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AN ANALYTICAL APPROACH ON LAS COLINAS EARTHQUAKE-INDUCED LANDSLIDE IN EL SALVADOR

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ABSTRACT

As geometry and topographic features become highly relevant when making assessment on Natural Disasters, this Team obtained a Digital Terrain Model (D.E.M.) for Las Colinas (El Salvador). The DEM, a product of photogrammetric data capture- allowed the authors to calculate in detail geometrical properties of the slide, and identify critical sections in the same. The obtained DEM was analyzed using both, pseudo and dynamic analysis methods in order to understand the behavior of the affected site when stroke by earthquake. Results show among others, the Factor of Safety and critical accelerations induced by the earthquake including amplification of the wave due to ground conditions.
Keywords: 2001 El Salvador Earthquake, Digital Terrain Model (DTM), Digital Elevation Model (DEM), Slope Stability, Earthquake-induced Landslides, Failure Mechanism, Pseudo-Static Analysis, Dynamic Analysis, Super FLUSH.

1. OUTLINE

On January 13 and February 13, 2001 two big earthquakes -M-7.6 and 6.6- hit Central-American country El Salvador, posing one of the biggest tragedies on this country's history. These earthquakes triggered many landslides along the country; Las Colinas, San Vicente, Rio Jiboa, etc; involving large volumes of material and causing hundreds of human loses. This time, and given the huge impact duet to the lose of more than 500 human lives, the Team has analyzed Las Colinas landslide and intends to present here the results obtained so far.

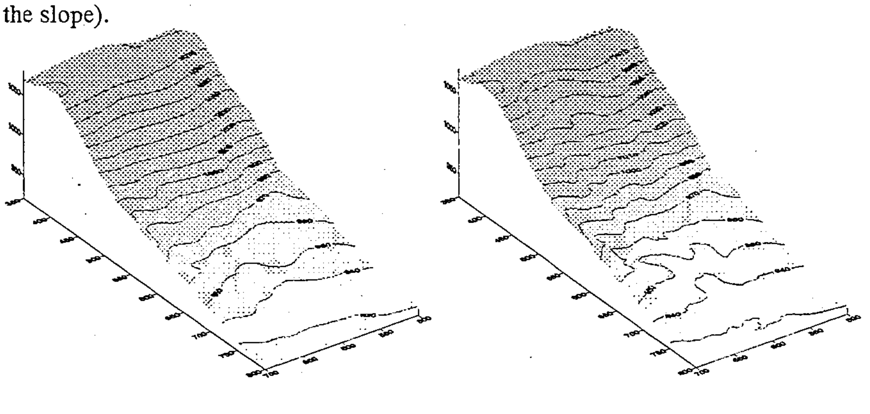
2. LAS COLINAS LANDSLIDE

The January 13 earthquake, about 110 km south-east of San Salvador with a 8.o km depth (11:33 local time) M 7.6, triggered what is known as Las Colinas landslide, as it affected the Las Colinas neighborhood of Santa Tecla killing about 500 people. The landslide (rapid earth flow) was originated at an elevation of about 1,070 m and traveled northward into the neighborhood. The material exposed appeared to be somewhat moist but not saturated, and traveled an unusually long distance from the base of the slope.

2.1 DIGITAL ELEVATION MODEL (D.E.M.)

Two sets of monochrome aerial photographs, before and post-quake conditions were scanned at 10 microns. The scanned data was correlated with a digitized map on pre-existing topographic; coordinates (X, Y) were set; and altitude references were taken. This data was then classified and put under mesh (X-Y grid spaced every 2,0 meters). Each point of the grid were defined. Having obtained the new set coordinates (X, Y and Z), the complete Three-Dimensional recreation (DEM) of the site was achieved.

The complete DEM for both situations -before and after- can be seen on figure 1. After obtaining longitudinal and cross sectional profiles based on the DEM for the affected area, and analyzing their properties, critical profiles were identified in X=626 and Y=414. From profile X=626, the area affected by the landslide can be subdivided on four main parts (Fig. 2). The sections described were found by comparing the original topographic features; this is before the earthquake, with those after the same. As contour lines before the earthquake show a similar pattern distribution (almost homogeneous for the steep part of the slope).



BEFORE *AFTER*

Fig. 1 – Block (3D) Diagram for Las Colinas Landslide (Units in Meters)

As Y-axis increases, four sections are identified:

Section 1. A first block that can be described as a "hollow". This block not only was observed to slide over a clearly defined rotational slip surface but also somehow expelled or pushed from its center. This phenomenon could be explained by the high N-S over E-W accelerations. The material involved on this first section traveled all along the slope reaching and running into the neighborhood.

Section 2. Between altitudes 1,040 and 985 on the same X=626 profile, a second section is easily recognized. If no noticeable in all the profiles.

