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# Vulnerability of Soil Slopes Against Seismic Damage Based on the Effect of Spatial Variability of Soil Properties on the Development of Permanent Seismic Displacements

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**Abstract:** The most accurate estimation of seismic slope stability is one of the most important areas of geotechnical seismic engineering. The assumption that soil consists of layers with some average values for soil parameters of each layer is not a realistic representation of actual conditions. The properties of a soil layer are not spatially invariant and the scale of changes can significantly affect the stability analysis of slopes. It is important to include in the analysis as many kinds of uncertainty, especially those resulting from the properties of soil mass and influencing the seismic stability of slopes.Stochastic methods have been introduced in order to calculate the uncertainty and spatial variability of soil parameters. Recent research took into account the spatial variation of parameters using the Random Field Theory. In theory, these variables exhibit autocorrelation, a trend in which the soil properties of a point appear to be correlated with the properties of neighbouring soil points (Vanmarcke, 1977). This study explores the influence of spatial variability of soil properties on the development of permanent displacements during seismic vibration of the slopes as well as the levels of seismic damage that can be caused. This effect is initially investigated for a fixed value of the maximum acceleration of the excitation, and then the results are expanded to include the effect of the seismic intensity level. The results show the curves of vulnerability of slopes against seismic damage and constitute a pretty useful tool for the design of slopes, taking performativity into account.

**Keywords:** Vulnerability, Slopes, Seismic Damage, Spatial variability, Permanent displacements

## Introduction

The main goal of this paper is to investigate the effects of spatial variability of soil properties on permanent displacement development during seismic vibration of the slopes, along with the extent of damage that can be caused due to the earthquake.

Using the random fields territorial properties given by bibliography [(Babu and Mukesh, 2016), (Cho, 2010), (Wu, 2013)], a new automated process was created through which a large number of numerical simulations for the seismic analysis of slopes was carried out.

In addition, the effect of the intensity of the seismic excitation was investigated by considering peak ground accelerations values $a_g$ of 0.05g, 0.1g, 0.2g, 0.3g, 0.4g and 0.5. By combining the effects of the spatial variability of soil properties, the frequency characteristics of excitation and the nonlinearity due to intensity, the probability of exceedance of a given value of displacement for different levels of peak ground acceleration is evaluated.The resulting data shows the fragility curves of slopes when faced with seismic damage and may become a useful tool for the planning of slopes, from a performative point of view.



- Selection and peer-review under responsibility of the Organizing Committee of the Conference

## Parametric Analysis

Then is recorded the typical slope geometry, the statistical parameters of the mechanical characteristics of the sloping soil mass, the values of the cross-correlation factor coefficient ρ between different soil properties, as well as the autocorrelation lengths which determine spatial auto-correlation on the vertical and the horizontal axis. (Alamanis, 2017)

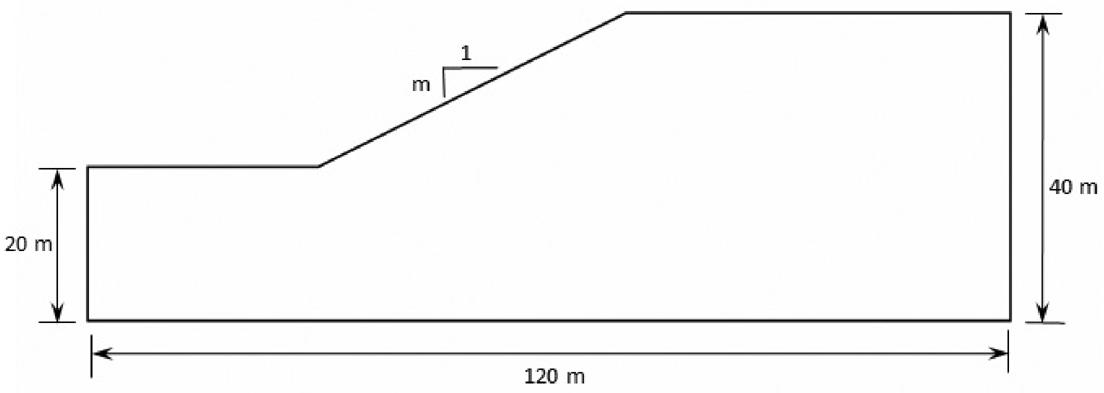



Figure 1. Sloping standard geometry with slope m: 1, where m receives different values

