A Simple Method for Assessing Effects of Earthquakes on Slopes

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SUMMARY A simple method is proposed for assessing the reduction in factor of safety of a slope due to an earthquake or of estimating the yield acceleration at which deformations might occur. The method is suitable for first approximations or for multi-point calculations such as required for risk or hazard mapping, where accuracy can be sacrificed in favour of highlighting regions of concern needing more detailed investigation or analysis. The simple "rule-of-thumb" is derived and the limitations discussed in relation to some validation calculations.

1. INTRODUCTION

For quantitative Risk Assessments, it is often convenient to have a quick and easy method of assessing the effects of an earthquake on soil slopes without the need for detailed analysis and computer methods.

Examples of such situations might be:

- Small budget tasks such as assessing stability of house sites
- Multi-site analyses such as assessing stability of road cuts or fills over long distances or mapping landslip hazard over large areas of irregular terrain

The purpose of this paper is to suggest a simple method of estimating the reduction in factor of safety of a slope due to an earthquake or, conversely, of estimating the "yield" acceleration at which an earthquake may cause deformation of a slope.

The recognised methods of taking account of earthquakes in slope stability evaluation have been extensively documented. For example, Martin (1988) gives a state-of-the-art account based primarily on the Makdisi and Seed (1978) method of assessing stability in terms of deformation. This, however, derives from the pseudo-static stability approach, using any of the various conventional analytical methods (See Bromhead, 1986). Sarma (1973, 1987) adopts a different approach, defining stability of a slope in terms of the critical acceleration which would just cause "failure". These methods may or may not require a computer. Simplified methods using charts or tables have been described by Prater (1979, 1985), Koppula (1984) and Hadj-Hamou & Kavazanjian (1985). All of the above examples, including the simplified methods, are more rigorous than that proposed in this paper but tend to require some consideration of the site specific complexities. The proposed simple "rule-of-thumb" depends only on the slope angle and the factor of safety of the slope immediately prior to the earthquake.

2. CONCEPT

The great majority of natural soils have sufficient fines to allow the sudden loading (or unloading) of an earthquake event to be considered undrained. In this situation, soil mechanics theory suggests that the shear strength on a potential slip surface during the first sudden shearing movements of an earthquake is the same as immediately before the earthquake. This implies that an earthquake only changes the "driving" forces and does not affect the "resisting" forces.

Of course, such a statement ignores the potential for strength loss due to cyclic loading, a factor which will be discussed in the next section.

Consider simple slopes as shown in Figure 1. The factor of safety (F) is defined by:

$$F = \frac{\text{Resisting forces/moments}}{\text{Driving forces/moments}} = \frac{R}{D} \qquad - (1)$$

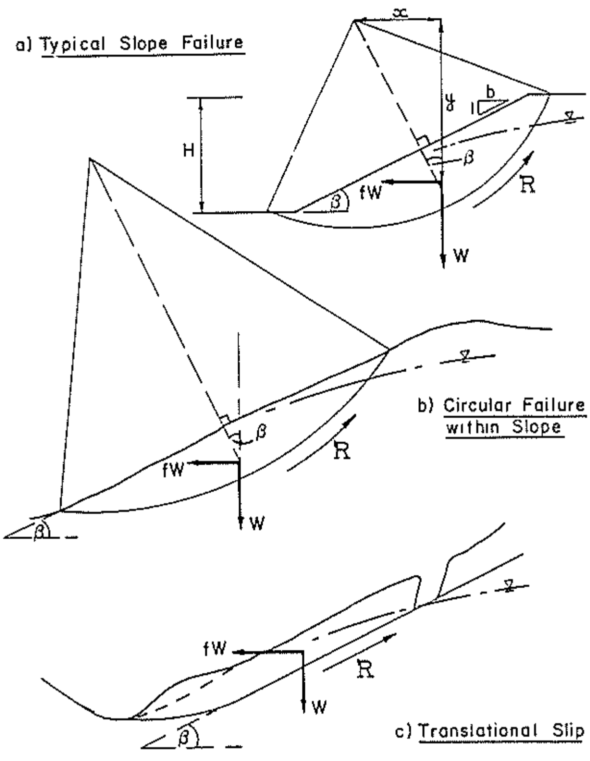

Figure 1: Failure modes

For static conditions, the factor of safety (F_o) is given by:

$$F_o = \frac{R}{Wx} \quad \text{for Figures 1(a) and (b)} \qquad \text{- (2a)}$$

where x is the horizontal distance between the centre of the slip circle and the centre of (slip) mass

$$\text{or} \quad F_o = \frac{R}{W\sin\beta} \quad \text{for Figure 1(c)} \qquad \text{- (2b)}$$

Now, if an earthquake causes a horizontal acceleration (fg) to be applied to the slip mass, then the "factor of safety" under earthquake (F_e) becomes:

$$F_e = \frac{R}{fWy+Wx} \quad \text{for Figures 1(a) and 1(b)} \qquad \text{-(3a)}$$

where y is the vertical distance between the centre of the slip circle and the centre of (slip) mass

$$\text{or} \quad F_e = \frac{R}{fW\cos\beta+W\sin\beta} \quad \text{for Figure 1(c)} \qquad \text{-(3b)}$$

From equations (2) and (3), the ratios of earthquake to static factors of safety are:

$$\frac{F_e}{F_o} = \frac{1}{1+f(y/x)} \quad \text{for Figures 1(a) and (b)} \qquad \text{-(4a)}$$

$$\text{or} \quad \frac{F_e}{F_o} = \frac{1}{1+f\cot\beta} \quad \text{for Figure 1(c)} \qquad \text{-(4b)}$$

For any circular slip contained entirely within a homogeneous slope, as illustrated in Figure 1(b), the ratio (y/x) is equal to $\cot\beta$. By examination of Figure 1(a), it is clear that (y/x) is approximately equal to $\cot\beta$ for most typical slips which are not deep seated and for slopes flatter than about 34° ($\cot\beta=1.5$). This can be checked using computer methods or stability charts (e.g. Janbu, 1968 or Cousins, 1978) and for either total stress or effective stress parameters. Further validation of this is discussed in the following section.

