Predicting Earthquake-Induced Landslide Displacements Using Newmark's Sliding Block Analysis

RANDALL W. JIBSON

A principal cause of earthquake damage is landsliding, and the ability to predict earthquake-triggered landslide displacements is important for many types of seismic-hazard analysis and for the design of engineered slopes. Newmark's method for modeling a landslide as a rigid-plastic block sliding on an inclined plane provides a workable means of predicting approximate landslide displacements; this method yields much more useful information than pseudostatic analysis and is far more practical than finite-element modeling. Applying Newmark's method requires knowing the yield or critical acceleration of the landslide (above which permanent displacement occurs), which can be determined from the static factor of safety and from the landslide geometry. Earthquake acceleration-time histories can be selected to represent the shaking conditions of interest, and those parts of the record that lie above the critical acceleration are double integrated to determine the permanent landslide displacement. For approximate results, a simplified Newmark method can be used, which estimates Newmark displacement as a function of landslide critical acceleration and earthquake shaking intensity.

One of the principal causes of earthquake damage is landsliding triggered by strong shaking. Earthquakes with magnitudes greater than 4.0 can trigger landslides on very susceptible slopes, and earthquakes with magnitudes greater than 6.0 can generate widespread landsliding (*1*). Accurately predicting which slopes will move and the severity of that movement, however, is difficult. In this paper a brief review of some published methods to predict earthquake-triggered slope displacement is given and it is demonstrated how these methods can be applied to practical problems. The ability to predict approximate amounts of earthquake-induced landslide movement can be used for regional seismic-hazard analysis and in designing slopes to withstand earthquake shaking.

The seismic performance of a slope can be evaluated in several ways. The simplest approach is pseudostatic analysis, in which an earthquake acceleration acting on the mass of a potential landslide is treated as a permanent static body force in a limit-equilibrium (factor-of-safety) analysis. Different earthquake accelerations are applied until the factor of safety is reduced to 1.0. The earthquake acceleration needed to reduce the factor of safety to 1.0 is called the yield acceleration, the exceedance of which is defined as failure. This procedure is simple and requires no more information than is needed for a static factor-of-safety analysis. Pseudostatic analysis is useful for identifying yield accelerations and hence peak ground accelerations (PGA) below which no slope displacement will occur. In cases where the PGA does exceed the yield acceleration, pseudostatic analysis has proved to be vastly overconservative because many slopes experience transient earthquake accelerations well above their yield accelerations but experience little or no permanent displacement (*2*). The utility of pseudostatic analysis is thus limited because it provides only a single numerical threshold below which no displacement is predicted and above which total, but undefined, "failure" is predicted. In fact, pseudostatic analysis tells the user nothing about what will occur when the yield acceleration is exceeded.

At the other end of the spectrum, advances in two-dimensional finite-element modeling have facilitated very accurate evaluation of strain potentials and permanent slope deformation (*3–6*). These highly sophisticated methods require a broad spectrum of data of extremely high quality and density, which, combined with the intensive computing capacity required, makes their general use prohibitively expensive (*7*).

Newmark (*8*) proposed a method of analysis that bridges the gap between simplistic pseudostatic analysis and sophisticated, but generally impractical, finite-element modeling. Newmark's method models a landslide as a rigid-plastic friction block having a known yield or critical acceleration, the acceleration required to overcome frictional resistance and initiate sliding on an inclined plane. The analysis calculates the cumulative permanent displacement of the block as it is subjected to the effects of an earthquake acceleration-time history, and the user judges the significance of the displacement. Laboratory model tests (*9*) and analyses of earthquake-induced landslides in natural slopes (*2*) confirm that Newmark's method fairly accurately predicts slope displacements if slope geometry, soil properties, and earthquake ground accelerations are known. Newmark's method is relatively simple to apply and provides a quantitative prediction of the inertial landslide displacement that will result from a given level of earthquake shaking. Results from Newmark's method also are useful in probabilistic analyses (*10,11*), which further enhances their utility.

PAST APPLICATIONS OF NEWMARK'S METHOD

Newmark's method has been applied rigorously in a variety of ways to slope-stability problems. Most applications have dealt with the seismic performance of dams and embankments (*11,12*), which was Newmark's original intent (*8*). Newmark's

U.S. Geological Survey, Box 25046, MS 966, Denver Federal Center, Denver, Colo. 80225.

method also has been successfully applied to landslides in natural slopes (*2*). Several simplified approaches have been proposed for applying Newmark's method; these involve developing empirical relationships to predict slope displacement as a function of critical acceleration and one or more measures of earthquake shaking. Virtually all such studies plot displacement against critical acceleration ratio—the ratio of critical acceleration to PGA. Figure 1 shows the approximate locations of such plots from three studies (*12–14*). The relationship between critical acceleration ratio and displacement is magnitude dependent, as shown by separate curves for different magnitudes in two of the studies (*12,14*); the single curve from Ambraseys and Menu (*13*) is for a narrow range of magnitudes. Interestingly, no general agreement on the locations or even the shapes of the curves is apparent; predicted displacements for a given critical acceleration ratio and magnitude differ by as much as two orders of magnitude. Clearly, no universally applicable relationship between critical acceleration ratio and displacement exists at present.