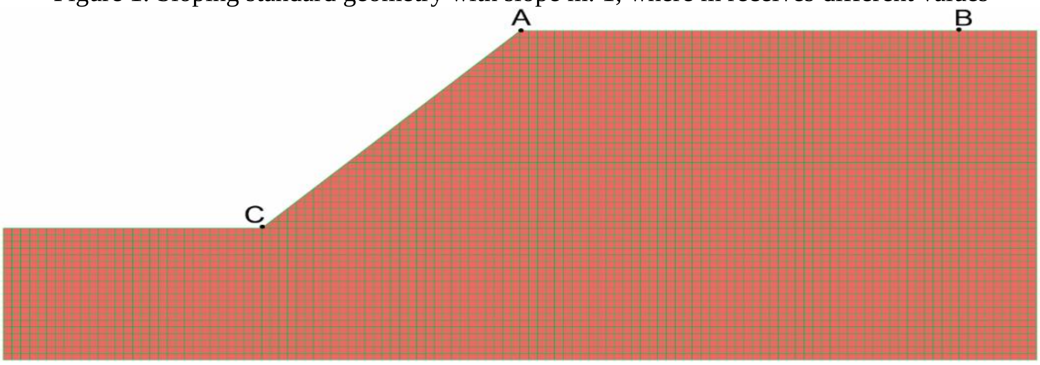



Figure 2. Geometry B: Differentiation of slope geometry with 1: 1 slope

Table 1. →Average values and standard deviations of spatially variable soil slope variables

| Parameter | μ Average value | σ typical dispersion | σ/μ coefficient of variation |
|---|---|---|---|
| c, kPa | 30<br>40<br>**50** | 9<br>12<br>**15** | 0.3<br>0.3<br>**0.3** |
| φ°, degrees | 20°<br>**30**<br>35 | 4°<br>**6**<br>7 | 0.2<br>**0.2**<br>0.2 |
| ψ°, degrees | **0°** | 0° | 0 |
| ρ, kg/$^{m3}$ | 1800<br>**2000**<br>2200 | 180<br>**200**<br>220 | 0.1<br>**0.1**<br>0.1 |
| E, kPa | 40000<br>**60000**<br>80000 | 8000<br>**12000**<br>16000 | 0.2<br>**0.2**<br>0.2 |
| v | 0.3 | 0 | 0 |

Table 2. Correlation of soil parameters

| **Correlation coefficient $\rho_{ij}$** | | | | | |
|---|---|---|---|---|---|
| **Parameter** | c (KPa) | φ° | ρ (KN/m$^3$) | E(KPa) | v |
| c | 1 | -0.5 | 0.5 | 0.2 | 0 |
| φ° | -0.5 | 1 | 0.5 | 0.2 | 0 |
| ρ | 0.5 | 0.5 | 1 | 0 | 0 |
| E | 0.2 | 0.2 | 0 | 1 | 0 |
| v | 0 | 0 | 0 | 0 | 1 |

Table 3. Autocorrelation value pairs used in the resolutions.

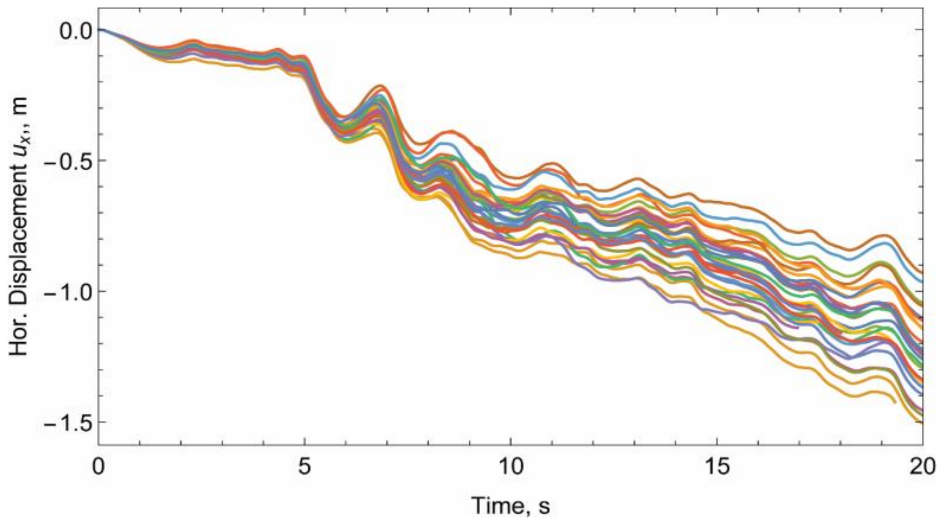
| **Lengths of spatial correlation** | | | |
|---|---|---|---|
| $l_x$, m | 20 | 40 | 20 |
| $l_y$, m | 2 | 2 | 4 |

