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Two-dimensional assessment of topographical site effects on earthquake ground response

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ABSTRACT: Amplification factors resulting from earthquakes were assessed for different sites of two real cases: the earthquakes in Colombia (1999) and El Salvador (2001). Major damage was reported concentrated towards the top of slopes and ridges. In El Salvador, a big landslide was triggered during the earthquake in a combined failure mechanism. The geological materials in both cases are medium to highly plastic, and consist of pyroclasts, epyclasts, paleosoils, and residual soils of volcanic origin. From both areas example sites were numerically modeled with the real acceleration records (frequency-independent) and with artificial sinusoidal functions with different frequencies. Results show higher amplification patterns along the top of the hills with an irregular amplification/deamplification trend within narrow ranges. Along the slopes, the amplification generally decreases towards the base with an about exponential trend, and in depth decrease linearly. The results of the landslide section were similar to the failed slope.

1 INTRODUCTION

Earthquakes are one of the main causes of loss of life and injuries throughout the world, and the major cause of damage and destruction of houses, infrastructure and other civil engineering structures. Therefore, it is highly important to determine the earthquake hazard and risk in an area, so that structures can be designed with appropriate factors of safety to withstand the destructive influence of an earthquake tremor. The surface accelerations caused by earthquakes are the main source of destruction, together with the structural conditions of the constructions.

Variations and trends in the damage patterns resulting from earthquakes have been observed and studied in detail in numerous countries. There are several factors that can influence damage patterns, such as source, path, and site effects. Site effects, like topography and geotechnical conditions of the ground, have a major influence leading to large variations of the response, e.g. amplification-deamplification of the seismic waves. Topography and geotechnical properties of the ground cannot be considered separately from each other, because their effects depend on each other.

Traditionally earthquake hazard assessment for the design of surface and subsurface structures is done based on, factors given by seismic codes, experimental approaches, and to a lesser extent on one-dimensional numerical modeling computer programs. One-dimensional numerical modeling assessments are not representative for mountainous areas where topography and lateral variations of the geological layers highly influence the ground response. Therefore, two- and three-dimensional numerical systems are promising tools to improve the state-of-the-art knowledge on the influence of site effects on ground response.

This research is an initial step in two-dimensional (2-D) assessment, using *FLAC* 4.0 (Itasca 2000), of amplification patterns along different topographies under varying dynamic loads. Two real cases were assessed:

1 A highly damaged area during the earthquake in January 25, 1999 in Armenia, Colombia.
2 A ridge along which a big landslide of 129000 m^3 was triggered during the earthquake of El Salvador in January 13, 2001, leaving several fatalities in Las Colinas neighborhood.

The results are compared with previous studies of the same regions with different elaborated and simplified amplification assessment approaches.

2 METHODOLOGY & BACKGROUND

2.1 *Study cases & methodology*

The areas chosen for this assessment correspond with small, simplified regions of approximately 1 km^2 each. The Colombian sites are slopes in a highly damaged area, and the sites from El Salvador belong to a part of the ridge where the landslide was triggered (Figs. 1 & 2).

For each site all the available geological, geophysical, geotechnical, and seismological reports were reviewed and compiled, and the numerical models were defined based on the reported data. NS and EW cross sections were selected from the digital elevation models (DEM) to create the geometrical configurations in *FLAC*. The 2D models were subjected to dynamic loads equal to the frequency-independent filtered acceleration histories of the real earthquakes, and also to a simulated sinusoidal artificial function to simulate a frequency-dependent dynamic load for comparison.

2.2 *Background*

On January 25, 1999 the region of Armenia and Pereira in the El Quindío and Risaralda Departments in Colombia suffered a strong earthquake (Ml 6.2), with a hypocentral depth of 17 km, related to a sinistral fault. This event affected more than 35 towns within an area of 550 km^2, leaving 1230 casualties. The city of Armenia, 13 km north from the epicenter, was the most affected urban area. INGEOMINAS (1999) compiled the geological, geotechnical, and geophysical conditions in detail. Castro (1999) proposed a relationship between the local topographical effect on site response and the damage density, based on an empirical (geometrical) assessment. He found that damages were concentrated towards some geological faults and within the 40 m near some slope crests. Hack et al. (2000) elaborated a 1-D ground response analysis and a microzonation of Pereira and Armenia, with a general analysis of the topographic effects on the response. Leenders (2000) and Hack et al. (in press) evaluated a 3-D ground response with the finite element (FEM) program DIANA for the Nueva Brasilia area, in Armenia, Colombia, finding that peak accelerations correspond with the dangerous resonance frequency ranges of local structures, near the top and close to the morphological edges. However, a trend in amplification factors could not be established.

On January 13, 2001 El Salvador underwent a strong earthquake (Mw 7.6), 100 km off the coast, with a hypocentral depth of 60 km (NORSAR et al., 2001), related to subduction. This event triggered thousands of landslides in scattered patches of high concentration within the southern half of the country. The Las Colinas was one of the most important ones, as it destroyed more than 400 houses killing approximately 500 people (Lotti & Associati-Enel.Hydro 2001). NORSAR et al. (2001) executed a 2-D model of the topographical amplification effect considering the source, but not the geological-geotechnical features.

