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Probabilistic Methodology for Seismic Deformation Assessment of Slopes in Regions with Low to Moderate Seismicity

Zeljko ZUGIC
Geotechnics department, The Highway Institute, Serbia

Abstract.. Earthquake-induced sliding deformations are commonly used to assess the seismic performance of slopes. These deformations are the cumulative, downslope movement of a sliding mass occurred due to earthquake shaking, and represent the valuable indicator of risk and possible damage above slope. Current probabilistic procedures that use seismic slope displacements to evaluate the potential for slope instability typically are developed on basis of significant seismic data. The most common procedures are based on a deterministic approach or a pseudo-probabilistic approach, in which the variability in the expected ground motion, soil properties, water level, geometry and predicted displacement are either ignored or not treated rigorously. Thus, beside all existing methods, the concept of actual hazard (i.e., the annual probability of exceedance) associated with the computed displacement has so far not been developed in cases of low to moderate seismic excitation when in most cases except the design code there is no valuable seismic data.

The paper defines methodology for quantifying the risk for earthquake-induced landslides in regions with low to moderate seismicity. It can be applied either for slopes the high seismicity regions for assessing the performance at lower levels of seismic excitation. The basic approach involves a probabilistic framework for computing the annual rate of exceedance of different levels of sliding displacement for a slope such that a sliding displacement hazard curve can be developed

The main simplification in the proposed approach is that the occurrence of peak slope deformation is a Poisson’s process. The procedure is based on logic tree analysis, commercial software and routines programmed by the authors for generating sets of input files, and forming slope performance curve.

The framework incorporates the uncertainties in the prediction of earthquake ground shaking, and in the assessment of soil properties, water level and slope geometry. The displacement hazard assessment is applicable both Newmark rigid block method and fully coupled analysis.

The procedure is extensively validated by performing a series of simulations using several real cases and theoretical examples. The advantages and limitations of proposed methodology were shown.

Application of the probabilistic procedure one is able to quantify the influence of certain factor on potential sliding displacement. Results confirmed the importance of treating the soil data variation. Another benefit is comparison and valorization of results obtained by deferent approaches (decoupled and coupled) for various slope cases. The advantages of using advanced methods (continuum approach) are demonstrated.

Keywords. Seismic slope stability, probabilistic approach, displacement hazard curve.

1. Introduction

There are two different types of complexity while trying to assess the seismic slope deformation in a probabilistic manner. One is related to the slope deformation technique and the other to the level of advancement of the probabilistic computation. Theoretically, it is possible to implement any of the probabilistic methods in any deformation assessment technique. The combining of the most advanced techniques for both stages will make the analysis extremely time consuming. The main idea for this research was to develop a procedure that will be complex enough to take into account the uncertainties associated with the main input parameters and simple enough to provide results within a reasonable time, without complex probabilistic computation, being applicable in the case of having an average amount and quality of seismic and geological data.

2. Proposed Methodology

The main simplification of the new simplified procedure is that the occurrence of peak slope permanent displacements in time can be treated as a (generalized) Poisson's process. It is a widely accepted assumption that strong (characteristic) earthquakes as well as peak ground motions from these earthquakes occur as a generalized Poisson's process. The slope seismic deformation in this approach is treated as a "peak ground motion" for a certain earthquake (Figure 1). Every occurrence of peak slope displacement in time is a product of specific combination of seismic, soil and water level conditions. The idea for this approximation came from Kim and Sitar (2013) who stated that if earthquake events are assumed to be Poisson process, then the failure events caused by earthquakes also become Poisson, thus simplifying the computation.

