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Landslide risk in the San Francisco Bay region

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ABSTRACT: We have used historical records of damaging landslides triggered by rainstorms, and a newly developed Probabilistic Landslide Assessment Cost Estimation System (PLACES), to estimate the numbers and direct costs of future landslides in the San Francisco Bay region. The estimated annual cost of future landslides in the entire region is about US $15 million (year 2000 $). The estimated annual cost is highest for San Mateo County ($3.32 million) and lowest for Solano County ($0.18 million). Normalizing costs by dividing by the percentage of land area with slopes equal or greater than about 10° indicates that San Francisco County will have the highest cost per square km ($7,400), whereas Santa Clara County will have the lowest cost per square km ($230). These results indicate that the San Francisco Bay region has one of the highest levels of landslide risk in the United States. Compared to landslide cost estimates from the rest of the world, the risk level in the Bay region seems high, but not exceptionally high.

1 INTRODUCTION

Landslides triggered by rainstorms occur nearly every year in the San Francisco Bay region. Most landslides occur during the late fall through early spring seasons, typically between December and April. During the fall-through-spring rainy seasons of 1968–69, 1972–73, 1981–82, and 1997–98, landslides were widespread and caused extensive damage to both public and private property (Figure 1). Following these years, the US Geological Survey (USGS) mapped the locations of landslides that caused damage (Figure 2), and compiled the direct costs of damage to public and private property (Taylor and Brabb, 1972; Taylor et al. 1975; La Vopa-Creasy, 1988; and Godt et al. 1999). The mapping and compilation were done for 10 counties in the region: Alameda, Contra Costa, Marin, Napa, San Francisco, Santa Clara, Santa Cruz, San Mateo, Solano, and Sonoma. We have used these data (see Table 1 for a summary of number and cost data), and a newly developed Probabilistic Landslide Assessment Cost Estimation System (PLACES, Crovelli and Coe, 2008), to estimate the expected or mean number of damaging landslides in the future, as well as the estimated mean economic losses from the landslides. In this paper, we limit our estimates of future numbers and costs to mean estimates because of page-length restrictions, but these same mean estimates are part of a considerably more complex analysis done by PLACES. For example, PLACES also calculates, for any specified future time, standard deviations, prediction-interval estimates (low, high) at any specified prediction level (percentage) and exceedance probabilities at any specified exceedance level (dollars). The complete PLACES analysis of damaging landslides in the San Francisco Bay region can be found in Crovelli and Coe (2008).

Readers should be aware of two important limitations when viewing the results presented in this paper. The first limitation is that all estimates of future landslide numbers and costs must be considered minimum estimates because historical records of damaging landslides in the San Francisco Bay region are incomplete. This is true for several reasons, including a) some years between 1968 and present (September 2007) have had landslides that caused damage (for examples, see Brown, 1988) that were not recorded by the USGS, b) there were undoubtedly some landslides that caused damage during the years when records were kept (i.e., 1968–69, 1972–73, 1981–82, and 1997–98) that were missed by the various USGS compilers, and c) historical records of costs from landslides triggered by earthquakes were not included in the study. The second limitation is that PLACES does not take into account any future increases or decreases in precipitation due to changing climatic conditions; it assumes that precipitation conditions in the future will be similar to those reflected by the historical record.

