MICROZONATION OF SLOPES IN A SEISMICALLY ACTIVE FOOTHILL REGION - A CASE STUDY

by

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SUMMARY

Microzonation maps identifying zones subject to seismically induced slope instability can be constructed by combining geotechnical, geological and regional seismic data. Maps produced by this technique can serve as a rational guide to planners and engineers for landuse planning is seismically active foothill regions. Both slope failures that may occur during earthquakes and mudflows that may occur in the seismically weakened slopes during the subsequent rainy season are considered by this technique.

INTRODUCTION

More than a thousand slope failures were observed in the San Fernando, California foothills following the 1971 earthquake (Morton, 1975). The seismically weakened slopes also developed numerous mudflows during the first significant rainy season (Badel, 1979). Similar slope failures have been reported in many seismically active foothill regions around the world (Pain, 1972; Okamoto, 1973) and have caused severe damage and loss of life.

Seismic zoning can be a useful tool for engineers and planners responsible for planning and design in foothill areas. A microzonation technique has been developed using the Lopez Canyon slope failures as a case study (Figure 1). This technique can be used in similar foothill areas elsewhere.

LOPEZ CANYON SLIDES AND MUDFLOWS

The 1971 San Fernando, California earthquake resulted in 21 seismically induced slides in Lopez Canyon and subsequently 28 mudflows in the seismically weakened slopes (Figure 2). The geology of Lopez Canyon and surface ruptures of the area were discussed by Oakeshoot (1975). Field mapping of the slope failures and geotechnical properties were reported by Yen, et al (1979).

The foothill area studied is below the San Gabriel Mountains, has a maximum relief of about 270 meters, and is about 12 or 13 Km south of the epicenter of the San Fernando earthquake (M = 6.5). The bedrock units belong to the Saugus, Towsley-Pico and Modelo formations, which range between Middle Pleistocene and Middle Myocene in age. These rocks are commonly coarse-grained sandstones and siltstones with varying amounts of conglomerates. The near-surface materials are severely to moderately weathered and form a residual soil mantle with gentle slopes. The soil mantle is generally loose silty or clayey sand containing varying amounts of small rock fragments. Dry densities of the soils are on the order of 11 kN/m^3.

Field investigations showed that the slides and subsequent mudflows occurred within the residual soil mantle and were not on bedding planes. All slope failures had a translational mode of failure and an average length-to-depth ratio of 50 with a maximum of 147.

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Since these failures were all in residual soils with shapes between 30° and 50°, it has been reasoned that the thin soil mantle on slopes steeper than 50° probably do not have sufficient inertial force to initiate sliding during an earthquake; the thick soil mantle on slopes flatter than 30° probably do not have enough downslope gravity component to overcome the soil strength to initiate sliding.

Generally, natural slopes in Lopez Canyon support only thin to moderate grass, weeds and scattered brush. Denser growth and trees are restricted to lower and flatter (less than 20°) areas of deeper soil. The exact soil densities and moistures at the time of slope failures are unknown. Rainfall records suggest that the soil moisture at the time of the 1971 earthquake could have been higher than normal but far from saturation. The record rainfall of the 1977-78 season that triggered mudflows suggests that the soil mantle could have been near saturation. Between the seismically induced slides of 1971 and the mudflows of 1977, some slide areas were eroded or overgrown somewhat and thus lost clarity. The dimensions and locations of the slope failures shown in Figure 2 are approximate.

MICROZONATION OF SLOPES

Since all the slope failures are planar and relatively long and occur within a soil mantle underlain by rock, a one-dimensional mathematical model consisting of an elastic layer bonded to an unyielding bedrock (Figure 4) was used to analyze the seismically induced slides (Yen and Trotter, 1978). One of the results of the mathematical analyses is that the likely size of the 1977 seismically induced slides can be estimated from the slope geometry and soil properties. The estimated slide length could serve as a rational guide for planning criteria such as structural set-backs or locations of transmission line corridors in seismically active foothill regions. The methodology of utilizing estimated slide lengths and mudflow data for zoning are presented below.

