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Effect of spatial variability of soil properties on the stability and permanent seismic displacements of highway slopes

Effet de la variabilité spatiale des propriétés du sol sur la stabilité et les déplacements sismiques permanents de talus des autoroutes

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ABSTRACT: The effect of spatial variability of soil properties, slope inclination and excitation characteristics on the development of permanent displacements is investigated using random fields, created by the Local Average Subdivision method. These random fields of properties are characterized by specific mean, variance, cross-correlation coefficients and autocorrelation lengths and used for performing stability and seismic analysis of various slopes using the finite difference software FLAC. Statistical analysis of the results of an extensive parametric investigation leads to the development of vulnerability curves, based on the permanent horizontal or resultant displacement for several seismic intensity levels. The results of parametric analysis show that the influence of spatial variability of soil properties is very important.

RÉSUMÉ: L'effet de la variabilité spatiale des propriétés du sol, de la pente de talus et des caractéristiques d'excitation sur le développement de déplacements permanents est examiné à l'aide de champs aléatoires, créés par la méthode de subdivision moyenne locale (LAS). Ces champs aléatoires des propriétés du sol sont caractérisés par moyenne spécifique, variance, coefficients de corrélation croisée et longueurs d'auto-corrélation, et sont utilisés pour effectuer des analyses de stabilité et sismiques de diverses pentes à l'aide du logiciel de différences finies FLAC. L'analyse statistique des résultats d'une vaste enquête paramétrique conduit à l'élaboration de courbes de vulnérabilité, basées sur le déplacement permanent horizontal ou résultant pour plusieurs niveaux d'intensité sismique. Les résultats de l'analyse paramétrique montrent que l'influence de la variabilité spatiale des propriétés du sol est très importante.

Keywords: spatial variability, random fields, slopes, permanent displacements, fragility

1 INTRODUCTION

Numerous studies have been undertaken in recent years to develop probabilistic approaches that account for the uncertainties of soil properties (Fenton et al. 1990, 2008, El-Ramly et al. 2002, Babu et al. 2004, Cho 2007, Griffiths et al. 2009). The present study examines the influence of the spatial variability of soil properties on the stability and seismic performance of highway slopes. The methodology is based on the development of random fields of soil properties characterized by specific mean, variance, cross-correlation coefficients and autocorrelation lengths, using the Local

Average Subdivison method (LAS) proposed by Fenton and Vanmarcke (1990).

2 NUMERICAL METHODOLOGY

2.1 Methodology

A fully automated procedure is created for the development of appropriate random fields of material properties, followed in a seamless manner by numerical analysis of an earth slope using the finite difference program FLAC (Itasca 2011). In each analysis, an evaluation of the slope stability is conducted initially, using the stress-strain relationship of the soil leading to a direct determination of the true failure mechanism, without any need for trial failure surfaces. Subsequently, a simulation of the seismic behavior of the slope is performed aiming at the evaluation of the permanent horizontal and vertical displacements at the end of the shaking. The numerical analysis is used in a Monte Carlo simulation procedure to examine parametrically the effect of the spatial variability of soil properties, the slope inclination and the earthquake excitation characteristics.

2.2 Model

Figure 1 illustrates the geometry of the slopes used in the study, whereas Fig. 2 presents the numerical discretization for the case of a slope inclination equal to 2:1. The characteristics of the other geometries considered are given in Table 1.

The constitutituve model used for the soil is the elastoplastic Mohr-Coulomb model, which is defined by the cohesion c, friction angle φ, density ρ, modulus of elasticity Young E, Poisson's ratio ν, and dilatancy angle ψ. All material properties are considered as randomly varied in space, except of the angle of dilatancy ψ and Poisson's ratio ν which are taken as constant. The mean values, μ, and standard deviations, σ, of soil properties used in this study are given in Table 2. The correlation coefficients ρ_{ij} of the above soil properties, obtained from available published data, are given in Table 3 (Alamanis 2017).