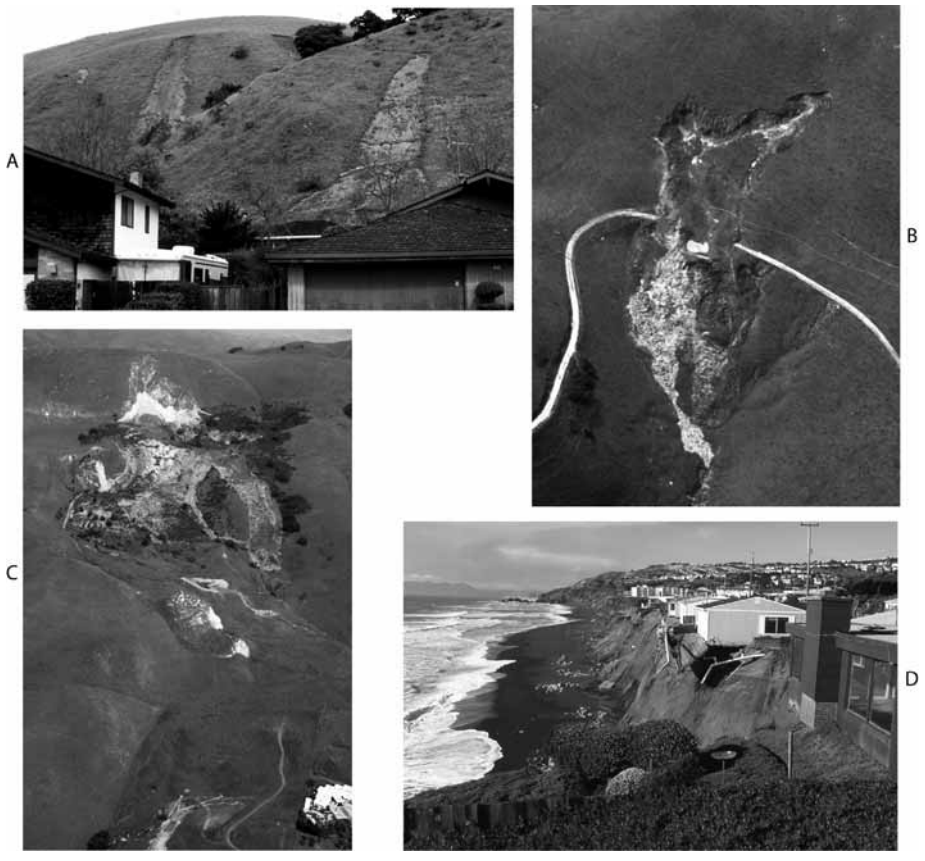

Figure 1. Examples of damaging landslides in the San Francisco Bay region from the 1997–1998 winter/spring season. A) Debris-flow scars in Alameda County. Relief visible is about 85 m. B) Earthflow in Contra Costa County. Road is about 6 m wide. C) Complex landslide at Mission Peak in Alameda County. Relief visible is about 600 m. D) Coastal bluff landslides in San Mateo County.

2 METHODS

PLACES uses conditional probability theory and laws of expectation and variance (e.g., Crovelli, 1992; Ross, 2000) to estimate numbers and costs of future damaging landslides. The total number of landslides $M(t)$ from all of years with one or more landslides during a time period of t years in each county is defined as:

$$M(t) = \sum_{i=1}^{N(t)} L_i$$

where random variable L_i is the number of landslides from the ith year with one or more landslides, and $N(t)$ is the number of years with one or more landslides that occur during a time period of t years in a particular area. The expected or mean number of future landslides $E[M(t)]$ is derived as:

$$E[M(t)] = E[N(t)]E[L]$$

where $E[N(t)]$ is the mean of $N(t)$ and E[L] is the mean of L.

The total cost of landslides $Y(t)$ from all of years with one or more landslides during a time period of t years in each county is defined as:

$$Y(t) = \sum_{i=1}^{N(t)} X_i$$

where random variable X_i is the cost of landslides from the ith year with one or more landslides. The

