A COMPARATIVE STUDY OF EMPIRICAL MODELS FOR LANDSLIDE PREDICTION USING HISTORICAL CASE HISTORIES

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ABSTRACT :

Landslides are one of the most damaging earthquake geohazard phenomena that have created considerable socio-economic losses in the past. Therefore, it is important to find out where and in what shaking conditions landslide can occur. This paper assesses the performance of two empirical models, i.e. the California method and USGS method, for the prediction of earthquake-induced landslides based on a number of ground motion parameters. The models are implemented in four case histories and the results compared with reality. It has been observed that the results obtained do not quite agree because the California method uses the peak ground acceleration of the earthquake motion while the USGS method uses the Arias intensity. The USGS method has also been compared to historical data and proved to be within the limit boundaries of the compiled data.

KEYWORDS: Landslides, earthquake, displacement, slope stability, case histories.

1. INTRODUCTION

Landslides are one of the most damaging earthquake geohazard phenomena that have created considerable socio-economic losses in the past. Prediction of landslides is therefore necessary for planning and mitigating the damages. The objective of this paper is to examine the performance of two empirical models for prediction of earthquake-induced landslides by comparing their results against observed data from case histories of landslide and slope response. The two methods focused in this paper are the so-called California Method (Blake *et al*., 2002) proposed by the ASCE Los Angeles Section Geotechnical Group, largely based on the studies by Bray and Rathje (1998), and the USGS Method proposed by Jibson *et al.* (1998).

Landslides, particularly coherent slides principally start moving as blocks of soil. Literature discusses the following methods for assessing the initiation of coherent, translational slides: the pseudo-static method, the dynamic finite element analysis, and the displacement block method. The latter is a compromise between the two former methods (Miles and Ho, 1999). Displacement block methods embrace the concept that the effect of earthquakes on slope stability is assessed by the deformations produced, rather than by the minimum safety factor (Seed, 1967). Permanent displacements over a certain limiting value will likely trigger a landslide. The magnitude of this limiting value depends on the mechanism of the slope failure, lithology, slope geometry and earlier slope movement (Wilson and Keefer, 1983). Romeo (2000) proposed 5 cm for rocky slopes, which display a brittle behaviour, while for more ductile soils he considers a critical displacement of 10 cm. After Newmark proposed his sliding block model in 1965, the method has been developed and undergone several improvements, amongst others relating seismic ground motion parameters to computed landslide displacements (Romeo, 2000). In addition, based on a compilation of historical landslides, an envelope has been proposed in the literature for the maximum distance to which landslides have been observed. The other objective of this paper is to study the robustness of the selected empirical model by its success in reproducing the envelope of historical landslides.

2. MODELING COHERENT SLIDES

The California and USGS methods are two empirical calculation models which estimate the earthquake-induced displacements for planar slope failures (translational slides). In the following these two methods are briefly outlined; moreover, they are applied to four case histories and their results are compared.

2.1. California Method

For calculation of the displacement induced by an earthquake the California method (Blake et al. 2002) uses Newmark-type displacement analysis. Slope deformation analysis requires estimation of the slope yield acceleration $a_y = k_y\, g$ (k_y is often referred to as yield seismic coefficient and can be estimated from the slope's safety factor and angle together with a Horizontal Equivalent Acceleration, HEA, which represents the severity of shaking within the slide mass instead of the maximum ground acceleration, MHAr, which is measured at bedrock). The California method has recommended the following expression for earthquake-induced displacement explicitly for assessing landslide hazard.

$$u = k_{\max} D_{5-95} \cdot 10^{1.87-3.477\frac{k_y}{k_{\max}}} \tag{2.1}$$

Where, u is the permanent displacement (in cm). The standard error is 0.35 in log 10-units. k_{max} = MHEA/g is the peak (acceleration) demand coefficient, where MHEA is the maximum equivalent acceleration. MHEA may be estimated from MHAr, NFR (a factor which accounts for nonlinear ground response effects as shear wave propagate upwards through the slide mass), the ratio T_s/T_m, where T_s is the fundamental period of the sliding mass and T_m the mean period of the earthquake motion. D_{5-95} is referred to as the significant duration of shaking (in seconds) which is the length of time between 5% and 95% of normalized Arias intensity and may be found empirically. Empirical estimations of these values are suggested by the California method (Blake *et al.* 2002).

