LANDSLIDES OF THE CINCINNATI, OHIO, AREA

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U.S. GEOLOGICAL SURVEY BULLETIN 2059–B

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By ROBERT W. FLEMING *and* ARVID M. JOHNSON

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The behavior of colluvial landslides is strongly affected by differences in thickness

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CONVERSION FACTORS

For the convenience of readers, the metric units used in this report may be converted to inch-pound units by using the following factors:

Multiply metric units	By	To obtain inch-pound units
micrometers (μm)	3.937×10^{-5}	inches
millimeters (mm)	0.03937	inches
centimeters (cm)	0.3937	inches
meters (m)	3.281	feet
kilopascals (kPa)	0.145	pounds per square inch

LANDSLIDES IN COLLUVIUM

By Robert W. Fleming[1] *and* Arvid M. Johnson[2]

ABSTRACT

The most common and destructive landslides in the Cincinnati, Ohio, area are formed in colluvium. Colluvium is formed from bedrock units by weathering and slaking of shales. The principal colluvium-producing bedrock unit is the Kope Formation, which occupies the lower 60–70 m of hillslopes between the level of the Ohio River and an upland some 150 m above the river level. This formation, which contains about 80 percent shale and 20 percent limestone, slakes readily to produce a stony, silty clay colluvium. Overlying formations contain smaller amounts of shale, typically produce smaller amounts of a more stone-rich colluvium, and support steeper slopes. The colluvium forms a wedge-shaped mass ranging up to about 15 m in thickness. In the upper parts of the slopes, grades are steeper and the colluvium is thinner.

We recognize a significant difference in landslide behavior in slopes underlain by thick and thin colluvium. Landslides in thick colluvium—that is, more than 2 m thick—typically occur in the spring but can occur at any time of the year in response to a disturbance, such as grading. During a movement episode, the landslides typically move only a few centimeters to perhaps a meter. In form, these thick landslides consist of a single zone of overlapping scarps at the head and multiple toe bulges downslope. The flanks of movement are indistinct; shear displacement is evidently distributed over a broad zone. Analysis of a 37-yr record of movement, as revealed in disturbance to trees at our Delhi Pike study site, showed a small amount of movement nearly every year. During the 37-yr interval, there were two episodes of abrupt movement of several centimeters, both during years of above-average precipitation. For the most part, however, movements occurred during years of normal precipitation, when water levels were below the failure surface except at the most downslope toe of movement.

Landslides in thin colluvium—that is, less than about 2 m thick—typically occur in the spring after the ground has thawed and before the vegetation has fully blossomed. Their movements are associated with rainfall, but precise timing has not been measured. Measurements of water levels in thin colluvium reveal that, during most springtimes, the colluvium is saturated to the ground surface for brief intervals. The thin landslides take the form of multiple scarps and a single toe of movement. For most thin landslides, the flanks are well-defined, simple boundaries. The multiple scarps are evidence for stretching or extension being the dominant form of kinematic behavior. Indeed, thin landslides are characterized by stick-slip behavior in which the landslides may accelerate after initial failure and slide completely out of their scars. During movement, they commonly pull themselves apart, leaving deposits that consist of separated hummocks or slabs of colluvium.

Four trenches were dug into the colluvium to examine the failure surfaces and to obtain samples for laboratory testing. The failure surfaces are paper thin, highly polished, and striated. At all scales of observation, roughness is evident in the surfaces. At a scale of a few micrometers, the surfaces have small steps between shiny surfaces that appear to be analogous to chatter marks on rocks in fault zones. At a larger scale, the surfaces are scratched by fossil fragments and sand-size grains in the colluvium. At a still larger scale, the surfaces bifurcate around rock fragments, and multiple surfaces occur where the shape of the failure surface is changing.

Residual shear tests were conducted on samples from near the failure surfaces. Strength parameters varied depending on the way the sample was prepared and tested. Minimum values were obtained in a ringshear device on samples that had the coarse fractions removed. A reasonable estimate of the residual strength parameters is an angle of internal friction of 16 degrees with a small cohesion intercept of 10 kPa. Other typical properties of the colluvium are LL=45, PI=22, sand = 10 percent, silt = 30 percent, and clay = 60 percent. The clay minerals are predominantly illite and mixed-layer clay. Stability analyses conducted by back-calculation gave expectable results for the thick landslides. At equilibrium, our measured values of residual strength are adequate

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to support the slope for the geometry and water conditions observed. For the thin landslides, the measured strength appears insufficient to support the slope. Additional strength provided by tree roots, roughness of the failure surface, or small residual cohesion could account for the discrepancy between apparent strength and stability.

INTRODUCTION

Annual per capita costs of damage due to landsliding in Hamilton County, Ohio (Cincinnati and vicinity), are among the highest of anywhere in the United States. Annual per capita costs for the period 1973–78 were $5.80, unadjusted for inflation; total costs of damage were nearly $31 million for the same 6-year period. Not included in this total was nearly $30 million expended after 1978 for a single landslide that occurred in 1974 in the Mt. Adams section of Cincinnati (fig. 1) (Fleming and Taylor, 1980).

A separate study of costs of landslide repair, done by students and faculty from the University of Cincinnati, found that the annual direct cost of emergency repairs to local streets in the City of Cincinnati is about $0.5 million. Deferred repairs of landslide damage to Cincinnati streets amounted to about $18.5 million in 1987 (Earth Surface Process Group, 1987).

The most common and destructive landslides are in slopes underlain by colluvium. The colluvium is derived by weathering of subjacent bedrock and accumulates on slopes as a wedge-shaped mass of stony clay.

Two distinct types of landslides occur in the colluvium. The two types have different morphologies and kinematic behavior, and they appear to be triggered by different stimuli. The most striking difference between the two types of landslides is in thickness. Thin landslides, less than 2 m thick, occupy the upper parts of hillslopes where the colluvium is thin. Thick landslides, more than 2 m thick, occupy the lower parts of the slopes.

In this chapter, we describe the Delhi Pike area, which is an area of landsliding we believe to be representative of landslides in colluvium throughout the Cincinnati metropolitan area. The area has been the focus of several detailed studies reported in other chapters in this bulletin. The purpose of this chapter is to describe the physical setting and movement styles of the landslides and, thus, to provide a context for the more narrowly focused chapters that follow.

ACKNOWLEDGMENTS

Önder Gökce, University of Cincinnati, helped map the landslides, logged borings and trenches, and read inclinometers and piezometers. He incorporated many of those data in his Ph.D. dissertation. Sherry Agard, U.S. Geological Survey, Denver, analyzed the tree cores. Roger Nichols, U.S. Geological Survey, Denver, conducted the drilling and testing program. The base map was prepared from aerial photographs by James Derrick. Property owners Dale Schmale, Edgar Allen, and the College of Mount St. Joseph granted access for the study. To all these people and to the college, we express our sincere appreciation.

GEOLOGY AND PHYSIOGRAPHIC SETTING

The landscape in the Cincinnati area consists of a dissected upland surface, hillslopes along the Ohio River and principal tributaries, and flood plains and terraces. Maximum relief is about 150 m. The uplands are mantled mainly by glacial deposits, mostly of Illinoian age. Sedimentary bedrock underlies the till at various depths. Bedrock is typically exposed in the upper parts of hillslopes as ledges of limestone and in the floors of some of the smaller postglacial valleys. The Ohio River and its tributaries (Mill Creek, Licking River, Little Miami River, Miami River, and Whitewater River; fig. 1) have been strongly imprinted by their glacial history and have flood plains and terraces of varying widths. Materials in the terraces and flood plains vary from sand and gravel to laminated silts and clays.

The bedrock geology of the Cincinnati area consists of very gently dipping (1–2 m/km) shale and limestone of Late Ordovician age. The shale beds in the bedrock sequence are poorly cemented and slake to their constituent grains in response to moisture and temperature changes. Three of the bedrock units contain significant amounts of shale and produce colluvium. These are, from the oldest, the Kope Formation, the Fairview Formation, and the Miamitown Shale. The Kope Formation occurs near the level of the Ohio River and occupies the lower 60–70 m of hillslopes along the Ohio River and its tributaries. The overlying 30-m-thick Fairview Formation and undifferentiated bedrock as much as about 50 m thick occupy the remaining slope between the river and an upland area, which is typically mantled by loess or glacial deposits.

In general, the amount of shale decreases upsection. The lower part of the Kope Formation contains about 80 percent shale. Shale content diminishes to about 70 percent in the upper 12 m of the Kope Formation, and the Fairview Formation and overlying undifferentiated bedrock contain less than 50 percent shale (Osborne, 1974; Ford, 1974; Luft, 1971, 1972; and Gibbons, 1972). The changing shale content commonly is expressed as a slight break in slope at the contact between the Kope and overlying formations; slopes formed on the Kope Formation are a few degrees flatter than slopes on overlying bedrock.

