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Effect of spatial soil variability, incline of slopes and seismic stimulation on permanent seismic slope displacement.

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***Abstract*-The parameters of shear strength, even within the same soil layer, will vary from point to point as a result of the natural heterogeneity of the materials. Stochastic methods have been introduced to calculate the uncertainty and spatial variability of soil parameters [1]. As opposed to deterministic methods, probabilistic methods allow the selection, based on the specifications of each project, of an acceptable risk level. Moreover, such methods are consistent with the concept of risk parameters of soil vibration and constitute their extension at the fault indicators level, being directly related to the performativity of constructions [2]. The main objective of this paper is to investigate the effect of spatial variability of soil, the slope of the banks and of seismic excitation on permanent seismic displacements [3]. The calculation of permanent displacements within probabilistic frames is achieved by combining the Local Average Subdivision (LAS) algorithm introduced by Fenton and Vanmarcke in 1990 [4] and finite difference software FLAC (Fast Lagrangian Analysis of Continua) used in this paper [5].**

***Keywords*: slope incline, uncertainty, stochastic methods, spatial variability, seismic stimulation, permanent seismic displacement.**

1. INTRODUCTORY NOTIONS

This paper investigates the effect of spatial variability of soil properties, the incline of the slopes, as well as the intensity and content of seismic frequency excitation on developing permanent displacement. For this purpose, static and dynamic simulations of a significant number of slopes with spatial variability of properties are analyzed and the results are compared with their equivalent of homogeneous slope analyses. The performance criterion under dynamic conditions is the residual displacement of the mass of the slopes at the end of seismic vibration. Based on experimental results of soil characteristics from the bibliography and use of the LAS methodology and the Mathematica program **[6]** , an extensive range of random fields was created via an automated process to express the spatial variability of soil properties with the desired characteristics. Then, by using the random fields territorial properties, a new automated process was created through which a large number of numerical simulations for the seismic analysis of slopes was carried out. The spatial variation of properties, as demonstrated through numerical simulations, significantly impacts the values of permanent displacements that appear when the slope is stimulated with a series of historical recordings of seismic vibrations as shown below.

2. EFFECT OF SPATIAL VARIABILITY OF SOIL PROPERTIES OF SLOPES IN SEISMIC DAMAGE

The parameters examined with regard to their impact on permanent seismic displacement are as follows:

1. Spatial variability of properties.
2. The characteristics of autocorrelation lengths l_x and l_y
3. Slope of the bank
4. The magnitude of the maximum seismic acceleration.
5. The characteristics of seismic excitation (frequency content).

2.1 Data of parametric analysis

Initially we present the parametric analysis data used for the resolutions. Taken into account are average values and variances of spatially-varying standard variables like: cohesion c, internal friction angle φ, density ρ, modulus of elasticity

Young E, while for the sake of simplicity the values of the diastolic angle ψ and Poisson's ratio ν, are taken as constants. Average values μ and standard dispersions σ of soil properties, and the σ/μ ratio are given in Table 1.

In table 2 the values of correlation coefficients ρ_{ij} between i and j parameters based on published experimental data are presented. Correlation coefficients values for which no experimental data have been found, such as between E and ρ , are taken as equal to zero.

Table 3 gives the values of spatial variability (autocorrelation) lengths l_x, l_y in the horizontal and vertical directions respectively

TABLE 1. AVERAGE VALUES AND STANDARD DISPERSION OF SPATIALLY-VARYING VARIABLES OF SOIL SLOPES. [7]

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

TABLE 2. CORRELATION OF SOIL PARAMETERS

Correlation factor ρ_{ij}					
Parameter	c (KPa)	φ°	ρ (KN/m3)	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. PAIRS OF AUTOCORRELATION VALUES USED IN THE RESOLUTIONS.

Lengths of spatial correlation			
l_x , m	20	40	20
l_y , m	2	2	4

TABLE 4. GEOMETRIC ELEMENTS OF SLOPES

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

Table 4 gives the characteristics of the three different slope geometries used in the analyses. The corresponding numerical discrepancies of the geometry for cases A, B and C of Table 4 are shown in Figures 1, 2 and 3. In each cross-section of the slopes, a few characteristic points (A, B, and C) are given in which the seismic response time has been calculated for further processing.