Table 4. Geometric slope elements

| | **Inclination of a slope** | **Slope height** | **Gradient slope angle** |
|---|---|---|---|
| Geometry A. | 2:1 | 20 m | 26.56$^o$ |
| Geometry B | 1:1 | 30 m | 45$^o$ |
| Geometry C | 4:3 | 30 m | 36.87$^o$ |

Then the parametric investigation of the influence of the spatial variability of the sloping soil properties is presented a) on stability under static conditions as well as b) on the permanent displacement under the seismic intensity of Lefkada, Kalamata, Kobe, Friuli and Northridge, the seismic recordings of which are used in research simulations. For this purpose, an analysis of static and dynamic simulations of a significant number of slopes with spatial variability of properties is carried out, and the results have been shown to be of great significance.

Based on experimental results of soil characteristics from the bibliography and the use of the L.A.S. methodology [(Fenton and Vanmarcke, 1990), (Griffiths and Fenton, 2007), (Fenton and Griffiths, 2008)] and the Mathematica program, an extensive range of random fields [(Fenton, Griffiths and Urquhart, 2003), (Griffiths and Fenton 2004)] was created via an automated process to express the spatial variability of soil properties with the desired characteristics. Then, using the random field properties, a new automated process was put together in order to create a large number of numerical simulations for static analysis, stability analysis and seismic analysis of the slope-ground foundation system utilizing the FLAC program (Itasca, 2011). Aggregate results of this survey are presented in Figures 3a and 3b.



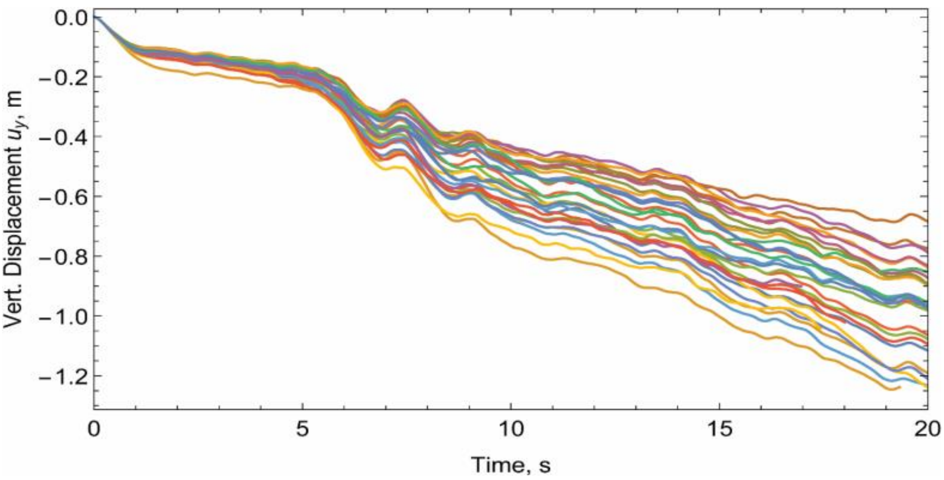



Figure 3. Geometry B (slope 1: 1): (a) horizontal and (b) vertical displacement at point B.