The colluvium varies in thickness depending on its position on the slope. In the lower part of the slope, colluvium is as thick as about 15 m. Colluvium thickness diminishes to a meter or less near the top of the Fairview Formation in the upper part of the slope.

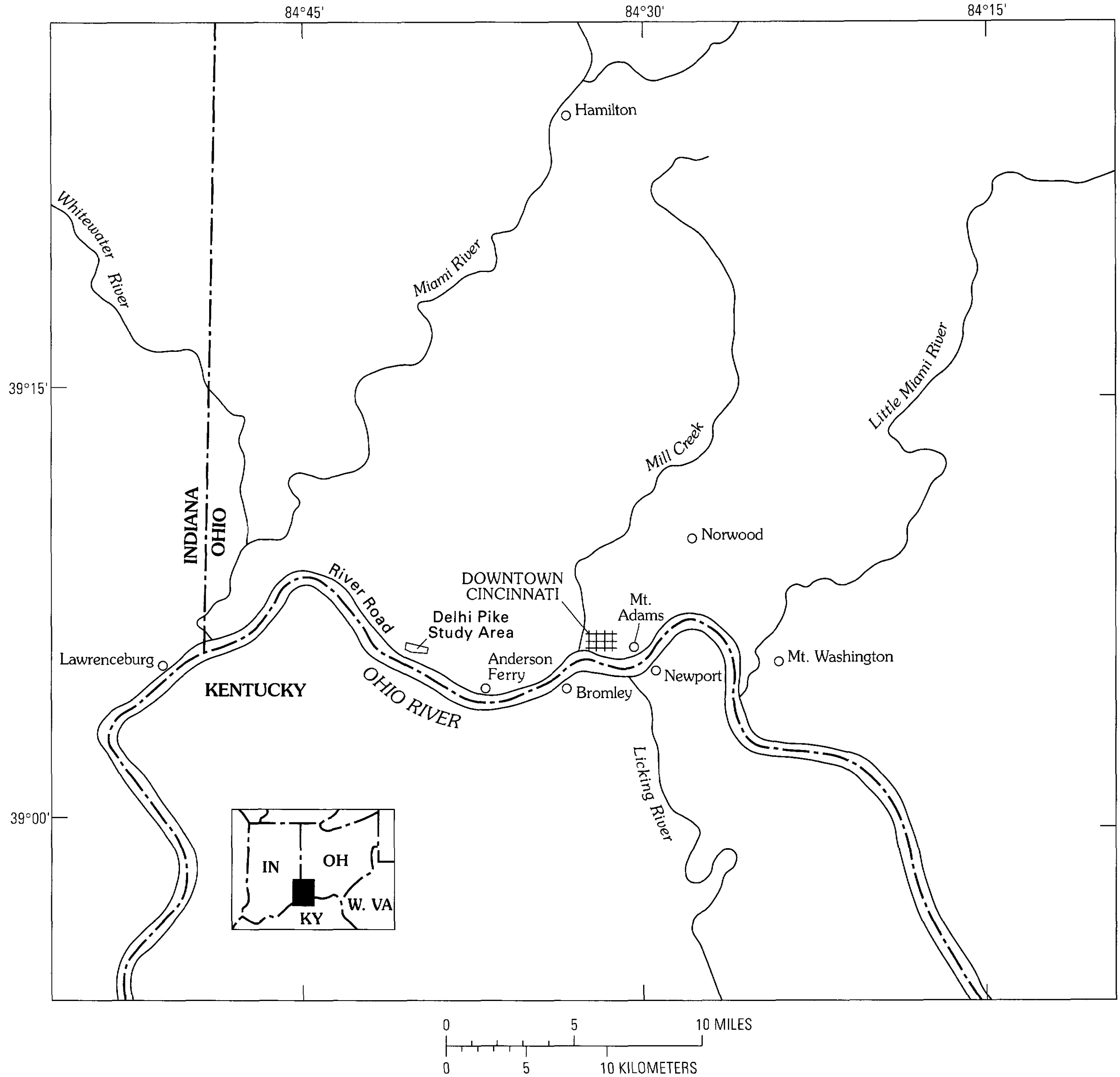

Figure 1. Location of the Delhi Pike study area and important geographic features in the Cincinnati, Ohio, area.

DELHI PIKE LANDSLIDE AREA

The Delhi Pike landslide area is about 12 km west of downtown Cincinnati in unincorporated Hamilton County, Ohio (fig. 1). The Delhi Pike landslides are just a few of the many landslides that occur within a narrow stretch of the Ohio River Valley extending from Mill Creek to the Miami River about 22 km farther west. This stretch of the valley was created when glacial ice of Illinoian age blocked a more northern channel, creating a lake. Silts and clays deposited in the lake have been involved in major landslides in other parts of the metropolitan area. The spilling of the lake eroded the modern channel of the Ohio River (Durrell, 1961a, 1961b).

The total width of this narrow section of the valley, as measured between the uplands of Ohio and Kentucky, is about 1.5 km, compared to a width of 2.5 km upstream and 4.0 km downstream. The narrow part of the valley lacks a continuous flood plain or terraces and essentially consists of slopes of colluvium from the level of the Ohio River to ledges of limestone outcrop near the top. Landslides have occurred along these slopes on both sides of the Ohio River. In 1973, extensive landsliding resulted in temporary closure of a 5-km stretch of State Route 8 west of Bromley, Ky. (fig. 1), and in the destruction of several homes. At the same time, in Ohio, landslides were destroying homes and sections of several roads. As part of this widespread landslide disaster, multiple landslides caused the permanent closure of Delhi Pike in our study area (The [Delhi Township] News, April 11, 1973, p. 1, "Sister's Hill too hazardous; closed by County Engineer").

Many of the streets, buildings, and railroads in the Delhi Pike area were constructed before the turn of the century. A topographic map of Cincinnati published in 1912 shows the same street and railroad alignments in the area that exist today. Transportation routes are parallel to the Ohio River and trend along the hillslopes roughly parallel to topographic contours. From the level of the Ohio River, at progressively higher elevations, are railroad tracks (12 m), River Road (about 20 m), and Hillside Avenue (about 40 m upslope from the river) (fig. 2). Delhi Pike was an old road that provided a connection between Hillside Avenue at elevation 170 m and Delhi Township at elevation 260 m in the uplands. A few homes were built on the downslope side of the lower part of Delhi Pike, but the upslope side was apparently too steep for development.

The colluvial slope has an overall concave-upward profile. Slope inclination increases from about 8° or less near the Ohio River to about 10°–12° along the section between River Road and Hillside Avenue. On the upslope side of Delhi Pike, the inclination is 18°–25°. The initial character of the lower, more gently sloping portions of the slope has been obscured by development. In undeveloped areas in other parts of the county, slopes at this level have a smooth but lobate texture; the lobes, typically 1 or 2 m high and 10–20 m across, appear to represent the distal ends of landslides or earthflows.

Only a few landslides have been active in historic time in the gentle slopes along River Road. Two notable slides occurred at North Bend, about 10 km downstream from Delhi Pike, and near Riverside-Harrison School, about 8.7 km upstream. The landslide at North Bend, near the William Henry Harrison Monument, occurred during the 1970's above the outside of a bend in the river, where the slope was locally oversteepened by river erosion and loaded with a small amount of fill. The other landslide, near the Riverside-Harrison School, occurred in response to an excavation for a railroad roundhouse in 1927 and ultimately destroyed about 40 homes (Von Schlichten, 1935). Both examples demonstrate that the thick colluvium near the level of the Ohio River will fail by landsliding if the hillslope is adversely disturbed.

