PROBABILISTIC APPROACH TO EARTHQUAKE-INDUCED LANDSLIDE HAZARD MAPPING

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SUMMARY

We present an approach to evaluate the relative seismic slope stability and failure potential suitable for regional hazard mapping. The critical acceleration necessary to initiate downslope movement of a simple sliding friction block analogue is the measure of landslide susceptibility. Curves of predicted downslope displacement versus critical acceleration, integrated from earthquake strong motion records are used to develop slope failure intensity matrices. These matrices, similar to damage proability matrices used in seismic risk studies, show the probabilities at each relative slope stability level, that a particular slope will experience some displacement (i.e., slope failure intensity) for various levels of seismic shaking. The method can be used in both scenario-based and probabilistic earthquake hazard analyses.

INTRODUCTION

Slope movements caused by earthquake shaking can occur at great distances from the earthquake source. An ability to predict the exact locations and severities of slope failures induced by a particular earthquake event is not possible at the present time. However, enough is known about the main factors related to slope instability and failure during seismic and other types of loading (such as rainfall) so that assessments of relative slope stability during earthquakes can be made (Refs. 1 and 2).

Slope gradient, surficial geology, degree of fracturing, geometry of bedding planes and other planes of weakness relative to the slope, water content, presence of pre-existing landslide deposits and intensity of shaking are all known to be important factors in evaluating slope failure potential. From an earthquake engineering viewpoint, severity of damage to structures and facilities affected by slope failures is directly related to the intensity of the slope movement. For example, Ref. 3 shows that even minor slope movements, which result in slight ground cracking, may be related to increased damage rates to underground components of water and natural gas supply systems. Therefore, it is desirable when doing earthquake-induced landslide hazard mapping, to predict not only the locations of potential slope movements during earthquakes, but also to estimate the intensity or severity of those movements.

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DYNAMIC SLOPE STABILITY ANALYSIS

We describe a method developed to map earthquake-induced slope failure hazards and estimate the potential of experiencing slope movements of varying severity for given levels of earthquake shaking intensity. The method is adapted from Newmark's dynamic slope stability analysis technique (Ref. 4) as applied by the U.S. Geological Survey (Ref. 5). We have employed this technique to evaluate the earthquake vulnerability of water and natural gas supply systems in the City of Oakland, California (Refs. 6 and 7).

Relative Seismic Slope Stability

Slope movement is modeled by a two-dimensional block sliding down an inclined plane (Figure 1). In equilibrium, the block remains stationary and the downslope forces are balanced by the cohesion and friction at its base. The downslope acceleration required to initiate movement of the block, called the critical acceleration, 'a_c', is a measure of the seismic slope stability. Values of 'a_c' are derived using the formula:

$$\frac{a_c}{g} = \frac{C}{\gamma H} + (\tan\phi\cos\theta - \sin\theta)$$

where 'C' is the cohesion of the materials, 'γ' is the weight density of the material, 'H' is the thickness of the slide block (assumed to 10 feet), 'ϕ' is the angle of internal friction of the material, and 'θ' is the slope angle.

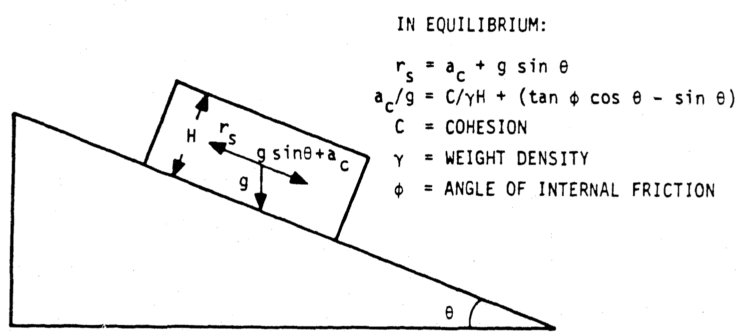

Figure 1. Force Balance for Simple Seismic Slope Stability Analyses

The values of cohesion, specific weight, and internal friction angle are related to site geology and water content or pore pressure. Six general lithology groups, with associated shear strength parameters, shown in Table 1 (Ref. 8), are used to determine the relative seismic slope stability values. Effective shear strength parameters are provided for saturated and unsaturated (optimum moist) conditions as well as for slopes with bedding planes, joints or other weak surfaces dipping parallel to or antiparallel to the downslope direction. For each lithology and slope gradient combination, a range of values of 'a_c' is computed. This range of values is compared to the 'a_c' limits for each relative seismic slope stability category and an appropriate level of stability is assigned (Table 2).