## Tolerable Movement Levels

Matasovic in 1991 performed a natural slope stability analysis (using the flysch strength parameters) with the static method, the pseudostatic method, the Newmark sliding solid upon an incline method, and the simplified Ishihara method. In this study, he pointed out the important problem of considering a level of tolerable movement because the behaviour of a slope during and after the seismic vibration is associated with the choice of the shear strength parameters of the material and the exact calculation of the seismic load. He has adopted as limits of tolerable movements for natural slopes the following:

Table 5. Determination of tolerable movements based on the damage caused on natural slopes (Matasovic, 1991)

| EFFECTS / DEFECTS | Tolerable movements (cm) |
|---|---|
| I. Destructive | 300 |
| II. Serious | 90 |
| III. Medium | 30 |
| IV. Small | 15 |
| V. Negligible | <3 |

The international experience presented in the above table showed the following:

- Displacements up to 10 cm of sliding solids on an inclined plane analysis (Newmark, 1965) are considered to be unlikely to lead to landslides and destruction.
- Larger displacements of 10 to 100 centimeters can cause ground breakage or decrease in strength, resulting in the failure of the project.
- Finally, estimated movements of more than 100 centimeters should characterize the work as unstable.

In natural slopes, tolerable movement depends on the structures that are grounded on the slope or at the foot of the slope. If there are buildings, permissible movement is equivalent to that of the foundations, and if there are no structures, the allowed movement may be greater.

In small dams and embankments, movements of a few centimeters or even a few tens of centimeters may be tolerable, provided the continuity of the dam filter is not interrupted. In road and highway embankments, the horizontal ground movement should be no more than about 5 cm, above which unacceptable deformation of the road surface is caused. In B-road embankments, the permissible movement may be greater e.g. in the order of 10 centimeters, because: (a) the risk of an accident is lower due to the less frequent passage of vehicles and (b) traffic disturbance is of lesser importance.

Significant attempts are made to approximate the above calculations. In particular, the probabilistic methods proposed for the calculation of permanent seismic displacements are few e.g [(Lin and Whitman, 1986), (Yegian et al., 1991)]. In addition, most of them either use simplistic slope models or are based on a limited number of analyses with real earthquake historical data.

Travassarou, after proposing a new empirical relationship for the calculation of permanent seismic displacements in slopes, stresses that the significant uncertainties surrounding the problem of permanent seismic displacements point to the usefulness of probabilistic calculation methods which take into account dispersion in the relevant parameters. [(Travassarou, 2006), (Bray and Travassarou, 2007)].

## Fragility Curves

Fragility curves have emerged in recent years as an indispensable tool for a number of purposes related to seismic risk management, such as calculating expected losses in future earthquakes, setting priorities for building and utility network reinforcement, seismic safety, etc.

The term fragility refers to the behaviour of a compromised item, which is due to a variable intensity phenomenon. Particularly in the case of an earthquake (Dakoulas, 2005), experience has shown that, apart from the buildings, utility networks and transportation infrastructure are also quite vulnerable in earthquakes. Failures that occur after an earthquake are due to the following phenomena caused by an earthquake:

- Soil vibration,
- Intersections with fractures
- Subsidence in transition zones from better to worse soil
- Landslides, i.e. mass movement of the slopes due to failure of the slope soil because of fracturing along a surface,
- Failures in public utility networks due to landslides are mainly due to a falling of rocks or slipping slopes that entrains the network.
- Liquefaction, i.e. the conversion of saturated, non-coherent soil, from solid to liquid with significant loss of strength.

Vulnerability curves are one of the key elements of stochastic seismic hazard. They connect seismic intensity with the probability of approaching a level of failure or destruction (small, moderate, widespread, catastrophic) for each hazard element.

## Results of this Investigation

Below are the fragility curves that can be used for the performative design of the slopes. More specifically, the expected permanent seismic shift (horizontal, vertical or resultant) is compared with different levels of seismic displacement corresponding to different levels of seismic damage and repair costs. The results of this study that lead to the creation of fragility curves are described in Table 6 below and in the following Figures 4 and 5.

Table 6. Seismic damage levels

| Seismic Damage | Displacement, m |
|---|---|
| Insignificant | 0.00- 0.25 |
| Small | 0.25-0.50 |
| Moderate | 0.50-1.00 |
| Large | 1.00-2.00 |
| Very large | > 2.00 |

Weibull Probability Density Functions for Different Values of Maximum Acceleration $a_{\max}$ are given in Figure 4 with probability density functions based upon Weibull. Figure 5 gives the possibility that the vertical permanent displacement $u_y$ exceeds a certain value $u_y$* and therefore presents the vulnerability of the slope against seismic damage. It constitutes a very useful tool for slope planning based on performance.

