Landslides caused by earthquakes

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ABSTRACT

Data from 40 historical world-wide earthquakes were studied to determine the characteristics, geologic environments, and hazards of landslides caused by seismic events. This sample of 40 events was supplemented with intensity data from several hundred United States earthquakes to study relations between landslide distribution and seismic parameters. Fourteen types of landslides were identified in the earthquakes studied. The most abundant of these were rock falls, disrupted soil slides, and rock slides. The greatest losses of human life were due to rock avalanches, rapid soil flows, and rock falls. Correlations between magnitude (M) and landslide distribution show that the maximum area likely to be affected by landslides in a seismic event increases from approximately 0 at M ≃ 4.0 to 500,000 km² at M = 9.2.

Threshold magnitudes, minimum shaking intensities, and relations between M and distance from epicenter or fault rupture were used to define relative levels of shaking that trigger landslides in susceptible materials. Four types of internally disrupted landslides—rock falls, rock slides, soil falls, and disrupted soil slides—are initiated by the weakest shaking. More coherent, deeper-seated slides require stronger shaking; lateral spreads and flows require shaking that is stronger still; and the strongest shaking is probably required for very highly disrupted rock avalanches and soil avalanches.

Each type of earthquake-induced landslide occurs in a particular suite of geologic environments. These range from overhanging slopes of well-indurated rock to slopes of less than 1° underlain by soft, unconsolidated sediments. Materials most susceptible to earthquake-induced landslides include weakly cemented rocks, more-indurated rocks with prominent or pervasive discontinuities, residual and colluvial sand, volcanic soils containing sensitive clay, loess, cemented soils, granular alluvium, granular deltaic deposits, and granular man-made fill. Few earthquake-induced landslides reactivate older landslides; most are in materials that have not previously failed.

INTRODUCTION

Earthquakes have long been recognized as a major cause of landslides. Earthquake-induced landslides have been documented from at least as early as 373 or 372 B.C. (Seed, 1968) and have caused tens of thousands of deaths and billions of dollars in economic losses during the present century. In some earthquakes, landslides have denuded thousands of square kilometres.

In spite of their geomorphic and economic significance, earthquake-induced landslides are not well understood. Among the unanswered questions are: How do the number and distribution of landslides depend on earthquake magnitude, ground-shaking intensities, and other seismic parameters? What types of landslides are caused by earthquakes? Which of these types are most hazardous to human life and property? What geologic materials are most susceptible to landslides in earthquakes? Do earthquakes reactivate landslides originally triggered by nonseismic causes?

To answer these questions, I studied landslides attributable to 40 historical earthquakes chosen to sample many climatic, geologic, and seismic settings in Earth's major seismic regions. These earthquakes, which have magnitudes from 5.2 to 9.5, are listed in Table 1.[1] To study landslides in smaller events, I also examined intensity reports from several hundred United States earthquakes.

I conducted a literature search for each earthquake listed in Table 1, and a bibliography of citations to original sources has been published elsewhere (Keefer and Tannaci, 1981). In addition, I conducted field studies of earthquakes 33 to 36 and 38 to 40, and other investigators provided unpublished data for earthquakes 9, 10, 16, 18, 27, and 30.

The first section of this report discusses types and numbers of landslides caused by earthquakes. The second section presents relations between seismic parameters and landslide distribution, and the third section discusses characteristics and geologic environments of each type of landslide. The fourth section discusses landslide hazards.

TABLE 1. HISTORICAL EARTHQUAKES IN WHICH LANDSLIDES WERE STUDIED

Earthquake	Date	Magnitude	Focal depth (km)	Maximum Modified Mercalli Intensity	Fault-rupture zone definition
1. New Madrid, Missouri	16 Dec 1811	7.5*	..	X–XI	..
	23 Jan 1812	7.3*	..	IX	..
	7 Feb 1812	7.8*	..	X–XI	..
2. Charleston, South Carolina	1 Sep 1886	6.8	..	X	..
3. San Francisco, California	18 Apr 1906	7.9† (8.25–8.3)	≤20	XI	f
4. Kansu (Haiyun), China	16 Dec 1920	7.8† (8.5)	25	XI–XII§	f
5. Bihar, India-Nepal	15 Jan 1934	8.1† (8.3)	15	X	i
6. Imperial Valley, California	19 May 1940	7.1	16	X	f
7. Vancouver Island, Canada	23 Jun 1946	7.2–7.3	30	VIII	g
8. Fukui, Japan	28 Jun 1948	7.25–7.3**	14–33	IX–X§	..
9. Puget Sound, Washington	13 Apr 1949	7.0	70	VIII	..
10. Khait, U.S.S.R.	10 Jul 1949	7.6	20–28	..	..
11. Assam, India	15 Aug 1950	8.6† (8.6–8.7)	14	X	..
12. Daly City, California	22 Mar 1957	5.3††	7–11	VII	a + k
13. Southeast Alaska	10 Jul 1958	7.7† (7.9)	15	XI–XII	f
14. Hebgen Lake, Montana	18 Aug 1959	7.1**	10–12	X	f
15. Chile	22 May 1960	9.5† (8.3–8.5)	<70	XI–XII	..
16. Alaska	28 Mar 1964	9.2† (8.3–8.4)	20–50	X–XI	t
17. Niigata, Japan	16 Jun 1964	7.3	40	VIII	s
18. Puget Sound, Washington	29 Apr 1965	6.5	58–63	VII–VIII	..
19. Parkfield-Cholame, California	28 Jun 1966	6.2	4–10	VII–IX	f
20. Inangahua, New Zealand	23 May 1968	7.1	12–21	X–XI	..
21. Peru	31 May 1970	7.9† (7.8)	35–43	VIII	a
22. Madang, Papua New Guinea	31 Oct 1970	7.1	41	VIII–IX	a
23. San Fernando, California	9 Feb 1971	6.5	8–13	XI	f + a
24. Honomu, Hawaii	26 Apr 1973	6.1	41–50	VIII	..
25. Indus Kohistan, Pakistan	28 Dec 1974	6.2	12	VIII	..
26. Kilauea, Hawaii	29 Nov 1975	7.1	5	VIII	f
27. Guatemala	4 Feb 1976	7.5	5	IX	f
28. Khulm, Afghanistan	19 Mar 1976	5.5	33–77	VIII–IX	..
29. Friuli, Italy	6 May 1976	6.3–6.5	8–26	VIII–X§	a
30. Darien, Panama	11 Jul 1976	7.0	3	..	..
31. Tangshan, China	27 Jul 1976	7.5† (7.7–8.0)	12–16	XI§	f + a
32. Khurgu, Iran	21 Mar 1977	6.9	29	VIII+	..
33. San Juan Province, Argentina	23 Nov 1977	7.4	17	IX	a
34. Izu-Oshima Kinkai, Japan	14 Jan 1978	6.8	4	IX–X§	f
35. Miyagi-ken-oki, Japan	12 Jun 1978	7.4	30	VII–IX§	a
36. Santa Barbara, California	13 Aug 1978	5.6	13	VII	a
37. Homestead Valley, California	15 Mar 1979	5.2††	≤4	VI	f
38. Coyote Lake, California	6 Aug 1979	5.4	10	VII	f + a
39. Mount Diablo, California	24 Jan 1980	5.8	8	VI–VII	f
40. Mammoth Lakes, California	25 May 1980	6.1	8	VII	f

Note: date is Greenwich Mean Time; magnitude is Richter surface-wave magnitude (M_s) unless otherwise noted. Data defining fault-rupture zone: f = surface fault rupture; a = aftershock hypocenters; i = zone of maximum intensity; g = geodetic measurements; t = tectonic ground-level change; k = known fault trace; s = tsunami source area.

*M_s determined from relations between magnitude, attenuation of Modified Mercalli Intensity, and particle velocity.

†M_w determined by Kanamori (1977); M_s given in parentheses.

§Intensity converted to Modified Mercalli using relations in Medvedev (1962).

**Method of magnitude determination not reported.

††Richter local magnitude (M_L).

Additional tabular material for this article may be secured free of charge by requesting Supplementary Data 84-11 from the GSA Documents Secretary.

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TYPES AND NUMBERS OF EARTHQUAKE-INDUCED LANDSLIDES

Landslide Classification

The term "landslide" encompasses many phenomena involving lateral and downslope movement of earth materials. Numerous landslide classifications based on morphology, material, mechanism of initiation, or other criteria have been proposed. The classification of earthquake-induced landslides shown in Table 2, based on the principles and terminology of Varnes (1978), categorizes landslides primarily by material and character of movement and secondarily by such other attributes as degree of internal disruption and water content.

[1]With a few exceptions noted in Table 1, M < 7.5 are Richter surface-wave magnitudes (M_S), and M ≥ 7.5 are moment magnitudes (M_W) of Kanamori (1977).

TABLE 2. CHARACTERISTICS OF EARTHQUAKE-INDUCED LANDSLIDES

Name	Type of movement	Internal disruption*	Water content† D	U	PS	S	Velocity§	Depth**
LANDSLIDES IN ROCK								
Disrupted slides and falls								
Rock falls	Bounding, rolling, free fall	High or very high	X	X	X	X	Extremely rapid	Shallow
Rock slides	Translational sliding on basal shear surface	High	X	X	X	X	Rapid to extremely rapid	Shallow
Rock avalanches	Complex, involving sliding and/or flow, as stream of rock fragments	Very high	X	X	X	X	Extremely rapid	Deep
Coherent slides								
Rock slumps	Sliding on basal shear surface with component of headward rotation	Slight or moderate	?	X	X	X	Slow to rapid	Deep
Rock block slides	Translational sliding on basal shear surface	Slight or moderate	?	X	X	X	Slow to rapid	Deep
LANDSLIDES IN SOIL								
Disrupted slides and falls								
Soil falls	Bounding, rolling, free fall	High or very high	X	X	X	X	Extremely rapid	Shallow
Disrupted soil slides	Translational sliding on basal shear surface or zone of weakened, sensitive clay	High	X	X	X	X	Moderate to rapid	Shallow
Soil avalanches	Translational sliding with subsidiary flow	Very high	X	X	X	X	Very rapid to extremely rapid	Shallow
Coherent slides								
Soil slumps	Sliding on basal shear surface with component of headward rotation	Slight or moderate	?	X	X	X	Slow to rapid	Deep
Soil block slides	Translational sliding on basal shear surface	Slight or moderate	?	?	X	X	Slow to very rapid	Deep
Slow earth flows	Translational sliding on basal shear surface with minor internal flow	Slight			X	X	Very slow to moderate, with very rapid surges	Generally shallow, occasionally deep
Lateral spreads and flows								
Soil lateral spreads	Translation on basal zone of liquefied gravel, sand, or silt or weakened, sensitive clay	Generally moderate, occasionally slight, occasionally high			X	X	Very rapid	Variable
Rapid soil flows	Flow	Very high	?	?	?	X	Very rapid to extremely rapid	Shallow
Subaqueous landslides	Complex, generally involving lateral spreading, and/or flow; occasionally involving slumping and/or block sliding	Generally high or very high; occasionally moderate or slight			X	X	Generally rapid to extremely rapid; occasionally slow to moderate	Variable

*Internal disruption: "slight" signifies landslide consists of one or a few coherent blocks; "moderate" signifies several coherent blocks; "high" signifies numerous small blocks and individual soil grains and rock fragments; "very high" signifies nearly complete disaggregation into individual soil grains or small rock fragments.

†Water content: D = dry; U = moist but unsaturated; PS = partly saturated; S = saturated.

§Velocity:

0.6 m/yr — 1.5 m/yr — 1.5 m/mo — 1.5 m/day — 0.3 m/min — 3 m/sec

extremely slow — very slow — slow — moderate — rapid — very rapid — extremely rapid

(velocity terminology from Varnes, 1978).

