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ROLE OF NUMERICAL MODEL AND PARAMETER VARIABILITY ON SEISMIC RESPONSE OF SLOPES: THE CASE OF LAS COLINAS LANDSLIDE

Filippo MARCHI¹, Amir M. KAYNIA², Guido GOTTARDI¹, Farrokh NADIM²

ABSTRACT

This paper presents the results of a sensitivity analysis on the influence of the strength, stiffness and damping parameters of the soil on the seismic response of a real slope. The analyses have been performed for the Las Colinas slope (El Salvador) using the finite element code PLAXIS and the data available in the literature. Las Colinas landslide was a destructive event which was triggered by the El Salvador earthquake on 13 January 2001. During this event, 183·500 m³ of volcanic deposit slid and struck the houses on the foothill, killing 500 people. In this study a sensitivity analysis was performed to highlight the influence of the parameter uncertainties on the seismic response of the slope.

The sensitivity analyses on the stiffness and strength parameters of the soil were performed by using their low, best and high estimates, using reported data and empirical equations. The sensitivity studies on the damping factor showed an unexpectedly large influence on the results. For a better understanding of this issue, the role of damping in each layer on the total response was examined separately. In addition, the effects of mesh and model sizes, as well as performance of different boundary conditions were investigated.

The results show that, while a suitable numerical tool is in general capable of predicting and simulating the seismic response and failure of a complex slope, it is essential to undertake a careful evaluation of the mechanical parameters and modelling features. The results also show that for a realistic assessment of the uncertainties of the response it is important to identify the parameters that have the largest influence on the total response.

Keywords: Numerical modelling; Earthquake; Slope stability; Boundary conditions; Las Colinas.

INTRODUCTION

Landslides are causing more and more victims, especially in Asia and America (Petley, 2006). In central Europe, which is moderately threatened by natural hazards, landslides have considerable economic and environmental consequences (NEDIES, 2003).

In particular, significant examples of earthquake-induced catastrophic landslides are often reported. In 1906 the San Francisco earthquake caused landslides for a total area of 40·000 km² (Keefer, 1984). In 1964, the Alaska earthquake (M = 9.2) produced more than 10·000 landslides covering an area of approximately 260·000 km²; the damages due to slope failures were estimated to be more than 50% of the total damages and 1/3 of the fatalities was due to landslides (Keefer, 1984). In 1970 in Perù, the Nevado Huascaran debris avalanche killed more than 18·000 people (Plafker et al., 1971). In 1989 the famous

¹ University of Bologna, e-mail: fil.marchi@gmail.com; guido.gottardi2@unibo.it

² Norwegian Geotechnical Institute & Int. Centre for Geohazards, e-mail: amir.m.kaynia@ngi.no; farrokh.nadim@ngi.no

Loma Prieta earthquake in California triggered thousands of landslides, covering approximately 15'000 km² for an economic damage of more than 30 million dollars (Keefer & Manson, 1995). Finally, the Northridge earthquake in California (M = 6.7) in 1994 induced more than 11'000 slope failures (Harp & Jibson, 2002).

The analyses of earthquake triggered landslides can be carried out using finite element and finite difference methods. However, such methods are sometimes used without the necessary awareness of the influence of the parameters and of the boundary conditions on the final results. In this paper, the case of Las Colinas landslide (El Salvador) is used to investigate sensitivity to boundary conditions and model parameters. In particular, the boundary condition effect is studied in relation to the model proportions, using standard absorbing and new load-boundary conditions. Sensitivity analyses on model parameters, with special attention to soil stiffness and damping, are performed to assess the variability of the relevant results.

LAS COLINAS CASE HISTORY

The 2001 Las Colinas landslide (Santa Tecla, El Salvador, Central America; Figure 1) occurred during a major earthquake. This landslide, involving about 183'500 m³ of volcanic deposit (Crosta et al., 2004), had a total runout of about 800 m, and resulted in about 500 casualties; it can be considered one of the most destructive landslides ever known. The total length measured along the landslide axis, from the upper crown to the toe of the accumulation, is about 715 m with a relief of 160 m. The slope on which the landslide occurred can be subdivided into two major sections: the source area and the transportation area. The upper slope area was characterized by an average pre-failure slope of about 35°. The post-failure morphology is characterized by a bowl-shaped niche, 100 m in diameter, subvertical in the upper part and sloping at 17-22° in the lower, more planar area. Tension cracks formed behind and on the two sides of the head scarp. The subvertical part of the failure surface shows clear sub-parallel layering of the volcanic deposit. The transportation area had an average slope of 28° and was disturbed by the transit of the failed mass with scouring of the surficial soil layer ranging between a few decimeters and about 7 m.



Figure 1. Las Colinas Landslide (Crosta et al., 2005)

The almost flat deposition area was completely covered by small middle class houses with a network of east and north trending roads (Figure 2). The flowing material destroyed all the existing buildings along its path. For more details see Crosta et al. (2005).



