SEISMICALLY INDUCED SHALLOW HILLSIDE SLOPE FAILURES

by

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SYNOPSIS

A one-dimensional pseudo static model is used to study shallow slides caused by the 1971 San Fernando seismic activity. Slide length and displacement can be estimated theoretically from the various bond strengths between the soil and base rock. Field investigation has shown a reasonable range for the pseudo static acceleration and a characteristic range for the dimensionless sliding length for three geological formations in the Lopez Canyon area north of San Fernando Valley, California.

INTRODUCTION

The San Fernando earthquake of February 9, 1971, resulted in numerous identified hillside slope failures. Among various modes of seismically triggered slope failures, the most common type of failures are the shallow hillside slides. This type of slope failures can generally be characterized by the shallow depth (less than 2 m.) in proportion to their length (10 meters or more) with extensive tensile cracks near the top of the slides. The slides were primarily observed in weathered, residual soil mantle overlaying bedrock. Figure 1 shows an example of such failures in the Towsley-Pico formation. The geographical distribution of the aerially mapped slides has been postulated to reflect local geology and suggests lithological control (Morton, 1975).

The shallow hillside slope failures are studied by a one-dimensional mathematical model which assumes a uniform elastic soil mantle bonded to a solid base. The bonding soil properties may exhibit rigid-plastic, elasto-plastic or strain-softening behavior. The seismic effect is replaced by an equivalent downslope acceleration which initiates failure when the stress exceeds the strength of the bonding material. The tensile zone in the soil layer provides an estimate of the slide length which is the extent of potential slope failure. A limited number of field data of failed slopes including slope angles, length of slides and conventional soil parameters have been collected to compare with the results of the theoretical analysis.

ANALYSIS

In Figure 2, an elastic soil layer, having a Young's modulus E and bonded to an unyielding base, is overcome by a seismic force expressed in a pseudo-static yield acceleration "a". The equation of equilibrium of a generic element is then obtained.

$$Eh \frac{\partial^2 u}{\partial x^2} = \tau - \gamma ha \qquad (1)$$

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in which h = the soil layer thickness, u = displacement, τ = bond strength, and γ = soil unit weight.

Depending on the boundary conditions and bonding strength, the displacement of the soil layer can be estimated by solving equation (1). The bonding strength may be either rigid plastic, elasto-plastic, strain-softening or other suitable forms. If the soil layer has an initial stress σ prior to failure, and the bonding strength τ is rigid plastic, the displacement is

$$u = \frac{1}{2} \left(\frac{\tau}{Eh} - \frac{\gamma a}{E} \right) x^2 + \frac{\sigma}{E} x + \frac{\sigma^2 h}{2E\tau} \tag{2}$$

The extent of the sliding length is important from the practical viewpoint. It is obtained by making u = o.

$$X_{cr} = \sigma \frac{(-1-\sqrt{\gamma\ ah/\tau})}{(\tau/h - \gamma a)} \tag{3}$$

The negative root is chosen as the failure surface extends upslope with larger accelerations. The sliding length can be expressed in terms of soil mechanics parameters. In a slope, the net available shear resistance of the bond is $c + \gamma\ h \cos\alpha \tan\phi - h \sin\alpha$ while σ may be simply expressed as

$$\sigma = \frac{1}{2} K \gamma h \tag{4}$$

The term K depends on the mode of failure and boundary conditions. Equation (3) can be rewritten into a dimensionless form as follows:

$$A = \frac{-1- \sqrt{a/B}}{B - a} \tag{5}$$

in which $A = \frac{2X_{cr}}{Kh}$ = dimensionless sliding length and $B = \frac{c}{Xh}$ $+ \cos\gamma \tan\phi - \sin\alpha$, i.e. a dimensionless soil strength. Equation (5) is plotted in Figure 3.

The elasto-plastic and idealized strain-softening bond can be treated together. S'p and S'r are the net peak and residual bond strength, respectively. The solution of equation (1) is

$$u = \frac{1}{2} \left(\frac{S'r}{Eh} - \frac{\gamma a}{E}\right) x^2 + \frac{\sigma}{E} x + \frac{1}{2S'r}\left(\frac{\sigma^2 h}{E} - \frac{S'p^2}{k}\right) \tag{6}$$

in which k is the slope of the linear elastic portion of the stress-displacement curve. For this case the sliding length, X_{cr} is as follows:

$$X_{cr} = \frac{-1}{S'r - \gamma ha} \left[\sigma h + \sqrt{\frac{\sigma^2 \gamma h^3 a}{S'r} + \frac{Eh}{k} S'p^2 - \frac{E\gamma h^2 a S'p^2}{S'r\ k}} \right] \tag{7}$$

It can also be rewritten into a dimensionless form as follows:

$$A = \frac{-1 - \left[\frac{a}{B_r}(1 - DB^2) + DB^2\right]^{\frac{1}{2}}}{B_r - a} \qquad (8)$$

in which $D = \frac{4E}{khK^2}$, $B_r \ \frac{C_r}{\gamma h} + \cos\alpha \tan\phi_r - \sin\alpha$, and C_r is residual cohesion.