Each of the above properties is considered as a Gaussian random field defined by its mean value μ, variance σ^2 and autocorrelation function $\rho(x,y)$. A widely used exponential autocorrelation function is employed, expressed as

$$\rho(x,y) = Exp(-\frac{|x-x'|}{l_x} - \frac{|y-y'|}{l_y}) \tag{1}$$

where l_x and l_y are the characteristic autocorrelation lengths in the horizontal and vertical directions, respectively. The values of l_x and l_y considered in this study are given in Table 4.

For the seismic analysis, the Mohr-Coulomb model is enhanced with a hysteretic sig3 model with parameters a =1, b =-0.55 and x_o =-1.22 (Itasca 2011).

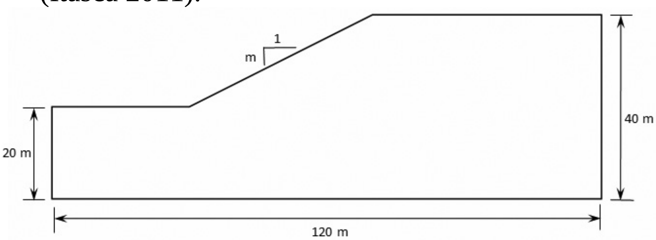

Figure 1. Typical geometry with slope m:1.

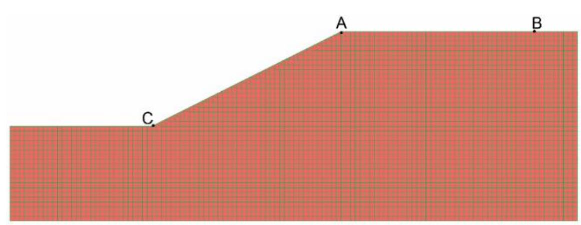

Figure 2. Geometry A: slope equal to 2:1

2.3 Earthquake Excitation

The numerical excitation consists of a series of acceleration records obtained from the Kalamata (1986), Lefkada (2003), Kobe (1995), Friuli (1976) and Northridge (1994) earthquakes.

Table 1. Slope geometry

Geometry	Inclination	Height (m)	Angle
A	2:1	20	26.56 °
B	1:1	30	45°
C	4:3	30	36.87 °

Table 2. Mean value and standard deviation of soil properties for the geometries A, B and C

Parameter	μ			σ/μ
	A	***B***	***C***	
c, kPa	30	50	30	0.3
φ°, deg	20°	30°	35°	0.2
E, MPa	60	80	80	0.2
ρ, t/m^3	2	2	2	0.1
ψ°, deg	0°	0°	0°	0
v	0.3	0.3	0.3	0

Table 3. Correlation coefficient of soil properties

Correlation factor ρ_{ij}					
Property	**c**	**φ°**	**ρ**	**E**	**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 4. Autocorrelation lengths

Lengths	L1	L2	L3
l_x, m	20	40	20
l_y, m	2	2	4

Table 5 provides the key elements of historical records. These records have been adjusted to match the Eurocode 8 acceleration spectra for hard soil and rock sites, calibrated for a peak ground acceleration of 0.3g. Fig. 3 plots the acceleration spectra of the five excitations and the Eurocode 8 design spectra.

3 ILLUSTRATIVE EXAMPLE

As an illustrative example, a earth slope is considered, having the geometry A of Figure 2 (slope 2:1), the soil properties given in Table 2 (case A), and correlation coefficients equal to those in Table 3. The autocorrelation lengths are l_x = 20 m in the horizontal direction and l_y = 2 m in the vertical direction (case L1 in Table 4). Figures 4a, 4b and 4c illustrate one realization of the spatial distribution of the random fields of soil cohesion c, friction angle φ and Young's elastic modulus E.

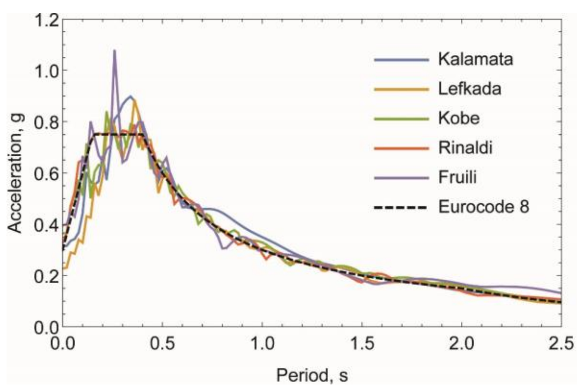

Figure 3. Acceleration spectra of modified seismic excitations and Eurocode 8 spectra for rock sites.