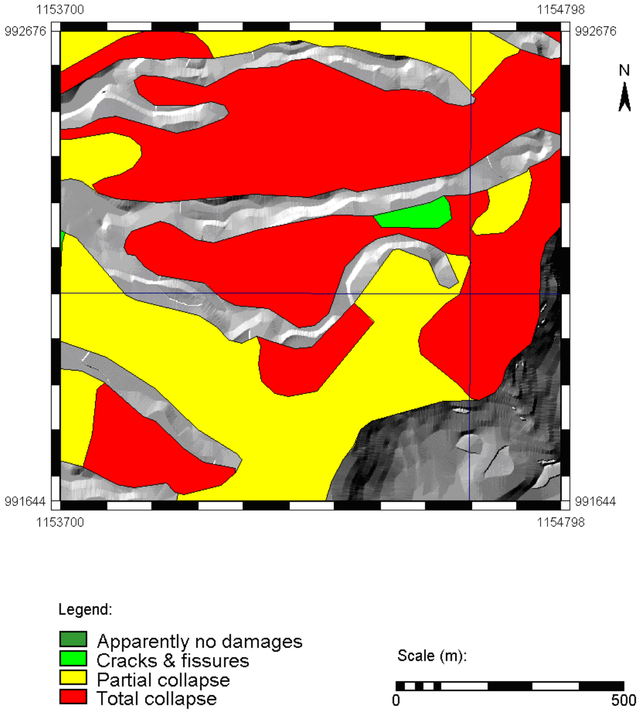

Figure 1. Digital elevation model (DEM) of the study case from Colombia, Brasilia Nueva neighborhood, with the damage patterns. The lines in magenta are the assessed cross sections (modified after Castro 1999).

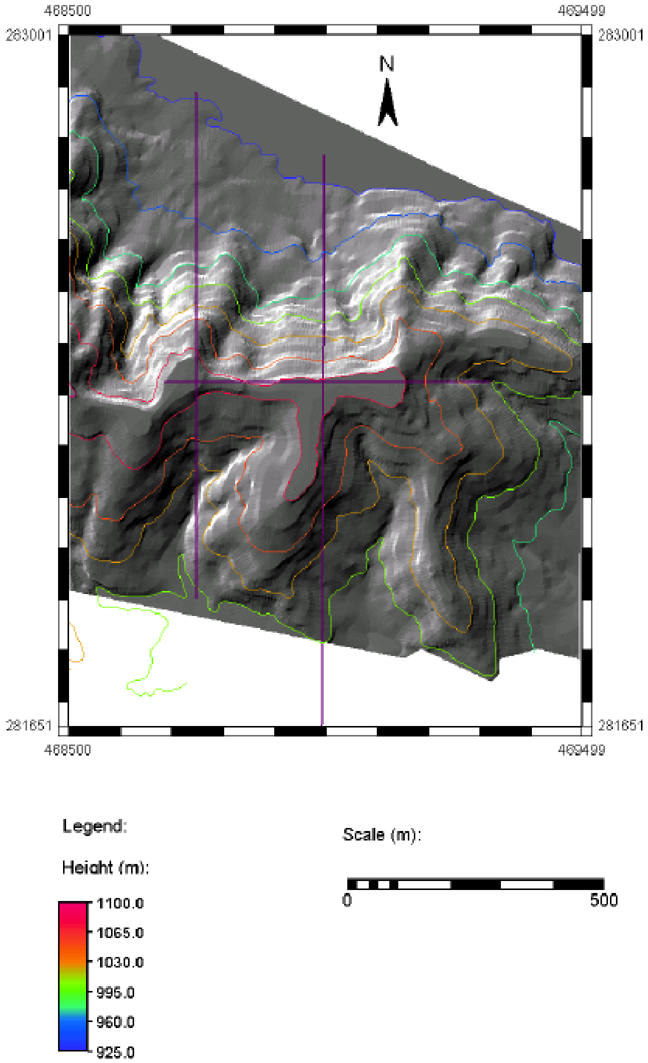

Figure 2. DEM of the eastern side of the El Bálsamo ridge (Las Colinas area). The lines in magenta are the assessed cross sections (Sigarán-Loría 2003).

Around the Las Colinas landslide several technical reports were developed by Costa Rican and Italian consultants (e.g. Lotti & Associati-Enel.Hydro, 2001). Lotti & Associati-Enel.Hydro (2001) made a detailed survey of the geological, geotechnical, and geophysical characteristics of the Bálsamo range, in order to better understand the triggering mechanism of the landslide. They modeled the area with 2-D FEM, as well as with limiting equilibrium methods. They also assessed the amplification factors following the Nakamura experimental method.

Both earthquakes have in common that the area with the higher damage concentrations (case of Colombia), and the area around the Las Colinas landslide (case of El Salvador), have similar geological settings. The subsurface is in both cases formed by pyroclastic (tephras, tuffs, breccias) and epyclastic (lahars) weak volcanic materials, with minor associated lava flows located on mountainous ranges.

2.3 *Ground motion parameters*

2.3.1 *Colombia earthquake*

The earthquake of January 25, 1999 was recorded on soil and rock, but the closest station to Armenia in rock was not considered reliable. Therefore a synthetic signal was recalculated for ground response analysis purposes by INGEOMINAS (1999) and Hack et al. (2000) for a station located 13 km from the epicenter in rock. This synthetic signal was properly corrected in time and frequency domains. The duration of the strong motion was estimated as 16 s. The estimated maximum accelerations are shown in Table 1. The frequencies of this event were high and the attenuation was low due to the small distance to the source. The predominant period was estimated to be 0.5 s (Ibidem), but there are also other important peaks between 0.1 and 0.3 s (Fig. 3), leading to damages on structures smaller than 5 storeys.