Seismically induced slides are transient hazards, i.e., hazards practically limited to the duration of earthquake or immediately thereafter; whereas mudflows in slopes whose soil has been seismically weakened by seismic events are potentially hazardous during and following each major rainstorm. Therefore, microzonation of slopes should consider both slides during earthquakes and also mudflows following earthquakes. Based on the observations in Lopez Canyon, mudflows occurred in the scarp areas of the 1971 slides or in and around the slide boundary. Mudflows also occurred in areas where the soil mantle was weakened by the 1971 event. For these reasons it has been assumed that, given enough rain, mudflows may occur in the same areas and be approximately the same size as seismically triggered slides.

A microzonation map of Lopez Canyon is shown in Figure 3. Although development of microzonation maps should consider many factors; such as magnitude and frequency of the earthquake, wave attenuation, geology, topography, and geotechnical parameters; in practice a map may be constructed by choosing parameters such as the maximum bedrock acceleration, slope geometry and a geotechnical parameter.

The bedrock acceleration for a given earthquake may be estimated from Schnabel and Seed (1973), or other attenuation correlations. The maximum horizontal bedrock acceleration at Lopez Canyon due to the 1971 earthquake is estimated to be $A_{max} = 0.45g$. Yen and Trotter (1978) showed that the maximum sliding length, X_{cr}, can be estimated by:

$$X_{cr} = \frac{\sigma_o\left[1+\left(\frac{\gamma\cdot a\cdot h}{\tau}\right)^{1/2}\right]}{\left(\frac{\tau}{h} - \gamma\cdot a\right)} \qquad (1)$$

where

γ = unit weight of soil
σ = lateral stress at the toe of a potential slide
X_{cr} = maximum sliding length
$\tau = c + \gamma h \cdot \cos\alpha \cdot \tan\phi - \gamma h \sin\alpha$
$s = c + \gamma h \cos\alpha \cdot \tan\phi$
c = cohesion, ϕ = angle of shearing resistance
h = soil mantle thickness

The term "a" in equation (1) is a pseudo-acceleration which accounts for the accumulative shaking effect causing sliding failure. Analysis of the Lopez Canyon slides showed that "a" can be estimated, in terms of the soil mantle strength, as

$$a = \frac{\tau}{\gamma h}\left[\frac{\sigma_o + c \cdot \cot\phi}{\sigma_o}\right]^2 \quad (2)$$

Therefore, once the soil mantle depth, strength and slope geometry are known, the maximum sliding length can be estimated.

This zoning procedure can be accomplished by converting the topographic map into various slope zones, e.g., 0° to 20°, 20° to 40°, 40° to 60°, etc. Geologic features such as faults, seismically weakened or shattered soil zones (existing in the southern parts of Lopez Canyon due to the 1971 earthquake) are then marked on the slope zones and the X_{cr} values for a given soil mantle are incorporated for zoning. Table 1 lists the criteria used for zoning Lopez Canyon, Figure 3.

In summary, for areas where previous slides and mudflow records are available, the microzonation procedure may be summarized as:

Step 1. Field reconnaissance to assess soil mantle (weathering depth) and estimate or conduct tests to establish representative soil strength parameters.

Step 2. Calculate "a" using equation (2).

Step 3. Calculate X_{cr}, using equation (1).

Step 4. Convert contour maps of the study area into slope zones and enter geologic and soil features X_{cr} to establish zoning criteria such as Table 1.

Step 5. Complete the microzonation map.

DISCUSSION

The microzonation map constructed in this manner applies to future seismic events equal or smaller than the previous events at a given site. This is because of two reasons: one reason is the implicit assumption that the strength of the soil weakened by the previous seismic shaking will be smaller or equal to the preshaking strength. The other reason is that the current data base of Lopez Canyon slope failures is limited. It is not prudent to generalize. To broaden the data base and to validate the present technique, additional case histories using field data and testing following a seismic event is recommended.