Figure 2. Las Colinas Landslide Aerial View (Crosta et al., 2005)

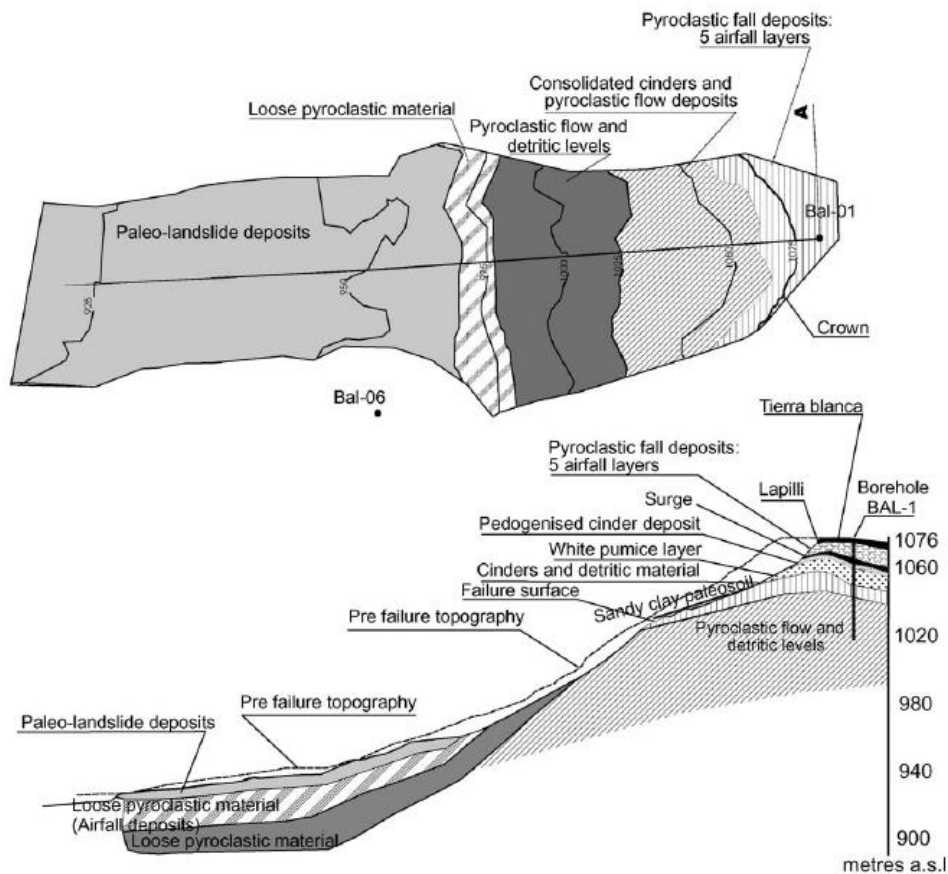


Figure 3. Lithological Map and Longitudinal Cross Section in Correspondence of Las Colinas Landslide Area (Crosta et al., 2005)

LITHOLOGICAL AND GEOTECHNICAL CHARACTERIZATION

The litho-stratigraphy of the area has been reconstructed from observing a series of outcrops and stratigraphical sections, and by borehole logs. Lithologies include pyroclastic air fall, cinders, pyroclastic flow and ignimbritic deposits. Pyroclastic fall deposit, with a total thickness of about 15 to 25 m, are formed by 5 characteristic levels (Figure 3): the Tierra Blanca unit, mainly cinders with change in thickness from the ridge to the slope toe; accretionary lapilli from a hydromagmatic eruption with variable thickness; discontinuous layer of lapilli and weakly vesiculated bombs with surge structures; surge deposit; white pumice and cinder layer with an average thickness of 1.5 m.

These deposits are generally weakly bonded with the exception for the accretionary lapilli. A layer of heterogeneous cinder deposits lies below the pyroclastic fall deposits and includes both debris and pumice material (San Salvador formation). Pyroclastic flow deposits and heavily fractured lava flows (Bálsamo formation or a lower member of the San Salvador formation) lay below the cinder deposits. Finally, ignimbrites of the Bálsamo formation form the core of the cordillera and outcrop on the northern slope and along the SE slope. The failure plane was well preserved with abundant striations produced during the initial sliding phase. Along the failure surface a clastic layer with abundant biotite and a paleosoil lying over a faulted and jointed ignimbrite was observed. This level and the paleosoil dip downslope to the north-northeast, with an average 17° inclination. Twelve boreholes have been drilled in the study area to depths ranging between 33 m and 90 m below the surface and it is important to notice that groundwater has never been observed during and after drilling (Crosta et al., 2005). Physical and mechanical characterization of the involved soils has been accomplished through laboratory and field tests. Classification and determination of index parameters have been based on tests on 76 samples. In situ properties have been evaluated through SPT (Standard Penetration Test) within the various boreholes (Crosta et al., 2005). The analyses that will be presented in this chapter will deal only with the triggering mechanism through slope stability analyses, whereas the issue of the runout distance will not be addressed. The parameters suggested by Crosta et al. (2005) for the various slope materials are listed in Table 1.

Table 1. Soil Units Parameters (Crosta et al., 2005)

Soil type	Angle of friction [°]	Cohesion [kPa]	Dry unit weight [kN/m ³]
Pyroclastic	30-35	60-80	11-16
Epiclastic	30-33	30-40	11-16
Paleosoil	20-24	5-10	11-16
Tuff	35-38	200	18

The relevant stiffness characteristics were here estimated with empirical relationships. For clayey materials, like the paleosoil one, the ratio between the shear modulus (G) and the undrained shear strength measured in a simple shear test (s_u) was given as a function of Plasticity Index (PI) and Overconsolidation Ratio (OCR) by Kramer (1996). For sandy materials, like all the other layers of the model, shear modulus (G) was given as a function of the mean principal effective stress (σ'_m) and of a coefficient ($K_{2,max}$) determined from the relative density or the void ratio, according to Kramer (1996). As no data were available, the relative density was obtained using the empirical chart by Schmertmann (1978). For this reason the variability in the strength parameters can be reflected also on the stiffness values. In order to gain insight into the effect of these uncertainties, the case was analyzed using three different sets of

parameters: the Base-Case model was established using the average value of both strength and stiffness parameters, the Low-Estimate model using the lowest values and the High-Estimate model the highest values. The values of these parameters are listed in Table 2. The Poisson's Ratio (ν) was assumed to be always 0.35 as its influence was considered minor. The Rayleigh damping was first assumed to be $\xi = 5\%$ at frequencies $f_1 = 0.5$ Hz and $f_2 = 5$ Hz.

