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Regression models for estimating coseismic landslide displacement

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Abstract

Newmark's sliding-block model is widely used to estimate coseismic slope performance. Early efforts to develop simple regression models to estimate Newmark displacement were based on analysis of the small number of strong-motion records then available. The current availability of a much larger set of strong-motion records dictates that these regression equations be updated. Regression equations were generated using data derived from a collection of 2270 strong-motion records from 30 worldwide earthquakes. The regression equations predict Newmark displacement in terms of (1) critical acceleration ratio, (2) critical acceleration ratio and earthquake magnitude, (3) Arias intensity and critical acceleration, and (4) Arias intensity and critical acceleration ratio. These equations are well constrained and fit the data well ($71\% < R^2 < 88\%$), but they have standard deviations of about 0.5 log units, such that the range defined by the mean ± one standard deviation spans about an order of magnitude. These regression models, therefore, are not recommended for use in site-specific design, but rather for regional-scale seismic landslide hazard mapping or for rapid preliminary screening of sites.

Keywords: Earthquake; Landslide; Seismic hazards; Newmark method

1. Introduction

Most moderate and large earthquakes trigger landslides, and in many cases these landslides account for a significant proportion of total earthquake damage. To address this hazard, methods for modeling and predicting landslide displacements during earthquakes have been evolving steadily since Newmark (1965) first introduced a simple model, still in common use, to estimate coseismic slope displacement. Newmark's (1965) method models a landslide as a rigid friction block that slides on an inclined plane when subjected to base accelerations approximating an earthquake. Landslide displacement is estimated by integrating twice with respect to time over the parts of an earthquake acceleration-time history that exceed the threshold acceleration required to overcome basal resistance and initiate sliding (Fig. 1). Computer programs to conduct rigorous Newmark analyses are readily available (Houston et al., 1987; Jibson and Jibson, 2003) and can be used to estimate seismically induced slope displacements at specific sites where the relevant data can be collected and appropriate strong-motion records can be selected to approximate the shaking the site will experience (e.g., Wilson and Keefer, 1983; Jibson, 1993; Jibson and Keefer, 1993; Pradel et al., 2005).

Wieczorek et al. (1985) were the first to use Newmark analysis as a basis for seismic landslide microzonation, and methods for such applications have evolved steadily since that first study (e.g., California Division of Mines and Geology, 1997; Jibson et al., 1998; Mankelow and

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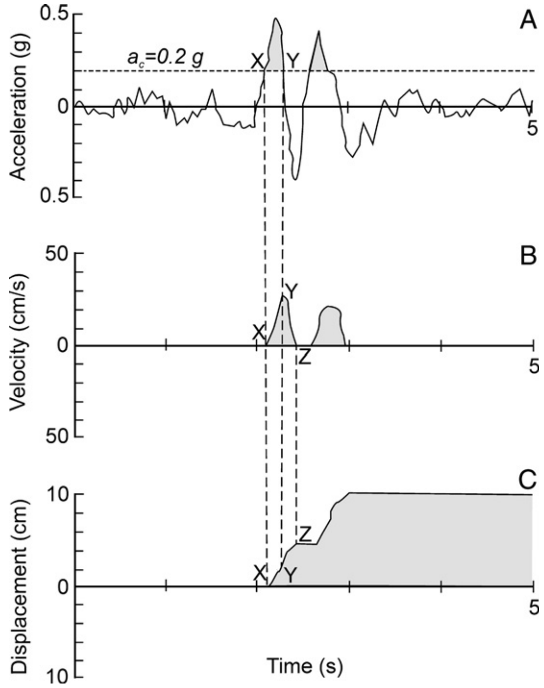

Fig. 1. Illustration of Newmark double-integration. A, Earthquake acceleration-time history with critical acceleration (short-dashed line) of 0.20 g superimposed. B, Velocity of landslide block versus time. C, Displacement of landslide block versus time. Points *X*, *Y*, and *Z* are for reference between plots.

Murphy, 1998; Luzi and Pergalani, 1999; Miles and Ho, 1999; Jibson et al., 2000; Miles and Keefer, 2000, 2001; Del Gaudio et al., 2003; Rathje and Saygili, 2006). Such applications generally involve GIS modeling in which study areas are gridded, and discrete estimates of coseismic displacement are generated for each grid cell. Conducting a rigorous Newmark analysis for each grid cell would require selection of unique strong-motion records for each cell, which is impractical. As an alternative, simple regression models that estimate Newmar displacement as a function of various geotechnical and seismological parameters facilitate GIS-based seismic landslide microzonation. Simple regression models can also be used for rapid, preliminary estimation of dynamic slope performance.

