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Permanent ground displacement across earthquake faults, landslides and natural slopes

Zeljko Zugić*, Mihajlo Aranđelović, Boris Folić

"a University of Belgrade, Innovation Center of the Faculty of Mechanical Engineering, Kraljice Marije 22, Belgrade, Serbia"

Abstract

Permanent ground displacement analysis methods, as very important aspect of the seismic dynamic analysis is explained in the paper. A methodology for probabilistic hazard assessment of permanent displacement across natural slopes and landslides caused by earthquake rupture is presented, compatible with regions with low to moderate seismicity, as well as comparison with the results of the other authors. The results show that for the most cases, in terms of displacement of earthquake faults the displacement hazard is small, in contrast to ground shaking hazard. From the other side, slope displacements (rockfalls landslides, mudflows) as side effects may cause huge consequences during the earthquake.

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1. Introduction

The deformation analysis of shear ruptures, as occur in landslides and earthquakes, is focus of this paper, Fig. 1. Since the seismic activity is one of the main causes of landslides deformation we focus on seismically induced ruptures considering both seismic faults and landslides. The permanent rupture displacement has been analyzed in terms of:

- Displacement magnitude
- Displacement frequency
- Rupture affection by fluids
- Rupture hazard relation to induced risk to people and environment

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* Corresponding author. Tel.: +381-63-31-40-40 ; fax: +381-11-8219681
E-mail address: zzugic@gmail.com

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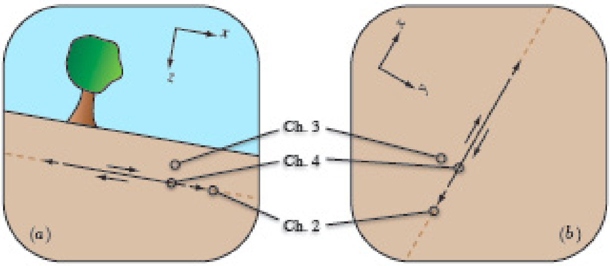

Fig. 1. (a) characteristic slope (b) seismic fault (Viesca 2011)

2. Displacement intensity

Talking about methods for permanent seismic deformation analysis, over the past 50 years, over 30 different deformation-based methods have been developed to compute seismic slope displacements. These procedures generally fall into one of the three categories: (1) rigid block-type procedures which ignore the dynamic response of slopes (2) decoupled procedures which account for the dynamic response, but "decouple" this response from the sliding response of slopes, and (3) coupled procedures which "couple" the dynamic and sliding response of slopes. The coupled analyses are, however, generally in terms of numeric analysis time consuming, and cannot be used routinely, especially in cases of probabilistic analyses that involve a significant number of repeated analyses of the problem.

From the other side seismic fault displacement analysis that is directly related to probabilistic seismic hazard analysis have some specific aspects in comparison to landslide slope analysis. The research by Todorovska et al (2007) has shown results for two hypothetical vertical strike-slip faults, which have same length, L = 100 km, but differ by their activity and by the manner in which the seismic moment rate is distributed over magnitudes. Beside the absolute value of maximal rupture displacement, the important issue is frequency of calculated displacement, that is topic of next chapter.

3. Displacement frequency

Being a direct consequence of an earthquake occurrence, the probabilistic model for rupture deformation is determined by the probabilistic model of earthquake occurrence. The section derives the model respectively for Poissonian earthquakes and for earthquakes occurring at a time dependent rate.

3.1. Hazard Model for Poissonian Earthquakes

Assuming that the earthquakes on the fault occur independently of one another, their number during specified exposure is Poissonian and their return period is an exponential random variable. For practical purposes, let us discretize the magnitudes of possible earthquakes, and let Mi,i=1 to N the possible magnitudes, and be the corresponding expected number of earthquakes during exposure t. Then, the event Dsite>d during time t, is a selective Poissonian process with rate that is a prorated value of the earthquake occurrence rate (for the fact that not every rupture will break the surface and extend to the site, and even if it does, the displacement may not exceed level d). Due to the statistical independence, the exceedance rate is a sum of the exceedance rates for the individual magnitude levels. The Poissonian process is memoryless, and is completely defined by the average rate