Table 1. Peak ground accelerations (PGA).

PGA cm/s^2	Colombia* CCALA Station	El Salvador** Santa Tecla Station
EW	448.5	590
Vertical	299.7	460
NS	356.8	760

* Hack et al. (2000)
** SNET & USGS (2002)

According to the recorded accelerations, the topography, and geological units of the area (e.g. soft, plastic pyroclasts), it is likely that amplification effects occurred during the event (Cardona 1999). Amplification of the seismic waves likely explains the damage patterns as described by Castro (1999).

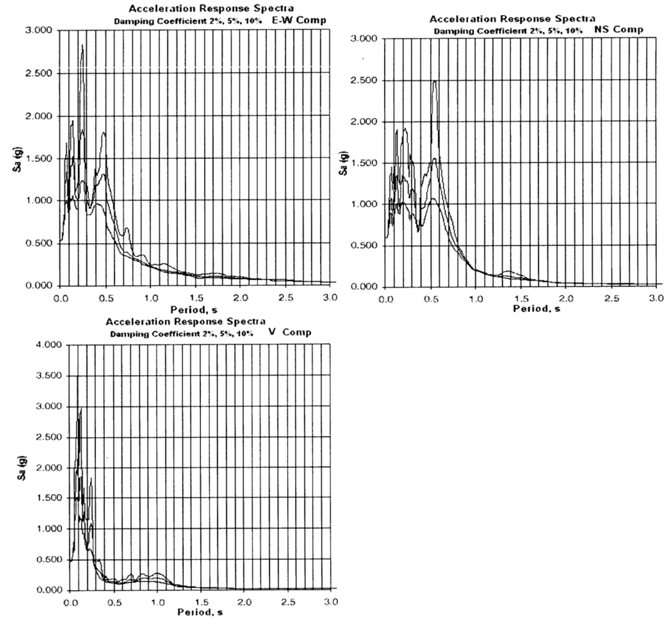

Figure 3. Acceleration response spectra from the accelerograph in soil CARME (Hack et al. 2000).

2.3.2 *El Salvador earthquake*

The event on January 13 had an average peak acceleration of 0.37 g. The highest acceleration recorded was the NS component, normal to the rupture and parallel to the slip direction (NORSAR et al. 2001). The closest station to Las Colinas (1 to 2 km from El Bálsamo range) is Santa Tecla, founded on weak rock, 115 km from the epicenter. The peak ground accelerations (PGA) are shown in Table 1. The acceleration response spectrum shows a range between 0.1 and 0.4 s, with another peak around 1.0 s. The fundamental period was around 0.35 s (Fig. 4).

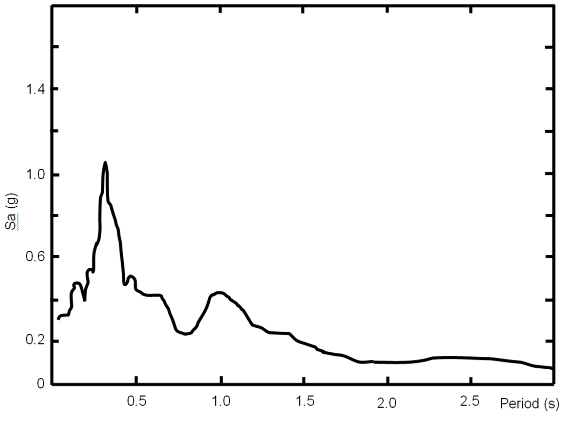

Figure 4. Acceleration response spectra for the earthquake of January 13, 2001, El Salvador (Cepeda & Salazar 2001).

At the El Bálsamo range it is likely a large amplification as shown by vertical cracks in the ground developed along the crest, high damages to structures, and by testimonies (NORSAR et al., 2001). The PGA could have approached values close to 1 g at the top of the ridge (In ibid.) and the Las Colinas landslide failed from a section with higher safety factor than others, which did not fail, in dry conditions (Lotti & Associati-Enel.Hydro 2001). Local geotechnical conditions also seem to have played an important role in the triggering mechanism of that landslide. According to the Nakamura assessment (Ibidem), the amplification along the Bálsamo range was considerable, demonstrating that the site effect was determinant in the triggering of the landslide (In ibid.).

3 GEOLOGICAL-GEOTECHNICAL SETTINGS

3.1 *Geotectonic settings*

Colombia and El Salvador are countries with a high seismic and volcanic activity due to their tectonic position. Both are close to subduction zones that generate complex mechanisms of stresses and strains in the regions, and comprise several neotectonic structures, which also induce seismicity.

3.1.1 *Colombia*

Colombia belongs to the South American tectonic plate and is close to different active borders: the subduction border of the Nazca plate in the Pacific Ocean, and the thrust boundary of the Caribbean Deformed Belt, along the Caribbean Sea, which divides the Caribbean plate from the South American plate. The subduction of the Nazca plate caused the Cenozoic magmatism and volcanism still present in the Andean belt, along the Cordilleras Central and Occidental. El Quindío Department belongs to the Central Cordillera, of the northern Andean belt, at the middle west of Colombia, where the epicenter of the 1999 earthquake was located. This earthquake was related to a local sinistral fault.