This paper briefly reviews previously published methods for estimating Newmark displacement, describes a much larger set of strong-motion data to be analyzed in generating new regression models, and then proposes regression models to estimate Newmark displacement as a function of (1) critical acceleration ratio, (2) critical acceleration ratio and magnitude, (3) Arias intensity and critical acceleration, and (4) Arias intensity and critical acceleration ratio.

2. Previous simplified approaches

Conducting a Newmark analysis requires characterization of two key elements: the dynamic stability of the slope to be analyzed and the earthquake shaking to which it will be subjected. Dynamic slope stability is quantified as the critical (or yield) acceleration (a_c), the threshold ground acceleration necessary to overcome basal sliding resistance and initiate permanent down-slope movement. In its simplest form, critical acceleration can be estimated as

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

where a_c is in terms of g, the acceleration of gravity, FS is the static factor of safety (the ratio of resisting to driving forces or moments in a slope), and α is the angle from the horizontal of the sliding surface (Newmark, 1965; Jibson, 1993).

Characterization of the seismic ground motion presents more challenges. At the time Newmark's method was published, few strong-motion records were available for analysis, and computing resources to conduct rigorous integrations were sparse; therefore, simple, generalized methods for estimating Newmark displacements (D_N) were developed. Newmark (1965) analyzed simple rectangular acceleration pulses as well as four actual strong-motion records to produce some graphical generalizations that could be used to estimate displacement as a function of the ratio of the critical acceleration to the peak ground acceleration (a_{max}); this ratio is commonly referred to as the critical acceleration ratio. Similar approaches were used subsequently to refine these estimates by using a variety of simple shapes for acceleration pulses (e.g., triangular, sinusoidal) as well as larger collections of actual strong-motion records (Sarma, 1975; Franklin and Chang, 1977; Hynes-Griffin and Franklin, 1984; Yegian et al., 1991). All of these early simplified generalizations graphically plotted Newmark displacement versus critical acceleration ratio, and some proposed simple equations to define upper bounds of Newmark displacements.

Ambraseys and Menu (1988) proposed various regression equations to estimate Newmark displacement as a function of the critical acceleration ratio based on analysis of 50 strong-motion records from 11 earthquakes. They concluded that the following equation best characterized the results of their study:

$$\log D_N = 0.90 + \log\left[\left(1-\frac{a_c}{a_{max}}\right)^{2.53}\left(\frac{a_c}{a_{max}}\right)^{-1.09}\right] \pm 0.30, \tag{2}$$

where D_N is in centimeters and the last term is the standard deviation of the model. Other studies have proposed regression equations of different forms, and including various additional parameters, to estimate Newmark displacement (e.g., Yegian et al., 1991).

Jibson (1993) suggested using Arias intensity (I_a) rather than peak ground acceleration to characterize the strong shaking. Arias (1970) defined this measure of the shaking content of a strong-motion record as

$$I_a = \frac{\pi}{2g}\int_0^d [a(t)]^2 dt, \tag{3}$$

where g is the acceleration of gravity, d is the duration of the strong shaking, a is the ground acceleration, and t is time. Because Arias intensity measures the total acceleration content of the record rather than just the peak value, it provides a more complete characterization of the shaking content of a strong-motion record than does the peak ground acceleration. Jibson (1993) proposed the following regression equation based on rigorous analysis of 11 strong-motion records for a_c values of 0.02, 0.05, 0.10, 0.20, 0.30, and 0.40 g:

$$\log D_N = 1.460 \log I_a - 6.642 a_c + 1.546 \pm 0.409 \tag{4}$$

where D_N is in centimeters, I_a is in meters per second, a_c is in terms of g, and the last term is the standard deviation of the model. This model fit the small input data set well ($R^2=87\%$), but making a_c a linear term made the model overly sensitive to small changes in a_c. Jibson et al. (1998, 2000) modified the form of this equation to make all terms logarithmic and then performed rigorous analysis on 555 strong-motion records from 13 earthquakes for the same a_c values as indicated for Eq. (4) to generate the following regression equation:

$$\log D_N = 1.521 \log I_a - 1.1993 \log a_c - 1.546 \pm 0.375. \tag{5}$$

This equation has been used in various contexts to assess and map regional seismic landslide hazards (e.g., Mankelow and Murphy, 1998; Miles and Keefer, 2000, 2001; Del Gaudio et al., 2003; Murphy and Mankelow, 2004; Haneberg, 2006). The data set from which this equation was generated, however, was heavily weighted toward the lower a_c values because of how the data set was constructed. The 555 strong-motion records analyzed had peak accelerations ranging from 0.03 to 1.78 g, but many more records had lower peak accelerations than had higher accelerations. Newmark displacements were calculated only for a_c values that were less than the peak acceleration, therefore, the data set included many more values for the lower a_c values than for the higher a_c values. This resulted in a model that is well constrained at lower values of a_c but is progressively less well fit for higher a_c values.

Other groups of studies have refined and expanded Newmark's model to account for the deformability of the system as well as the dynamic displacement. These approaches generally fall under two categories: (1) decoupled models (Makdisi and Seed, 1978; Lin and Whitman, 1983) and (2) fully coupled models (Bray and Rathje, 1998; Rathje and Bray, 1999, 2000). The present study does not deal with these more complex models but is limited to traditional rigid-block Newmark models.

3. Methods and data

To produce well-constrained regression models for predicting Newmark displacement, a data set of Newmark displacements was constructed for a_c values of 0.05, 0.10, 0.20, 0.30, and 0.40 g, the range of practical interest for seismic slope-stability problems. Table 1 shows 30 earthquakes from which a set of 2270 single-horizontal-component strong-motion records were obtained. These records include those described by Jibson and Jibson (2003) in addition to 129 new records from the 2004 Niigata-Ken-Chuetsu, Japan, earthquake. All of the records used are from either free-field stations or single-story structures. A mixture of site conditions is represented: 10% of the sites are on hard rock, 27% on soft rock, 49% on stiff soil, and 14% on soft soil.

To model displacement as a function of critical acceleration ratio, a rigorous Newmark double-integration was performed for each of the 2270 strong-motion records for all critical accelerations that were less that the peak acceleration of the record. This yielded a data set containing 6632 Newmark displacements along with corresponding critical accelerations, peak accelerations (a_{max}), and earthquake magnitudes (moment magnitude, **M**).

Modeling displacement as a function of critical acceleration and Arias intensity required sampling the entire data set to produce a smaller data set that was evenly distributed across the range of critical accelerations to be analyzed (0.05–0.40 g). Of the 2270 strong-motion records, 184 had peak accelerations greater than 0.4 g, the upper-bound critical acceleration. Therefore, I selected 175 records for each of the five a_c values to be analyzed; the records were evenly distributed across the range bounded by the critical acceleration of the data subset to the highest peak acceleration in the record collection. Thus, the final data set included 875 rigorously determined Newmark displacements, 175 for each of the five a_c values analyzed. Also included in the data

Table 1
Earthquakes and number of strong-motion records used for Newmark analysis

Earthquake	Date	Magnitude (**M**)	Number of records
Cape Mendocino, CA	04/25/1992	7.1	12
Chi-Chi, Taiwan	09/21/1999	7.6	629
Coalinga, CA	05/05/1983	6.4	92
Coyote Lake, CA	08/06/1979	5.7	22
Daly City, CA	03/22/1957	5.3	2
Duzce, Turkey	11/12/1999	7.1	20
Friuli, Italy	05/06/1976	6.5	10
Hilo, HI	11/29/1975	7.2	1
Imperial Valley, CA	05/18/1940	6.0	2
Imperial Valley, CA	10/15/1979	6.5	67
Kern County, CA	07/21/1952	7.5	10
Kobe, Japan	01/17/1995	6.9	24
Kocaeli, Turkey	08/17/1999	7.4	41
Landers, CA	06/28/1992	7.3	78
Loma Prieta, CA	10/17/1989	6.9	136
Mammoth Lakes, CA	05/25/1980	6.3	6
Mammoth Lakes, CA	05/27/1980	6.0	8
Morgan Hill, CA	04/24/1984	6.2	49
Nahanni, Canada	12/23/1985	6.8	6
Niigata-Ken-Chuetsu, Japan	10/23/2004	6.6	129
Nisqually, WA	02/28/2001	6.8	158
North Palm Springs, CA	07/08/1986	6.0	63
Northridge, CA	01/17/1994	6.7	376
Parkfield, CA	06/28/1966	6.0	9
San Fernando, CA	02/09/1971	6.6	42
Santa Barbara, CA	08/13/1978	6.0	8
Superstition Hills, CA	11/23/1987	6.5	32
Tabas, Iran	09/16/1978	7.4	14
Westmoreland, CA	04/26/1981	5.8	12
Whittier Narrows, CA	10/01/1987	6.0	212