Table 5. *Historical Seismic Excitation Records*

Earthquake	Mw	R (km)	Recording	Component	PGA (g)
Kalamata (1986)	6.0	12	Prefecture	Hor.	0.25g
Lefkada (2003)	6.4	10	Lefkada	Trans.	0.60g
Kobe (1995)	7.2	20	Port Island	horizontal	0.57g
Northridge (1994)	6.7	30	Rinaldi	Hor. 318	0.47g
Friuli (1976)	6.5	19	Friuli	Hor.	0.35g

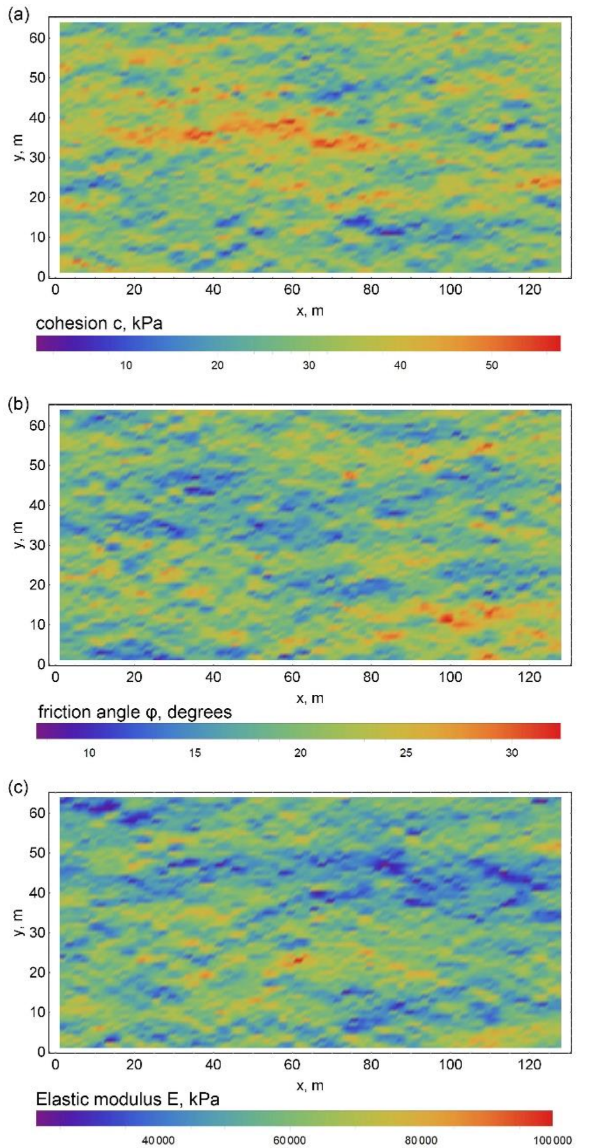

Figure 4. Representation of a random field of soil properties: (a) cohesion, (b) friction angle and (c) Young's elastic modulus.

3.1 Static Stability

The slope stability is analyzed using the strength reduction method to determime the factor of safety FS. This is achieved using a trial-and-error technique whereby numerical simulations are performed for a range of parameter values until the critical strength parameters are found.

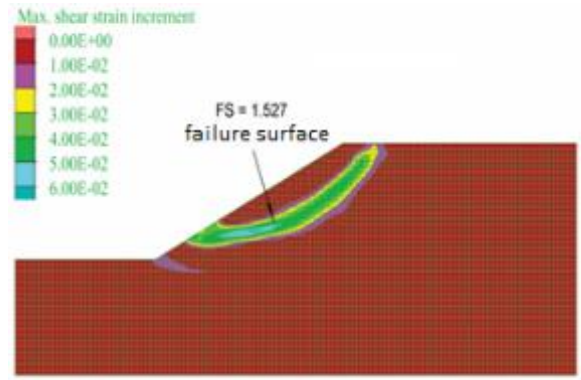

Figure 5. Slope stability analysis for random field soil properties and failure zone. Factor of Safety FS = 1.527.