2.2. USGS Method

Another displacement method has been suggested by Jibson *et al.* (1998) who has tested the method against the landslides induced by the Northridge, California earthquake in 1994. For areas with a calculated displacement larger than 10 cm, it has been observed that approximately 27% of the total area had experienced landslides. Jibson *et al.* found a regression line for the Newmark displacement, D_n (in cm), as a function of the Arias intensity, I_a (m/s), and the yield seismic coefficient, k_y. The regression line for the displacement induced by earthquake is:

$$\log D_n = 1.521 \log I_a / 1.993 \log k_y - 1.546 \tag{2.2}$$

A disadvantage with Eqn. 2.2 is that the Arias intensity is not readily known even when an earthquake magnitude is assumed. Travasarou *et al.* (2003) proposed an empirical relationship for estimation of the Arias intensity as a function of M – the moment magnitude, r_{fault} – the distance to the fault in km (may be set equal to the epicentral distance), and parameters S_C and S_D characterizing the soil type and F_N and F_R as fault type indicators.

3. PERFORMANCE OF EMPIRICAL MODELS AGAINST CASE HISTORIES

3.1. Case 1: Landslide movement during Northridge Earthquake

California Method: Pradel *et al.,* (2005) have described in detail a landslide case induced by the 1994 Northridge Earthquake (M = 6.7) with a distance to the fault equal to r = 23 km. A pipeline break showed that the induced displacement was approximately 50 mm. Two strong motion stations were used in the study to obtain the maximum horizontal accelerations (MHA) for the site: Malibu Canyon (MCN) and Topanga Canyon (TOP). With the period of the sliding mass, T_s =0.177s, and various parameters such as the significant duration, D_{5-95}, the mean period, T_m, and NRF values, the corresponding values of MHEA were computed and listed in Table 3.1.

Pradel *et al.,* (2005) estimated the yield seismic coefficient of the soil, $k_y = a_y/g$, as a function of the ground water level on the day of the earthquake. The best estimate for the water level yielded k_y= 0.037, while one meter higher ground water level gave 0.026 and one meter lower resulted in 0.052. The theoretical yield coefficient is $k_{y,t}$ = 0.0771 and FS_{static} = 1.49. Using the different estimates of k_y the displacements, *u,* have been calculated (Table 3.1). According to the computations, the mean displacement is 48 cm for the best estimate of the yield seismic coefficient. The mean displacements for the lowest and highest yield coefficients are 68 cm and 30 cm, respectively. For the theoretical yield coefficient, the displacement has a mean value of 15 cm.

Table 3.1 Landslide parameters for Northridge earthquake and displacements found by the California-method

Measuring Stations	MHA (m/s^2)	NRF	$D_{5\text{-}95}$ (s)	T_m (s)	MHEA (m/s^2)	k_{max}	$u(k_y$=0.037) (cm)	$u(k_y$=0.026) (cm)	$u(k_y$=0.052) (cm)	$u(k_{y,t}$=0.077) (cm)
MCN270	2.35	1.156	9.2	0.22	1.727	0.176	22.33	36.82	11.29	4.01
MCN360	2.65	1.123	8.6	0.23	1.955	0.199	28.72	44.68	15.72	6.29
TOP000	3.92	1.000	8.8	0.32	3.339	0.340	93.02	120.48	65.37	38.25
TOP090	2.84	1.101	9.4	0.27	2.334	0.238	47.72	65.37	28.80	13.38

From Pradel *et al.* (2005) the actual displacement is known to be 5 cm which is in the same order of magnitude as those computed for the MCN records by the California method for the highest k_y, but considerably lower than those calculated for the TOP records. So, if a displacement of 15 cm is considered to be the threshold for sliding, as proposed in the California method, then the use of this method would indicate a "landslide" at this site. The displacements calculated with the theoretical yield coefficient are lower, which indicates that the k_y-values of Pradel *et al.* (2005) are too low. For this case, the displacements from the MCN270 and MCN360 measurements are in fairly good accord with the measured 5 cm.