set were the peak accelerations, critical accelerations, and Arias intensities of the records analyzed. There was some overlap in the records selected in the different a_c groupings.

4. Regression equations for predicting Newmark displacement

This section presents a variety of regression equations of different forms that can be used to estimate Newmark displacement.

4.1. Newmark displacement as a function of critical acceleration ratio

As has been discussed previously, the commonest approach to a simplified estimation of Newmark displacements has been to correlate displacement with the critical acceleration ratio (a_c/a_{max}). Functional forms having the greatest utility are those that mimic the theoretical values at the extrema of the range of critical acceleration ratio: functions should predict displacements approaching infinity when $a_c/a_{max}=0$ and approaching zero when $a_c/a_{max}=1$. Fig. 2 shows the present data set plotted in terms of Newmark displacement and critical acceleration ratio. Between a_c values of about 0.2 and 0.8 g the data would be well fit by a straight line in semi-log space. At the two ends of the range, however, the data clearly tail upward at low a_c values and downward at high a_c values, as would be expected. Ambraseys and Menu (1988) explained a rational basis for the functional form they proposed [Eq. (2)], and their functional form matches the characteristic shape apparent in the data; therefore, a regression line using this functional form was fit to the present data set:

$$\log D_N = 0.215 + \log\left[\left(1-\frac{a_c}{a_{max}}\right)^{2.341}\left(\frac{a_c}{a_{max}}\right)^{-1.438}\right] \pm 0.510, \quad (6)$$

where D_N is in centimeters, and the last term is the standard deviation of the model. The equation has an R^2 value of 84% and is thus well fit to the data at a very high level of statistical significance. The exponents in Eq. (6) are similar in value to those in Eq. (2), which gives the curves a similar shape; the constant term is lower in value, which shifts the curve downward. Fig. 2 compares Eqs. (2) and (6) to the data set. Eq. (2), derived from a set of 50 strong-motion records, lies well above Eq. (6) and thus overestimates displacement across the entire a_c range.

I experimented with several hundred alternative functional forms, and, except for some high-order polynomials, none had better fits or behaved correctly at the extrema. Some polynomial models did yield marginally better fits (increase in R^2 value of only 0.3%), but they did not yield satisfactory estimates at the extrema: (1) when the critical acceleration ratio approaches zero, the predicted displacement is limited by the value of the regression constant rather than approaching infinity, and (2) when the critical acceleration ratio approaches one, a polynomial model predicts a finite displacement rather than approaching zero.

4.2. Newmark displacement as a function of critical acceleration ratio and moment magnitude

Ambraseys and Menu (1988) stated that Eq. (2) is valid only for the fairly narrow magnitude (M_s) range of 6.6–7.2. Duration tends to increase with increasing magnitude, and duration has a significant effect on Newmark displacement; therefore, I separated the data into three