If $B_r = B$, the solution represents the elasto-plastic bond. Furthermore, if $D=0$, the solution is for the rigid plastic bond, same as equation (5). Figure 4 is plotted for $D=50$ which is an estimate based upon field and laboratory tests. If $a = o$, equations (3) and (7) will be reduced to that of one-dimensional static stability analyses (Christian and Whitman, 1969). This psuedo acceleration "a" could be interpreted as a relative measure for seismic slope safety. However, the real acceleration depending on slope, topography, time history, etc. (Davis 1973, Mostagher et al, 1975) is difficult to evaluate quantitatively.

FIELD DATA

A total of 16 slides were mapped and sampled in Lopez Canyon area about 20 km south of the epicenter. Most of the slides are located in the residual soil mantle of the Modelo (8 slides) and Towsley-Pico formation (7 slides). The only slide mapped in the Saugus formation is in the darker unit derived from mudstones. No slides occurred in the cemented, coarser unit of sandstone. This observation of slide prone material composed of silty or clayey sands is illustrated in Figure 5. Laboratory results of hand driven "undisturbed" samples indicate a low to medium density with a dry unit weight varying from 60 to 100 pcf. Stress-strain curves suggested that a rigid-plastic behavior may be an acceptable assumption. Most of the stress-strain data available are from samples taken from Modelo formation and the calculated dimensionless parameters are plotted in Figure 3. (Modelo, O; Towsley-Pico +; and Saugus formation, brown unit, Δ). $K = Kp$ (coefficient of lateral passive pressure) is used for this calculation because the slides analyzed are toed out from the slopes. The dimensionless parameter A for Modelo formation ranged from 11 to 36 with "a" between 0.5 and 1.7. Even though only limited data are available for Towsley-Pico and Saugus formations, Figure 3 does show the difference of the 3 lithologic units. More field and laboratory work is needed in this aspect.

CONCLUSIONS

1. The simplified mathematical model is proposed to describe the seismically induced shallow hillside failures.

2. Slides are found to be abundant in the loose to medium dense residual soil mantles of silty or clayey sands.

3. There appears to be a range in the value of the characteristic parameter, A, and the ratio of slope length to failure depth that is influenced by the boundary condition (K) and the lithology of the parent rock.

4. A pseudo acceleration term "a", which requires further study, could be interpreted as a relative measure of resistance to slope failure during a seismic shaking.

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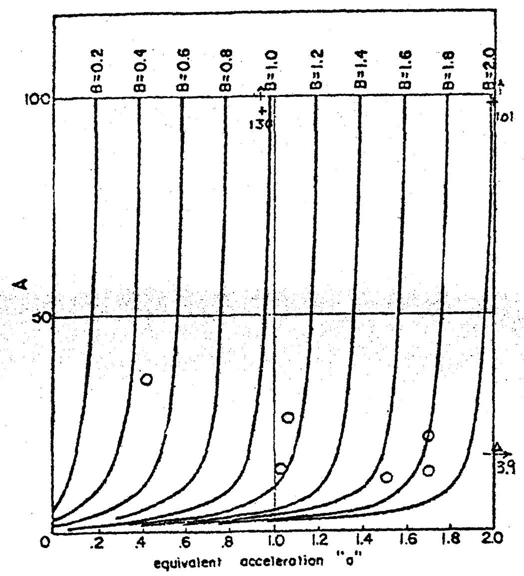

Fig. 3 Zones of Failure (Rigid Plastic)

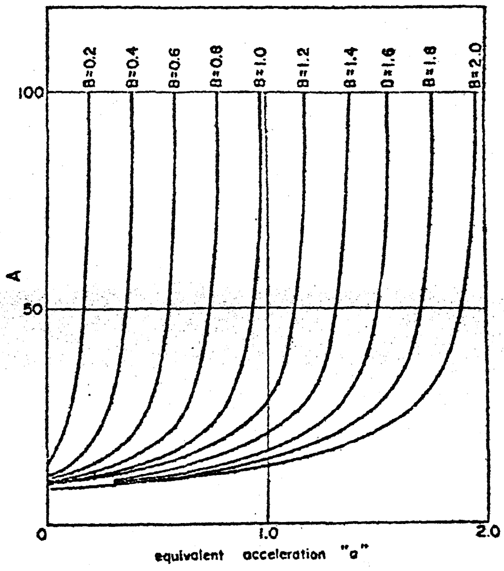

Fig. 4 Zones of Failure (Elasto-Plastic)

