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STATISTICAL ANALYSIS OF FACTORS AFFECTING LANDSLIDE DISTRIBUTION IN THE NEW MADRID SEISMIC ZONE, TENNESSEE AND KENTUCKY

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ABSTRACT

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More than 220 large landslides along the bluffs bordering the Mississippi alluvial plain between Cairo, Ill., and Memphis, Tenn., are analyzed by discriminant analysis and multiple linear regression to determine the relative effects of slope height and steepness, stratigraphic variation, slope aspect, and proximity to the hypocenters of the 1811–12 New Madrid, Mo., earthquakes on the distribution of these landslides. Three types of landslides are analyzed: (1) old, coherent slumps and block slides, which have eroded and revegetated features and no active analogs in the area; (2) old earth flows, which are also eroded and revegetated; and (3) young rotational slumps, which are present only along near-river bluffs, and which are the only young, active landslides in the area.

Discriminant analysis shows that only one characteristic differs significantly between bluffs with and without young rotational slumps: failed bluffs tend to have sand and clay at their base, which may render them more susceptible to fluvial erosion.

Bluffs having old coherent slides are significantly higher, steeper, and closer to the hypocenters of the 1811–12 earthquakes than bluffs without these slides. Bluffs having old earth flows are likewise higher and closer to the earthquake hypocenters.

Multiple regression analysis indicates that the distribution of young rotational slumps is affected most strongly by slope steepness: about one-third of the variation in the distribution is explained by variations in slope steepness. The distribution of old coherent slides and earth flows is affected most strongly by slope height, but the proximity to the hypocenters of the 1811–12 earthquakes also significantly affects the distribution.

The results of the statistical analyses indicate that the only recently active landsliding in the area is along actively eroding river banks, where rotational slumps formed as bluffs are undercut by the river. The analyses further indicate that the old coherent slides and earth flows in the area are spatially related to the 1811–12 earthquake hypocenters and were thus probably triggered by those earthquakes. These results are consistent with findings of other recent investigations of landslides in the area that presented field, historical, and analytical evidence to demonstrate that old landslides in the area formed during the 1811–12 New Madrid earthquakes.

Results of the multiple linear regression can also be used to approximate the relative susceptibility of the bluffs in the study area to seismically induced landsliding.

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INTRODUCTION

Among the most dramatic effects of the New Madrid earthquakes of 1811–12 were numerous landslides along the bluffs bordering the Mississippi alluvial plain in western Tennessee and Kentucky. In his report of a field investigation of the New Madrid earthquakes conducted in 1904, Fuller (1912, p.59) stated: "Probably no feature of the earthquake is more striking than the landslides developed in certain of the steeper bluffs ... From the vicinity of Hickman in southwestern Kentucky at least to the mouth of the Obion River, about halfway across the state of Tennessee ... the landslides are a striking feature. Skirting the edge of the bluffs, in the vicinity of Reelfoot Lake, a characteristic landslide topography is almost constantly in sight ...".

Although a few historical descriptions of the landslides resulting from the 1811–12 earthquakes exist, no studies, either historical or contemporary, have examined the distribution of landslides triggered by the earthquakes and the factors related to that distribution. The present study examines some factors related to landsliding — stratigraphic variation, slope height and steepness, hypocentral distance to the 1811–12 earthquakes, and slope aspect — and uses discriminant analysis and multiple linear regression to relate these factors to landslide distribution in a part of the New Madrid seismic zone.

The statistical analyses will test the hypothesis that each of these factors significantly influences the landslide distribution. Rejection of that hypothesis for any of the factors will indicate that that factor does not measurably affect the distribution of landslides in the area. Those factors significantly affecting landslide distribution can then be used to determine the probable origin of the existing landslides and to estimate the potential for future landsliding in the area.

Widespread landsliding along bluffs in the New Madrid seismic zone was documented and described in detail in recent investigations (Jibson and Keefer, 1988; Jibson, 1985). Field and historical evidence presented in those studies suggests that many of these landslides formed during the 1811–12 New Madrid earthquakes. Preliminary statistical analyses of the regional distribution of these landslides (Jibson and Keefer, 1984) indicate that several factors normally related to slope stability, including the estimated severity of ground shaking from the 1811–12 earthquakes, correlate with the distribution of landslides in the area and thus probably influenced that distribution.

The area investigated includes more than 300 km of bluffs forming the eastern edge of the Mississippi alluvial plain between Cairo, Ill., and Memphis, Tenn. (Fig.1). These bluffs are in the epicentral region of the 1811–12 New Madrid earthquake sequence, which produced thousands of shocks including three major events having estimated surface-wave magnitudes (M_s) between 8.4 and 8.8 (Nuttli and Herrmann, 1984).

The study area lies on the eastern flank of the northern Mississippi embayment, a broad, south-southwest plunging syncline whose axis approximately coincides with the Mississippi River. Embayment deposits exposed in the bluffs thus generally dip no more than about 20° to the west-northwest in

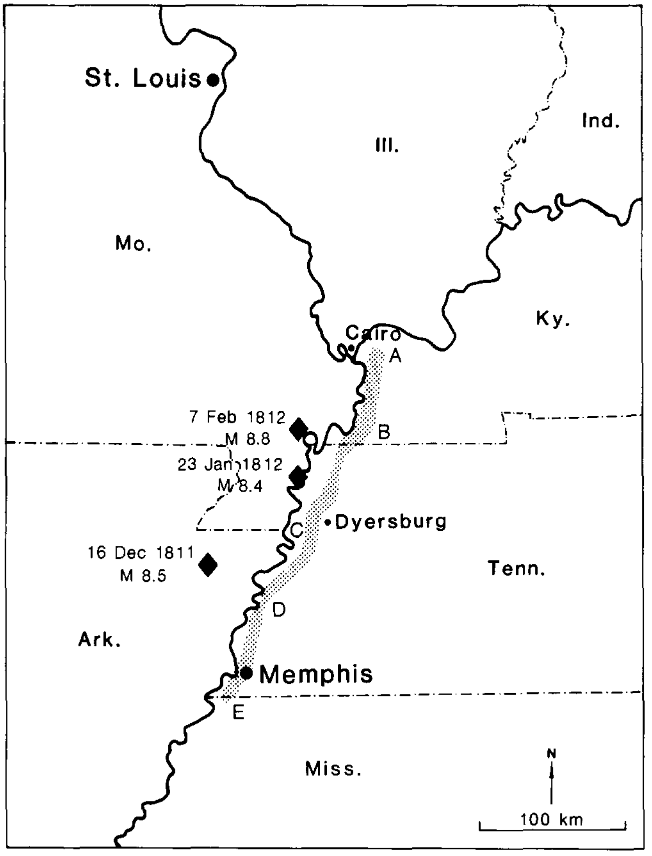


Fig.1. Location map showing study area (shaded) and the estimated epicenters, dates, and surface-wave magnitudes of the 1811–12 earthquakes (from Nuttli, 1973; Nuttli and Herrmann, 1984).

most of the area. The region is seismically active, as evidenced by the 1811–12 earthquake sequence and continuing seismicity.

The average height of the bluffs in this area is 35 m, though in some areas the bluffs reach heights of 70 m. Slope angles of the bluffs range from a few degrees to vertical; most bluffs have 15–25° slopes. The bluffs trend north-northeast, approximately parallel to the Mississippi River. Locally, however, the bluff-line is sinuous where the river has eroded arcuate meander scars.

The Eocene Jackson Formation (Conrad, 1856) forms the base of the bluffs throughout most of the study area. Exposures as thick as 45 m are present. The composition of the Jackson Formation is highly variable; it generally consists of discontinuous layers of shallow-marine embayment deposits of clay and silt ranging from a few centimeters to several meters thick. In some areas the Jackson Formation contains clean, uncemented sand layers as thick as several meters interbedded with soft clays. The Eocene beds generally dip a few degrees west-northwest (out of the bluff face in most of the area), but the amount and direction of dip vary locally; the amount of dip is generally less than 20°. The unconformity on top of the Eocene section is highly irregular. In areas where it has been mapped, this surface is approximately parallel to the present ground surface.

Lying unconformably on the Jackson is as much as 20 m of Pliocene terrace gravels and sands of the Lafayette Formation (McGee, 1891; Potter, 1955). The gravel and sand lenses are commonly uncemented but at some localities contain concretionary beds as much as 2 m thick. The Lafayette is locally saturated where water tables are perched and is probably subject to large seasonal fluctuations in groundwater conditions. The unit pinches out in some areas.

The bluffs are capped by 5–50 m of Pleistocene loess lying unconformably on the Lafayette and Jackson Formations. The average thickness of the loess in the area is about 15 m. Loess is glacially derived, eolian silt that commonly forms vertical faces owing to the presence of vertical fractures. Vertical slopes can be supported because the loess in the study area has cohesion imparted by a clay binder or calcareous cementation or both (Krinitzsky and Turnbull, 1969).

DESCRIPTION OF LANDSLIDES

Along the bluffs in the study area, 221 large (greater than 50 m wide) landslides were identified on airphotos and subsequently examined on the ground. These landslides were plotted on an inventory map and classified morphologically (after Varnes, 1978) as described by Jibson and Keefer (1988) and Jibson (1985). Three classes of landslides were mapped: old coherent slides, earth flows, and young rotational slumps. The existence of the landslides was also classified with respect to certainty as *definite*, *probable*, or *questionable*. The relative numbers and characteristics of the different landslide classes are summarized in Table I.

Old coherent slides

Old coherent slides (Fig.2) constitute 65% of the landslides. Included in this class are both translational (block) slides and rotational (slump) slides, both of which remained intact or coherent. All the slides are eroded and revegetated and show no sign of activity for at least the past several decades. These landslides are deep-seated (typically deeper than 20 m, as judged from landslide geometries and subsurface investigations) and have basal shear surfaces in the clayey Eocene materials that form the base of the bluffs.

Translational and rotational slides were grouped together because heavy tree cover and eroded features generally made it impossible to distinguish between them. Where distinctions could be made, nearly equal numbers of translational and rotational slides were recognized.