3.2. Hazard Model for Earthquakes with Time Dependent Hazard Rate

It has been observed that some faults, tend to produce large earthquakes more frequently than predicted by a truncated linear Gutenberg-Richter fit to observed seismicity data. Also, consistent with the elastic rebound theory of earthquakes, the chance of a large earthquake on a fault depends on the time elapsed since the previous one, as it takes time to replenish the strain energy to generate another large earthquake. This has been the basis for the characteristic earthquake model where the characteristic earthquake for a fault is the one that ruptures the entire fault, and the likelihood of the next event depends on the time elapsed since the previous such event. Such processes can be modeled as one step memory renewal process, e.g. with lognormally distributed return period, and require an additional input parameter—the time elapsed since the previous such event. Due to lack of data and lack of regularity in the occurrence of large earthquakes (either the segment or the magnitude is not repeated), uncertainty in the segmentation, and the interaction between neighboring segments and possibility of a joint rupture in a large earthquake, this time dependent model has been applied to a small number of faults, mostly along the plate boundaries, and the time until the next characteristic event is often modeled as an exponential random variable. probability of exceedance in 50 years. The different lines correspond to estimates when all events contribute to the hazard, and when only the Gutenberg-Richter events or the characteristic events contribute to the hazard.

3.3. One of the possible approaches

The above mentioned common assumption is that an earthquake is generated through a random process and it is independent of its last occurrence- the basis for considering earthquake occurrences a Poisson process in PSHA.

Similarly, ground motions are also characterized by a Poisson's process. Another assumption is that the annual rate of occurrence (or exceedance) for an event (i.e., T=1 yr) is numerically equal to its annual probability of occurrence (or exceedance). As a result, a conversion is not necessary between rates of occurrence/exceedance and probabilities of occurrence/exceedance, and in the following sections the terms rate and probability are used interchangeably. This approximation is used for rare events (such as earthquakes) where λ is small and is often called the "rare event assumption" proposed by Bazzurro and Cornell (2002).

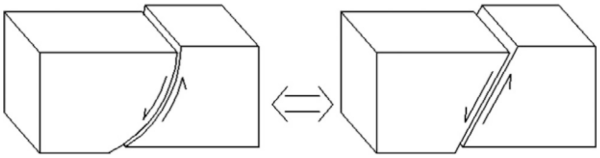

Fig. 2. Analogy between landslide and seismic fault displacement

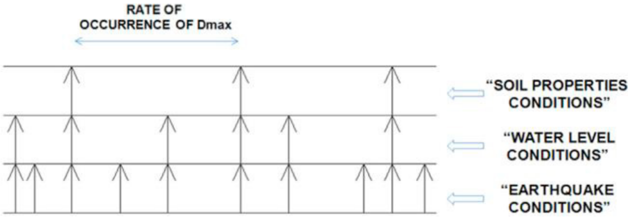

Fig. 3. Occurrence of peak deformation as Poisson's process.

Finally, the main assumption of the procedure proposed by Zugic et.al. (2015) 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 (Fig. 2). Every occurrence of peak slope displacement in time is a product of specific combination of seismic, soil and water level conditions (Fig. 3). 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.

Let D be a random variable representing, for an earthquake that has rupture d the soil surface, the absolute value of the displacement across the sliding surface at the ground surface, and Dslope be the same type of displacement at the site ,which may or may not have been affected by the earthquake, and let p(d,t) be the probability that Dslope exceeds level d during the exposure period. Being a direct consequence of an earthquake occurrence, the probabilistic model for this event (exceedance of a certain level of displacement) has been determined by the probabilistic model of earthquake occurrence, as explained by Zugic et.al (2015). Figure 4 (b) shows that the hazard estimate is quite sensitive to the modeling assumptions affecting the distribution and the number of events over earthquake magnitudes.