Other studies of this type have related critical acceleration ratio to some normalized form of displacement that could not be compared directly with the curves in Figure 1. Yegian et al. (*11*) calculated exceedance probabilities for displacement normalized by PGA, the equivalent number of earthquake shaking cycles, and the square of the period of the base motion. Lin and Whitman (*10*) used simple, artificial ground-motion wave forms (triangular, rectangular, or sinusoidal) to relate critical acceleration ratio to displacement normalized by PGA.

Wilson and Keefer (*2*) applied Newmark's method to a landslide triggered by the 1979 Coyote Creek, California, earthquake. The slide occurred near a strong-motion instrument, and the landslide displacement predicted in the Newmark analysis using the record from that instrument agreed well with the observed displacement. This method of using real acceleration-time histories to predict displacements in natural slopes has been applied to experimentally predict and map seismic slope stability in San Mateo County, California (*15*). It also has been adapted to back-analyze shaking conditions required to trigger landslides formed in the Mississippi Valley during the 1811–1812 New Madrid earthquakes (*16*).

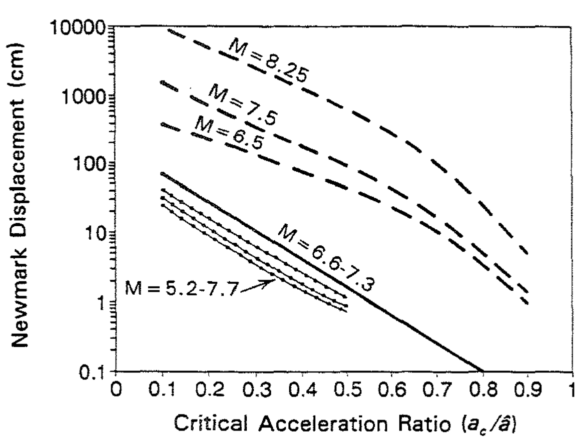

FIGURE 1 Newmark displacement as a function of critical acceleration ratio plotted from the results of three studies: Makdisi and Seed (*12*), dashed lines; Ambraseys and Menu (*13*), solid line; and Franklin and Chang (*14*), dotted lines.

CONDUCTING A NEWMARK ANALYSIS

Before describing the application of Newmark's method, the limiting assumptions need to be stated. Newmark's method treats a landslide as a rigid-plastic body; that is, the mass does not deform internally, experiences no permanent displacement at accelerations below the critical or yield level, and deforms plastically along a discrete basal shear surface when the critical acceleration is exceeded. Thus, Newmark's method is best applied to translational block slides and rotational slumps. Other limiting assumptions commonly are imposed for simplicity but are not required by the analysis:

1. The static and dynamic shearing resistance of the soil are taken to be the same (*7,8*).
2. The effects of dynamic pore pressure are neglected. This assumption generally is valid for compacted or overconsolidated clays and very dense or dry sands (*8,12*).
3. The critical acceleration is not strain dependent and thus remains constant throughout the analysis (*7,8,12,13*).
4. The upslope resistance to sliding is taken to be infinitely large such that upslope displacement is prohibited (*7,8,13*).

The procedure for conducting a Newmark analysis is outlined in the following sections and simple examples of its application are provided.

Critical Acceleration

The first step in the analysis is to determine the critical acceleration of the potential landslide. One way to do this is to use pseudostatic analysis, where critical acceleration is determined by iteratively employing different permanent horizontal earthquake accelerations in a static limit-equilibrium analysis until a factor of safety of 1.0 is achieved.

Newmark (*8*) simplified this approach by showing that the critical acceleration of a potential landslide is a simple function of the static factor of safety and the landslide geometry; it can be expressed as

$$a_c = (\mathrm{FS} - 1)g \sin \alpha \qquad (1)$$

where a_c is the critical acceleration in terms of g, the acceleration due to earth's gravity; FS is the static factor of safety; and α is the angle (herein called the thrust angle) from the horizontal that the center of mass of the potential landslide block first moves. Thus, determining the critical acceleration by this method requires knowing the static factor of safety and the thrust angle.

Factor of Safety

As noted by Newmark (*8*), modeling dynamic slope response requires undrained or total shear-strength parameters. During earthquakes, slope materials behave in an undrained manner because excess pore pressures induced by dynamic deformation of the soil column cannot dissipate during the brief duration of the shaking. Undrained strength also is called total strength because the contributions of friction, cohesion, and pore pressure are not differentiated, and the total strength is expressed as a single quantity.

The factor of safety can be determined using any appropriate method that uses undrained or total shear strength. In materials whose drained and undrained behaviors are similar, drained or effective shear strengths could be used if undrained strengths were unavailable or difficult to measure. This allows great flexibility for users. For a rough estimate of displacement, a simple factor-of-safety analysis, perhaps of an infinite slope using estimated shear strength, could be used. At the other end of the spectrum, a highly detailed site study could be conducted to determine the factor of safety very accurately. Clearly, the accuracy of the safety factor, and the resulting predicted displacement, depends on the quality of the data and analysis, but the user determines what is appropriate.

Thrust Angle

The thrust angle is the direction in which the center of gravity of the slide mass moves when displacement first occurs. For a planar slip surface parallel to the slope (an infinite slope), this angle is the slope angle. For simple planar block sliding, the thrust angle is the inclination of the basal shear surface. For circular rotational movement, Newmark (*8*) showed that the thrust angle is the angle between the vertical and a line segment connecting the center of gravity of the slide mass and the center of the slip circle. For irregular shear surfaces, the thrust angle can be approximated visually by estimating an "equivalent" circular surface or by averaging the inclinations of line segments approximating the surface.

