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Evaluation of seismic resilience of levees through the development of fragility curves

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Abstract

As natural or artificial earthen structures that provides flood protection adjacent to rivers or coastal areas, levees should be verified for several relevant design situations. For this verification, Eurocode 7 adopts semi-probabilistic approach, which utilizes statistical methods to select characteristic values of geotechnical parameters, thus neglecting spatial correlation between the same parameter at different sampling points, and cross-correlation between different parameters at the same sampling point. The degree of uncertainty involved in calculation of levee response to seismic loads is especially high and implementation of probabilistic approach for evaluation of seismic resilience of levees will yield more reliable insight into the behaviour of levees both during low and high waters. This paper contributes to the efforts of levee seismic vulnerability evaluations, through development of fragility curves as functions that describe the conditional probability of levee stability failure over the full range of seismic and water loads to which the levee might be exposed.

Key words: slope stability, Newmark, seismic loading, fragility curves, flood protection

1 Introduction

Levees are structures that run parallel to rivers and serve the purpose of flood protection, and as such are prone to more uncertainties than other earthen structures such as dams [1]. The sources of those uncertainties refer to complex and highly variable foundation soil conditions alongside both riverbanks, variable cross section solutions with variable soil parameters due to different borrow sites available during construction, variable geometry due to different expected loading conditions, and loading intensity. To mitigate this high variability, for analyses purposes, the levees are divided into smaller reaches with sufficiently similar geometry and subsurface conditions which can be represented by a single two-dimensional model. When those sources of uncertainties are thus minimised, the uncertainties are reduced to inherent soil variability of the foundation soil and levee body, and loading conditions.

When considering different loading conditions which can occur on such structures (rainfall, high water level, seismic ground accelerations, etc.), the deterioration mechanisms which induce failure (external erosion, internal erosion, stability [2]) and which are directly or indirectly triggered by specific load types, must be considered. Extensive studies have been conducted with various approaches regarding slope stability with respect to rainfall [3,4], high water levels [5,6], and peak ground accelerations [7,8], as well as combinations of various events [9]. Since levees are designed for very rare events with low probability of occurrence [1], it is debatable whether certain combinations such as seismic loading together with high water events should even be considered. Their joint occurrence has been discussed by [10]. To check the effect of a 100-year water event occurring at the same time as a seismic event compared to only the seismic event, a fragility curve are constructed within this study, for the joint event occurrence. Since the focus of this study is to investigate the response of a levee with an arbitrary cross section to a seismic event, only sliding failure mechanisms are considered. For that purpose, Eurocode 1998-5 defines three acceptable analysis types to compute seismic response, namely numerical dynamic analyses by finite element of finite different methods, rigid block method, and pseudo-static methods [11]. Each method has been extensively used in practice for various natural and artificial slopes [12–15], each with their own benefits [16]. As Eurocode 1998-5 defines limit state for slopes as unacceptably large permanent displacements that are "significant for both the structural and functional effect of the structure" [11], the Newmark pseudo-dynamic analysis [17] is used in this study to construct fragility curves which can be later used in risk assessment and categorization of levees [18,19], based on calculated probabilities of failure. Few attempts have been made to estimate the displacement directly from seismic parameters [20–22] and also probability of failure directly from on results of Newmark displacement analyses and other seismic parameters [23] based on historic earthquake data and numerical simulations.

2 Methodology

To assess the stability and reliability of river levees when exposed to seismic loading, the Newmark rigid sliding block method is employed, which has a clear benefit over the pseudo-static analysis in that it considers the whole seismic record instead of only the peak accelerations, while being relatively simple compared to full numerical dynamic analyses. The first step in conducting probabilistic analyses is the selection of random variables. For this study, one random variable (the variability of the levee body shear strength) is considered. As the levee body material is constructed from a fine-grained soil, the strength is modelled as undrained with the same undrained shear strength as in the static case [2,11]. The variability of the undrained shear strength has been selected according to recommendations for slope stability with a coefficient of variation (CoV) of 40% [1], which is accordant to the mean variability of undrained shear strength reported in literature [24], with a normal probability distribution. The berm and crown materials', as well as foundation soil's parameters, are modelled with deterministic values of shear strength parameters. The soil parameters are shown in Table 1.