Within the Delhi Pike study area, the slopes have failed extensively (fig. 2). Hillside Avenue is deformed along much of its length, and numerous empty lots containing

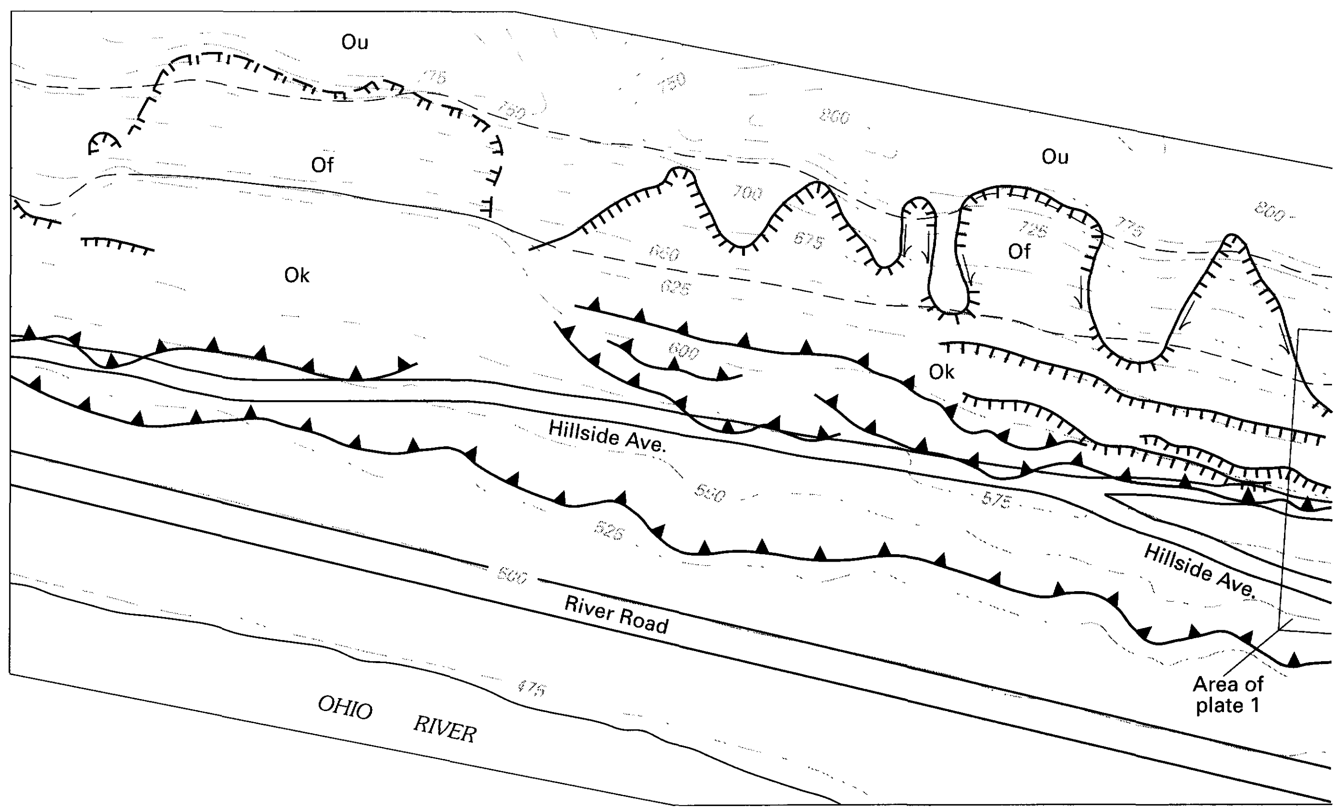

Figure 2 (above and facing page). Geologic map of the Delhi Pike study area. See figure 1 for location. Contact between the Kope (Ok) and Fairview (Of) Formations is exposed in cut slope in western part of the map area. Contact was projected through map area using apparent dip angle from published geologic maps of areas directly across the Ohio River in Kentucky (Gibbons, 1972). The Fairview Formation was assumed to be 30 m thick.

house foundations and overgrown remnants of driveways and walls attest to a long history of slope movements. Still farther upslope are scarps, scars, and lobes produced by failure of a thinner mantle of colluvium.

DELHI PIKE STUDY AREA

Within the area of extensive landslides shown in figure 2, a smaller area containing both thick and thin landslides was selected for detailed study (pl. 1). The trace of Delhi Pike extends east-west across the middle of the area and divides shallow landslides uphill from deep-seated landslides downhill. Subsurface conditions were investigated with borings and trenches. Instrumentation was installed in both shallow and deep slides to determine the geometry and water conditions and to obtain samples for laboratory testing.

THICK LANDSLIDES

The heads of the thick landslides are in the fill on the downhill edge of Delhi Pike. The fill contains overlapping low scarps and tension cracks (pl. 1) extending to the break in slope at the shoulder of the road. These cracks, which indicate stretching or extension of the landslide material, are confined to the fill area. All indications of landsliding farther downslope are of shortening or compression. The compressional features are difficult to recognize in natural slopes but are well expressed where they intersect a wall, road, or walkway. Figure 3 consists of two photographs of toes of deep-seated landslides; locations are shown on the map of the Delhi Pike landslide complex (pl. 1).

The lowermost toe (fig. 3*A*) is a broad bulge in Hillside Avenue, where the vertical component of displacement is larger than the horizontal component. The edge of the road showed no visible offset even though the bump grew perceptibly over the 5-yr period of observation. Farther uphill, displacement on another toe of movement (fig. 3*B*) is almost entirely horizontal.

The deep-seated landslide did not displace inclinometer casings enough during our monitoring period of 1979–80 to allow us to accurately determine the positions of failure surfaces. Based on borings, the maximum depth to the failure surface was about 4 m at the head of the slide (including the thickness of side-hill fill), 2.3 m near the stone walls (boring W1), about 6 m near boring 9, and about 3.5 m at boring 20 (locations shown in pl. 1).

The shape of the failure surfaces can be inferred from the mappable features at the ground surface. The head of the landslide consists of a narrow zone, as much as 4–5 m wide, of extensional faults and cracks. The faults and cracks are vertical to steeply dipping downslope. The horizontal offset of Delhi Pike is smaller than the vertical separation of blocks of displaced road (fig. 4). Bulges and other indications of shortening are evident at the first break in slope downslope from the head. These bulges apparently

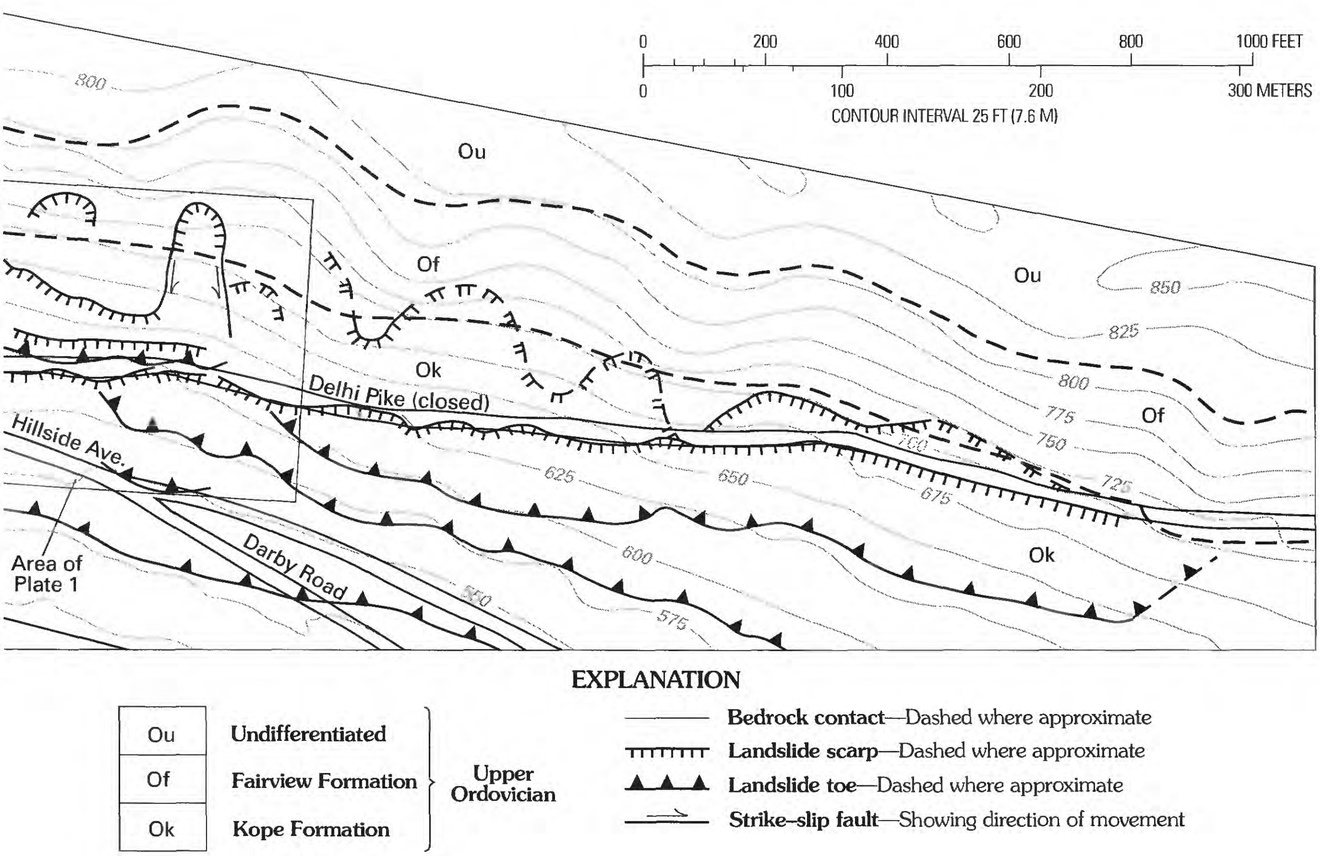

Figure 3. Emergent toes of deep-seated landslides near intersection of Hillside Avenue and Darby Road. See map on plate 1 for locations. *A*, View west toward the intersection. The broad bump in the middle of view is a toe for a thick landslide that extends 60 m upslope. Note the tilted utility pole at the left of the view and damage to the stone wall on the right. The asphalt paving over the bump has recently been replaced. The dark-colored marks in the eastbound (oncoming) lane are produced by vehicles scraping on the road surface after bouncing over the bump. The road has not been significantly displaced laterally; the principal movement direction is vertical. *B*, Stairway, about 18 m farther upslope, displaced a few centimeters to the right (south). Principal movement direction is horizontal.