3.1.2 *El Salvador*

El Salvador forms part of the Caribbean plate. It is close to the Middle American Trench, in the Pacific Ocean, along which the Cocos plate subducts. The volcanic chain (evolved volcanic arc) extends from Guatemala to central Costa Rica along 1100 km. The main horizontal compressive stress vectors are oriented NE, parallel to the subduction direction. The earthquake from January 13, 2001, was related to the subduction process, 60 km deep in a pure normal fault. Las Colinas landslide took place in the Bálsamo Range, which belongs to a structural high of a horst and graben structures, oriented E-W approximately (Lotti & Associati-Enel.Hydro 2001).

3.2 *Geological context*

3.2.1 *Colombia*

The "Brasilia Nueva" area belongs to the Central Cordillera of the northern Andean belt. The local geology in the study area consists of layers and lenses of pyroclastic and epyclastic deposits (ashes, lapilli, residual soils, paleo-soils, pyroclastic flows, lahars), plus some human-made landfills. The source of the volcanic materials is associated to the Quindío, Santa Isabel, and Cerro Santa Rosa volcanoes (INGEOMINAS 1999).

The local deepest layer considered basement for the numerical models consists of slightly weathered pyroclast flows, debris and mud flows. They have thicknesses higher than 25 m, and are associated to the Upper Pliocene (Ibidem). The previous unit is overlayed by pyroclastic deposits of interstratified ashes (silty clay) and lapilli (fine to coarse sand), 8 to 50 m thick, of Upper Pleistocene to Holocene ages. Their upper part is usually weathered to a residual soil. The residual soil varies between 3 and 12 m thick and shows two levels, an upper clayed silt and a lower silty sandy clay layer (In ibid.). The landfills have been placed in order to equalize the deep valleys in the terrain that are the natural drainage channels, in particular in the initial sections of the valleys. The landfills consist of organic soils, ash, lapilli, construction material, and other dumped materials. Their spatial distribution is not well known, but in Brasilia Nueva area consist of small superficial patches (Castro 1999).

3.2.2 *El Salvador*

The area of "Las Colinas" belongs to El Bálsamo Range. This range is a monoclynal oriented WNW-ESE, with a steepest slope towards the north. The rock mass consists of Cenozoic pyroclastic and epyclastic deposits, with minor paleosoils and lava flows. The volcanic layers show a small dip towards the north, and the landslide triggered by the 2001 earthquake occurred in the northern slope.

The core of the Bálsamo range corresponds with tuffs, ignimbrites and basaltic-andesitic lavas, the last at the western side, out of the assessed sections. The pyroclastic flow materials are considered to be the basal layer for the numerical models due to their geotecnical properties. All these materials are considered to have Lower Pleistocene-Pliocene ages (Lotti Associati & Enel.Hydro 2001). Overlying the pyroclastic flows there is a heterogeneous unit of "brown ashes" (Ibidem), which comprises basaltic fall and epyclastic deposits, brownish in color due to weathering processes. In the central and eastern part of the range are overlying the tuffs (area of the landslide), but towards the west are on top of the lava flows. In the eastern side of the range at the base of these "brown ashes" there is a local layer of paleosoil with 1.5 m thickness. This layer is rich in biotite and is associated to the basal part of the "brown ashes" unit. This geological unit shows varying thicknesses between 20 and 80 m, and is from Pleistocene to Holocene age (In ibid.). The upper unit corresponds with sub-parallel pyroclastic layers of fall and surge deposits with thicknesses between 15 and 25 m, having an upper 1 m soil layer as overburden. Its age is Pleistocene to Holocene (Lotti & Associati & Enel.Hydro 2001).

3.3 *Geotechnical context*

The geotechnical units were defined based on the detailed characterizations accomplished by INGEOMINAS (1999), Castro (1999), Leenders (2000), and Lotti & Associati-Enel.Hydro (2001), comprising laboratory and *in situ* tests, as well as geophysical surveys.

3.3.1 *Colombia*

According to the geological setting, four geotechnical units were identified (ash & lapilli layers, residual soils, saprolite, pyroclastic flow & lahars), but for the numerical modeling purposes, two simplified geotechnical units were defined, grouping the weak materials in one unit. The defined layers are:

1. upper volcano-clastic deposits, comprising the ash and lapilli layers, residual soils, and landfills, of 33 m thick, and
2. lower pyroclastic flows and lahars, which are taken as the base of the numerical models (Table 2).

Table 2. Simplified geotechnical units for Brasilia Nueva area, Colombia*.

Unit	Density kg/m^3	vs m/s	Poisson ratio	E Pa	Gmax Pa	c Pa	Φ °
Upper	1560	262	0.35	5.67 E+8	2.10 E+8	7.4 E+4	34
Lower	1800	1300	0.3	2.00 E+9	7.70 E+8	1.5 E+5	36.5

*Values based on INGEOMINAS (1999), Castro (1999), Hack et al. (2000), Leenders (2000), Sigarán-Loría (2003). vs = shear wave velocity; E = Young modulus; Gmax = shear modulus; c = cohesion of the mass; Φ = internal angle of friction of the mass.

3.3.2 *El Salvador*

According to the geological context, four geotechnical units are present in the area: pyroclasts, brown ashes, paleosoils, and tuffs. These were simplified in three geotechnical units for the numerical models, including the paleosoils as part of the brown ashes unit. The modeled units are:

1. Upper pyroclasts, constituted by interstratified ashes of silty sand granulometries with low-medium plasticity, some layers are loose while others consolidated. The thickness varies between 10 and 30 m.
2. Intermediate epyclasts, consisting of the brown ashes and the paleosoils, both consist mainly of silt with minor fine sand and mud proportions with medium-low plasticity. The thickness is around 30 m in the area where the landslide occurred.
3. Lower tuffs & ignimbrites, basal unit of the models and eastern side of the range (Table 3).