The translational block slides are characterized by horst-and-graben topography consisting either of one or few large horst blocks with broad, interven-

TABLE I

Landslide characteristics

	Old coherent slides	Young rotational slumps	Earth flows
Number:			
Definite	73	16	26
Probable	43	5	11
Questionable	30	3	14
Total	146	24	51
Length (m):			
Minimum	60	60	90
Median	180	150	180
Maximum	4180	240	460
Width (m):			
Minimum	80	170	80
Median	400	500	370
Maximum	2350	2450	3540
Slope height (m):			
Minimum	10	10	20
Median	40	40	30
Maximum	80	60	80
Slope angle (°):			
Minimum	6	13	6
Median	18	23	15
Maximum	31	34	28

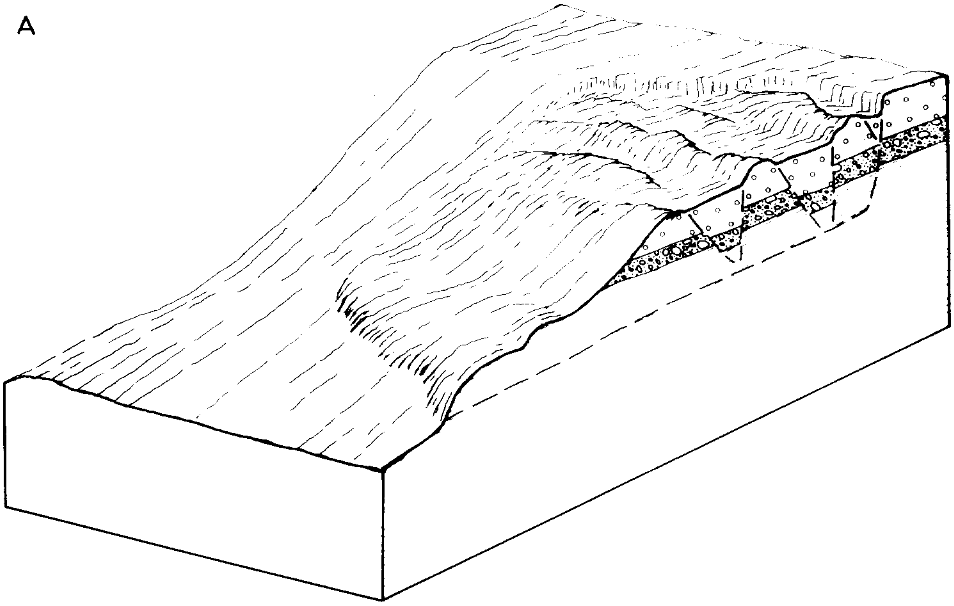
ing grabens, or of several smaller horst-and-graben blocks arranged in stair-step fashion (Fig.3). The toe areas commonly have pressure ridges where soil at the base of the slope was presumably compressed and deformed as the landslide blocks moved down and out from the parent slope. These landslides have basal shear surfaces inclined 4–25° from the horizontal and have moved as much as 100 m.

The old rotational slumps (Fig.2) are characterized by either single or multiple rotational blocks that in most cases appear to have rotated a large amount (Fig.4) relative to the younger slumps. Several of these slides had sag ponds at their heads, but few of these remain owing to headward erosion of gullies and draining of the ponds.

The old coherent slides all appear to be of similar age based on amount of scarp retreat, degree of erosion of ridges, vegetation density and age on scarps and disrupted areas, and other evidence discussed by Jibson (1985).

Jibson (1985) conducted a stability analysis of a translational block slide near Dyersburg, Tenn., that was chosen as being representative of the old coherent slides in the area. The investigation included: (1) drilling to determine stratigraphy, measure in-situ soil properties, and retrieve undisturbed soil samples; (2) laboratory testing to determine soil index properties (grain-size distribution, Atterburg limits, bulk density, water content) and shear

A



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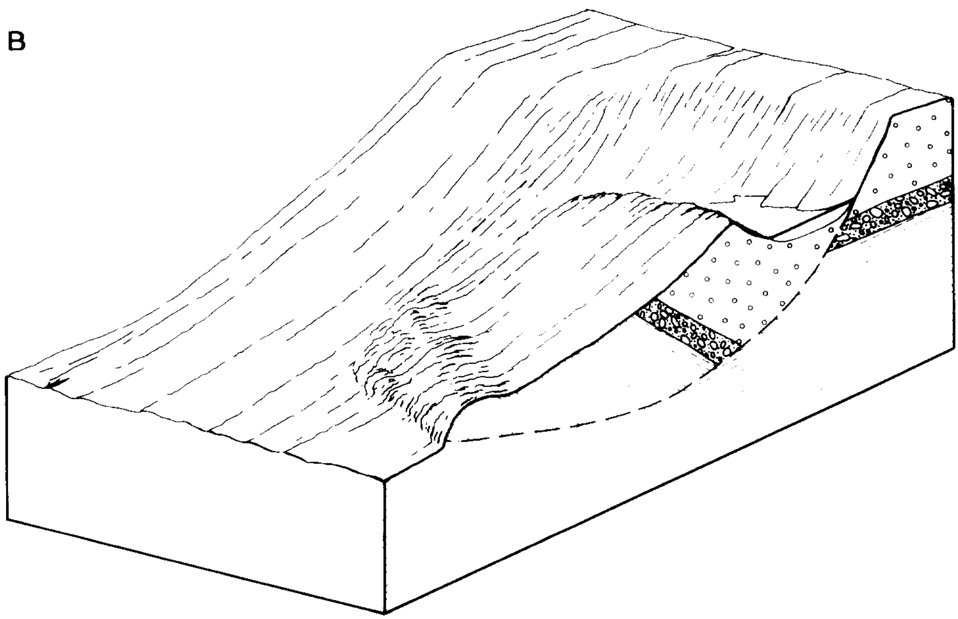

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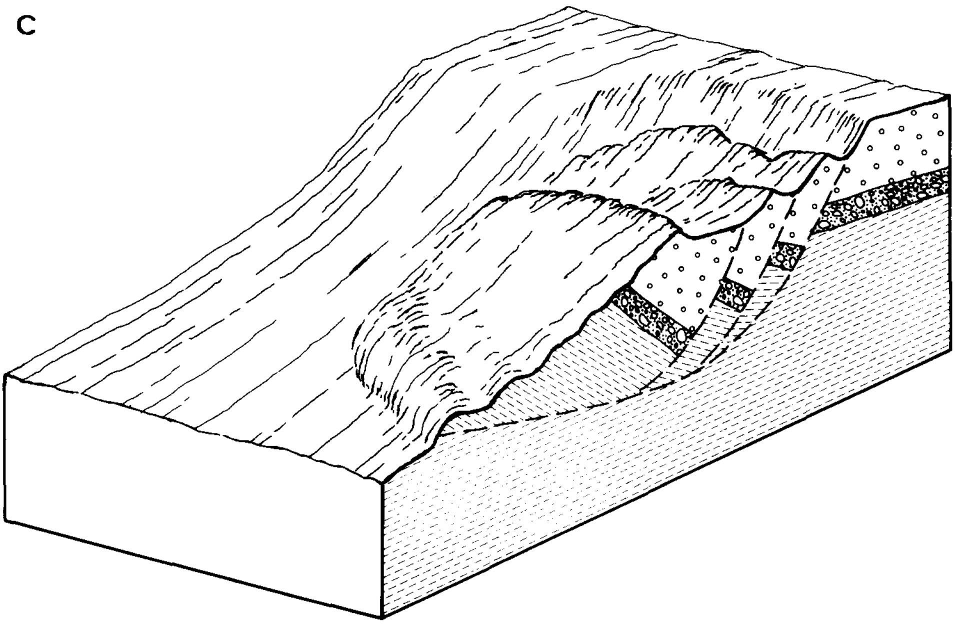

Fig.2. Generalized drawings of old coherent landslides in the study area, all of which are eroded, revegetated, and have not been active for at least several decades. The heavy dashed line denotes the slip surface; the Jackson Formation is shown by the parallel dashed pattern, the Lafayette Formation by the cobble pattern, and the loess by the small open circles. A. Translational block slide, characterized by horst-and-graben topography and hummocky compressional toe. B. Single-block rotational slump, characterized by a massive single slump block rotated a large amount and relict sag ponds on the head. C. Multiple-block rotational slump, characterized by a large initial slump block and successive smaller blocks forming a stepped head and scarp.

strengths (peak and residual drained strength from cyclic direct shear, undrained strength from triaxial shear); (3) detailed modeling of the shear strength, bulk density, and water content in the pre-landslide bluff; (4) analyzing the static slope stability in a broad range of groundwater conditions; and (5) analyzing the dynamic slope stability (using the Newmark (1965) displacement analysis) to estimate the effects of the 1811–12 earthquakes.

Results of the investigation show that, in aseismic conditions, the minimum factor of safety*[1] in the worst possible groundwater condition (when the water table is at the top of the bluff, and seepage occurs along the entire bluff face) is 1.32, which indicates that the bluff is statically stable even in an unrealisti-

*[1]The factor of safety (FS) is the ratio of forces tending to inhibit or resist slope movement (shear resistance) to those tending to initiate slope movement (shear stress). Thus, slopes having factors of safety greater than unity are stable; those having factors of safety less than unity are unstable and will undergo deformation.

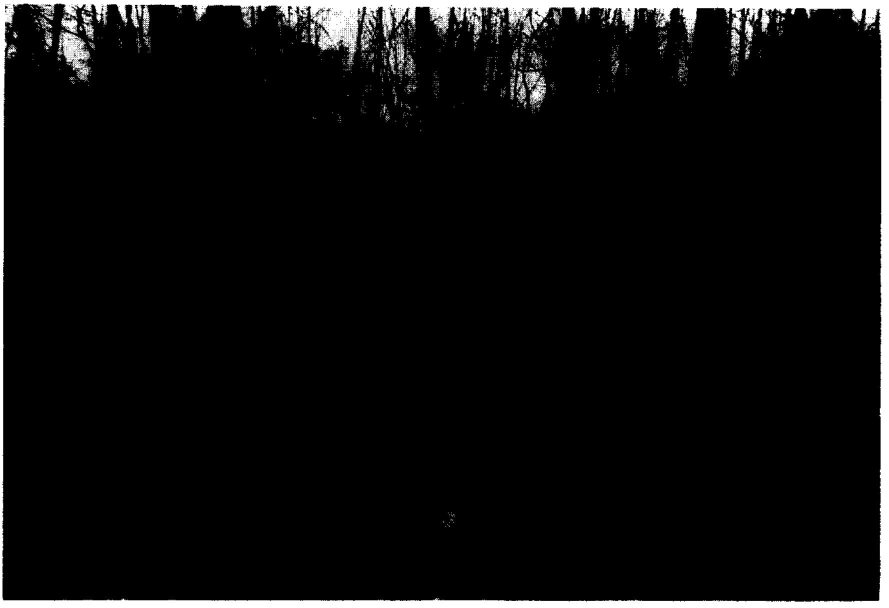

Fig.3. Graben near the head of a translational block slide near Dyersburg, Tenn.

