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ADOBE-TYPE DWELLINGS: A METHOD TO OPTIMIZE THEIR REPLACEMENT

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SUMMARY

Empirical relationships between ground shaking, collapse of adobe dwellings and associated deaths are used with a seismic hazard algorithm to develop probabilistic estimates of the percentage of adobe structures that are expected to collapse and the related loss of life for a given characterization of the seismicity and housing inventory of a region. The methodology provides a basis for ranking earthquake preparedness and home renovation programs.

INTRODUCTION

The data from the 1950 census of the Americas shows that masonry, including adobe in its various forms, is the most common wall material used in Central and South America (ref. 1). There are various types of masonry used in wall construction: sun-dried mud, plain or reinforced with straw, branches or twigs; bamboo and similar fibers lashed together and covered with earth; and baked bricks and/or concrete blocks. Adobe walls have proved to be a highly efficient and durable means to support vertical loads. However, the ability of adobe walls to carry horizontal loads is quite low. For example, the collapse of adobe dwellings during two major earthquakes (Managua, 1972; Guatemala, 1976) caused over 30,000 deaths (refs. 5 and 9).

Reports of damage and loss of life from six earthquakes were reviewed to establish empirical correlations between the amplitude of ground motion and adobe collapse, and between adobe collapse and the number of fatalities. These correlations were then used with a seismic hazard algorithm to develop probabilistic estimates of adobe collapse and associated fatalities. These probabilities can be used in conjunction with housing inventory data to optimize housing replacement efforts.

REGRESSION ANALYSIS

Statistical data pertaining to eight areas during six study earthquakes are summarized in Table 1. Three parameters are used in the empirical correlations: ground motion parameter, damage ratio, and fatality ratio. These parameters are defined below:

Ground Motion Parameter (GMP, in g): Spectral acceleration at a structural period of 0.15 sec (5 percent critical damping), multiplied by a factor reflecting the influence of earthquake duration (ref. 12) The duration factor is shown in Figure 1. When response spectra are not available, the spectral acceleration at T=0.15 sec is assumed to be 2.3 times the peak ground acceleration, which is the average spectral acceleration for foundation conditions varying between stiff and deep soil deposits (refs. 12 and 13).

Damage Ratio (DR): Number of collapsed or demolished adobe dwellings divided by the total number of buildings of adobe construction within a given area.

Fatality Ratio (FR): Number of deaths due to adobe collapse divided by the total number of people living in adobe dwellings within a given area.

In this limited data set, general trends may be seen between GMP and DR, and between DR and FR (Figures 2 and 3). The data are insufficient to provide an indication of the validity of the duration factor, or of the influence that the hour at which the earthquake occurs has on the number of fatalities.

The relation betweeen GMP and DR is shown in Figure 2. The selection of the functional form used in the regression analysis considered two properties of the data. First, the DR should asymptotically approach unity as the GMP increases without limit. Second, as shown in Figure 2, there is no damage for small GMP values. To reflect these two features a two piece algebraic form was used

$$DR(GMP) = \begin{cases} 1 - \exp[a(GMP-b)] & \text{for } GMP > b, \\ 0 & \text{for } GMP \leq b. \end{cases} \quad (1)$$

where a and b are constants to be determined in the regression analysis. The least-squares fit gives $a = -3.77 \pm 0.79$ and $b=0.25 \pm 0.02$. The standard error of a single observation is 0.14.

For the FR/DR relation, a log model was used. The correlation between log FR and DR is approximately linear once data points representing no fatalities are removed (Figure 3). This winnowing of the data removes the 1974 Lima and 1977 Cancete aftershocks. In addition, the 1985 Michoacan earthquake is not used because fatalities associated specifically with adobe collapse are not available. The least-squares fit of the remaining data is given by

$$\log_{10} FR(DR) = -4.825 + 3.755\, DR \quad (2)$$

with a standard error of 0.88. This curve is shown in Figure 3.

