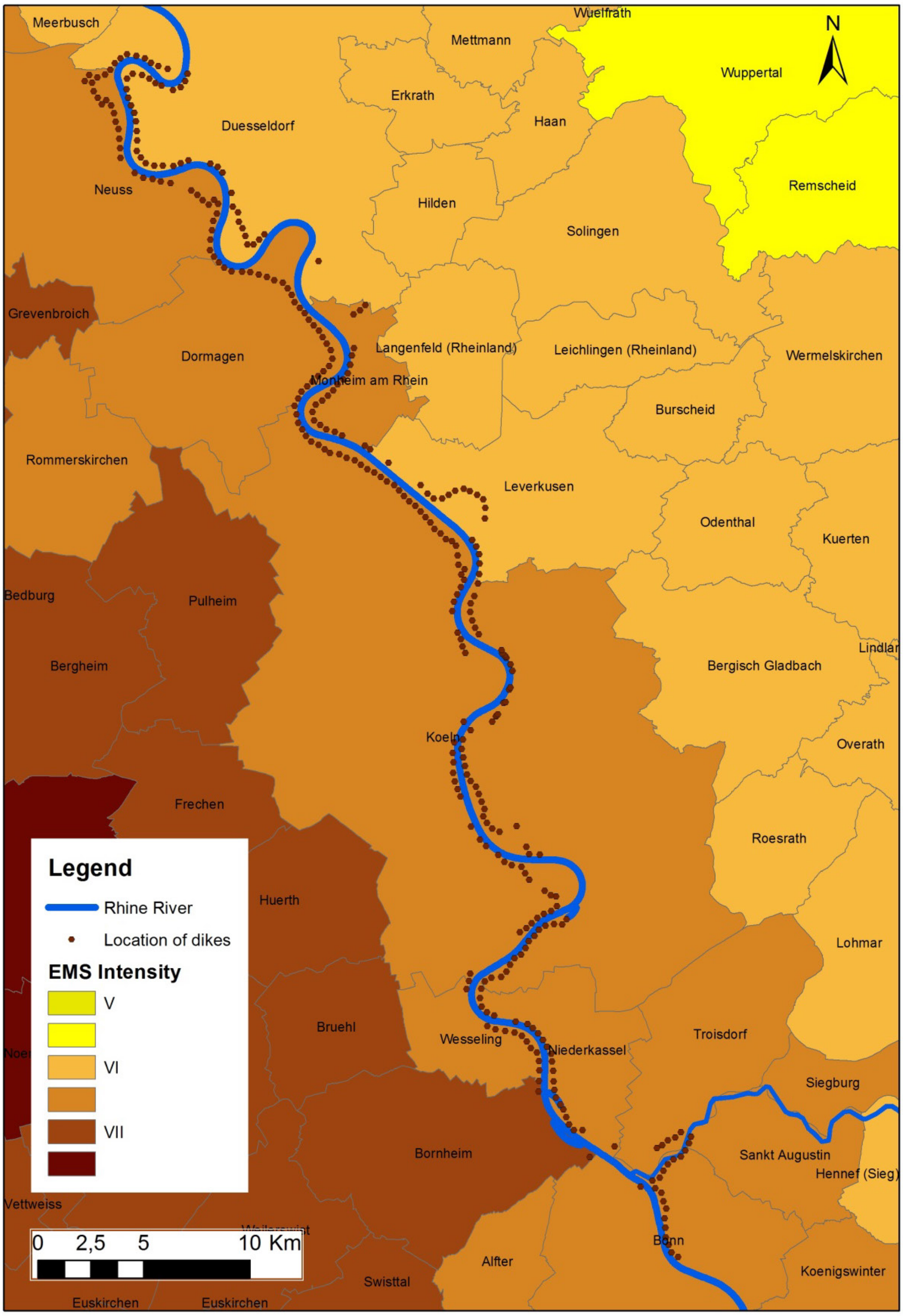

Figure 1: Location of flood protection dikes along the Rhine and the spatial distribution of seismic hazard in the study area~~. The points correspond to the geometric centres of the existing dike sections on both sides of the river. The hazard estimates are given~~ in terms of EMS intensities for an exceedance probability of 10% in 50 years (Grünthal et al., 1998)~~ and are referred to the centres of communities~~.

Data and Method

The probability of a dike failure is considered in terms of liquefaction potential, estimated using the method of Seed and Idriss (1971). ~~According to this approach, t~~The liquefaction potential ~~of an area or a site~~ can be assessed with a factor of safety (FS) against liquefaction, which is determined as the ratio of the capacity of the soil to resist liquefaction (CRR: Cyclic Resistance Ratio) and the seismic demand placed on the soil layer (CSR: Cyclic Stress Ratio).

The CSR value can be estimated using the following expression:

$$CSR = 0.65 \cdot \frac{a_{max}}{g} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot r_d \ , \qquad (1)$$

where a_{max} is the horizontal peak ground acceleration (PGA), g is the gravitational acceleration, σ_{vo} and σ'_{vo} are the total and effective overburden stresses (pressure imposed by above layers) of the soil, respectively, and r_d is a stress reduction factor that depends on the depth. For the calculation of the vertical stresses as a function of depth, we also consider the variations in the water level in the river, which influences the phreatic surface and degree of saturation in the dike core.

As for the CRR value, there are different methods for estimating the soil resistance to liquefaction (~~e.g.,~~ Youd et al., 2001, Kramer and Mayfield, 2007). Probably the most common is the method based on standard penetration testing (SPT). In our study, due to the lack of SPT data ~~in the area under consideration~~, we use an approach based on the correlation between penetration resistance and the angle of internal friction for sandy soils (Table 1, Peck, 1974).

Table 1: Relationship between the angle of internal friction and SPT-values (Peck, 1974)

SPT, N-Value ~~(blows/ foot)~~	Density of sand	ϕ (degrees)
<4	Very loose	<29
4 – 10	Loose	29 - 30
10 – 30	Medium	30 - 36
30 – 50	Dense	36 - 41
>50	Very dense	>41

In addition to the friction angle, for modelling the bearing capacity of earthen dikes, we also consider other geotechnical parameters such as specific weight, porosity and fines content. Statistical information about the characteristics of dikes used for liquefaction analysis is presented in Table 2. The typical values for the specific weight and friction angle found in dikes were taken from Vorogushyn et al. (2009) and the references therein. The fines content values are adapted from a dike at the Rhine River in the Netherlands (Van Duinen, 2013).~~ We assume that these soils' properties can appropriately characterize the flood protection dikes along the Rhine.~~

Table 2: Geotechnical parameters of dikes adopted in this study

Soil properties	Mean	Standard deviation	Minimum	Maximum
Specific weight γ (kN/m3)	18	1	13	21
Friction angle ϕ	29.2	0.3	20.8	37.6
Fines content FC (%)	5	1	3	11

The performance of ~~the~~ dikes under seismic ground-motion loading is analyzed using a simplified one-dimensional model assuming that below the water level the soil is in a saturated state. Hence, the phreatic line within the dike body is assumed to be horizontal (obviously, this is a conservative assumption that presumes the sufficiently long duration of the flood water rise or impoundment). A cross-section of the generic dike model is shown in Fig. 2.