Fig.4. Single-block rotational slump east of Reelfoot Lake, Tenn. The tree-covered area to the left of the road is the main slump block, which has rotated a large amount. The arrow on the left indicates the toe of the landslide; the arrow on the right indicates the top of the head scarp.

cally high groundwater condition. In the most likely groundwater scenario, the minimum factor of safety is 1.82. Therefore, this landslide probably could not have formed in aseismic conditions.

The dynamic analysis shows that, regardless of groundwater conditions, even if the water table is below the basal shear surface, earthquake shaking of severity similar to that produced in 1811–12 would induce enough displacement in the slope to reduce soil strengths to residual values and lead to catastrophic failure of the bluff.

Earth flows

Earth flows (Fig.5) constitute 24% of the landslides. Characteristic features are gently hummocky topography and ridges of accumulated material in the toe area (Fig.6). Earth flows tend to form on the lowest, gentlest slopes, on the average, of the three landslide classes (Table I). The morphology of the heads of some of the earth flows indicates that initial movement may have involved slumping, which then changed to earth flow as the landslide moved downslope. A few earth-flow complexes that have been cleared of timber contain active earth flows that have fractured ground and show evidence for slope movement in the last several years (Fig.7). The majority of the earth flows, however,

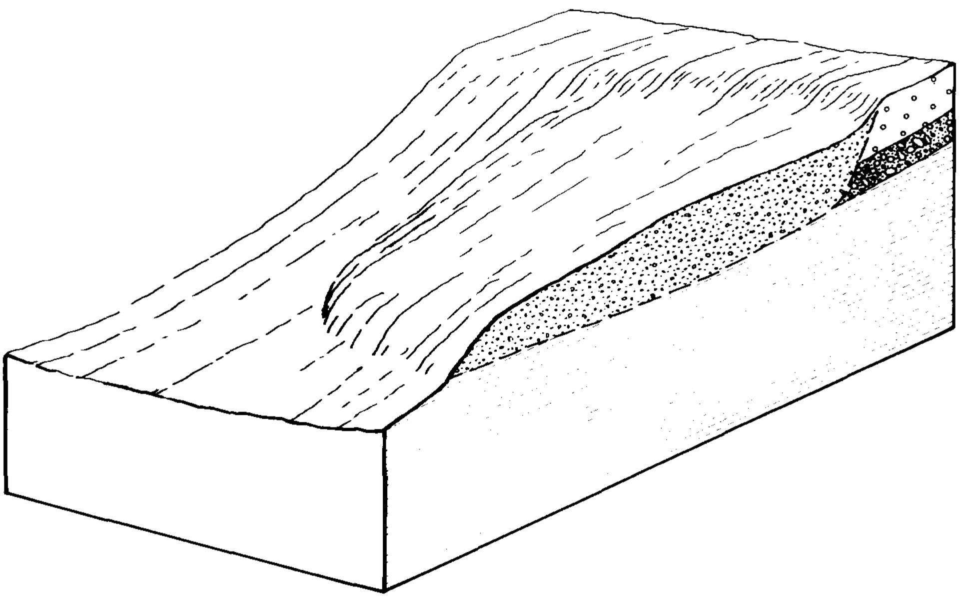

Fig.5. Generalized drawing of earth flow in the area. Descriptions of symbols are given in Fig.2. Earth flow topography is subdued and is characterized by broad, bowl-shaped head-and-scarp areas, hummocky bodies, and gently bulging toes. Except for a few instances where vegetation has been cleared, earth flows in the area are eroded, revegetated, and show no signs of movement in the last several decades. Above the heavy dashed line indicating the slip surface is slightly to moderately disrupted landslide material from all three stratigraphic units.

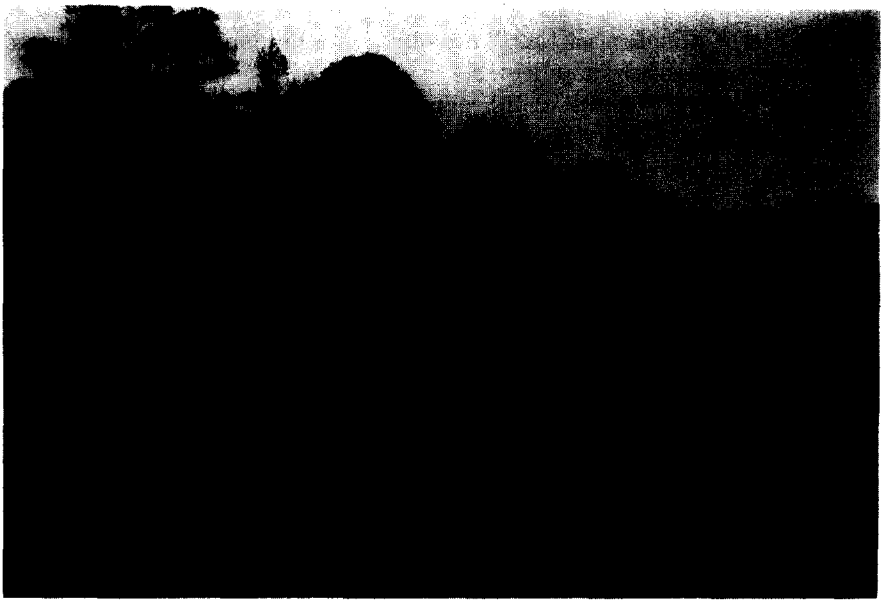

Fig.6. Gently bulging toe of an earth flow near Lenox, Tenn.

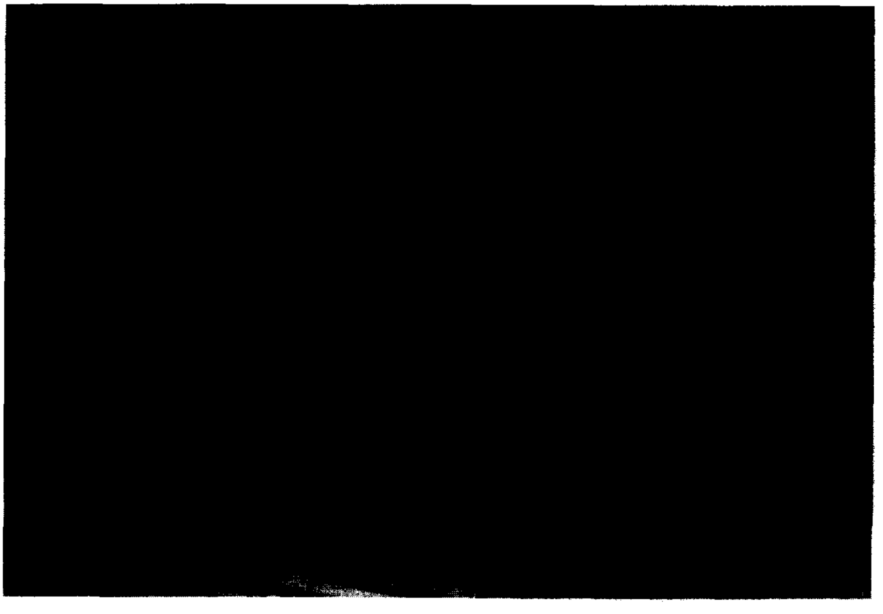

Fig.7. Active part of older earth flow complex near Lenox, Tenn. The older, bowl-shaped head and scarp is visible upslope from the open ground cracks on the active part of the landslide. The few active or recently active earth flows in the area occur where vegetation has been cleared.

including all those on forested slopes, are eroded and revegetated and show no sign of movement for at least the past several decades. The degree of erosion and revegetation appears similar to that on the old coherent slides.

A representative earth flow near Lenox, Tenn., was analyzed (Jibson, 1985) in the same manner as the old coherent slide described above. The static slope stability analysis yielded a minimum factor of safety of 1.30 in the worst possible groundwater scenario; in the most likely scenario the factor of safety was 2.05. This indicates that the earth flow probably could not have formed in aseismic conditions. The dynamic analysis showed that large displacements and catastrophic slope failure would result from ground-shaking similar to that experienced in 1811–12.

Young rotational slumps

The remaining 11% of the landslides are young rotational slumps (Fig.8). Bluffs containing young slumps were located on a map showing historic channels of the Mississippi River (Fisk, 1944); the young slumps are present only along bluffs where the Mississippi River has impinged since 1820. Approximately 30 km of bluffs, or 11% of the overall length, has been subject to fluvial erosion since that time. The young slumps occur on the steepest, highest slopes, on the average, of the three landslide classes (Table I) and are

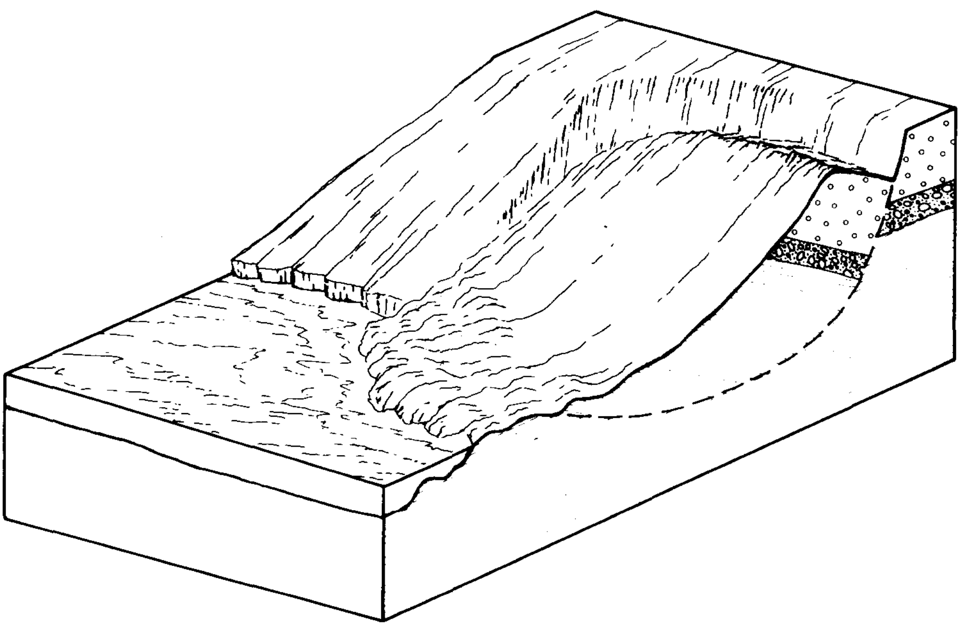

Fig.8. Generalized drawing of young rotational slump. Descriptions of symbols are given in Fig.2. These landslides are characterized by a massive single slump block that has rotated a small amount; by steep, fresh scarps; and by disrupted or young vegetation. Young slumps form where the river channel impinges on and oversteepens the bluff.