USGS Method: The Arias intensity and the slope yield seismic coefficients (Pradel *et al.* 2005) were used for calculating the displacements in this method. Using the different yield coefficient values together with the theoretical values calculated in the previous section, the displacements, D_n, were computed as listed in Table 3.2.

Table 3.2 Displacements from Northridge earthquake estimated by USGS method

Station	Arias Intensity	D_n (k_y = 0.037)	D_n (k_y = 0.052)	D_n (k_y = 0.026)	D_n ($k_{y,t}$ = 0.077)
MCN270	0.674 m/s	11.1 cm	5.6 cm	22.5 cm	2.6 cm
MCN360	0.751 m/s	13.1 cm	6.7 cm	26.5 cm	3.0 cm
TOP000	1.365 m/s	32.6 cm	16.5 cm	65.8 cm	7.6 cm
TOP090	0.999 m/s	20.3 cm	10.3 cm	41.0 cm	4.7 cm

The results of prediction by the USGS method are in better agreement with the observed displacements. The mean of the displacements calculated for the best estimate of yield coefficient (k_y = 0.037) is 19.3 cm which seems to indicate a too high yield coefficient, as suggested in the California-testing. However, the mean value for the displacements calculated from the theoretical yield coefficient ($k_{y,t}$ = 0.077) is 4.5 cm, which is in good agreement with the measured displacements of 5 cm.

3.2. Case 2: Debris slump caused by Suusamyr Earthquake

California Method: In August 1992 an earthquake with surface wave magnitude M_s = 7.3 took place in the Suusamyr valley, Kyrgyzstan. Havenith *et al.* (2000) studied the seismically induced surface effects with special focus on a triggered debris slump 5 km from the fault scarp and the epicentre. The displacements of the debris slump were in the order of 70 m. For this earthquake $D_{5\text{-}95}$ = 18.5 s, T_m/T_s = 0.838 and MHA = 1.37 m/s^2. Using these parameters the following were computed: MHEA = 0.827 m/s^2 and k_{max} = 0.084.

Havenith *et al.* (2000) found the yield strength by applying a constant horizontal acceleration to the slope, and iterating till the factor of safety became 1; this resulted in k_y = 0.05. The theoretical yield seismic coefficients are $k_{y,t}$ = 0.397 for the lowest ground water, and $k_{y,t}$ = 0.031 for the highest ground water level. The displacement u = 1.0 cm was calculated using k_y = 0.05. Use of the theoretical $k_{y,t}$ values gives $u \approx 0$ for low ground water and

$u = 6.0$ cm for high ground water. The displacements calculated from a theoretical yield coefficient lie over and under the displacement calculated from k_y as suggested by Havenith *et al.* so that k_y may be assumed correct. But for any of the yield coefficients the method gives a small estimation of the displacement indicating that a landslide would not have been predicted from these input data. Havenith *et al.* calculated the classical Newmark displacement to 0.06 m, which is more than the displacement calculated here for k_y, but still not enough to indicate a landslide, or anything compared to the actual 70 m displacement.

One of the reasons the California method performs poorly here is believed to be the low acceleration used in the computations. By accounting for the site response and the acceleration amplification in the soil layer one can compute larger slope displacements. The analyses indicate that by just doubling the input acceleration, the displacement increases from 1 cm – which is below any threshold of sliding – to 21 cm, which is large enough to indicate a landslide. This simple parametric study underscores the importance of making good estimates of the induced accelerations in the slope.

USGS Method: According to Havenith *et al.* (2000) the yield seismic coefficient is $k_y = 0.05$. The parameters needed for computing the displacement by this method are: magnitude of the earthquake, $M \approx M_s = 7.3$, the rupture distance $r = 5$ km, $S_C = 0$ and $S_D = 1$ for deep soil condition, and $F_N = 0$ and $F_R = 1$ for the reverse fault mechanism. This gives the Arias intensity $I_\alpha = 5.90$ m/s. Using $k_y = 0.05$ and $I_\alpha = 5.9$ m/s the slope displacement is computed to be equal to $D_n \approx 166$ cm. A calculated displacement larger than 1 m will likely induce a slide. So for this case the USGS method predicted the outfall of the earthquake correctly.

