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Rational selection of critical acceleration factors for sliding stability

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ABSTRACT

The horizontal seismic loading coefficient is an essential input in evaluating the seismic adequacy of slopes, such as those in open-pit mines and natural slopes. In some cases, the coefficient is established through dynamic finite element analyses, which are time-consuming and require a new analysis for each facility, including a new suite of accelerograms. The values of the coefficient are sometimes incorporated in design manuals, but the procedures for establishing the values are seldom transparent. The usual situation is that the values arise from consensus, experience, and previous practice. In this paper, the Urzúa–Christian model for normalized sliding displacement has been extended to develop the critical acceleration value corresponding to the probability of observing prescribed amounts of sliding displacement. The method has been applied to two sets of data based on probabilistic seismic hazard analyses. The results show that, to satisfy the criterion that there must be 0.1 probability of the sliding displacement exceeding 100 cm if a maximum credible earthquake (MCE) occurs, the critical acceleration must be approximately 0.13 *g*. This means that a slope with these parameters in this environment must be stable enough that a horizontal acceleration of 0.13 *g* is necessary to put it in a state of sliding motion. In the case of the operational basis earthquake (OBE), which is a much smaller ground motion, the criterion of 0.1 probability of 100 cm of sliding is achieved for a slope with a critical acceleration of 0.35 *g*.

1. Introduction

The horizontal seismic loading coefficient is an essential input in evaluating the seismic adequacy of slopes, such as those in open-pit mines and natural slopes. The coefficient is usually expressed as a fraction of the acceleration of gravity and is multiplied by the weight of a potential sliding mass to give a horizontal force on the sliding mass. When the force is applied as a static load, the result is called a pseudo-static analysis because it does not include actual dynamic behavior but replaces it with an equivalent static problem. The static horizontal load factor is usually designated K_a.

In some cases, the coefficient is established through dynamic finite element analyses, but these procedures are time-consuming and require a new analysis for each facility, including a new suite of ground motion records. Values of the coefficient are sometimes incorporated in design manuals, but the procedures for establishing these values are seldom transparent. The usual situation is that the K_a values arise from consensus, experience, and previous practice. This paper proposes a rational way to establish the seismic coefficient.

The present paper describes a methodology and gives an example of its application in a particular environment using relations developed from accelerograms recorded in Chile during large earthquakes and other parameters derived from seismic hazard studies for Chilean projects. Urzúa and Christian (2013) showed that the basic relations between the logarithms of normalized displacements and the acceleration ratios evaluated from other sets of records (Northridge 1994, Chi Chi 1996) are close to those derived from the Chilean records, but application of the proposed methodology for locations exposed to different seismic hazards requires that comparable relations be developed from accelerograms recorded in that region and that the other parameters—Arias intensity, period, and peak ground acceleration—also be evaluated for the particular local conditions. In other words, this paper presents the results for one region and are not intended to apply to all locations in the world. Comparable plots for other locations must be based on seismological data for those regions.

Since Newmark (1965) described the sliding block analytical procedure, many researchers have investigated the consequences of applying it in a variety of situations. Seed (1979) proposed using a design horizontal acceleration factor a_c of 0.15 with a factor of safety greater than 1.15. Hynes-Griffin and Franklin (1984) noted that values of a_c should be related to the peak ground acceleration and indicated that 1 m was an acceptable displacement criterion for dams. Stewart et al. (2003) proposed a method for estimating a_c for housing developments in

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Southern California. Bray and Travasarou (2009) also proposed a method for estimating a_c in terms of acceptable displacement and seismic demand. Urzúa and Christian (2013) describe a number of other proposed methods to estimate seismic displacement and, by implication, to estimate a_c from the acceptable displacement.

2. The Urzúa–Christian analysis of seismic records

Urzúa and Christian (2013) computed the sliding displacement from suites of strong-motion records made during three Chilean offshore subduction zone earthquakes. The suite from the 1985 M = 7.8 earthquake was recorded in the Valparaiso region, the suite from the 2007 M = 7.7 earthquake in the Tocopilla region, and the suite from the 2010 M = 8.8 earthquake in the Maule region. The suites represent not only three different events but also three different regions of Chile: Maule in the south, Valparaiso in the central region, and Tocopilla in the north. Using the sliding block method (Newmark, 1965; Yegian et al., 1991), Urzúa and Christian computed the sliding displacements for each accelerogram and for a range of values of the ratio between the critical acceleration for the slope (a_c) and the maximum acceleration in the record (a_{max}).The "critical acceleration" is usually the horizontal acceleration just necessary to reduce the pseudo-static factor of safety to unity or less. There are several published relations between a_c/a_{max} and estimated displacements, but the sliding displacements predicted by those relations do not always correspond well with the displacements computed from the three sets of records (see Urzúa and Christian, 2013 for references).