Fig.9. Young slump shown at flood stage along the Mississippi River. Note the steep, bare scarp and the small amount of rotation compared to the old slump shown in Fig.4.

characterized by massive single slump blocks that form where the river has undercut the bluffs (Fig.9). They are differentiated from old slumps on the bases of less rotation, less eroded scarps and heads, absence of multiple blocks, and, in some cases, lack of vegetation.

FACTORS AFFECTING LANDSLIDE DISTRIBUTION

Modern theories of soil mechanics are highly refined and have explicitly quantified interrelationships among various factors influencing slope stability. The stability of a slope is normally expressed by the factor of safety, the ratio of forces tending to inhibit or resist slope movement (shear resistance) to those tending to initiate or drive that movement (shear stress).

Factors contributing to the shear resistance of a slope include: (1) the shear strengths of slope materials, typically expressed as friction angle and cohesion for aseismic slope stability, and as total undrained shear strength for seismic slope stability; (2) the bulk densities of the slope materials; (3) the slope geometry; (4) the distribution of pore-water pressure within the soil mass; and (5) the geometry of the potential slip surface.

Factors related to the shear stress within a slope include: (1) the slope geometry; (2) the bulk densities of the slope materials; and, if a slope is subjected to earthquake shaking, (3) the duration of ground accelerations large enough to deform the slope.

Of the above factors, only variation in slope geometry is easily and accurately quantifiable on a regional basis.

Variations in shear strength, pore-pressure distribution, bulk density, and slip-surface geometry vary greatly throughout the area, both between and within geologic units, and accurate measurement of these properties at enough sites to permit quantification of their regional variation is infeasible. Data are either nonexistant or so sparse as to be nearly useless. Variation in ground-shaking from the 1811–12 earthquake sequence is unknown because no seismic instruments existed at that time, and epicentral intensity reports from observers are sparse owing to the small population in the area at the time of the earthquakes.

Despite the inability to measure variations in the parameters explicitly included in factor-of-safety equations, we can measure more easily quantified factors that are indexes of these parameters. For example, existing stratigraphic data allow interpolation along the bluffs of the thicknesses of the formations present. This information may be a useful index of interformational variation in shear strength and bulk density; it may also relate to slip-surface geometry and groundwater distribution. The slope aspect may also relate to slip-surface geometry and groundwater conditions because the regional dip of the stratigraphic section to the west-northwest may make slopes facing in that direction more likely to have potential seepage- and slip-surfaces daylight in the slope face. Intensity of earthquake shaking may also be related to slope aspect, if the pattern of seismic shaking generated by the 1811–12 earthquakes was directional. This possible effect can be examined directly by measuring the slope aspect with respect to the direction to the 1811–12 earthquake epicenters.

Observation and theory indicate that seismic shaking attenuates with distance, so the distance to the estimated 1811–12 earthquake hypocenters provides an easily measured index of the duration and acceleration of the 1811–12 ground-shaking that is independent of specific earthquake source parameters. The lack of strong-motion records for large earthquakes in the central United States makes it infeasible to use more refined ground-motion parameters that take into account duration and acceleration content of strong ground motion, both of which are related to the seismic stability of the slopes being studied (Wilson and Keefer, 1983).

Several different factors used as possible indexes of ground-shaking were substituted individually into the statistical models in place of hypocentral distance to determine if any would yield higher correlations. Epicentral distance, logarithm of epicentral distance, logarithm of hypocentral distance, and the peak ground accelerations estimated using the relationship given by Nuttli and Herrmann (1984) were each substituted. The logarithmic factors were tested because earthquake waves attenuate exponentially (though not linear exponentially) with distance. None of these variations improved the correlation, so hypocentral distance probably is as accurate an index of ground motion as can be used for this analysis.

To provide a framework for measuring spatial variations of index factors, the bluffs were divided into 762-m-long (2500-ft.-long) segments. This length was chosen as the shortest segment length that would result in a manageable data base.

Factors measured or derived for each segment include slope height, slope angle, thickness of each stratigraphic unit, minimum hypocentral distance, sum of the hypocentral distances, slope aspect, and the epicentral angle (defined in the following section).

Quantification of factors related to landslides

Slope height and slope angle relate directly to the factor of safety against slope failure (Hoek and Bray, 1977); both were determined from elevation contours on 1:24,000-scale topographic maps. Where the bluff is of nonuniform height, the average slope height over the segment was determined. Slope-angle measurements are probably less accurate in some cases than those of slope height because the map scale requires too close a spacing between contour lines for accurate representation of slopes steeper than about 40°. Except in those areas along active river banks, however, few slopes steeper than 40° were observed in the study area. Another difficulty arose because many slopes have complex profiles and thus have a continuous variation in slope angle; therefore, the angle between the base and the crest of the slope was used. This method presumably yields a consistent index of relative slope steepness.

To characterize the stratigraphic variation as accurately as possible, we compiled all available stratigraphic data on a cross-section of the bluffs and interpolated across segments between data locations. Several information sources were used: Roberts and Collins, 1928; Whitlatch, 1940; M.L. Marcher and R.E. Lounsbury, 1959, unpublished data; Schreurs and Marcher, 1959; Olive, 1967, 1974; Moore and Brown, 1969; Finch, 1971a, b; Lee, 1974; Hart, 1979; Jibson, 1985.

The Eocene Jackson Formation ranges in composition in the area from almost entirely silty clay to mostly sand that contains thinner clay interbeds. Available data suggest that the clay facies predominates in the northern half of the area, from the Forked Deer River, near Dyersburg, Tenn. (Fig.1), northward, and that the sand-with-clay facies predominates in the southern half. The thickness and the facies of the Jackson Formation at each bluff segment were recorded from the observed or interpolated stratigraphic data.

The distance from each of the estimated hypocenters of the three largest earthquakes in the 1811–12 sequence to each bluff segment was measured, and the minimum distance between the bluff segment and a hypocenter was determined. Also, the sum of the three hypocentral distances was determined and used as an index of the proximity, collectively, to the entire earthquake sequence rather than to any one of the events. A significant influence of this factor on landslide distribution would suggest that repeated exposure to strong ground-shaking reduced the stability of a bluff segment.

The approximate epicenter locations shown in Fig.1 are from Nuttli (1973) and Hopper et al. (1983). These locations were estimated using intensity data gleaned from early newspaper accounts of the earthquakes as well as from subsequent field investigations of the geologic effects in the epicentral region. Though the locations of the epicenters are approximate, they represent the best current estimates. Focal depths are estimated to be 40 km (Nuttli and Herrmann, 1984).

Slope aspect was determined by measuring the azimuth perpendicular to each bluff segment on topographic maps. Also measured was the angle (hereafter called the epicentral angle) between this slope aspect and the perpendicular to the line connecting the estimated epicenters of the 1811–12 earthquakes.

Distribution of landslides

Figure 10 shows the spatial distributions along the bluffs of the definite and probable landslides (those considered in the statistical analyses) belonging to the three morphological classes.

Young rotational slumps (Fig.10a) are present only along recently active river bluffs and thus probably result from fluvial erosion along the bases of these bluffs (Jibson and Keefer, 1988; Jibson, 1985). The only near-river parts of the bluffs free from landslides are the reveted areas in and around Memphis that are continually monitored and protected from erosion and slope failure by engineering works. By contrast, almost two-thirds of the length of unprotected, near-river bluffs are covered by young rotational slumps. No young slumps are present along parts of the bluffs away from the river.

Old coherent slides (Fig.10b) are distributed nearly uniformly along the bluffs in the study area, although they are slightly less heavily concentrated in the central part of the area and at the extremities.

Earth flows (Fig.10c) predominate in the central area; a few are also scattered throughout the rest of the area. The area of earth flows extends both north and south of the boundary separating the clay from the sand-with-clay facies of the Jackson Formation, which suggests that the distribution of earth flows is unaffected by this facies change, though the distribution may be affected by some other geologic factor not measured in this analysis. Earth flows are concentrated in the area nearest to the hypocenters of the New Madrid earthquakes, which suggests that they are triggered by stronger ground shaking than the other types of landslides.

Effects of various factors on landslide distribution

To examine general trends in landslide distribution with respect to several of the factors, we grouped the bluff segments by incremental values of each factor; the corresponding values of landslide incidence were then averaged for each increment. Because young rotational slumps occur only along actively eroding river banks, only the incidence of old coherent slides and earth flows was plotted. The factors examined in this way include slope height, slope angle, minimum hypocentral distance, sum of the hypocentral distances, slope

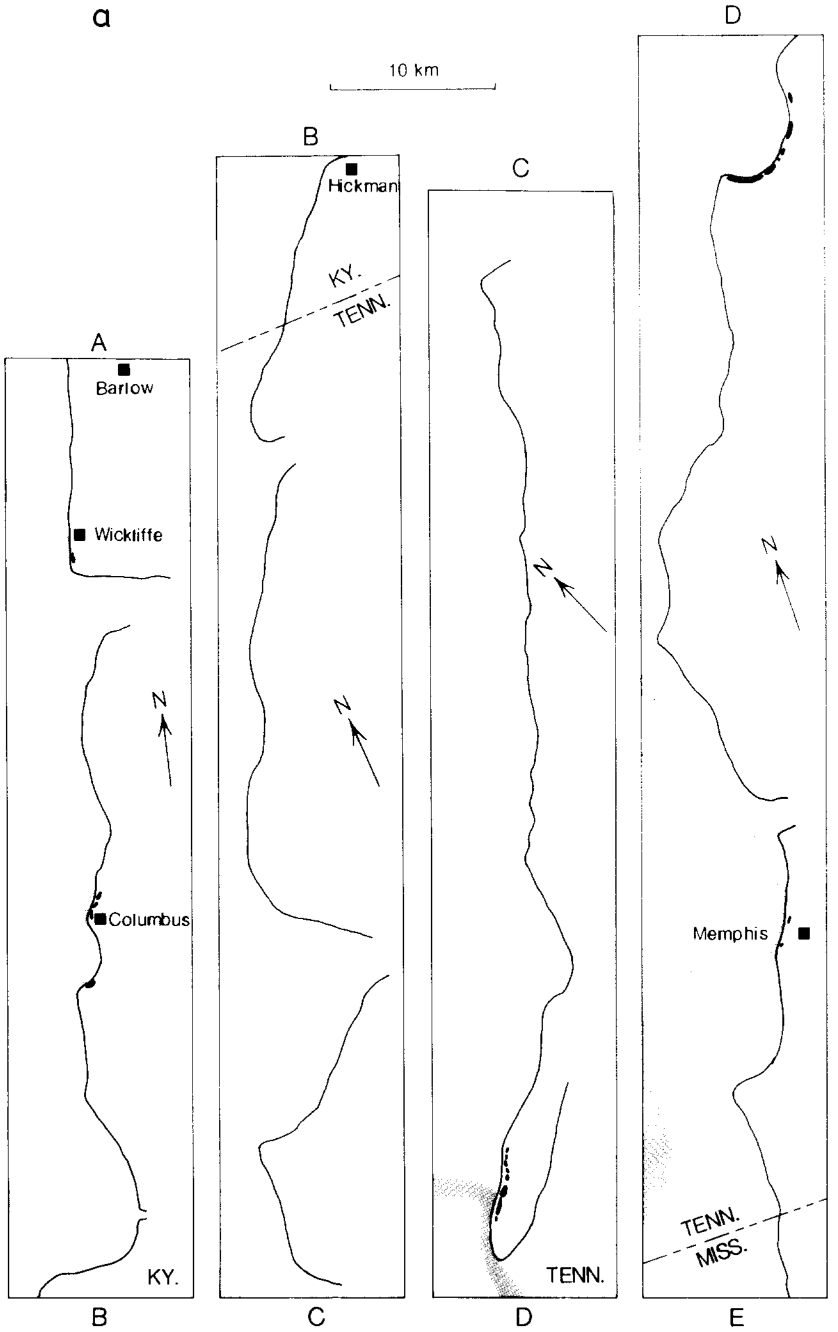
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Fig.10a