Table 1. Shear Strength Parameters for Regional Analysis of Slope Stability

GEOLOGIC UNIT	SATURATED STATE[1]				UNSATURATED STATE[2]			
	ALONG PLANES[3] OF WEAKNESS		THROUGH ROCK[4]		ALONG PLANES[3] OF WEAKNESS		THROUGH ROCK[4]	
	ϕ'	$C'/\gamma H$	ϕ'	$C'/\gamma H$	ϕ	$C/\gamma H$	ϕ	$C/\gamma H$
1. QUATERNARY - UNCONSOLIDATED OR SEMI CONSOLIDATED, SANDY CLAY OR CLAYEY SAND PREDOMINATING	-	-	15°	0.4	-	-	30°	0.5
2. TERTIARY SEDIMENTS - CONSOLIDATED SHALE, MUDSTONE OR SILTSTONE, BENTONITIC CLAYS A PROMINENT CONSTITUENT	7.5°	0.25	10°	1.0	15°	0.5	20°	1.25
3. TERTIARY SEDIMENTS - CONSOLIDATED SANDSTONE OR CONGLOMERATE, POORLY CEMENTED	10°	0.5	20°	1.25	20°	0.75	35°	1.5
4. SERPENTINE - HIGH TALC CONTENT, USUALLY SHEARED	7.5°	0.125	10°	0.5	10°	0.25	20°	0.75
5. FRANCISCAN - HIGHLY FRACTURED, FAULT GOUGE AND SHATTERED ROCK	7.5°	0.25	15°	0.75	15°	0.5	30°	1.0
6. FRANCISCAN - RELATIVELY INTACT SANDSTONE, GRAYWACKE, AND WELL CONSOLIDATED SHALE, LOCALLY CEMENTED	10°	0.5	20°	1.5	20°	0.75	35°	2.0

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[1]Effective strength parameters, rock saturated but pore water pressure not considered in analysis.

[2]Fundamental strength, rock not saturated or pore water pressure considered in analysis.

[3]Failure path along well defined bedding planes, faults, or pre-existing slip surfaces.

[4]Failure path crossing bedding, through largely intact rock.

Source: D.E. Moran, personal communication (1981).

Table 2. Relative Seismic Slope Stability

SLOPE	LITHOLOGY: 1. QUATERNARY ALLUVIUM	2. TERTIARY SEDIMENTS - SHALES, MUDSTONES, SILTSTONES		3. TERTIARY SEDIMENTS - SANDSTONE, CONGLOMERATE		4. SERPENTINE		5. FRANCISCAN - HIGHLY FRACTURED		6. FRANCISCAN - INTACT	
		D	A	D	A	D	A	D	A	D	A
SATURATED											
0-5%	S	H	V	V	V	M	V	H	V	V	V
5-15%	H	M	V	S	V	M	S	M	V	S	V
15-30%	H	M	V	H	V	L	H	M	V	H	V
30-50%	M	U	V	M	V	U	M	U	S	M	V
50-70%	L	U	S	M	V	U	M	U	H	M	V
>70%	L	U	H	L	S	U	L	U	H	L	V
UNSATURATED											
0-5%	V	V	V	V	V	H	V	V	V	V	V
5-15%	V	S	V	V	V	H	V	S	V	V	V
15-30%	V	H	V	V	V	M	V	H	V	V	V
30-50%	S	H	V	S	V	L	S	H	V	S	V
50-70%	H	M	V	H	V	U	H	M	V	H	V
>70%	H	L	V	H	V	U	H	L	V	H	V

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Explanation

D - DIP: Stability along planes of weakness, failure path along well defined bedding planes, faults or pre-existing slip surfaces.

A - ANTIDIP: Stability through rock, failure path crossing bedding, through largely intact rock.

SATURATED: Saturated state, effective strength parameters used, rock saturated but pore pressure not considered in analysis.

UNSATURATED: Unsaturated, fundamental strength, rock not saturated (or pore pressure considered in analysis), optimum moisture content.