**Depth: "shallow" signifies thickness generally <3 m; "deep" signifies depth generally >3 m.

Material is classified as "rock" or "soil" on the basis of its state prior to landslide initiation. "Rock" signifies firm, intact bedrock. "Soil" signifies a loose, unconsolidated, or poorly cemented aggregate of particles, which may or may not contain organic material. The term "soil" thus encompasses the entire regolith and all man-made fills. Some cemented soils form steep slopes tens of metres high, and the cemented soil-rock boundary is gradational in mechanical behavior. Varnes makes a distinction between coarse-grained soils, called "debris," and fine-grained soils, called "earth," but grain-size data are not available from enough earthquake-induced landslides to make such a differentiation here.

Movement characteristics of earthquake-induced landslides are summarized in Table 2 and discussed below under "Landslide Characteristics and Geologic Environments." Landslides are grouped by similarities in movement, internal disruption, and geologic environments into major categories of disrupted slides and falls, coherent slides, and lateral spreads and flows. In classifying earthquake-induced landslides, the term "rock avalanche" is used for the sake of brevity to be synonymous with both "rock-fall avalanche" and "rock-fall–debris flow" as defined by Varnes (1978). In addition, I grouped all subaqueous landslides together for ease in discussing their geologic environments.

Numbers of Landslides in Historical Earthquakes

For each of the 40 historical earthquakes studied (Table 1), I classified the landslides and determined the total number of each type (Table 3). Classification was made from written descriptions, photographs, and (or) field observations. Numbers of landslides were determined by direct count or by delineating areas affected by landslides and estimating the number of landslides in a unit area. I calibrated the latter estimates using field observations, measurements on aerial photographs, and detailed maps of earthquake-induced landslides in different terrains in several earthquakes. The order-of-magnitude ranges in numbers of landslides in Table 3 account for errors in these methods.

Numbers of landslides that could not be classified are also indicated in Table 3; except for earthquakes 1, 3, 7, 9, 13, 15, 16, and 18, the number of unclassified landslides is comparatively small.

The number of landslides caused by an earthquake generally increases with increasing magnitude. For example, earthquakes in Table 3 with $M < 5.5$ caused a few tens of landslides at most, whereas earthquakes with $M > 8.0$ caused several thousands at least. However, local geologic conditions and seismic parameters other than magnitude also determine the numbers of landslides triggered. Moreover, certain apparent anomalies in the trend of number of landslides increasing with magnitude are due to the inexact methods used or to incomplete geographic coverage by the data for some earthquakes. In particular, the anomalously low numbers of landslides reported in earthquakes 4, 7, 9, 10, 15, 18, and 32 are probably due to lack of observations in certain areas affected by the earthquakes.

Table 3 also shows how many pre-existing landslides were reactivated in each earthquake. Except for earthquakes 3, 23, and 29, the number of reactivations is small compared to the total number of landslides. This rarity is due in part to lack of systematic recognition of reactivations, but, even allowing for this, these data show that most earthquake-induced landslides occur in materials not previously involved in landslides. Reactivations are most likely during seismic shaking that is stronger than that causing the pre-existing landslides or during an earthquake that occurs when pre-existing landslides are marginally stable due to other causes. The latter condition explains the many reactivations in the 1906 San Francisco and 1976 Friuli, Italy, earthquakes (3 and 29 in Table 3), as both occurred during seasons of high precipitation, when reactivations in the affected regions were common under nonseismic conditions (Lawson and others, 1908; Ambraseys, 1976). The many reactivations in the 1971 San Fernando earthquake (23 in Table 3) may have been due to the exceptionally high ground acceleration in this event (Trifunac and Hudson, 1971).

To determine the relative abundance of different types of earthquake-induced landslides, the estimated numbers of each type were totaled for all 40 historical earthquakes (Table 4). In calculating the total numbers from the order-of-magnitude estimates in Table 3, a numerical rating of "1" was considered to represent 5 landslides, a rating of "2" to represent 50 landslides, and so on up to a rating of "5," considered to represent 50,000 landslides. In a similar manner, a rating of "1–2" was considered to represent $\frac{1}{2} \times (5 + 50) = 28$ landslides, a rating of "2–3" to represent $\frac{1}{2} \times (50 + 500) = 275$ landslides, and so on. The total numbers thus obtained and listed in Table 4 are also order-of-magnitude estimates.

TABLE 3. TYPES AND NUMBERS OF LANDSLIDES IN HISTORICAL EARTHQUAKES

Earthquake	Magnitude	Landslides in rock: Disrupted slides and falls: Rock falls	Rock slides	Rock avalanches	Coherent slides: Rock slumps	Rock block slides	Landslides in soil: Disrupted slides and falls: Soil falls	Disrupted soil slides	Soil avalanches	Coherent slides: Soil slumps	Soil block slides	Slow earth flows	Lateral spreads and flows: Soil lateral spreads	Rapid soil flows	Subaqueous landslides	Unclassified	Reactivations
15. Chile	9.5	··	··	··	1–2	··	1	4	4	3	1	··	2	3	2	3–4	··
16. Alaska 1964	9.2	4–5	3–4	2	··	1	··	2	2	3–4	2–3	2	4	1	3	4	2
11. Assam, India	8.6	5	5	··	··	··	··	5	··	··	··	··	3–4	··	··	··	··
5. Bihar-Nepal	8.1	3–4	··	··	1	··	··	··	··	4	4	··	4	··	··	1	··
3. San Francisco	7.9	4	4	1	3	3	3–4	3–4	··	3–4	··	1–2	3	2	··	4–5	3–4
21. Peru	7.9	4–5	4–5	1	··	··	1	4–5	··	4	4	··	2–3	1–2	··	··	··
4. Kansu, China	7.8	··	··	··	··	··	··	··	··	··	··	··	··	3	··	··	··
1. New Madrid	7.8	1	··	··	··	··	··	··	··	··	3	··	4	··	··	4	··
13. SE Alaska 1958	7.7	··	3	1	1–2	··	··	··	··	3–4	··	··	3–4	··	1–2	3	1
10. Khait, U.S.S.R.	7.6	··	··	1	··	··	··	··	··	··	··	··	··	3	··	··	··
31. Tangshan, China	7.5	··	··	··	··	··	··	··	··	3–4	··	··	3–4	1–2	··	··	··
27. Guatemala	7.5	5	··	1	2–3	1	··	5	··	··	··	··	3–4	··	1	··	1
35. Miyagi-ken-oki	7.4	3–4	3–4	··	··	··	··	··	··	3	··	··	2	1	··	··	1
33. Argentina	7.4	4	4	··	··	··	1–2	1–2	··	3–4	3–4	··	3–4	··	··	··	··
17. Niigata	7.3	3	··	··	··	··	··	··	··	3	··	··	3–4	1	··	1–2	··
8. Fukui	7.25–7.3	··	··	··	··	··	2	··	··	3	3	··	3	··	··	1	··
7. Vancouver Island	7.2–7.3	··	··	··	··	··	1	··	··	2	··	··	2	··	2	3	··
6. Imperial Valley	7.1	··	··	··	··	··	··	3	··	3	3	··	3	··	··	··	··
14. Hebgen Lake	7.1	3–4	··	1	··	··	··	··	··	1	··	1	1	··	··	··	1
20. Inangahua, N.Z.	7.1	2	2	1	1–2	1	2	1–2	··	2–3	2	··	2–3	2	··	··	1–2
22. Papua New Guinea	7.1	3	··	··	··	··	··	··	4	2–3	··	3	2	··	1	··	··
26. Hawaii 1975	7.1	3	··	··	2–3	··	··	··	··	··	··	··	··	··	··	··	··
9. Puget Sound 1949	7.0	1–2	··	··	··	··	··	··	··	1	··	··	1	··	1	2	1
30. Panama	7.0	3	3	··	··	··	3	3	3	··	··	··	··	··	··	··	··
32. Khurgu, Iran	6.9	3	3	··	··	··	··	··	··	1	··	··	··	··	··	··	··
2. Charleston	6.8	··	··	··	··	··	··	··	··	2–3	2–3	··	2–3	··	··	··	··
34. Izu-Oshima	6.8	3	3	··	··	··	··	3	··	2–3	··	··	··	2	··	··	··
18. Puget Sound 1965	6.5	··	··	··	··	··	··	··	··	1	··	··	1	··	··	2	··
23. San Fernando	6.5	3	··	··	3	2	3	3	3	3	1	··	1	1	··	··	3
29. Friuli, Italy	6.3–6.5	4	3	··	··	··	··	··	··	2	··	··	··	··	··	2	4
25. Pakistan	6.2	4	··	··	··	··	··	2	··	2	··	··	··	··	··	··	··
19. Parkfield	6.2	··	··	··	··	··	2	2	··	2	2	··	··	··	··	··	1–2
24. Hawaii 1973	6.1	··	··	··	··	··	2–3	··	··	2–3	··	··	··	··	··	··	··
40. Mammoth Lakes	6.1	4	4	1	··	··	··	··	··	··	··	··	1	··	··	··	··
39. Mount Diablo	5.8	2	··	··	··	··	1–2	··	··	2	··	1	··	··	··	··	··
36. Santa Barbara	5.6	2	2	··	··	··	1–2	··	··	1	··	··	1	··	··	··	··
28. Afghanistan	5.5	2	··	··	··	··	2	2	··	2	··	··	··	··	··	··	··
38. Coyote Lake	5.4	2	··	··	··	··	··	··	··	1	··	··	··	··	··	··	1
12. Daly City	5.3	··	··	··	··	··	··	2	··	1	··	··	··	1	··	1	1
37. Homestead Valley	5.2	1	··	··	··	··	··	··	··	1	··	··	··	··	··	··	··

Note: 1 signifies 1 to 10 landslides; 1–2 signifies 1 to 100 landslides; 2 signifies 10 to 100 landslides; 2–3 signifies 10 to 1,000 landslides; 3 signifies 100 to 1,000 landslides; 3–4 signifies 100 to 10,000 landslides; 4 signifies 1,000 to 10,000 landslides; 4–5 signifies 1,000 to 100,000 landslides; 5 signifies more than 10,000 landslides; ·· signifies no landslides of this type reported.

TABLE 4. RELATIVE ABUNDANCE OF EARTHQUAKE-INDUCED LANDSLIDES

Landslide type, listed in order of decreasing total numbers
Very abundant: >100,000 in the 40 historical earthquakes
Rock falls Disrupted soil slides Rock slides
Abundant: 10,000 to 100,000 in the 40 historical earthquakes
Soil lateral spreads Soil slumps Soil block slides Soil avalanches
Moderately common: 1,000 to 10,000 in the 40 historical earthquakes
Soil falls Rapid soil flows Rock slumps
Uncommon: 100 to 1,000 in the 40 historical earthquakes
Subaqueous landslides Slow earth flows Rock block slides Rock avalanches

Note: method of calculating total numbers of landslides explained in text.

The most abundant landslides in the 40 earthquakes were rock falls, disrupted soil slides, and rock slides; their abundance indicates both that they are especially susceptible to initiation under seismic conditions and that geologic environments that produce them are widespread in seismic regions. Subaqueous landslides, slow earth flows, rock block slides, and rock avalanches were uncommon in the 40 earthquakes (Table 4). The apparent rarity of subaqueous landslides is due in part to difficulties of observation; most reports thereof derive from shipborne geophysical surveys, submarine cable breaks, or damage to port facilities, and these data cover only a small fraction of the subaqueous environment. The reported numbers of the other uncommon types, however, are probably good approximations of their actual numbers. The rarity of these landslides indicates low susceptibility to initiation by seismic shaking, restricted distribution of environments that produce them, or both.