Figure 4. View to northeast of landslide scarp for thick slide that heads on Delhi Pike.

reflect predominantly horizontal displacement; a cistern that was originally about 3 m from the stone wall (Mr. Dale Schmale, oral commun., 1980) near boring 14 is now only 2 m away, and the wall has not been perceptibly displaced vertically.

The next series of bulges and thrusts occurs just downhill from a break in slope above Hillside Avenue (pl. 1, fig. 3). The displacement of the stone and concrete work on the slope is nearly horizontal. Still farther downslope, at Hillside Avenue, the displacement direction is predominantly upward. This toe of movement appears to be the downslope limit of active sliding. In plan view, the toes are lobate and have local relief of a few centimeters to about 2 m.

Trench 1 was placed through one of the landslide lobes on the east side of the study area. Here, the colluvium consists of two separable units, a brown pedologic soil overlying yellowish-gray colluvium (pl. 1). One slickensided failure surface was found in the trench wall. Toward the upslope end of the trench, the surface was within the yellowish-gray colluvium; toward the downslope end of the lobe, the yellow-gray colluvium had overridden part of the brown pedologic soil. The failure surface was essentially horizontal at a depth of about 2 m. Boring 11 is about 4 m west of trench 1 and contains an inclinometer casing. The casing, originally 6.6 m long, has been constricted at a depth of 3.6 m (measured May 10, 1990). Thus, at this lobe of the landslide complex, at least two failure surfaces exist, one at a depth of about 2 m and the other at 3.6 m. The failure surface at 2 m apparently created the lobe containing trench 1 and boring 11 (pl. 1). The failure surface at 3.6 m may reach the surface at the 560-ft (171-m) contour. If so, the deeper failure surface slopes about 7° downhill toward Hillside Avenue. We do not know whether movement has occurred on the shallower surface since our study began, but if it has, the amount was insufficient to constrict the inclinometer casing at that depth.

SEQUENCE OF MOVEMENT

A sketchy history of the overall movement of the thick landslide can be inferred from deformation of features on the landslide and from an interview with the property owner, Mr. Dale Schmale (oral commun., 1981). Prior to abrupt movement of the landslide in the spring of 1973, the property identified as 5434 Hillside Avenue contained four structures—a house, a barn, a garage, and a shed. The house was at least 100 yr old and was situated on the flat area near borings 9, 10, and 14 (pl. 1). The garage, barn, and shed were east of the house near trench 1. Mr. Schmale purchased the property in 1972 and was involved in remodeling the house when it was destroyed by movement. The first indication of trouble was when a 400-yr-old tree, located at a toe of movement just east of boring W1, toppled onto the house (Schmale, oral commun., 1981). At that time, there were cracks in Delhi Pike, but Mr. Schmale had noticed no evidence for sliding on his property. Within a few days after the tree toppled, the house and other structures were deformed beyond repair. The entire episode of movement occurred in a 3-week period of April 1973.

As recently as 1990, the overall appearance of the property remained as it was in 1973. Small amounts of movement had occurred that were sufficient to squeeze the borings closed and to reestablish the bulge in Hillside Avenue, in spite of repeated repairs. However, there had been no episodes of abrupt movement similar to the episode in 1973.

Additional inferences can be made about movement of the thick landslides from disturbance to trees. Trees on undisturbed hillslopes tend to grow vertically from the tip of the stem and to form concentric growth rings (Kozlowski, 1971). When a tree is tilted, it responds to the change both internally and externally. New growth from the stem tip continues to grow vertically, producing a bend or curve in the stem. Eccentric growth in the trunk creates asymmetric tree rings and reaction wood. In conifers, the growth rings are wider and reaction wood forms on the downslope side (Agard, 1979). In general, reaction wood can be distinguished visually from normal wood in that it is darker, has a denser, smoother appearance, and has little contrast between early wood and late wood in a growth ring (Agard, 1979).

Tree cores were used to examine the growth behavior of two pine trees on the thick landslide at Delhi Pike. The pine trees were planted in the early 1940's in an open area along the driveway to the house at 5434 Hillside Avenue. Both trees have been tilted and deformed in response to landslide movements. The positions of the trees relative to nearby landslide features are shown in figure 5.

Figure 6*A* is a photograph of the two pine trees viewed northwest from near the site of the house at 5434 Hillside Avenue. The tree on the left is termed the "west tree" and the tree on the right the "east tree." The bulge in the foreground is a toe bulge that, from right to left, trends through dry grass and crosses the ivy-covered stone wall about in line with the west tree. The bulge passes just to the right of the

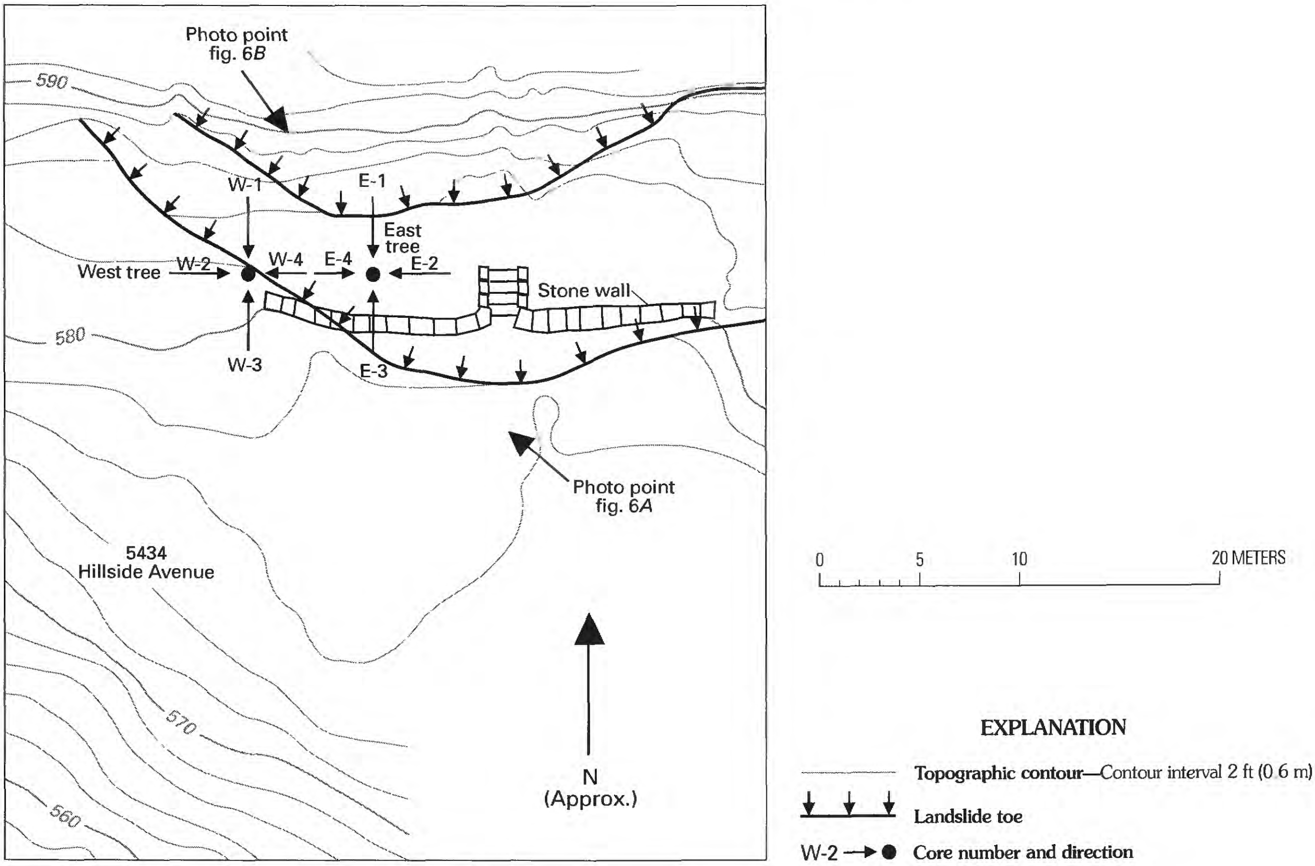

Figure 5. Sketch map of positions of tilted pine trees, walls, and landslide toes on the property at 5434 Hillside Avenue.

west tree, and landslide movement has pushed the tree toward the left or downslope. In response, the tree has grown straight for about 5 m and then is continuously curved except for one small, more abrupt bend about halfway to the top. The continuously curved portion of the tree appears to be a response to small annual increments of landslide movement, and the single, abrupt bend could be a response to one event of more than normal movement of the landslide.