Relative Seismic Slope Stability Units

V - VERY STABLE: Not Likely to Move Under Severe Shaking, $a_c \geq 0.7g$

S - STABLE: May Undergo Slight Movement Under Severe Shaking, $0.5g < a_c < 0.7g$

H - HIGH: May Undergo Moderate Movement Under Severe Shaking; Some Landslides Related to Steep Slopes, Saturated Conditions, and Adverse Dips, $0.3g < a_c < 0.5g$

M - MODERATE: May Undergo Major Movement Under Severe Shaking or Moderate Movement Under Moderate Shaking; Numerous Landslides, Rock Falls Abundant, Unconsolidated Material Undergoing Deformation and Failure, $0.1g < a_c < 0.3g$

L - LOW: May Undergo Major Movement Under Moderate Shaking; Abundant Landslides of All Types, $0.01g < a_c < 0.1g$

U - UNSTABLE: May Undergo Major Movement Under Slight Shaking; Most of Area and/or Materials Failing, e.g., Northern California Coastal Area, $a_c < 0.01g$

The earthquake-induced slope failure susceptibility map is then prepared from two initial maps: one showing ranges of slope gradient, the second showing lithology. The lithology map, showing the six generalized units described above also delineates regions with a component of bedding plane dip in the down-slope direction. By overlaying these two maps, the relative seismic slope stability can be contoured (Figure 2) for the region, according to the data listed in Table 2.

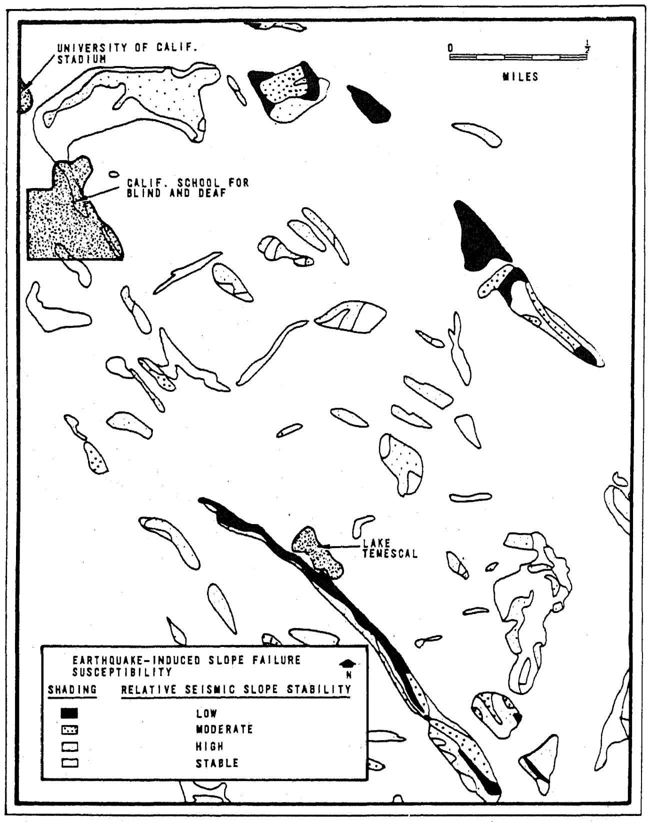

Figure 2. Earthquake-Induced Slope Failure Susceptibility - Northeast Oakland

Slope Failure Potential

The slope failure susceptibility map described above is independent of the earthquake shaking environment. When earthquake shaking is considered, slope failure potential can be determined. Using dynamic slope stability analysis, slope displacement curves can be computed for particular earthquake time histories by integrating these accelerograms above different levels of critical acceleration and plotting the calculated displacements as a function of the critical acceleration. Smoothed slope displacement curves for actual earthquake time histories developed by the USGS (Ref. 5) are shown in Figure 3. A simple fail/no-fail criteria (with a displacement threshold of 5 centimeters) was used in that study, reasoning that for greater displacements the shear strength of the slide block deteriorates so that the overall slope displacement is indeterminant. Since we have found direct correlations of structure or component damage with ground failure intensity, we define five levels of slope failure intensity, based upon the amount of displacement predicted by the simple dynamic analysis (Table 3). Although we do not expect the actual amount of displacement predicted by this simple model to be an accurate estimate of actual movement expected during an earthquake, these five intensity levels are believed to be useful indices of the relative slope failure severity expected in real earthquakes.