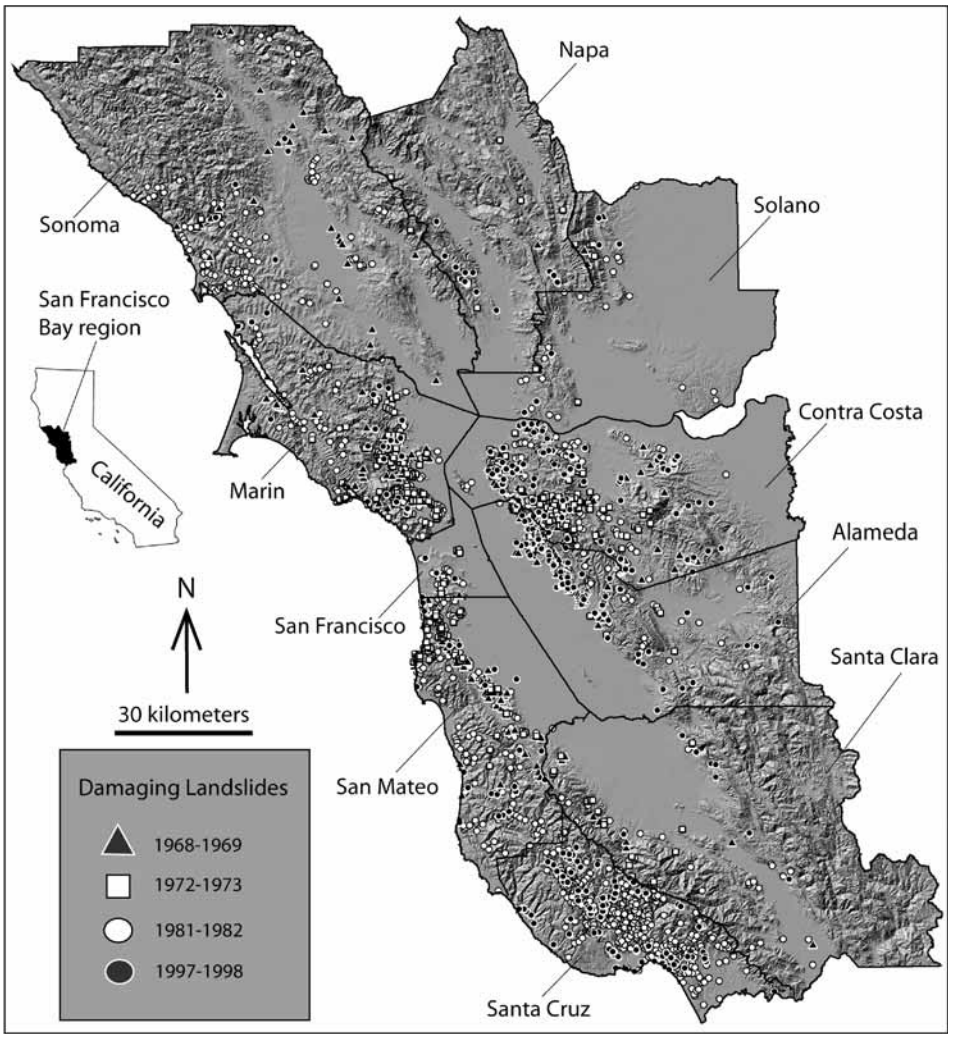

Figure 2. Map showing damaging landslides in the 10-county (see labels) San Francisco Bay region.

expected or mean cost of future landslides $E[Y(t)]$ is derived as:

$$E[Y(t)] = E[N(t)]E[X]$$

where $E[X]$ is the mean of X.

The public and private costs of landslides $Z(t)$ are fractions of the total cost of landslides. The expected or mean public or private cost of future landslides $E[Z(t)]$ is derived as:

$$E[Z(t)] = E[F]E[Y(t)]$$

where $E[F]$ is the mean of F, while random variable F is the fraction or percentage/100 of public or private costs.

Table 2 contains a listing of the mean values that are the component factors described above for each county in the San Francisco Bay region.

3 RESULTS

Results from the PLACES analysis are shown in Table 3. Santa Cruz County has the highest estimated mean number of future landslides (about 18 per year),

Table 1. Summary of recorded historical numbers and costs of landslides in San Francisco Bay region between 1968 and 2007. Length of historical record is 39 years for all counties, except Santa Cruz which is 35 years. All costs are given in August, 2000 dollars. Costs were converted to August 2000 dollars using the Consumer Price Index for shelter and guidelines described by the U.S. Department of Labor (1997). The percent change from each period to August 2000 was determined using the formula $(((CPI_{August,2000} - CPI_{previous\ period})/(CPI_{previous\ period})) * 100)$. CPI values used were 30.5 for March, 1969; 37.5 for March, 1973; 97.0 for February, 1982; and 222.9 for August, 2000. Percent change values to August 2000 were 630.8% from March 1969; 494.4% from March, 1973; 129.8% from February, 1982; and 17.8% from February, 1998. See Crovelli and Coe (2008) for a complete record of historical landslide numbers and costs including a breakdown of public and private costs.