3.3. Case 3: Slope failure induced by Niigata-Ken Chuetsu earthquake

California Method: On October 23, 2004, a Magnitude $M = 6.8$ earthquake struck the southern part of Niigata region, Japan. Two aftershocks with $M = 6.0$ and $M = 6.5$ followed in less than an hour. Three days earlier Typhoon No. 23 had given the area heavy rain, and consequently more than 3,000 landslides were triggered in the areas around the epicentres (Onoue *et al.,* 2006; Tsukamoto *et al.,* 2006; Toyota *et al.,* 2006). Many natural slopes failed along the Shimano river, amongst them was the Yokowatashi landslide (Onoue *et al.,* 2006). The distance of the Yokowatashi slope from the main epicentre is approximately $r = 10$ km (r_{fault} assumed the same). The slide happened on a slope with an average angle $\beta = 22^\circ$. When the Niigata earthquake struck, a 2.5- 4 m deep block of saturated soil was loosened and slid 72 m west towards the river. The failure occurred in a 5-10 mm thick seam of tuff sand with an internal friction angle $\varphi = 31°$, cohesion $c = 23.8$ kN/m^2 and unit weight $\gamma = 18$ kN/m^3. The information from the slide was implemented in the California method to estimate a block displacement.

Assuming ground water level at the surface, the factor of safety and the yield seismic coefficient were calculated equal to 1.75 and 0.28, respectively. The ratio T_s/T_m was equal to 0.102; however, according to the California method this ratio should be taken at least equal to 0.5. To compute the maximum equivalent acceleration, MHEA, and the slide displacement, a shear wave velocity $V_s = 275$ m/s (USGS, 2007) was used. The displacements computed for the two different measured accelerations are listed in Table 3.3.

Table 3.3 Earthquake data (Onue *et al.*, 2006) and calculated MHEA and displacements u

Measuring direction	MHA$_r$	MHEA	u
EW	7.3 m/s^2	5.38 m/s^2	8.3 cm
NS	10.8 m/s^2	7.77 m/s^2	41.7 cm

Compared to the actual sliding displacement of 72 m, the calculated displacements are very small. But the displacement caused by the north-south acceleration might be enough to trigger a landslide. It is interesting to note that the maximum equivalent horizontal acceleration, MHEA, is less than the real peak accelerations. If the real value of T_s/T_m had been used instead of 0.5, MHEA would have been greater and the displacements would have become approximately 500 cm and 1000 cm, respectively. With these values it would be easier to argue for the satisfactory performance of the California method.

USGS Method: The Arias intensity was calculated as a function of soil type, fault type, magnitude and site-source distance. Shallow, stiff soil gives $S_C = 1$ and $S_D = 0$, and the reverse fault of the Niigata earthquake gives $F_N = 0$ and $F_R = 1$ (NIED, 2007). With moment magnitude $M = 6.8$ and site-source distance $r = 10$ km, the Arias intensity was found equal to $I_a = 1.56$ m/s. With the same safety factor used in the California method, i.e. $FS_{static}= 1.75$, the displacement was calculated as $D_n = 0.71$ cm which is far too little to induce a landslide.

3.4. Case 4: Landslide movement during Coyote Lake Earthquake

California Method: The Coyote Lake, California, earthquake struck with a local magnitude $M_L = 5.7$ ($\approx M = 5.7$) on 6 August 1979 (Wilson and Keefer, 1983). A fissure opened in a pre-existing slump 9 km north-east of the epicentre and $r_{fault} = 0.1$ km from the fault. The fissure had an 18 mm horizontal and 9 mm vertical offset. The slope material was weak shale of the Berryessa formation, fissile and with close joints. The material parameter were estimated as $\varphi= 25°$ and $c = 14.4$ kPa. Wilson and Keefer (1983) used STABR program to find the factor of safety FS = 1.492, and a yield seismic coefficient $k_y = 0.22$. The slide movement was rotational with an approximate depth $H = 10$ m. With an assumed shear wave velocity $V_s = 360$ m/s (CGS website, 2007) one obtains $T_s/T_m = 0.5$ and $D_{5\text{-}95} = 4.6$ s. The calculated MHEA and the displacement are summarized in Table 3.4. From this table it is seen that the Gilroy #6 acceleration record gives about 13 mm displacement, which is in fairly good agreement with the observed horizontal displacement of 18 mm.