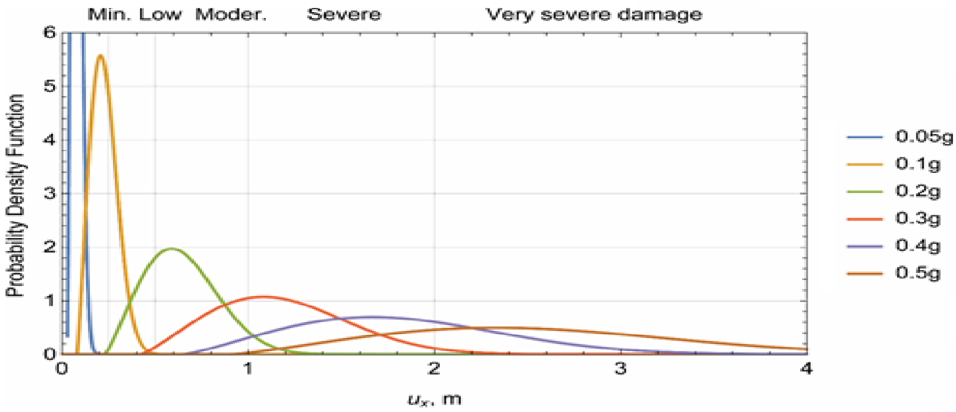



Figure 4. Probability density function of the horizontal permanent displacement $\boldsymbol{u_x}$ for various values of the maximum acceleration $a_{max}$ = 0.05g, 0.1g, 0.2g, 0.3g, 0.4g and 0.5g. (Description of the numerical results with the Weibull distribution)

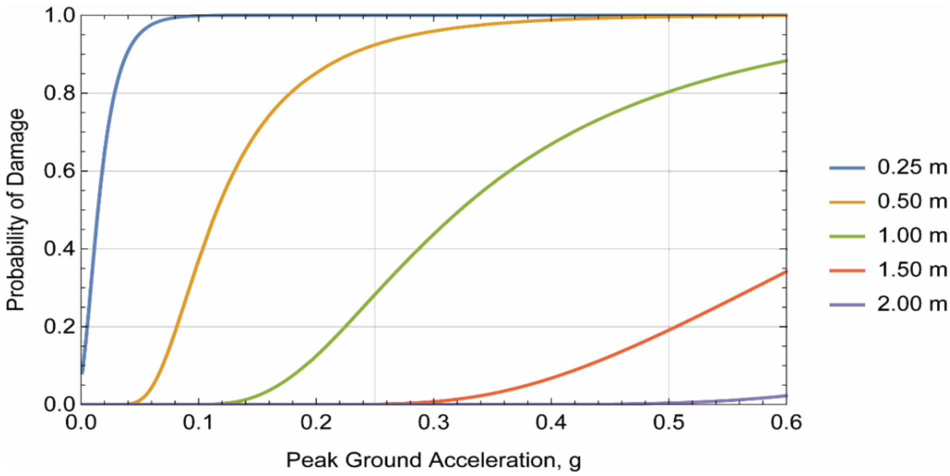



Figure 5. Slope fragility curves: The probability that the vertical permanent displacement $\boldsymbol{u_y}$ will exceed a certain value $\boldsymbol{u_y}$* in terms of maximum acceleration $a_{max}$. (Description of the numerical results with the Weibull distribution)

## Conclusion

**1.** The statistical treatment of results of numerical simulations leads to the creation of two kinds of design diagrams: (a) the first shows the probability of exceeding a particular value of permanent displacement for various values of maximum excitation and (b) the second shows the fragility curves, which express the probability of seismic damage in connection to the size of seismic intensity for various values of permanent seismic displacement.
**2.** The results show the curves of vulnerability of slopes against seismic damage and constitute a pretty useful tool for the design of slopes, taking performativity into account.
**3.** The parametric analysis of the research leads to the conclusion that the vulnerability of the soil slopes to seismic damage is significantly affected by the spatial variability of the soil properties, since they lead to the development of permanent displacements that are highly dispersed.
4. It is therefore desirable for the parametric investigation of this research to be expanded, so as to best describe the uncertainty, and the overall conclusions to be reassessed in order for them to be taken into account in any long-term regulatory provisions.

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