County in the San Francisco Bay region	Total number of recorded historical damaging landslides	Total cost per of recorded historical damaging landslides (US $ millions)	Mean cost recorded historical damaging landslide (US $ millions)
Alameda	256	73.338	0.286
Contra Costa	444	95.825	0.216
Marin	442	71.347	0.161
Napa	45	15.867	0.353
San Francisco	39	9.632	0.247
San Mateo	356	129.636	0.364
Santa Clara	72	25.065	0.348
Santa Cruz	635	77.999	0.123
Solano	51	7.014	0.138
Sonoma	195	77.457	0.397
All Counties	2,535	583.180	0.230

whereas San Mateo County has the highest estimated mean cost from future landslides (about 3.3 million dollars per year). San Francisco County has the lowest estimated mean number of future landslides (about 1 per year), whereas Solano County has the lowest estimated mean cost from future landslides (about $0.18 million per year). The total estimated mean numbers and costs of future landslides for the entire region are about 67 and $15 million per year, respectively. Within the region as a whole, private and public costs from future damaging landslide are about evenly split ($7.3 million for public and $6.7 million for private, Table 3), but differences between public and private costs within individual counties are highly variable.

The land susceptible to damaging landslides in each county is variable. We estimated the susceptible land area in each county by using slope values calculated from a 30-m Digital Elevation Model and slope cutoff of 17 percent (about 10 degrees, see Table 3, column 6). Costs of future landslides were normalized by dividing by the area of each county with slopes greater or equal to 17 percent. Normalized results (Table 3, column 7) indicate that San Francisco County will have the highest cost per square km ($7,400), whereas Santa Clara County will have the lowest cost per square km ($230). At least in part, these results reflect variations in the density of development on hillslopes in each of the counties. Most hillslopes in San Francisco County are developed, whereas Santa Clara County has a large area in the eastern part of the county that is undeveloped.

4 DISCUSSION

The estimated direct mean costs from landslide damage in the Bay region as a whole are about $15 million per year (Table 3, column 2). Schuster (1996) indicates that the total losses (including both direct and indirect costs) from landslides in the US range from $1 to 2 billion (1996 $) per year. On the basis of this estimate, the estimated annual direct costs from landslides in the Bay region are a minimum of 1.2 to 0.6 percent of the US total. A comparison of the estimated annual cost of $15 million, to landslide costs in other parts of the US, indicates that the San Francisco Bay region has one of the highest levels of landslide risk in the US. For example, a recently completed study by the Oregon Department of Geology and Mineral Industries (Wang et al., 2002) indicated that losses due to landslides for the entire State of Oregon in a typical year are about $10 million, whereas the exceptional winter of 1996–97 produced landslide damages within the state that totaled about $100 million. In another recent example, the State of Utah estimated that costs from landslides in 2001 (a moderately (?) active year for landslides within the state) exceeded $3 million (Ashland, 2003), although the 1983 Thistle landslide in Utah is widely acknowledged as the most costly single landslide in North American history (Schuster, 1996), with direct costs exceeding $200 million (Ashland, 2003). In the eastern US, the metropolitan areas of Pittsburgh, Pennsylvania and Cincinnati, Ohio have historically been highly susceptible to damaging landslides (Fleming & Taylor, 1980). In Pennsylvania, Delano (2002) found that landslide costs for Allegheny County (the County including and surrounding Pittsburgh) were about $3.65 million for the two year period of 2001–2002, or about $1.8 million per year. In Ohio, Pohana (1992) suggested that landslide costs for Cincinnati between 1993 and 1997 would be $8.5 million, or about $1.7 million per year. These costs are similar to those in many of the counties in the San Francisco Bay region (see Table 3, column 3), but much less than the maximum mean estimated

Table 2. Estimated mean values used to calculate results shown in Table 3. Costs are given in year 2000 US$. In some counties, public and private costs do not sum to 100 because some costs from 1968–69 were placed in a "Miscellaneous" category (see Taylor and Brabb, 1972).

