TECHNICAL NOTE

Value of Injuries in the Northridge Earthquake

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The economic equivalent value of deaths and injuries in the 1994 Northridge earthquake has not previously been calculated, although number of injuries by category of treatment has. Using dollar-equivalent values for injuries accepted and used by the U.S. government for evaluating the cost-effectiveness of risk-mitigation efforts, the value of injuries in the 1994 Northridge earthquake is estimated to be $1.3 to 2.2 billion in 1994 (90% confidence bounds, equivalent to $1.8 to 2.9 billion in 2005). This is equivalent to 3–4% of the estimated $50 billion (in 1994) estimated direct capital losses and direct business interruption losses. If injuries in the 1994 Northridge earthquake are representative of injuries in future U.S. events, then the economic value of future earthquake injuries—the amount that the U.S. government would deem appropriate to expend to prevent all such injuries—is on the order of $200 million per year (in 2005 constant dollars). Of this figure, 96% is associated with nonfatal injuries, an issue overlooked by current experimental research. Given the apparently high cost of this type of loss, this appears to represent an important gap in the present earthquake research agenda. [DOI: 10.1193/1.2194529]

INTRODUCTION

California's recent earthquake history, particularly the 1994 Northridge earthquake, shows that moderate earthquakes can be costly and deadly, and that even in California, there remains substantial risk of injuries in earthquakes. To understand this risk properly, it is worthwhile to quantify past injury experience in both human and economic terms.

Injuries by treatment category. In 1998, public-health researchers at UCLA (Shoaf et al. 1998, Peek-Asa et al. 1998, Mahue-Giangreco et al. 2001) estimated the number of people injured in the 1994 Northridge earthquake. (In epidemiology, and as used here, the term "injuries" includes fatal ones). They reviewed coroner reports and hospital records to determine the number of hospitalized injuries and performed a population-based survey to estimate the number of non-hospitalized injuries. The population-based survey involved computer-assisted telephone interviews of 1,830 residents of Los Ange-

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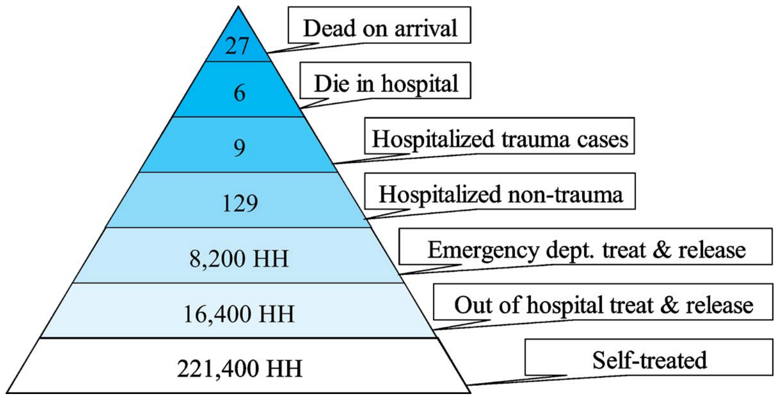

Figure 1. Northridge earthquake injuries (after Seligson and Shoaf 2003). "HH" indicates number of households in which at least one person experienced this level of injury.

les County between 6 and 24 months after the earthquake. Results are shown in Figure 1, which counts the number of injuries in terms of whether and how they were treated.

The figure of 33 deaths (the top two levels of the pyramid in Figure 1) may seem surprising, given previously reported figures such as 57 by EERI (1995). The UCLA figure only includes deaths that resulted from physical injuries directly or indirectly caused by the earthquake. Medical deaths such as heart attacks that occurred around the time of the earthquake were excluded. Furthermore, the estimated number of injuries is two to three times that reported elsewhere (OES 1994, Durkin 1995). The reason is likely related to where injured people sought care: 66% of those interviewed by UCLA were treated in clinics, private physicians' offices, the Red Cross, and elsewhere outside of hospitals, where the likelihood of being counted in official tallies was small.

Causes of injuries. As detailed in Shoaf et al. (1998), the majority of injuries were minor (cuts, bruises, and sprains) caused by nonstructural objects (55% of injuries, resulting from falling objects, pictures, lights, broken glass, etc.), followed by falls (22%) and behavior such as jumping out of a window or catching a falling television (15%). Less than 1% were associated with structural damage.