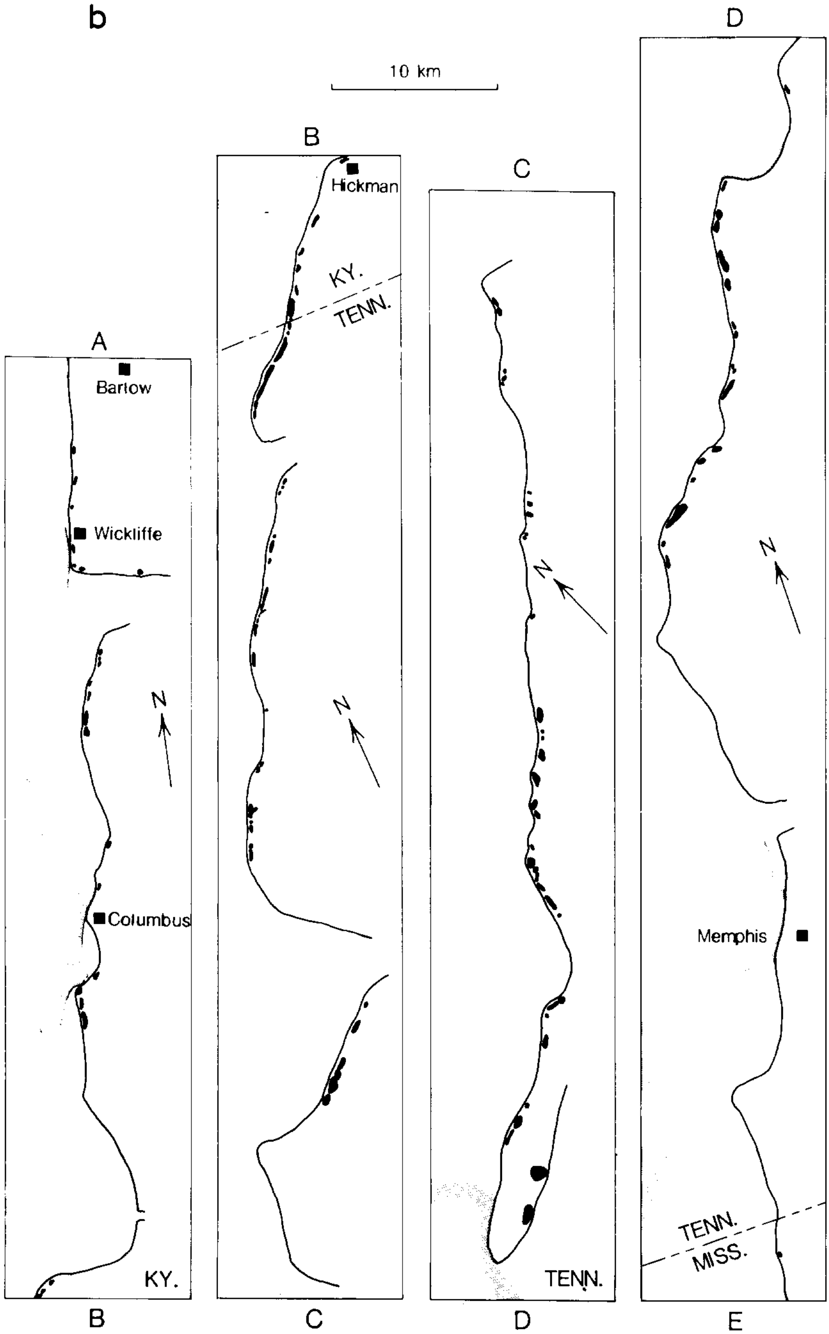
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Fig.10b

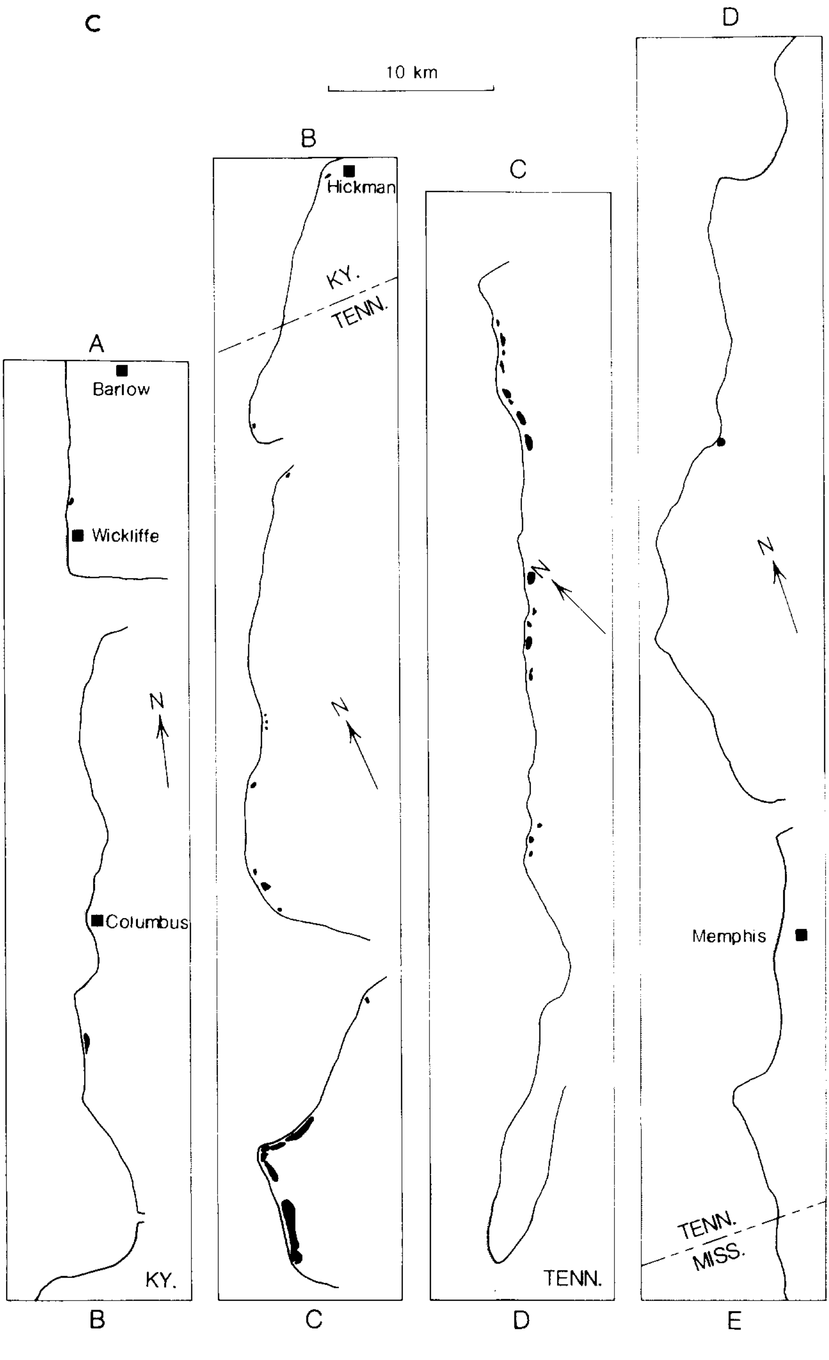

Fig.10. Strip maps of the bluffs in the study area showing the distribution of young rotational slumps (a), old coherent slides (b), and earth flows (c). The heavy line denotes the base of the bluff; areas east of this line are uplands; areas to the west are alluvial plains. Landslides are shown in black; the Mississippi River is shown in gray.

aspect, and epicentral angle. These factors were chosen because they were more accurately measured than the stratigraphic thicknesses. Also, much of the variation in stratigraphic thickness is directly related to slope height.

Slope height was grouped into 3-m increments, slope angle into 5° increments, minimum hypocentral distance into 10-km increments, and sum of the hypocentral distances into 40-km increments. Figure 11 shows that all of the resulting plots have very good best-fit lines, which indicates that increased incidence of old coherent slides and earth flows is related to increases in slope height and slope angle, and decreases in the minimum distance and the sum of the distances to the estimated 1811–12 earthquake hypocenters.

The effect of slope angle is more accurately characterized by a two-segment line, shown dashed in Fig.11B. This suggests that for slopes steeper than about 16° the average incidence of these landslides is independent of slope angle, whereas for slopes less than 16° slope angle affects landslide occurrence.