Calculation of Critical Acceleration

Figure 2 shows a simple hypothetical slope and the critical failure surface having the lowest factor of safety (1.4) in undrained conditions. Newmark's (*8*) geometric construction indicates a thrust angle of 30 degrees. According to Equation 1, a factor of safety of 1.4 and a thrust angle of 30 degrees would yield a critical acceleration of 0.20 *g*.

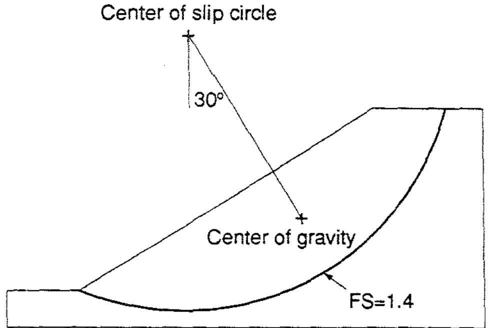

FIGURE 2 Model of hypothetical slope: basal shear surface, heavy line; FS, factor of safety; thrust angle is 30 degrees.

Selection of Earthquake Acceleration-Time History

The most difficult aspect of conducting a Newmark analysis is selecting an input ground motion, and many ways of doing so have been proposed. Most studies have used some combination of the two approaches mentioned by Newmark: (*a*) scaling acceleration-time histories from actual earthquakes to a desired level of PGA (*12,14*) and (*b*) using single or multiple cycles of artificial acceleration pulses having simple rectangular, triangular, or sinusoidal shapes (*10,11*). Both of these approaches yield useful results, but both also have inherent weaknesses. Scaling an acceleration-time history by simply expanding or contracting the acceleration scale does not accurately represent ground motion from earthquakes of different magnitudes or proximities because magnitude and source distance also affect the duration and predominant periods of shaking. And using simple artificial pulses of ground shaking is an unnecessary oversimplification in light of the current availability of digitized acceleration-time histories having a broad range of attributes.

Selecting a time history requires the user to know something of the shaking characteristics or design requirements pertinent to the situation of interest. Common design or hazard-assessment criteria include (*a*) a specified level of ground shaking, (*b*) a model earthquake of specified magnitude and location, or (*c*) an acceptable design amount of earthquake-triggered displacement.

Specified Level of Ground Shaking

Criterion a is by far the simplest; it requires only that the user locate a sampling of digitized acceleration-time histories having the desired measure of earthquake shaking intensity near the specified level. PGA is a common measure of ground-shaking intensity, and digitized time histories having a wide variety of PGAs, even exceeding 1 *g*, are currently available.

PGA measures only a single point in an acceleration-time history and is thus a rather crude measure of shaking intensity. A more comprehensive and quantitative measure of total shaking intensity developed by Arias (*17*) is useful in seismic hazard analysis and correlates well with the distribution of earthquake-induced landslides (*18*). Arias intensity is the integral over time of the square of the acceleration, expressed as

$$I_a = \pi/2g \int[a(t)]^2\, dt \qquad (2)$$

where I_a is Arias intensity, in units of velocity, and $a(t)$ is the ground acceleration as a function of time. An Arias intensity thus can be calculated for each directional component of a strong-motion record. In cases where a given level of Arias intensity can be specified, selecting a strong-motion record of similar intensity is quite simple, and currently available records span a range of Arias intensities up to $I_a \approx 10$ m/sec.

Specified Earthquake Magnitude and Location

Criterion b can be somewhat more difficult. If acceleration-time histories exist for earthquakes of the desired magnitude that were recorded at appropriate distances, they can be used. Satisfying both magnitude and distance requirements is often impossible, however, so it may be necessary to estimate shaking characteristics at the site of interest using published empirical or theoretical relationships that predict PGA, duration, and Arias intensity as a function of earthquake magnitude and source distance. Estimated shaking characteristics can then be compared with those from existing time histories to provide a basis for selecting appropriate records.

An example of this procedure is from the Mississippi Valley, where large earthquakes occurred in 1811–1812 but where no strong-motion records exist. The problem is to predict the performance of a slope in a moment-magnitude (**M**) 6.2 earthquake centered at least 8 km away. If no time histories for that magnitude and distance existed, shaking characteristics at the site would have to be estimated.

PGA can be estimated using the attenuation relationship of Nuttli and Herrmann (*19*) for soil sites in the central United States:

$$\log \hat{a} = 0.57 + 0.50m_b - 0.83 \log (R^2 + h^2)^{1/2} - 0.00069R \qquad (3)$$

where

$\hat{a}$ = PGA (cm/sec²),
m_b = body-wave magnitude,
R = epicentral distance (km), and
h = focal depth (km).

An M6.2 earthquake corresponds to $m_b = 5.8$ (*20*). For $m_b = 5.8$, an epicentral distance of 8 km, and a minimum focal depth of 3 km, Equation 3 predicts a PGA of 491 cm/sec² or 0.50 *g*.

Estimating the Arias intensity at the site can be done in more than one way. Wilson and Keefer (*21*) developed a relationship among Arias intensity, earthquake magnitude, and source distance:

$$\log I_a = \mathbf{M} - 2 \log R - 4.1 \qquad (4)$$

where I_a is in meters per second, **M** is moment magnitude, and R is earthquake source distance in kilometers. For **M**6.2 and R = 8 km, Equation 4 predicts an Arias intensity at the site of 1.97 m/sec.