Table 3.4 MHEA values and displacements for different acceleration measures

Measuring station	MHA_r	NRF	MHEA	*u (cm)*
Gilroy #6	4.12 m/s	0.984	3.74 m/s^2	1.28
Coyote Creek	2.26 m/s^2	1.167	247 m/s^2	0.07

USGS Method: For applying the USGS method the soil type was considered as rock, which gives $S_C = 0$ and $S_D = 0$,. Furthermore, the fault was a strike slip type resulting in $F_N = 0$ and $F_R = 0$. Using $r_{fault} = 0.1$ km and $M = 5.7$, the Arias intensity was calculated as $I_a = 0.254$ m/s (Travasarou *et al.*, 2003). With the yield coefficient $k_y = 0.22$ the displacement was found to be $D_n = 0.073$ cm which compared to the measured displacement of 18 mm is too small.

4. COMPARISON AND CONCLUSION FROM CASE HISTORIES

The various parameters derived using the California and USGS methods for the case histories studies in the previous sections are summarized in Table 4.1. The table shows that the California method is sensitive to the changes in the peak ground acceleration, but the variation of results for the four cases are not consistent enough to indicate for which combination of parameters the California method yields unrealistic results. The displacement values calculated by the USGS method are affected by both the yield coefficient and the earthquake magnitude. Table 4.1 shows that for cases 3 and 4 the USGS method gives unrealistic results for too high yield coefficients and for too low magnitudes. It is also important to note that the displacement equation proposed in the USGS method uses the Arias intensity, which for Cases 2-4 has been estimated empirically. Using the empirically estimated Arias intensity for Case 1, where the intensities are known, one computes lower values than the ones stated; this in turn leads to lower displacements. This could also be a reason for the low displacement values in Cases 3 and 4. Although it is difficult to draw a definite conclusion on the basis of these four case histories, it appears from the computed values that the USGS method (Jibson *et al.,* 1998) together with the empirical Arias intensity according to Travasarou *et al.*, (2003) is more appropriate for the cases with low to medium yield seismic coefficients ($k_y < 0.2$) and strong and larger magnitudes ($M \geq 6$).

This does not authenticate USGS method or discredit the California method, rather provides an incentive for more studies of case histories. As the USGS method demands less input parameters than the California method, the USGS method was used in the comparison with historical data of landslide in the following.

Table 4.1 Comparison of important parameters for Cases 1-4

	k_y	MHA$_r/g$	M	r (km)	Obs. Disp.	Comp. Disp. (cm)
Case 1	L, 0.077	M, 0.3	S, 6.7	23	5 cm	Cal: 15, USGS: 4.5
Case 2	L, 0.05	L, 0.14	Ma, 7.3	5	20 m	Cal: 1, USGS: 166
Case 3	H, 0.28	H, 1.1	S, 6.8	10	72 m	Cal: 42, USGS: 0.7
Case 4	H, 0.22	M, 0.4	Mo, 5.7	9	1.8 cm	Cal: 1.3, USGS: 0.03

