Report on Earthquake-Induced Landslides, Guatemala City

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NOTES ON GIS ANALYSIS

Rock Strength Data

Rock strength information was incorporated by examining geologic data previously gathered for landslide analysis of the study area. Using existing shapefiles, existing lithologies were grouped into 5 categories based on material and likelihood for slope failure. (Those units showing the greatest potential for sliding were categorized as 5). Any inconsistencies in the data (for instance, the same lithology units occasionally being mapped as having differing potential for sliding) were reviewed and edited, using the presence of mapped slides to help in instances of conflicting data.

After reviewing literature sources comparing relative soil strength values of common sub-surface materials (such as Selby 1983 and Harp et al.1981), we derived the following strength value estimations to best represent the ground conditions present within the study area.

Classification of Rock Strength Parameters:

	Phi Angle	Unit Weight (kN/m3)	Cohesion (Kpa)
1 Alluvium, (Quaternary)	32	19	0
2 Andesites, rocas volcanicas, Dacita (Tertiary, Cretaceous)	42	26	35000
3 pomez, tefra diamictones pomaceos (Quaternary)	35	17	35
4 tefra, pomez gris a blanco (Quaternary)	35	17	35
5 pomez, tefra interestratificada, (Quaternary)	35	17	35

Table from M.J. Selby's *Slope Materials and Processes* *(1983)*.

TABLE 5.2. *Typical soil and rock properties*

(a)

Type and material	Unit weight (Saturated/dry) kN/m^3	Friction angle (1) degrees	Cohesion kPa
COHESIONLESS			
Sand			
Loose sand, uniform grain size	19/14	28–34	
Dense sand, uniform grain size	21/17	32–40	
Loose sand, mixed grain size	20/16	34–40	
Dense sand, mixed grain size	21/18	38–46	
Gravel			
Gravel, uniform grain size	22/20	34–37	
Sand and gravel, mixed grain size	19/17	48–45	
Compacted broken rock			
Basalt	22/17	40–50	
Chalk	13/10	30–40	
Granite	20/17	45–50	
Limestone	19/16	35–40	
Sandstone	17/13	35–45	
Shale	20/16	30–35	
COHESIVE			
Clay			
Soft bentonite	13/6	7–13	10–20
Very soft organic clay	14/6	12–16	10–30
Soft, slightly organic clay	16/10	22–27	20–50
Soft glacial clay	17/12	27–32	30–70
Stiff glacial clay	20/17	30–32	70–150
Glacial till, mixed grain size	23/20	32–35	150–250
Rock			
Hard igneous rocks: granite, basalt, porphyry	(2) 25 to 30	35–45	35 000–55 000
Metamorphic rocks: quartzite, gneiss, slate	25 to 28	30–40	20 000–40 000
Hard sedimentary rocks: limestone, dolomite, sandstone	23 to 28	35–45	10 000–30 000
Soft sedimentary rock: sandstone, coal, chalk, shale	17 to 23	25–35	1 000–20 000

(b) *Frictional strength of selected clay minerals*

Clay minerals	Effective friction angle for soil at constant volume $(\phi'_{cv})°$	Effective residual friction angle $(\phi'_r)°$
Smectites	15–20	5–11
Kaolinites	22–30	12–18
Allophane	30–40	30–40
Halloysite	25–35	25–35

Notes: 1. Higher friction angles in cohesionless materials occur at low confining or normal stresses.
2. For intact rock, the unit weight of the material does not vary significantly between saturated and dry states with the exception of some materials such as porous sandstones.

Sources: Data from Hoek and Bray (1977); Wesley (1977); Lupini *et al.* (1981); Boyce (1985).

Newmark Displacement Calculations

Predicted Newmark Displacement values were modeled using an assortment of raster-based analysis techniques. The following expounds upon specific input parameters used in the model construction.

Magnitude

An earthquake event representing a moment magnitude (M) of 7.5 was selected for the analysis. Reasons for using an M 7.5 event are twofold. Firstly, this presents a similar magnitude to the 1976 event, which was centered approximately 160km NE of Guatemala City. Secondly, choosing the same 7.5 magnitude as that which appears in other works (Villagran et al. 1997) allows for direct comparison of modeling capabilities between works.

Fault Selection

Review of existing literature revealed the Micxo fault zone as the fault system closest to the study area. This fault zone is composed of low angle, en echelon thrust faults trending N10-N20 degrees E. Due to the close proximity to Guatemala City and the association of secondary movement along these faults during the 1976 event, parts of the Mixco fault zone were chosen as the source for earthquake initiation for this study. A series of faults closely grouped together and located in the northwest portions of the study area were used to construct an approximate zone of origin for modeling purposes.