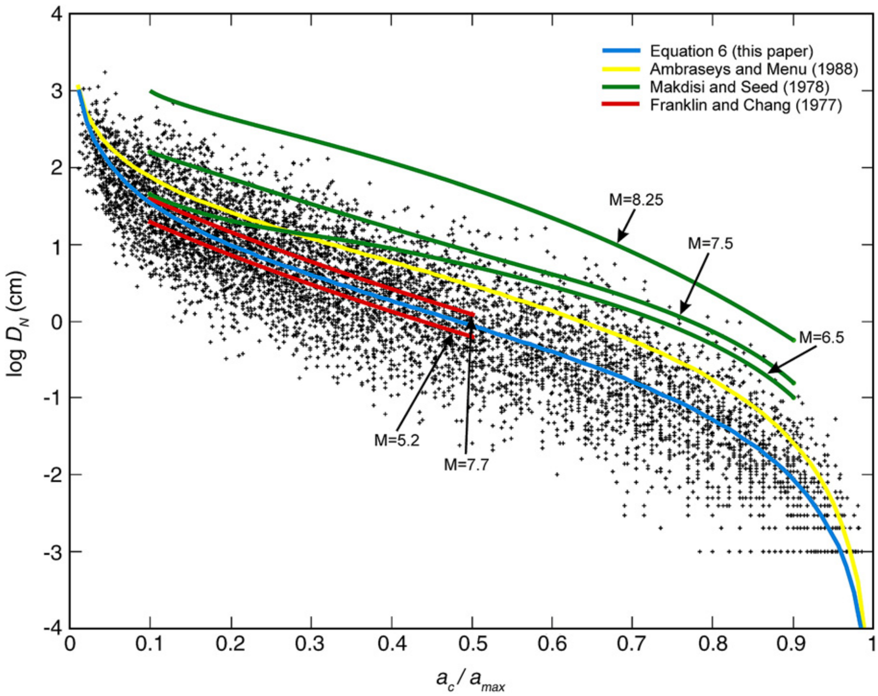

Fig. 2. Newmark displacements plotted logarithmically as a function of critical acceleration ratio. Results of various other studies are shown for comparison; green lines are centroids of areas delineated by Makdisi and Seed (1978) for the magnitudes indicated.

magnitude ranges ($\mathbf{M}<6.0$, $6.0\leq\mathbf{M}<7.0$, and $\mathbf{M}\geq 7.0$) to test for magnitude dependence. Although the data for these ranges broadly overlap, best-fit curves through each subset of the data show the magnitude-dependence of Newmark displacement (Fig. 3). Therefore, I developed a separate model that takes magnitude into account. This produces an equation that should be applicable across the magnitude range of the data set, $5.3\leq\mathbf{M}\leq 7.6$:

$$\log D_{\mathrm{N}} = -2.710 + \log\left[\left(1-\frac{a_{\mathrm{c}}}{a_{\max}}\right)^{2.335}\left(\frac{a_{\mathrm{c}}}{a_{\max}}\right)^{-1.478}\right] + 0.424\mathbf{M}\pm 0.454, \qquad (7)$$

where $\mathbf{M}$ is moment magnitude. The exponents are nearly identical to those in Eq. (6), which gives the curves similar characteristic shapes; the magnitude term simply shifts the curve up or down. Eq. (7) has an R^2 value of 87%, a small but significant increase over the value for Eq. (6).

4.3. Newmark displacement as a function of Arias intensity and critical acceleration

As stated previously, Arias (1970) intensity is, in many ways, superior to peak acceleration in characterizing the shaking content of an earthquake record because it accounts for all acceleration peaks (not just the maximum) and, implicitly, for duration. Jibson et al. (1998, 2000), expanding on the initial work of Jibson (1993), showed the utility of using the following functional form for correlating Newmark displacement with Arias intensity and critical acceleration:

$$\log D_{\mathrm{N}} = A\log I_{\mathrm{a}} + B\log a_{\mathrm{c}} + C\pm\sigma, \qquad (8)$$

where A, B, and C are the constants to be determined by the regression and σ is the standard deviation of the model. Using Eq. (8), I regressed the 875 Newmark displacements extracted from the present data set and generated the following regression equation, which has an R^2 value of 71%:

$$\log D_{\mathrm{N}} = 2.401\log I_{\mathrm{a}} - 3.481\log a_{\mathrm{c}} - 3.230\pm 0.656, \qquad (9)$$

where D_{N} is in centimeters, I_{a} is in meters per second, and a_{c} is in terms of g.