The east tree is about midway between two toe bulges (fig. 5). The same toe bulge that is pushing the west tree forward is about 3 m downslope from the east tree. Another toe bulge is about 3 m upslope from the east tree. The trunk of the east tree is straight in the lower 5 m and has a gentle bend over the next 5 m to an abrupt bend about 10 m from the base (fig. 6*B*). The abrupt bend is apparently a response to a dramatic uphill tilt to the tree. In the year following the abrupt tilting, the east tree put out a large branch on its uphill side (fig. 6*B*). From the abrupt bend to the top of the tree, the trunk is somewhat, but not systematically, contorted. Counting sets of branches from the tops of both trees down to the abrupt bends shows that both bends were created about the same time, a little more than 20 yr before the 1980 growing season.

Cores were taken from the trees at heights of 30–50 cm above the ground. The core numbers and directions of coring are shown on figure 5. The cores were examined microscopically and the rings were counted and measured by Sherry Agard (U.S. Geological Survey, Denver, Colo.).

The results for the west tree are in figure 7. Shown are the thicknesses of the growth rings for the downhill (W3), uphill (W1), and the lateral (W2 and W4) sides of the tree. Also plotted is the percent eccentricity of the growth rings on opposite sides of the tree. Both W2 and W4 penetrated the center of the tree and established that the tree was a 40-cm-high sapling in 1943.

For W2 and W4, the growth rings are almost exactly the same size through 1947, when the east side of the tree (W4) began producing consistently thicker rings. This pattern continued through 1980 with exceptions only in 1962–63 and 1970. For cores W3 and W1, the downhill portion of the growth ring, which is the direction of tilt, was consistently thicker than the uphill portion. Exceptions occurred only during 1963–65 and 1969.

The data for the east tree are plotted on figure 8. Cores E3 and E1 are the downhill and uphill sides of the tree, respectively, and E4 and E2 are the left and right sides of the tree as viewed looking uphill. E6 is a core taken from a point just above the abrupt bend about 10 m above the ground surface. The E6 core passed through the center of the trunk and continued through the tree.

Figure 6. Two pine trees tilted by landslide movement at 5434 Hillside Avenue. *A*, Both trees as seen from the southeast. "West tree" is on left and "east tree" is on right. *B*, "East tree" as seen from the northwest.

The east tree is strongly tilted upslope, and the E1 growth rings (uphill side) are consistently thicker than those on the downhill side. Exceptions are in 1949–50, 1955, 1962–63, and 1968. The trend of the eccentricity shows increasing thickness of the uphill side of the ring relative to the downhill side. The core for E6 dates the year of strong tilting as 1958 or 1959.

For both the east and west trees, the year 1959 is a year of markedly suppressed growth. The east tree also experienced suppressed growth in 1958. Growth was somewhat suppressed in both trees in 1965, but we have found no other evidence of landslide movements that year.

The combined observations of external changes to the trees (curved trunks and abrupt bends) and the tree-ring data lead to the following conclusions. There were active slope movements at the site as early as the mid-1940's, but the tree-ring data cannot be extended back in time beyond those years. The most dramatic movement apparently occurred in 1958, following near-record precipitation in calendar year 1957. Abrupt tilting and suppressed growth affected both trees during the 1959 growing season.

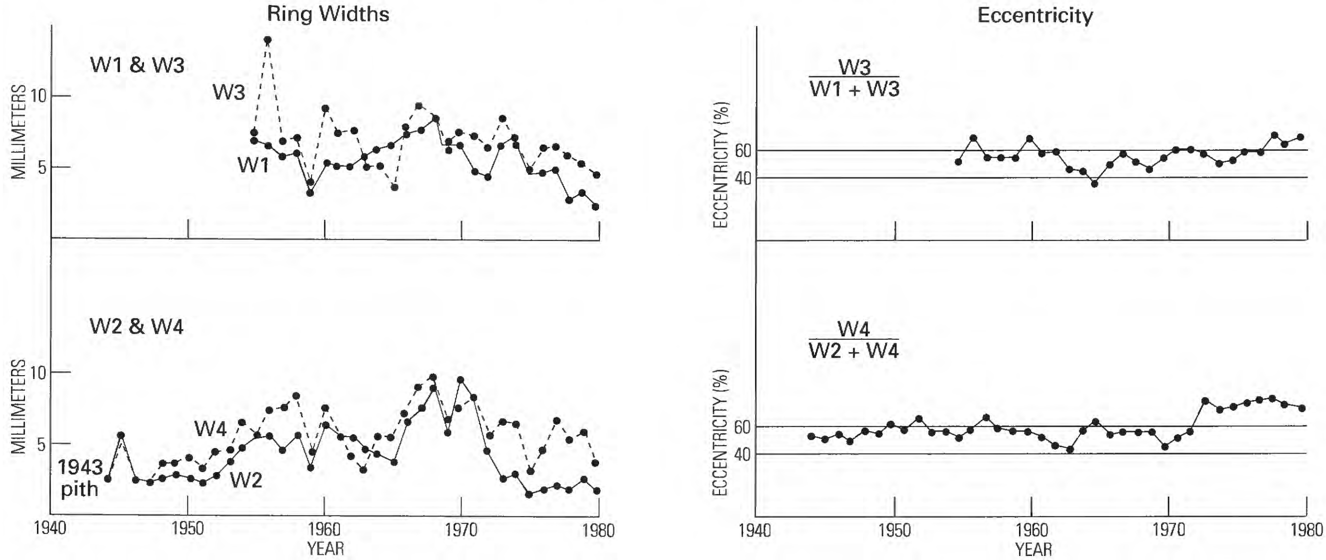

Figure 7. Thickness of growth rings in the "west tree" of figure 6, plotted as a function of time. Cores are from the uphill (W1), downhill (W3), and lateral (W2 and W4) sides of the tree. Also plotted is the percent eccentricity of rings on opposite sides of the tree.

We were able to measure a small amount of movement in an inclinometer casing in boring 8 and with an extensometer (for locations, see pl. 1) during 1979–80. The inclinometer casing was deformed slightly by movement during the winter of 1979–80. Extensometer 2 extended through a storm drain that crossed under Delhi Pike about 25 m east of the pine trees. The upslope end of the extensometer was attached to a box culvert in nonmoving ground between the thin landslides uphill and the cracks in Delhi Pike downhill. Movement was measured from December 1979 to June 1980. The extensometer automatically recorded elongation in increments of 1.73 mm by punching a paper tape; movement was sampled every 15 min. The first indication of movement was on January 30, 1980, when 5.2 mm was measured over an 8-hr period. Additional movement of at least 7 mm was distributed over the next 4 months; the recorder was inoperable for 2½ weeks in April. Overall, 12.1 mm was measured during the 6-month interval.

Although our measurements clearly showed movement during 1979 and 1980, the tree rings formed in those years had no irregularities in growth-ring thicknesses (figs. 7 and 8). We suspect that a small amount of movement occurs during most years, but large, abrupt movements of the thick slides at Delhi Pike apparently occurred only during 1958–59 and 1973.

The current owner of the property, Mr. Schmale, can testify that the perception of small movements is difficult without a good reference feature for measurement. Even though the pine trees along his driveway at 5434 Hillside Avenue had been strongly tilted by 1972, there was no evidence of distress in his house standing less than 10 m downslope from the lower toe bulge shown in figure 5 (Mr. Dale Schmale, oral commun., March 17, 1981). Active landsliding had already damaged property several hundred meters east of Mr. Schmale's property. However, it was Mr. Schmale's impression that the ditch and shoulder of Delhi Pike were intact and free from cracks in 1972. Abrupt movement in the early spring of 1973 revealed several layers of patching in Delhi Pike, which would have covered preexisting cracks but proves the existence of pre-1972 movement uphill from Schmale's house. Because the 100-yr-old house was virtually free of structural distress at the time of abrupt landsliding in 1973, it is unlikely that displacement had occurred on throughgoing landslide failure surfaces then. The displacement occurring in the Delhi Pike apparently extended to a toe only 10–15 m downhill and did not involve the house. At the time of our study (1979–81), we were able to identify two additional landslide toes downslope from the house, and movement on those failure surfaces responsible for the landslide toes was measured in inclinometer casings in borings 9 and 20.

We interpret these observations to mean that the slope was failing progressively, perhaps beginning with the construction of Delhi Pike in the 1800's. The failure process consisted of creating multiple failure surfaces, which produced several toes of movement at increasing distances downslope, beginning from a single scarp in Delhi Pike. The 100-yr-old farm house was not destroyed until progressive failure produced a failure surface that emerged farther down the slope. The single scarp on Delhi Pike is now the upper part of a landslide that contains at least four toes and, presumably, four separate failure surfaces that emanate from the single failure surface near the scarp.