Moisture

Scenarios were run in which two levels of saturation (*m*) were represented. ("*m*" represents a dimensionless ratio between the height of watertable above failure surface, and the depth of failure surface below ground surface) The first run, with an *m* value 0.25, represents relatively drier moisture conditions which may be found during months like May and June. The second scenario calculated with an *m* value of 0.75 represents wetter ground conditions, and may be representative of conditions found during the rainy season months such as August and September.

Depth of Failure

An average value of 3.33m was chosen to represent depth of failure below the surface. This values appears commonly in earthquake-induced landslide modeling works such as Keefer 1984 and Miles and Keefer 1999.

Factor of Safety

Using the infinite slope model, the static factor of safety of a slope (FS) can be expressed as:

$$FS = \frac{c'}{\gamma z \sin \beta} + \frac{\tan \varphi'}{\tan \beta} - \frac{m \gamma_w \tan \varphi'}{\gamma \tan \beta}$$

Where:

c' = effective cohesion (Pa= N/m^2).

γ = unit weight of soil (N/m^3).

m = z_w/z (dimensionless).

γ_w = unit weight of water (N/m^3).

z = depth of failure surface below the surface (m):

z_w = height of watertable above failure surface (m).

β = slope surface inclination (°).

φ' = effective angle of shearing resistance (°) aka friction angle.

Ground Motion Attenuation Relationship

A strong motion attenuation relationship developed by Climent et al. (1994) and used in Villagran et al. (1997) was used to derive the following relation for peak ground acceleration (PGA);

$$\ln PGA = -1.687 + 0.533M - 0.537\ln(R) - 0.00302R + 0.327(S)$$

Where PGA is in m s^{-2}, M is the moment magnitude of 7.5, R is the hypocentral distance (km), and S is a site factor with 1 for soil (anything listed as Quaternary) and 0 for rock.

Newmark Displacement

We used the following equation developed by Randall Jibson (2007) to calculate Newmark Displacement as a function of critical acceleration ratio and moment magnitude;

$$\log \mathrm{Dn} = -2.710 + \log\left[\left(1 - \frac{ac}{amax}\right)^{2.335}\left(\frac{ac}{amax}\right)^{-1.478}\right] + 0.424M$$

Where critical acceleration = (FS -1) sinβ. Final displacements for the two moisture scenarios were mapped to show displacement in centimeters, with maps masking out areas of slope surfaces ≤ 5 degrees.

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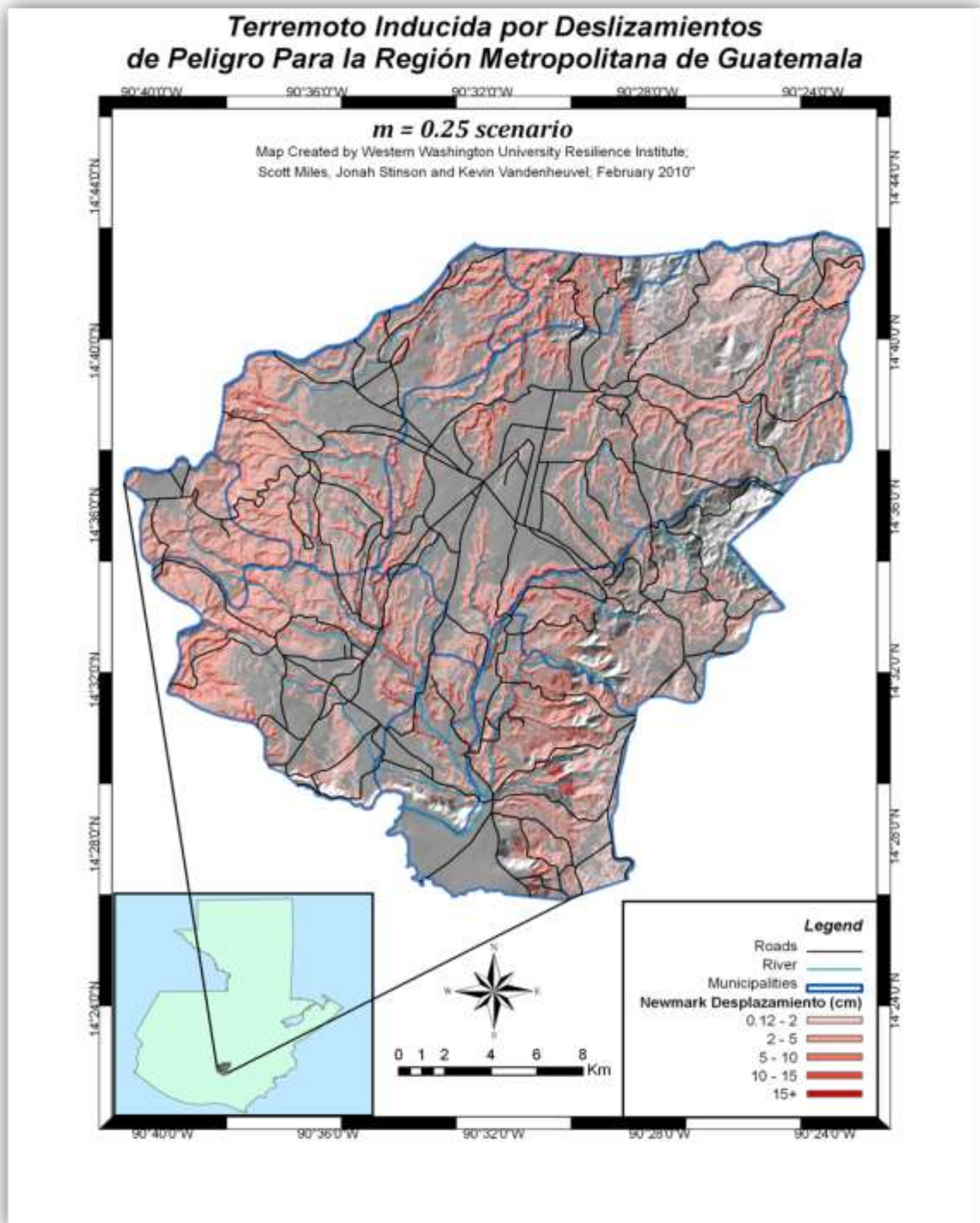
NEWMARK DISPLACEMENT MAPS