HAZARD ALGORITHM

Cornell (ref. 14) and McGuire (refs. 15 and 16) present summaries of early work and general procedures for the evaluation of earthquake hazard. Many different formulations of this problem are possible, but all depend in part on the calculation of the number of times per year that a given ground motion parameter (in this case, the 0.15 second spectral acceleration modified to account for duration) is equalled or exceeded at the sites of interest assuming some model for earthquake sources (for example, one or more active faults), the relative frequency of occurrence of earthquakes with different magnitudes, and the rate of attenuation of the ground motion parameter with distance for a given magnitude earthquake.

In this study, the simple case of the hazard from a single large fault of length L with upper and lower magnitude bounds of M_u and M_l was considered. The expected annual number of exceedances of a given GMP at the site is

$$N(GMP) = \bar{n}_{M_l} \int_X \int_L \int_{M_l}^{M_u} P(gmp>GMP \mid m, l, x)\ f_M(m)\, f_L(l)\, f_X(x)\, dm\, dl\, dx \quad (3)$$

where $\bar{n}_{M_l}$ is the expected annual number of earthquakes of magnitude M_l or greater along the fault, x indicates rupture location on the fault, l is rupture length for magnitude m, P is the probability that the site ground motion parameter, gmp, will exceed some specified value, GMP, given an earthquake of magnitude m and rupture length l centered at location x on the fault. The three terms f_M, f_L, and f_X are probability density functions for earthquake magnitude, fault rupture length, and hypocenter location, respectively.

In this study, the hazard algorithm was extended to find the expected annual number of exceedances of damage ratio DR given N(GMP) and the expected annual number of exceedances of fatality ratio FR given N(DR). Because N(FR) depends only on N(DR) in the formulation, in analogy with equation (3)

$$N(DR) = \int_{GMP} P(dr>DR \mid GMP) \frac{d\,(1-N(GMP))}{dGMP} \, dGMP \qquad (4)$$

and

$$N(FR) = \int_{DR} P(fr>FR \mid DR) \frac{d(1-N(DR))}{dDR} \, dDR\,. \qquad (5)$$

Because methods to calculate N(GMP) are well known, the problem is solved by finding expressions for P(dr>DR | GMP) and P(fr>FR | DR). The mean values for these probabilities are given by equations (1) and (2). The least-squares fitting procedure used in the derivation of equations (1) and (2) assumes that the data are normally distributed. However, both DR and FR are restricted to the interval [0,1] so that the normal distribution must be truncated and renormalized. A beta distribution is more appropriate for this type of restricted data, but for the limited data used in this study, the truncated normal distribution is adequate. With this assumption, the probabilities P(dr>DR | GMP) and P(fr>FR | DR) can be computed and equations (4) and (5) can be evaluated.

The average annual fatality ratio, $\overline{FR}$, is given by

$$\overline{FR} = \int_0^{\infty} \frac{d(1-N(FR))}{dFR} \, FR \, dFR \qquad (6)$$

A similar equation gives the average annual damage ratio.

EXAMPLE

To demonstrate the method, eight scenarios are considered to evaluate the effect of distance, site geology, and dwelling density on damage and fatality hazard from earthquakes. Two site distances are considered: 0 km and 50 km from the center of a fault. At each site distance, rock and deep cohesionless soil site geologies are considered (ref. 12). Finally, for each distance/geology condition, low and high dwelling densities are considered. These eight scenarios are shown in Figure 4. A comparison of the results for these eight scenarios is made following a discussion of the hazard calculations.

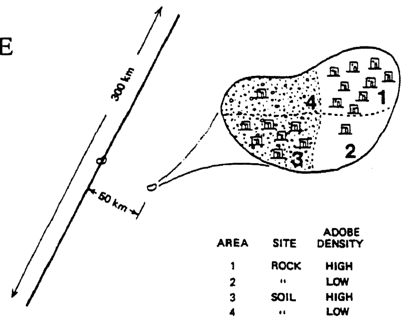

Fig. 4. Scenarios used in sample calculations.