It should be noted that the assumption of Rayleigh damping that has become common in most time domain finite element models is basically for mathematical convenience. The pioneering work on soil damping (e.g. Seed and Idriss, 1970) has established the dependence of damping on the level of cyclic shear strain in the soil. Laboratory tests often indicate damping values of the order of 1-2 % at very low shear strains increasing to about 20-30 % at shear strains in the order of 1% to 10%. While inclusion of soil damping, consistent with the test results, has been recently achieved in one-dimensional site response analyses (e.g. Phillips and Hashah, 2009) no such attempt has been done in two and three dimensional finite element solutions in the time domain. Therefore, any solutions based on Rayleigh damping, such as those in this study, should be considered as approximations to the real soil behavior as regards damping.

Table 2. Models Parameter

Low-Estimate				Base-Case				High-Estimate			
γ [kN/m ³]	G [kPa]	C [kPa]	ϕ [°]	γ [kN/m ³]	G [kPa]	C [kPa]	ϕ [°]	γ [kN/m ³]	G [kPa]	C [kPa]	ϕ [°]
Loose Pyroclastic											
12	41490	60	30	13.5	73750	70	33	15	101630	80	35
Cinders											
12	69710	30	30	13.5	109180	35	32	15	137330	40	33
Paleosoil											
12	5500	5	20	13.5	8250	7.5	22	15	11000	10	24
Tuff											
18	137260	200	35	18	179340	200	37	18	210820	200	38

FINITE ELEMENT NUMERICAL MODELLING

First of all a very large model (total length = 1750m) was used to ensure that boundary influence on the results could be neglected. The geometry of the model presented a ratio between the thickness of the soil on each side of the slope and the distance from the relevant boundary equal to 1/7; moreover the boundary condition used was the standard earthquake boundary implemented in PLAXIS (Brinkgreve et al., 2008) which consists of dampers in the horizontal and vertical directions. The model is presented in Figure 4 and Figure 5.

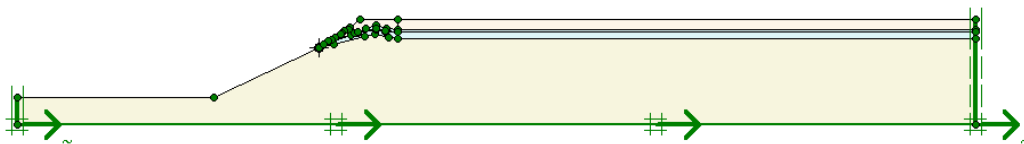


Figure 4. Las Colinas Model

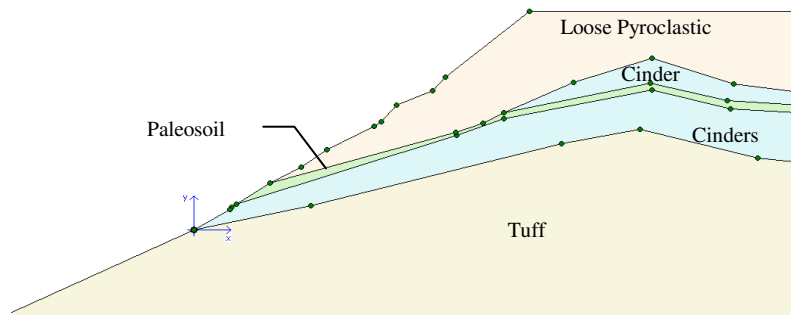


Figure 5. Crucial Area Enlarged from Figure 4

For the dynamic excitation, the 13 January 2001 accelerogram recorded at San Rafael Hospital (Cepeda et al., 2004) was used. This signal was corrected for a linear displacement drift. The corrected acceleration time history is plotted in Figure 6. The total duration of the excitation is 74 s and the data are recorded every 0.005 s.

The calculation was carried out in two phases: (1) application of the gravity load; (2) imposition of the acceleration time history at the base of the model. The results of the analyses with the different sets of parameters are presented in terms of displacements in Figure 7; this parameter is considered the most representative even if the response of the slope is more complex. The displacement time history shows some dynamic oscillation and a larger component of permanent displacements. The yielding of the soil, mostly in the paleosol layer, is responsible for the development of permanent downslope displacements varying between 2 m and 5 m for the different models. In this case, the Low-Estimate model shows the largest displacements. The rather large variability in the results emphasizes the importance of sensitivity analyses.