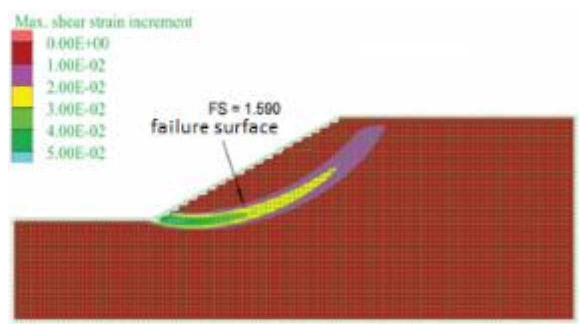

Figure 6. Homogeneous soil stability analysis with the FLAC program. Factor of Safety FS = 1.590.

The failure surface is given in Fig. 5, which shows the distribution of the maximum equivalent shear strain increment within the slope. For comparison purposes, Fig. 6 shows the corresponding failure surface of a similar slope with a homogeneous soil and properties equal to the mean values of those used in the above example. It is noted that the spatial variability of properties affects both the factor of safety and the location of the failure surface.

3.2 Seismic behavior

Figure 7 shows the horizontal permanent displacement u_x at the end of the seismic shaking, having a maximum value of about 2.10 m in the area of the lower half of the slopes. The settlement u_y, not shown here, has a maximum value about 1.30 m of the top horizontal surface. The results of the analysis show that a significant mass of soil moves to the left due to the inertial forces that develop during seismic vibration. This is shown in Figure 8, which displays the distribution of the maximum equivalent shear strain increment at the end of shaking. Indeed, there is a local zone in which there is a significant concentration of maximum equivalent shear deformation forming a failure surface.

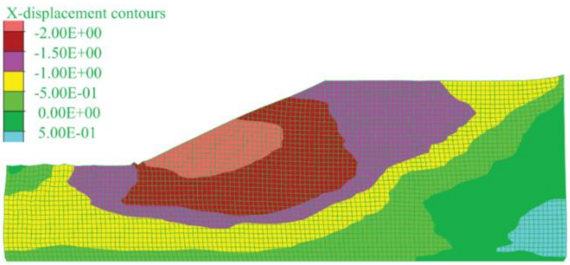

Figure 7. Permanent horizontal displacement after the end of seismic vibration.

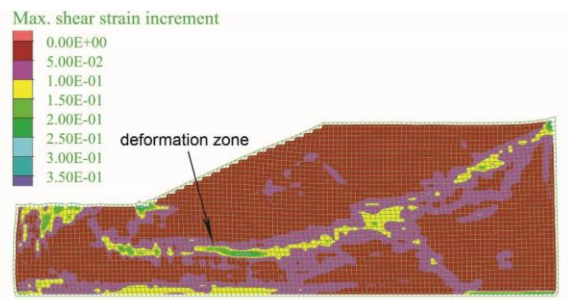

Figure 8. Maximum equivalent shear deformation at the end of seismic vibration.

The evolution of the horizontal and vertical displacement at point A (see Fig. 1) is given in Fig. 9, with residual values at the end of shaking equal to 1.42 and 1.25 m, respectively. It is interesting to compare the results of Fig. 9 with those of Fig. 10 of a homogeneous slope with properties equal to the average values of the random fields used in previous example. For the homogeneous soil, the values of the horizontal and vertical displacements at point A are 1.04 and 1.04 m, respectively. Consequently, spatial variability of properties has a significant effect on the permanent deformations of the slopes.

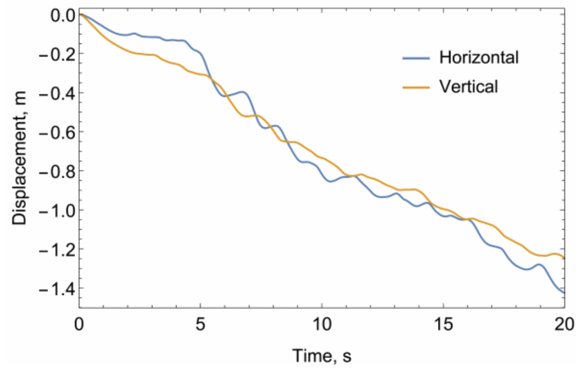

Figure 9. Horizontal and vertical displacement at point A for heterogeneous soil.