Figure 12 shows rosette plots of average landslide incidence versus slope aspect (in 20° increments) for different classes of landslides. Old coherent slides

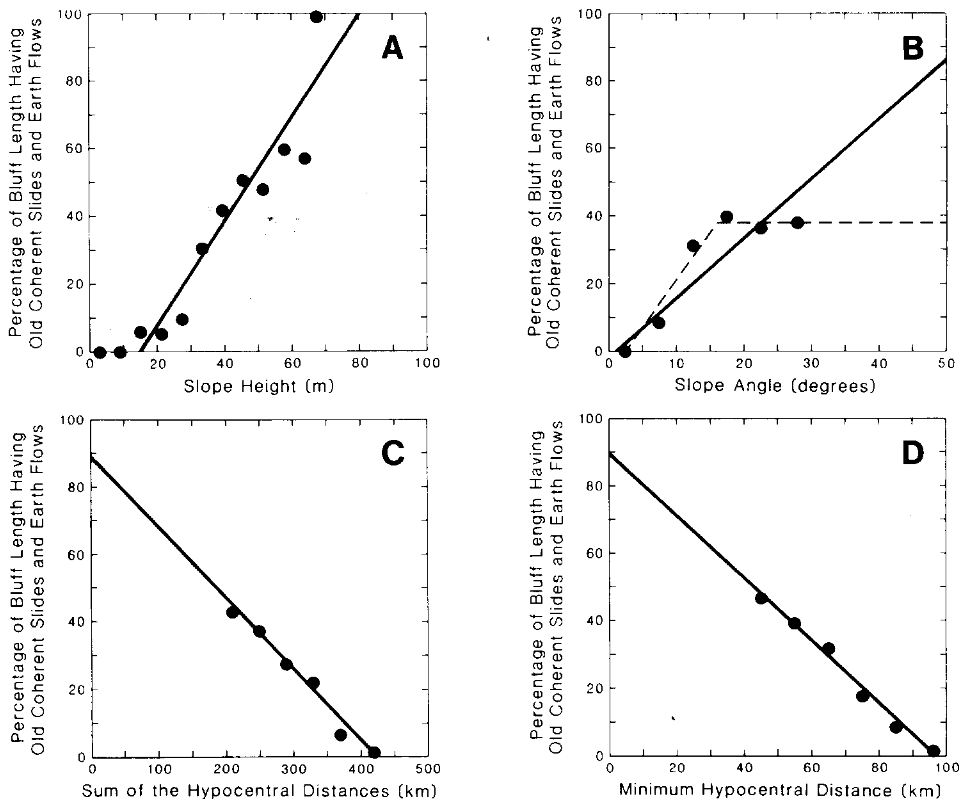

Fig.11. Incrementally averaged plots showing incidence of old coherent slides and earth flows versus: A. slope height; B. slope angle; C. sum of the hypocentral distances; and D. minimum hypocentral distance. Dashed line in B suggests that slope angle may have no effect on landslide incidence for slopes steeper than about 16°.

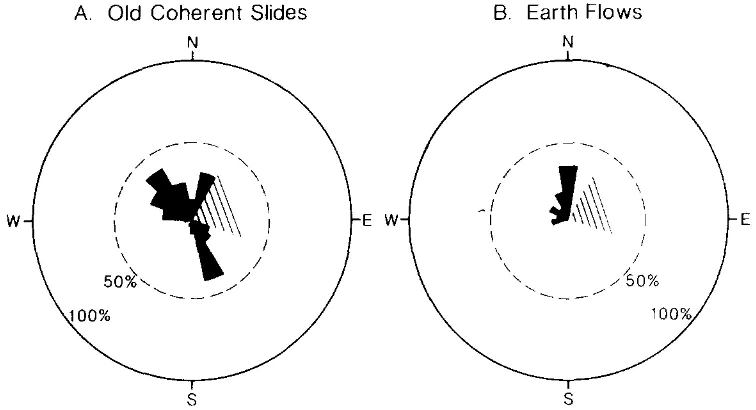

Fig.12. Rosette plots showing average incidence of old coherent slides (A), and earth flows (B), for different slope aspects. Hachured areas denote directions in which no bluff segments face.

(Fig.12A) are notably absent on bluffs oriented between 170° and 270°, and the large spikes at 10–30° and 150–170° represent averaged landslide incidence from only 7 of the more than 400 bluff segments in the area. Thus, the large majority of old coherent slides are on bluffs facing within several degrees of west-northwest (300°), which suggests that the regional dip in that direction affects landslide distribution. A preferred direction of strong ground motion from the earthquakes may also have an effect.

Figure 12B shows the orientation of bluffs containing earth flows. Virtually all earth flows formed along bluffs facing between 160° and 280°, and the large spike facing due north reflects average landslide incidence from only six bluff segments. This predominantly west-northwest-facing distribution again strongly suggests that the regional dip affects the distribution of earth flows.

Figure 13 shows the relation between landslide incidence and epicentral angle plotted over 20° increments. For old coherent slides (Fig.13A) the plot is similar to the previous one: landslides are absent between −60° and −140°. The hour-glass shape of the plot may indicate that the epicentral angle affects opposite-facing bluffs similarly. For earth flows (Fig.13B) virtually all the landslides occur on bluffs having epicentral angles between 60° and −60°; they are equally distributed on either side of zero. This suggests that the distribution of earth flows in the area is affected by the epicentral angle.

STATISTICAL ANALYSIS OF LANDSLIDE DISTRIBUTION

Plotting averaged data is useful to see general trends of individual variables, but more rigorous statistical analyses that measure the effect of a large number of factors individually and collectively are more effective techniques whereby the interrelationship between these factors and landslide distribution can be quantified. Statistical analyses were conducted for two purposes: (1) to

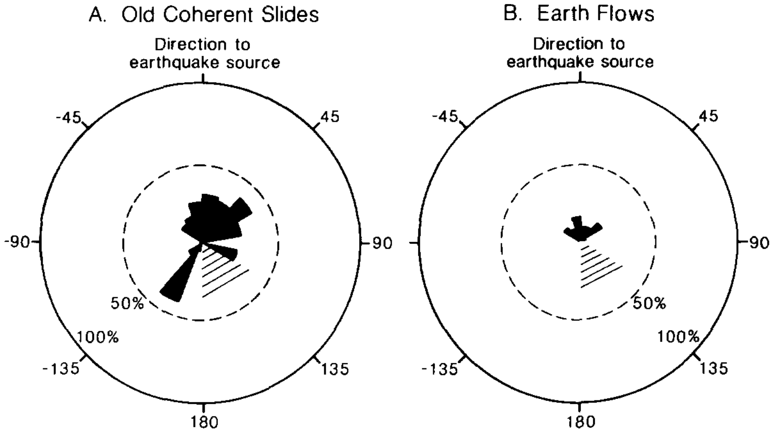

Fig.13. Rosette plots showing average incidence of old coherent slides (A), and earth flows (B), for different epicentral angles. Hachured areas denote ranges of angles for which no data exist.

detect and measure correlation between each of the factors and landslide incidence singly and as a group in order to better understand the origins of the existing landslides; and (2) to model landslide incidence as a function of the significant variables in order to assess relative susceptibility to seismically induced landsliding in future earthquakes.

Two types of statistical analysis were performed: (1) a discriminant analysis, which shows statistical differences between samples; and (2) multiple linear regression, which compares all factors possibly related to landsliding simultaneously with landslide incidence to see what combination best accounts for the landslide distribution. We used the simplest, linear models as a first approximation because most of the index factors being tested are not explicitly related to slope stability or landslide incidence by any currently known empirical or theoretical equations. Nonlinear factors were introduced in subsequent analyses, but none improved correlation. In each analysis, values at each bluff segment for each of the quantified factors were treated as independent variables. The dependent variables were the percentages of bluff length occupied by definite and probable landslides of the three morphological classes. The MINITAB program (Pennsylvania State University, 1982) was used to conduct all analyses.

The independent variables were tested for cross-correlation by simple regression. Table II shows the correlations between the independent variables in terms of the coefficient of determination (R^2), which is the percentage of variation in one variable explained by the other. Values of R^2 greater than about 25% are considered to be of practical significance (P. Switzer, Stanford University Statistics and Geology Departments, pers. commun., 1984; R. Bernknopf, U.S. Geological Survey, pers. commun., 1985) and are indicated in Table II.

TABLE II

Cross-correlation between independent variables, given as R^2 in percent

	Slope height	Slope angle	Formation thicknesses					Hypocentral distances		Slope aspect
			Loess	Lafay-ette	Jackson (total)	Jackson clay facies	Jackson sand facies	Minimum	Sum	
Slope angle	12.7									
Loess thickness	28.6*	13.5								
Lafayette Fm. thickness	9.8	6.0	24.7							
Jackson Fm. total thickness	29.7*	6.2	11.3	58.8*						
Jackson Fm.: clay facies	17.6	0.0	0.3	11.2	24.8					
Jackson Fm.: sand/clay facies	4.6	8.0	9.9	28.1*	40.6*	12.4				
Minimum hypocentral distance	19.8	0.4	9.1	0.1	1.8	6.4	0.6			
Sum of hypocentral distances	21.2	0.2	8.6	0.0	2.4	2.5	0.1	86.1*		
Slope aspect	6.9	17.7	22.5	22.9	23.0	0.1	29.1*	1.8	2.8	
Epicentral angle	8.6	7.2	28.5*	29.3*	24.7	0.0	29.8*	4.8	9.2	26.5*

*Indicates cross-correlation of practical significance (greater than 25%).

Note: This table is analogous to the simple correlation matrix used to measure multicolinearity. Such a table can be constructed from the data above by dividing each R^2 value by 100% and taking the square root to obtain r, the correlation coefficient.

Some of the variables have significant cross-correlation (for example, slope height and loess thickness, Table II). That some groups of variables should be correlated, such as the earthquake-related variables with each other and stratigraphic thicknesses with slope height, is obvious. A few of the correlated variables are not so easily explained, however; these include the correlation of slope aspect and epicentral angle with several of the stratigraphic variables. The effect of cross-correlations will be discussed below as they relate to each analysis.

Discriminant analysis

A discriminant analysis was conducted for each class of landslide by separating the bluff segments into two groups: (1) those containing landslides or parts of landslides of a certain class; and (2) those not containing landslides of that class. The independent variables from these two samples were then statistically compared for each landslide class to determine which of them would enable discrimination between bluffs where those landslides did and did not occur. The means and standard deviations of the two samples and a t-statistic were calculated using a formula given by Ryan et al. (1976, p.141). From the t-statistic, the attained significance, P, which is the probability that the two samples are statistically identical, was determined (Ryan et al., 1976). Results of the discriminant analysis are shown in Table III.

Young rotational slumps

The young rotational slumps are present only along those 28 bluff segments, out of a total of 375, where the river has impinged on the bluffs within the last several decades. Therefore, comparing areas of landslide incidence with areas away from the river where these landslides are not present is not entirely appropriate. The first four columns in Table III show this comparison including all bluffs, and several of the factors show significant differences. However, the three factors related to earthquakes are the same for the two groups, which confirms the hypothesis that the distribution of young slumps is unrelated to the 1811–12 earthquakes.