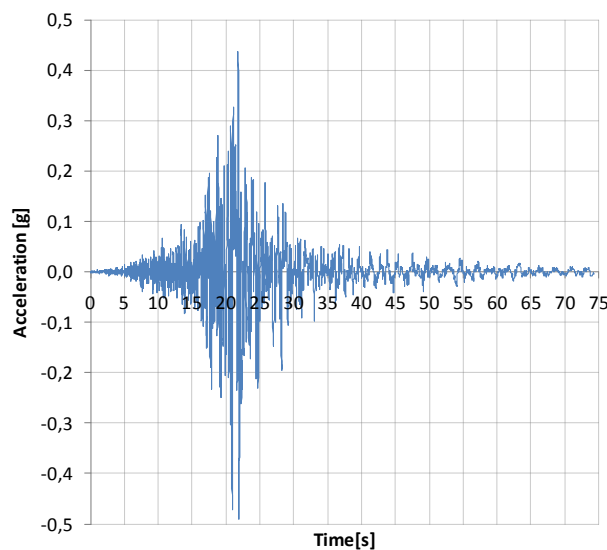


Figure 6. Corrected Acceleration Time History

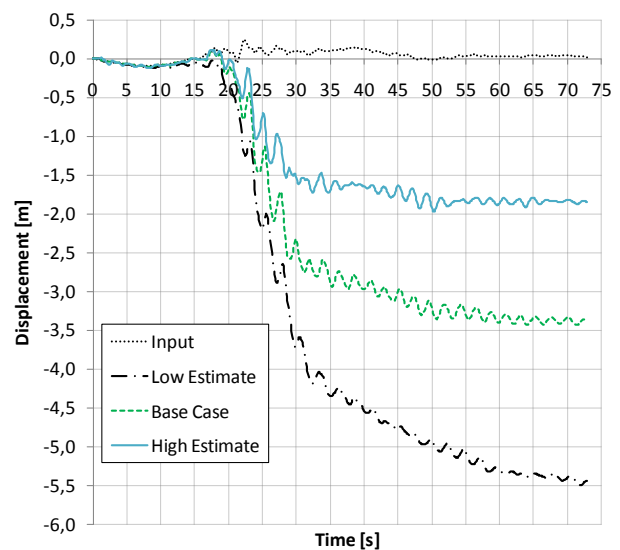


Figure 7. Displacement Plot at Top of Slope

Figure 8 displays a contour map of the shear strains in the most critical part of the model for the Base-Case analysis. The strain concentration shows that failure of the slope occurs mainly into the weak paleosoil layer.

In order to test the reliability of the model, mesh performance was tested. Mesh 1 was realized generating the finest standard mesh implemented in PLAXIS (968 elements), Mesh 2 was realized from Mesh 1 by refining the critical clusters (1'225 elements) and, finally, Mesh 3 was obtained from Mesh 1 with a double refinement of the crucial clusters and another refinement along the line closer to the slip surface (1'779 elements). The Mesh arrangements were tested using the Base-Case values of stiffness and strength parameters. Figure 9 displays the horizontal displacements at the top of the slope; result comparison of outlines a very small influence of the mesh size. Mesh 2 was used for all further analyses.