The relative-abundance rankings in Table 4 are dominated by the larger earthquakes. A separate determination of relative abundances in the 11 earthquakes in Table 3 with $M < 6.5$ shows that these triggered proportionally more rock falls, rock slides, and soil falls and proportionally fewer landslides of all other types. These 11 earthquakes produced no reported soil avalanches, rock slumps, or rock block slides, but intensity reports from earthquakes other than the 40 listed in Table 1 indicate that rock slumps and rock block slides were produced by some events as small as $M \approx 5.0$. No subaqueous landslides were reported in events with $M < 7.0$, but this absence of reports is probably due in part to difficulties of observation. Given that many earthquake-induced subaqueous landslides involve lateral spreading, rapid flow, or both, they probably occur in earthquakes as small as those that cause other lateral spreads and flows.

LANDSLIDE DISTRIBUTION AND SEISMIC PARAMETERS

Five measures were chosen to relate seismic parameters to landslide distribution. These measures are (1) the smallest earthquakes that cause landslides, (2) the relation between magnitude and area affected by landslides, (3) the relation between magnitude and maximum distance of landslides from the epicenter, (4) the relation between magnitude and maximum distance of landslides from the fault rupture, and (5) the minimum shaking intensity at which landslides are triggered.

For consistency in comparing earthquakes from many regions, teleseismic Richter surface-wave magnitudes (M_s) were used in these determinations wherever possible for earthquakes in Table 1 with $M < 7.5$. The four exceptions for which M_s was not reported and for which another magnitude was used are noted in Table 1. M_s values generally were not reported in the intensity data for earthquakes with $M < 5.5$, and so for correlations involving these smaller events Richter local magnitudes (M_L) were used. The M_s and M_L scales, however, saturate at large magnitudes (Kanamori, 1977; Hanks and Kanamori, 1979). To circumvent this problem, moment magnitudes (M_w) determined by Kanamori (1977) were used preferentially for earthquakes with $M \geqslant 7.5$. The M_w scale connects smoothly with the M_s scale for many earthquakes in the range of $M_s = 7.5$–8.3 (Kanamori, 1977).

The Smallest Earthquakes That Cause Landslides

To determine the smallest earthquakes that cause landslides, I examined intensity reports for United States earthquakes from 1958 to 1977 inclusive. These reports, published annually in *United States Earthquakes,*[2] were compiled primarily from newspaper articles, accounts of residents in the affected regions, and questionnaires sent to postmasters. Most reports were compiled without systematic searches for landslides and thus provide only an approximate estimate of the smallest earthquakes that cause landslides. More systematic and rigorous data, however, are not generally available for small events.

United States Earthquakes for 1958–1977 inclusive contained descriptive information and magnitude determinations for 300 earthquakes, of which 62 had $M_L < 4.0$. Only 1 report of landslides was found in the data for these 62 earthquakes, and this report, involving an event with $M_L = 3.5$, was judged of questionable validity by the compilers of *United States Earthquakes.* With this exception, the smallest earthquake reported to have caused landslides had $M_L = 4.0$. Wherever descriptions in *United States Earthquakes* were detailed enough, the landslides were classified, and these results were combined with data in Table 3 to estimate the following as the smallest earthquakes likely to cause landslides of various types: (1) $M_L \approx 4.0$: rock falls, rock slides, soil falls, and disrupted soil slides; (2) $M_L \approx 4.5$: soil slumps and soil block slides; (3) $M_L \approx 5.0$: rock slumps, rock block slides, slow earth flows, soil lateral spreads, rapid soil flows, and subaqueous landslides; (4) $M_s \approx 6.0$: rock avalanches; and (5) $M_s \approx 6.5$: soil avalanches. The estimate of $M_L \approx 5.0$ as the minimum magnitude for lateral spreads and flows is consistent with previous work suggesting $M \approx 5$ as the minimum magnitude for soil liquefaction (Kuribayashi and Tatsuoka, 1975, 1977; Youd, 1977).

In spite of the lack of reports of landslides in earthquakes smaller than these, the possibility of smaller events occasionally causing landslides

[2] *United States Earthquakes* was published before 1971 by the U.S. Department of Commerce Coast and Geodetic Survey, from 1971 to 1974 inclusive by the U.S. Department of Commerce National Oceanic and Atmospheric Administration (NOAA), and since 1974 jointly by NOAA and the U.S. Geological Survey.

cannot be discounted. All types of earthquake-induced landslides (Table 2) can also be triggered by nonseismic causes and, if failure of a slope is imminent before an earthquake, a landslide could be initiated even by weak shaking.

Two cases of possible association between landslides and small earthquakes are discussed by Mathews and McTaggart (1978) and by Voight (1978). Voight (1978) reported that an earthquake with an estimated M $\leqslant$ 3.5 shook the Gros Ventre Valley of Wyoming 18 to 20 hr before the June 23, 1925, Gros Ventre rock avalanche. Mathews and McTaggart (1978) reported that two earthquakes with M = 3.2 and 3.1 occurred within one minute of latitude and longitude (±16 km) and at approximately the same times as the two main phases of movement of the January 9, 1965, rock avalanche near Hope, British Columbia.

Evidence for seismic triggering of the Gros Ventre and Hope landslides is somewhat circumstantial—at Gros Ventre because of the long delay between the reported earthquake and the landslide and at Hope because the first seismic event could have been caused by initial rupture of the landslide shear surface (Barry Voight, 1983, written commun.) and the second by crustal loading due to the first phase of slide movement (W. G. Milne, personal commun. *in* Mathews and McTaggart, 1978). Nevertheless, the possibility exists that small earthquakes were in part responsible for the Gros Ventre and Hope landslides and that small events could also occasionally trigger other landslides from marginally stable slopes.

Magnitude and Area Affected by Landslides

For 30 of the historical earthquakes in Table 1, data were complete enough to determine the areas affected by landslides (Fig. 1). Each area was measured by drawing a boundary around all reported landslide localities and calculating the size of the region enclosed. Such areas are those where ground shaking was strong enough to trigger landslides on susceptible slopes. Not all slopes within these areas produced landslides, and zones of high landslide density were commonly interspersed with zones having few or no landslides. Most areas affected by landslides were irregular in shape and asymmetric with respect to epicenters and fault ruptures. Nevertheless, areas affected by landslides show a strong correlation with magnitude (Fig. 1).

An approximate upper-bound fit of the data in Figure 1 shows the greatest area likely to be affected by landslides in an earthquake of given magnitude. Extension of the upper bound to M < 5.3 is based on the intensity data, which suggest that few landslides are caused by events smaller than $M_L \simeq 4.0$. Landslide locations in these intensity data are not precise enough to determine the areas affected by landslides or maximum distances of landslides from epicenters or fault ruptures. However, as these data indicate a lack of landslides in events smaller than M $\simeq$ 4, the upper bound must be curved approximately as shown to approach an area value of A = 0 at M $\simeq$ 4.

Scatter in the data in Figure 1 shows that factors other than magnitude also determine the area affected by landslides. Some scatter may be due to inclusion of offshore earthquakes, because difficulties in observing underwater areas probably cause the reported areas of landslides to be smaller than they actually are. For this reason, the upper bound is curved to pass above the point for the 1964 Alaska earthquake (16 in Table 1). Except for this event and the 1978 Izu-Oshima Kinkai, Japan, earthquake (34 in Table 1), however, areas affected by landslides in the offshore earthquakes plot within the data field defined by the onshore events, indicating that scatter due to inclusion of offshore events is minor. Other factors possibly causing scatter include regional differences in seismic attenuation, uncertainties in area and magnitude determinations, seismic parameters other than magnitude, and local geologic conditions. Geologic conditions influence the area by controlling the distribution of susceptible sites, an effect most evident for small events where the area shaken is small and may contain only a few, scattered susceptible slopes.

The area affected by landslides is in part determined by the focal depth of the earthquake. In Figure 1, areas of one offshore and all onshore earthquakes with focal depths $\geqslant$ 30 km (earthquakes 7, 9, 18, 22, and 24) plot on or near the upper bound, indicating that seismic shaking strong enough to trigger landslides propagates over larger areas in these deeper events. Other seismic parameters, including the specific ground-motion characteristics of the earthquake, almost certainly influence the area affected by landslides, but these effects were not studied because few strong-motion records exist in zones of landsliding in the historical earthquakes.

The data in Figure 1 indicate that regional differences in seismic attenuation have little effect on the area of landsliding in an earthquake. Three earthquakes from the Puget Sound–Vancouver Island region (7, 9, and 18) that produced landslides over comparatively large areas (Fig. 1) were all deep. No anomalies possibly related to regional differences in attenuation are found in data from other regions represented by two or more onshore events. Of the eight onshore earthquakes from California, for example, four (23, 38, 39, and 40) caused landslides over comparatively large areas, one (3) over an area that is about average, and three (6, 12, and 19) over areas that are relatively small. Of the three Himalayan earthquakes, one (5) has an area that plots on the upper bound, one (11) on the lower margin of the data field, and one (25) near the middle of the data field. The two earthquakes in

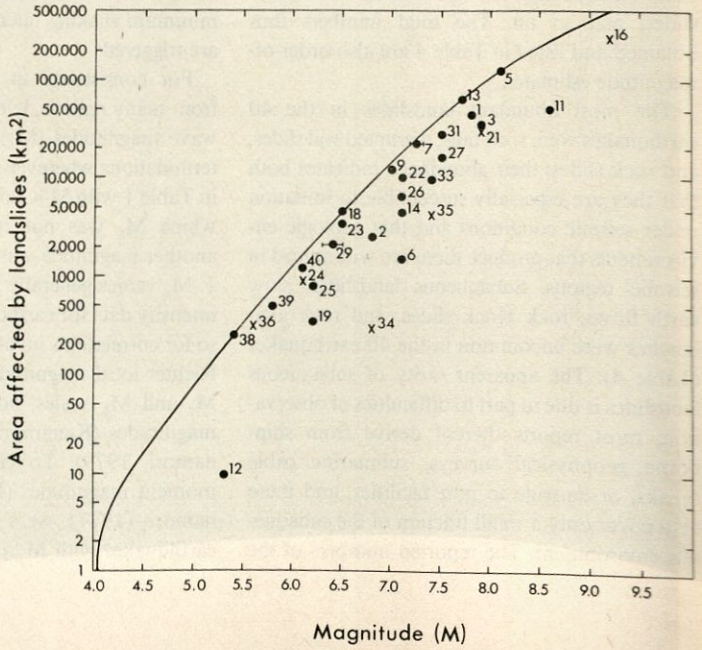

Figure 1. Area affected by landslides in earthquakes of different magnitudes. Numbers beside data points are earthquakes listed in Table 1. Dots = onshore earthquakes; x = offshore earthquakes. Horizontal bars indicate range in reported magnitudes. Solid line is approximate upper bound enclosing all data.