Using limit equilibrium methods [25–27] incorporated in Slide2 v9.010, Rocscience Inc., circular sliding surfaces are found for 200-5000 samples of the undrained shear strength obtained through Latin Hypercube sampling. Iteratively, the critical pseudo-static coefficients are found for each slip surface by bringing them to failure (Fs=1), which served as one of the input parameters for the Newmark sliding block analyses. The other input required for Newmark analyses is a seismic record. For this purpose, the accelerograms showing ground accelerations in three orthogonal directions of the recent earthquake that occurred in Zagreb region in March 2020 is selected. As the levees are linear structures that curve along rivers, and their dominant failure mode is perpendicular to the longitudinal direction, the larger of the two perpendicular horizontal accelerations are used (North-South direction, $a_{g,max}$ of 0.22g), regardless of the real orientation of the selected cross section. The vertical accelerations are not considered with this analysis method, but even when conventional pseudo-static limit equilibrium analyses are conducted the vertical coefficient is often ignored due to its lower impact on the factor of safety [28]. The selected accelerogram is then divided by the gravitational acceleration to obtain a plot of 'coefficient of horizontal acceleration' vs. 'time'. Now each time the coefficient of seismic acceleration surpasses the critical coefficients, the diagram is integrated twice over the range on which the coefficient is exceeded to calculate the total permanent displacements, as shown in Fig. 1. From the resulting displacement for each sampled strength value, a response surface methodology [29] is implemented to find the geometric reliability index, as defined by the Hasofer-Lind method [30] also known as the First-Order Reliability Method (FORM), which is the most efficient method for estimating probability of failure (p_f) for problems involving one design point [24]. In this case, since there is only one random variable considered, the RSM will generate a 1D response curve, obtained by fitting the results with the Gaussian function which yielded best fitting with coefficient of regression over 0.99 for all calculated cases. Then, the reliability index (β) is the shortest distance from the mean of the variable's probability distribution to the design point, defined by Eq. (1) being equated to zero, and is equal to the number of standard deviations that the undrained shear strength required to reach critical displacement ($c_{u,c}$) is from the mean, as shown in Eq. (2). In Eq. (1), *g(x)* is the performance function, *d (cm)* is the permanent slope displacement, and d_c *(cm)* is the critical (allowable) slope displacement.

$$g(x) = d - d_c \tag{1}$$

$$\beta = \left(c_{u,c} - \mu_{c_u}\right) / \sigma_{c_u} \tag{2}$$

Table 1. Soil parameters

Material	c' [kPa]	ϕ [°]	c_u [kPa]		γ [kN/m³]
			μ	CoV	
Levee body	-	-	25	40 %	18
Crown and berm	1	30	-	-	20
Foundation soil	0	36	-	-	19
Distribution	*constant*	*constant*	*normal*		*constant*

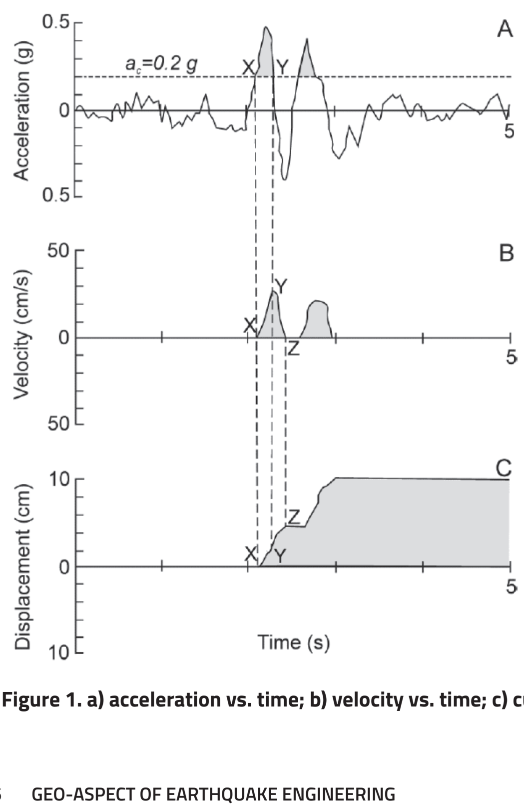

Figure 1. a) acceleration vs. time; b) velocity vs. time; c) cumulative displacement vs. time [31]

To construct the fragility curves, the load (the seismic record) is scaled repeatedly [7] with scale factors (SF) from 2 to 4, and the whole process then conducted for each scale factor. The same analysis is made for two design cases, one where with completely dry levee and foundation soil (DC1), and the other with 100-year high water event (DC2).