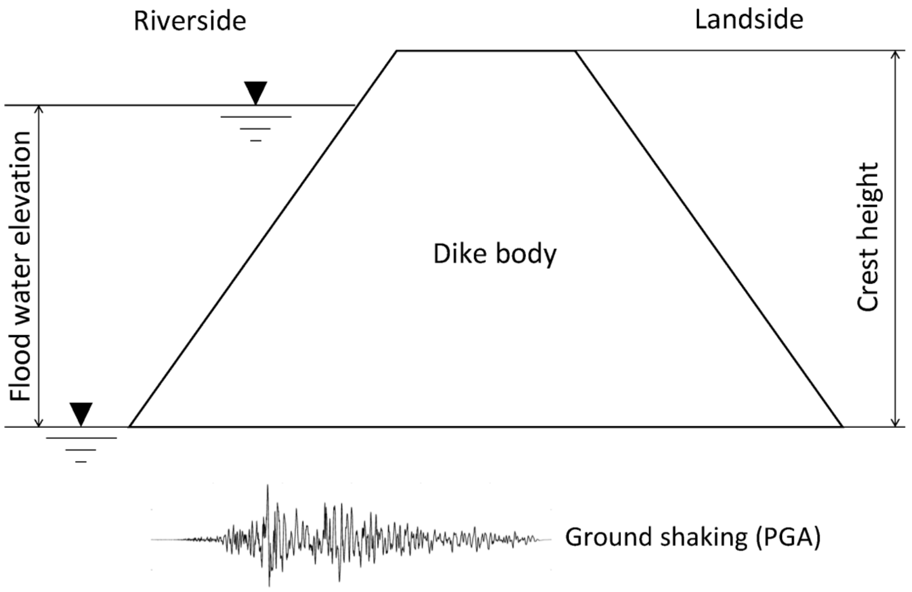

Figure 2: Generic dike model to illustrate the ~~for~~ earthquake-flood-dike interaction ~~studies~~

For the development of dike fragility curves, we assume a generic dike height of 5 meters. When integrated into the dynamic flood-earthquake hazard model, the actual dike height and corresponding water level ~~will~~ need to be taken into account.

In the computational algorithm, the material properties of ~~the~~ dikes are assumed to be homogeneously distributed throughout the cross-section of the dike ~~body~~core.~~;~~ H~~h~~owever, they can vary spatially along the river, from one cross-section to another, keeping in mind the range of existing uncertainties of the geotechnical parameters as specified in Table 2.

For quantifying the liquefaction potential, the values of CSR (reflecting the level of seismic ground shaking) and CRR (depending on the dike material properties and the water level) are calculated for all points of the dike cross-section from the crest to the bottom (with a discretization interval of 5 cm). Once both the CSR and CRR values have been determined at a certain point under certain load conditions, we can calculate the factor of safety against liquefaction (FS) employing the relationship (Seed and Idriss, 1971):

$$FS = \frac{CRR}{CSR} \tag{2}$$

At the points where the loading (CSR) exceeds the resistance (CRR), i.e., the factor of safety is below 1, one can expect the initiation of liquefaction~~, which can cause the development of significant deformations of the earthen structure and, consequently, can lead to~~ that can lead to the functional failure~~ of the dike~~.

In this study, we neither analyze the degree of soil deformations caused by liquefaction nor consider the variety of possible ~~damage~~ failure states of the affected ~~earthen~~ structure. Instead~~, as a first approximation~~, we conservatively assume that the initiation of liquefaction (FS ≤ 1) in any point throughout the dike body corresponds to the failure (loss of function) of the dike. ~~In other words, the limit state corresponding to the probable breach in the dike section due to earthquake-induced liquefaction is defined as FS = 1.~~

~~In view of the uncertainties in the parameters of the dikes, c~~Computations ~~alculations~~ of the liquefaction potential~~ (in terms of FS)~~ are done ~~through~~ in a Monte-Carlo simulation~~s~~ (MCS) considering the variability (uncertainty) of the geotechnical parameters of the dikes ~~as described in~~ (Table 2). Based on a frequency analysis of the MCS results, dike failure probabilities are computed for different points of the discretized two-dimensional load space, considering possible combinations of peak ground acceleration and ~~the~~ flood water level.

Fragility surface

~~Unlike the commonly used~~ In the single hazard fragility analysis~~ (when~~, the ~~damage~~ failure probability is expressed as a function of ~~a~~ single hazard load parameter(s).~~),~~ In a multi-hazard fragility analysis the response of the structure is described as a function of multiple-hazard load parameters.~~ should properly take into account all of the relevant hazards and their possible combinations and therefore the fragility relationship should be presented in the corresponding multi-dimensional form~~. Thus, ~~in the considered case of a dike subjected to two hazards (earthquake and flood), we present~~in our case the calculated fragility results are presented in the three-dimensional form with seismic and hydraulic load described by peak ground acceleration and water level, respectively (Fig. 3).~~, where two horizontal axes represent the space of different possible combinations of the two hazards, while the vertical axis specifies the damage (failure) probability. The developed fragility surface for the earthen dikes is shown in Fig. 3, where the points constituting the surface correspond to the occurrence of the limit state (FS = 1) related to the dike failure due to earthquake-triggered liquefaction. Therefore, t~~ The fragility surface represents ~~defines (on the interval from 0 to 1)~~ the conditional failure probability~~ of earthen dikes as a function of both the seismic (PGA level) and flood (impoundment level) loading~~ given the combination of load.

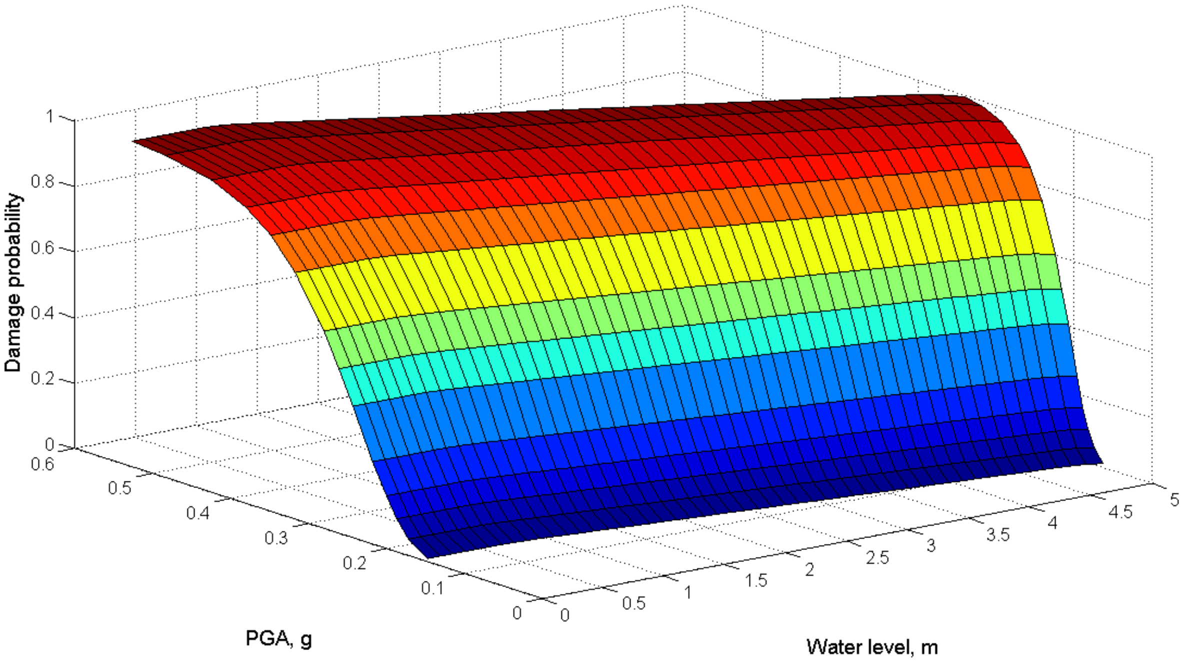

Figure 3: Multi-hazard fragility surface~~ for the dikes depending on ground shaking level (PGA, g) and water level (m)~~for liquefaction failure of a dike.