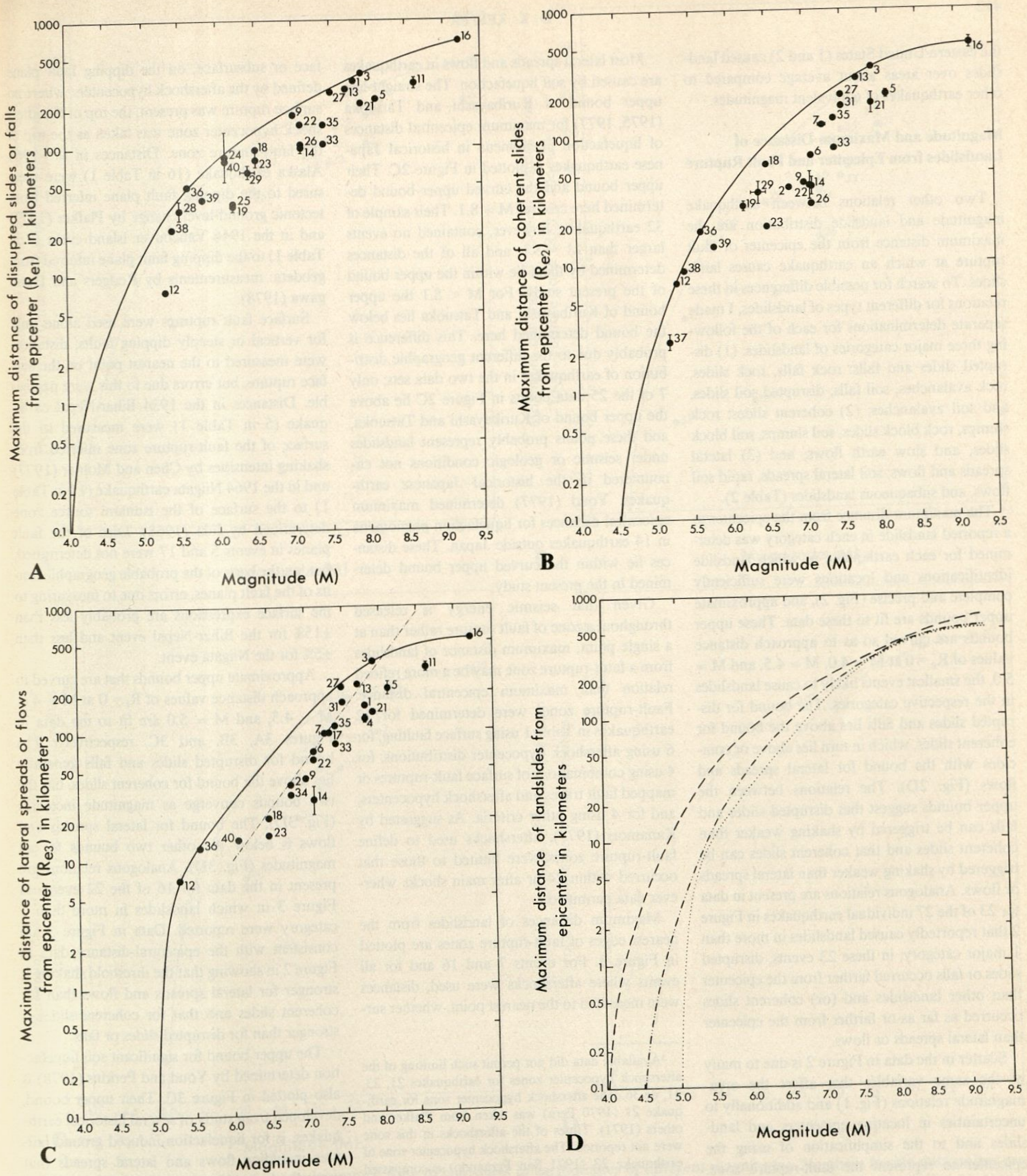

Figure 2. Maximum distance from epicenter to landslides for earthquakes of different magnitudes. Numbers beside data points are earthquakes listed in Table 1. Vertical bars indicate uncertainties, where known, in locations of epicenters, in locations of most distant landslides, or both. Horizontal bars indicate range in reported magnitudes. A. Maximum distance from epicenter to disrupted slide or fall. Solid line is approximate upper bound enclosing all data. B. Maximum distance from epicenter to coherent slide. Solid line is approximate upper bound enclosing all data. C. Maximum distance from epicenter to lateral spread or flow. Solid line is approximate upper bound enclosing all data. Dot-dash line is upper bound determined by Kuribayashi and Tatsuoka (1975, 1977) for soil-liquefaction phenomena in earthquakes in Japan. D. Comparison of upper bounds from A, B, and C. Dashed line is bound for disrupted falls and slides, dash–double-dot line is bound for coherent slides, and dotted line is bound for lateral spreads and flows.

the eastern United States (1 and 2) caused landslides over areas about average compared to other earthquakes of equivalent magnitudes.

Magnitude and Maximum Distance of Landslides from Epicenter and Fault Rupture

Two other relations between earthquake magnitude and landslide distribution are the maximum distance from the epicenter or fault rupture at which an earthquake causes landslides. To search for possible differences in these relations for different types of landslides, I made separate determinations for each of the following three major categories of landslides: (1) disrupted slides and falls: rock falls, rock slides, rock avalanches, soil falls, disrupted soil slides, and soil avalanches; (2) coherent slides: rock slumps, rock block slides, soil slumps, soil block slides, and slow earth flows; and (3) lateral spreads and flows: soil lateral spreads, rapid soil flows, and subaqueous landslides (Table 2).

The maximum distance from the epicenter to a reported landslide in each category was determined for each earthquake in which landslide identifications and locations were sufficiently complete and precise (Fig. 2), and approximate upper bounds are fit to these data. These upper bounds are curved so as to approach distance values of $R_e = 0$ at $M \simeq 4.0$, $M \simeq 4.5$, and $M \simeq 5.0$, the smallest events likely to cause landslides in the respective categories. The bound for disrupted slides and falls lies above the bound for coherent slides, which in turn lies above or coincides with the bound for lateral spreads and flows (Fig. 2D). The relations between the upper bounds suggest that disrupted slides and falls can be triggered by shaking weaker than coherent slides and that coherent slides can be triggered by shaking weaker than lateral spreads or flows. Analogous relations are present in data for 23 of the 27 individual earthquakes in Figure 2 that reportedly caused landslides in more than 1 major category; in these 23 events, disrupted slides or falls occurred farther from the epicenter than other landslides and (or) coherent slides occurred as far as or farther from the epicenter than lateral spreads or flows.

Scatter in the data in Figure 2 is due to many of the same variables that affect the area-magnitude relations (Fig. 1) and additionally to uncertainties in locating epicenters and landslides and to the simplification of using the epicenter to represent the fault-rupture zone. Earthquakes with focal depths ⩾30 km generally caused disrupted slides and falls and coherent slides at epicentral distances greater than shallower events of equal magnitude. For reasons that were not determined, focal depth had little or no effect on the maximum epicentral distances of lateral spreads or flows.

Most lateral spreads and flows in earthquakes are caused by soil liquefaction. The straight-line upper bound of Kuribayashi and Tatsuoka (1975, 1977) for maximum epicentral distances of liquefaction phenomena in historical Japanese earthquakes is plotted in Figure 2C. Their upper bound and the curved upper bound determined here cross at $M \simeq 8.1$. Their sample of 32 earthquakes, however, contained no events larger than $M = 8.1$, and all of the distances determined by them lie within the upper bound of the present study. For $M < 8.1$ the upper bound of Kuribayashi and Tatsuoka lies below the bound determined here. This difference is probably due to the different geographic distribution of earthquakes in the two data sets; only 7 of the 25 data points in Figure 2C lie above the upper bound of Kuribayashi and Tatsuoka, and these points probably represent landslides under seismic or geologic conditions not encountered in the historical Japanese earthquakes. Youd (1977) determined maximum epicentral distances for liquefaction phenomena in 14 earthquakes outside Japan. These distances lie within the curved upper bound determined in the present study.

Given that seismic energy is released throughout a zone of fault rupture rather than at a single point, maximum distance of landslides from a fault-rupture zone may be a more refined relation than maximum epicentral distance. Fault-rupture zones were determined for 12 earthquakes in Table 1 using surface faulting, for 6 using aftershock hypocenter distributions, for 4 using combinations of surface fault-ruptures or mapped fault traces and aftershock hypocenters, and for 4 using other criteria. As suggested by Kanamori (1977), aftershocks used to define fault-rupture zones were limited to those that occurred within 24 hr after main shocks wherever data permitted.[3]

Maximum distances of landslides from the nearest edges of fault-rupture zones are plotted in Figure 3. For events 7 and 16 and for all events where aftershocks were used, distances were measured to the nearest point, whether surface or subsurface, on the dipping fault plane defined by the aftershock hypocenters; where no surface rupture was present, the top of the aftershock hypocenter zone was taken as the top of the fault-rupture zone. Distances in the 1964 Alaska earthquake (16 in Table 1) were measured to the dipping fault plane inferred from tectonic ground-level change by Plafker (1972) and in the 1946 Vancouver Island event (7 in Table 1) to the dipping fault plane inferred from geodetic measurements by Rodgers and Hasegawa (1978).

Surface fault ruptures were used alone only for vertical or steeply dipping faults; distances were measured to the nearest point on the surface rupture, but errors due to this were negligible. Distances in the 1934 Bihar-Nepal earthquake (5 in Table 1) were measured to the surface of the fault-rupture zone inferred from shaking intensities by Chen and Molnar (1977) and in the 1964 Niigata earthquake (17 in Table 1) to the surface of the tsunami source zone determined by Iida (1968). Dips of the fault planes in events 5 and 17 were not determined, but, on the basis of the probable geographic limits of the fault planes, errors due to measuring to the surface expressions are probably less than ±15% for the Bihar-Nepal event and less than ±5% for the Niigata event.

Approximate upper bounds that are curved to approach distance values of $R_f = 0$ at $M \simeq 4.0$, $M \simeq 4.5$, and $M \simeq 5.0$ are fit to the data in Figures 3A, 3B, and 3C, respectively. The bound for disrupted slides and falls generally lies above the bound for coherent slides, but the two bounds converge as magnitude increases (Fig. 3D). The bound for lateral spreads and flows is below the other two bounds for all magnitudes (Fig. 3D). Analogous relations are present in the data for 16 of the 22 events in Figure 3 in which landslides in more than 1 category were reported. Data in Figure 3 are consistent with the epicentral-distance data in Figure 2 in showing that the threshold shaking is stronger for lateral spreads and flows than for coherent slides and that for coherent slides is stronger than for disrupted slides or falls.

The upper bound for significant soil liquefaction determined by Youd and Perkins (1978) is also plotted in Figure 3C. Their upper bound, developed from study of several historical earthquakes, is for liquefaction-induced ground failures including flows and lateral spreads that moved at least 100 mm in gently sloping, Holocene flood-plain, deltaic, or eolian materials. Differences between the two upper bounds in Figure 3C are due in large part to inclusion in the present study of lateral spreads and flows in other materials and of lateral spreads with reported displacements as low as 40 mm. Considering data points on the upper bound of the

[3]Available data did not permit such limiting of the aftershock hypocenter zones for earthquakes 21, 23, 31, or 36. The aftershock hypocenter zone for earthquake 21 (1970 Peru) was taken from Plafker and others (1971). Times of the aftershocks in this zone were not reported. The aftershock hypocenter zone of earthquake 23 (1971 San Fernando) encompassed shocks from 58 to 98 hr after the main shock located by Wesson and others (1971). The fault-rupture zone of earthquake 31 (1976 Tangshan, China) was determined by Butler and others (1979) using aftershock locations, but times of these aftershocks were not reported. The fault-rupture zone of earthquake 36 (1978 Santa Barbara) was determined by Lee and others (1978) using aftershocks that occurred within 104.4 hr after the main shock.