3 Results and discussion

For the analysis, the cross section of a levee situated on the southern side of Drava river between rivers Bednja and Plitvica is chosen as a representative homogeneous river levee constructed from cohesive material. A numerical model cross section is shown in Fig.2 along with resulting critical slip surfaces for DC1/SF3. Since the method used for analysis is the Newmark method which gives permanent displacements instead of factors of safety, the probability of failure defined previously actually refers to probability of exceedance of any defined limit state. While some recommendations regarding allowable displacements of dams and natural slopes exist [16, 32–34], there are no definitive recommendations regarding allowable displacements for any type of small embankments such as levees or dikes. Bray and Travasarou [35] in their study proposed a method of selecting the appropriate pseudo-static coefficients for pseudo-static analyses based on allowable displacements, which were taken as 5, 15 and 30 cm as relevant values to demonstrate the chosen displacement on the coefficients. Such values, from 5 - 15 cm, are also reported in other studies [23, 36–40]. Thus, this order of magnitude of allowable displacements is also selected for this study, and two fragility curves are constructed for each seismic record, one for the limit state of 5 cm (LS5) and the other for 15 cm (LS15) displacement. Due to some very low valued samples of undrained shear strength which resulted with extremely high displacements, displacement values of only up to around 40 cm are taken in consideration to achieve better curve fitting around the design points. For analyses calculated with 5000 samples, a probability distribution is fitted to the resulting displacement data to investigate the underlying probability distribution, which is shown in Fig. 3 to be log-normal. As the displacements seem to be log-normally distributed, the performance function defined by Eq. (1) is also log-normally distributed. However, since the logarithm of the performance function is normally distributed, the inverse of the normal cumulative function is used to calculate the conditional probability of failure, as also suggested by [41].