DEFORMATION CAUSED BY THICK LANDSLIDES

One of the more interesting aspects of the deeper seated landsliding along Hillside Avenue is that so much evidence

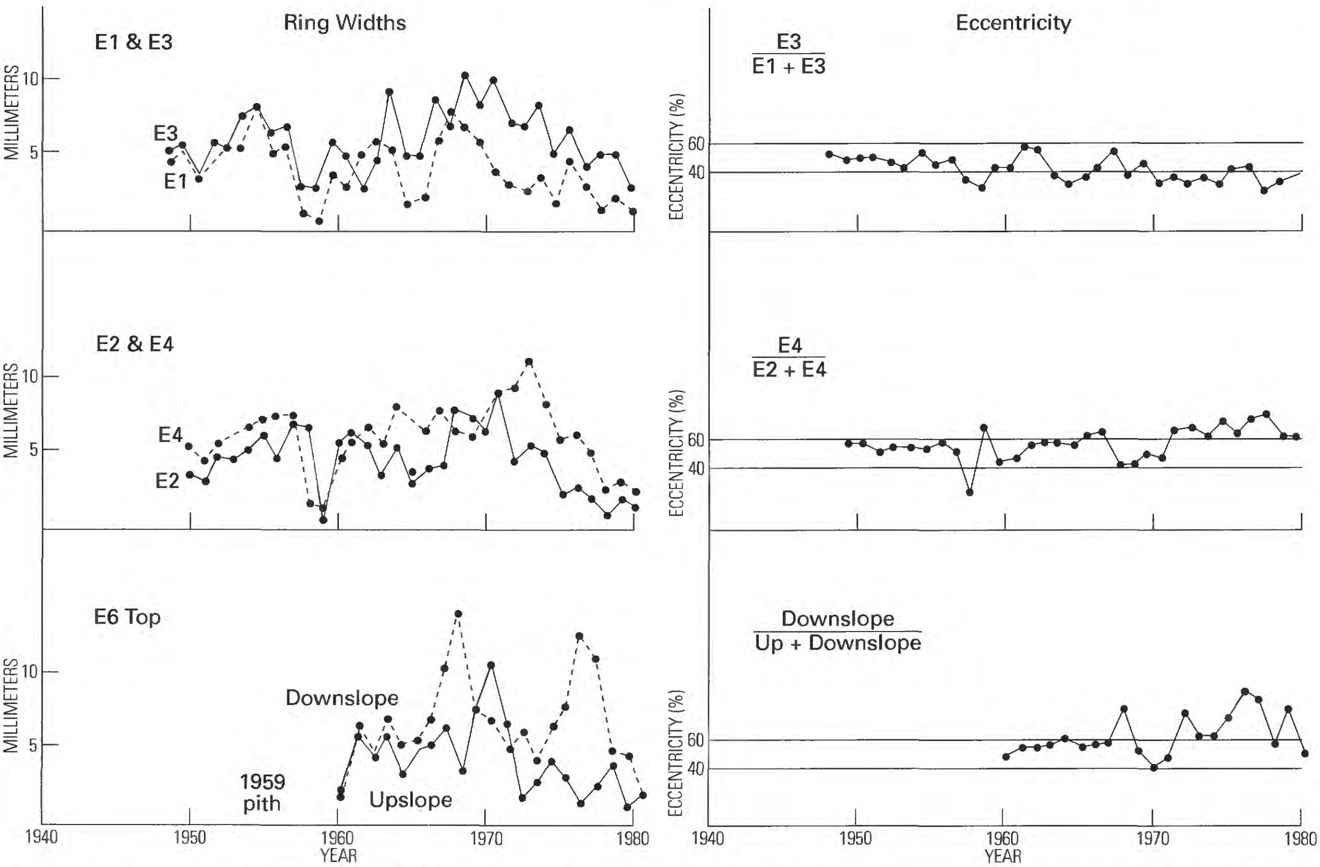

Figure 8. Thickness of growth rings in the "east tree" of figure 6, plotted as a function of time. Cores are from the uphill (E1), downhill (E3), and lateral (E2 and E4) sides of the tree. E6 is the tree core from just above the sharp bend shown in figure 6*B*. The bend probably formed in 1958. Also plotted is the percent eccentricity of rings on opposite sides of the tree.

of past development remains in place. We counted nearly 30 foundations along Hillside Avenue between Anderson Ferry Road and Delhi Pike for houses that apparently have been destroyed by landsliding. The landslides have been damaging structures in this area for more than a century. Homes involved in movement episodes typically are distressed to the point that they must be razed. Yet, the cumulative movement of all these events has not markedly deflected the alignment of Hillside Avenue, and foundations of destroyed structures are recognizable and persist. Evidently, the deep-seated landslides undergo significant internal deformation relative to the amount of sliding displacement.

The deformation that is typical in landslide toes is illustrated in figure 9. The view is of a landslide toe encroaching on asphalt pavement along a break in slope at Anderson Ferry Road and River Road (fig. 1). This photograph, taken in August 1982, documents deformation that occurred over a period of about 9 years.

The bulge in the asphalt was about 26 m wide at the uphill edge and encroached 6.1 m into the blacktopped area. At the uphill edge, the blacktop was elevated 1.5 m, while it was displaced horizontally a maximum of 1 m in the middle. The horizontal displacement diminished to zero at the edges of the bulge. The distal edge of the bulging blacktop is not thrust over adjacent, unfailed blacktop but merely elevated vertically. Thus, the direction of displacement at the leading and flanking edges of the deformed blacktop in the toe appears to be nearly vertical upward. Six meters back from the leading edge, motion is 1.5 vertical to 1.0 horizontal.

Figure 10 shows another example of deformation produced by movement of a landslide toe. In this case, at a landslide in the Mt. Adams area of Cincinnati, the curb of the street has not been displaced, but two slabs of concrete sidewalk have been lifted and displaced over the curb. For the larger slab on the right, horizontal displacement is 0.60 m, and the uphill edge of the slab is elevated 0.82 m.

The early stages of formation of a landslide toe were expressed along a driveway from Hillside Avenue just west of Delhi Pike. A slope underlain by colluvium was cut to provide access for construction of new apartments. Shortly after the cut was made, cracks formed in the colluvial slope about 25 m uphill from the edge of the road. A small bulge formed along the edge of the road, involving as much as 2 m of the paved surface. A photograph taken in 1982 (fig. 11) shows a bulged patch on the blacktop surface and a bulge along the edge of the driveway. In the foreground along this bulge on the edge of the driveway, several near-vertical shear surfaces are exposed. Tabular limestone fragments

Figure 9. Bulge produced by landslide toe in asphalt parking area at Anderson Ferry Road and River Road. Vertical displacement in the toe greatly exceeds horizontal displacement.

Figure 10. Landslide toe formed in Mount Adams section of Cincinnati. Ratio of vertical to horizontal displacement is 1.4:1.

within the colluvium are preferentially oriented with their minimum dimension normal to the shear surfaces. At other places, limestone fragments in colluvium do not show a strong preferential orientation. Here, the fragments have been reoriented by pervasive shearing such that the cross-sectional area exposed to shear is a minimum.

SUBSURFACE WATER IN THICK LANDSLIDES

The abrupt movement of thick landslides in April 1973, which destroyed several homes, occurred during a period of excessive precipitation. However, over a period of years, movement of the thick landslides appears to have been

Figure 11. Near-vertical bump formed in landslide toe. Limestone clasts have been preferentially oriented with their minimum dimension at right angles to the direction of pervasive shearing. The bump has formed without appreciable horizontal offset.

caused as much by construction activity as by excess precipitation.

Our drilling and trenching failed to find saturated conditions anywhere within the thick colluvium except in boring 20 at the toe. Saturated conditions must exist at other places in the colluvium, for we noted a line of springs near boring 12 (pl. 1) and an ephemeral spring near boring 14. Boring 12 was flooded with surface water from the springs and provided no worthwhile data, but colluvium in borings 9, 10, 13, and 14 was unsaturated.

The typical subsurface water condition was illustrated by measurements in boring 13. There, the colluvium was not saturated. Free water was first encountered in the first limestone bed under the colluvium that was penetrated by drilling. This water was under artesian pressure and responded to an annual cycle of maximum pressure in the late spring and minimum pressure in the early fall (fig. 12). In those parts of the landslide that extend nearly to the contact between bedrock and colluvium (that is, the head region), the artesian pressures could significantly reduce stability. Most of the toes of the thick landslides are entirely within the colluvium and significantly removed from the bedrock containing artesian water. The effect of the artesian pressure is dissipated a short distance from the contact between bedrock and colluvium (R.L. Baum, U.S. Geological Survey, oral commun., 1985).