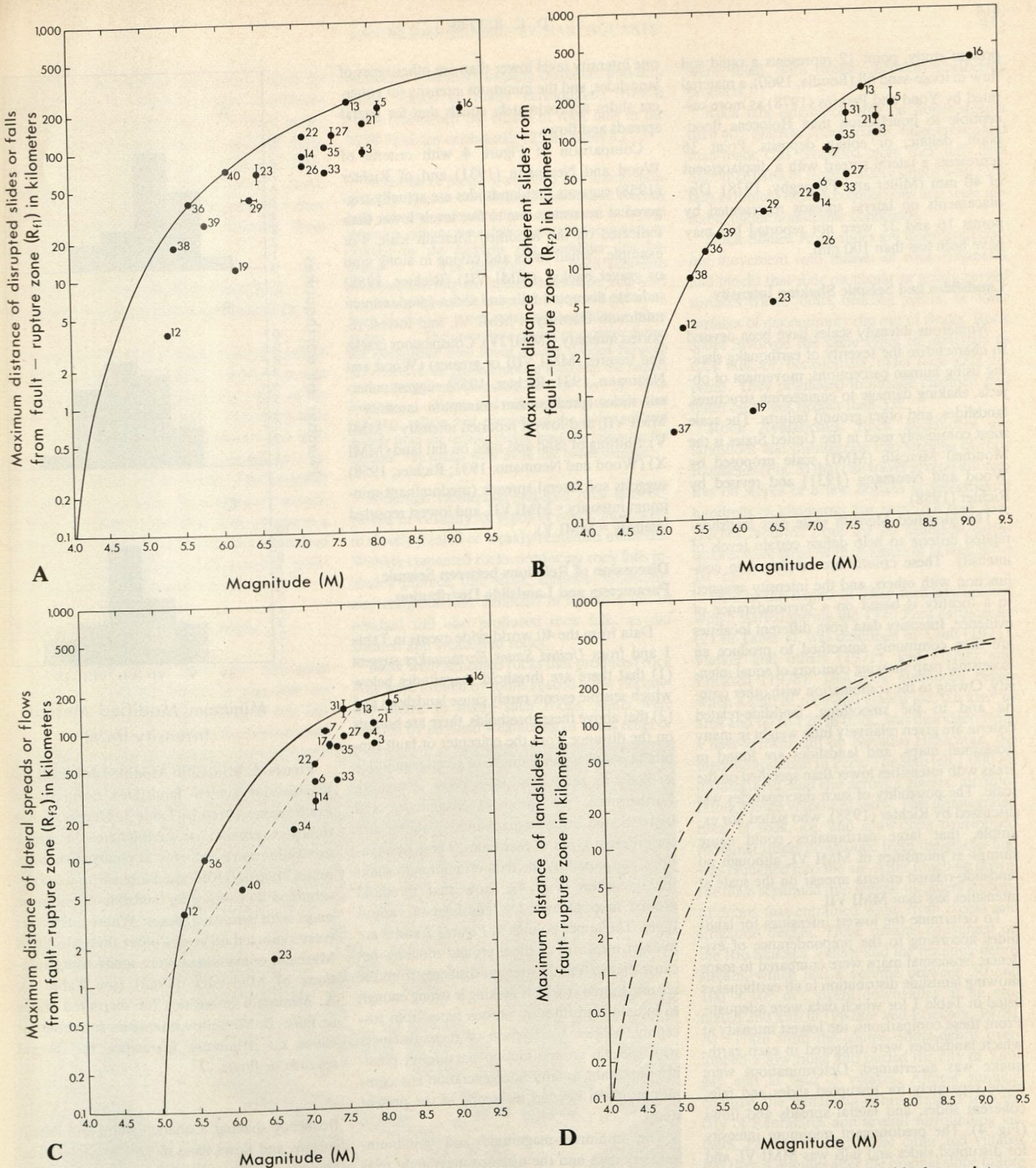

Figure 3. Maximum distance from fault-rupture zone to landslides in earthquakes of different magnitudes. Numbers beside data points are earthquakes listed in Table 1. Vertical bars indicate uncertainties, where known, in boundaries of fault-rupture zones, in locations of most distant landslides, or both. Horizontal bars indicate range in reported magnitudes. A. Maximum distance from fault-rupture zone to disrupted slide or fall. Solid line is approximate upper bound enclosing all data. B. Maximum distance from fault-rupture zone to coherent slide. Solid line is approximate upper bound enclosing all data. C. Maximum distance from fault-rupture zone to lateral spread or flow. Solid line is approximate upper bound enclosing all data. Dot-dash line is upper bound determined by Youd and Perkins (1978) for significant soil-liquefaction phenomena. D. Comparison of upper bounds from A, B, and C. Dashed line is bound for disrupted slides and falls, dash–double-dot line is bound for coherent slides, and dotted line is bound for lateral spreads and flows.

present study, point 12 represents a rapid soil flow in loose-sand fill (Bonilla, 1960), a material rated by Youd and Perkins (1978) as more susceptible to liquefaction than Holocene floodplain, deltaic, or eolian deposits. Point 36 represents a lateral spread with a displacement of 40 mm (Miller and Felszeghy, 1978). Displacements on lateral spreads represented by points 16 and 31 were not reported but may have been less than 100 mm.

Landslides and Seismic Shaking Intensity

Numerous intensity scales have been devised to characterize the severity of earthquake shaking using human perceptions, movement of objects, shaking damage to engineering structures, landslides, and other ground failures. The scale most commonly used in the United States is the Modified Mercalli (MMI) scale proposed by Wood and Neumann (1931) and revised by Richter (1958).

The Modified Mercalli scale uses landslide-related criteria to help define certain levels of intensity. These criteria are employed in conjunction with others, and the intensity assigned to a locality is based on a preponderance of evidence. Intensity data from different localities are then commonly smoothed to produce an isoseismal map showing contours of equal intensity. Owing to the combination with other criteria and to the smoothing, landslide-related criteria are given relatively little weight in many isoseismal maps, and landslides are found in areas with intensities lower than specified on the scale. The possibility of such discrepancies was discussed by Richter (1958), who stated, for example, that large earthquakes could cause slumps at intensities of MMI VI, although no landslide-related criteria appear on the scale at intensities less than MMI VII.

To determine the lowest intensities for landslides according to the preponderance of evidence, isoseismal maps were compared to maps showing landslide distribution in all earthquakes listed in Table 1 for which data were adequate. From these comparisons, the lowest intensity at which landslides were triggered in each earthquake was ascertained. Determinations were made separately for disrupted slides and falls, coherent slides, and lateral spreads and flows (Fig. 4). The predominant minimum intensity for disrupted slides and falls was MMI VI, and the lowest intensity reported in any earthquake was MMI IV (Fig. 4). The predominant minimum intensity for coherent slides, lateral spreads, and flows was MMI VII, and the lowest intensity reported was MMI V. Disrupted slides and falls, then, are triggered, on the average, at one intensity level lower than are other types of landslides, and the minimum intensity for coherent slides approximately equals that for lateral spreads and flows.

Comparison of Figure 4 with criteria of Wood and Neumann (1931) and of Richter (1958) suggests that landslides are actually triggered at intensities one to five levels lower than indicated on the Modified Mercalli scale. For example, "small slides and caving in along sand or gravel banks" (MMI VII) (Richter, 1958) indicate disrupted falls and slides (predominant minimum intensity = MMI VI, and lowest reported intensity = MMI IV). Conspicuous cracks and fissures (MMI VIII or greater) (Wood and Neumann, 1931; Richter, 1958) suggest coherent slides (predominant minimum intensity = MMI VII, and lowest reported intensity = MMI V). Shifting of sand and mud on flat land (MMI X) (Wood and Neumann, 1931; Richter, 1958) suggests soil lateral spreads (predominant minimum intensity = MMI VII, and lowest reported intensity = MMI V).

Discussion of Relations between Seismic Parameters and Landslide Distribution

Data from the 40 world-wide events in Table 1 and from *United States Earthquakes* suggest (1) that there are threshold magnitudes below which seismic events rarely cause landslides and (2) that above these thresholds, there are bounds on the distance from the epicenter or fault rupture at which an earthquake of given magnitude is likely to cause landslides (Figs. 2 and 3). Furthermore, the threshold magnitudes and upper-bound distance-magnitude relations vary for different types of landslides. These observations, supported by the data on minimum shaking intensities (Fig. 4), show that threshold ground motions exist for landslides of various types. The upper bounds in Figures 2 and 3 are indirect measures of these ground motions, because they define the greatest distances from the seismic source at which shaking is strong enough to initiate landslides of various types from susceptible slopes. Correlation of these distances with specific ground-motion parameters possibly important in landslide generation is a complex problem beyond the scope of the present study.

The minimum-magnitude and minimum-intensity data and the distance-magnitude relations indicate that rock falls, rock slides, soil falls, and disrupted soil slides have the lowest threshold ground-motions. The occurrence of these landslides in small events (M ≃ 4.0), in particular, suggests that these landslides can be dislodged by one or a few pulses of high-frequency shaking. Coherent slides and lateral spreads and flows have higher thresholds. The absence of rock avalanches from events smaller than M ≃ 6.0 (with possible rare exceptions such as the Gros Ventre and Hope landslides) and of soil avalanches from events smaller than M ≃ 6.5 indicates that these landslides generally have still higher thresholds. Coherent slides, lateral spreads and flows, rock avalanches, and soil avalanches are probably also more prone to triggering by the longer-duration, lower-frequency shaking characteristic of large earthquakes. Previous analyses of coherent slides (Wilson and Keefer, 1983) and of the soil liquefaction that causes most lateral spreads (Seed, 1968, 1979) indicate that shaking duration does have a significant effect on initiating these landslides.

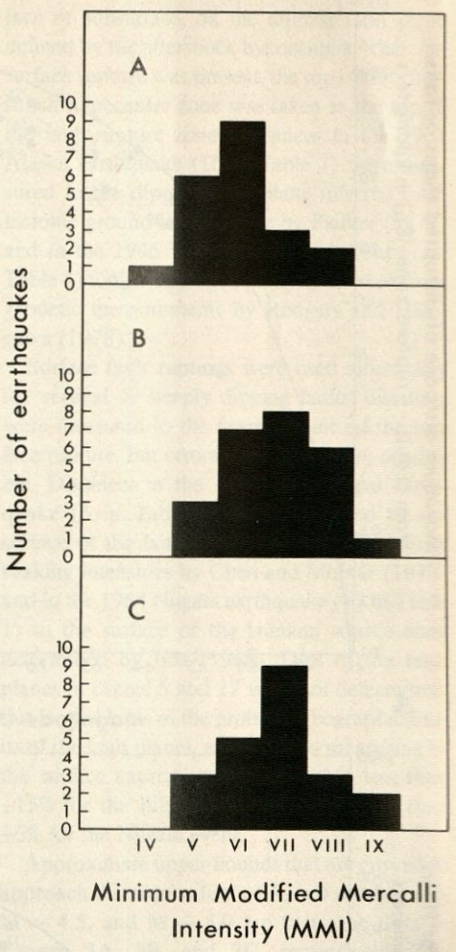

Figure 4. Minimum Modified Mercalli intensities at which landslides occurred in earthquakes listed in Table 1. Height of bar indicates number of earthquakes in which landslides were reported at a particular minimum intensity. Minimum intensities were determined by comparing landslide-distribution maps with isoseismal maps. Where intensities were reported on scales other than Modified Mercalli, conversions were made using relations of Medvedev (1962) (see Table 1). A. Minimum intensities for disrupted slides or falls. B. Minimum intensities for coherent slides. C. Minimum intensities for lateral spreads or flows.

LANDSLIDE CHARACTERISTICS AND GEOLOGIC ENVIRONMENTS

Characteristics and geologic environments of earthquake-induced landslides discussed in this section are defined exclusively from data on the 40 earthquakes listed in Table 1. Discussion thus pertains specifically to environments that produce landslides under seismic conditions, although in most of the same environments landslides also occur in the absence of seismic shaking. Whether a particular slope produces a landslide in an earthquake depends on details of material strength, slope configuration, pore-water pressure, and ground motion.