Table 3. Geotechnical simplified units of Las Colinas, El Salvador*

Unit	Density kg/m^3	vs m/s	Poisson ratio	E Pa	Gmax Pa	c Pa	Φ °
Upper	1500	120	0.42	6 E+7	2.10 E+7	7 E+4	30
Intermediate	1540	570	0.33	3.6 E+8	1.36 E+8	3.4 E+4	30
Lower	1900	1100	0.26	3.8 E+9	1.5 E+9	2 E+5	38

*Values based on Lotti & Associati-Enel.Hydro (2001), Sigarán-Loría (2003). vs = shear wave velocity; E = Young modulus; Gmax = shear modulus; c = cohesion of the mass; Φ = internal angle of friction of the mass.

It is likely that the landslide of Las Colinas was related to the weak mechanical characteristics of the brown ashes and the paleosoil, which acted as sliding plane, as well as to the slight dip of the units towards the failure direction. Statically the units were stable, however the amplification effect during the earthquake triggered the landslide. The failure plane shows striations and most of it occurred along the paleosoil layer and base of the brown ashes, which seem to have had an important role in the failure mechanism (Lotti & Associati-Enel.Hydro 2001). The slide occurred on dry material and no pore water-pressures influenced the failure. Static back-analysis of the stability with limit equilibrium and 2-D FEM techniques were done for different sections along the landslide and along areas that did not slide (Lotti & Associati-Enel.Hydro 2001). The results of the back-analyses showed that the section where the slide occurred had actually higher safety factors than the other sections were no failure occurred.

4 THE MODELS

The models are developed in *FLAC* 4.0, under a non-linear, time domain approach. The mechanical characteristics of the rock masses in both Colombia and El Salvador cases (pyroclasts and epyclasts mainly) are not controlled by discontinuities. As it is likely that concentrations of shear stress cause new failure planes, the Mohr-Coulomb constitutive model is considered the most suitable to be used during the dynamic loading. Two sections from the Colombia site are assessed: one N-S and one E-W (Fig. 1). For the El Salvador case, two N-S and one

E-W sections are modeled (Fig. 2). The eastern N-S section is along the landslide failure, the other N-S section is 250 m west of the landslide. The cross sections are simplified from the DEM's in order to get simple geometries (Fig. 5).

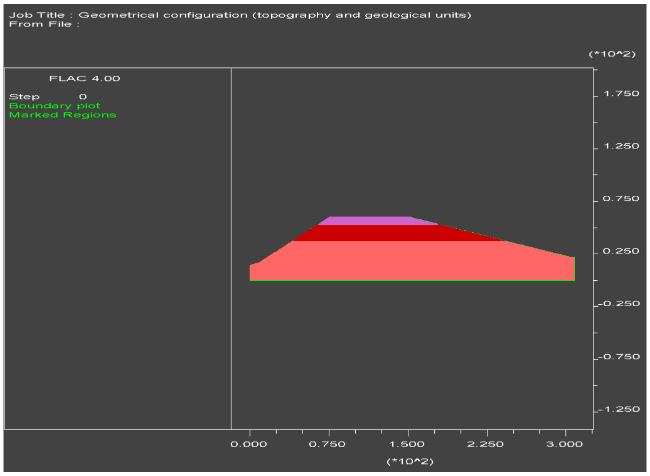

Figure 5. Example of a model geometry. Section N-S (along Las Colinas landslide), El Salvador. North is to the left.

The models for the Colombia case consist of two-layers and the models for the El Salvador case of three-layers (Tables 2 & 3). The dimensions of the models range between 400-988 m length, 100-200 m height, and 24-120 m deep. Dry conditions are assumed for simplification, and because no influence of water pressures has been noted. In order to guarantee a proper wave transmission and avoid distortions and reflections free-field boundaries are used along the vertical limits of the models; element sizes are chosen (4 m for Colombia, 2 m for El Salvador), following the empirical statement of Kuhlemeyer & Lysmer (1973) (in Kramer 1996), prescribing the element size to be within 1/10 of the longest wavelength. Rayleigh damping is used to represent the energy dissipation with a 5% damping. The loads applied are based for the Colombian case on synthetic histories (frequency-independent), and sinusoidal artificial functions simulating frequencies of 2 & 5 Hz with 0.4 g of PGA. For the El Salvador case a sinusoidal artificial function of 2.86 Hz is used.

5 2-D AMPLIFICATION PATTERNS

5.1 *The amplification site effect*

Local amplification effects related to topography have been noticed in several parts of the world. The amplification is higher towards crests (e.g. Boore 1972, Bouchon 1973, Celebi 1987, Geli et al. 1988, Pedersen et al. 1994, Bouchon & Barker 1996, Sincraian & Oliveira 2001). For a single slope the effect can be neglected if it is lower than 15º, and it is considered to decrease linearly along the slope until it reaches unity at the base (Paolucci 2002). The amplification level has been reported to be generally lower than four times the amplitude of the incoming waves (Sánchez-Sesma & Campillo 1993). The literature is not conclusive whether the topographic effect has a stronger influence than other site effects such as geology (e.g. Ashford et al. 1997, Paolucci 2002). The incidence angle and direction of approach have also a marked influence on the final response (Ashford & Sitar 1997).