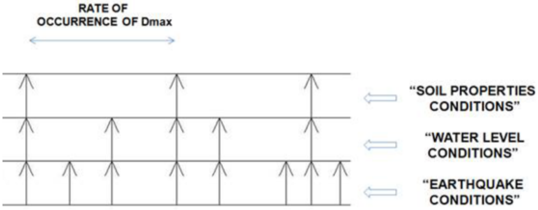

Figure 1. Logic tree generation

The goal is to perform cumulative frequency (frequency of non-exceedance) analysis - analysis of the frequency of occurrence of values of a phenomenon which are less than the referent value, where the phenomenon may be time or space dependent. The observed phenomenon is seismic deformation of slope therefore, it is time dependent. In order to obtain the performance curve, a lot of simulations should be done and the performance curve will be defined by interpolation between the calculated simulations. Firstly, the deterministic analysis should be done with median values of input parameters. For time dependent events, 50% of exceedance during the exposure time should be used and also mean values of space dependent variables. All the branches of the logic tree are generated around this median event where for the hazard curve is later centered on this point. The work flow of the proposed methodology is presented in Figure 2. Numerous of simulations need to be performed in order to mix the different ground motions, soil properties, water level and geometry scenarios The general idea and main difference in comparison with earlier probabilistic studies are performing the limited number of "wisely" selected simulations. From this reason, the logic tree approach has been used instead of Monte-Carlo simulations. Therefore, beside the reliable input data and computation software the engineering judgment is necessary. Five steps are proposed:

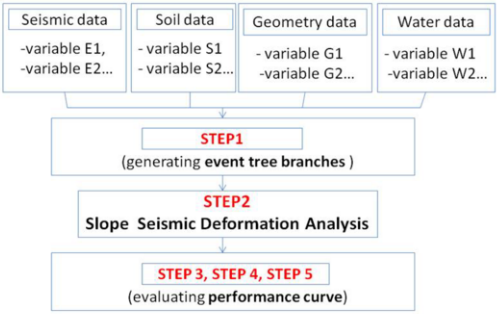

Figure 2. Proposed methodology

Step 1. *Defining the possible scenarios, construction of an logic tree, assigning branch's weights.* For generating sets of inputs for numerical simulations, a logic tree approach has been used. In a logic tree, often a normal distribution is assumed for each node, but if there are reliable data some other probability distribution can be employed. For this application, the three point approximation method is proposed by Keefer and Bodily (1983) as well as method of Saygili (2008) that include five branches.

Step 2. *Calculation of seismic displacement for every branch of the logic tree.* Slope deformation analysis can be performed by using any of the available methods rigid block (Newmark 1965), or the continuum mechanics approach. Important property of this procedure fully defined in (Zugic et al. 2015) should be mentioned here in case of calculating the sliding displacement for same hazard level for different soil property branches. It starts running for the upper to lower values of soil strength. Therefore, in case of obtaining displacement less than "zero" displacement, (will be explained in step 4.) the procedure start analyses for another seismic event branch, and consider all other soil branches to be "zero". It improves analysis to run faster especially in cases when there are many "zero" events.

Step 3. *Assigning weight to calculated displacements, representing each calculated* *displacement against its total weight, obtaining the cumulative fractal curve.* The procedure for obtaining fractile hazard curves involves a relationship between annual probability and cumulative weights at each sliding displacement level: as shown in the left part of Figure 5, to develop a cumulative weight curve, the weights of the displacements are summed from lower D to higher D for a given value of D. The probability for each D value is derived from the cumulative weight curve. This procedure corresponds with findings of Abramson and Bommer (2005) that argued that the uncertainty is better represented by fractile hazard curves.

Step 4. *Treating the small displacement events.* It is expected that some of the branches will give zero or very small displacement. As outlined in Travasarou and Bray (2003), permanent displacements can be modeled as a mixed random variable, which has a certain probability mass at zero displacement and a probability density for finite displacement values.

Step 5. *Transforming the fractile axis into rate of occurrence - obtaining the sliding displacement hazard curve.* The procedure for getting probability of exceedance for certain D from the fractile curve is described in literature Zugic et al. (2014) It is based on the above described assumption about the occurrence of a peak slope permanent displacement in time.

3. Application and Results

3.1. Observed Case Study and Geotechnical Models

The slope that was observed is placed at huge complex landslide Umka-Duboko in Belgrade, Sebia (Jelisavac et al. 2006; Jelisavac and Zugic 2014). All the input data is presented at table 1. where five different classes of curves has been generated. Two different numerical models has been observed (Figure 3 and Figure 4) in order to compare different seismic deformation assessment methods.