~~Considering the fragility surface as a whole (Fig. 3) one can get a general idea about the main features of the probable dike performance under the multi-hazard conditions, in particular, one can see that, as should be expected, the damage probability for the dikes is proportional to the level of ground shaking, continuously increasing from 0 to 1. At the same time, an increase in the water level can lead to an increased damage probability, even at lower levels of PGA.~~

~~To investigate more details and consider additional aspects required for the quantitative fragility analysis of the structures, t~~The fragility surface can be interpreted as a set of iso-lines corresponding to different percentiles of the calculated distribution of the FS values, as shown in Fig. 4. The presented iso-lines correspond to the occurrence of the limit state (FS = 1) and specify the failure probabilities in the two-dimensional space of hazards (in units of PGA and flood water level).~~, which are the prerequisites (thresholds) of the initiation of liquefaction in the dike body~~.

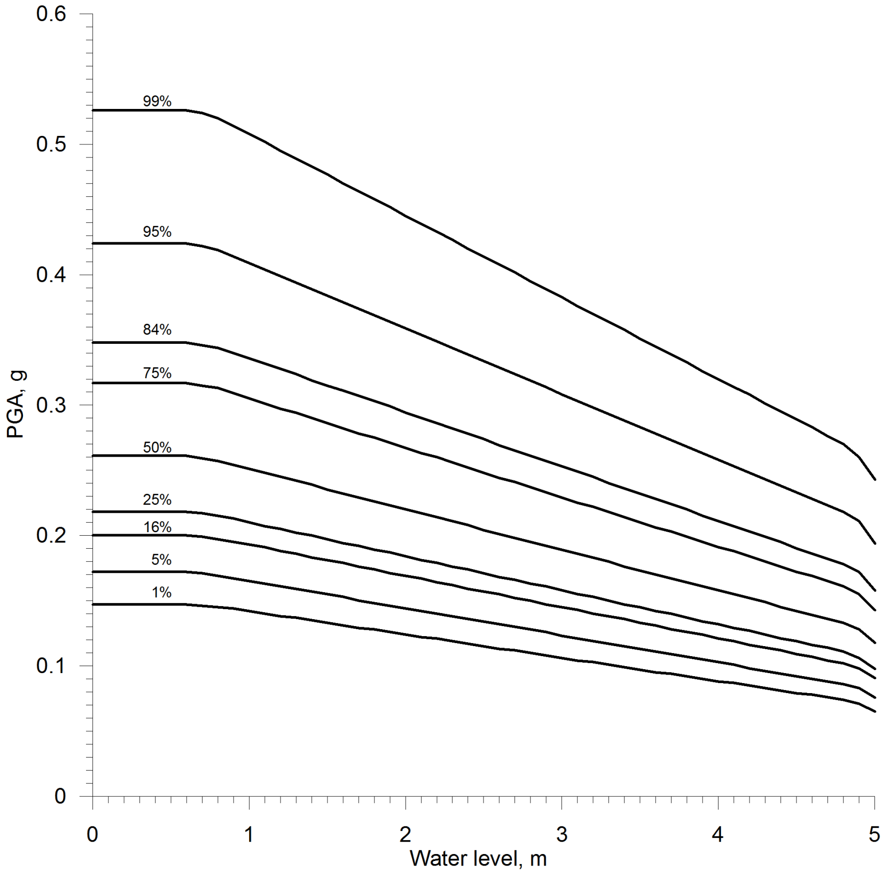

Figure 4: Dike ~~damage occurrence~~failure probability in the PGA and water level space ~~(percentiles) depending on PGA and flood water level~~

It becomes apparent that liquefaction failure can be initiated already at small water levels given sufficient earthquake load. On the other turn, a certain degree of shaking is required for liquefaction failure even at the maximum water levels ~~On the left edge of the graph~~ (Fig. 4). ~~one can see that for the water level at the toe of the~~

~~dikes (without extra-flooding) t~~The estimated PGA threshold ranges from 0.15 g to 0.54 g for the interval from 1 to 99 percentiles ~~(covering 98% of all calculated values) and from 0.17 g to 0.42 g for 5 to 95 percentiles; the median value marks the level of 0.26 g.~~ When the flood water rises up to about 0.7 - 0.8 m, it has no visible effect on the PGA threshold, while further increases in water levels lead to a considerable shift towards lower PGA values ~~(~~and this change is ~~practically~~ linear~~)~~. ~~On the other edge, w~~When the ~~flood~~ water level reaches the top of the structure, the threshold PGA values ~~(~~and ~~therefore~~ the liquefaction occurrence probabilities~~)~~ change significantly. In comparison with the initial state (water level at the toe of the dike~~s~~)~~, when the water level equals the crest height~~, the PGA threshold values decrease to between 0.07 - 0.24 g (for the interval from 1 to 99 percentiles) ~~and to 0.08 - 0.19 g (for 5 to 95 percentiles), while the mean PGA value indicates a level of 0.12 g~~. Comparing ~~the values for~~ the two ~~edge cases~~extreme cases, ~~one can see that, following the water rise,~~ the liquefaction triggering PGA threshold values decrease more than half and ~~concurrently~~ the spread of the values becomes ~~considerably~~ narrower. Water level is thus a considerable factor determining the dike core moisture content and liquefaction failure.