5.2 *Amplification patterns*

The PGA from the responses are measured at different points in three main directions along and below the surface of each cross section, taking as zero-reference point the slope crest (Fig. 6).

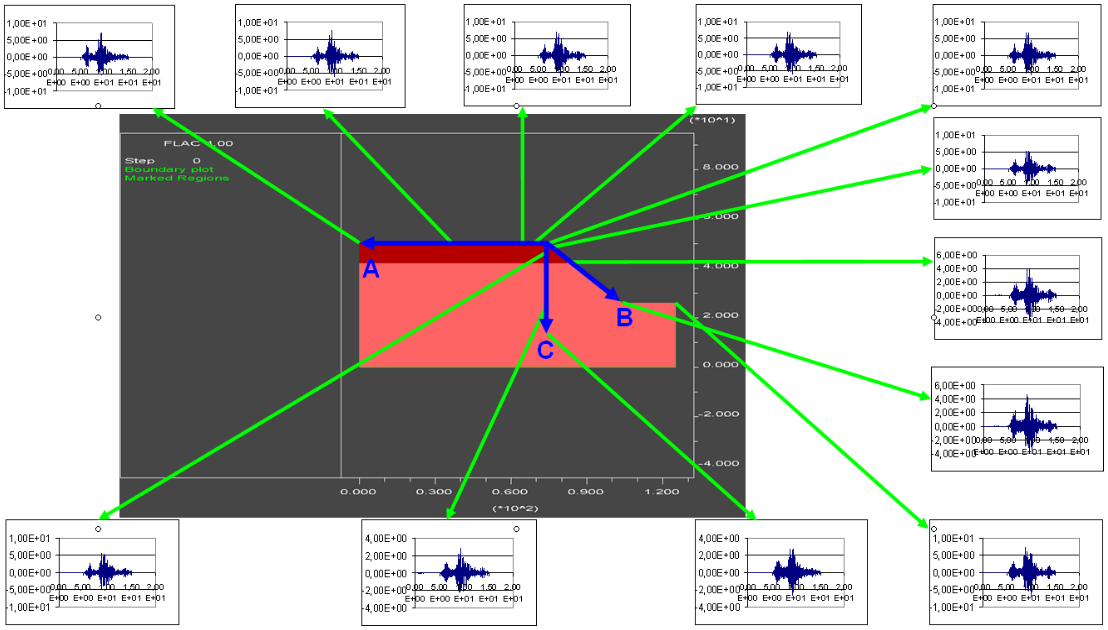

Figure 6. Patterns of measurement of the PGAs: A) along the ridge, B) along the slope face, and C) below the surface in vertical direction.

5.2.1 *Results of the Colombian case*

The E-W section has been subjected to stresses following two sinusoidal functions simulating frequency dependent histories at 2 and 5 Hz. The higher frequency function (5 Hz) is highly amplified (maximum amplification factor is about 4.2), while for the 2 Hz function the amplification effect is very small (<1.17, Fig. 7). The N-S section shows higher amplification than the E-W section for the 2 Hz frequency, but the amplification is still below the amplification of the 5 Hz function of the E-W section (Fig. 8). In all cases the amplification is maximum along the ridge, with a decreasing trend along the slope downwards. Along the N-S section the slope response seems to be slightly higher than the response below the surface (Fig. 8).

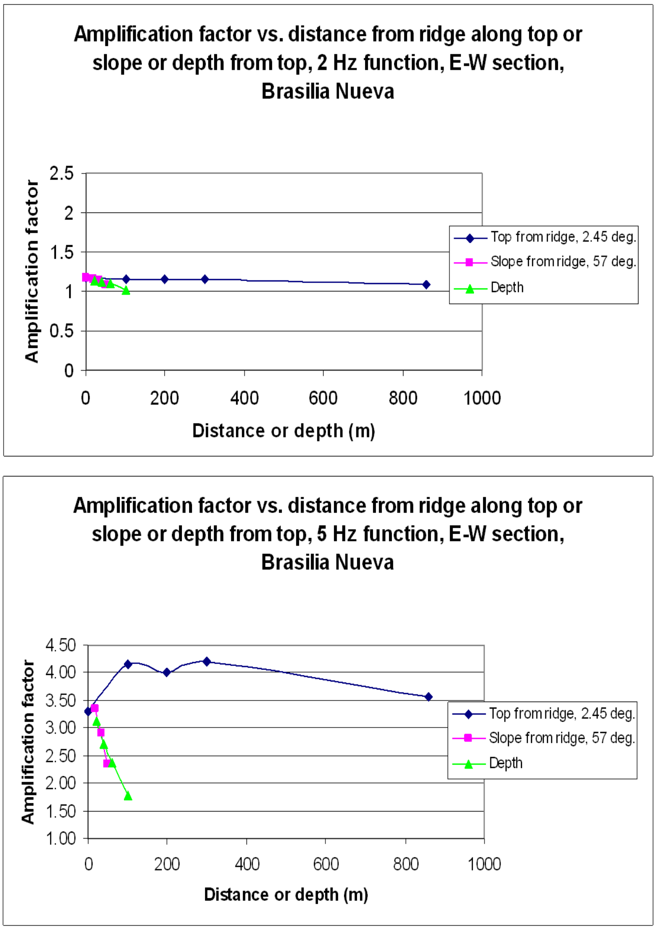

Figure 7. Example of amplification factors E-W section. Zero-point (reference) is the slope crest. Slope angle: 57°, ridge angle: 2.45°.