Arias intensity also correlates closely with the combination of PGA and duration. R. C. Wilson (U.S. Geological Survey, unpublished data) developed an empirical equation using 43 strong-motion records to predict Arias intensity from PGA and a specific measure of duration:

$$I_a = 0.9T\hat{a}^2 \qquad (5)$$

where I_a is in meters per second, $\hat{a}$ is PGA in *g*'s, and T is duration (hereafter called Dobry duration) in seconds, defined as the time required to build up the central 90 percent of the Arias intensity (*22*). Estimating Arias intensities using this method requires an estimate of the duration of strong shaking. Dobry et al. (*22*) proposed an empirical relationship between duration and earthquake magnitude:

$$\log T = 0.432M - 1.83 \qquad (6)$$

where T is Dobry duration in seconds and M is unspecified earthquake magnitude (probably local magnitude, M_L). In the magnitude range of interest, M_L-values are generally identical to **M**-values (*20*), so M = 6.2 yields a Dobry duration of 7.1 sec. If this duration and the PGA of 0.50 *g* estimated above are used in Equation 5, an Arias intensity of 1.59 m/sec is predicted, which agrees fairly well with that estimated by Equation 4.

These three indexes of shaking intensity—PGA, duration, and Arias intensity—form a rational basis for selecting strong-motion records for analysis. Caution and judgment must be used in making these estimates, however, because the process of combining values from Equations 3–6, each of which has a range of possible error, compounds the uncertainty at each step. For this example, three records are chosen whose shaking characteristics reasonably match those estimated (Table 1). Selecting multiple records that span the range of estimated shaking characteristics provides a range of displacements whose significance the user can judge.

Specified Design Displacement

Criterion c differs from the first two in that a limiting damage level (landslide displacement) is specified rather than the level of ground shaking. An example is to estimate the maximum level of ground shaking a slope having a critical acceler-

TABLE 1 Shaking Characteristics of Strong-Motion Records

Earthquake Recording Site, Component	PGA[a] (*g*)	Duration[b] (s)	I_a[c] (m/s)	Displacement[d] (cm)
Example Site (estimated values)	0.50	7.1	1.59-1.97	
27 June 1966 Parkfield, Calif. Parkfield Station 2, 65°	0.49	4.1	1.64	10.9
15 Oct. 1979 Imperial Valley, Calif. El Centro Array #8, 140°	0.61	6.8	1.60	3.5
Oct. 1979 Imperial Valley, Calif. El Centro Differential Array, 360°	0.49	6.6	2.12	3.9

[a] Peak ground acceleration
[b] Duration as defined by Dobry et al. (22)
[c] Arias intensity
[d] Calculated by Newmark's method

ation of 0.20 g could experience without exceeding 10 cm of displacement.

One approach to this problem is simply to analyze iteratively several strong-motion records to find those that yield about 10 cm of displacement at $a_c = 0.20\ g$. The magnitudes, source distances, focal depths, PGAs, Arias intensities, and durations of these records could then be examined to discern the approximate range of conditions the slope could withstand. Obviously, this approach could be time consuming, but it would produce a variety of possible threshold ground-shaking scenarios.

An easier approach to this type of problem is to apply the simplified Newmark method discussed subsequently.

Calculating Newmark Displacement

Once the critical acceleration of the landslide has been determined and the acceleration-time histories have been selected, Newmark displacement can be calculated by double integrating those parts of the strong-motion record that lie above the critical acceleration. Several methods for doing this, some rigorous and others highly simplified, have been proposed (*7,8,12,13*); perhaps the most useful rigorous method was developed by Wilson and Keefer (*2*). Figure 3*A* shows a strong-motion record having a hypothetical a_c of 0.2 g superimposed. To the left of Point X, accelerations are less than a_c, and no displacement occurs. To the right of Point X, those parts of the strong-motion record lying above a_c are integrated over time to derive a velocity profile of the block. Integration begins at Point X (Figure 3*A* and *B*), and the velocity increases to Point Y, the maximum velocity for this pulse. Past Point Y, the ground acceleration drops below a_c, but the block continues to move because of its inertia. Friction and ground motion in the opposite direction cause the block to decelerate until it stops at Point Z. All pulses of ground motion exceeding a_c are integrated to yield a velocity profile (Figure 3*B*), which in turn is integrated to yield a cumulative displacement profile of the landslide block (Figure 3*C*).

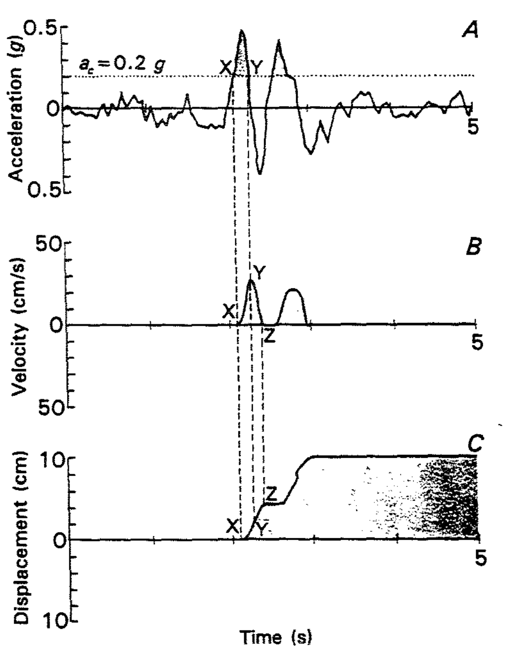

FIGURE 3 Demonstration of the Newmark-analysis algorithm, adapted from Wilson and Keefer (*2*). Points X, Y, and Z are discussed in text; *A*, earthquake acceleration-time history with critical acceleration (*dotted line*) of 0.20 *g* superimposed; *B*, velocity of landslide block versus time; *C*, displacement of landslide block versus time.