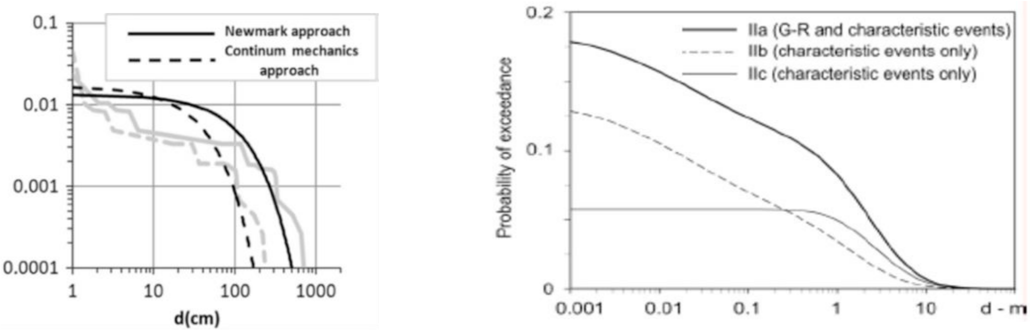

Fig. 4. (a) Landslide displacement curve (Zugic et. al. 2015) (b) seismic fault displacement curve (Todorovska et. Al. 2007)

4. The role of fluid on rupture displacement

The fluids affect the rupture displacement in terms of effective stress state along the sliding surface, as well as the effect on the siding(rupture) mechanism, especially considering the variability of the fluids in time domain. The general aim of research from Viesca (2011) is to understand the role pore fluids play in the deformation of geomaterials. The focal point is the deformation surrounding shear ruptures, as occur in landslides and earthquakes. Heating and weakening of the seismic faults Rice (2006), during dynamic excitation can have significant impact.

The role of fluid in rupture initiation, propagation, and runout is often central in landslide processes. In the experiment of Cooper et al. (1998) decreases in measured pore pressure during early-stage slope movement indicate a stabilizing dilative suction preceding total slope failure. Subaerial flume studies of densely or loosely packed sandy sediment also show a tendency for dilatant stabilization in the case of dense sediments and transition to debris flow when loosely packed Iverson et al. (2000).

Monitoring shearing rates and pore pressures in experimental conditions Moore and Iverson (2002) observe the diffusive nature of such stabilization in relatively coarse and fine-grained sediments. The question remains how to appropriately determine the pore pressure within a finite thickness shear zone approximated by a sliding surface. Specially, contributions from processes within the shear zone may be lumped into the surface behavior in addition to contributions from material deformation beyond the shear zone.

When concerned with slip-surface pore pressures, current modeling of dynamic rupture propagation has included inelastic porosity changes as either a slip-proportional porosity changes Rice (1980) or a transition to a rate-dependent steady-state porosity. The variation of pore pressure state effect along the sliding surface on rupture displacement frequency curve analyzed by Zugic (2012) is shown in Fig 5.

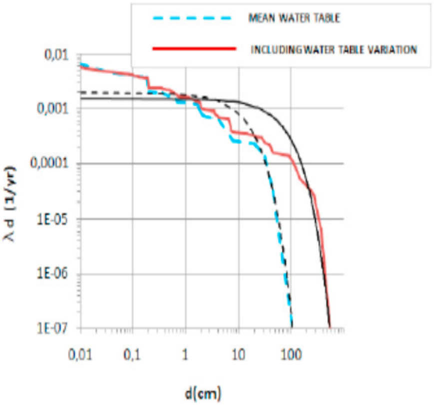

Fig. 5 Impact of water level (effective pore pressure) on rupture displacement

5. Conclusion

Although the common use of the displacement-based approach comes from the structural and earthquake engineering, there is significant benefit of use in geotechnical engineering and seismology. The rupture displacement analysis is important task directly connected with estimate of vulnerability and risk on people and properties.

The presented results show that for the most cases, in terms of displacement of earthquake faults the displacement hazard is small, in contrast to ground shaking hazard. Therefore, most of the damages on buddings and infrastructure are induced by free vibrations induced by earthquake shaking.

However, it is shown that slope displacements (rockfalls landslides, mudflows) may cause huge consequences during the earthquake. This stresses importance of understanding landslides as secondary natural hazard that may occur as side effect during or after earthquake.

Rupture displacement can't be analyzed independently to frequency of its occurrence, considering the uncertainty of seismic activity occurrence, impact of fluids and many other variables.

Beside the scientific purpose, the aim of generating the displacement hazard curves is to obtain valuable inputs for damage and lost assessment, that are necessary for insurance industry. For example, for the case of the landslide that induce road deformation, deformation curve can be transformed into financial loss curve, through the repair ratio index approach.

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