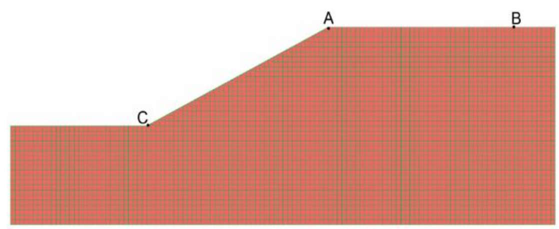

Figure 1. Geometry A: Discrimination of slope geometry with a 2:1 slope.

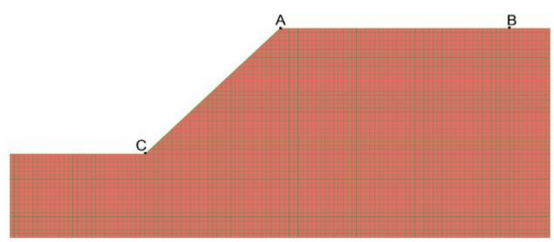

Figure 2. Geometry B: Discrimination of slope geometry with 1:1 slope.

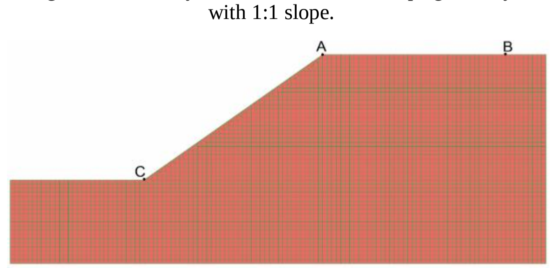

Figure 3. Geometry C: Discrimination of slope geometry with 4:3 slope.

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2.2 Seismic stimulation

Seismic stimulation for the following analyses uses five historical acceleration recordings from the earthquakes of Kalamata (1986), Lefkada (2003), Kobe (1995), Northridge (1994) and Friuli (1976) **[8].** Table 5 provides the key elements of historical records. Also, Figure 4 shows the Eurocode 8 spectrum calibrated for a maximum acceleration of 0.3g.

TABLE 5. HISTORICAL SEISMIC EXCITEMENT RECORDS

Earthquake	**Magnitude Mw**	**Concentric Distance 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

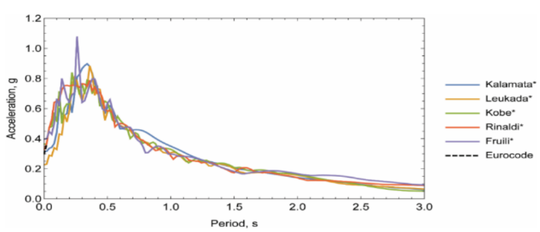

Figure 4. Sequencing responses of modified seismic stimuli and rock design according to the Eurocode 8. The stimuli were modified so that the acceleration spectrum would approach that of Eurocode 8.

3. REPRESENTATIVE RESULTS OF PARAMETRIC ANALYSES

This section presents representative results of seismic response and permanent displacements of extremities, on the three geometry cases given in figures 1, 2 and 3, by mutual stimulation based on the Lefkada earthquake (2003). Aiming for comparable results of parametric analyses, we used geometry extremities and combinations of strength parameters that approximately lead to a minimum safety factor under the FS = 1.5. Despite this, it is evident that there are significant fluctuations in the response and permanent displacement of the slopes due to the spatial variability of the soil properties.

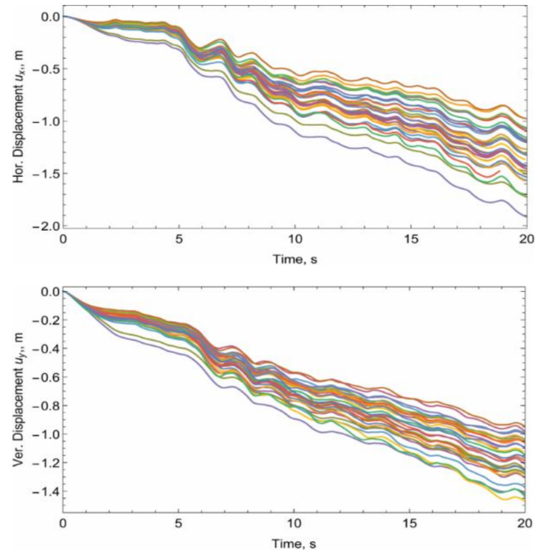

Figure 5. Geometry A: (a) horizontal and (b) vertical displacement at point A.