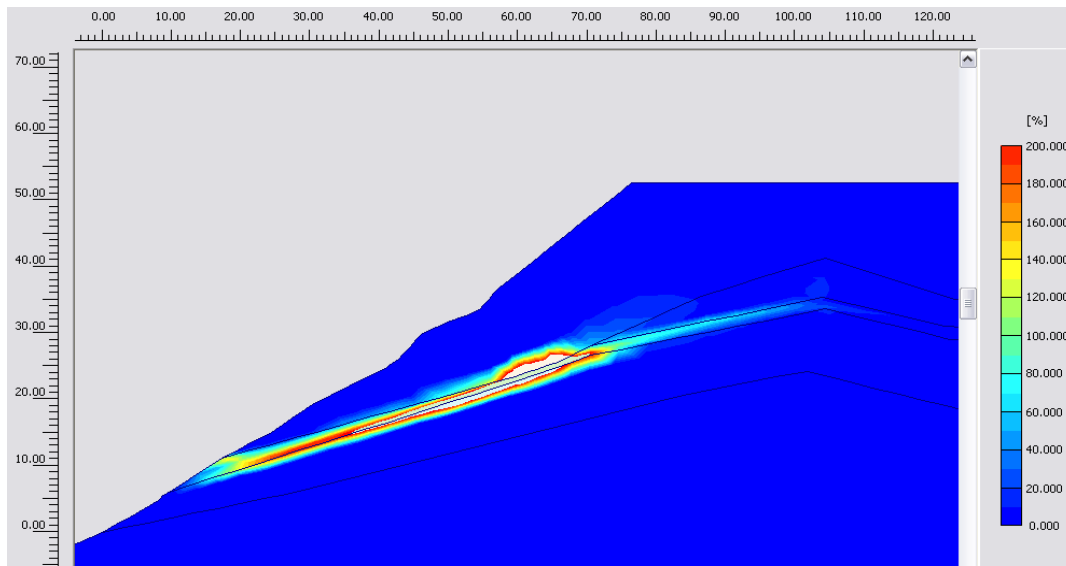


Figure 8. Contour Plot of Earthquake-Induced Shear Strains

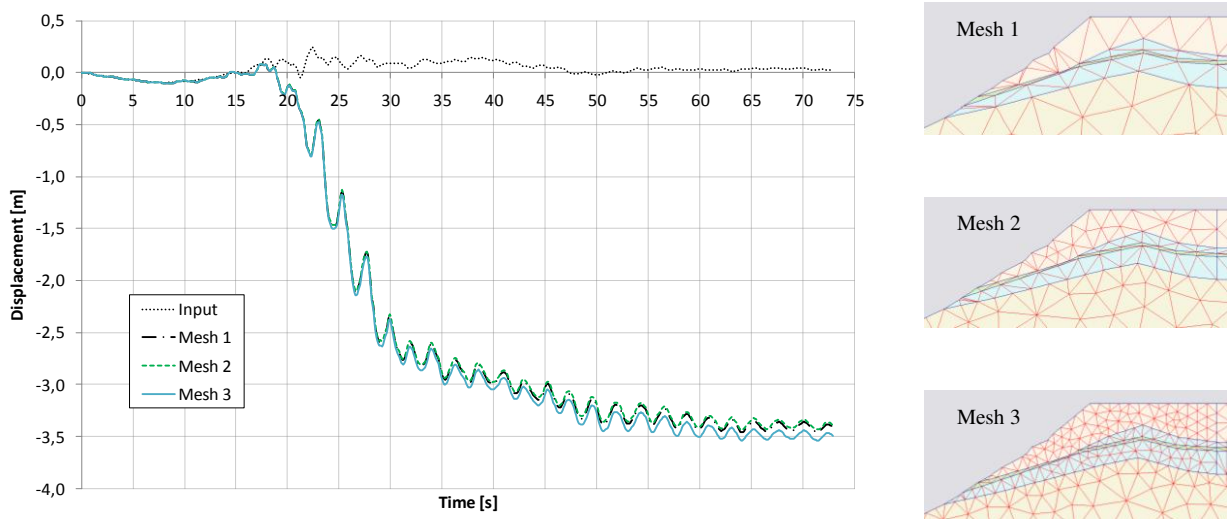


Figure 9. Displacement Plot at Top of Slope for Different Mesh Sizes

A series of analyses of simple models (Marchi, 2010) showed that the model proportions (i.e. the ratio between the length and the height of the model) and boundary conditions are crucial issues for its accuracy. A model is usually considered sufficiently large if the ratio between the thickness of the soil at each side of the slope and the relevant distance from the boundary is 1/3. Such condition was tested here with two different boundary configurations: i) PLAXIS standard earthquake boundary conditions and ii) a new load-boundary, which was realized by fixing the vertical displacements at the boundary and applying triangular lateral loads, with the basic idea of simulating the horizontal stress state.

Figure 10 displays the results of these analyses. The first model had a ratio between the depth of the soil on each side of the slope and the distance from the boundary equal to 1/7 and was coupled with the standard adsorbing boundaries (Stnd Bound. + Long Model), the second had such ratio equal to 1/3 coupled with the standard adsorbing boundaries (Stnd Bound. + Medium Model) and the third had such ratio equal to 1/3 coupled with the load boundaries (Load Bound. + Medium Model). The graph shows that using the smaller model coupled with standard boundary consistently underestimates displacements, while the load boundary tends to perform very well when compared to the realistically reliable long model. The remaining analyses in this study were performed by using the long model.

PARAMETRIC ANALYSIS

Crucial parameters for the results are soil stiffness (shear modulus) and damping. The shear modulus is very important in a dynamic analysis because it is the governing parameter for the wave propagation. In order to investigate this parameter, three analyses were performed starting from the Base-Case parameter values and varying only the shear modulus. Considering the G values used for the Base-Case model as 100%, two other cases were made by taking G values respectively as 66% (2/3) and 150% (3/2); G is varied simultaneously in all the layers.

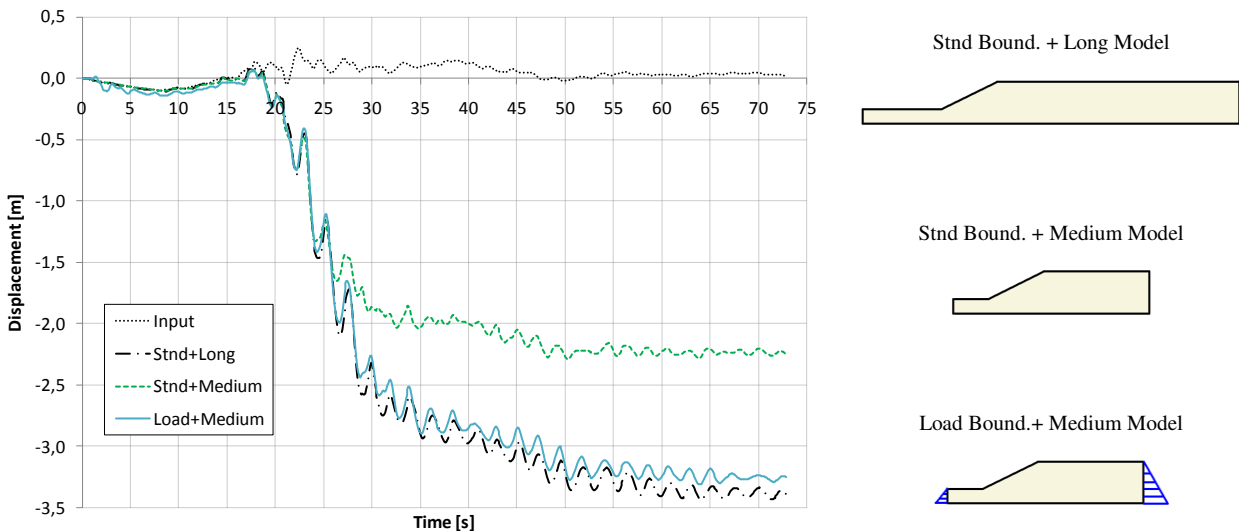


Figure 10. Displacement Plot at Top of Slope for Different Proportions and Boundaries

Figure 11 displays the horizontal displacements at the top of the slope, while Figure 12 displays the response spectra of the results. The effects of G variability can be better noticed in the latter plot as it affects the range of frequencies amplified by the model. Shear modulus can affect the response considerably and it is not always straightforward to predict how G influences the result trend.