Seismic Model

The hypothetical fault considered in this example is 300 km long with seismicity parameters appropriate for Central America. Upper and lower bound magnitudes of 5.0 and 8.0, respectively, are used. The activity rate, $\bar{n}_{Ml}$, is taken as 0.034, and the magnitude density function, f_m, is modelled by the standard Gutenberg-Richter model with a b-value of 0.43. The hypocenters are distributed uniformly along the length of the fault at zero depth, leading to f_X=1/300 km^{-1}. The rupture length-magnitude relation and its density function, f_L, are modelled by the Bonilla and others (ref. 17) relation for strike-slip events.

Attenuation

The attenuation relation for spectral response on rock at 0.15 sec given by Joyner and Boore (ref. 18) is used. The predicted rock spectral acceleration is modified for the duration and soil effects following Seed and Idriss (ref. 12). These relations are used to compute the probability of exceedance of the ground motion parameter, P(gmp>GMP | m, l, x).

Results

The GMP, DR, and FR hazard curves for the four distance and site geology combinations are shown in Figures 5-7 for this example. The average damage ratios and fatality ratios for the four cases are listed in Table 2.

The average annual number of fatalities per 10,000 people is found by scaling the average fatality ratio by the adobe dwelling density. The annual fatalities for the eight scenarios are listed in Table 3.

CONCLUSIONS

The example shown in the paper indicates that the derived ground motion/collapse and collapse/fatality relationships, when used with a dwelling inventory and a seismicity model, provide a basis for ranking earthquake preparedness and home renovation programs at local and regional levels. For the assumptions used in the example calculations, foundation condition has little effect for shaking damage, and hazard scales linearly with adobe structure density. Distance from the seismic source is an important contributor to optimal mitigation schemes.

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Table 1. Earthquake, Collapse, and Fatality Data

Earthquake Name	Date	Hour (local)	Mag	Locality	GMP[1] (g)	DR[2] (%)	FR[3] (%)	Ref.
San Juan	1/15/44	20:55	7.4	San Juan	0.88	80-100	17	2, 3
Managua	12/23/72	0:29	6.25	Managua	0.43	70	2-4	4, 5
Lima	10/03/74	9:00	7.5	Lima	0.50	54	0.01	6, 7
				La Molina	0.70	54		6, 7
Lima*	11/09/74	7:00	7.2	Lima	0.14	0	0	6, 7
				La Molina	0.29	0	0	6, 7
Guatemala	2/04/76	3:01	7.5	Guatemala City	0.55	75	0.38	8, 9
				Amatitlan	0.29	25	0.06	8, 9
Caucete	11/23/77	6:26	7.4	Caucete	0.50	72	0.30	10
				San Juan	0.25	5	0	10
Caucete*	12/06/77	14:05	5.9	Caucete	0.05	0	0	10
				San Juan	0.02	0	0	10
Michoacan	9/19/85	7:17	8.1	Mexico City	0.30	2	?	11

* Aftershock
1 Ground Motion Parameter
2 Damage Ratio
3 Fatality Ratio

Table 2. Average Annual Damage Ratios and Fatality Ratios for the Example Problem

Distance (km)	Site Geology	DR (%)	FR (%)
0	rock	0.39	0.014
0	soil	0.36	0.013
50	rock	0.048	0.00074
50	soil	0.050	0.00066

Table 3. Average Fatalities per 10,000 people for the Fatality Ratios of Table 2

Distance (km)	Site Geology	Adobe Dwelling Density	Annual	100 years
0	rock	20%	0.28	28
0	soil	20%	0.26	26
50	rock	20%	0.015	1
50	soil	20%	0.013	1
0	rock	80%	1.12	112
0	soil	80%	1.04	104
50	rock	80%	0.060	6
50	soil	80%	0.052	5