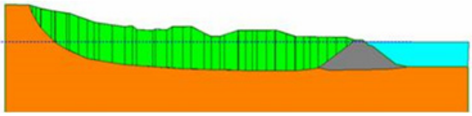

Figure 3. Slope/W rigid block model

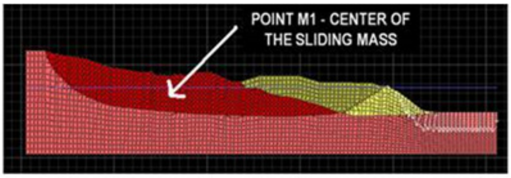

Figure 4. FLAC continuum approach model

3.2. Obtained Results

Figure 6 and figure 7 represent the slope performance assessment in cases of real (0.1g in 475 years) and hypothetical sites (0.18g in 475 years). The impact of considering uncertainties of soil properties (in this case the residual shearing strength of sliding surface) are considered for both cases. One can see that, at a lower level of displacement (Figure 6), the soil properties have a bigger influence on the annual rate of occurrence, while at the bigger level this influence is almost negligible, which is consistent with results presented by Kim and Sitar (2013). In Figure 6 one can notice (on the interpolated curve) the bigger probability at a lower level of displacement hazard in the curve where soil uncertainty is neglected. This is rather a product of interpolation and big concentration of zero events in cases of low seismicity. In cases of higher seismicity (Figure 7) this phenomenon does not occur. This outcome stresses the importance of treating the soil uncertainties in cases of lower seismic excitation and agrees with findings other authors (Kim and Sitar 2013; Ratje and Bray 1999; Rathje and Saygili 2008; Saygili 2008) that stated that neglecting the soil uncertainties may lead to unconservative results. Figure 8 presents influence of using a different number of branches in the logic tree analysis on the obtained sliding displacement curve. For preliminary analysis, three branch analyses are sufficient to ensure an insight into the slope seismic deformation but it is quite unconservative, especially at higher levels of sliding displacement hazard. The influence of a variation of Gmax (initial shear modulus of sliding mass) on slope displacement calculated by decoupled approach is presented in Figure 9.