For the time being, should one wish to zone an area for a postulated unprecedent seismic event, Figure 5 may be used as a first approximation. Figure 5 is normalized by the maximum bedrock acceleration a_{max} so that it can be used to extrapolate the present data base. In Figure 5, a_y is a pseudo-static yield acceleration.

$$a_y = \cos\alpha \tan\phi + \frac{c}{\gamma h} - \sin\alpha \quad (3)$$

and a_f is the acceleration term calculated from field data to account for the accumulative shaking effect which cause a slope of length X_{cr} to fail (Yen and Wang, 1977):

$$a_f = \frac{\tau}{\gamma h} + \frac{2\tau_o}{\gamma \cdot X_{cr}} + \frac{\tau_o^2 \cdot h}{\gamma \cdot \tau \cdot X_{cr}} \qquad (4)$$

Using the dimensionless plot of Figure 5, microzonation of slopes subject to a future large earthquake in accordance with the following steps:

Step 1. Field reconnaissance to assess soil mantle thickness and estimate or conduct tests to establish representative soil strength parameters.

Step 2. Calculate a_y using equation (3).

Step 3. Select design earthquake and estimate a_{max} using approximate attenuation correlation.

Step 4. Calculate a_y/a_{max} and use Figure 5 to calculate a_f.

Step 5. Use a_f as a in eq. 1 to calculate X_{cr}.

Step 6. Convert contour map of the study area into slope zones and enter geologic and the anticipated slope failure length, X_{cr}.

Step 7. Complete the microzonation map.

For example, using the steps outlined above, Lopez Canyon has been re-zoned for a M = 8.5 earthquake originating on the San Andreas fault (Condoretti, 1980).

CONCLUSIONS

Results of field mapping, laboratory tests and analyses of previous studies can be used for microzonation of slopes in seismically active foothill regions. The Lopez Canyon case study showed promise that this method can be a rational approach for landuse planning utilizing seismic, geologic and geotechnical input. Similar studies are urged to be carried out in other seismically active foothill areas to improve and confirm the proposed methodology.