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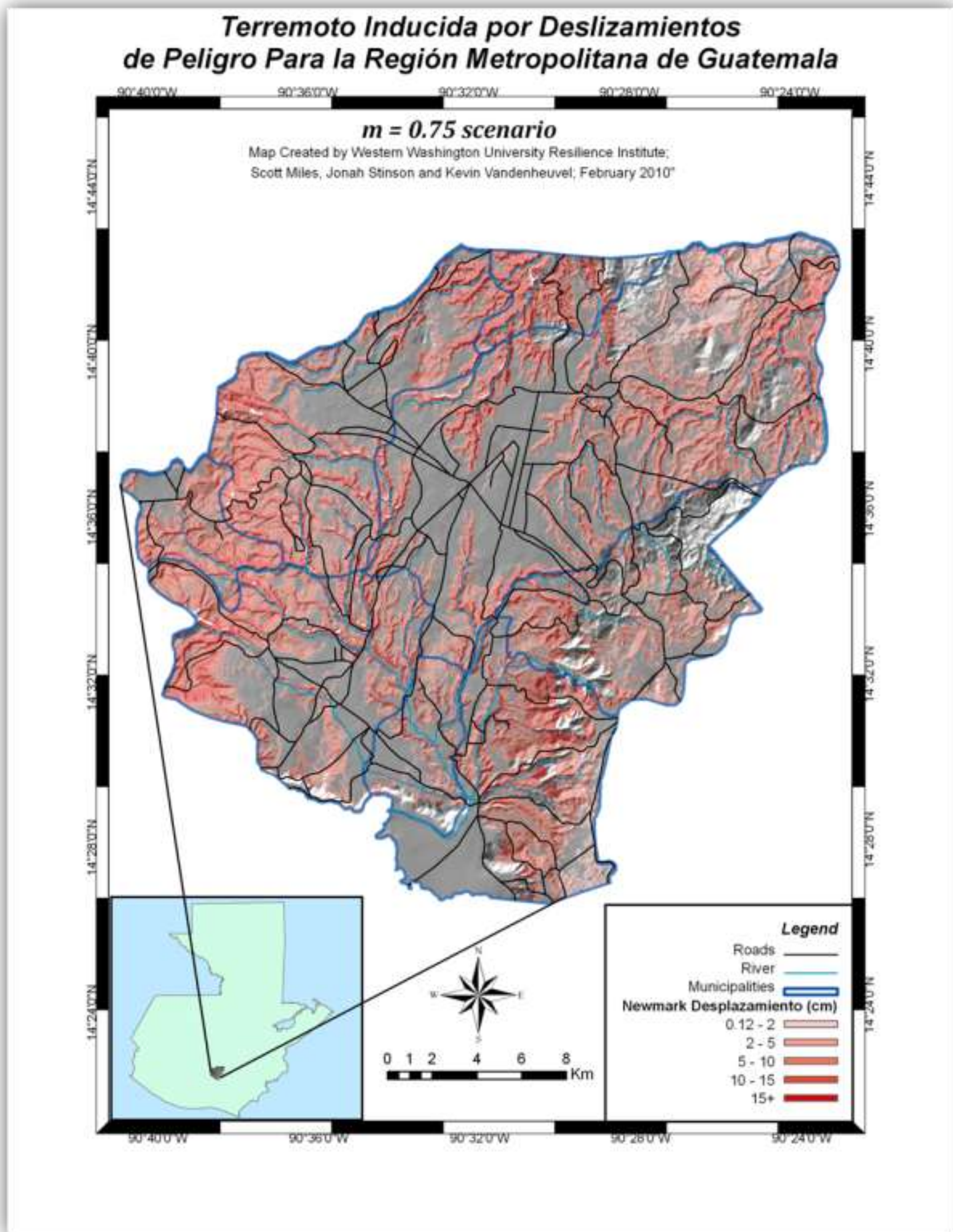