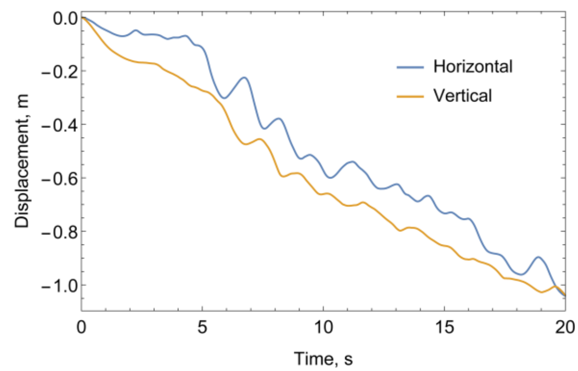

Figure 10. Horizontal and vertical displacement at point A for homogeneous soil .

4 PARAMETRIC ANALYSIS

This section summarizes some key results of an extensive parametric investigation using the three slope geometries of Table 1. The soil properies used in the parametric analysis for the three geometries (A, B, and C) are given in Table 2, the cross-correlation coefficients in Table 3, and the autocorrelation length scenarios in Table 4. The seismic analyses were performed using the excitation records in Table 5, modified to match the Eurocode 8 acceleration spectra, as shown in Fig. 3.

4.1 Slope stability under static conditions

Initially, the effect of spatial variability of soil properties on the factor of safety FS under static conditions is considered. To this end, the distribution of the ratio FS/FS_0 is examined, where FS_0 is the factor of safety of a homogeneous slope having similar geometry and material properties equal to the average value μ of properties of the heterogenous slopes. Fig. 11 plots the distribution of FS/FS_0 from 168 similar slope stability analyses. It can be seen that the results can be described with a normal distribution with average value slightly less than one (μ=0.986) and a relatively small standard deviation (σ=0.044), corresponding to a range of variation from 0.86 to 1.12.

Fig. 12 plots the probability density of the ratio FS/FS_0 for the three slopes and for a slope having a mean value of FS equal to μ=1.5 and standard deviation σ/μ=0.045. It is evident from Fig. 12, that a slope with average values of strength parameters that result into an average factor of safety value FS =1.5, may have a real FS factor which ranges between 1.3 and 1.7 due to the spatial variability of soil properties. The reduction of the FS from 1.5 obtained for the homogeneous slope to a probable 1.3 due to the variability of soil properties, may in some cases lead to the conclusion that the FS value is inadequate, since in many cases the requirement for the minimum factor of safety is larger than 1.3.

4.2 Seismic behavior-accumulation of permanent deformations

To investigate the effect of the spatial variability of soil properties, it is desirable to separate the effect of the characteristics of the seismic excitation used in the analysis from the influence of spatial variability of material properties. To this end, the ratio $f_x = u_x/\bar{u}_x$ is considered, where u_x is the permanent horizontal displacement at the end of the shaking and $\bar{u}_x$ is the permanent hor. displacement of a homogeneous slope with property values equal to the average values of those of the heterogeneous slope.