Objective: Value of injuries. Given these improvements in quantifying the number and causes of earthquake injuries in the 1994 Northridge earthquake, this paper addresses the question of their economic value. While it is problematic to assign a dollar value to human lives and nonfatal injuries, government entities and others do so frequently, and for good reason: to allocate limited resources in a consistent, cost-effective manner. The U.S. government has required for at least a decade that regulatory and other actions be deemed cost-effective before they are funded (e.g., Clinton 1993, 1994; U.S. Department of Transportation n.d.).

VALUE OF INJURIES

There are a number of methodologies for estimating the cost of injuries. The U.S. Department of Transportation assigned dollar values to statistical injuries avoided, based on a study by the Urban Institute (1991). (The phrase “statistical injuries” is used here to indicate that these are not injuries to particular people in an immediate situation, but rather to unknown people at an unknown future date.) These values are used to estimate the benefits of regulatory action and risk remediation, and have been used by the Federal Aviation Administration (FAA 1998) and Federal Highway Administration (FHWA 1994). The Urban Institute (1991) figures are comprehensive costs for statistical injuries, reflecting pain and lost quality of life, medical and legal costs, lost earnings, lost household production, etc. The comprehensive cost is dominated by pain and lost quality of life, which represent 60–80% of the total. Lost wages represent 5–18%, while medical costs represent a relatively small portion of the comprehensive cost, typically 5–6%.

These values can be controversial, so some discussion is warranted. The Urban Institute’s (1991) comprehensive costs were not limited to highway safety. They were averaged from 49 distinct studies of the value of small changes in safety, of which only 11 had to do with automobiles. They included 30 studies of the additional wages that people demand to accept elevated safety risks; 5 of the market prices for products that provide additional safety (e.g., safer cars, smoke detectors, houses in less polluted areas); 6 of the cost of safety behavior (e.g., roadway speed choice and decisions about smoking); and eight surveys (e.g., about auto safety and fire safety).

The 49 studies produced fairly consistent values. They ranged from $1.0 to 3.6 million for the value of a statistical fatality avoided. Their average was $2.2 million; their standard deviation, $0.6 million. The Urban Institute (1991) authors addressed the value of nonfatal injuries by dividing the value of fatal risk reduction by the ratio of the years of lost life in a fatality versus the years of functional capacity at risk (meaning pain or impaired mobility, cognition, self care, and other measure of quality of life).

Again, these values are not arbitrary figures selected by a government agency or contractor. Nor are they values that people would demand to receive a known injury (“how much money would you take to receive a minor scalp laceration right now?”). Rather they are values of such an injury implied by what people have paid or demand to be paid for slight increases or decreases in life safety. For example, if people have been observed to pay $100 to decrease by 1 in 10,000 their chance of death from some particular peril, the implied value of avoiding one statistical fatality would be $100/0.0001, or $1 million.

As noted above, the U.S. government adopted such values and they are therefore used here. The dollar values to prevent statistical injuries are shown in Table 1. They are expressed in terms of the Abbreviated Injury Severity (AIS) code, a classification system developed by the Association for the Advancement of Automotive Medicine (AAAM 2001). The AIS scale is an anatomical scoring system, in that it reflects the nature of the injuries and resulting threat to life. It was originally developed for use in quantifying automobile-related injuries, but has been broadened to include other types and causes of

Table 1. Federal values of statistical deaths and injuries avoided, in 1994 US$

AIS level		Sample injuries (drawn from AAAM 2001)	Comprehensive cost (FHWA 1994)
1	Minor	Shoulder sprain, minor scalp laceration, scalp contusion	$5,000
2	Moderate	Knee sprain; scalp laceration >10 cm long and into subcutaneous tissue; head injury, unconscious <1 hr	$40,000
3	Serious	Femur fracture, open, displaced, or comminuted; head injury, 1–6 hr unconsciousness; scalp laceration, bloodloss >20% by volume	$150,000
4	Severe	Carotid artery laceration, blood loss >20% by volume; lung laceration, with blood loss >20% by volume	$490,000
5	Critical	Heart laceration, perforation; cervical spine cord laceration	$1,980,000
6	Fatal	Injuries that immediately or ultimately result in death	$2,600,000

injuries. The AIS dictionary (AAAM 2001) currently lists approximately 1,300 injuries, each with a distinct 7-digit numerical injury identifier. Table 1 shows a few example injuries from each AIS level.

The comprehensive costs shown in Table 1 are not uncertain. They are not mean values with statistical distributions, but rather discrete values chosen by the agencies of the federal government to represent the benefit associated with avoiding one such statistical injury. Note also that each AIS level 1 through 5 represents a range of injuries. Despite that, and regardless of how the reader would value any particular sample injury or how he or she imagines it would be treated, the federal government assigns it the value shown for use in benefit-cost analysis.