Section 3. This section is very different from the first one described above, while the first could be described as a "hollow" this one is a slice clearly slipped above the already mentioned translational failure surface.

Section 4. The material in this one is deposited above the original ground surface on shallow layers, having run into the neighborhood hundreds of meters. From an analysis of aerial photographs our team concluded that the real distance traveled by the debris flow into the neighborhood from the toe of the slide was ***360 mts.***

By analysis of the obtained DEM, the total failed volume for the whole slide body was estimated to be about ***170,000 cubic meters.***, the deposited material was found as much as ***152,000 cubic meters.*** By the same procedure, volumes for the four sections above mentioned were also calculated; results can be seen on table 1.

Table 1. Volumes of material involved in Las Colinas

SECTION	VOLUME (Cubic meters)		TOTAL ERODED
	FAILED	DEPOSITED	MATERIAL
1	66,293.38	*0.24*	66,293.14
2	60,302.17	*5,299.89*	55,002.28
3	34,204.11	*827.69*	33,376.41
4	8,844.83	*11,379.12*	*2,534.29 (-)*
TOTAL	169,644.48	17,506.94	152,137.54

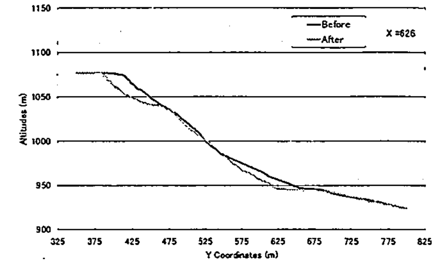


Fig. 2 Longitudinal Profile X=626

2.2 LAS COLINAS SLOPE STABILITY ANALYSIS (Pseudo Static Method and Dynamic Method)

Once the geometry of the landslide was obtained by means of DEM and soil conditions for the main failed block (Block 1) grasped, a slope stability analysis by ***pseudostatic method*** was performed. Horizontal and vertical static seismic forces that were used to simulate the potential inertial forces due to ground accelerations in the earthquake were introduced to modify the limit equilibrium analysis. As the failure for the block is a typical circular one; the Factor Of Safety (FOS) was found by means of a modified Bishop's method;. Unit Weight (Bulk Unit Weight) γ_t = 13.161 KN/m^3, was used to calculate the correspondent FOS and Horizontal seismic coefficient, results can be seen on Table 2.

Table 2. Las Colinas pseudostatic and dynamic slope stability analysis

Upper layer		*Pseudostatic Analysis*			*Dynamic Analysis*	
c *(KN/m2)*	Φ *(°)*	Factor Of Safety *FOS*	Horizontal Seismic Coefficient *(kh)*	Ground Acceleration *(Critical)*	PGA *(Max)*	Equivalent Block Acceleration
19	39.2	2.12	0.421	412.61 gal	919 gal	589 gal

From these results we can conclude that the slope was stable enough before the earthquake, as the Factor of Safety 2.12 (>1.0) shows; from the pseudostatic analysis we also found out that ground motion acceleration equivalent to 412.6 gal. *(k_h = 0.421)* determined the boundary conditions for the slope stability (FOS=1.0). Bigger accelerations than this one would result on a failure of the slope.

Dynamic analysis using Super FLUSH and considering soil properties and correlations as well as seismic wave data from the site [1)] would allow us to check the veracity of the predicted acceleration.. The equivalent Acceleration for the upper failed block was found to be **589 gal.** with a **919 gal** peak registered in the upper part. This analysis shows that the seismic wave, inducing (registered) accelerations near the site *-490 gal for NS and 460 gal for EW* [1)]*-* showed amplification phenomena on Las Colinas site, and all the found values agree with the above assumption; this is, **412 gal** and higher accelerations were enough to induce a failure on the slope.

3. CONCLUSIONS

- By using a detailed DEM from Aerial Photographs, geometry of the slide has been grasped and used for a further analysis. The total failed volume was estimated to be about ***170,000 cubic meters.*** The eroded material was found as much as ***152,000 cubic meters.*** From an analysis of aerial photographs our team concluded that the real distance traveled by the debris flow into the neighborhood from the toe of the slide was ***360 mts.***
- ***Pseudostatic*** slope stability analysis performed for conditions before the earthquake, showed that the slope, with a Factor of Safety = 2.12, was stable enough before the event, however, based on the same analysis we were able to determine that a ground motion acceleration bigger than 412 gal.would make the site unstable. ***Dynamic*** analysis confirmed the assumption from the pseudostatic analysis, as wave amplifications reporting accelerations as high as 900 gal (bigger than 412 gal) caused failure in the slope due to the earthquake.

REFERENCE

1) Centro Sismologico para America Central (http://www.cepredenac.org)