The algorithm of Wilson and Keefer (*2*) permits both downslope and upslope displacement by using the thrust angle to explicitly account for the asymmetrical resistance to downslope and upslope sliding. If pseudostatic yield acceleration is used and the thrust angle is not readily obtainable, the program can be simplified to prohibit upslope displacement. This prohibition was justified by Newmark (*8*), as well as by others (*7,10,13,14*), because a_c in the upslope direction is generally so much greater than a_c in the downslope direction that it can be assumed to be infinitely large. In most cases, the upslope a_c is greater than the PGA, and no error is introduced by prohibiting upslope displacement.

Integration programs for calculating Newmark displacement can be customized to accept acceleration-time histories in either of two formats: successive pairs of time and acceleration values or a single string of acceleration values sampled at a constant time interval. The latter is the simpler approach and ensures that the integration is performed consistently throughout the time history. Table 2 shows a simple BASIC program that uses the algorithm of Wilson and Keefer (*2*) modified to prohibit upslope displacement; the program accepts a string of acceleration values at a constant time interval.

Digitized strong-motion records can be obtained in several ways. Analog strong-motion records can be manually digitized to obtain a data file of time-acceleration pairs. Such a file can be used in a Newmark integration program that accepts paired data, or it can be resampled at a constant time interval by a simple linear interpolation program. Also, strong-motion records from many worldwide earthquakes are available in digital format from the National Oceanic and Atmospheric Administration's National Geophysical Data Center in Boulder, Colorado.

SIMPLIFIED NEWMARK METHOD

The previous sections contained a description of how to rigorously conduct a Newmark analysis. Although this approach is straightforward, many of its aspects are difficult for the average user: acquiring digitized strong-motion records can be very time consuming, and locating an appropriate record for the conditions to be modeled is not always easy. Also, writing the integration program can be difficult. For these reasons, a simplified approach for estimating Newmark displacements would be helpful.

As discussed above, previous studies have proposed general relationships between Newmark displacement and some normalized parameter or parameters of critical acceleration (*10–14*). Any of these that include parameters appropriate to a problem of interest can be applied with relative ease. Most

TABLE 2 BASIC Program for Calculating Newmark Displacement

Program Step	Instruction
1	REM Program for calculating Newmark displacement
2	REM Input data should be in units of cm/s/s
3	PRINT "Input file should be in cm/s/s"
4	INPUT "What is the name of the input file";A$
5	OPEN "I", #1, A$
6	INPUT "What is the critical acceleration in g's";T:T=980.665*T
7	INPUT "What is the digitization interval in seconds";D
8	INPUT "What is the duration of the record in seconds";Z
9	K=Z/D
10	Q=0
11	R=0
12	S=0
13	Y=0
14	V=0
15	U=0
16	FOR I=1 TO K
17	INPUT #1,A
18	IF V<0.0001 THEN 20
19	GOTO 26
20	IF ABS(A)>T THEN 22
21	GOTO 24
22	N=A/ABS(A)
23	GOTO 27
24	N=A/T
25	GOTO 27
26	N=1
27	Y=A-N*T
28	V=R+D/2*(Y+S)
29	IF V>0 THEN 32
30	V=0
31	Y=0
32	U=Q+D/2*(V+R)
33	Q=U
34	R=V
35	S=Y
36	NEXT I
37	PRINT "Total displacement in centimeters is ";U
38	END

depend directly on PGA, which, as noted, is a widely used but rather crude measure of shaking intensity. Therefore, a simplified method based on Arias intensity, a better measure of shaking intensity, is proposed below.

To develop an empirical relationship among Newmark displacement, critical acceleration, and Arias intensity, 11 strong-motion records were selected having Arias intensities between 0.2 and 10.0 m/sec (Table 3), which span the range between the smallest shaking intensities that might cause landslide movement and the largest shaking intensities ever recorded. For each strong-motion record, Newmark displacement was calculated for several critical accelerations between 0.02 and 0.40 g, the range of practical interest for earthquake-induced landslides (Figure 4). Data points for each critical acceleration plot fairly linearly in the log-log space of Arias intensity versus Newmark displacement. Best-fit lines from regression models for each value of critical acceleration have excellent fits (R^2 = 0.81–0.95), and the lines are roughly parallel and proportionately spaced, which suggests that a multivariate model would fit the data well. Therefore, a multivariate regression model of the following form was constructed:

$$\log D_N = A \log I_a + B a_c + C \pm \sigma \qquad (7)$$

where

D_N = Newmark displacement (cm),
I_a = Arias intensity (m/sec),
a_c = critical acceleration (g),
A, B, C = regression coefficients, and
σ = estimated standard deviation of the model.