The proposed method started with the closed form solution for the sliding-block displacement for cyclic input motion (Yegian et al., 1991):

$$D_R = f(a_c/a_{max})\left[a_{max}NT^2\right] \tag{1}$$

In this expression D_R is the cumulative sliding displacement, a_c and a_{max} are already defined, N is the number of cycles, and T is the period of the cycle. The function $f\,(a_c/a_{max})$ is a dimensionless function that depends on the shape of the input motion; different shapes of input pulses (rectangular, triangular, sinusoidal, etc.) yield different forms of the function. Fig. 1 shows the function for sinusoidal input as originally developed by Yegian et al. (1991) and independently confirmed by the present authors. A noted feature of the function $f\,(a_c/a_{max})$ is that, for $a_c/a_{max} \leq 0.5$, it is nearly linear against a logarithmic vertical scale. At larger values of the acceleration ratio, the function drops off sharply, and it is

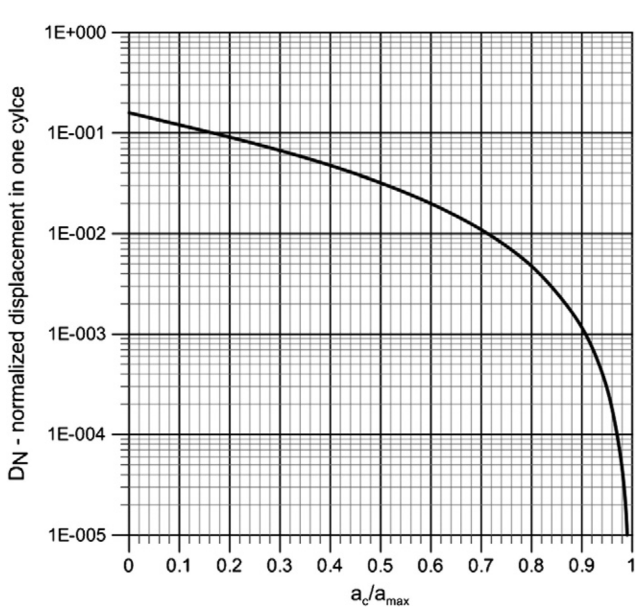

Fig. 1. Sliding displacement during a single sinusoidal pulse (after Yegian et al., 1991).

usually agreed that values of $a_c/a_{max} > 0.5$ are not of engineering interest (Franklin and Chang, 1977). When it is necessary to consider values of $a_c/a_{max} > 0.5$ or to design against sliding displacements on the order of centimeters, the present methodology could be extended to include the non-linear portion of the function in Fig. 1, but at the cost of additional computational complexity.

The second input to the revised method is the Arias (1970) intensity, defined as

$$I_a = \frac{\pi}{2g}\int_0^t [a(\tau)]^2\, d\tau \tag{2}$$

in which g is the acceleration of gravity, a is the ground acceleration, and τ is the variable of integration equal to time. It is customary to integrate over the entire duration of the strong motion record (t = length of record), but t can be any time after the start of the record so that I_a is actually a function of time. If there is no other indication, I_a is taken as the value integrated over the entire record. The Arias intensity has units of velocity and is usually expressed in meters per second (m/s) or centimeters per second (cm/s).

For a sinusoidal acceleration pulse of period T and amplitude a_{max}, the Arias intensity is

$$I_a = \frac{\pi}{2g}\int_0^t |a(\tau)|^2\, d\tau = \frac{\pi}{2g}\int_0^t a_{max}^2 \sin^2(2\pi\tau/T)\, d\tau \tag{3}$$

Integrating over a single period gives the Arias intensity for a single pulse:

$$I_a = \frac{\pi}{4g} a_{max}^2 T \tag{4}$$

and for N pulses, with the ground acceleration expressed as K_a in units of g (i.e., $a_{max} = K_a g$)

$$I_a = \frac{\pi}{4} NgTK_a^2 \tag{5}$$

Substituting Eq. (5) into Eq. (1) and performing some algebraic manipulation yields

$$D_R = h(a_c/a_{max})\left[\frac{I_a T}{K_a}\right] \tag{6}$$

in which $h(a_c/a_{max})$ is a dimensionless function that incorporates the shape of the accelerogram as well as constants such as $\pi/4$. In other words, a rational way to normalize the computed or estimated sliding displacements in a dimensionless plot is to divide the computed values by the bracketed term in Eq. (6), which has units of displacement.

Fig. 2 shows the result of applying the method to the three suites of Chilean records. The figure was constructed by the following process:

(1) A series of ten values of (a_c/a_{max}) was selected, starting with 0.05 and increasing in units of 0.05 to a final value of 0.5.
(2) The values of a_{max}, I_a, and T were computed for each accelerogram.
(3) The sliding block analysis was performed for each value of (a_c/a_{max}) and for each accelerogram. The analyses were run twice: once with the signs of the accelerations in the original sense and once with them reversed.
(4) The cumulative displacement in each case was divided by (I_aT/K_a) and the results plotted with a logarithmic vertical axis as dimensionless displacements D_N.
(5) For each value of (a_c/a_{max}) the mean and the standard deviation of the $\log_{10} D_N$ were computed.
(6) After calculations had been completed for all values of (a_c/a_{max}), straight lines were run through the ten sets of values of the mean and the mean plus and minus one standard deviation of $\log_{10} D_N$.