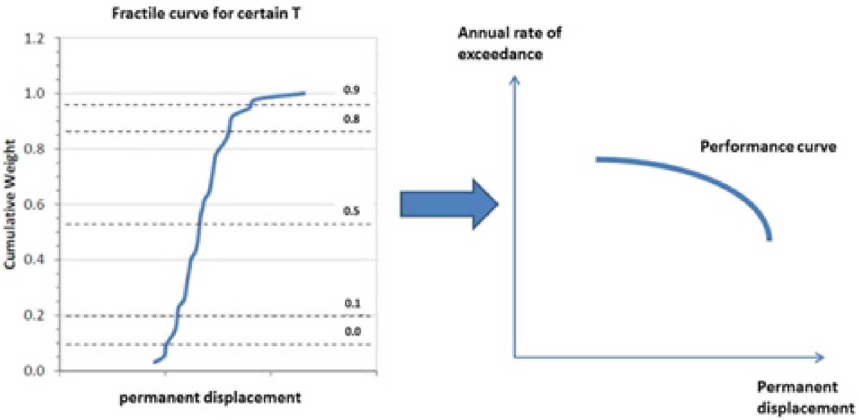

Figure. 5 Transformation of the fractile curve into a performance curve

Table 1. Inputs for logic tree analysis

Curve	**Curve A**	**Curve B**	**Curve C**	**Curve D**	**Curve E**
Number of branches	27 (9 without soil data)	27 (9 without soil data)	125	25	125
Seismic information	Serbia PGA=0.1g For 475 years	Hypothetical site PGA=0.18g For 475 years	Serbia PGA=0.1g For 475 years	Serbia PGA=0.1g For 475 years	Serbia PGA=0.1g For 475yearss
Target response spectrum	M<5.5 Type 2 EC8	M>5.5 Type 1 EC8	M<5.5 Type 2 EC8	M<5.5 Type 2 EC8	M<5.5 Type 2 EC8
			Seismic data		
Peak ground acceleration	+1,6σ (0.13g) mean (0.064g) -1,6σ (0.04g)	+1,6σ (0.315g) mean (0.015g) -1,6σ (0.077g)	-2σ (0.215g) -1,6σ (0.126g) mean (0.064g) +1,6σ (0.044g) +2σ (0.0335g)	-2σ (0.215g) -1,6σ (0.126g) mean (0.064g) +1,6σ (0.044g) +2σ (0.0335g)	-2σ (0.215g) -1,6σ (0.126g) mean (0.064g) +1,6σ (0.044g) +2σ (0.0335g)
Seismic time history record	+1,6σ (rec.16) mean (rec.18) -1,6σ (rec.4)	-1,6σ (rec.16) mean (rec.5) +1,6σ (rec11)	-2σ (rec.12) -1,6σ (rec.7) mean (rec.18) +1,6σ (rec.9) +2σ (rec.3)	mean (rec.18)	mean (rec.18)
			Soil data		
Friction angle at sliding surface	-1,6σ (8.5°) mean (11°) +1,6σ (13.5°)	-1,6σ (8.5°) mean (11°) +1,6σ (13.5°)	-2σ (7.88°) -1,6σ (9.44°) mean (11°) +1,6σ (12.56°) +2σ (14.13°)	-2σ (7.88°) -1,6σ (9.44°) mean (11°) +1,6σ (12.56°) +2σ (14.13°)	-2σ (7.88°) -1,6σ (9.44°) mean (11°) +1,6σ (12.56°) +2σ (14.13°)
Shear modulus of sliding mass	mean(6200 kPa)	mean(6200 kPa)	mean(6200 kPa)	mean(6200 kPa)	-2σ (2950 kPa) -1,6σ (2575 kPa) mean (6200 kPa) +1,6σ (7825 kPa) +2σ (9450 kPa)

The influence of shear modulus of sliding mass on sliding performance of slope is bigger at lower level of sliding displacement. Continuum mechanic approach was applied for curve D in order to be able to generate the curve within a reasonable amount of time.

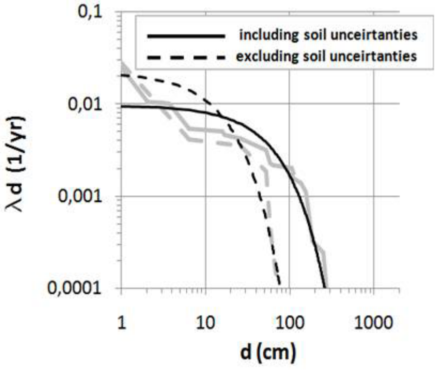

Figure 6. Curve A - lower seismicity zone

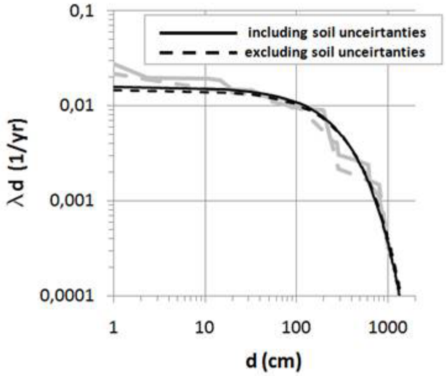

Figure 7. Curve B – hypothetical site

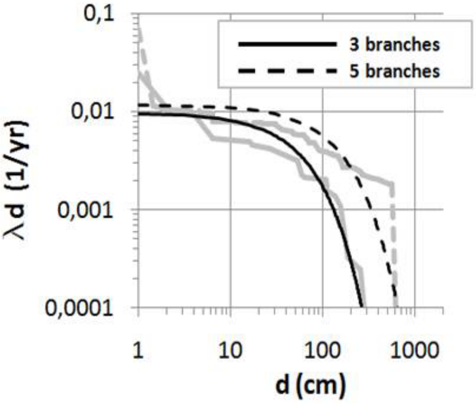

Figure 8. Influence on different number of branches (curves A and C)