Probably during exceptional periods of precipitation, saturation and elevated pore-water pressures in the thick colluvium are more extensive than we found. However, inasmuch as we measured movement of the thick landslide during a period of below-average precipitation and during a period when water levels were generally below the various failure surfaces, saturation of the colluvium is not necessary for renewed movement on the existing failure surfaces.

SUMMARY OF THICK LANDSLIDES

The thick landslides occur in colluvium that is thicker than about 2 m. Morphologically, they consist of a simple head, a complex of toes, and poorly expressed flanks. The heads occupy a narrow zone containing a few scarps and open cracks; the horizontal component of displacement in the heads is smaller than the vertical component. The toes of movement typically emerge at several places downslope. If the toe emerges at a sharp break in slope, such as a roadcut, the vertical component of displacement is much larger than

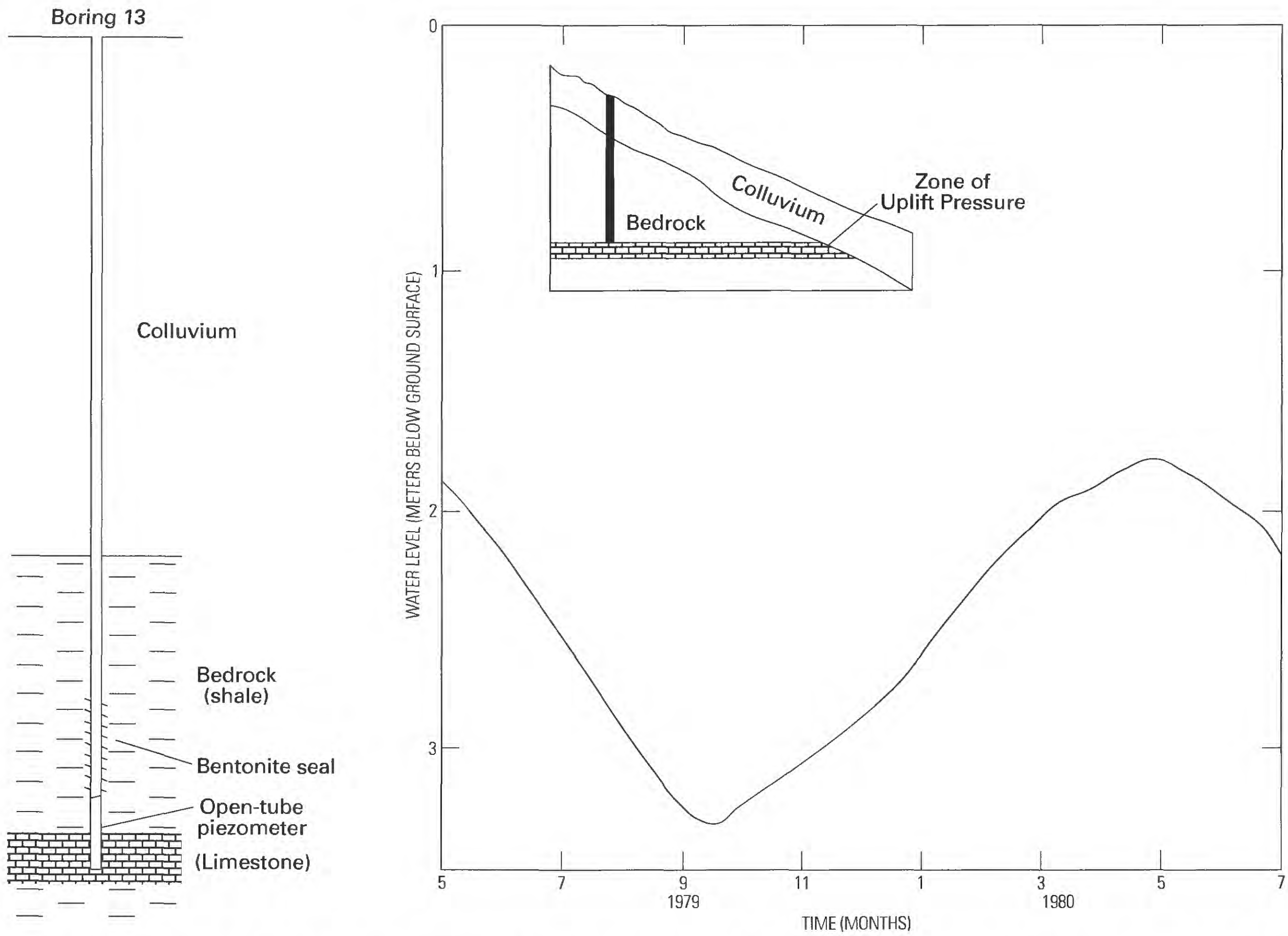

Figure 12. Water-level record of one year for an open-tube piezometer (No. 13, pl. 1) sealed in a limestone layer in bedrock. Depth to layer was 3.4 m, and water level varied from 3.3 m during September 1979 to 1.8 m about May 1, 1980. The line of intersection of the limestone layer with the base of the colluvium is a zone of artesian pressure that develops a head as great as 1.5 m during the spring. (See inset figure.) (From Fleming and others, 1981.)

the horizontal component. If the toe emerges at a smooth or flat part of the slope, displacement is virtually all horizontal, and the lobe of moving ground may override the preexisting ground surface. The flanks of the landslide lobes are poorly expressed and could not be located in the field. Shear displacement on the landslide flanks is evidently distributed over too broad an area to produce cracking or faulting. However, the distributed shear may contribute to the extensive structural damage to homes that seems to take place when only small amounts of displacement have occurred.

The presence of a single head and multiple toes implies a single failure surface under the upper part of the landslide that splays into multiple failure surfaces farther downslope. The failure surface(s) appear to be contained within the colluvium rather than at the contact between colluvium and bedrock.

Eccentric growth rings and reaction wood in tree cores and multiple generations of asphalt patching on Delhi Pike are evidence that the thick landslide began to form at the head and enlarged progressively. The position of the uppermost cracks in the head roughly coincides with the boundary between cut and fill in the roadbed. The abrupt movement that occurred in 1958–59 apparently extended only a few meters downslope from the cracks in the road to a complex of toes. The house and other structures on the property were destroyed by another episode of abrupt movement in 1973. Presumably, new failure surfaces formed that successively emerged farther down the slope in 1973 and later. Movement appeared to be continuing in 1990 on at least the deepest of these surfaces, which emerged as a bump in new asphalt on Hillside Avenue.

Abnormally large amounts of annual precipitation coincided with the abrupt movement episodes in 1958 and 1973. The association between excessive precipitation and landsliding has been so thoroughly documented for landslides around the world that it is unnecessary to do so here. We measured about 12 mm of movement of the thick Delhi Pike landslide during our only period of monitoring in 1979–81.

Precipitation during the entire period of our study was average to below average, and water levels in open piezometers were generally below the level of the failure surface(s).

Our measurements in open-tube piezometers failed to document saturated conditions within the colluvial body of the landslide, although we did find water under artesian pressure in the limestone layers in the underlying bedrock. The pressures varied on an annual cycle, producing minimum values during the fall and maximum values in late spring. Most of the failure surfaces are well above the contact between bedrock and colluvium and, thus, subsurface water pressure in the bedrock is not a major control on the reactivated movement of these thick landslides.

THIN LANDSLIDES

The thin landslides occur on the uphill side of Delhi Pike (fig. 2) where slopes are significantly steeper than in the area of thick slides. Slope inclinations range from about 18° to 25°. An open woods of maple and ash trees, typically spaced about 3 m apart and lacking any appreciable understory, occupies the upper part of the slope. Farther downslope, near Delhi Pike, the hillslope supports a dense understory of various shrubs and vines and a canopy of small locust and elm trees. The change in vegetation occurs a short distance from the contact between the Kope and Fairview Formations.

For the most part, the slope is devoid of obvious scarps, flanks, or landslide toes. Rather, the hillslope has a very gentle undulatory surface superimposed on a series of irregularly spaced topographic benches. Slopes that have not failed within historical time may lack the well-defined scarps and flanks that are commonly observed in landslide deposits. More recent slope failures show all the classic features of landslides and, even though they quickly reestablish a vegetative cover, they remain recognizable topographic forms. Our experience with excavations and landslides throughout the metropolitan area is that virtually all these colluvial slopes have failed at some time in the past, and a trench anywhere through the colluvium would reveal a continuous failure surface near the colluvium-bedrock contact.

The typical form of the area underlain by thin landslides is best expressed toward the western edge of the area shown in figure 2, uphill from Hillside Avenue. Uppermost scarps of the slides extend into and beyond areas underlain by Fairview Formation and form a crudely scalloped upper boundary within the colluvium. The upslope ends of the landslides are broad amphitheaters with generally smooth slopes. Over most of the area, the scarps are expressed as a slight but continuous break in slope. The portion of the landslide on the Fairview Formation contains widely scattered benches and ramps that are subparallel to the topographic contours. These benches appear to be remnants of slide blocks that have detached from the scarp and been smoothed over time.