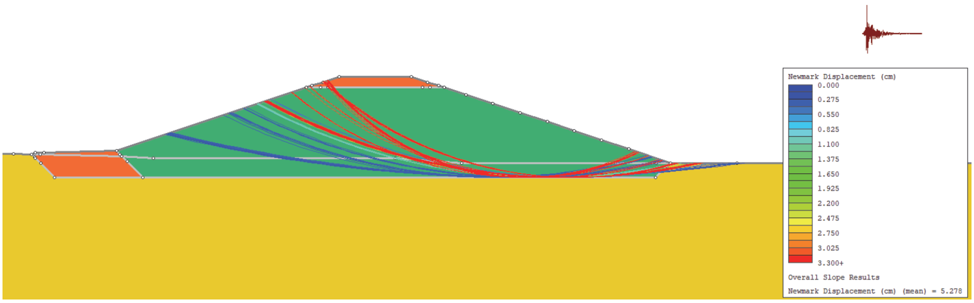

Figure 2. Surfaces with corresponding permanent displacements – DC1/SF3

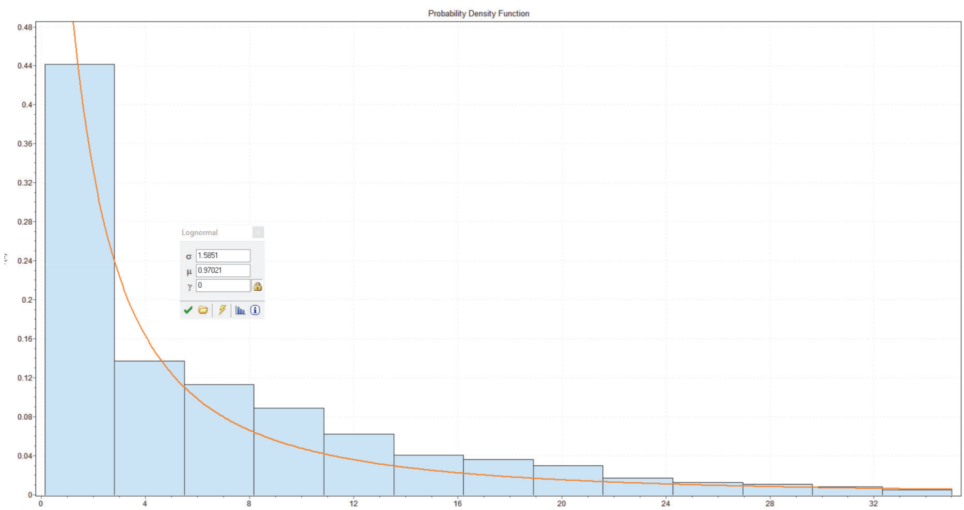

Figure 3. Probabilistic distribution of displacements

Fig. 4 shows the resulting fragility curves for both design cases (DC) and limit states (LS), where the conditional probability of exceedance is shown on the vertical axis while the scale factor on the horizontal axis. The fragility curves follow the expected increasing trend with increasing scale factor, and decreasing of exceedance of conditional probability with increase of limit state value. It is however interesting to note that for lower scale factors, the 100-year water level does not influence the displacements as much as for higher scale factors. Another thing to note is that the fragility curve for DC2/LS5 goes only up to SF3. The reason for this is that after reaching a critical undrained shear strength value, the failure mode changes from slope failure to either movement of the whole levee as a block, or rotational failure only though the foundation soil, and no longer depends on the levee body material strength. Moreover, as the foundation soil is modelled deterministically in this study, the minimum displacement after reaching the critical levee body strength becomes constant, and if this value is higher than the limit state value, a reliability index cannot be calculated, but the conditional probability of exceedance surely is 1 even though it refers to a different failure mode. By carefully adjusting the soil parameters, an optimal levee design could be achieved for new levees, where all the components [2] that participate in the various failure modes have the same conditional probability of exceeding some unwanted behaviour.

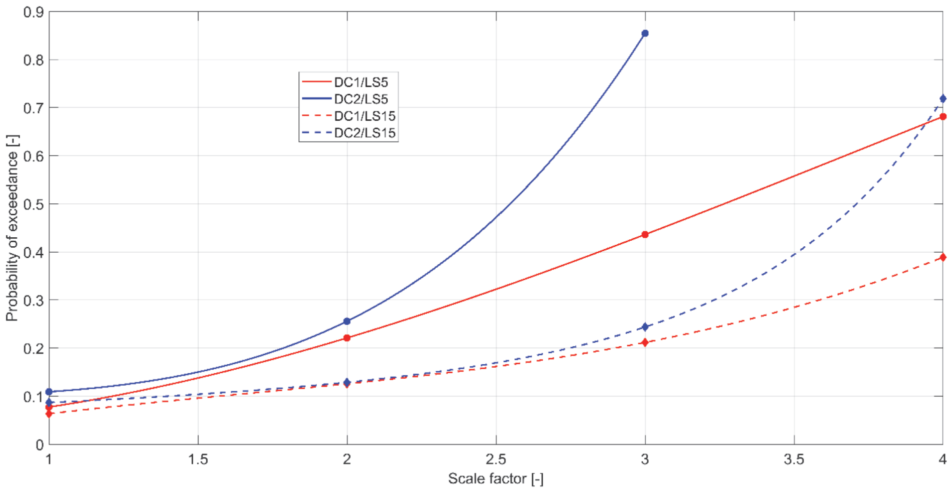

Figure 4. Fragility curves for defined design cases and limit states.

Even though calculations in this study are conducted using the static shear strength of soil, some soils may exhibit strength reduction due to cyclic loading and excessive displacements. If strength reduction due to cyclic loading is of concern, the undrained shear strength can be reduced by 20%, as recommended by [2]. However, if displacements required for reaching residual strength are known, then after affirming which slopes would undergo such displacement, which do not automatically indicate failure, additional stability analyses can be conducted using residual parameters to assess their stability after the earthquake [36].

4 Conclusion

The Newmark rigid sliding block method is an efficient and reliable method for assessment of the behaviour of river levees under seismic loading conditions. Coupled with efficient probabilistic methods such as the FORM, quick assessment of seismic resilience can be made for earthen flood protection structures such as river levees, through the development of fragility curves. By applying historical seismic records to the demonstrated methodology, sets of fragility curves can be constructed to obtain conditional probabilities of exceedance of unwanted behaviour for expected earthquakes. When data on probabilities of exceedance of defined seismic loads is available, as well as for other loading events such as floods, total probabilities of exceedance can be calculated, which can be further utilized for risk assessment [42]. While discussing probabilities, the sources of uncertainties should be emphasized, which in this case referred only to the levee body with relatively high variability. As most components of levees are constructed from earthen material, it is to be expected that soil variability, which is inherently big, has great impact on the reliability of the whole structure. Thus, a weight should be put on site investigation whose impact on risk has been identified to be among the most significant [43]. Moreover, with reliable data about existing foundation soil and available materials for construction, the levee components (including foundation soil) which affect stability can be optimized in terms of material choice, compaction, geometry, foundation soil improvement, etc., which would result in an overall optimized levee cross section.

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