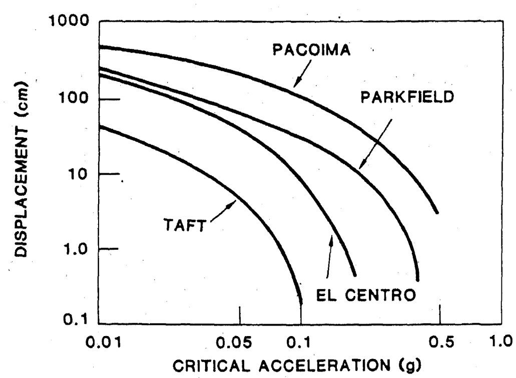

Figure 3. Plots of Displacement Versus Critical Acceleration, for Selected Earthquakes (Modified from Ref. 5)

In regional earthquake hazard mapping, earthquake shaking is generally described by isoseismal maps showing regions expected to experience various levels of shaking intensity for a given earthquake input. In order to compute slope failure potential using isoseismal data as the shaking input, it is first necessary to convert the displacement versus critical acceleration curves for the earthquake time histories into curves showing displacement versus ground shaking intensity. Such curves were prepared from the curves in Figure 3 by correlating the peak velocity of each earthquake accelerogram with Modified Mercalli Intensity (Figure 4). These curves were drawn for each 'a_c' bounding the various seismic slope stability levels, (the shaded region corresponding to a 'Moderate' relative stability value).

For a given value of relative seismic slope stability and an expected earthquake shaking intensity, more than one level of slope failure intensity might be predicted according to the data in Figure 4. Additional sources of uncertainty in predicting the actual location and intensity of slope movements during earthquakes exist. Therefore, we have developed 'slope failure intensity matrices' for each relative slope stability category (Table 3). These matrices are similar to structural damage probability matrices used in earthquake engineering. Each matrix lists the probabilities that slopes of a particular relative stability value will experience some level of movement (slope failure intensity) for different amounts of earthquake shaking. For example, at a shaking level of MMI 8, slopes classified as moderate stability (i.e., $0.1_g < a_c < 0.3_g$) would be expected to have a failure intensity of 'Heavy', five percent of the time, a failure intensity of 'Moderate', ten percent of the time, and a failure intensity of 'Light' the rest of the time. The actual probability values shown in these matrices were determined using expert judgment guided by the data shown in Figure 4. Future detailed studies of earthquake-induced slope movements are necessary to evaluate the validity of these numbers and provide data necessary to improve these first-order estimates.

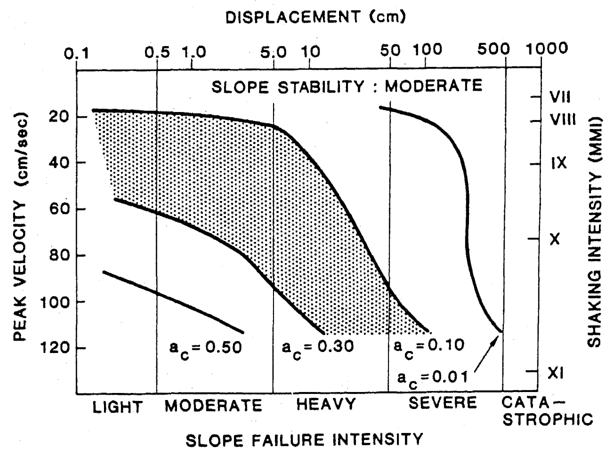

Figure 4. Plots of Displacement Versus Shaking Intensity for Seismic Slope Stability Analysis

CONCLUSIONS AND RECOMMENDATIONS

A simple method of evaluating earthquake-induced slope failure potential has been described. Dynamic slope stability analysis provides the basic method used to produce slope failure susceptibility maps. Relative seismic slope stability values are derived considering slope gradient, lithology, bedding plane dip and moisture content. Slope failure potential is defined as the probability of experiencing a given level of slope failure intensity within a susceptible area, when that area is subjected to a prescribed level of seismic shaking. This simple method does not attempt to differentiate between the possible forms of slope failure, such as rock falls or rotational slumps, that may be expected to occur. Previous studies (Ref. 5) defined slope failure by a fail/no fail criteria, whereas we consider five levels of slope failure intensity. Recent studies (Ref. 3) have shown significant increases in damage rates to underground components of water and natural gas supply systems in regions of relatively minor ground failure, and suggest correlations between the severity of ground failure and damage to structures.

Slope failure potential is presented in simple, 'slope failure intensity matrices', similar to damage probability matrices used in earthquake risk studies. In these matrices, slope failure intensity is related to earthquake shaking intensity by a probability value or slope failure potential. We have successfully applied this method in a scenario-based study of the earthquake vulnerability of water and natural gas supply systems in Oakland, California (Refs. 6 and 7). The method is also well-suited to probabilistic analyses similar to those used for liquefaction hazards (Ref. 10).