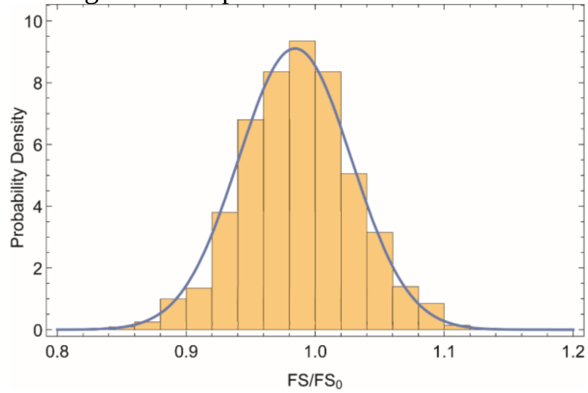

Figure 11. Data distribution and probability density of the ratio FS / FS_0

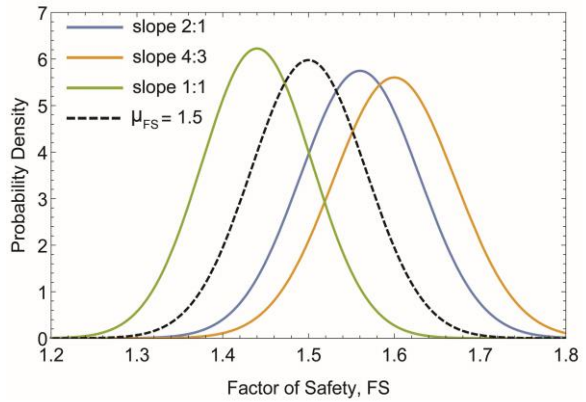

Figure 12. Probability density of the factor of safety for the three slopes and a slope having μ_{FS} =1.5 and σ_{FS}/μ_{FS} = 0.045.

Figure 13a shows the probability density of the results of permanent horizontal displacement ratio $f_x = u_x/\bar{u}_x$ at the top of the slope (point A in Fig. 2) from all seismic analyses using geometry A for a peak ground acceleration of 0.3g. Similaly, Fig. 13b plots the probability density of the permanent vertical displacement ratio $f_y = u_y/\bar{u}_y$ at the top of the slope. As shown in Fig. 13a, the average permanent hor. displacement of slope A with spatial variability of properties is about 19% greater than the hor.

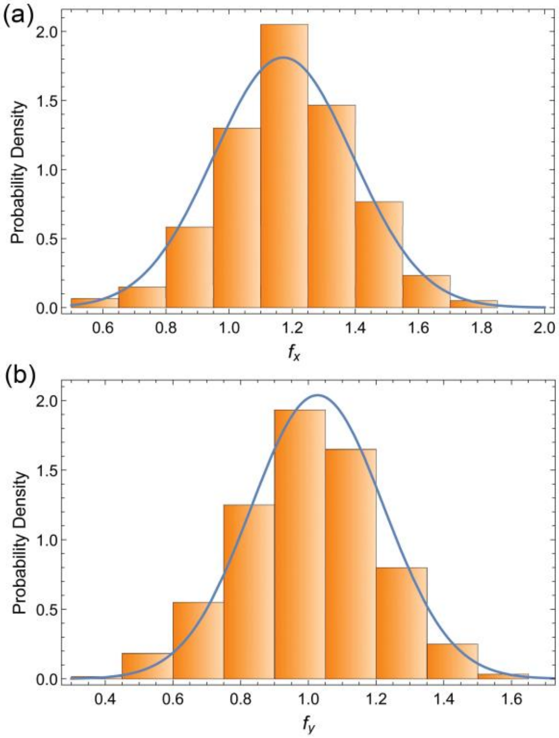

Figure 13. Distribution of (a) hor. displacement ratio $f_x = u_x / \bar{u}_x$ and (b) vert. displacement ratio $f_y = u_y / \bar{u}_y$ and probability density function of the normal distribution. (Slope 2:1).

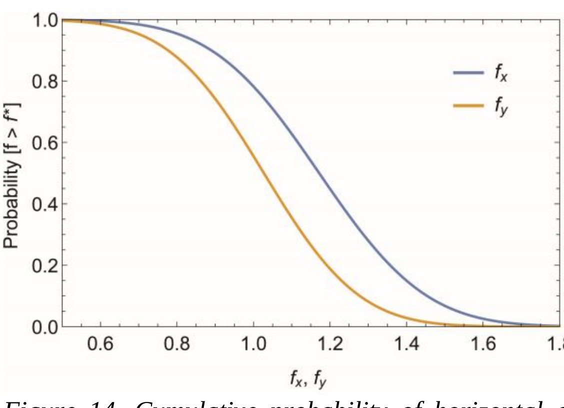

Figure 14. Cumulative probability of horizontal and vertical displacement ratios f_x and f_y.

displacement of a homogeneous slope with the same geometry subjected to the same excitation. The maximum theoretical deviation of the displacement corresponding to $\mu + 3\sigma$ is equal to 1.89, i.e. 89% greater than the horizontal displacement value of the homogeneous slope. This means that about 78% of cases of heterogeneous slopes will undergo permanent displacements that will be larger than those predicted for homogeneous slopes. This is shown in Fig. 14, which plots the cumulative probability for ratios f_x and f_y. For vertical displacements, the results in Fig. 14 show that 55% of heterogeneous slopes will undergo larger displacements than those of corresponding to homogeneous slopes.