Fig. 4 graphically compares this regression model with the previous model by Jibson et al. (1998, 2000) and with best-fit lines through each of the five a_{c} subsets of the database. Eq. (9) more closely fits the best-fit lines through the data subsets than does the previous model; the improvement is most pronounced

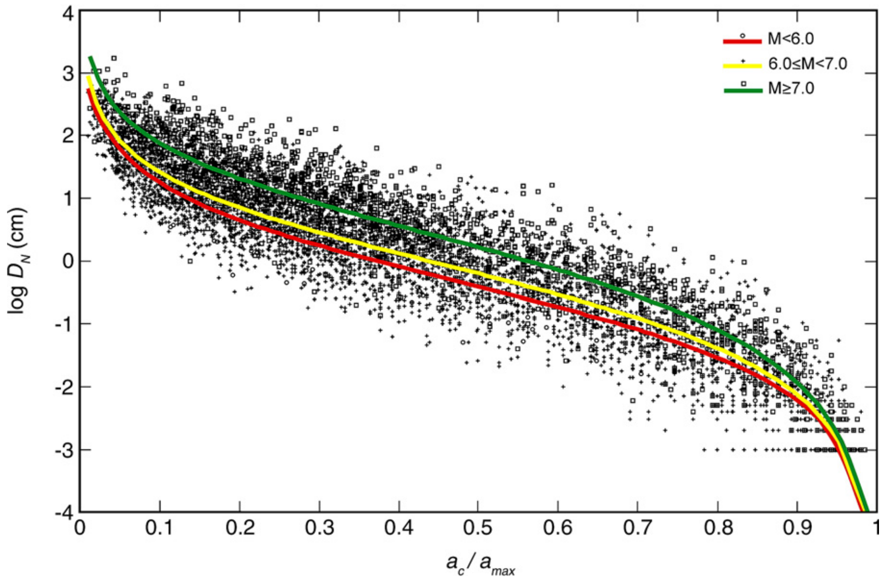

Fig. 3. Newmark displacements plotted logarithmically as a function of critical acceleration ratio for different earthquake magnitudes. Data are separated into three magnitude groups, and best-fit lines for each group are shown: $\mathbf{M}<6.0$, $6.0\le\mathbf{M}<7.0$, and $\mathbf{M}\ge 7.0$.

for moderate and large values of a_c. In all cases, the best-fit lines of the new model more closely parallel with the best-fit lines through the data subsets, which results in more consistent predictions across a broad range of possible input values.

4.4. Newmark displacement as a function of Arias intensity and critical acceleration ratio

To further constrain the variability in ground motion, peak acceleration can also be included in this type of

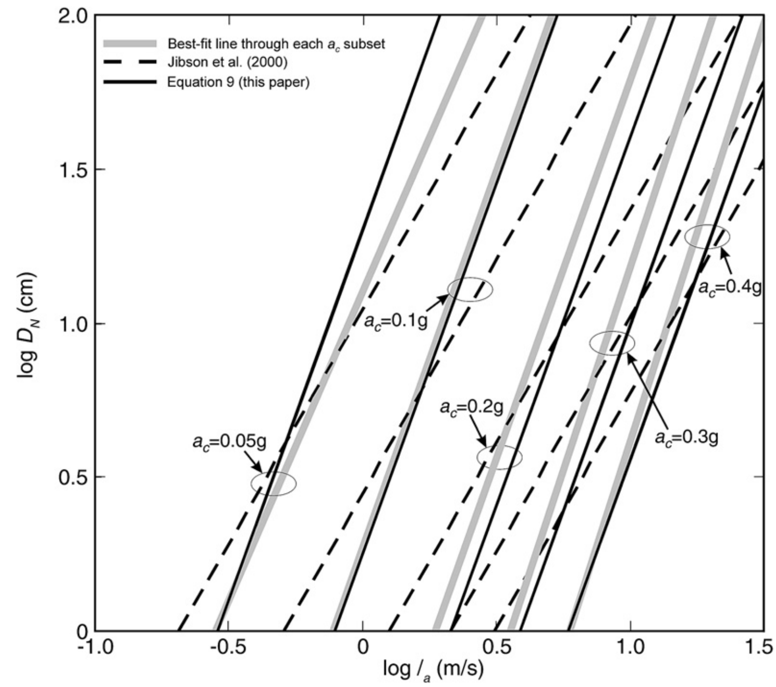

Fig. 4. Best-fit lines showing Newmark displacement as a function of Arias intensity in log–log space. The data set was separated into five subsets based on the five a_c values used to construct the data set. Gray lines are best-fit lines through each a_c data subset; solid black lines are best-fit lines from the present study [Eq. (9)]; dashed black lines are best-fit lines from Jibson et al. (1998, 2000) [Eq. (5)]. Ellipses enclose lines pertaining to the critical accelerations indicated.

model [Eq. (9)]. As previously described, peak acceleration is most commonly included as a ratio with critical acceleration. This yields the following equation, in which the R^2 value improves to 75%, and the standard deviation decreases slightly:

$$\log D_N = 0.561 \log I_a - 3.833 \log(a_c/a_{max}) - 1.474 \pm 0.616. \quad (10)$$

A shortcoming of this model is that even when a_c equals or exceeds a_{max} a small, but finite, displacement will be predicted. This is true for any model that uses a parameter such as Arias intensity, which characterizes ground motion in different terms than the dynamic stability of the slope.