The resulting model has an R^2 of 0.87, and all coefficients are significant above the 99.9 percent confidence level:

$$\log D_N = 1.460 \log I_a - 6.642 a_c + 1.546 \pm 0.409 \qquad (8)$$

This model yields the mean Newmark displacement when σ is ignored; the variation (σ) about this mean results from the stochastic nature of earthquake ground shaking. Thus, two strong-motion records having identical Arias intensities can produce different Newmark displacements for slopes having the same critical acceleration. Therefore, Equation 8 yields a range of displacements that must be interpreted with considerable judgment. Figure 5 shows critical acceleration lines defined by Equation 8. The model underestimates Newmark displacement (Figure 4) at low levels of Arias intensity (less

TABLE 3 Strong-Motion Records Selected for Analysis

Earthquake Recording Site, Component	M [a]	PGA [b] (g)	Duration [c] (s)	I_a^d (m/s)
15 Oct. 1979 Imperial Valley, Calif., Coachella Canal, Station 4, 135°	6.5	0.13	10.4	0.20
6 Aug. 1979 Coyote Lake, Calif., Coyote Creek, San Martin, 250°	5.8	0.21	3.8	0.25
21 July 1952 Kern County, Calif., Taft School, 111°	7.5	0.14	17.7	0.46
6 Aug. 1979 Coyote Lake, Calif., Gilroy Array, San Ysidro School, 270°	5.8	0.23	8.5	0.60
15 Oct. 1979 Imperial Valley, Calif., Calexico Fire Station, 225°	6.5	0.28	11.1	0.86
1 Oct. 1987 Whittier Narrows, Calif., Bulk Mail Center, 280°	6.0	0.45	5.5	1.23
15 Oct. 1979 Imperial Valley, Calif., El Centro differential array, 360°	6.5	0.49	6.6	2.12
24 Nov. 1987 Superstition Hills, Calif., Parachute Test Site, 225°	6.5	0.46	10.1	4.15
15 Oct. 1979 Imperial Valley, Calif., Bonds Corner, 230°	6.5	0.79	9.8	6.00
9 Feb. 1971 San Fernando, Calif., Pacoima Dam, 164°	6.6	1.22	6.7	9.08
16 Sept. 1978 Tabas, Iran, 74°	7.4	0.71	16.1	9.96

[a] Moment magnitude
[b] Peak ground acceleration
[c] Duration as defined by Dobry et al. (22)
[d] Arias intensity

than 0.5 m/sec) for very small critical accelerations (0.02 g), but otherwise the data are well fit by the model.

Equation 8 can be applied to the example summarized in Table 1. For the lower estimated Arias intensity of 1.59 m/sec and a critical acceleration of 0.2 g, the mean value from Equation 8 is 3.2 cm, and the range bracketing two standard deviations is 1.3 to 8.3 cm. For the higher value of Arias intensity of 1.97 m/sec, Equation 8 yields a mean value of 4.4 cm and a range of 1.7 to 11.4 cm. Displacements calculated from the three selected strong-motion records fall within this range, and the mean values from Equation 8 are very close to two of the three calculated displacements. Thus, the simplified Newmark method presented here yields reasonable results.

Equation 8 and Figure 5 can be applied to estimate the dynamic performance of any slope of known critical acceleration because they are derived from generic values of critical acceleration that are not site specific. Thus, several types of

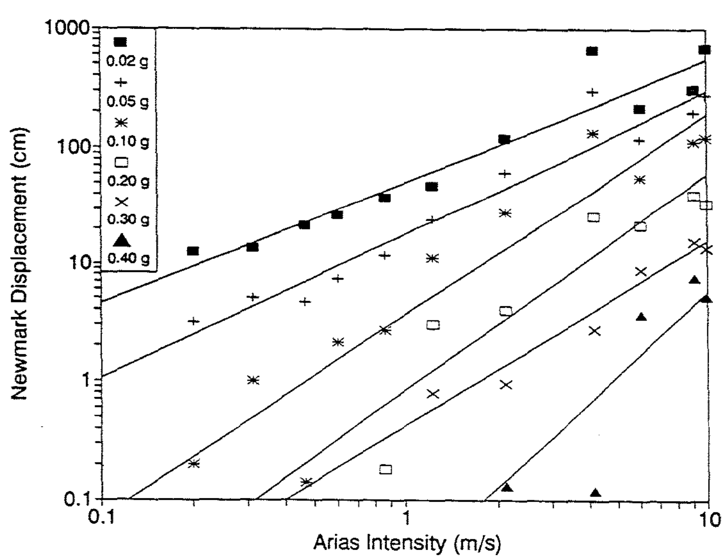

FIGURE 4 Newmark displacement plotted as a function of Arias intensity for different values of critical acceleration. Lines are best fits from regressions for each value of critical acceleration plotted.