If one knows the number of injuries of each AIS level, it is straightforward to estimate the economic value of injuries in the Northridge earthquake by Equation 1:

$$Y = \sum_{s=1}^{6} N_s V_s \tag{1}$$

where Y denotes the total estimated value of injuries, N_s denotes the estimated number of injuries whose severity level is s, and V_s denotes the value of avoiding one statistical injury of severity s.

For the present work, Shoaf applied professional judgment as an expert in public health and earthquake injury epidemiology to relate the injury categories depicted in Figure 1 to the AIS levels of Table 1. The result is shown in Table 2. Note that there is some overlap between AIS levels for a given level of treatment, but the categories do approximately correspond to AIS levels 1 to 6 from bottom to top.

It may be tempting to ignore or discount the two bottom categories of Figure 1. Although 7% of all injuries were treated outside of emergency rooms (the category second from the bottom), this was real care for real injuries, care that must be planned for and

Table 2. Estimated value of injuries in the 1994 Northridge earthquake, in 1994 US$

Treatment	AIS	Count (N_s)	Unit cost (V_s), 1994		Total cost ($M)	
			Lower	Upper	Lower	Upper
Dead on arrival	6	27	2,600,000	2,600,000	70	70
Die in hospital	5–6	6	1,980,000	2,600,000	12	16
Hospitalized trauma cases	4–5	9	490,000	1,980,000	4	18
Hospitalized non-trauma cases	2–3	129	40,000	150,000	5	19
Emergency dept. treat & release	1–2	8,200	5,000	40,000	41	328
Out of hospital treat & release	1–2	16,400	5,000	40,000	82	656
Self treat	1	221,400	5,000	5,000	1,107	1,107
Total[1]		246,000		1994 $M:	$1,300	$2,200
				2005 $M:	$1,700	$2,900

[1] Total injuries rounded to 3 significant figures; total dollar amounts rounded to 2 significant figures

that costs time and money. And although 90% of injuries were not treated (the bottom category of Figure 1), FHWA figures and AIS definitions do not distinguish treated from untreated injuries.

Table 2 details the result of applying Equation 1 using Figure 1, Table 1, and our mapping between treatment and AIS level. Considering the uncertain mapping from treatment to AIS level, the value of injuries in the 1994 Northridge earthquake is estimated to be $1.3 to 2.2 billion in 1994, or $1.7 to 2.9 billion in 2005 (using a Consumer Price Index deflator). More precisely, U.S. government would assign a value today of approximately $1.7 to 2.9 billion to mitigation measures that would prevent all of those injuries. To put this figure in perspective, the 1994 Northridge earthquake caused documented costs of $24 billion, with perhaps an additional $30 billion in previously unreported costs, of which a total of approximately $50 billion was for direct capital losses and direct business interruption (Eguchi et al. 1998, Seligson and Eguchi 2005). The $50 billion (1994 US$) does not include the economic value of injuries. Thus the economic-equivalent value of injuries in the Northridge earthquake represents 3–4% additional human loss over the $50 billion in estimated direct-capital and business-interruption losses.

The expected annual loss due to earthquake in the United States is on the order of $4.4 billion per year for direct capital losses and business interruption (FEMA 2001). If injuries in the Northridge earthquake are representative of those in future earthquakes, then the economic value of future earthquake injuries is on the order of 3–4% of $4.4 billion in 2000 constant dollars, or approximately $200 million per year today.

Nonfatal injuries in the Northridge earthquake account for most of the total cost. The bulk of this value is attributable to AIS scores 1 and 2. Only 4% of the total amount is associated with fatalities. Thus it appears that the vast bulk of the value to be gained through casualty risk mitigation is in reducing nonfatal injuries. What is being done to address this source of risk?

INJURIES IN BUILDING CODES AND PERFORMANCE-BASED PROCEDURES

When considering earthquake injuries, performance analyses both for older and newer buildings focus on evaluating or controlling life-threatening injuries, but tend to ignore nonfatal ones. For example, *FEMA-227* (VSP Associates 1992) deals with the economic value of deaths avoided in its treatment of the costs and benefits of seismic rehabilitation of hazardous buildings, but does not consider nonfatal injuries. Vision 2000 (SEAOC 1996) does not mention injury prevention as a performance objective. *FEMA-356* (ASCE 2000), which defines whole-building performance levels in its performance-based earthquake engineering methodology, explicitly mentions (and accepts) the potential for injuries under its life-safety structural and nonstructural performance levels, but makes no mention of nonfatal injuries under the immediate occupancy, damage-control, or operational performance levels (at which levels the vast majority of injuries probably occur). The authors are aware of no laboratory research in the United States to improve our understanding of and ability to model nonfatal earthquake injuries. (For that matter, the same can be said of fatal injuries, beyond efforts to estimate collapse potential. Only a fraction of occupants in collapsed buildings are killed, and little is known about that process either.)