Disrupted Slides and Falls in Rock

Rock Falls. Rock falls are individual boulders or disrupted masses of rock that descend slopes by bounding, rolling, or free fall. They are the most abundant earthquake-induced landslides (Table 4), causing casualties and economic losses in many earthquakes. Hewitt (1976) described the effects of rock falls in the 1974 Pakistan earthquake (25 in Table 1):

> Thousands of people were killed and several times as many injured . . . . Homes, bazaars, and recently built schools, uncounted tiers of terraced fields and irrigation systems were shaken apart by the tremors or crushed by the rockfalls and landslides that followed . . . . The survivors . . . faced enormous problems carrying the injured downslope, and relief supplies upslope, over steep, snow-covered paths that were blocked or borne away by landslides at many points . . . . The immediate causes of damage during the earthquake were about equally divided between the effects of the ground motion itself and the impact of rockfalls and landslides set off by the earth tremors . . . . Farms and villages in the steep-walled tributary valleys and narrows of the Indus suffered mainly from the terrible rain of boulders following the tremors. The results were more like bomb damage.

Although earthquake-induced rock falls occurred in virtually all types of rocks, most were in closely jointed or weakly cemented materials. Weakly cemented rocks producing rock falls included pumice, tuff, shale, siltstone, sandstone, and conglomerate. Boulders in moraine and in residual soil also produced rock falls, as did sheared and weathered rocks.

Most well-cemented rocks that produced rock falls were broken by joints spaced a few decimetres apart. In many such rocks, joints were opened by physical weathering or stress relief or were filled with weak chemical-weathering products.

Rock falls originated only on slopes steeper than 40°. Narrow spurs, ledges, ridge crests, and man-made cuts produced more rock falls than did other parts of slopes. Many slopes with rock falls exhibited talus accumulations and were unstable under nonseismic conditions.

Rock Slides. Rock slides are disordered during movement into masses of rock fragments and blocks that slide on planar or gently curved surfaces where joints, bedding planes, or other surfaces of discontinuity dip out of slopes. Rock slides involved the same types of materials as rock falls, or, occasionally, older rock-slide deposits. They originated in hillside channels and flutes on slopes steeper than 35°.

Rock Avalanches. Rock avalanches are landslides that disintegrate into streams of rock fragments (Fig. 5) that can travel several kilometres on slopes of a few degrees at velocities of hundreds of kilometres per hour. All rock avalanches reported from the 40 historical earthquakes were large, with volumes of at least 0.5×10^6 m^3.

One of the largest of these rock avalanches, which started during the 1970 Peru earthquake (21 in Table 1), was described by Cluff (1971), Plafker and others (1971), and Plafker and Ericksen (1978). This rock avalanche began when a slab of rock and glacial ice, 0.6 km^2 in area and 60 to 120 m thick, was dislodged from a near-vertical cliff on Nevados Huascarán, the highest mountain in Peru. The slab fell 1,000 m, disintegrated, and slid across a glacier, incorporating a large volume of snow. This disintegrated mass of rock, ice, and snow then overtopped morainal ridges downslope from the glacier and was launched into the air. After touching down, the mass separated into several turbulent streams of debris that entrained water from creeks and irrigation ditches. These streams converged on the Rio Shacsha Valley, and the resulting debris stream, which had a volume between 50 and 100×10^6 m^3, swept downvalley at an estimated 280 km/hr (Plafker and Ericksen, 1978). At 11 km from the source, some debris overtopped a low ridge and buried the city of Yungay and at least 3 villages. Almost simultaneously, the remaining debris crashed into the city of Ranrahirca and several surrounding villages. Passing through these cities and villages less than 4 minutes after the original slope failure on Nevados Huascarán, the landslide killed at least 18,000 people (Plafker and others, 1971); it was thus the most destructive landslide in this century and perhaps in all of history.

The kinetic energy necessary for long-distance transport of rock-avalanche material is produced

Figure 5. Aerial view of two rock avalanches in Mount Baldwin cirque, eastern Sierra Nevada, caused by the 1980 Mammoth Lakes, California, event (40 in Table 1). These rock avalanches are relatively small; each has a volume of ~500,000 m^3. Slope above avalanche on left has relief of ~270 m.

by initial fall from steep, high slopes. Avalanche paths consist of steep source slopes where the avalanches accelerate and, except where constrained by narrow canyons, of gentle runout slopes where they decelerate and come to rest. Approximately 100 rock avalanches were reported in earthquakes in Table 1. Data on source-slope inclination and height, available for 50 of these rock avalanches, show that minimum inclination and height were, respectively, 25° and 150 m. All but one of these 50 originated on slopes undercut by active fluvial erosion or by active, Holocene, or late Pleistocene glacial erosion. The single exception, triggered by the 1906 San Francisco earthquake (3 in Table 1), was on a slope bordered by a small stream; this slope was probably undercut by fluvial erosion at some time in the past when flow in the stream was greater than at present.

Data on geologic conditions, reported for 27 of the rock avalanches, showed that most slopes that produced them were intensely fractured, with the rock being broken by several sets of fractures spaced a few centimetres to a few decimetres apart. Most such slopes also exhibited at least one of the following additional signs of low strength or potential instability: (1) conspicuous planes of weakness—faults, master joints, bedding planes, or foliation surfaces—dipping out of the slope, (2) significant weathering of the rock, (3) weak cementation of the rock, or (4) geologic or historical evidence of previous landsliding.

Coherent Slides in Rock

Rock Slumps. Each rock slump consists of one or a small number of coherent, deep-seated blocks (Table 2) that slide on basal shear surfaces curved so that movement involves a component of headward rotation. Earthquake-induced slumps were initiated on slopes steeper than 15° in igneous and metamorphic rocks as well as in sedimentary rocks. Specific rock types involved in slumps in the 40 historical earthquakes were basalt with interbedded ash and breccia, pumice, andesite, granite, greenstone, slate, schist, amphibolite, shale, siltstone, and sandstone. Most of these rocks were weak, either because they were poorly cemented, closely jointed, weathered, or sheared. Older rock-slump deposits were reactivated in the 1906 San Francisco and 1971 San Fernando earthquakes (3 and 23 in Table 1).

Rock Block Slides. Rock block slides, also generally deep-seated (Table 2), consist of one or a few blocks that slide on planar or gently curved basal shear surfaces. Movement thus involves little or no rotation. Basal shear surfaces are bedding planes or other discontinuities that dip out of slopes, allowing the blocks to move without significant distortion. In the earthquakes listed in Table 1, rock block slides originated on slopes steeper than 15° in tuff, andesite, weakly cemented pumice, and weakly cemented or closely jointed shale, mudstone, siltstone, and sandstone.

Disrupted Slides and Falls in Soil

Soil falls. Soil falls are blocks or disrupted masses of soil that descend slopes by bounding, rolling, or free fall. Most soil blocks break apart during transport or impact. In the earthquakes listed in Table 1, soil falls originated on steep slopes such as coastal bluffs, canyon walls, stream banks, terrace faces, and cut slopes. Although 63° was the minimum slope inclination reported for soil falls, they probably took place on slopes at least as gentle as 40°, the minimum observed for rock falls. Most soil falls involved weakly cemented sand or gravel; a few were in unconsolidated or weakly cemented clay.

Disrupted Soil Slides. Disrupted soil slides consist of sheets of soil, a few decimetres to a few metres thick (Fig. 6), that disintegrate during movement into chaotic jumbles of small blocks and individual soil grains. Most slide on basal shear surfaces formed at soil-bedrock contacts or at boundaries between different soil layers; a few move on basal zones of weakened, sensitive clay.

The material most commonly involved in disrupted soil slides was loose, unsaturated, residual or colluvial sand with little or no clay; tens of thousands of disrupted soil slides in such material occurred in earthquakes 12, 23, 27, and 30 (Table 3). The 1960 Chile earthquake (15 in Table 1) caused thousands of disrupted soil slides in a saturated volcanic soil consisting of alternating layers of scoriaceous gravel and sensitive clay produced by weathering of fine-grained ash. The slides were restricted to deforested slopes, which were unstable under nonseismic conditions and which had been fissured by a foreshock of the earthquake (Wright and Mella, 1963). In the 1970 Peru earthquake (21 in Table 1), saturated deposits of fluvioglacial and landslide material as well as till, volcanic ash, and colluvium failed in thousands of disrupted soil slides (Plafker and others, 1971). Materials producing smaller numbers of disrupted soil slides in other earthquakes were sandy or silty man-made fill, fault gouge, flood-plain alluvium, terrace deposits, and cemented sand, silt, and clay. The minimum slope inclination for disrupted soil slides was 15°.

Soil Avalanches. Soil avalanches, more disaggregated and faster moving than disrupted soil slides, generally consist of streams of grains and small blocks of soil. Many travel far beyond the bases of the slopes on which they originate. In the earthquakes listed in Table 1, soil avalanches originated on slopes steeper than 25° in unsaturated sand, older soil-avalanche deposits, and the same volcanic soil that produced disrupted soil slides in the 1960 Chile earthquake (15 in Table 1).

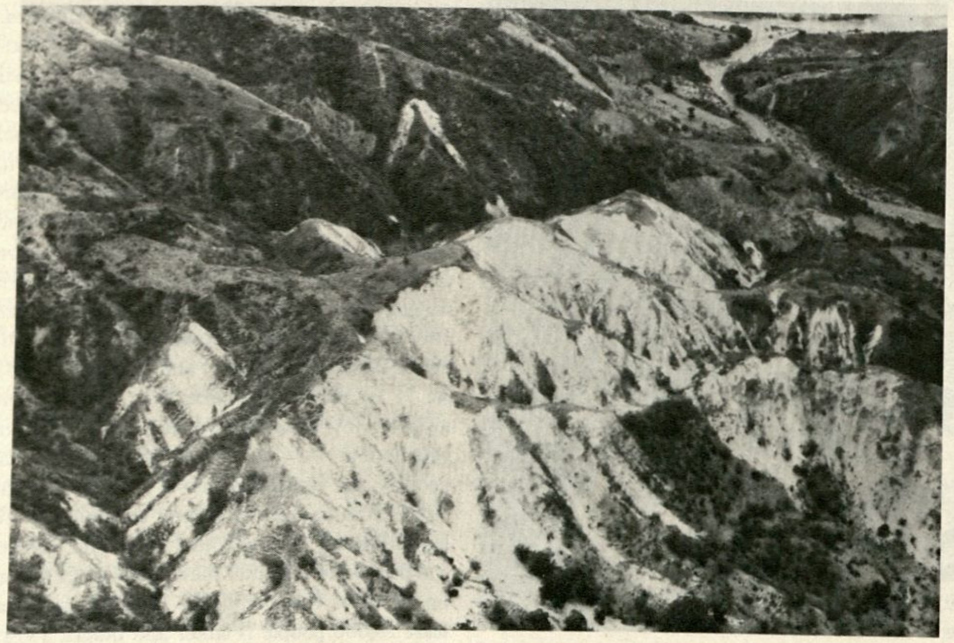

Figure 6. Aerial view of coalescing, disrupted soil slides caused by the 1976 Guatemala earthquake (27 in Table 1). Slides stripped away vegetation and sheets of sandy residual soil, generally <0.6 m thick, exposing white pumice bedrock. Slopes in foreground have relief of ~30 m. Photograph from Harp and others (1981).