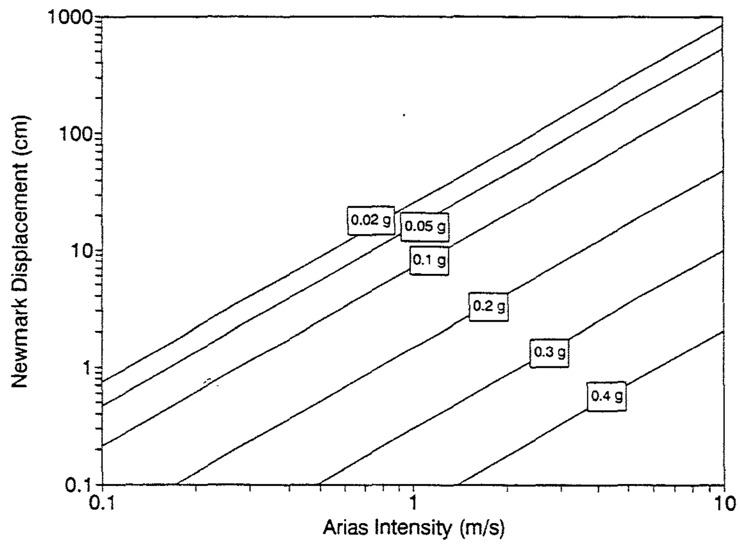

FIGURE 5 Newmark displacement as a function of Arias intensity for several values of critical acceleration as modeled by the regression equation shown.

hazard analyses for earthquake-triggered landslides can be developed:

1. If the Arias intensity at a site can be specified, and if the critical acceleration of the slope can be determined, the Newmark displacement can be estimated.
2. If critical displacement can be estimated and the critical acceleration of the slope is known, the threshold Arias intensity that will cause slope failure can be estimated.
3. If a critical displacement and Arias intensity can be estimated, the threshold critical acceleration below which slope failure will occur can be estimated.

INTERPRETING NEWMARK DISPLACEMENTS

The significance of Newmark displacements must be judged by their probable effect on a potential landslide. Wieczorek et al. (*15*) used 5 cm as the critical displacement leading to macroscopic ground cracking and general failure of landslides in San Mateo County, California; Keefer and Wilson (*23*) used 10 cm as the critical displacement for coherent landslides in southern California; and Jibson and Keefer (*16*) used this 5- to 10-cm range as the critical displacement for landslides in the Mississippi Valley. In most soils, displacements in this range cause ground cracking, and previously undeformed soils can lose some of their peak shear strength and end up in a weakened or residual-strength condition. In such a case of strength loss, a static stability analysis in residual-strength conditions can be performed to determine the slope stability after earthquake shaking ceases.

Any level of critical displacement can be used according to the parameters of the problem under study and the characteristics of the landslide material. Highly ductile materials may be able to accommodate more displacement without general failure; brittle materials might accommodate less displacement. What constitutes failure may vary according to the needs of the user. Results of laboratory shear-strength tests can be interpreted to estimate the strain necessary to reach residual strength.

DISCUSSION OF RESULTS

Any idealized model is limited by its simplifying assumptions. The fundamental assumption of Newmark's model is that landslides behave as rigid-plastic materials; that is, no displacement occurs below the critical acceleration, and displacement occurs at constant shearing resistance when the critical acceleration is exceeded. This assumption is reasonable for some types of landslides in some types of materials but it certainly does not apply universally. Many slope materials are at least slightly sensitive—they lose some of their peak undrained shear strength as a function of strain. In such a case, Newmark's method would underestimate the actual displacement because the strength loss during shear would reduce the critical acceleration as displacement occurs. For such materials, the Newmark displacement might be considered a minimum displacement and so would be unconservative.

Some highly plastic, fine-grained soils behave as viscoplastic rather than rigid-plastic materials. The viscous response of these soils results in part from low permeability and high cohesion, and the result can be a radically dampened seismic response. Some active, slow-moving landslides having factors of safety at or below 1.0 have experienced negligible inertial displacement even during large earthquakes (*24*) because of viscous energy dissipation. In Newmark's method, displacement depends on the critical acceleration, which in turn depends on the static factor of safety. Therefore, a landslide at or very near static equilibrium should have a very low critical acceleration (theoretically, $a_c = 0$ if FS = 1) and thus should undergo large inertial displacements in virtually any earthquake. Thus, Newmark's method probably overestimates landslide displacements in viscoplastic materials.

Generally, Newmark's method has considered static and dynamic shear strength to be the same and has ignored dynamic pore-pressure response; this has permitted use of static shear strengths, which are much more easily determined than dynamic strengths. For many soils, this assumption introduces little error, but static and dynamic strengths differ significantly for some soils. In such cases, dynamic shear-strength testing may be required, or static strengths can be adjusted by an empirical correction factor (*12*). Similarly, dynamic pore-pressure response, if considered significant, can be measured in dynamic tests or accounted for empirically by reducing the static shear strength.

Ongoing research is addressing ways to account for strain-dependent strength reduction, viscoplastic behavior, and the effects of the vertical component of ground shaking. Results of such research will facilitate refinement of dynamic landslide modeling and improve the ability to predict dynamic slope response.

CONCLUSION

Newmark's method is useful for characterizing seismic slope response. It presents a viable compromise between simplistic pseudostatic analysis and sophisticated finite-element modeling, and it can be applied to a variety of problems in seismic slope stability. The new simplified method presented here provides an easy way to estimate ranges of possible displacement in cases where the seismic shaking intensity can be estimated.