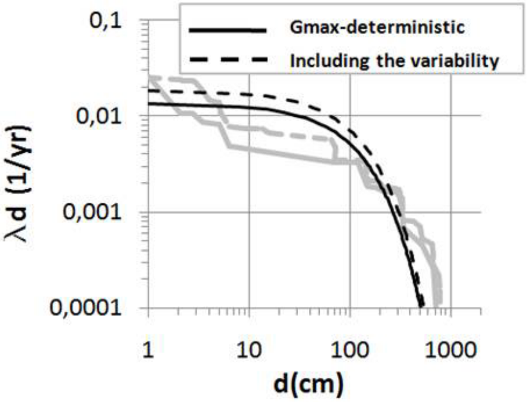

Figure 9. Influence of employing uncertainties of shear modulus of sliding mass (curves D and E)

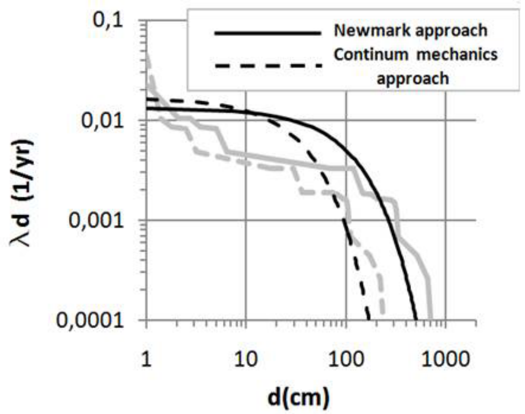

Figure 10. Influence on different sliding assessment techniques (Curve D)

Differences in results between the Newmark and continuum approach analyses for particular slope case (Figure 10) are analyzed in terms of the following factors: fundamental period of the potential sliding mass, level of seismic loading, frequency content of the input motion and the yield acceleration.

There are scenarios where the Newmark sliding block procedure is unconservative in predicting seismically induced permanent displacements. That is mainly because the computed slope displacement is influenced predominantly by low frequency average motion that amplifies and is not sensitive to high frequency motion. However, the Newmark deformation analyses results may be justified, if the fundamental period of the slope is sufficiently low (i.e., shallow soil deposits with T

< 0.2 second). The observed slope is quite shallow; therefore the obtained difference in the results (two to four time's larger displacement obtained by the Newmark method) was expected. The influence of the level of seismic loading on the accuracy of results is shown on Figure 10. The Newmark method can be unconservative in cases of very low displacement hazard but in those cases the difference in the results is insignificant from the engineering viewpoint. The analysis in terms of the frequency content, yield acceleration and all other issues can be found in Zugic et al. (2014).

4. Conclusions

The proposed procedure represents a valuable tool for generating the hazard displacement curve and can be used for preliminary analysis as well as for a complex analysis in cases of availability of reliable seismic and geotechnical inputs.

The main advantage is possibility to assess sliding displacement hazard in probabilistic manner by performing a reasonable amount of simulations. Therefore, the displacement hazard curve can be obtained in reasonable amount of time, even in case of employing the most advanced continuum approach deformation assessment technique. That is big advantage in comparison with the other approaches.

On the basis of the presented results, it is important to accentuate that assessing of the seismic deformation of slopes in a probabilistic manner is an iterative procedure. The possibility to add a new uncertain parameter in the next iteration and upgrade the analysis is a very good property of proposed technique. The adding one more set of branches to logic tree analysis is quite quick and simple, having in mind that all the probabilistic computation results from the previous step can be used. Performing of some kind of sensitivity study (Garevski et al. 2012) might also be quite useful, before starting applying the proposed procedure. The main outcomes from this work are:

- Verification of the new procedure for obtaining slope deformation hazard curve
- Confirmation and quantification of the importance of treating the soil data variation
- The impact of shear modulus of sliding mass on slope deformation is highlighted
- The advantages of using advanced methods (continuum approach) are shown
- Confirmation of the applicability of Newmark rigid block method in some specific cases

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