TREATMENT OF UNCERTAINTY

Discussion so far has treated uncertainty only briefly, and indeed some parameters of Equation 1 are known with certainty. The number of people in the top four treatment categories of Table 2 were determined by a thorough survey of hospitals, not by sampling. The values V_s for a given AIS level are accepted by agencies of the federal government and are therefore fixed. However, there are some uncertainties in the present analysis. Because a population-based survey was used to produce the estimated number of people in the last three categories of Table 2, the parameter N_s in Equation 1 is uncertain in these three cases. Because the mapping from treatment category to AIS is uncertain in five cases, the value of V_s for those five treatment levels is uncertain.

Thus eight of the values in Equation 1 are uncertain. The total value of injuries in the Northridge earthquake is therefore uncertain, but the uncertainty can be estimated. We used a quadrature method presented by Julier and Uhlmann (2002) to estimate the mean and variance of the total value of injuries. The method estimates the mean, variance, and several higher moments of a function of uncertain variables, as follows:

$$E[Y] = \sum_{i=0}^{n} f(X_i) w_i$$

$$Var[Y] = \sum_{i=0}^{n} f(X_i)^2 w_i - \left(\sum_{i=0}^{n} f(X_i) w_i \right)^2 \tag{2}$$

where

$$\begin{aligned} X_0 &= E[X] & w_0 &= k/(n+k) \\ X_i &= E[X] + (\sqrt{(n+k)P_X})_i \;\; i = 1,2 \ldots n & w_i &= w_{i+n} = 1/(2(n+k)),\;\; i = 1,2 \ldots n \\ X_{i+n} &= E[X] - (\sqrt{(n+k)P_X})_i \;\; i = 1,2 \ldots n & & \end{aligned} \tag{3}$$

and where Y is the output value of interest; X is the vector of basic uncertain input variables being sampled; $f(X)$ is the function that estimates Y; X_i is one sample of vector X; P_X is the covariance matrix of X, $(\sqrt{(n+k)P_X})_i$ is the ith column of the matrix square root of $(n+k)P_X$; n is the number of uncertain variables; and k is any real number ($k \in \mathfrak{R}$).

In the present application, Y is the value of injuries in the Northridge earthquake. Equation 1 gives the function $f(X)$. Uncertain X's are taken as (a) N_s, the number of persons each of the bottom three categories of Table 2, and (b) V_s, the value associated with the middle five treatment categories (i.e., the mapping from treatment to AIS). Thus in Equation 2, $n=8$. The value $n+k$ is set to 3, per Julier and Uhlmann (2002). The standard deviation of the number of injuries in the bottom three categories of Table 2 is taken as $N_i/\sqrt{m_i}$, where N_i represents the total estimated number of persons in treatment category i, and m_i represents the number of survey respondents in treatment category i. To calculate the standard deviation of V_s where the mapping from treatment category to AIS was uncertain, the two possible values of V_s are treated here as equally likely. Off-diagonal covariances are taken as zero (uncorrelated X's).

Using Equation 2, the expected value injuries is estimated to be \$1.8 billion in 1994, with a standard deviation of just over \$250 million, or 14% of the expected value. Thus the 90% confidence bounds (5th and 95th percentile) for the value of injuries in the 1994 Northridge earthquake are \$1.3 to \$2.2 billion in 1994, or \$1.8 to \$2.9 billion in 2005.

CONCLUSIONS

The 1994 Northridge earthquake injured approximately 246,000 people, according to recent research. Using U.S. government figures for the equivalent economic value of fatal and nonfatal injuries, one can estimate a total dollar value of these injuries to be \$1.3 to 2.2 billion in 1994 (\$1.8 to 2.9 billion in 2005), or approximately 3–4% of the estimated \$50 billion in direct capital and business-interruption losses. Of the injury cost, 96% is associated with nonfatal injuries. Less than 1% is associated with structural damage. The majority of the injury cost is associated with nonstructural damage. This is an issue largely ignored by code writers and other officials. The implication is that earthquake-induced nonfatal injuries in the United States are worthy of substantial research and mitigation.

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