~~The comparative analysis above indicates that a rise of flood water level can lead to an increase in the fragility (and, correspondingly, the damage probability) of the earthen dikes and, therefore, this effect of impoundment should be taken into consideration when analysing the performance of the flood protection earthen dikes in multi-hazard (earthquake and flood) environment.~~

~~In addition to the three-dimensional fragility surface (Fig.3), displaying the fragility of the structure in the continuous form, the next graph (Fig. 5) gives an alternate presentation of the calculated results in the form of the discrete fragility functions (more conventional for single hazard analyses), showing the relationship between the damage occurrence probability of the dikes and the level of seismic ground shaking. The set of six fragility functions is present, each of which includes the influence of the flood water level, for the six discrete states (from 0 – i.e., at the toe of the dike, to 5 m – i.e., reaching the top of the dike).~~

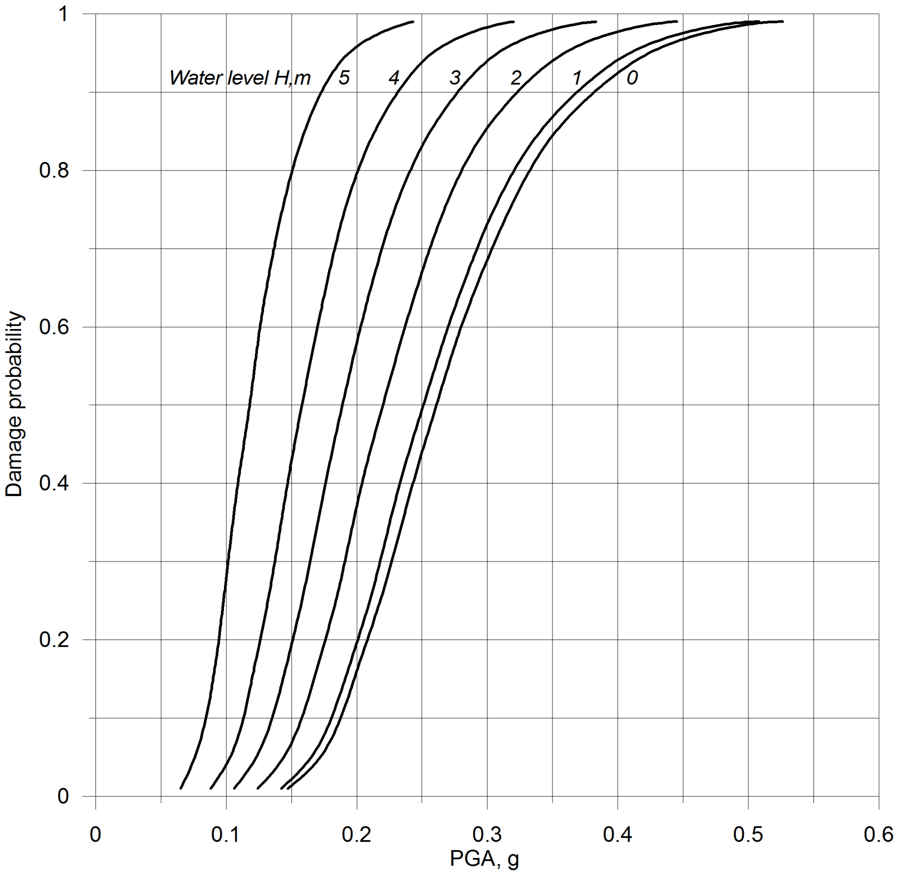

Figure 5: Fragility functions for ~~the~~ earthen dikes ~~as a function of damage (failure) probability vs PGA~~ for different water levels ranging from dike toe to assumed crest height. ~~(from 0 to 5 m)~~

~~As can be concluded, considering the usable range of the liquefaction triggering PGA values (Fig. 5), t~~The developed dike fragility model may find practical application in regions of low to moderate seismicity. For the lower PGA values (0.15 - 0.30 g) the contribution of the effect of impoundment can be more critical than for the higher PGA, ~~(~~when earthquake ground shaking is sufficiently strong to trigger liquefaction under conditions without extra-flooding (Fig.5)~~)~~. It should be stressed here that presented fragility curves represent the conservative estimates due to the assumption of full saturation of a dike core below the water level. In practice, some time is however required for the development of the phreatic line. More sophisticated dynamic models considering the degree of soil saturation can be adapted in future to adjust failure probability estimates.

~~The presented fragility relationships (which can be used either in the form of the integral fragility surface or as a set of fragility functions for discrete hazard levels) related to the dike damage due to earthquake-triggered liquefaction are essential for the assessment of probability of the failure of earthen flood protection structures in earthquake and flood prone areas, where the effect of interaction between flooding~~

~~and seismic loading should be taken into account in risk computations. At the same time, we note that the presented fragility estimates should be considered as preliminary, bearing in mind, in particular, the simplifications of the one-dimensional dike performance model used in the computations, as well as the conservative assumption about the dike failure even if liquefaction occurs in one point of the dike body. Needless to say, the validation of the models is required as an indispensable consequence of any kind of modelling.~~

Dike failure probability assessment

~~For the goals of the dike failure probability assessment~~To estimate the actual failure probability of a dike in the area of interest, the developed multi-hazard fragility functions should be combined with the probabilistic hazard estimates ~~(including both~~of earthquake and flood considering their respective return period values~~) for the area of interest~~.

~~As mentioned above, the obtained results are integral to multi-risk analyses in earthquake and flood prone areas around Cologne and aimed to be used for generating a series of flood scenarios with different return periods (from 100 to 1000 years)~~The developed fragility curves are intended to be used in a subsequent multi-risk analysis study along~~ for~~ the Rhine River reach between Andernach (Rhine-km 613.8) and Düsseldorf (Rhine-km 744.2) considering flood scenarios with return periods between 20 and 1000 years. In particular, the effect of multi-hazard is expected to manifest for flood return periods below the dike design level (200-year return period on the middle Rhine). In the single-type flood hazard analysis only piping failure could possibly impact dikes below design level, whereas multi-hazard consideration would slightly increase the probability of failure if the occurrence of earthquakes and subsequent liquefaction is taken into account. The effect of multi-hazard consideration on total risk is expected to decrease with increasing flood return period beyond design level since dikes would fail (in most cases) due to overtopping anyway.~~ Those flood scenarios will take into consideration the probable interaction of the earthquake and flood hazards in the area.~~

~~Keeping this purpose in mind, t~~The seismic hazard calculations were implemented for all locations at~~of~~ the~~ earthen dikes~~ center points of dike segments ~~-~~on both sides of the Rhine River reach (~~as shown in~~ Fig. 1). The input data for the seismic hazard analyses were taken in accordance with the regional model of Grünthal et al. (2010). The hazard calculations were implemented using the GEM (Global Earthquake Model) OpenQuake software (Crowley et al., 2011a, b) for soil sites characterized by 300 m/s shear wave (S-wave) velocity in the uppermost 30 m, which was assigned considering the results of previous ~~engineering~~ seismological studies in the area (Tyagunov et al., 2006b, Parolai et al., 2007). Note that amongst the waves generated by an earthquake, the S-wave, that are those for which the motion is perpendicular to the direction of wave propagation are expected to determine the largest impact on the building structures. Their variations in the velocity of propagation, accounted in the calculation, are used as a proxy to estimate the spatial differences in the amplitude of shaking. The set of calculated seismic hazard curves ~~(~~in terms of PGA~~)~~ characterize~~ing~~ the range of probable level of ground shaking for the different dike locations is shown in Fig. 6. In total, 339 dike sections are analysed: 157 of them are on the left side and 182 on the right side of the river.