At present, the method we have developed is primarily theoretical, based upon a simple dynamic model and professional experience. Data recently discussed in Ref. 11 indicate the general validity of the dynamic model. Additional data are needed to substantiate (or correct) the values of slope

Table 3a. Slope Failure Intensity Matrices

SLOPE STABILITY: UNSTABLE; $a_c < .01$ g	MMI				
DAMAGE STATE	X	IX	VIII	VII	VI
CATASTROPHIC	25	20	15	10	10
SEVERE	55	50	45	40	30
HEAVY	20	30	40	50	60
MODERATE	0	0	0	0	0
LIGHT	0	0	0	0	0
$\sum P_i$	100%	100%	100%	100%	100%

SLOPE STABILITY: HIGH; $0.3 < a_c \leq 0.5$ g	MMI				
DAMAGE STATE	X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	0	0	0	0	0
HEAVY	0	0	0	0	0
MODERATE	10	5	0	0	0
LIGHT	90	95	100	100	100
$\sum P_i$	100%	100%	100%	100%	100%

SLOPE STABILITY: LOW; $.01 < a_c \leq 0.1$ g	MMI				
DAMAGE STATE	X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	20	15	10	10	5
HEAVY	50	45	40	35	25
MODERATE	20	30	35	30	30
LIGHT	10	10	15	25	40
$\sum P_i$	100%	100%	100%	100%	100%

SLOPE STABILITY: STABLE; $0.5 < a_c \leq 0.7$ g	MMI				
DAMAGE STATE	X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	0	0	0	0	0
HEAVY	0	0	0	0	0
MODERATE	5	0	0	0	0
LIGHT	95	100	100	100	100
$\sum P_i$	100%	100%	100%	100%	100%

SLOPE STABILITY: MODERATE; $0.1 < a_c \leq 0.3$ g	MMI				
DAMAGE STATE	X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	5	0	0	0	0
HEAVY	15	10	5	0	0
MODERATE	25	20	10	0	0
LIGHT	55	70	85	100	100
$\sum P_i$	100%	100%	100%	100%	100%

SLOPE STABILITY: VERY STABLE; $0.7 \leq a_c$	MMI				
DAMAGE STATE	X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	0	0	0	0	0
HEAVY	0	0	0	0	0
MODERATE	0	0	0	0	0
LIGHT	100	100	100	100	100
$\sum P_i$	100%	100%	100%	100%	100%

Table 3b. Slope Failure Intensity Scale

LIGHT - INSIGNIFICANT GROUND MOVEMENT, NO APPARENT POTENTIAL FOR LANDSLIDE FAILURE, GROUND SHAKING ONLY EFFECT. PREDICTED DISPLACEMENT LESS THAN 0.5 CM..

MODERATE - MODERATE GROUND FAILURE, SMALL CRACKS LIKELY TO FORM, (HAVING EFFECTS SIMILAR TO LURCH PHENOMENA). PREDICTED DISPLACEMENT BETWEEN 0.5 CM AND 5.0 CM.

HEAVY - MAJOR GROUND FAILURE MODERATE CRACKS AND LANDSLIDE DISPLACEMENTS LIKELY (HAVING EFFECTS SIMILAR TO LIQUEFACTION, LATERAL SPREAD PHENOMENA). PREDICTED DISPLACEMENT BETWEEN 5.0 CM AND 50 CM.

SEVERE - EXTREME GROUND FAILURE, LARGE CRACKS AND LANDSLIDE DISPLACEMENTS LIKELY (HAVING EFFECTS SIMILAR IN SEVERITY TO LARGE-SCALE FAULT RUPTURE). PREDICTED DISPLACEMENT BETWEEN 50 CM AND 500 CM.

CATASTROPHIC - TOTAL FAILURE, LANDSLIDE MOVES LARGE DISTANCES CARRYING EVERYTHING WITH IT. PREDICTED DISPLACEMENT GREATER THAN OR EQUAL TO 500 CM.

failure potential presented in the slope failure intensity matrices. It is, therefore, important that data describing earthquake-induced slope failure intensities be obtained during investigations following future earthquakes. Tectonic fault rupture displacements are generally measured at present, and limited data on lateral spread and landslide displacements have been collected. Similar data on ground failure intensity in liquefaction (and lurching) and differential subsidence areas would also be desireable.

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