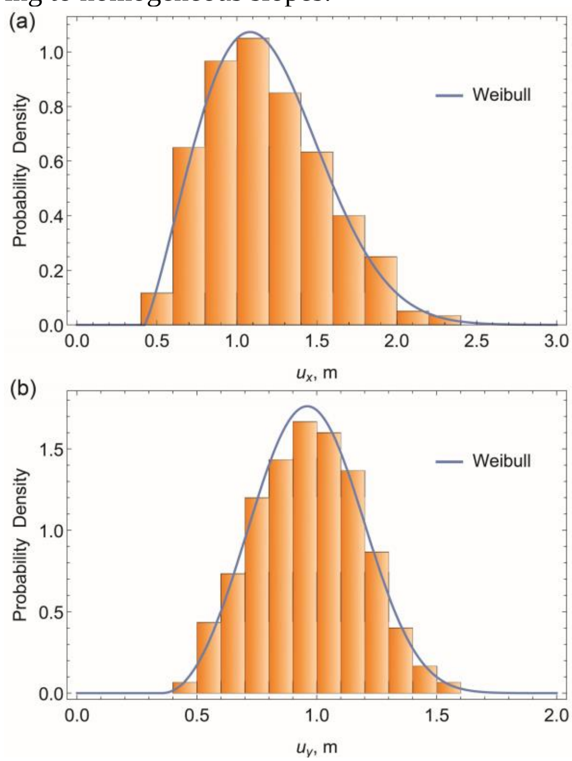

Figure 15. Distribution of (a) hor. displacement u_x and (b) vert. displacement u_y and probability density of the Weibull distribution. (Slope 2:1).

Moreover, the results of all analyses show that, in addition to the spatial variability of soil properties, the distribution of the horizontal and vertical displacements (u_x and u_y) depends substantially on the frequency characteristics of the seismic excitation. Figs. 15a and 15b plot the distribution of the permanat hor. displacement u_x and (b) vert. displacement u_y, from all numerical simulations using geometry A subjected to peak ground acceleration of 0.3g. The range of variation for u_x is from 0.5m to 2.5 m and for u_y from 0.4 m to 1.6 m.

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. The results suggest that, for a given homogeneous slope and earhquake excitation, the displacement u_i can be expressed as $u_i = a_i(a_g / g)^{b_i}$, where a_i and b_i are constants. 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, as shown in Fig. 16.

5 CONCLUSIONS

For the spatial variability of soil properies considered in this study, the main conclusions derived from the results of the parametric investigation are as follows:

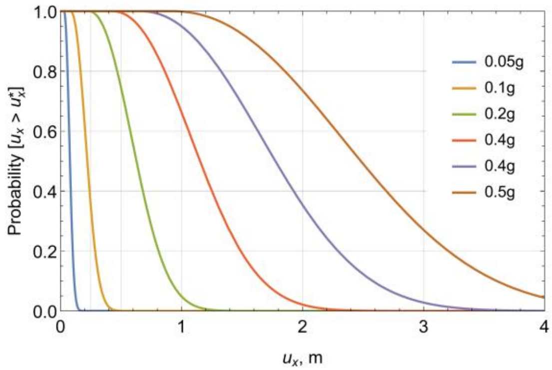

Figure 16. Probability of exceedance of a certain value of horizontal displacement for different levels of peak ground acceleration.

1. The spatial variability of soil properties may affect the factor of safety by approximately ±13%.

2. Slopes with spatially variable soil properies have a 78% probability to experience larger permanent horizontal displacements compared to those predicted for homogeneous slopes.

3. The probabilistic approach used in this study allows a realistic evaluation of the effects of the spatial variability and earthquake excitation characteristics on the slope permanant displacement.

A more comprehensive analysis of the results will be presented elsewhere.

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