The responses for the acceleration histories show similar trends, although there is more clear the lower values below the surface, than along the slopes, and there is a loose on the linearity. Both the E-W and N-S sections gave similar amplifications, being around 2 along the ridge and the upper part of the slopes (Fig. 9).

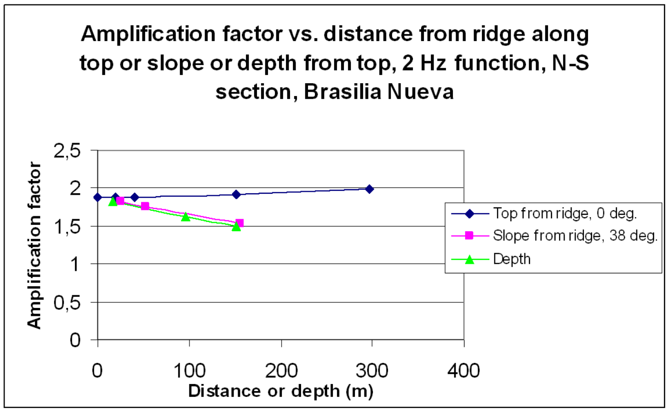

Figure 8. Example of amplification factors N-S section. Slope angle: 38°, ridge: flat.

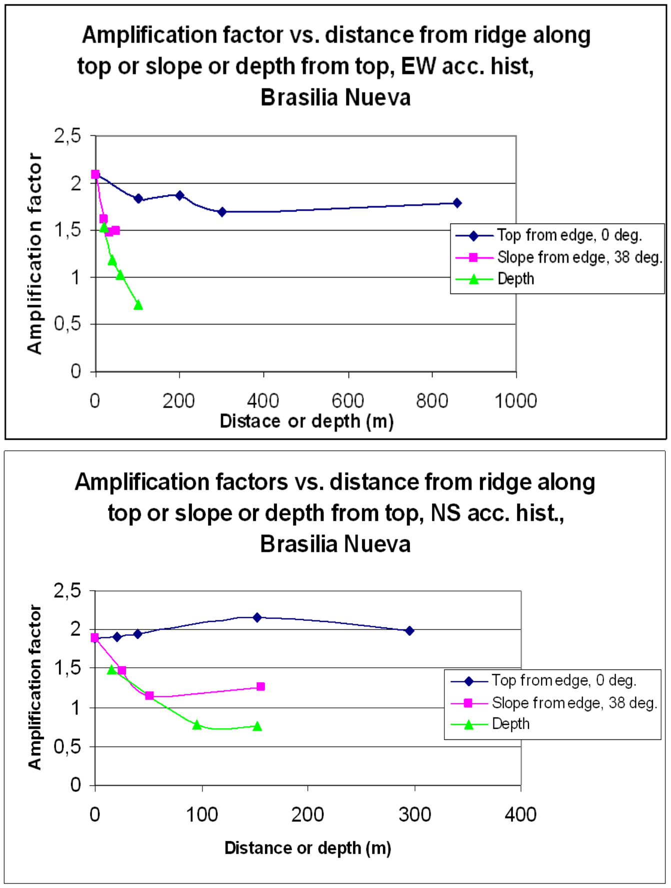

Figure 9. Example of amplification factors for real E-W & N-synthetic histories.

5.2.2 *Results of the El Salvador case*

The model is subjected to one sinusoidal function with a frequency of 2.86 Hz on the two N-S sections. The section along which the Las Colinas landslide failed shows amplification factors along the top of the ridge ranging between 2 and 2.7. The other N-S section, where no failure occurred (so-called “Paraiso” area) shows similar but lower amplification with factors between 2 and 2.3. Below the surface the amplification effect is much lower, decreasing with a linear trend (Fig. 10).

The northern slope, where the slide failed shows large amplifications decreasing towards the base, similar to the southern slope. The amplifications along the southern slope that has a lower slope angle, are, however, slightly higher. In the Paraiso section, the northern slope shows a similar decreasing trend, except for the point at the base of the slope that shows amplification. For this section, only two points are measured along the southern slope. These give lower values than the northern slope (Fig. 10).

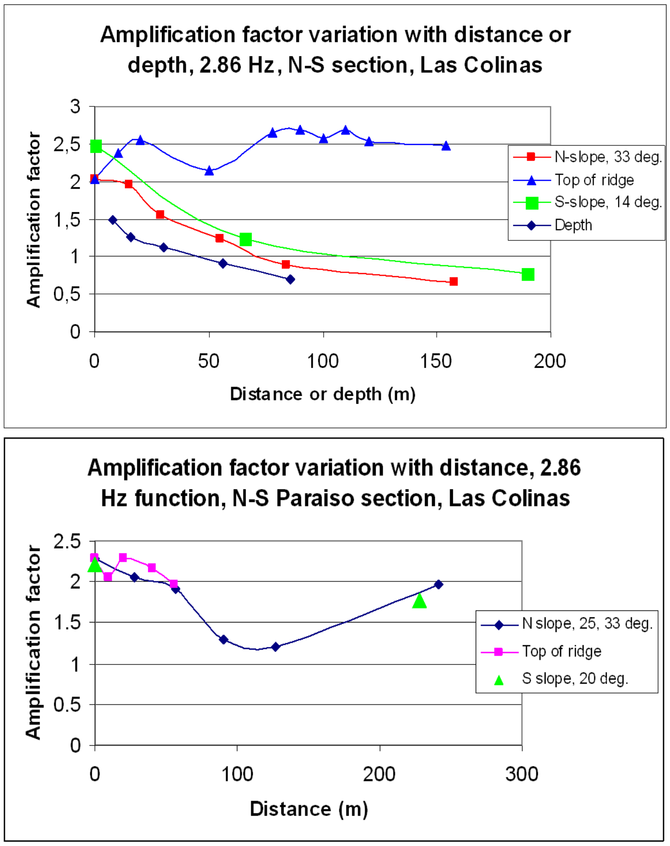

Figure 10. Example of amplification factors N-S sections. Upper: Las Colinas, along landslide; lower: Paraíso, without slope-failure.