5. Discussion

It is important to remember exactly what these new equations are: they are models of models. Newmark's (1965) sliding-block model has proved very useful in modeling dynamic slope performance, but it is highly simplistic and contains many assumptions that might or might not approximate reality in various situations. Newmark's method treats a landslide as a rigid-plastic body: the mass does not deform internally (neither from shaking nor basal shear), it experiences no permanent displacement at accelerations below the critical or yield level, and it deforms plastically along a discrete basal shear surface when the critical acceleration is exceeded. Thus, Newmark's method is most appropriately applied to landslides in fairly stiff material that move as a coherent mass along a well-defined slip surface. Because actual landslides do not always behave in this idealized manner, rigorously calculated Newmark displacements have always been considered indices of dynamic slope performance rather than precise predictions of actual slope displacement (Jibson et al., 1998, 2000; Rathje and Bray, 2000). The newly developed regression equations are models to predict what displacement a rigorous Newmark analysis would yield; thus, they are approximations of what is already a fairly simplistic model.

Newmark's (1965) approach and subsequent variations and applications of it were developed to analyze the seismic behavior of earth dams and embankments (e.g., Franklin and Chang, 1977; Makdisi and Seed, 1978; Seed, 1979; Lin and Whitman, 1983). These large earth structures commonly have well-defined, homogeneous properties; are constructed largely of relatively ductile fine-grained materials; and are principally subject to deep modes of failure. To better model such engineered earth structures, so-called fully coupled analyses recently have been developed that overcome Newmark's original assumption of internal rigidity by taking into account the dynamic deformation of the soil mass and the effects of coseismic displacement on the response of the slide mass (Bray and Rathje, 1998; Rathje and Bray, 1999, 2000). These and other studies (e.g., Kramer and Smith, 1997; Wartman et al., 2003, 2005; Lin and Wang, 2006) make clear that traditional Newmark analysis–the rigid-block analysis dealt with in this paper–does not yield acceptable results for the seismic performance of large engineered earth structures in many cases and, therefore, should not be used for such situations. Wartman et al. (2003, 2005) and Rathje and Bray (1999, 2000) provide detailed treatments of specific combinations of site and shaking conditions that are and are not adequately modeled by rigid-block analysis.

Rigid-block analysis as modeled herein is best suited to a very different type of slope failure: earthquake-triggered landslides in natural slopes (first proposed by Wilson and Keefer, 1983). Keefer's (1984, 2002) analysis of data from worldwide earthquakes indicated that the large majority of earthquake-triggered landslides are shallow, disrupted failures in brittle materials, most commonly rock falls and rock slides. Documentations of landslides from several earthquakes have indicated that such landslides commonly make up 90% or more of triggered landslides (e.g., Harp et al., 1981; Harp and Jibson, 1995, 1996; Keefer and Manson, 1998; Jibson et al., 2004, 2006). These types of landslides are well-suited to rigid-block analysis because the brittle surficial material behaves rigidly and the relatively thin landslide masses do not experience significant site response that would modify the incident ground motions. Therefore, the proposed models in this paper are most appropriately applied to thinner landslides in more brittle materials rather than to deeper landslides in softer materials. This includes the vast majority of seismically triggered landslides in natural slopes, which makes the proposed models particularly applicable to regional analysis of seismic landslide hazards.

Many thousands of strong-motion records are currently available from a variety of web sites, and data sets many times larger than the one used in this paper could be constructed. I tested samples of the data set described in this paper to determine the sensitivity of the regression models to the size of the data set. Models generated using data from several hundred strong-motion records were virtually identical to those generated using the entire data set (2270 records). This suggests that the data set used to generate the regression models in this paper is sufficiently large to encompass the range of variation that would be present in any sample of comparable size taken from all of the currently available strong-motion records.