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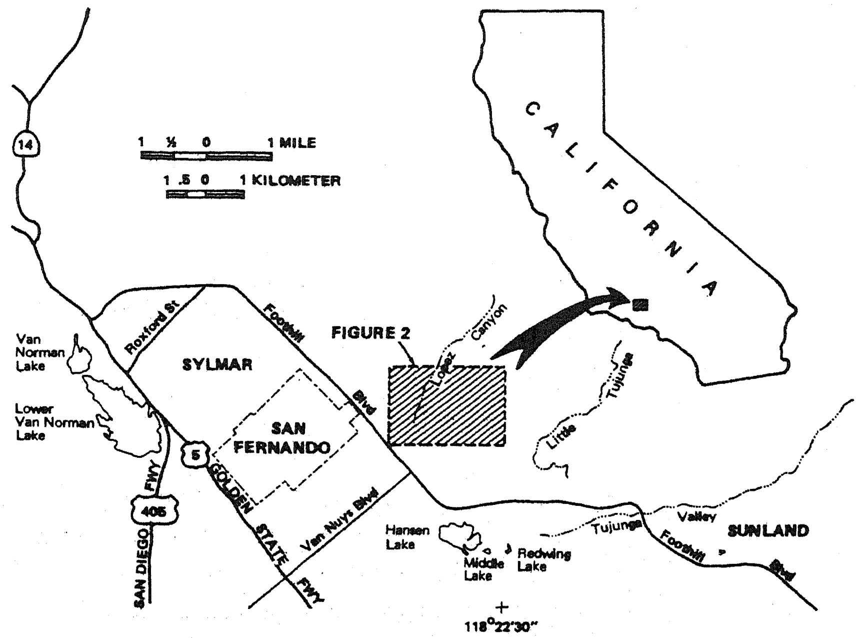
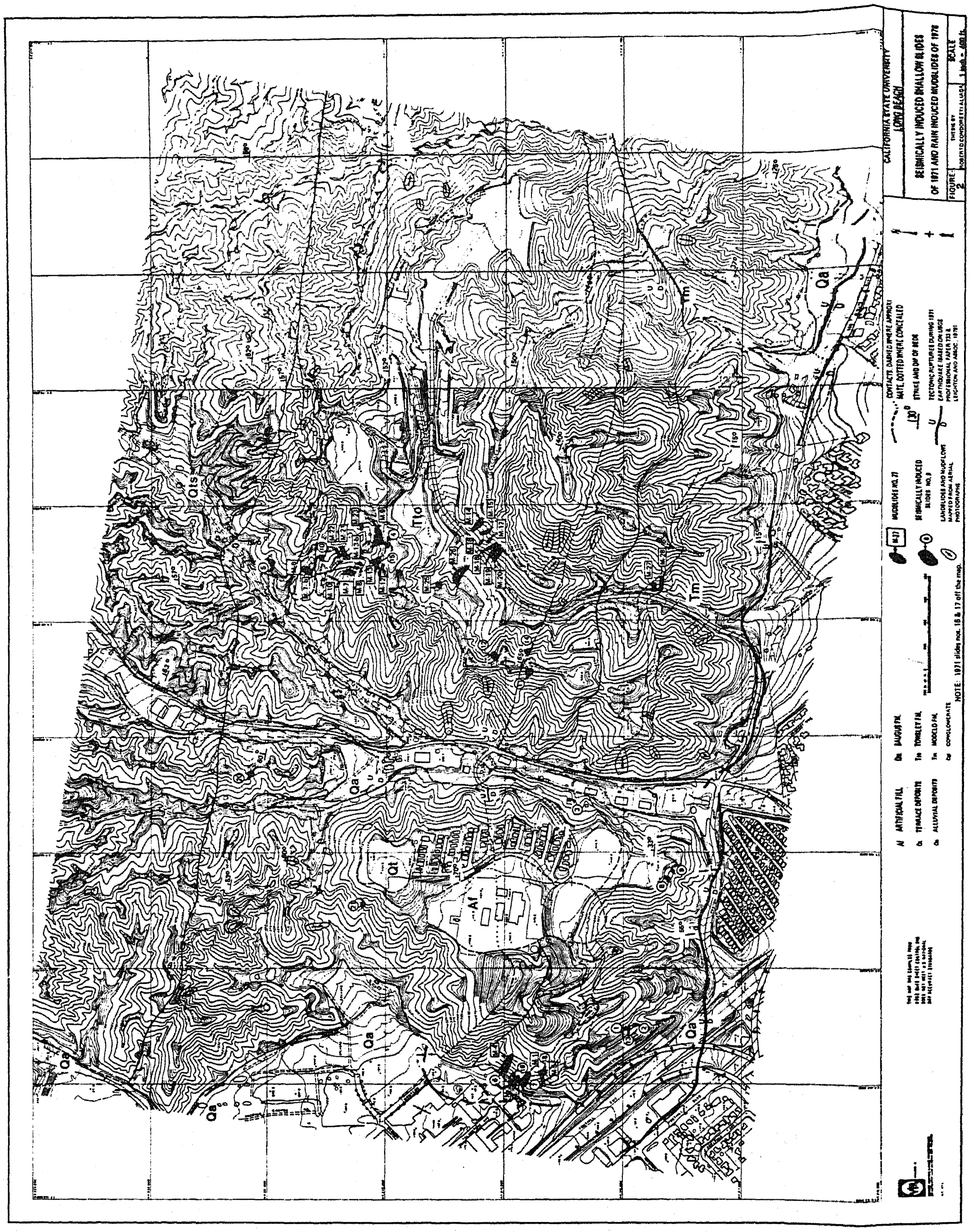