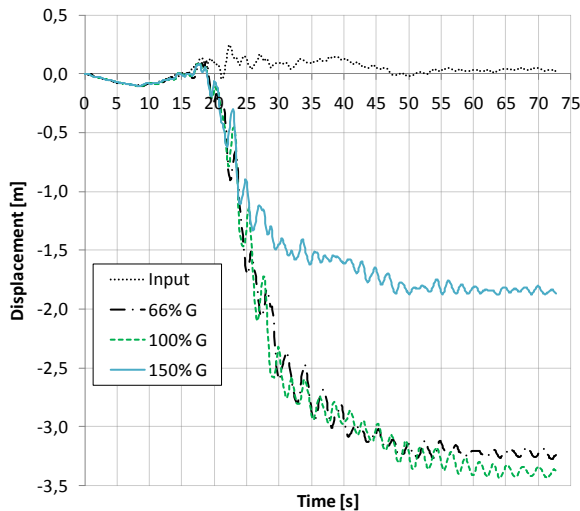


Figure 11. Displacement Response for Different Shear Modulus Values

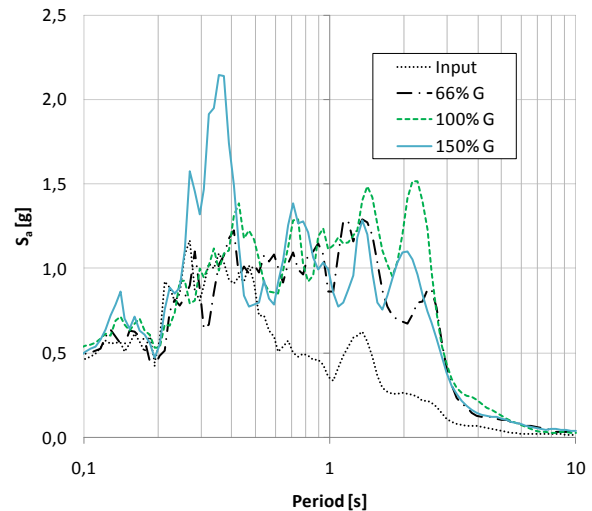


Figure 12. Response Spectra for Different Shear Modulus Values

In the previous analyses, the Rayleigh damping was assumed to be $\xi = 5\%$ at frequencies $f_1 = 0.5$ Hz and $f_2 = 5$ Hz. In order to investigate the impact of this assumption, a sensitivity analysis was finally carried out. The value of damping ratio ξ was kept constant, while only the higher frequency f_2 was varied. In this way the effect of damping higher frequencies is more evident. One of these analyses was realized assuming f_2 value equal to 3Hz and in the third analysis f_2 value was assumed to be 10Hz. The damping parameters were varied simultaneously in each layer. In this case all the model materials had the same damping coefficient.

Figure 13 represents the time histories of the displacements at the top of the slope for the three damping cases. The plot indicates that the influence of Rayleigh damping is critical. In contrast, the importance of these parameters is often neglected and their values are roughly estimated. The variation of the upper frequency (f_2) changes the range of frequency above which the response is overdamped and under which the response is underdamped. The graph shows that these frequencies play an important role and influence critically the final displacement at the top of the slope.

Figure 13 shows a significant influence of damping which required further investigation. The damping parameters were then kept constant in the entire model and were varied only in one layer at a time. In order to better highlight the differences, the values used for the higher frequency (f_2) were taken equal to 3 Hz and 10 Hz.

The results of these analyses are plotted in Figure 14. In order to provide a reference, the previous results (with homogeneous damping in all layers, see Figure 13) are reported in thicker solid lines. The results show that tuff and cinders have a limited influence on the total results even if the tuff layer is very thick. A moderate effect can be related to the loose pyroclastic materials but it is mainly the paleosoil that affects the model behavior. In Figure 15 only the most relevant analyses in terms of spectra are also plotted.