TABLE 5. SOIL-SLUMP MATERIALS

Man-made fill (23)	Sand dunes (2)	Fluvioglacial deposits (1)
Flood-plain alluvium (12)	Terrace deposits (2)	Ground moraine (1)
Old slump deposits (5)	Cemented sand and gravel (1)	Playa deposits (1)
Colluvium (3)	Volcanic ash (1)	Lacustrine deposits (1)
Till (3)	Pyroclastic deposits (1)	Deltaic deposits (1)
Alluvial fan deposits (3)	Sensitive clay (1)	Barrier island deposits (1)

Note: numbers in parentheses are total number of the 40 historical earthquakes (Table 1) in which slumps occurred in a particular material.

Coherent Slides in Soil

Soil Slumps. Soil slumps, generally deep-seated (Table 2), consist of one or a few coherent blocks that slide on basal shear surfaces curved so that movement involves headward rotation. These landslides are characterized by crescent-shaped scarps, blocks with surfaces tilted back toward the crests of slopes, and bulging toes.

Man-made fill was the most common material in earthquake-induced soil slumps; 23 earthquakes listed in Table 1 caused slumps in fill (Table 5). Many slumped fills were uncompacted or poorly compacted. Slumps in fill composed of sand or silt were more common than in fill composed of clay. Earthquakes caused fill to slump both on hillsides and on alluvial and coastal flood plains, where slumps were most abundant in embankments built over marshes or filled river channels.

Flood-plain alluvium produced soil slumps in more of the historical earthquakes than did any other natural material (Table 5), and sandy alluvium produced more slumps than did coarser or finer material. Other natural materials involved in slumps are listed in Table 5. Older slump deposits were reactivated in five of the historical earthquakes (Table 5), but the 1906 San Francisco earthquake (3 in Table 1) is the only one in which more than a few reactivations were reported. Except for one slump on a 7° slope, triggered by the 1978 Miyagi-ken-oki, Japan, earthquake (35 in Table 1), the minimum slope inclination reported for soil slumps was 10°.

Soil Block Slides. Soil block slides, also generally deep-seated (Table 2), slide in a translational manner on planar or gently curved shear surfaces. These slides have grabens at their heads (Fig. 7), some have internal fissures or grabens as well, and pressure ridges mark the toes of many.

The Government Hill slide, which caused major damage in Anchorage, Alaska, during the 1964 earthquake (16 in Table 1), is an example of a large soil block slide. According to Hansen (1966), the slide had an area of 4 hectares, was 27 m deep, and incorporated 7×10^5 m^3 of material. It involved a river bluff 25 m high. About 120 m behind the original bluff line, a wing of an elementary school dropped into the graben at the head of the slide (Fig. 7). The slide also contained two arcuate, internal grabens, arranged concentrically and curved convex-headward in plan view. Horsts between the grabens slid laterally with little vertical displacement. The slide moved 20 m, presumably during the strong ground shaking, which lasted 4 to 7 minutes. In addition to the school, the slide destroyed or damaged four houses and much equipment and track in a railroad yard at the foot of the bluff.

Material in the Government Hill slide consisted of glacial outwash underlain by the Bootlegger Cove Clay, a periglacial sediment containing lenses of liquefiable sand and silt and zones of weak, sensitive clay. The near-horizontal shear surface under the slide was in saturated clay with a peak shear strength of less than 50 kPa and a sensitivity of as much as 40 (Hansen, 1966).

Other block slides as large as or larger than that at Government Hill occurred on river or coastal bluffs elsewhere in Anchorage in event 16; on the Mississippi River bluffs near New Madrid, Missouri, in event 1; and on the Rio San Pedro bluffs in Chile in event 15. Bluff heights ranged from 16 to >60 m and bluff inclinations from 6° to near-vertical. The block slides in Anchorage involved both sensitive clay and liquefiable sand and silt (Hansen, 1966; Seed, 1968). The block slides along the Mississippi River moved on layers of saturated sand and gravel that were underlain by impermeable clay (Fuller, 1912); those along the Rio San Pedro moved on 2- to 6-cm-thick beds of saturated, well-sorted lacustrine silt (Davis and Karzulovic, 1963). These large soil block slides were all in areas of old landslides; some reactivated the older landslide material, whereas others involved nearby material that had not failed previously.

Earthquakes listed in Table 1 also caused many smaller soil block slides, most of which were in sandy or silty flood-plain alluvium or man-made fill. Most fills that produced block slides were on flood plains and composed of

Figure 7. Elementary school destroyed by the Government Hill slide, a large soil block slide in Anchorage, Alaska. One wing of school dropped into graben at head of slide. Slide triggered by the 1964 Alaska earthquake (16 in Table 1). Photograph from Hansen (1966).

alluvial materials. Other materials producing block slides were till, volcanic ash, colluvium, clayey playa sediment, lacustrine sediment, terrace gravel, sandy eolian sediment, sandy alluvial-fan sediment, and periglacial sediment. Basal shear surfaces of most block slides were probably saturated, as the slides were in areas with high water tables. Many soil block slides involved flat-topped slopes and near-horizontal basal shear surfaces. The frontal slopes in areas of soil block slides were reported to be as gentle as 5°.

Slow Earth Flows. Slow earth flows are tongue- or teardrop-shaped bodies of clay, silty clay, or clayey silt bounded by discrete lateral and basal shear surfaces. These landslides move primarily by boundary shear; internal deformation is minor. Basal shear surfaces are saturated. Slow earth flows in the earthquakes listed in Table 1 were in clayey residual soil, clayey loam, till, volcanic ash, colluvium, and older earth-flow deposits. The minimum reported slope inclination for these slow earth flows was 10°.

One of the largest earthquake-induced earth flows was initiated at least five days after the 1959 Hebgen Lake earthquake (14 in Table 1) and continued moving for at least a month. This earth flow, which reactivated an older landslide, was probably initiated because (1) faulting and crustal warping in the earthquake increased the surface inclination, and (2) the earthquake increased the local ground-water flow (Hadley, 1964).

Lateral Spreads and Flows in Soil

Soil Lateral Spreads. Soil lateral spreads move in a translational manner on zones of liquefied gravel, sand, or silt or, occasionally, on sensitive clay rendered fluid by disturbance. All these basal zones are saturated. More disrupted than soil slumps or soil block slides, soil lateral spreads contain numerous internal fissures and grabens.

In the earthquakes listed in Table 1, soil lateral spreads were most common in granular man-made fill and flood-plain alluvium (Table 6). Most alluvial lateral spreads were along active or abandoned river channels or in marshes. Composition of alluvium in lateral spreads was predominantly silt, silty sand, or fine-grained sand. Most alluvial materials in lateral spreads were Holocene; a few were Pleistocene.

Man-made fills that failed by lateral spreading ranged in composition from silt to sandy gravel, but most were composed of fine-grained sand. In some lateral spreads in fill, the basal zones of liquefied material were in the fills themselves, and many of these fills had not been compacted during placement. In other lateral spreads in fill, the basal, liquefied zones were in natural foundation materials underlying the fills. Foundation materials that liquefied included river-channel, marsh, and other flood-plain deposits, terrace deposits, lacustrine deposits, and reclaimed land.

Materials other than alluvium and fill that produced soil lateral spreads are listed in Table 6. Sensitive clay produced one lateral spread in the 1946 Vancouver Island earthquake (7 in Table 1). Another lateral spread, the Turnagain Heights landslide in Anchorage produced by event 16, involved both sensitive clay and liquefiable sand and silt (Hansen, 1966; Seed and Wilson, 1967; Seed, 1968; Voight, 1973). All other lateral spreads in earthquakes in Table 1 were underlain by zones of liquefied granular material. Findings in Table 6 agree with previous work showing that materials with the highest susceptibilities to liquefaction are man-made fill and alluvium (Kuribayashi and Tatsuoka, 1975, 1977; Youd, 1977; Youd and Hoose, 1977; Youd and Perkins, 1978), deltaic deposits (Youd and Hoose, 1977; Youd and Perkins, 1978), and eolian deposits such as sand dunes (Youd, 1977). The minimum slope inclination reported for lateral spreads in the 40 historical earthquakes was 0.3°, the same as reported by Youd (1975).

At least two earthquakes listed in Table 1—the 1906 San Francisco and 1978 Miyagi-ken-oki events (3 and 35 in Table 1)—triggered lateral spreads in soils that had previously liquefied (Keefer, 1978, 1980; Youd and Hoose, 1978). Instances of reliquefaction in other earthquakes are discussed by Kuribayashi and Tatsuoka (1975, 1977) and Youd (1977).

Rapid Soil Flows. Rapid soil flows are streams of soil grains, usually but not always mixed with water, that flow in a fluid-like fashion at high velocities (Table 2). Some rapid soil flows travel several kilometres on slopes of only a few degrees yet transport boulders weighing hundreds of tons.

The characteristics of fluid-like flow, high velocity, and great distance of transport are illustrated by some particularly large flows triggered by the 1920 earthquake in Kansu Province, China (4 in Table 1). These flows, some of which covered several square kilometres, are among the most destructive landslides in history. As they swept through valleys carved in loess, they killed at least several thousand and perhaps as many as 100,000 people (Varnes, 1978).

One group of these flows was described by Close and McCormick (1922): "The most appalling sight of all was the Valley of the Dead, where seven great slides crashed into a gap in the hills three miles long, killing every living thing in the area except three men and two dogs. The survivors were carried across the valley on the crest of the avalanche, caught in the cross-current of two other slides, whirled in a gigantic vortex, and catapulted to the slope of another hill. With them went house, orchard, and threshing-floor, and the farmer has since placidly begun to till the new location to which he was so unceremoniously transported."

Describing another flow, Close and McCormick continued: "This was the most striking freak of the earthquake. A quarter-mile section of an old road, with the big poplars which line it, was cut off from the highway by a landslide and carried on the back of the river of earth for nearly a mile, where it was left in an almost natural position. All this took place in a few seconds of time."

Despite this example, most flows were highly disaggregated, according to Close and McCormick: "In each case the earth which came down bore the appearance of having shaken loose clod from clod and grain from grain, and then cascaded like water, forming vortices, swirls, and all the convolutions into which a torrent might shape itself."

The flows in Kansu Province were in loess on terraced hillsides and on the walls of U-shaped valleys. Slope inclinations were not reported. The water content of the loess is uncertain. According to the descriptions of Close and McCormick (1922), however, the loess may have been dry, and in this sense the flows are possibly unique among those in the 40 historical earthquakes.

Rapid soil flows in saturated loess killed 15,000 people near Khait in the Soviet Union in

TABLE 6. SOIL LATERAL-SPREAD MATERIALS

Flood-plain alluvium (19)	Beach deposits (3)	Glacial outwash (1)
Man-made fill (18)	Beach bar deposits (2)	Glaciolacustrine deposits (1)
Deltaic deposits (5)	Estuarine deposits (2)	Playa sediments (1)
Sand dunes (4)	Periglacial sediments (1)	Organic marine mud (1)
Coastal sand spits (4)	Barrier islands (1)	Carbonate silt in a thermal spring (1)
Alluvial fan deposits (3)	Tidal flats (1)	Sensitive clay of undetermined origin (1)
Lacustrine sediments (3)	Terraces not on flood plains (1)	

Note: numbers in parentheses are total number of the 40 historical earthquakes (Table 1) in which lateral spreads occurred in a particular material.

earthquake 10 in 1949 (A. M. Sarna-Wojcicki, 1980, oral commun.). These flows started in 1- to 2-m-thick layers of loess on slopes as steep as 30°. The main shock of the earthquake at Khait probably caused fissures in the loess, and most flows occurred several hours or days after the main shock during a period of heavy rainfall and aftershocks.

In the 1960 Chile and 1974 Izu-Oshima Kinkai, Japan, earthquakes (15 and 34 in Table 1), rapid soil flows formed in volcanic soils consisting of interbedded layers of scoriaceous gravel and ash containing sensitive clay. In these and other earthquakes, flows also occurred in dune sand, sandy residual and colluvial soils, silty and sandy alluvial fan deposits, flood-plain alluvium, and man-made fill. Fill that flowed included poorly compacted well-sorted sand, poorly compacted volcanic loam and scoria, mine tailings composed of silt and sandy silt, moderately loose sandy gravel, and reclaimed land on flood plains.