REFERENCES

1. Keefer, D. K. Landslides Caused by Earthquakes. *Geological Society of America Bulletin,* Vol. 95, No. 6, 1984, pp. 406–421.
2. Wilson, R. C., and D. K. Keefer. Dynamic Analysis of a Slope Failure from the 6 August 1979 Coyote Lake, California, Earthquake. *Bulletin of the Seismological Society of America,* Vol. 73, No. 3, 1983, pp. 863–877.
3. Elgamal, A. W., A. M. Abdel-Ghaffar, and J. H. Prevost. 2-D Elastoplastic Seismic Shear Response of Earth Dams: Application. *Journal of Geotechnical Engineering,* Vol. 113, No. 5, 1987, pp. 702–719.
4. Prevost, J. H., A. M. Abdel-Ghaffar, and S. J. Lacy. Nonlinear Dynamic Analysis of an Earth Dam. *Journal of Geotechnical Engineering,* Vol. 111, No. 7, 1985, pp. 882–897.
5. Seed, H. B., K. L. Lee, I. M. Idriss, and F. I. Makdisi. The Slides in the San Fernando Dams During the Earthquake of February 9, 1971. *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 101, No. 7, 1975, pp. 651–688.
6. Taniguchi, E., R. V. Whitman, and W. A. Marr. Prediction of Earthquake-Induced Deformation of Earth Dams. *Soils and Foundations,* Vol. 23, No. 4, 1983, pp. 126–132.
7. Chang, C. J., W. F. Chen, and J. T. P. Yao. Seismic Displacements in Slopes by Limit Analysis. *Journal of Geotechnical Engineering,* Vol. 110, No. 7, 1984, pp. 860–874.
8. Newmark, N. M. Effects of Earthquakes on Dams and Embankments. *Geotechnique,* Vol. 15, No. 2, 1965, pp. 139–159.
9. Goodman, R. E., and H. B. Seed. Earthquake-Induced Displacements in Sand Embankments. *Journal of the Soil Mechanics and Foundations Division,* ASCE, Vol. 92, No. SM2, 1966, pp. 125–146.
10. Lin, J. S., and R. V. Whitman. Earthquake Induced Displacements of Sliding Blocks. *Journal of Geotechnical Engineering,* Vol. 112, No. 1, 1986, pp. 44–59.
11. Yegian, M. K., E. A. Marciano, and V. G. Ghahraman. Earthquake-Induced Permanent Deformations: Probabilistic Approach. *Journal of Geotechnical Engineering,* Vol. 117, No. 1, 1991, pp. 35–50.
12. Makdisi, F. I., and H. B. Seed. Simplified Procedure for Estimating Dam and Embankment Earthquake-Induced Deformations. *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 104, No. GT7, 1978, pp. 849–867.
13. Ambraseys, N. N., and J. M. Menu. Earthquake-Induced Ground Displacements. *Earthquake Engineering and Structural Dynamics,* Vol. 16, No. 7, 1988, pp. 985–1006.
14. Franklin, A. G., and F. K. Chang. *Earthquake Resistance of Earth and Rock-Fill Dams: Permanent Displacements of Earth Embankments by Newmark Sliding Block Analysis.* Miscellaneous Paper S-71-17, Report 5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1977.
15. Wieczorek, G. F., R. C. Wilson, and E. L. Harp. *Map Showing Slope Stability During Earthquakes in San Mateo County, California.* Miscellaneous Investigations Map I-1257-E. U.S. Geological Survey, 1985.
16. Jibson, R. W., and D. K. Keefer. Analysis of the Seismic Origin of Landslides: Examples from the New Madrid Seismic Zone. *Geological Society of America Bulletin,* Vol. 105, No. 4, 1993, pp. 521–536.
17. Arias, A. A Measure of Earthquake Intensity. In *Seismic Design for Nuclear Power Plants,* Massachusetts Institute of Technology Press, Cambridge, 1970, pp. 438–483.
18. Harp, E. L., and R. C. Wilson. Shaking Intensity Thresholds for Seismically Induced Landslides. *Geological Society of America Abstracts with Programs,* Vol. 21, No. 5, 1989, p. 90.
19. Nuttli, O. W., and R. B. Herrmann. Ground Motion of Mississippi Valley Earthquakes. *Journal of Technical Topics in Civil Engineering,* Vol. 110, No. 1, 1984, pp. 54–69.
20. Heaton, T. H., F. Tajima, and A. W. Mori. Estimating Ground Motions Using Recorded Accelerograms. *Surveys in Geophysics,* Vol. 8, 1986, pp. 25–83.
21. Wilson, R. C., and D. K. Keefer. Predicting Areal Limits of Earthquake-Induced Landsliding. In *Evaluating Earthquake Hazards in the Los Angeles Region—An Earth-Science Perspective,* Professional Paper 1360, U.S. Geological Survey, 1985, pp. 316–345.
22. Dobry, R., I. M. Idriss, and E. Ng. Duration Characteristics of Horizontal Components of Strong-Motion Earthquake Records. *Bulletin of the Seismological Society of America,* Vol. 68, No. 5, 1978, pp. 1487–1520.
23. Keefer, D. K., and R. C. Wilson. Predicting Earthquake-Induced Landslides, With Emphasis on Arid and Semi-Arid Environments. In *Landslides in a Semi-Arid Environment,* Inland Geological Society, Riverside, Calif., Vol. 2, 1989, pp. 118–149.
24. Jibson, R. W., C. S. Prentice, C. J. Langer, E. A. Rogozhin, and B. A. Borissoff. Unusual Landslides and Other Strong-Shaking Effects of the 29 April 1991 Racha Earthquake in the Republic of Georgia. *Bulletin of the Seismological Society of America,* submitted 1992.

Publication of this paper sponsored by Committee on Engineering Geology.