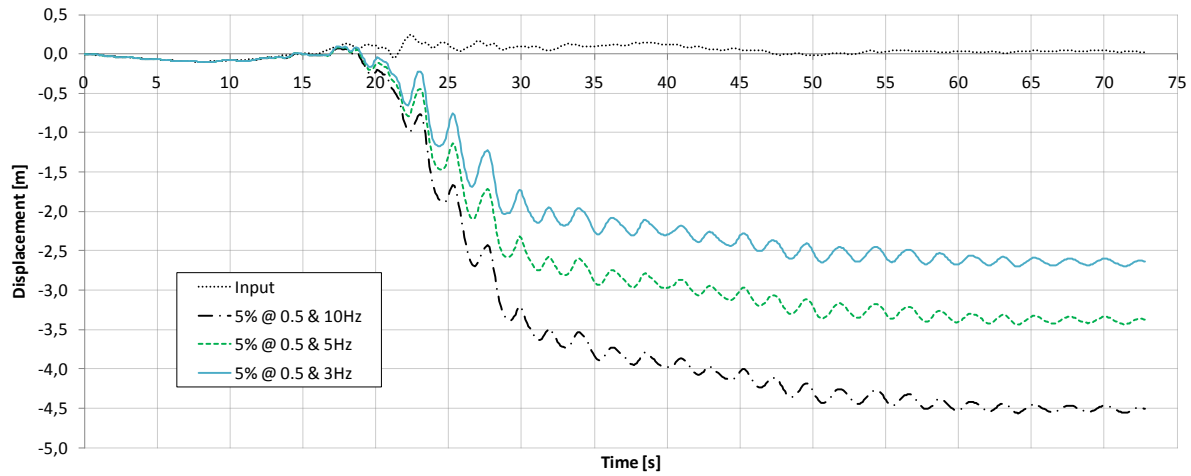


Figure 13. Displacement Time Histories at Top of Slope for Different Damping Conditions

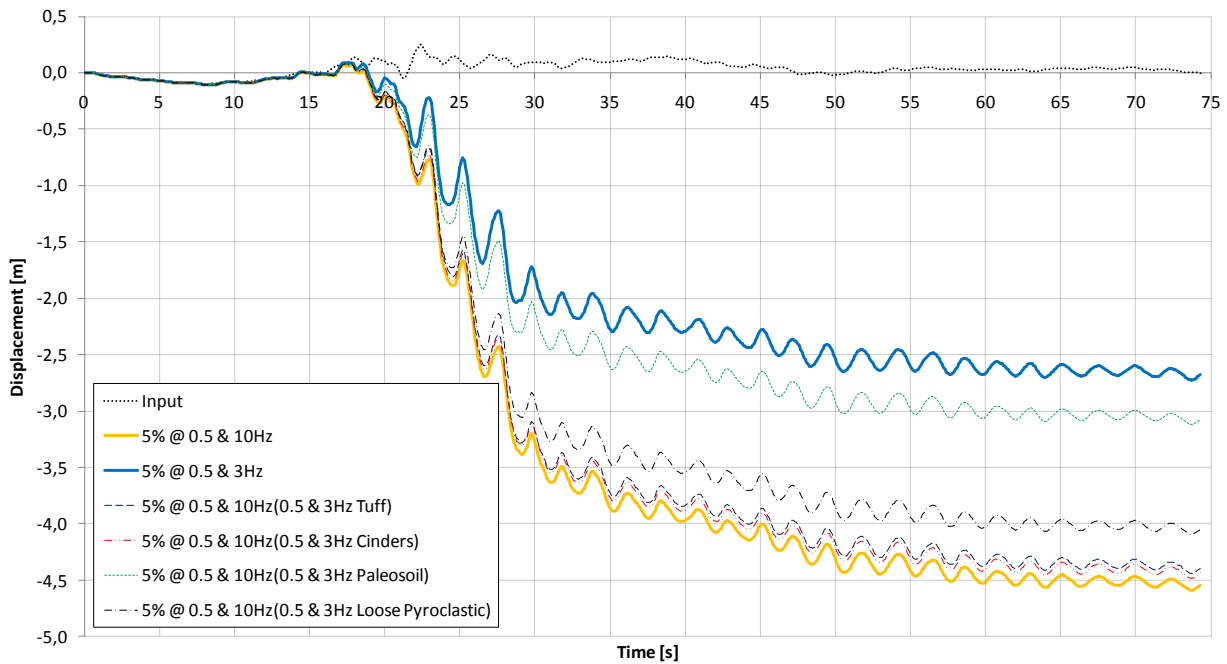


Figure 14. Displacement Time Histories at Top of Slope for Different Damping Assumptions in the Selected Layers