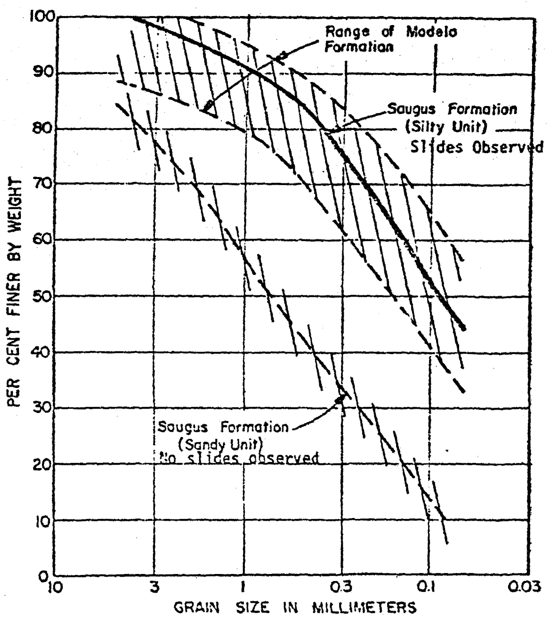

Fig. 5 Grain Size Distribution Diagrams

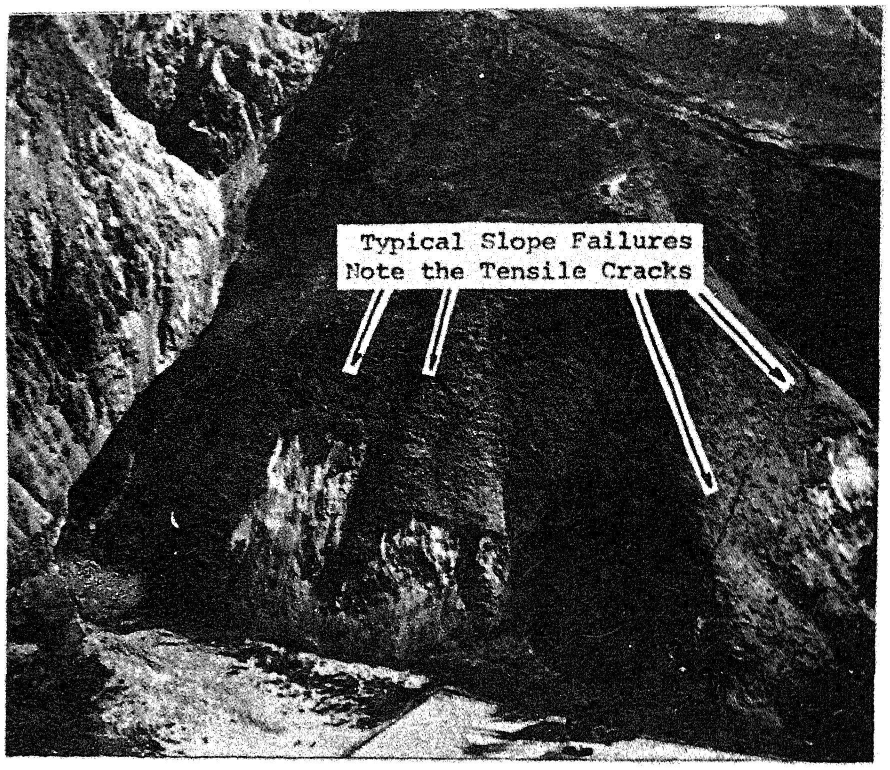

Figure 1. Seismically Induced Hillside Failures of Feb. 9, 1971
(Ridge East of Arroyo Ave., West of Lopez Canyon)
Courtesy of City of Los Angeles, Dept. of Bldg. & Safety

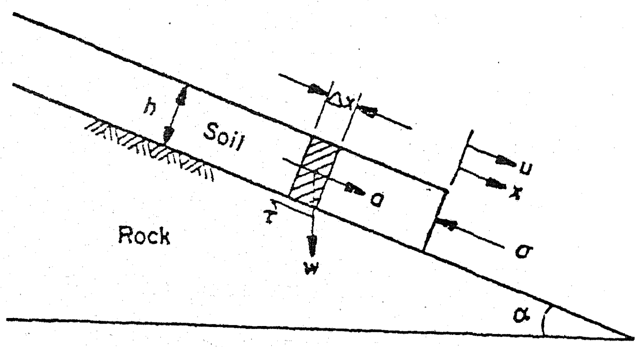

Fig. 2 One Dimensional Model