TABLE 6. PERMANENT DISPLACEMENT OF SLOPES.

Geometry (incline)		**Homogeneous soil (m)**	**Spatial soil variability**		
			Minimum value (m)	**Maximum value (m)**	**Maximum deviation (%)**
A (2:1)	Horizontal	1.04	0.97	1.92	84.6
	Vertical	1.04	0.94	1.42	36.5
B (1:1)	Horizontal	0.45	0.51	1.5	233.3
	Vertical	0.38	0.36	1.73	355.3
C (4:3)	Horizontal	0.45	0.78	1.44	220.0
	Vertical	0.39	0.64	1.27	225.6

Figures 6, 7, 8 show the results of permanent horizontal, vertical and total deformations at the end of seismic vibration for the 6 seismic intensity levels and the 5 seismic excitements examined. The change in the mean value of the permanent horizontal displacement can be approximated by the equation $f[x] = ax^b$ (1) where x is the ratio a_g/g of the maximal acceleration of excitation (α_g) to the acceleration of gravity (g), while a and b are parameters of the equation.

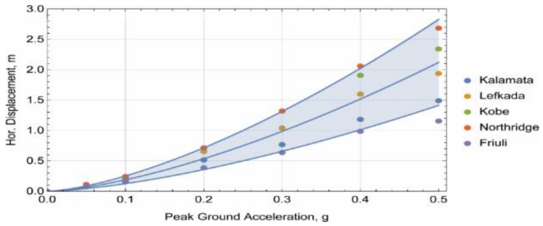

FIGURE 6: INFLUENCE OF THE MAXIMUM ACCELERATION AND THE FREQUENCY CONTENT OF THE STIMULATION ON THE PERMANENT HORIZONTAL DISPLACEMENT OF THE SLOPE CORNICE WITH A 2: 1 GRADIENT (POINT A) .

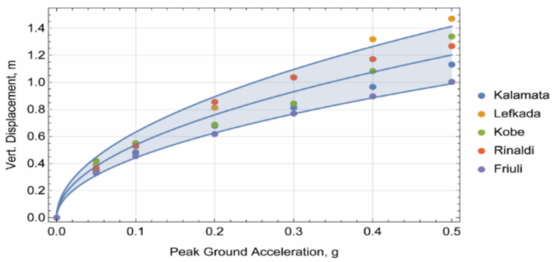

FIGURE 7: INFLUENCE OF THE MAXIMUM ACCELERATION AND THE FREQUENCY CONTENT OF THE EXCITATION ON THE PERMANENT VERTICAL DISPLACEMENT OF THE SLOPE CORNICE WITH A 2: 1 GRADIENT (POINT A) .

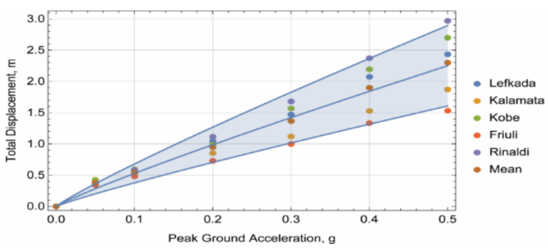

Figure 8: Influence of the maximum acceleration and the frequency content of the stimulation on the permanent total displacement of the slope with a 2:1 gradient (Point A)

4. EFFECT OF SLOPE INCLINE

The results of Table 7 are presented for the purpose of investigating the effect of slope incline on permanent displacements.