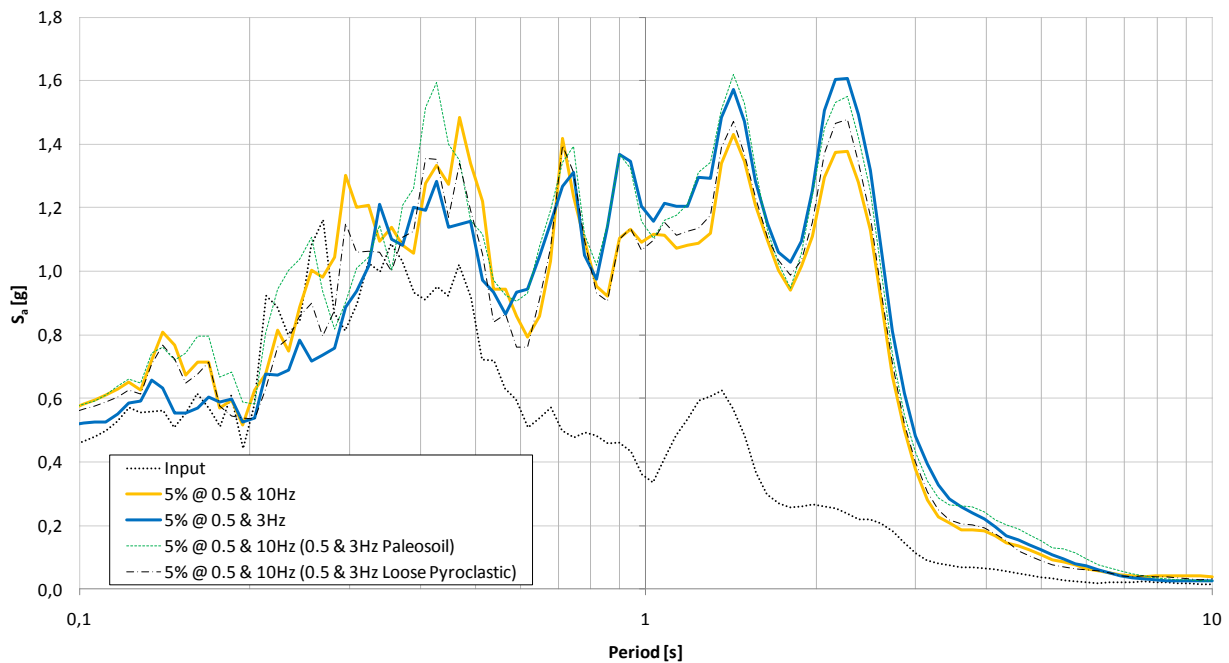


Figure 15. Response Spectra at Top of Slope for Different Damping Assumptions in the Selected Layers

CONCLUSIONS

The analyses performed outlined some interesting results and allow formulating the following remarks:

- The effect of model proportions and boundary conditions can consistently affect the results. In this case, a very long model (ratio between the thickness of the soil on each side of the slope and the relevant distance from the border of 1/7) showed to be accurate and reliable. Assuming this ratio equal to 1/3 (medium model), as usual, showed that if standard boundaries are used the resulting displacements are considerably underestimated. In contrast, if a slightly more sophisticated load-boundary is coupled the results become very close to what expected.
- As expected, shear modulus turned out to have a large influence on the global response. Moreover, it is not possible to exactly predict how G affects the trends in the results.
- Contrary to what is commonly assumed, the estimate of Rayleigh parameters is extremely important for the accuracy of the model; these analyses showed special sensitivity to the damping effect, even in a thin layer.
- In order to realize an accurate model, it is very important to identify the layers and the parameters that have major effects on the results. Sensitivity analyses on these aspects are therefore recommended in any project, in order to gain more confidence into the model parameters and possible relevant limitations.

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REFERENCES

- Brinkgreve R.B.J., Broere W., Waterman D. et al., 2008. Plaxis 2D Version 9.0 User Manual.
- Cepeda, J.M., Benito, M.B., Burgos, E.A., 2004. Strong-motion characteristics of January and February 2001 earthquakes in El Salvador. In: Rose, W.I., Bommer J.J., Lopez, D.L., Carr, M.J., Major, J.J. (Eds.), Natural Hazards in El Salvador. Special Paper, vol. 375. Geological Society of America, Boulder, Co, pp. 405-421.
- Crosta, G.B., Imposimato, S., Roddeman, D., Chiesa, S., 2004. The 2001 Las Colinas landslide, El Salvador: from geology to numerical modelling. Proceeding of the 9th International Symposium on Landslides, Rio de Janeiro, Brasil, June 2004.
- Crosta, G.B., Imposimato, S., Roddeman, D., Chiesa, S., Moia F., 2005. Small fast-moving flow-like landslides in volcanic deposits: The 2001 Las Colinas Landslide (El Salvador), Engineering Geology 79 (2005) p. 185-214.
- Harp, E.L., Jibson, R.W., 2002. Anomalous concentrations of seismically triggered rock falls in Pacoima Canyon: are they caused by highly susceptible slopes or local amplification of seismic shaking? Bulletin of the Seismological Society of America 92, 3180-3189.
- Keefer, D.K., 1984. Landslide caused by earthquakes, Geological Society of America Bulletin 105, p. 521-536.
- Keefer, D.K., and Manson M.W. 1995. Landslide produced by the 1989 Loma Prieta earthquake – regional distribution and characteristics, in The Loma Prieta, California, Earthquake of October 17, 1989 – Landslides, D.K. Keefer (Editor), U. S. Geol. Surv. Profess. Pap. 1551-C.
- Kramer, S.L., 1996. Geotechnical Earthquake Engineering, William J. Hall Edited.
- Marchi, F., 2010. Application of numerical methods to earthquake stability assessment of slopes, Master thesis, Alma Mater Studiorum – Università di Bologna.
- NEDIES, 2003. Lesson learnt from Natural Landslide Disaster in Europe, European Commission Joint Research Center. In: Hervas, J. (Ed.), Natural and Environmental Disaster Information Exchange System NEDIES. http://eussoils.jrc.ec.europa.eu/Esdb_Archive/eussoils_docs/other/eur20558EN.pdf.
- Petley, D.N., 2006. An analysis of the occurrence of fatal landslide in 2005. Geophysical Research Abstracts 8, 02139.
- Phillips, C. and Hashash, Y.M.A. 2009. Damping formulation for nonlinear 1D site response analyses. Soil Dynamics and Earthquake Engineering, 29, 1143–1158.
- Plafker, G., Ericksen, G.E., Fernandez Concha, J., 1971. Geological aspects of the May 31, 1970, Perù earthquake: Seismological Society of America, Bulletin, v. 61, p. 543-578.
- Schmertmann, J.H., 1978. Guidelines for Cone Penetration Test, Performance and Design, Report No. FHWA-TS-78-209, U.S. Department of Transportation, Washington, D.C.
- Seed, H.B. and Idriss, I.M. 1970. Soil moduli and damping factors for dynamic response analyses. Report EERC70-10, Earthquake Engineering Research Center, University of California, Berkeley, USA.