The second four columns in Table III use only the natural, near-river bluffs in the analysis. Those near-river bluffs protected by revetment in and near Memphis are not included in the analysis, so the comparison is between bluff segments with and without young rotational slumps in areas where fluvial erosion occurs naturally. Only the thickness of the sand-with-clay facies of the Jackson Formation differs significantly between areas where young rotational slumps do and do not occur along the river banks. This suggests that the Mississippi River may undercut bluffs composed of sand more readily than those composed of clay, though no observations have confirmed this. Most significant, however, is that the values of other factors normally related to slope stability do not differ significantly between locations where young slumps do and do not occur. This suggests that oversteepening of the bluffs by fluvial erosion outweighs all other factors in determining where rotational slumps form in aseismic conditions in the study area.

TABLE III

Results of discriminant analysis

	Young rotational slumps*[1] (all bluffs)				Young rotational slumps*[2] (natural near-river bluffs)				Old coherent slides*[1]				Earth flows*[1]			
	Mean	S.D.	*t*	*P* (%)	Mean	S.D.	*t*	*P* (%)	Mean	S.D.	*t*	*P* (%)	Mean	S.D.	*t*	*P* (%)
Slope height (m)			5.11	0.0*			1.57	22.0			8.13	0.0*			4.78	0.0*
Landslides	44	10			47	8			42	11			43	13		
No landslides	34	15			31	20			30	16			33	15		
Slope angle (°)			6.55	0.0*			1.62	20.0			4.82	0.0*			0.71	48.0
Landslides	24	6			24	6			18	5			16	4		
No landslides	16	6			17	9			15	6			16	6		
Loess thickness (m)			1.98	5.4			2.26	8.6			4.33	0.0*			4.32	0.0*
Landslides	19	8			20	8			20	15			22	10		
No landslides	16	14			11	8			13	13			15	15		
Lafayette Fm. thickness (m)			4.50	0.0*			0.73	52.0			0.72	47.0			2.52	1.3*
Landslides	6	4			6	4			2	7			3	4		
No landslides	2	7			5	5			2	7			2	8		
Jackson Fm. thickness (m)			3.67	0.1*			0.68	54.0			0.99	11.4			3.53	0.1*
Landslides	19	8			20	10			14	11			17	11		
No landslides	12	12			16	13			13	3			11	12		

Jackson Fm.: clay facies thickness (m)			0.11	91.0			1.12	35.0			0.69	49.0			2.20	3.2
Landslides	7	12			8	12			8	10			11	13		
No landslides	7	10			15	13			7	10			6	9		
Jackson Fm.: sand/clay facies thickness (m)			3.29	0.3*			4.99	0.0*			2.11	3.6			1.11	27.0
Landslides	13	11			13	12			7	12			7	9		
No landslides	5	11			0	1			4	11			5	12		
Minimum hypo-central distance (km)			0.60	55.0			0.92	42.0			3.74	0.0*			6.12	0.0*
Landslides	65	8			64	5			60	11			55	10		
No landslides	64	14			68	8			65	15			65	14		
Sum of hypocentral distances (km)			1.49	15.0			1.03	38.0			3.97	0.0*			10.53	0.0*
Landslides	290	38			282	26			256	48			220	31		
No landslides	277	69			301	37			283	74			282	66		
Slope aspect (°)			4.47	0.0*			2.93	2.6			4.27	0.0*			3.73	0.0*
Landslides	317	34			319	35			298	39			301	27		
No landslides	286	42			284	19			279	44			284	45		
Epicentral angle (°)			1.22	23.0			0.30	79.0			2.56	1.1*			6.37	0.0*
Landslides	35	26			35	27			35	32			24	17		
No landslides	41	33			31	24			44	35			44	35		

*[1]Sample size (n) is 375.
*[2]Sample size (n) is 28.
*Indicates that the samples are statistically different at a confidence level greater than 97.5 percent.
Abbreviations: S.D. = standard deviation; P = probability that the samples are identical; t = t-statistic.

Old coherent slides

For old coherent slides, slope height shows the most significant difference ($t = 8.13$): bluffs having landslides average about 12 m higher than those without slides. Average slope angles are 3° steeper where landslides are present. The thickness of the loess overburden, probably related to overall slope height (see Table II), is the only stratigraphic variable that differs significantly; it averages about 8 m greater where landslides occur. The slope aspect differs by about 20° between areas that have and those that do not have landslides; the mean orientation of bluffs having landslides coincides with the regional dip to west-northwest (about 300°). This suggests that the interaction of regional dip with the bluff face affects slope stability. All three factors related to earthquakes, the minimum distance and the sum of the distances to the estimated 1811–12 earthquake hypocenters and the epicentral angle, have significant differences, which conforms to other evidence (Jibson, 1985) showing that these landslides are, indeed, related to the 1811–12 earthquakes. Both the minimum distance and the sum of the distances to the earthquake hypocenters average less at landslide locations. Bluffs having smaller epicentral angles tend to have more landslides than those having greater epicentral angles. This might suggest that the most violent shaking radiated from the earthquake source and thus made bluffs facing directly toward or directly away from the source most susceptible to having landslide blocks pulled away from the parent slope.

Earth flows

For earth flows, the most significant factors are those related to the 1811-12 earthquakes: both the minimum distance and the sum of the distances to the earthquake hypocenters are less where earth flows are more abundant, and bluffs having smaller epicentral angles contain more landslides of this type. This suggests that these landslides formed most readily where ground-shaking was most intense and where it was directed toward the bluff face. Slope height is significantly greater where the earth flows form, as are the thicknesses of the loess and the Lafayette Formation. The slope aspect also differs significantly; the average orientation of bluffs containing earth flows coincides with the west-northwest regional dip.

Differences between landslide classes

Comparison of means and standard deviations shown in Table III can also be used to examine the differences in each factor between bluffs where the different types of landslides are present. Slope height does not differ significantly between bluffs where landslides of the three classes are present; the average height of bluffs having landslides is 40–50 m. Old coherent slides and earth flows are present on slopes of approximately equal steepness (16–18°), but young rotational slumps are present on much steeper slopes (24°), probably as a result of fluvial erosion undercutting the bluffs where they formed.

Few significant differences exist in stratigraphic thicknesses of various units where the different classes of landslides are present. The only significant difference is that young rotational slumps are more abundant where the sand-with-clay facies of the Jackson Formation is present.

The most pronounced difference between the landslide classes is in their proximity to seismic sources. Earth flows tend to be closest to the epicentral area, old coherent slides next closest, and young rotational slumps the farthest from the epicentral area. Locations of the young rotational slumps are constrained by the presence of the river and are strongly affected by the presence of the sand-with-clay facies of the Jackson Formation. Bluffs having these characteristics are coincidentally distant from the earthquake sources, so a comparison of hypocentral distance using young rotational slumps may be inappropriate.

Bluffs containing earth flows and old coherent slides tend to be oriented in about the same direction (298–301°), whereas bluffs having young rotational slumps have a more northerly (317°) average orientation. A much greater difference is seen in the epicentral angle. Both earth flows and old coherent slides have significantly smaller epicentral angles than do the young rotational slumps.

Summary

The discriminant analysis shows that young rotational slumps tend to form where the sand-with-clay facies of the Jackson Formation is present, which may make the bluffs more susceptible to fluvial erosion. However, no other factors differ significantly between where these landslides do and do not occur.

Both old coherent slides and earth flows tend to form where bluffs are higher, where the loess is thicker, where the bluffs face approximately 300°, and, most significantly, on bluffs that are closer to the hypocenters of the 1811–12 earthquakes. These landslides are also more abundant along bluffs having small epicentral angles, though the cross-correlation between this factor and slope aspect ($R^2 = 26.5\%$) makes it unclear which factor relates more strongly. Also, steeper slopes have more old coherent slides than flatter slopes.

Multiple linear regression

A stepwise multiple linear regression analysis was conducted to determine the combined effects of the 11 independent variables. This analysis is useful for determining which factors best account for landslide incidence in the presence of all other factors; specifically, can one factor significantly improve the regression model in the presence of another factor or factors? In this analysis, a test statistic is calculated for each variable in the regression equation. If any are below the 97.5% confidence level, then the smallest one is removed and a new regression equation is calculated. If no variable can be removed, a test statistic is calculated for each variable not in the equation and the largest one is then added provided it is above the 97.5% confidence level. When no more variables can be added or deleted, the procedure ends. The regression equation thus calculated has the form:

$$Y = A + B_1X_1 + B_2X_2 + \ldots + B_nX_n \quad (1)$$

where Y is the dependent variable, X_1, X_2, ..., X_n are the independent variables, A is a constant, and B_1, B_2, ..., B_n are the coefficients of the independent variables.

Coefficients of determination (R^2) and t-statistics are calculated at each step in the analysis. R^2 is the percentage of variation in the dependent variable, landslide incidence, explained by the independent variables. The t-statistic is used to test the null hypothesis that the coefficient of a particular independent variable (B_i) in the regression equation is actually zero. If the null hypothesis is rejected, the coefficient is significantly different from zero and the variable explains a significant amount of variation in the dependent variable. For the sample size in this study, values of the t-statistic greater than 2.58 (2.76 for the near-river, young-rotational-slump data set) lead to rejection of the null hypothesis at the 99.5% confidence level.

Results of the regression analyses are presented for each landslide class as well as for the combined old-coherent-slide and earth-flow classes. This combined data set is used because these landslides are not spatially restricted to bluffs recently undercut by fluvial erosion, as are the young rotational slumps, and because they comprise all the old landslides in the area and are the landslides most likely associated with the 1811–12 earthquakes.

Multiple linear regression is appropriate only if the variables included are independent. If cross-correlation exists between two or more of the variables, the effect of one variable may mask the effect of another variable. Table II shows the amount and significance of cross-correlation between the independent variables.

The results of the multiple linear regression are shown in Table IV. For young rotational slumps, the analysis was conducted only for the naturally occurring, near-river bluff segments. Only slope angle was included in that model; none of the other factors could statistically improve the model in the presence of slope angle. This again shows that oversteepening of the bluffs by fluvial erosion outweighs all other factors in the formation of young rotational slumps. Slope angle accounts for almost 30% of the variation in the distribution of young rotational slumps.

For old coherent slides, slope height and slope angle were included in the model. Combined, they account for almost 20% of the variation in landslide distribution. The absence of earthquake-related factors is inconsistent with previous evidence presented, but the cross-correlation between slope height and the sum of the hypocentral distances (see Table II) probably explains why the latter factor was not included in the model.

Variation in the distribution of earth flows is accounted for by the minimum distance and sum of the distances to the earthquake hypocenters, and by the presence of the sand-with-clay facies of the Jackson Formation. These factors yield an explained variation of almost 20%. The proximity to seismic sources even outweighs the effect of slope height, which was the first variable selected in the stepwise procedure.