Figure 1. Location of Study Area

Ranking \ Parameter	Slope Angle	Existing Slides	Existing Faults or Weakened Soils	Slope Length
High	30°–50°	Yes	Yes	Yes
Moderate	30°–50°	No	Yes	Yes
Low	30°–50°	No	No	Yes
	$> 50^\circ$	No	Yes	No
	$< 30^\circ$	No	Yes	No
No Failure Anticipated	$> 50^\circ$	No	No	No
	$< 30^\circ$	No	No	No

Table 1 — Criteria for Slope Zoning in Lopez Canyon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LONG BEACH
SEISMICALLY INDUCED SHALLOW SLIDES OF 1971 AND RAIN INDUCED MUDSLIDES OF 1978
FIGURE: 2
THESIS BY ROBERTO CONDORETTI ALIAGA
SCALE 1 inch = 400 ft.
Af ARTIFICIAL FILL
Qt TERRACE DEPOSITS
Qa ALLUVIAL DEPOSITS
Qs SAUGUS FM.
Tto TOWSLEY FM.
Tm MODELO FM.
cg CONGLOMERATE
MUDSLIDES NO. 77
SEISMICALLY INDUCED SLIDES NO. 8
LANDSLIDES AND MUDFLOWS MAPPED FROM AERIAL PHOTOGRAPHS
CONTACTS. DASHED WHERE APPROXIMATE, DOTTED WHERE CONCEALED
STRIKE AND DIP OF BEDS
TECTONIC RUPTURES DURING 1971 EARTHQUAKE (BASED ON USGS PROFESSIONAL PAPER 733 & LEIGHTON AND ASSOC. 1979)
NOTE: 1971 slides nos. 16 & 17 off the map.
Qts
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Af
Tm
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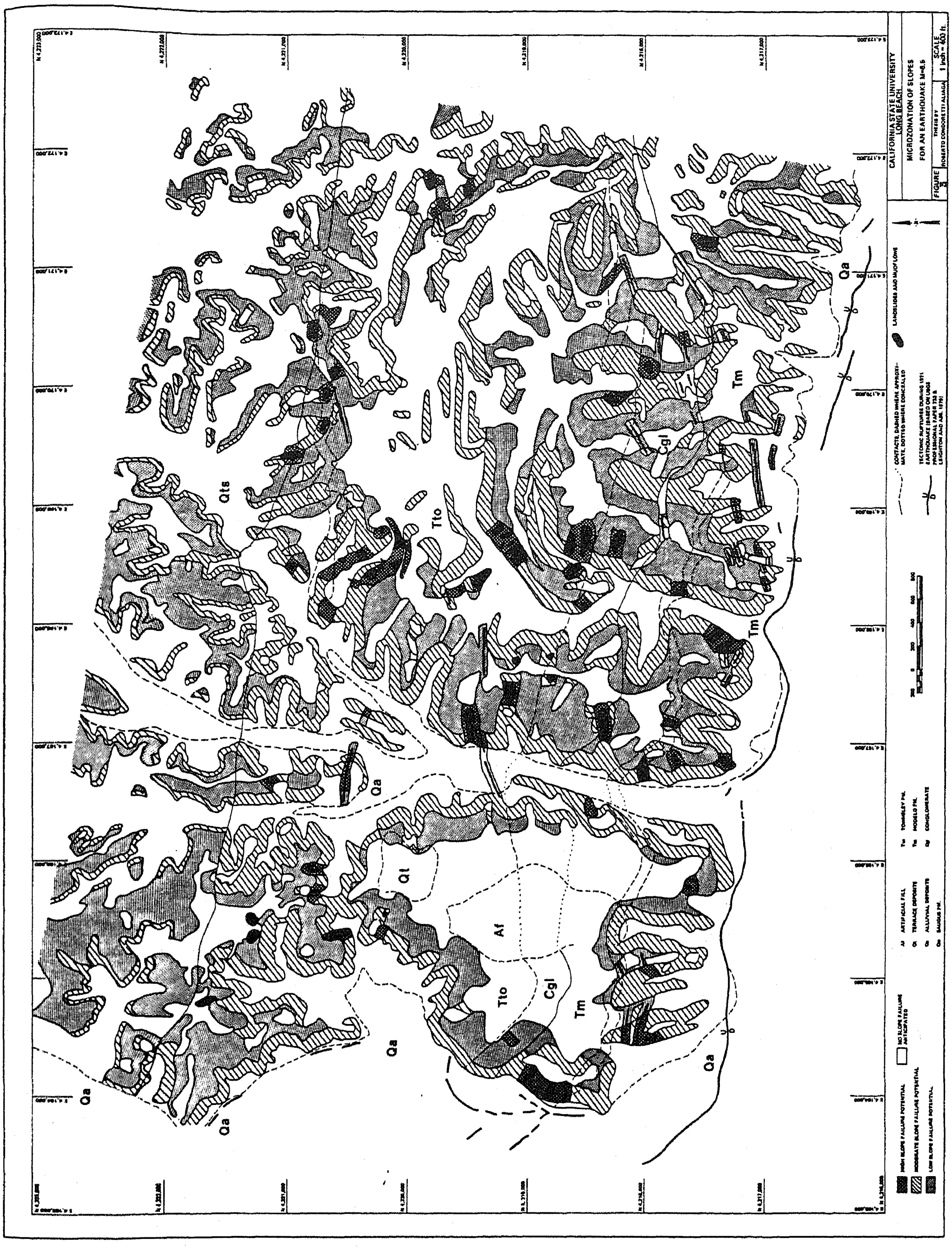
CALIFORNIA STATE UNIVERSITY
LONG BEACH
MICROZONATION OF SLOPES
FOR AN EARTHQUAKE M=6.6
FIGURE
THESIS BY
ROBERTO CONDORETTI ALIAGA
SCALE
1 inch = 400 ft.
LANDSLIDES AND MUDFLOWS
Qa
Qts
Qt
Af
Tto
Cgl
Tm