Shear strain and displacement vectors of Las Colinas section suggest failure along the slope where the slide failed. The Paraiso section shows a similar behavior, however, here no failure occurred (Fig. 11). The responses of the acceleration records indicate a problem and may not be reliable. The problem is presumed to be related either to the filtering process applied to the original signal, or to the station foundation, which may not correspond to the base material used in the models. It was a far-field event instead of a near-field.

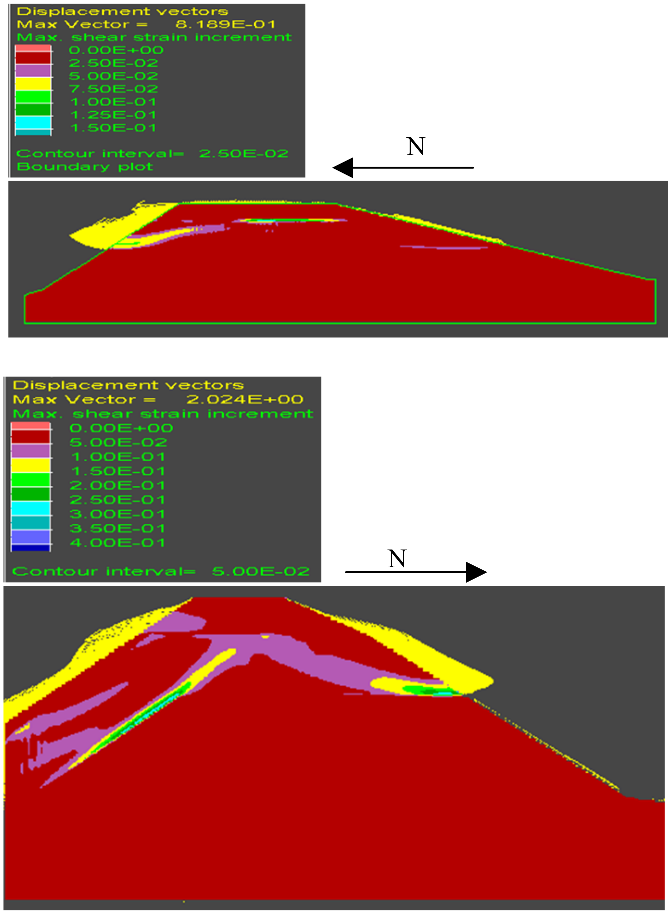

Figure 11. Shear strain & displacement vectors N-S sections. Upper: Las Colinas section, lower: Paraiso section. Displacement vectors are in meters.

6 COMPARISON WITH PREVIOUS MODELS

The ground response of the earthquake in Colombia in 1999 was modeled by Hack et al. (2000) with the 1-D system SHAKE for microzonation purposes. A small area of Brasilia Nueva was evaluated with a 3-D FEM by Leenders (2000). The E-W section of Colombia modeled in this research is within the area assessed by Hack et al. (2000), and both are inside the 3-D area evaluated by Leenders (2000). As SHAKE models horizontal, semi-infinite layers, it cannot assess the amplification due to topographic effects, or effects related to lateral variations in shape or position of the geological units. Therefore the responses are generally lower than the amplifications found with *FLAC* and DIANA (Table 4).

Table 4. Comparison between amplifications (expressed in percentages) found with three different numerical systems for Brasilia Nueva area, Colombia.*

	Component		
System	EW	NS	Vert
SHAKE 1D*	109%	168%	233%
FLAC 2D	180-200%	190-215%	233-260%
DIANA 3D**	105-190%	180-200%	120-130%

*Source: Hack et al. (2000); Leenders (2000).

The results obtained for the El Salvador case are generally similar to the results obtained by the back-analyses with limit-equilibrium and 2-D FEM techniques from Lotti & Associati-Enel.Hydro (2001). Generally it is demonstrated that the northern slopes from the ridge are unstable under earthquake loading. The Nakamura assessment gave amplification factors between 1.6 and 4.2 (In ibid.), a broader range than those obtained with *FLAC* (2-2.7 along the top of the ridge) in this research. Why there was no physical slope failure in the Paraiso section during the earthquake, while the area is supposed to have a lower safety factor (Ibidem), is not clear yet. It is speculated whether the geological model differs from the real ground conditions, being not representative the assessed models.

7 CONCLUSIONS

The results from the artificial sinusoidal functions give similar patterns of amplification to those obtained with the real synthetic acceleration histories. In general, the highest amplifications are found along the top of the slopes. Along the slopes, the amplification decreases downwards linearly for the artificial functions, in the case of Colombia, but for the Las Colinas section in El Salvador a more exponential relation is found. The variation in the amplification factors along the slopes for the Colombia site shows some curvature towards the base of the slope. The responses found below the surface, generally decrease with depth. The rates of reduction of amplification with depth are higher than the rates of reduction down the slopes surfaces.

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