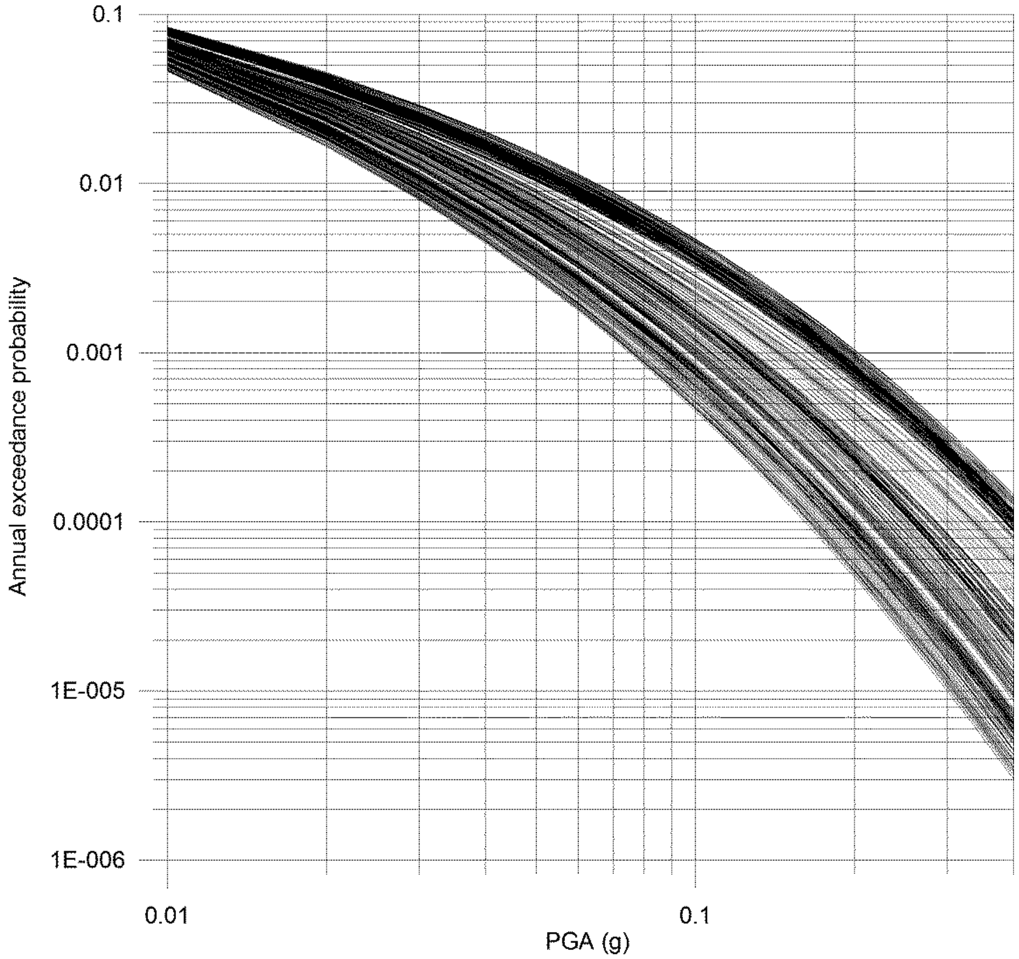

Figure 6: Seismic hazard (mean) curves for the locations of the dikes along the Rhine River~~ (see Fig. 1)~~. Each curve corresponds to one dike segment.

The calculated PGA values vary in space for different points along the river stretch and the ~~probable ~~level of ground shaking depends on the return period of interest. Thus, for the level of exceedance probability of 10% in 50 years, ~~(~~which is the common standard in the practice of earthquake engineering and corresponds to an average return period of 475 years~~)~~, the PGA estimates vary over a range of about 0.06 – 0.15 g. For a shorter return period of 100 years, PGA varies in the range of about 0.03 – 0.06 g, whereas for a longer return period of 1000 years the range is about 0.08 – 0.20 g. Note, however, that for the return periods longer than 1000 years, even higher levels of ground shaking are probable in the area and such low probability phenomena ~~in reality ~~cannot be ruled out.

~~A remarkable fact is that t~~The spread in the calculated PGA values is not very large, because the ~~line~~ course of the Rhine River and corresponding dikes ~~(and correspondingly the locations of flood protection dikes)~~ closely follows the shape of the seismic hazard zones around Cologne (Grünthal et al., 1998, DIN 4149, 2005). ~~,~~ ~~t~~Therefore the seismic hazard distribution in the area under study (Fig. 1) appears rather uniform.

On the basis of the obtained results and referring to the liquefaction susceptibility categorization for different soil types (Youd and Perkins, 1978, HAZUS-MH, 2003), one can make a qualitative conclusion that in this area, there is a risk of dike damage due to liquefaction induced by seismic ground shaking. ~~It is worth mentioning here that a~~According to observations from past earthquakes (Sasaki et al., 2004) seismic damage to river dikes can be triggered by PGA of 0.16 g or higher. ~~At the same time, it is also interesting to note, taking into consideration the observations of Santucci de Magistries et al. (2013) and Quigley et al. (2013),~~ There is even evidence that the PGA threshold ~~in~~for liquefaction occurrence can be even less than 0.10 g (Santucci de Magistries et al., ~~(~~2013~~)~~, ~~and~~ Quigley et al., ~~(~~2013).

The actual dike failure probabilities can be quantified by considering the probabilities of occurrence of the earthquake ground shaking level and flood return periods at different dike locations combined with the presented fragility curves. The simultaneous occurrence of a flood and an earthquake should be assumed. The typical duration of a flood wave of 30 days is considered for the Rhine. It is assumed that no dike repair actions are undertaken in this period, which may affect the probability of failure. Thus, the earthquake probability is computed for this period to be combined ~~. Therefore, the total failure probability can be calculated from~~ in the following expression to determine the actual failure probability~~:~~

$$P(F) = \iint P\left(F \middle| \cancel{S} S_i^{30}{}_{\cancel{i}}, W_j\right) * P\left(S_i^{30} \cancel{S_i}\right) * P\left(W_j\right) dSdW, \qquad (3)$$

where $P\left(F \middle| S_i^{30}, W_j\right)$ is the conditional failure probability given ~~that~~ the combination of the seismic ground shaking S_i^{30} within a time window of 30 days and the water level W_j ~~takes place~~;

$P\left(S_i^{30}\right)$ is the probability of occurrence of ~~that~~ the seismic input S (peak ground acceleration) ~~corresponds to~~of the level *i* within a time window of 30 days;

$P(W_j)$ is the probability that the water level W corresponds to the level *j.*

~~In other words, t~~The first ~~term of the~~factor in the integral ~~equation~~ represents the conditional failure probabilities ~~for the dikes due to liquefaction~~, which can be obtained from the multi-hazard fragility surface (Fig. 3), while the second and ~~the~~

third ones~~terms~~ represent probabilistic estimates of the seismic (PGA level) and flood hazard (water level) at the dike locations and can be obtained from the corresponding hazard curves.

For the situation without ~~extra-~~flooding~~ (when the flood water does not exceed the level 0.7-0.8 m, see Fig. 4), the damage risk for the earthen dikes due to earthquake-induced liquefaction can be estimated using the simplified form of the equation above, in particular, omitting the influence of the water elevation and considering only the seismic effects, i.e., in fact, using the traditional single hazard approach.~~

~~Thus, jointly analysing the calculated~~ by combining the seismic hazard curves (Fig. 6) with the fragility curve corresponding to the water level ~~equal to~~of 0 m (Fig. 5), ~~we conclude that it is likely that~~ the earthquake-triggered liquefaction~~ (and therefore dike damage)~~ may occur at some of the considered dike locations ~~even under natural conditions without extra-flooding, though its occurrence~~though the probability is not very high.~~ Preliminary quantitative estimates assuming no impoundment of the dikes, show that the level of liquefaction occurrence and, correspondingly, the damage risk for the dikes located in different points along the Rhine River (Fig.1) varies (in dependence on the level of seismic hazard, Fig.6)~~ The probability varies in this case within the range of 1 - 4~~5~~*10^{-5}~~^{4}~~ per year.