L-Low, M-Medium, H-High, S-Strong, Ma-Major, Mo-Moderate, Cal-California

5. COMPARISON OF USGS METHOD WITH HISTORICAL DATA

It is instructive to investigate whether or not the displacement calculations by the USGS method concur with historical landslides caused by earthquakes. Much information on historical landslides has been compiled by Keefer (1984, 2002) and Rodríguez *et al.*, (1999). The data has been used to establish a limiting value/curve for landslides induced by earthquakes. This has, among others, been implemented by relating the maximum distance from epicentre that a landslide has been observed, r_{max}, to the earthquake magnitude, M. The outer boundaries of landslide occurrences are often called Keefer envelopes (1984). The historical data contains no site-specific information; however, by calculating the displacement proposed by Jibson *et al.*, (1998) as a function of magnitude and epicentral distance (which affects the Arias intensity) one may investigate whether USGS method for extreme conditions conforms to the historical data represented by the Keefer envelope. This can be done for the magnitude range $4.7 \leq M \leq 7.6$ and, assuming $r_{fault} = r$, for the site-source distance $0.1 \leq r \leq 250$ km. One may set a threshold displacement, for example 15 cm as proposed in the California method, to indicate initiation of landslide. For a fixed yield coefficient and D_n = 15 cm the M-r-curve can be plotted as a function of other parameters. If this curve lies above the upper boundary of Keefer (1984) and Rodríguez *et al.* (1999), one might conclude that the method by Jibson *et al.*, (1998) overestimates landslide occurrence since no landslides has been observed outside this boundary. If on the other hand, the computed M-r-curve lies below the boundary, then one could conclude that the USGS method is in accordance with the historical landslide data. Different input parameters were tried in the following to see how the M-r-curve by the USGS method correlates with historical data. Because of missing site information, the displacement has to be calculated for different variations of input parameters. In the following calculations these parameters were kept constant: Depth to the sliding layer, $H = 2$ m; ground water at surface; internal friction angle, $\varphi = 0$ (undrained behaviour); soil unit weight, $\gamma = 20$ kN/m^3; the soil type parameters for shallow stiff soil, $S_C = 1$ and $S_D = 0$, and the fault type parameters for normal faults, $F_N = 1$ and $F_R = 0$ (Travasarou *et al.*, 2003). The slope angle, β, and the cohesion (shear strength), c, were varied to give a range of displacements. The static factor of safety must be greater than 1; therefore, the soil strength and slope parameters were chosen such as to give a safety factor between 1 and 2.

A case for a slope with factor of safety 1.1 (for instance for the combination c = 20 kPa and $\beta = 35^{\circ}$) was considered. Fig 5.1 displays the contour lines of permanent displacement predicted by the USGS method as a function of magnitude and site-source distance together with the Keefer envelope. This figure show that for the selected set of soil/slope parameters not even the curve for 1 cm displacement is close to the Keefer envelope. If on the other hand, one associates landslides to the threshold displacement of D_n = 15 cm, a parametric study on the slope angle can be performed.

Figure 5.2 shows the influence of slope angle on the landslide M-r curve for a soil strength, c = 20 kN/m^3. The slope angle was varied between 27° to 44°. As this figure shows an increase in slope angle brings the M-r-curve closer to the Keefer envelope. A decrease in the soil strength c would also give this effect, as the safety factor decreases. As seen in Fig 5.2, the displacement increases steeply when the slope angle rises above 40°, but still the Keefer envelope is only intersected by the M-r-curve for 44° for a 15 cm displacement.

To estimate the displacement induced in the most critical slopes, a constant factor of safety FS = 1.01 was chosen. The background for this choice is that the induced displacement depends on the yield seismic coefficient (which in turn depends on *FS* and the slope angle *β*), the earthquake magnitude and the site-source distance. The M-r curves have been plotted in Fig 5.3 for the following two combinations of slope angle, *β,* and soil strength, *c*: [5°, 3.51 kPa] and [20°, 12.98 kPa].

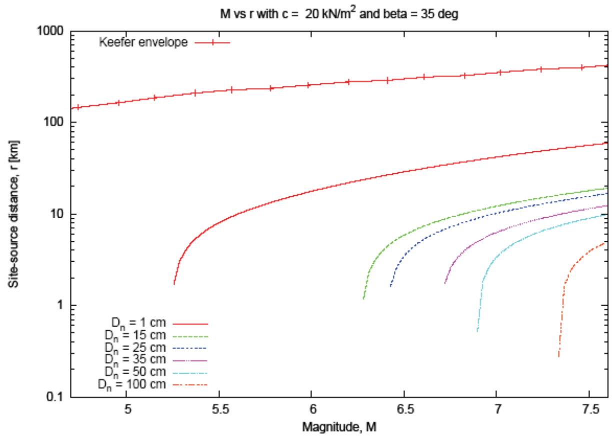

Figure 5.1 Variation of displacement, D_n, caused by earthquake with magnitude *M* at distance *r* for FS = 1.1