TABLE IV

Parameter coefficients, t-values, and R^2-values from stepwise multiple linear regression

	Step: 1	2	3	4	5
Young rotational slumps ($n=28$)					
Constant	−1.86				
Slope angle (°)	2.75				
(t-value)	(3.31)				
R^2 (%)	29.6				
Old coherent slides ($n=375$)					
Constant	−8.26	−19.57			
Slope height (m)	0.89	0.75			
(t-value)	(7.94)	(6.61)			
Slope angle (°)		0.96			
(t-value)		(3.01)			
R^2 (%)	16.1	18.3			
Earth flows ($n=375$)					
Constant	−7.72	17.33	19.79	11.97	20.73
Slope height (m)	0.49	0.33	0.20	0.16	
(t-value)	(5.83)	(3.70)	(2.05)	(1.72)	
Sum of hypocentral distances (km)		−0.03	−0.03	−0.09	−0.10
(t-value)		(3.51)	(3.74)	(4.65)	(5.31)
Jackson Fm.: clay thickness (m)			0.46	0.59	0.72
(t-value)			(3.31)	(4.25)	(5.48)
Minimum hypocentral distance (km)				0.30	0.31
(t-value)				(3.37)	(3.56)
R^2 (%)	9.4	12.6	15.5	18.3	17.6
Old coherent slides and earth flows ($n=375$)					
Constant	−15.98	−41.47	−14.50		
Slope height (m)	1.38	1.25	1.12		
(t-value)	(12.61)	(11.53)	(9.36)		
Slope aspect (°)		0.15	0.14		
(t-value)		(3.87)	(3.64)		
Sum of hypocentral distances (km)			−0.07		
(t-value)			(2.74)		
R^2 (%)	32.5	35.5	36.9		

The 99.5% confidence level for $n>30$ is $t=2.58$; for $n=28$ it is $t=2.76$.

The combined old-coherent-slide and earth-flow class has a total explained variation of 37%. This greater value indicates that these classes are affected similarly by many of the factors because correlation is higher for the combined class than for either class individually. The factors included in this model are slope height, slope aspect, and sum of the hypocentral distances. This indicates that, in addition to slope height, the proximity to seismic sources affects the distribution of old coherent slides and earth flows in the study area. The inclusion of slope aspect in the model suggests that the regional dip to the west-northwest may affect the susceptibility of a bluff to landsliding.

In both the individual and combined classes of old coherent slides and earth flows, slope height is the dominant independent variable. Also significant are the hypocentral distances, but the marginally significant correlation between them and slope height makes it difficult to appraise the effects of hypocentral distance when slope height is constant. To attempt such an appraisal, the bluff segments were grouped into 3-m height increments and the occurrence of old coherent slides and earth flows was regressed against the minimum hypocentral distance and the sum of the hypocentral distances for each height increment. This enabled examination of the effect of increasing hypocentral distance on landslide incidence for bluff segments of a given slope height.

When landslide occurrence was regressed against the sum of the hypocentral distances, 13 of the 17 slope-height increments in which landslides occurred had best-fit lines with negative slopes, which indicates the data are nonrandomly distributed.*[1] Negative slopes indicate that landslide incidence decreases as hypocentral distance increases. Slope values are remarkably concordant: the average is −0.89 and the standard deviation is only 0.33. If there were little or no correlation between landslide occurrence and hypocentral distance, approximately half the slopes would be positive and half would be negative; moreover, large variations in the slope values would likely be seen. Thus, the predominantly negative and concordant slope values suggest a significant negative correlation between distance from seismic sources and incidence of old coherent slides and earth flows when slope height is constant.

For minimum hypocentral distance, 12 of the 17 regressions yielded negative slopes; the average of these slope values is −1.85 with a standard deviation of 1.04. This result also suggests a negative correlation between hypocentral distance and the occurrence of old coherent slides and earth flows for a given slope height.

The slopes of the best-fit lines from the regressions are simply the ratios of landslide incidence (in percentage of bluff-length failed) to hypocentral distance (in km). This ratio, termed the "landslide decay ratio", can be used to approximate the effect of decreasing hypocentral distance on landslide incidence for a bluff of given height. The landslide decay ratio for the sum of the hypocentral distances suggests that, for a given slope height, landslide incidence decreases almost 1% for each 1-km increase in sum of the hypocentral distances. For minimum hypocentral distance the landslide decay ratio suggests that landslide incidence decreases almost 2% for each 1-km increase in minimum hypocentral distance.

Refinement of these approximations is possible by plotting the landslide decay ratios against the bluff-height increment from which they were derived, as shown in Fig.14. Both plots have reasonable best-fit lines. The fact that the absolute values of the landslide decay ratios increase as bluff height increases suggests that sensitivity to seismic shaking increases as bluff height increases.

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*[1]If the data were random, the probability that 13 of 17 values would be negative is 0.02.

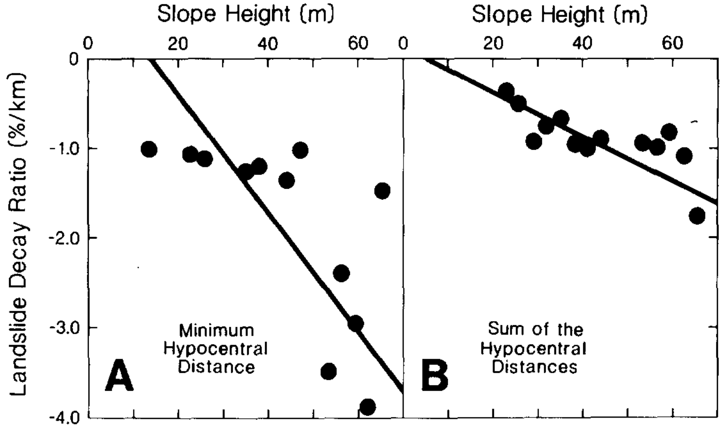

Fig.14. Landslide decay ratio (percent change in landslide incidence per kilometer of hypocentral distance) plotted against slope height for: A. minimum hypocentral distance; and B. sum of the hypocentral distances.

SUMMARY AND DISCUSSION

The statistical analyses show strong correlations between landslide occurrence and several of the independent variables.

The distribution of young rotational slumps is most strongly correlated with slope angle, probably related to oversteepening of the bluffs by fluvial erosion. This is consistent with field observations indicating that young rotational slumps are present only along river-bank bluffs. The presence of the sand-with-clay facies of the Jackson Formation was correlated to a lesser extent. No earthquake-related variables affected the distribution of young rotational slumps.

The distribution of old coherent slides and earth flows is most strongly correlated with slope height. The effect of slope height on factor of safety can be illustrated using generalized slope stability charts that relate factor of safety to slope height and angle, shear strength, and bulk density (Hoek and Bray, 1977, pp.232–238). If, for example, we assume uniform values, typical of the soils in the study area (Jibson, 1985), for bulk density (19 kN/m^3), cohesion (48 kPa), friction angle (25°), and slope angle (20°), a slope 30 m high has a factor of safety of about 1.7. Increasing the slope height to 45 m, however, reduces the factor of safety to about 1.5.

Incidence of old coherent slides and earth flows is also related to the proximity to the 1811–12 earthquake sources, the slope aspect, and the epicentral angle to the 1811–12 earthquakes. These findings, consistent with field and historical evidence from previous investigations (Jibson and Keefer, 1988; Jibson, 1985), indicate that the old coherent slides and earth flows in the study area are related to the 1811–12 earthquakes.

Of the two hypocentral-distance variables, the sum of the hypocentral distances provided the strongest statistical correlation. This suggests that successive occurrences of strong ground motion from events of similar magnitudes weakened the bluffs and made them increasingly susceptible to slope failure. The first episode may not have caused catastrophic failure, but may have induced a small amount of displacement or disturbance of the bluff material that reduced its shear resistance. A subsequent earthquake, though of similar or even lower magnitude, or some other event, such as a major rainstorm, could then cause catastrophic failure in the weakened material. Such occurrences have been documented in other earthquakes (Wright and Mella, 1963; Seed, 1968; Saleem, 1977; Ambraseys et al., 1981; Harp et al., 1981).

Another possible reason that the sum of the hypocentral distances had higher correlations than the minimum hypocentral distance is that errors in the estimates of the locations of the hypocenters might compensate each other when added, which would make the sum term more accurate than the minimum-distance term.

The parameters included in the regression models all had very high levels of statistical significance (greater than 99.5%), but none of the models explained more than about one-third of the total variation in landslide distribution. This indicates that: (1) the included variables, though only indexes of the parameters that actually control slope stability, have a significant effect on the landslide distribution; and (2) other parameters not included in the model account for much of the unexplained variation. Lithologic and structural variation in the bluffs, groundwater levels, and variations in material properties are probably the most critical of these other parameters, based on field observations in the study area and studies of other landslide-prone areas (Terzaghi, 1950; Keefer, 1984).

The models summarized in Table IV show the significance of the included variables and thus indicate the probable origins of the landslides in the study area: old coherent slides and earth flows probably formed during the 1811–12 earthquakes, and young slumps formed under the influence of fluvial erosion.

The regression models in Table IV can also be used as a first approximation of relative landslide susceptibility in future earthquakes. Equation 2 can be used to estimate the relative susceptibility of the bluffs in the study area to coherent slides and earth flows in a future sequence of earthquakes similar to that in 1811–12 (i.e., three major shocks along the 1811–12 epicentral line):

$$PF = 1.12(SH) + 0.14(SA - 90^\circ) - 0.07(SD) - 14.50, \qquad (2)$$

where PF is the relative percentage of the length of a bluff segment expected to fail, SH is the slope height in meters, SA is the slope aspect*[1] in degrees, and SD is the sum of the distances from the three assumed hypocenters in kilometers. Hypothetical input values representing the least hazardous conditions observed in the area ($SH = 15$ m, $SA = 280^\circ$, $SD = 430$ km) yield a percent-

*[1]The slope aspect is changed by 90° in eq.2 to rectify the transformation required for the regression analysis. Because virtually no data exist for slope aspects less than 90°, eq.2 applies only to slopes facing between 90° and 360°.

age of bluff length expected to fail (*PF*) of -1%, which is very close to zero. This is consistent with field observations that low bluffs and bluffs distant from the earthquakes contained no landslides. Input values representing the most hazardous conditions in the area ($SH = 70$ m, $SA = 300°$, $SD = 150$ km) yield a *PF* of 83%, also consistent with observations that most very high bluff segments near the earthquakes failed nearly completely. Thus, eq.2 yields reasonable results over the range of possible input data for the study area.

Regression models using more detailed data describing groundwater conditions, spatial variation of material properties, and lithologic and structural variation would probably explain more of the variation in landslide distribution and therefore more accurately characterize relative landslide susceptibility in earthquakes. The difficulty in obtaining such data, however, may preclude such detailed modeling.

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