~~Perhaps, the dike damage risk itself (without taking into consideration effects and consequences of possible floods) may not generate much interest to practitioners. However, one should bear in mind the essential level of existing flood hazard in the area as well as possible temporal coincidence of flooding and strong earthquakes. Actually, t~~The current design criteria of fluvial dikes take into account only flood hazard and do not consider potential multi-hazard impact. Therefore, in case of probable temporal coincidence of flooding and strong earthquakes, dike protection structures may fail due to liquefaction at flood return periods below the design level. This may lead to perplexity and negatively affect population, infrastructure, and flood response, requiring emergency actions.

~~The~~A comprehensive quantitative risk analysis ~~of the performance of the flood protection system of dikes, including~~considering the joint probability of seismic and flood events and their ~~probable~~ interactions in time and space ~~over the whole area, however, is not a straightforward task and will require a special study~~requires continuous hydraulic model and multi-hazard integration. This goes beyond the scope of presented research. Here, ~~just~~ for the illustration ~~of the practical application~~ purpose~~of the developed fragility functions~~, we present an example ~~of~~for estimation~~ng~~ of the ~~damage risk~~failure probability for a ~~single~~ specific dike section.

~~Exemplarily, f~~For a left-side dike section at Rhine-km 668 near the town Wesseling (south to the city of Cologne, Fig.1), the average maximum water levels were estimated for three return periods 200, 500 and 1000 years, using a dynamic probabilistic-deterministic coupled 1D-2D model (Vorogushyn et al., 2010) setup for the study area at the Rhine River within the EU-FP7 MATRIX project (Garcia-Aristizabal and Marzocchi, 2013). The hydraulic model uses the flow records at gauge Andernach (Rhine-km 613.8) for estimation of hydrographs and corresponding return periods. Hydrographs are then routed with a coupled 1D-2D model considering dike breaches and associated inundation. The estimated water levels at the selected location are: for the 200-year return period (p=0.005 per year) 50.38 m asl (above sea level); for 500-year (p=0.002) and 1000-year (p=0.001) 50.49 m and 50.52 m asl, correspondingly.

Assuming the height of the dike of 5 metres at the selected location, the dike would be impounded by 4.50 metres during a 200-year flood event. Correspondingly, the estimated impoundment level would reach 4.61 m for the 500-year and 4.64 m for the 1000-year flood scenarios. The small difference between the calculated estimates can be explained, in particular, by the used model, which considers ~~considering~~ dike breaches upstream, i.e. the water level at one dike location depends on performance of other dike sections (e.g., if one of the upstream dikes fails, the water ~~breakout~~ outflow would reduce the flood loads on the other dike sections). ~~In this view, therefore, it could be supposed that the values above (about 4.65 m) represent a kind of the upper limit of water elevation level for the dike under consideration.~~

~~As described above, the level of total risk (failure probability) for the dike under multi-hazard conditions can be estimated combining the multi-hazard fragility curves (Fig.3-5) with the flood and earthquake hazard curves and taking into consideration different possible combinations of ground shaking and water levels. Here, in the illustrative example, we employ the calculated seismic hazard curve for Wesseling (which belongs to the most upper part of the curves shown in Fig.6). As for the flood hazard at the location, we use the above-mentioned estimates of water level (impoundment of the dike) characterized by different probabilities of occurrence (return periods of 200, 500 and 1000 years).~~

Combining the flood hazard estimates with seismic hazard curves and fragility function for the point of interest, the probability of liquefaction at Wesseling without flooding is ~~The estimated probability of liquefaction occurrence in the dike body due to seismic vibration under normal conditions (without extra flooding), which, in point of fact, reflects the single hazard risk for the selected dike at Wesseling, is~~ about ~~4.7~~3.9*10^{-}~~^{4}~~^{5} per year. ~~Considering the combined effect of the two hazards as described in the previous paragraphs, one can see that, on the one hand, their interaction may increase the probability of liquefaction occurrence, though, on the other hand, the probability of the multi-hazard interaction itself decreases proportionally to the product of the single hazard probabilities. Needless to say, different multi-hazard interaction scenarios have different occurrence probabilities and all of them contribute to the total risk. With the use of the equation (3)~~Applying Eq. 3, we obtain for the 200-year flood scenario the ~~damage probability value about~~liquefaction failure probability of 1~~.2~~*10^{-6}~~^{5}~~ per year, for the 500-year flood –

about 4.~~9~~1*10^{-}~~^{6}~~^{7} per year and for the 1000-year flood – about 2.1~~5~~*10^{-}~~^{6}~~^{7} per year. All these ~~values~~ return period scenarios contribute to the total risk value~~ and properly the multi-hazard damage probability for the dike should be integrated over the entire range of flood return periods (probabilities)~~. Consequently, it is ~~reasonable to think that consideration of the whole range of~~expected that the multi-hazard interaction scenarios~~ (covering the complete hazard curves) may~~ essentially increase the total risk level in comparison with the estimated single hazard risk level though the combined probabilities of earthquake and floods are very small.~~.~~

~~Therefore, as could be expected, in the event of the probable temporal coincidence of flooding and strong ground shaking, the total risk of the dike damage due to liquefaction is increasing. One should bear in mind, however, that, as indicated above, the obtained quantitative risk estimates are calculated solely for the purpose of illustration of the approach and not intended for practical applications.~~

Nevertheless, dike failures due to liquefaction in case of a multi-hazard impact bears the potential of surprise and malign consequences, which should be considered in a comprehensive risk assessment (Merz et al., 2015). In particular, under hydraulic load below the (hydraulic) design level (< 200-year return period at the German Rhine reach), dikes might be considered predominantly safe in a single-type hazard analysis, whereas the occurrence of liquefaction would dramatically change flood inundation patterns and loss distribution. Though not necessarily extreme, but still significantly strong floods and 'unexpected' dike failures in combination may still harmfully affect the densely populated areas with high asset concentration such as floodplains along the Rhine. Hence, a quantitative multi-risk analysis is advocated in earthquake and flood prone areas considering the effect of dike liquefaction despite a relatively small probability of the joint occurrence of both perils. ~~At the same time, based on the obtained results, we may conclude that the level of the failure risk for the dikes due to earthquake-induced liquefaction cannot be categorized as negligible for decision making. As the area under study is densely populated and characterized by high concentration of valuable exposure, one should bear in mind that probable failure of the flood defence system may be fraught with far-reaching disaster consequences. This should be the scope of future research.~~

~~More detailed and comprehensive quantitative damage risk estimates for the flood protection system and potential consequences for the entire area under study will be obtained in the framework of the above-mentioned flood scenarios for different return periods, which will combine the seismic and flood hazard assessments with the newly developed multi-hazard fragility functions for liquefaction as well as with those related to other probable dike breach mechanisms.~~

Conclusions

A methodology for multi-hazard fragility and ~~damage risk (~~failure probability~~)~~ analyses of fluvial ~~earthen~~ dikes in earthquake and flood prone areas ~~and a preliminary application~~ is presented. The system of flood protection dikes along the Rhine River in the area around Cologne is analysed, considering their possible ~~damage~~ failures due to liquefaction induced by seismic ground shaking in combination with flooding. ~~As a first approximation, w~~We conservatively assume ~~that~~ the initiation of liquefaction at any point throughout the dike body ~~corresponds~~ leads to the dike failure ~~(loss of function) of the flood protection dike~~.