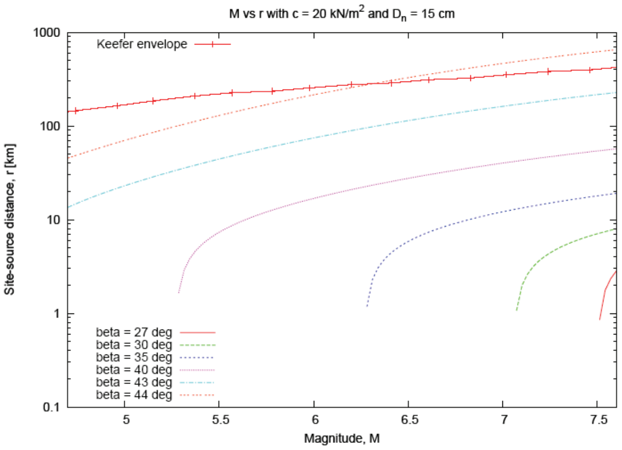

Figure 5.2 Variation of slope angle (*β*), earthquake magnitude, *M*, and *r*, for D_n = 15 cm and c = 20 kPa

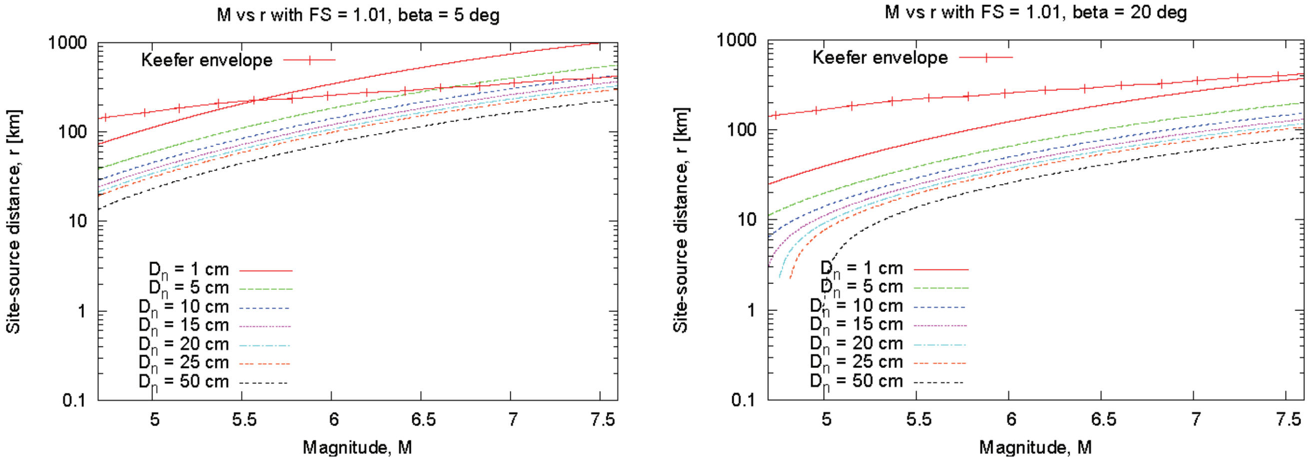

Figure 5.3 M-r-curves with FS = 1.01: $\beta = 5^\circ$ and *c*=3.51 kPa (left), $\beta = 20^\circ$ and *c*= 12.98 kPa (right)

The curves for slopes with *FS* = 1.01 (Fig 5.3) show that the permanent displacement for a slope with a fixed safety factor actually decreases for increased slope angle. The reason for this is that the horizontal force from an earthquake gives less thrust downslope in steeper slopes. This means that the soil strength itself it not of such importance, but it depends which slope angle it is combined with to give a low yield coefficient. The worst case is for low safety factor and low slope angle.

In conclusion, the USGS empirical method gives a smaller distance between landslide location and epicentre than the historical data of Keefer (1984) and Rodríguez *et al.,* (1999). Only for slopes with very low safety factors or slopes with low safety factors and low slope angles do the M-r-curves for 15 cm displacement actually reach the Keefer envelope. In an assessment of empirical models, such as USGS or California method, one should note that empirical models are mostly based on translational slope failure, while the historical database is compiled of all types of landslides; this would increase the gap between the historical data and empirical models. Despite all these limitations, the results presented in the preceding sections demonstrate that the empirical methods studied here, namely, USGS and California methods, are useful tools for predicting landslides and mapping of landslide-prone areas.

7. ACKNOWLEDGEMENT

This study was partly supported by the European Commission through the Specific Targeted Research Project SAFER *Seismic Early Warning for Europe*, under Contact 036935, Sustainable Development, Global Change and Ecosystems, in the 6th Framework Program.

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