APPENDIX: BACKGROUND NOTES ON 1976 EVENT AND GEOTECHNICAL ASPECTS

’76 event: predominantly rock falls and debris slides of less than 15,000m3 volume.

Regional distribution depends on 5 factors: 1) seismic intensity, 2) lithology, 3) slope 4) topographic amplification of seismic ground motion, 5) regional fractures.

Presence of pre-earthquake slides has no apparent effect on distribution

Epicenter in Montagua fault zone, runs E-W. Death toll in 76 could have been much higher if slides had been on canyon slopes in heavily populated areas.

Highway blockages seriously hindered rescue efforts in the past.

The plateau that G.C. is built on is along the continental divide; deeply incised by canyons “barrancos”. Plateau is underlain by Pleistocene Pumice deposits more than 100m thick, a brittle material with low tensile strength. The interlocking texture of this provides enough shear strength however to support nearly vertical slopes 100m high. More than 90 % of the slides in 76 were within these pumice deposits or their residual soils.

Debris slides were most abundant in areas where thin soil (<0.6m) is formed on pumice bedrock. This soil consists of medium-grained to coarse sand-size fragments of weathered pumice and includes small amounts of clay. Failure occurred by decoupling at or near soil/bedrock interface. At the time of the 76 quake, soil was dry. Most slides disaggregated into small debris avalanches.

Average tensile strength of pumice is likely less than 35 KPa. Ability of pumice to stand in high vertical cliffs yet undergo brittle fracture from seismic shaking in part due to mechanical strength imparted by cohesion due to the interlocking fabric of the highly angular pumice clasts.

Rock falls in non-pumice types still resembled rock falls in pumice for the most part; the main difference in that weathered andesite (common in highlands) failures were common along preexsisting fracturesd or joint surfaces and not in intact rock (like pumice). [Again, the reason for this is likely due to the low tensile strength of pumice].

High density of slides in the highlands to the SW of GC (not near epicenter) due to west-ward propagating source of energy. Most slides occurred in areas where MMI is VI to VII. Field observations of the degree of structural damage in many slide-affected areas suggest that the threshold shaking intensity for triggering in the most susceptible localities corresponds to MMI of VI.

Pumice deposits are not welded or extensively cemented but have undergone some compaction under their own weight. Thus the pumice has little cohesive strength and derives most of the shear strength from high coefficient of friction (phi) due to angularity and interlocking fabric of individual particles.
Near GC , soil thickness is commonly 1m thick, but thins out to 0.5m to the north within a distance of 10km.

Slope- rockfalls generally occurred in steep (50+) areas, debris slides 35-30 degree slopes. Particular areas hard hit were Rios Pixcaya, Motagua, Los Chocoyos, and Las Vacas. High percentage of failures resulted from high dynamic stresses imposed by the amplification of seismic waves by the existing canyon topography.

The tefras-product of airborne ash falls-are less dense, better sorted, lower tensile strength and more friable than the ash-flow tuffs. Tuff units generally poorly sorted, unreworked, nearly unstratified mixtures of coarse ash, pumice, and lithic fragments. Tephra units are generally only a few meters thick in GC area, wheras ash-flow is bulk of basins. Lots of lateral variability in thickness of pumice deposits though from canyon to canyon.

In the GC area, more rock falls than debris slides. Fractures exposed in the rock-fall scarps were N10-N20 degrees E; this orientation approximately parallels the Mixco fault zone (echelon faults)

Because few seismically induced landslides in GC in ‘76 were thicker than 10m, about 95% of the landslide areas could have been avoided if dwellings had not been closer than 10m to the canyon margins or had not been built along the canyon slopes below the plateau rim.

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