The ~~damage potential~~failure probability ~~of the earthen structures~~ is presented as a three-dimensional fragility surface ~~showing the failure probability~~ as a function of both earthquake ground shaking (PGA) and flood water level (impoundment of the dike). Quantitative fragility analysis shows that a rise in flood water level ~~can~~ reduces the liquefaction triggering PGA threshold due to high moisture content in the dike core.~~, leading, therefore, to an increase in fragility and, correspondingly, the failure probability of the dikes. Therefore, this effect should be taken into consideration when analysing the performance of the flood protection earthen dikes in multi-hazard (earthquake and flood) prone areas.~~

~~The combined consideration of the obtained fragility estimates and the seismic hazard calculated in the dike locations along the Rhine River allows us to conclude that in the area around Cologne, there is a risk of damage to the earthen dikes due to earthquake-triggered liquefaction even without impoundment of the dikes.~~ When considering earthquake and flood hazard and the developed fragility curves, the non-zero liquefaction probability for an exemplary dike location becomes evident. Though the probability of joint occurrence of both perils is rather low, we argue that such incidents bear a high potential of surprise with substantial negative consequences. The latter can be, however, avoided by multi-risk considerations and awareness at civil protection authorities and within the public.~~Furthermore, in the event of the probable temporal coincidence of flooding and strong earthquakes, the risk of damage to the dikes and therefore the consequential impacts can increase.~~

~~Based on the results obtained for the study area, we conclude that the level of the damage risk for the flood protection dikes due to earthquake-induced liquefaction cannot be categorized as negligible and therefore should be taken into account in the risk calculations and disaster management policy in the region.~~

The ~~presented results~~developed fragility curves for liquefaction will be used for ~~generating a series of flood scenarios with different return periods and~~ comprehensive ~~quantitative~~ multi-risk assessment study ~~in the area around Cologne~~along the Rhine River in a subsequent work.~~,~~ This will tak~~ing~~e into ~~consideration the probable~~ the interaction of ~~the existing~~ earthquake and flood hazards into account, dynamic inundation effects and damage modelling.~~.~~

Acknowledgements

The presented research~~ leading to these results~~ has received funding from the European Community’s Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 265138.

References

Allsop, W., Kortenhaus, A., Morris, M., Buijs, F., Hassan, R., Young, M., Doorn, N., van der Meer, J., van Gelder, P., Dyer, M., Redaelli, M., Utily, S., Visser, P., Bettess, R., Lesniewska, D., and ter Horst, W.: Failure mechanisms for flood defence structures, FLOODSite Project Report T04 06 01, FLOODSite Consortium, 2007. 203 p.

Apel, H., Thieken, A., Merz, B., and Blöschl, G. (2004): Flood risk assessment and associated uncertainty, Nat. Hazards Earth Syst. Sci., 4, 295-308.

Armbruster-Veneti, H. (1999): Über das Versagen von Erddämmen, Wasserwirtschaft, 89, 504–511.

Athanasopoulos-Zekkos, A. and Seed R. B. (2013): Seismic Slope Stability of Earthen Levees. Proc. of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013, 1423-1426.

Briaud, J., Chen, H., Govindasamy, A., and Storesund, R. (2008): Levee Erosion by Overtopping in New Orleans during the Katrina Hurricane. J. Geotech. Geoenviron. Eng. 134, SPECIAL ISSUE: Performance of Geo-Systems during Hurricane Katrina, 618–632.

Crowley, H., Monelli, D., Pagani, M., Silva, V., and Weatherill, G.: OpenQuake User’s Manual, www.globalquakemodel.org (last access: 30 May 2012), 2011a.

Crowley, H., Monelli, D., Pagani, M., Silva, V., and Weatherill, G.: OpenQuake Book, www.globalquakemodel.org (last access: 30 May 2012), 2011b.

DIN 4149, 2005. Bauten in deutschen Erdbebengebieten - Lastannahmen, Bemessung und Ausführung üblicher Hochbauten.

Fink, A., Ulbrich, U. and Engel, H. (1996): Aspects of the January 1995 flood in Germany, Weather, 51, 34-39.

Fleming, K., Parolai, S., Garcia-Aristizabal, A., Tyagunov, S., Vorogushyn, S., Kreibich, H., Mahlke, H. (2016): Harmonizing and comparing single-type natural hazard risk estimations. - Annals of Geophysics, 59, 2.

Foster, M., Fell, R. and Spannagle, M. (2000): The statistics of embankment dam failures and accidents, Canadian Geotechnical Journal, Vol. 37, No. 5, National Research Council Canada, Ottawa, 1000–1024, ISSN 0008-3674.

Garcia-Aristizabal, A. and Marzocchi, W. (2013): Deliverable: D3.3: Scenarios of cascade events, EU-FP7 Project MATRIX (New methodologies for multi-hazard and multi-risk assessment methods for Europe), URL: http://matrix.gpi.kit.edu/downloads/MATRIX-D3.03.pdf.

Grünthal, G., Mayer-Rosa, D., and Lenhardt, W. A. (1998): Abschätzung der Erdbebengefährdung für die D-A-CH-Staaten – Deutschland, Osterreich, Schweiz. Bautechnik, 10, 753–767, 1998.

Grünthal, G., Thieken, A.H., Schwarz, J., Radtke, K.S., Smolka, A. and Merz, B. (2006): Comparative risk assessments for the city of Cologne – Storms, Floods, Earthquakes, Natural Hazards, 38, 21-44. doi:10.1007/s11069-005-8598-0

Grünthal, G., Wahlström, R., and Stromeyer, D. (2009): The unified catalogue of earthquakes in central, northern, and northwestern Europe (CENEC) – updated and expanded to the last millennium, J. Seismol, 13, 517–541, 2009.

Grünthal, G., Arvidsson, R., and Bosse, Ch. (2010): Earthquake Model for the European-Mediterranean Region for the Purpose of GEM1, Scientific Technical Report SRT10/04, GFZ, 36, 2010.

HAZUS-MH (2003): Multi-hazard loss estimation methodology, HAZUS-MH MR4 Technical Manual, Federal Emergency Management Agency, Washington DC, 2003.

Hofherr, T. and Kunz, M. (2010): Extreme wind climatology of winter storms in Germany. Climate Research, 41, 105-123.

Huang, W. C., Weng, M. C., Chen, R. K. (2014): Levee failure mechanisms during the extreme rainfall event: a case study in Southern Taiwan, Natural Hazards, January 2014, Volume 70, Issue 2, 1287-1307. doi:10.1007/s11069-013-0874-9

Idriss, I. M. and Boulanger, R. W. (2008): Soil Liquefaction During Earthquakes. EERI MNO-12, 2008.