County in the San Francisco Bay region	Mean number of landslides from years with one or more damaging landslides, $E[L]$	Mean cost of landslides from years with one or more damaging landslides, US$ millions, $E[X]$	Mean number of years with one or more landslides that occur annually (i.e., $t = 1$ year), $E[N(t)]$	Mean percentage of total costs that are public, $E[F]$	Mean percentage of total costs that are private, $E[F]$
Alameda	64.00	18.335	0.103	28.109	71.622
Contra Costa	111.00	23.956	0.103	64.421	34.907
Marin	110.50	17.837	0.103	60.412	38.259
Napa	11.25	3.967	0.103	40.462	45.388
San Francisco	9.75	2.408	0.103	34.850	65.150
San Mateo	89.00	32.409	0.103	56.184	37.283
Santa Clara	18.00	6.266	0.103	68.786	20.859
Santa Cruz	317.50	39.000	0.057	34.189	65.811
Solano	12.75	1.754	0.103	92.197	7.803
Sonoma	48.75	19.364	0.103	31.824	31.390

Table 3. Estimated mean annual numbers and costs of future damaging landslides in the San Francisco Bay region. All costs are given in year 2000 US $.

County in the San Francisco Bay region	Mean number of future damaging landslides per year, $E[M(t)]$	Mean cost of future damaging landslides per year (US $ millions), $E[Y(t)]$	Mean future cost to public property per year (US $ millions), $E[Z(t)]$	Mean future cost to private property per year (US $ millions), $E[Z(t)]$	Land area (sq. km) with slopes equal or greater than 17 percent (about 10°)	Mean cost of future damaging landslides per sq. km of land with slopes equal or greater than 17 percent (US $ per sq. km)
Alameda	6.56	1.88	0.53	1.35	1,123	1,674
Contra Costa	11.39	2.46	1.58	0.86	919	2,678
Marin	11.33	1.83	1.11	0.70	902	2,029
Napa	1.15	0.41	0.17	0.19	1,594	257
San Francisco	1.00	0.25	0.09	0.16	34	7,396
San Mateo	9.13	3.32	1.87	1.24	783	4,240
Santa Clara	1.85	0.64	0.44	0.13	2,746	233
Santa Cruz	18.14	2.23	0.76	1.47	1,076	2,064
Solano	1.31	0.18	0.17	0.01	453	398
Sonoma	5.00	1.99	0.63	0.62	2,757	722
All Counties	66.86	15.18	7.34	6.73	12,385	1,226

cost of $3.3 million in San Mateo County (Table 3, column 3).

A comparison of estimated annual landslide costs in the San Francisco Bay region to those in other parts of the world, indicates that the $15 million estimated in the Bay region is high, but not exceptional. For example, Hungr (2004) indicates that the expected costs due to damaging landslide in western Canada range from $28 to $64 million (Canadian $) per year. In Hong Kong, Lam (2004) estimated that total direct costs from cyclones, rainstorms, floods, and landslides between 1994 and 2003 were about US $45 million, or about $4.5 million per year. Glade (1998) lists annual average direct costs from landslides for 15 countries, including the US. Of these 15 countries, five have annual costs less than the $15 million estimated for the Bay region.

5 CONCLUSIONS

We have used historical landslide cost data to estimate numbers and direct costs of future damaging landslides for each of the 10 counties in the San Francisco

Bay region. Future direct costs were estimated using a newly developed Probabilistic Landslide Assessment Cost Estimation System (PLACES). Santa Cruz County has the highest estimated number of annual damaging landslides (about 18), whereas Napa, San Francisco, and Solano Counties have the lowest estimated number of damaging landslides (about 1 each). Estimated direct annual costs from future landslides for the entire 10 county region are about US $15 million (year 2000 $). San Mateo County has the highest estimated costs ($3.32 million), whereas Solano County has the lowest estimated costs (about $0.18 million). Estimated direct costs are also presented in terms of public and private costs, and cost per square km of land with slopes greater than 17 percent (about 10°).

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