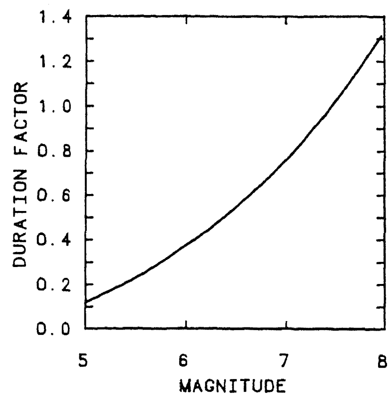

Fig. 1. Factor for duration effect. (from Seed and Idriss, ref 12)

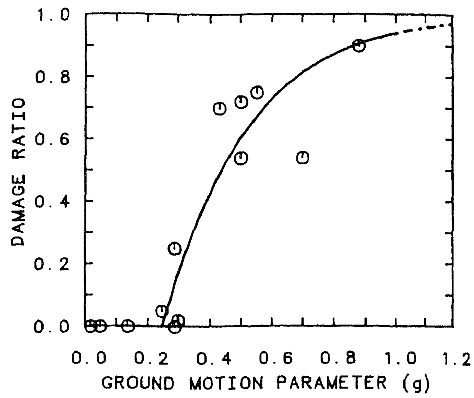

Fig. 2. Damage ratio data and empirical fit (Equation 1).

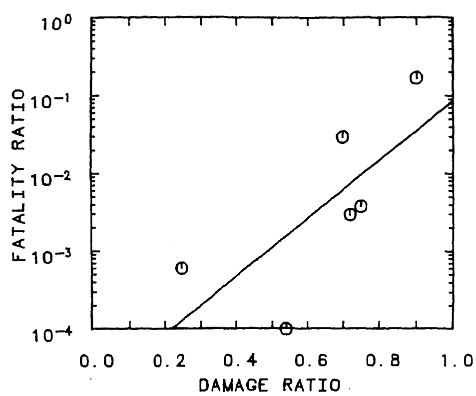

Fig. 3. Fatality ratio data and empirical fit (Equation 2).

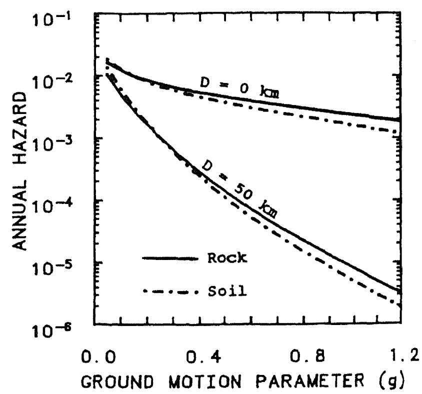

Fig. 5. Ground motion parameter hazards for the example discussed in the text.

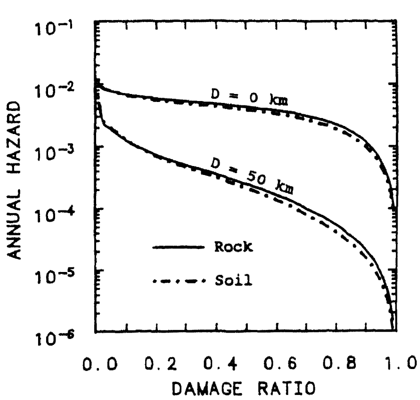

Fig. 6. Example damage ratio hazards.

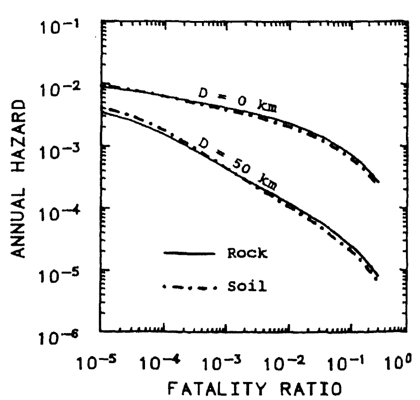

Fig. 7. Example fatality ratio hazards.