In summary, therefore, the reduction in factor of safety of any slope of face angle β, subjected to a horizontal acceleration (fg), is given approximately by:

$$F_e/F_o = 1/(1+f\cot\beta) = 1/(1+fb) \qquad \text{-(5)}$$

where $b = \cot\beta$

Alternatively, the yield acceleration coefficient (f_y) is given by equation (5) when $F_e=1$:

$$f_y = (F_o-1)/\cot\beta = (F_o-1)/b \qquad \text{-(6)}$$

3. VALIDITY

There are several factors which lay the simple formulae of equations (5) and (6) open to question. For example:

(a) Strength loss:

Almost all soils exhibit some tendency to increase pore pressures on repeated cyclic loading. However, it is now generally recognised (e.g. Seed and Idriss, 1982) that substantial strength loss does not occur until the effective onset of "liquefaction". Soils susceptible to liquefaction, though dangerous, are relatively infrequent in slopes and would, of course, negate the purpose of this paper.

(b) Shear surface:

One of the simplifying assumptions is that the critical slip surfaces for the static and dynamic conditions are the same. This, of course, may not be true because the static factor of safety (F_o) could be calculated using effective stress methods whereas the factor of safety under earthquake conditions (F_e) would be calculated using total stress methods. This does not appear to make much difference (see paragraph d following).

(c) Vertical acceleration:

The simple method allows for only horizontal accelerations. This is the normal assumption in almost all other dynamic stability methods. Prater (1979) points out that the peaks of the horizontal and vertical components of acceleration are generally not in phase and suggests that a value of 0.3 for the ratio of vertical/horizontal acceleration would be realistic. Equation (5) can be modified to allow for a vertical acceleration to give:

$$\frac{F_e}{F_o} = \frac{1}{1+f_v+f_hb} \approx \frac{1}{1+f_h(b+0.3)} \qquad \text{-(7)}$$

where f_v and f_h are the vertical and horizontal acceleration coefficients and $f_v \approx 0.3\, f_h$.

(d) Geometry:

As discussed previously, the geometric assumptions are only true for translational slides and circular slips contained entirely within a slope. Such failure modes, however, make up a large proportion of the types of slips which do occur in natural slopes as a result of an earthquake (e.g. Hopkins et al., 1991). Deep seated "base" failures tend to be rare in this context, particularly because accelerations tend to be greater towards the top of a slope.

To validate the approach for more generalised conditions and slopes typical of road cuts or water retention embankments (for example), conventional pseudo-static stability studies were carried out using the autosearch facility of the computer program UTEXAS2 (Wright, 1985). The cases tested are summarised in Figure 2 and the results are shown in Figure 3. It can be seen that, despite the varied geometry and groundwater conditions, the relationship holds reasonably well for b>1.5, though it can't be accused of being conservative.

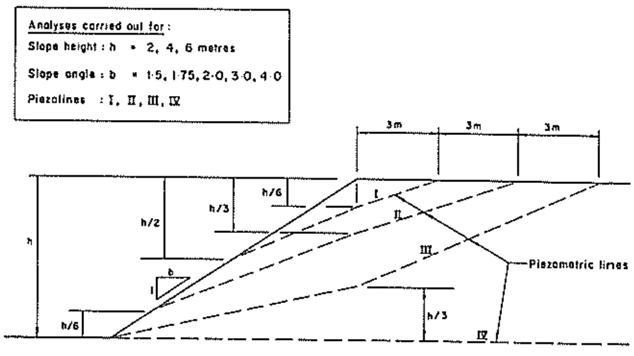

Figure 2: Validation test examples

4. CONCLUSION

A simple method has been suggested for assessing the effects of earthquakes on a slope. It is probably best to use the method for estimating the "yield" acceleration for subsequent estimates of slope deformation. Ignoring vertical accelerations, the relationship is given as:

$$f_y = (F_o-1)/b$$

where f_yg = the "yield" acceleration (g = gravity)

F_o = the static factor of safety immediately prior to the earthquake

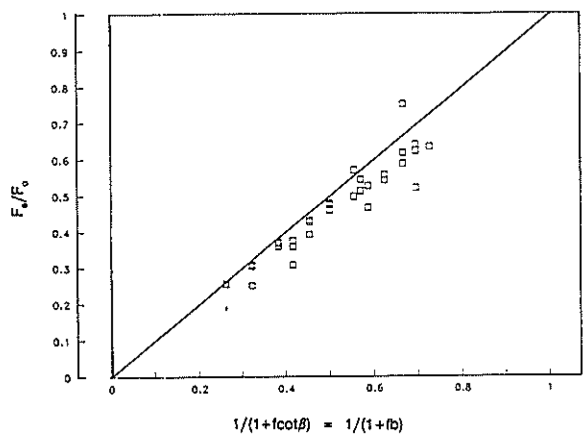

Figure 3: Results of validation tests (excluding results with numerical problems)

b = the slope "gradient" or the cotangent of the slope angle

To allow for the vertical component of ground acceleration, it is suggested that the value of 0.3 may be added to "b" in the above relationship.

There are many limitations of this very simple "rule-of-thumb" but if it is used for just approximate estimates (as would be the case for any deformation estimate) or for multi-site analyses such as would be required for risk analyses for road cuts, flood defences or landslip hazard mapping, then the approximations compare very favourably with other assumptions relating to variations in geometry, groundwater conditions and soil parameters.

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