KATARISK (2003): Disasters and Emergencies in Switzerland. Risk assessment from a civil protection perspective. Federal Office for Civil Protection (Switzerland), 2003, 82 p.

Kishida, T., Boulanger, R. W., Abrahamson, N. A., Driller, M. D., and Wehling, T. M., (2009): Seismic response of levees in the Sacramento-San Joaquin Delta, Earthquake Spectra, 25 (3), 557–582.

Kramer, S. L. (1996): Geotechnical Earthquake Engineering, Prentice Hall, New Jersey, 1996. 653 p.

Kramer, S. and Mayfield, R. (2007): Return Period of Soil Liquefaction. J. Geotech. Geoenviron. Eng., 133(7), 802–813.

Krzhizhanovskaya, V.V. Shirshov, G.S. Melnikova, N.B. Belleman, R.G. Rusadi, F.I. Broekhuijsen, B.J. Gouldby, B.P. Lhomme, J. Balis, B. Bubak M. (2011): Flood early warning system: design, implementation and computational modules. Procedia Computer Science, 4, 106-115, DOI: 10.1016/j.procs.2011.04.012

Marcuson, W.F.III, Hynes, M.E. and Franklin, A.G. (2007): Seismic Design and Analysis of Embankment Dams: The State of Practice. Proc. of the 4th Civil Engineering Conference in the Asian Region. June 25-28, 2007, Taipei.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M.L., Di Ruocco, A. (2012): Basic principles of multi-risk assessment: a case study in Italy. Nat Hazards. doi:10.1007/s11069-012-0092-x

Merz, B., Vorogushyn, S., Lall, U., Viglione, A., Blöschl, G. (2015): Charting unknown waters - On the role of surprise in flood risk assessment and management. - Water Resources Research, 51, 8, 6399-6416. doi: 10.1002/2015WR017464

Mignan, A., Wiemer, S., and Giardini, D. (2014): The quantification of low-probability-high-consequences events: part I. A generic multi-risk approach, Nat. Hazards, doi:10.1007/s11069-014-1178-4

Nagy, L. (2012): Statistical evaluation of historical dike failure mechanism. Riscuri ul Catastrofe, XI, 11 (2), 2012, 7-20.

Newmark, N. M. (1965): Effects of Earthquakes on Dams and Embankments, Geotechnique, 15 (2), 139-160.

Ozkan (1998): A review of consideration on seismic safety of embankments and earth and rock-fill dams. Soil Dynamics and Earthquake Engineering, 17, 439-458.

Parolai, S., Grünthal, G., Wahlström, R. (2007): Site-specific response spectra from the combination of microzonation with probabilistic seismic hazard assessment — an example for the Cologne (Germany) area. Soil Dynamics and Earthquake Engineering, 27, 1, 49-59.

Peck, R. B., Hanson, W. E., and Thornburn, T. H. (1974): Foundation Engineering. John Wiley & Sons, New York.

Quigley, M.C., Bastin S., Bradley B.A. (2013): Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence. Geology, 41 (2013), 419–422.

Rosidi D. (2007): Seismic Risk Assessment of Levees. Civil Engineering Dimension, Vol.9, No.2; 57-63.

Sasaki, Y., Kano, S., and Matsuo, O. (2004): Research and Practices on Remedial Measures for River Dikes against Soil Liquefaction. Journal of Japan Association for Earthquake Engineering, Vol.4, No.3 (Special Issue), 2004, 312-335.

Santucci de Magistries, F., Lanzano, G., Forte, G., Fabbrocino, G. (2013): A database for PGA threshold in liquefaction occurrence. Soil Dynamics and Earthquake Engineering, Volume 54, November 2013, 17-19.

Schweckendiek, T., Vrouwenvelder, A., Calle, E.O.F. (2014): Updating piping reliability with field performance observations. Structural Safety, 47, 13-23.

Seed, H. B., and Idriss, I. M. (1971): Simplified procedure for evaluating soil liquefaction potential. J. Geotech. Engrg. Div., ASCE, 97(9), 1249–1273.

Sellmeijer, J. B., (1989): On the mechanism of piping under impervious structures. Ph.D. thesis, Delft University of Technology, The Netherlands.

Selva, J. (2013): Long-term multi-risk assessment: statistical treatment of interaction among risks. Natural Hazards, 67(2),701-722. doi:10.1007/s11069-013-0599-9

Singh, R. and Roy, D. (2009): Estimation of Earthquake-Induced Crest Settlements of Embankments. American J. of Engineering and Applied Sciences 2 (3): 515-525.

Tyagunov, S., Grünthal, G., Wahlström, R., Stempniewski, L., Zschau, J. (2006a): Seismic risk mapping for Germany. Natural Hazards and Earth System Sciences (NHESS), 6, 4, 573-586.

Tyagunov, S., Hollnack, D., Wenzel, F. (2006b): Engineering-Seismological Analysis of Site Effects in the Area of Cologne. Natural Hazards, 38, 2006, 199-214.

Van Baars, S., and Van Kempen, I. M. (2009): The Causes and Mechanisms of Historical Dike Failures in the Netherlands. Official Publication of the European Water Association (EWA). ISSN1994-8549

Van Duinen (2013): Data of Spui dike at Oud-Beijerland, The Netherlands, personal communication, 18.01.2013.

Vorogushyn, S., Merz, B., Apel, H. (2009): Development of dike fragility curves for piping and micro-instability breach mechanisms. Natural Hazards and Earth System Sciences 9, 1383–1401.

Vorogushyn, S., Merz, B., Lindenschmidt, K.-E., and Apel H. (2010): A new methodology for flood hazard assessment considering dike breaches, Water Resources Research, 46 (8), 2010, doi:10.1029/2009WR008475

Vrouwenvelder, A. C. W. M., Wubs, A. J. (1985): Een probabilistisch dijkontwerp (A probabilistic dyke design). Technical Report B-85-64/64.3.0873, TNO-IBBC, Delft, The Netherlands, (in Dutch).

Wang, M., Chen, G., and Iai, S. (2013): Seismic performances of dyke on liquefiable soils, Journal of Rock Mechanics and Geotechnical Engineering 01/2013; 5 (4), 294–305.

Wolff, T. F. (2008): Reliability of levee systems. In Phoon, K. K., editor, Reliability-based design in Geotechnical Engineering, chapter 12, pages 449–496. Taylor & Francis, London and New York.

Youd, T. L. and Perkins, D. M. (1978): Mapping liquefaction-induced ground failure potential, J. Geotech. Eng. Division, 104, 443–446.

Youd, T., Idriss, I., Andrus, R., Arango, I., Castro, G., Christian, J., Dobry, R., Finn, W., Harder, L., Jr., Hynes, M., Ishihara, K., Koester, J., Liao, S., Marcuson, W., III, Martin, G., Mitchell, J., Moriwaki, Y., Power, M., Robertson, P., Seed, R., and Stokoe, K., II (2001): Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils. J. Geotech. Geoenviron. Eng., 127 (10), 817–833.