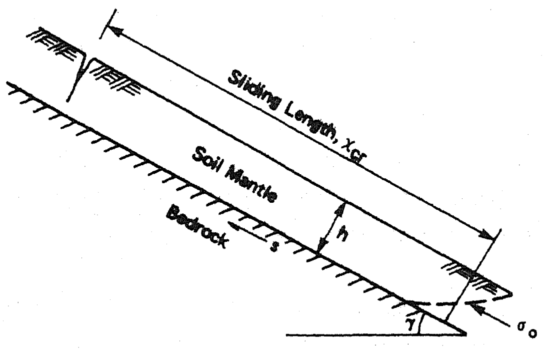

Figure 4. Idealized One–Dimensional Slide Model

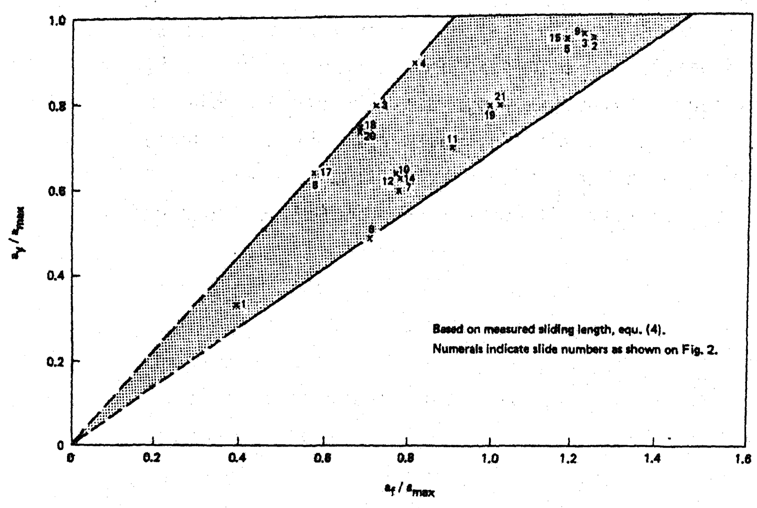

Figure 5. Normalized Acceleration of Seismically Induced Slides in Lopez Canyon