All flows, possibly excepting those in Kansu Province, were in saturated soils. These saturated flows were triggered either by a combination of shaking and high rainfall as in the 1949 Khait and 1960 Chile earthquakes (10 and 15 in Table 1) or by shaking at sites with high water tables or flowing springs. The minimum slope reported for a saturated flow was 2.3°.

Subaqueous Landslides. All submarine or sublacustrine landslides are herein grouped as "subaqueous landslides." Although a few earthquake-induced subaqueous landslides move primarily by slumping or block sliding, most involve lateral spreading, rapid flow, or both.

The 1964 Alaska earthquake (16 in Table 1) caused more submarine landslides than did any of the other historical earthquakes (Table 3), and most of these landslides in Alaska were in Holocene deltaic sediments. Most of these deltaic sediments were composed of sand and gravel derived from glacial outwash; some were composed of silty clay, clayey silt, or silty sand. At Valdez, where a submarine landslide occurred in 1964, similar landslides had occurred previously during earthquakes in 1899, 1908, 1911, 1912, and 1925 (Coulter and Migliaccio, 1966).

Submarine landslides caused by the 1964 Alaska and other earthquakes in nondeltaic areas involved coarse-grained till and material from sand spits, tidal flats, beaches, alluvial fans, and offshore areas. Sublacustrine landslides in the historical earthquakes were in lake silt, outwash gravel and sand, alluvial fans, and, most commonly, Holocene deltaic sediments composed of sand, gravelly sand, sandy gravel, or gravel. The minimum slope inclination reported for subaqueous landslides was 0.5°, but at most landslide localities slopes were steeper than 10°.

TABLE 7. TOTAL DEATHS BY LANDSLIDE TYPE

Landslide type	Estimated total deaths in 24 earthquakes*	Number of earthquakes in which deaths occured
Rapid soil flows	25,000–115,000?	5
Rock avalanches	21,000–30,000	6
Rock falls	800–2,500	11–12
Soil lateral spreads		
Soil slumps	≤3,100?[†]	4
Soil block slides		
Rock slides	≤1,000?	1?
Subaqueous landslides	48–84	3
Disrupted soil slides	≤80?	1?
Soil avalanches	≤80?	1?
Rock slumps	17	1
Soil falls	≤12?	1?

Note: query (?) indicates estimate made from incomplete data.
*Data on deaths due to landslides were not available for 9 of the 40 earthquakes, and no deaths due to any causes were reported in 7 of the earthquakes.
[†]Most estimated deaths occurred in the 1934 Bihar-Nepal earthquake (5 in Table 1), in which the percentage of deaths due to landslides was assumed to be equal to the percentage of landslide-caused economic losses.

DEATHS AND ECONOMIC LOSSES CAUSED BY LANDSLIDES

Rapid soil flows, rock avalanches, and rock falls together caused at least 90% and possibly more than 99% of the reported landslide deaths in the 40 historical earthquakes (Table 7).[4] Rock avalanches and rapid soil flows, the two leading causes of death, are similar in that they can travel several kilometres at high velocities on slopes of a few degrees. Most deaths caused by these landslides were due to burial of cities or villages located on gently sloping ground several kilometres from the sites of landslide initiation. Both rock avalanches and rapid soil flows are relatively uncommon in earthquakes (Table 4) and occur under a limited range of geologic conditions.

Rock falls, the third leading cause of death (Table 7), are also the most abundant landslides in seismic events (Table 4) and occur in virtually all types of rocks on slopes steeper than 40°. Areas at risk from rock falls are limited by distances that boulders can bound or roll once they reach the bases of the steep slopes on which the rock falls originate; the maximum such distance reported in earthquakes listed in Table 1 was ~800 m.

Deaths possibly due to rock slides and soil falls were all in areas with abundant rock falls, and deaths possibly due to disrupted soil slides and soil avalanches were all in areas with abundant rapid soil flows (Table 8).[4] Data for these areas did not permit differentiation of deaths caused by the various landslide types, and these deaths may all have been due to rock falls and rapid soil flows. Whereas, then, earthquake-induced rock slides, soil falls, disrupted soil slides, and soil avalanches probably pose some hazard to life, such hazards cannot be evaluated quantitatively from these data.

Other types of earthquake-induced landslides causing deaths were soil slumps, soil block slides, soil lateral spreads, subaqueous landslides, and rock slumps. All but one death caused by soil slumps, block slides, or lateral spreads were due to disruption of foundations and subsequent collapse of buildings. The one exception was caused by an automobile crash on a road damaged by a soil slump. Subaqueous landslides carried away people on beaches, nearshore islands, or the distal margins of deltas or generated waves that drowned people in coastal areas. The one rock slump that caused deaths was large, with a volume of 2×10^6 m^3, and destroyed several houses. These types of earthquake-induced landslides thus pose threats to human life under certain circumstances, but these threats are not as severe or pervasive as those from rapid soil flows, rock avalanches, or rock falls.

Earthquake-induced landslides have also damaged many types of engineering structures and caused a large percentage of the total economic losses in several earthquakes (Table 9).[5] Economic losses were reported from all types of earthquake-induced landslides except slow earth flows. Data on economic losses due to landslides in most earthquakes, however, were descriptive rather than quantitative. In order to estimate the relative hazard of economic loss due to various types of landslides, I determined the number of historical earthquakes (Table 1) in which damage was reported from each type. Results were as follows: soil slumps (27 earthquakes), soil lateral spreads (18), rock falls (14), soil block slides (8), disrupted soil slides (8), rapid soil flows (6), rock avalanches (5), rock slides (5), soil falls (3), subaqueous landslides (3), rock slumps (2), soil avalanches (1), and rock block slides (1).

This ranking underestimates the economic effects of a few catastrophic landslides, such as the rock avalanche at Nevados Huascarán, Peru, and the rapid soil flows near Khait, Soviet Union, and in Kansu Province, China. These landslides destroyed substantial portions of vil-

[4]Landslide-related deaths in each individual earthquake are listed in Table 8, which is in the GSA Data Repository. Tables 8 and 9 may be secured by requesting Supplementary Data 84-11 from the GSA Documents Secretary.

[5]Table 9, which lists economic losses, types of structures damaged, and types of landslides causing damages, is in the GSA Data Repository. See footnote 4 for details.

lages or cities, indicating that rapid soil flows and rock avalanches are as hazardous to civil works as they are to human life.

The propensity of soil slumps, soil lateral spreads, and soil block slides to cause economic losses in earthquakes is due to their abundance (Table 4) and to their common occurrence on gentle slopes in man-made fill and in alluvium on flood plains, which are likely locations for human habitation. Rock falls and, to a lesser extent, disrupted soil slides and rock slides are likely to cause damage in earthquakes because they are abundant (Table 4), even though this damage is restricted to localities on or near steep slopes. Except for soil avalanches, most of which were in uninhabited areas, the lower amount of damage reported from other types of landslides correlates with the relative rarity of these landslides in earthquakes (Table 4). Although no economic losses were reported from slow earth flows in the earthquakes listed in Table 1, slow earth flows have caused economic losses under nonseismic conditions (Záruba and Mencl, 1969). The lack of reported losses from slow earth flows in these earthquakes thus does not preclude their causing economic losses in other earthquakes.

CONCLUSIONS

Study of a sample of 40 historical earthquakes shows that 14 types of landslides are caused by seismic events. In order of decreasing abundance, these are: rock falls, disrupted soil slides, rock slides, soil lateral spreads, soil slumps, soil block slides, soil avalanches, soil falls, rapid soil flows, rock slumps, subaqueous landslides, slow earth flows, rock block slides, and rock avalanches.

The area affected by landslides in an earthquake correlates with the magnitude, and the upper bound in Figure 1 gives the approximate maximum area likely to be affected by landslides in an event of given magnitude. This area increases from 0 at $M \simeq 4.0$ to approximately 500,000 km^2 at $M = 9.2$. Factors other than magnitude that control the area affected by landslides include local geologic conditions, earthquake focal depth, and the specific ground-motion characteristics of a particular event.

Certain threshold levels of ground shaking are necessary for triggering the various types of landslides. Indirect measures of these thresholds are the smallest earthquakes that cause landslides, the maximum distance of landslides from the epicenter or fault rupture (Figs. 2 and 3), and the minimum intensity for landslides (Fig. 4). These measures indicate that rock falls, rock slides, soil falls, and disrupted soil slides are initiated by the weakest shaking. In particular, these shallow, highly disrupted landslides from steep slopes are probably susceptible to the short-duration, high-frequency shaking characteristic of small earthquakes. Coherent, generally deep-seated landslides are initiated by stronger and probably longer-duration shaking, and lateral spreads and flows by shaking that is still longer and stronger. With possible rare exceptions, rock avalanches and soil avalanches have the highest thresholds of all.

Modified Mercalli shaking intensities for landslides determined by comparing isoseismal maps with maps of landslide distribution are one to five levels lower than those indicated by explicit criteria on the Modified Mercalli scale. This discrepancy suggests a need for revision of landslide-related criteria on the scale to conform to intensities based on other criteria. Suggested revised criteria are (1) that shallow, highly disrupted landslides from steep slopes are common at MMI VI, (2) that rapid soil flows, soil lateral spreads, and coherent deep-seated slides from gentler slopes are common at MMI VII, and (3) that landslides of all types occasionally occur at intensities one to two levels lower than the levels at which they are common.

This study has identified several materials that are especially susceptible to earthquake-induced landslides. These materials and the predominant types of landslides in each are: (1) weakly cemented, weathered, sheared, intensely fractured, or closely jointed rocks (rock falls, slides, avalanches, slumps, and block slides), (2) more-indurated rocks with prominent discontinuities (rock falls, slides, block slides, and, possibly, slumps), (3) unsaturated residual or colluvial sand (disrupted soil slides and soil avalanches), (4) saturated residual or colluvial sand (rapid soil flows), (5) saturated volcanic soils containing sensitive clay (disrupted soil slides, soil avalanches, and rapid soil flows), (6) loess (rapid soil flows), (7) cemented soils (soil falls), (8) deltaic sediments containing little or no clay (soil lateral spreads and subaqueous landslides), (9) flood-plain alluvium containing little or no clay (soil slumps, block slides, and lateral spreads), and (10) uncompacted or poorly compacted man-made fill containing little or no clay (soil slumps, block slides, lateral spreads, and rapid soil flows).

Although most or all types of earthquake-induced landslides pose some hazard to human life and property, historical evidence shows that the predominant threats to life are from rock avalanches, rapid soil flows, and rock falls. Zones at risk from rock falls extend only a few hundred metres from the bases of steep slopes, but zones at risk from rock avalanches or rapid soil flows extend for several kilometres from localities of landslide initiation. Leading causes of property damage, in addition to these three types of landslides, are soil slumps and soil lateral spreads.

Not all earthquake-induced landslides are in areas with histories of landsliding or at localities where slopes are unstable under nonseismic conditions. Some materials, such as the loess of central Asia and the pumice of the Guatemalan highlands, form steep, high slopes under nonseismic conditions yet disintegrate readily in seismic shaking. In addition, few earthquake-induced landslides reactivate old landslides. Indicators of landslide susceptibility under nonseismic conditions thus should be applied with caution to earthquake-induced landslides; accurate prediction of landslides caused by earthquakes requires analysis of materials and geologic environments that are particularly susceptible to landslides when the triggering mechanism is seismic shaking.

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