TABLE 7. SOIL PROPERTIES, STATIC SAFETY FACTOR AND MEAN VALUES OF PERMANENT DISPLACEMENTS OF HOMOGENEOUS SLOPES FOR THE FIVE SEISMIC STIMULI (PGA = 0.30G)

Inclination of a slope	c, kPa	ϕ°	FS	$\bar{u}_x$, m	$\bar{u}_y$, m	$\bar{u}$, m
2:1	50	30	2.58	0.39	0.35	0.53
4:3	50	30	1.71	0.41	0.47	0.63
1:1	50	30	1.45	0.76	0.54	0.94

The following formulas show the probability density functions of the component permanent displacement u for the three slope inclines, i.e. 2:1, 4:3 and 1:1. The best-described distributions are Weibull, Extreme Value and Gamma **[9].**

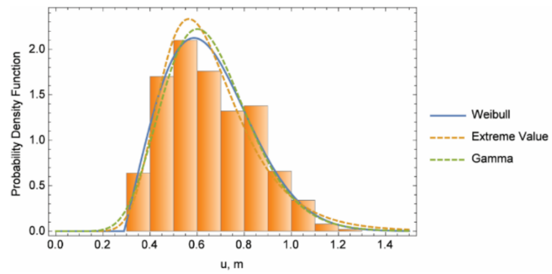

FIGURE 9: COMPONENT PERMANENT DISPLACEMENT *U* FOR A 2:1 GRADIENT (PGA = 0.30G)

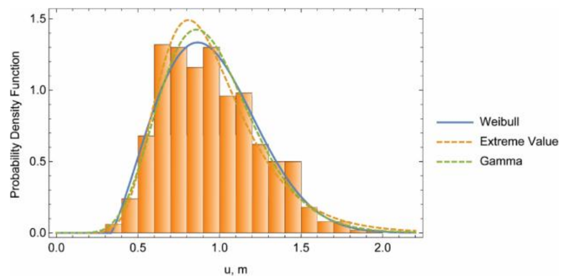

FIGURE 10: COMPONENT PERMANENT DISPLACEMENT *U* FOR 4:3 (PGA = 0.30G).

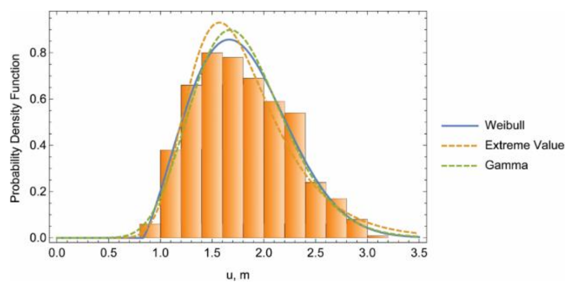

FIGURE 11: COMPONENT PERMANENT DISPLACEMENT *U* FOR A 1:1 GRADIENT (PGA = 0.30G).

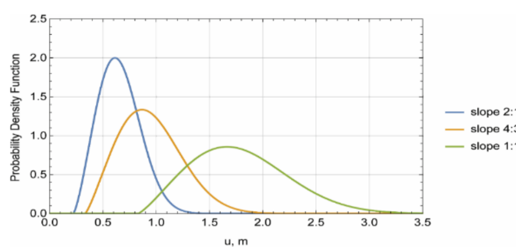

FIGURE 12: PROBABILITY DENSITY FUNCTION OF THE COMPONENT PERMANENT DISPLACEMENT *U* FOR SLOPE SLOPES OF 2:1, 4:3 AND 1:1 (PGA = 0.30G).

5. CONCLUSIONS

1. The nonlinear variation of the seismic slope permanent displacement with the magnitude of the seismic intensity (ie the maximum acceleration $a_{g\max}$) can be described with an exponential

function of the form $a\,(a_{g\max}/g)^b$, where a, b are stable.

2. For a fixed value of seismic intensity, distribution of permanent displacement resulting from different seismic excitations follows an approximately uniform distribution. The effect of the frequency content of seismic excitation is important as it generates a range of variation of results equal to $\pm 40\%$ in the case of horizontal displacement and $\pm 20\%$ in the case of vertical displacement. However, it is desirable to increase the number of seismic stimuli with different frequency content for a better statistical description of the effect of the seismic excitation characteristics.

3. Regarding the effect of slope incline, the results show that, as slope incline increases, the mean and standard dispersion of permanent seismic displacement significantly increase.

4. The present investigation has shown that the calculation of rates of movement of slopes under seismic loading can be carried out pragmatically with probabilistic and stochastic methods. Differences in the response due to spatial variability of soil properties are quite significant. It is desirable for the parametric investigations of this research to be further extended in order to best describe the uncertainties and the overall conclusions to be reassessed in order to be taken into account in long-term regulatory provisions.

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