Site conditions can significantly affect some strong-motion characteristics, but the shaking parameters used in the regression models should not be overly sensitive to different site conditions. Peak ground acceleration is used only as a ratio of the critical acceleration, and Arias intensity is used simply to express the total energy content of the earthquake at the site, regardless of the specific frequency or amplitude content of the shaking. To determine if site conditions significantly affect the regression models, the data used in the models were separated into soil and rock categories, and separate regression models were generated to quantify the differences. Values of the regression coefficients and constants for the soil and rock models differed by only 5–7%, an insignificant difference as compared to other uncertainties in the models. Therefore, separate models for different site conditions are deemed unnecessary.

Fig. 2 compares the results from the present study [Eq. (6)] to those from some previous studies. The curve from Ambraseys and Menu (1988) has the same functional form as that defined by Eq. (6), but their curve lies well above the curve from the present study. This difference is most likely attributable to the small (50) collection of strong-motion records they analyzed. Franklin and Chang (1977) analyzed a larger collection of records (about 200), and their results, though spanning only part of the range under present consideration, compare quite well with the best-fit curve from Eq. (6). Makdisi and Seed (1978) used a few records from only three earthquakes, and their curves lie well above those from the other studies. This result is not surprising because they used the so-called decoupled method, which accounts for the dynamic deformation of the sliding block and thus produces amplified accelerations in sliding blocks that are fairly thick (representing deep landslides). Interestingly, however, the Makdisi and Seed curve for the largest earthquakes defines the upper bound of the current data set and thus can be considered a conservative upper limit of the displacement that would be predicted by a rigid-block analysis.

The newly developed models [Eqs. (6), (7), (9), and (10)] yield mean values of displacement when the standard deviation (the last term in the equations) is ignored. All of these equations have standard deviations of roughly ± 0.5 log units, corresponding to a range of estimated Newmark displacements of an order of magnitude. This broad range results largely from the stochastic nature of seismic shaking and the difficulty in characterizing that shaking using single numerical measures such as peak acceleration or Arias intensity: multiple strong-motion records having identical Arias intensities or peak accelerations will yield different displacements for a given critical acceleration. The calculated uncertainty in the equations is an indirect measure of the stochastic properties of the input seismic ground motions and should be accounted for when applying these predictive equations to practical problems. For example, specification of the standard deviations of the models facilitates these models being incorporated into probabilistic hazard models (Rathje and Saygili, 2006). If a deterministic analysis is undertaken, it might be considered conservative to use the mean plus one or even two standard deviations, depending on the desired level of design conservatism.

One could argue that a regression model that yields a range of displacements spanning an order of magnitude is of little practical use. These regression equations are not intended for applications in site-specific projects where accurate estimates of displacement are required for design purposes; software to conduct rigorous analyses in such conditions is readily available (Jibson and Jibson, 2003). Rather, the intended use of these equations is for regional-scale assessment and mapping of seismic landslide hazards in which the dynamic stabilities of the grid cells in a map area are estimated and compared. In such efforts, the *relative* hazard is the principal concern, and a comparison of mean estimated displacement values is entirely appropriate to quantify relative hazard. Local and regional judgment can be applied to such a hazard classification to insure that the absolute hazard categories are realistic in terms of past experience and regional conditions. The regression equations also could be used appropriately to screen individual sites rapidly in order to estimate dynamic performance and evaluate what additional, more detailed, studies will be required.

6. Conclusion

Newmark (rigid-block) analysis is a valuable tool to predict the performance of natural slopes during earthquake shaking. For relatively shallow, brittle failures, which comprise the vast majority of landslides triggered by earthquakes, rigid-block analysis provides a reasonable estimate of coseismic landslide displacement and thus overall slope performance. The regression equations presented in Eqs. (6), (7), (9), and (10) are well constrained ($71\% < R^2 < 88\%$) and predict Newmark displacement in terms of (1) critical acceleration ratio, (2) critical acceleration ratio and earthquake magnitude, (3) Arias intensity and critical acceleration, and (4) Arias intensity and critical acceleration ratio. The range defined by the mean $\pm$ one standard deviation in each of these equations spans about an order of magnitude;

therefore, these regression models are not recommended for use in site-specific design, but rather for regional-scale seismic landslide hazard mapping or for rapid preliminary screening of sites.

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