Downslope, on the Kope Formation, the benches and ramps are more consistently parallel to the topographic contours. The amphitheaters that produce the scalloped upper limit to sliding exist upslope from the Kope Formation; downslope, on the Kope Formation, slopes become straight without significant bulges or swales parallel to the contours. The benches on these straight slopes are 15–30 m long and consist of a stretch of slope about 2 m wide that is flatter than the overall slope and a similar width that is steeper.

Such benches are common on slopes formed on the upper part of the Kope Formation throughout the Cincinnati metropolitan area. We initially believed that these features were toes or lobes of thin landslides (Fleming and others, 1981, fig. 6). Later trenching of several of these benches revealed that they overlie a limestone layer in the bedrock. The benches invariably contain a small-displacement listric fault in the colluvium that connects with the failure surface at the base of the landslide. Thus, the more or less continuous benches are not lobes or toes of movement. The listric fault is evidence of stretching and arching of the colluvium over a buried limestone layer.

The toe of thin-landslide movement (fig. 2) is at Delhi Pike where colluvium has spilled onto the uphill side of the road. Figure 13, a photograph of Delhi Pike from about the location of trench 2 (for location, see pl. 1), gives the impression that the road is very crooked. The road, however, contains only a gentle curve toward the left in the middle of the view and a curve to the right in the distance; otherwise it is straight. The uphill side of the road is covered in varying amounts by lobes of thin slide debris that have accumulated since the road was closed in 1973. The downhill edge of the road has been displaced by scarps of the thick landslides, but the uphill side of Delhi Pike has not moved.

The general form of the thin landslides, then, is multiple scarps and a simple, single toe. This general form is

Figure 13. View uphill along Delhi Pike from the location of trench 2. Landslides affect both sides of road. Despite appearances, the road is not crooked; thin landslides from upslope have spilled onto the left side and scarps of thick landslides have broken the right side of the road.

expressed even more definitively at other thin landslides in the Cincinnati metropolitan area. Two examples are described below:

In 1980, a thin landslide on a slope near the Delhi Pike landslide complex literally pulled itself apart by stretching movement. The landslide, described by Riestenberg and Sovonick-Dunford (1983), was broken into numerous separate blocks. Some blocks slid completely out of the landslide scar, and others were connected to each other only by tree roots. A careful analysis of striations on the exposed failure surface and a match of trees and roots allowed Riestenberg and Sovonick-Dunford (1983) to reconstruct the sequence of failure. The landslide apparently failed from the top down; two elements at the extreme upper scarp were the first to fail. Twelve individual blocks could be traced from their initial to final positions. At the conclusion of movement, several blocks from upslope overrode blocks that were farther downslope.

This style of failure (that is, landslide debris being pulled apart into separate blocks, some of which slide completely out of the landslide scar) is evidence for a large reduction in resistance to sliding following the initial movement. Riestenberg and Sovonick-Dunford (1983) attributed the large initial strength to tree roots. Failure of the roots that extended through the potential failure surface could have resulted in a dramatic loss in strength. Riestenberg and Sovonick-Dunford (1983) calculated that the roots could have increased the factor of safety against sliding ninefold.

Another example of extreme extension of thin landslides is shown in figure 14. This landslide, which occurred in 1973 a few kilometers east of downtown Cincinnati along Columbia Parkway, is typical of many thin landslides. The landslide slid completely out of its site of failure, moved about 20 m over the ground surface, and spilled over a retaining wall onto Columbia Parkway. In figure 14*A*, part of the landslide path is indicated by the light-colored material in the middle of the view. The initial failure occurred at the uphill end of the light-colored area. Individual landslide blocks that have separated during movement but remain on the slope are on the right side of the light-colored area. Unfailed material is on the left. At the extreme upper end of the scar, bedrock was exposed (not visible in the photograph) at the sole of the landslide. The lower part of the landslide scar contains four discontinuous benches or undulations. At least two of these benches continue to the left into the unfailed colluvium and are probably expressions of buried limestone layers in the bedrock underlying the colluvium.

The benches that are visible in the light-colored area in figure 14*A* are formed within the colluvium. Here, the colluvium has not failed to the level of the bedrock as part of the initial landslide but, rather, has been overridden by landslide debris from the deeper scar upslope. The landslide apparently pushed away a layer of the upper part of the slope including the vegetation, the pedologic A horizon, and underlying colluvium to a depth that contained most of the tree roots. Figure 14*B* shows a portion of the landslide debris that has spilled over the retaining wall onto Columbia Parkway. The retaining wall was not damaged by the shallow landslide, which, by the time it reached the wall, was moving over unfailed colluvium. Note the colluvium piled against the uphill side of the tree on the far left side of figures 14*A* and *B*. This movement history also is suggestive of a large drop in strength following initial failure of the landslide.

THE THIN LANDSLIDE AT DELHI PIKE

We studied one of the thin landslides uphill from Delhi Pike that appeared to be actively moving. Borings, trenches, open-tube piezometers, and movement indicators were placed as shown in plate 1. Seven shallow, open-tube piezometers were installed at the bedrock-colluvium interface. One inclinometer was placed in the 6.5-m-deep boring 7. A recording extensometer was installed across the two scarps near the head of the slides. Trenches 2, 3, and 4 were excavated through the colluvium into the bedrock to expose the failure surface. Trench 4 was excavated after a 1-yr period of monitoring.

This apparently active landslide has well-defined features (pl. 1). It is about 65 m long and 30 m wide in its upper part. The width is indeterminate in the lower part because the flanks are indistinct. In the upper part of the landslide, the ground surface is very irregular and bumpy; the bumps there correspond to individual landslide blocks that have pulled apart. Depressions separating these blocks are marked by distinct scarps on their upslope sides. Large flagstones of limestone (as large as 1.0×0.5×0.15 m) are scattered over the ground surface, and chips of weathered shale are present in the depressions between blocks. Topographically, the landslide surface is depressed as much as 0.5 m within the flanks in the upper 40 m. Farther downslope, the flanks are level with adjacent materials, and the surface contains benches that are similar to those farther west.

The uppermost scarp, at an approximate elevation of 220 m (720 ft) is about 1 m high and devoid of vegetation. There are several other scarps in the upper half of the landslide. Along some of these scarps, the separation between landslide blocks is wider at the flanks (2–3 m) than in the interior of the landslide (<1 m). This pattern of opening gives the curious impression that displacement was larger at the flanks than in the interior of the landslide.

In three places—uphill and downhill from boring P–5 and uphill from boring P–7—the wavy pattern on the map

Figure 14 (on facing page). Thin landslide along Columbia Parkway, east of downtown Cincinnati. *A*, Slide path was created when landslide from upslope slid completely out of its original position and pushed the colluvium and vegetation, including roots, off the remainder of the underlying colluvium. Undulations in the light-colored colluvium in the path of movement are benches reflecting limestone layers in underlying bedrock. *B*, Landslide debris has spilled over retaining wall onto Columbia Parkway.


A
B

in plate 1 depicts areas where displacement has separated the blocks all the way to the failure surface at the colluvium-bedrock contact.

An old, abandoned road that crossed the slide a few meters downhill from extensometer 1 has been offset about 7 m. Farther downhill, an additional 2–3 m of displacement is revealed by the size of scarps. Thus, the maximum displacement of the landslide was apparently about 10 m.

There is no evidence at the toe for 10 m of displacement, and there are no indications of shortening in the landslide uphill from the mapped toe at Delhi Pike. Thus, we suspect that this landslide occurred before the abrupt movement in 1973 that caused closure of Delhi Pike. If so, as much as 600 m^3 of landslide debris may have been hauled away from the road surface. If not, there is a very large discrepancy between the amount of displacement evident in the area of stretching and the amount observable at the toe.

No movement was recorded by the extensometer and the inclinometer during the year of monitoring in 1979–80. In 1990, the landslide appeared superficially to be unchanged since the end of our monitoring in 1981; clearly, it had made no large, abrupt movements in that time. However, the inclinometer in boring 7 was found to be squeezed closed at a depth of 2 m. Thus, the thin landslides do displace colluvium with small creeplike movements as well as the abrupt stretching failures observed in other places.

The time of activity of thin landslides throughout the metropolitan area is restricted to the interval between the spring thaw and the leafing of vegetation. Episodes of movement of thin landslides usually occur during major storms in the period of mid-March to early May. During the remainder of the year, either the vegetation is serving as an effective agent for dewatering the thin colluvium or the ground is frozen. Open-tube piezometers were dry except during the spring, when water levels responded almost immediately to rainfall (fig. 15). The behavior of subsurface water in the thin colluvium has been described by Gökce (1989) and by Haneberg and Gökce (in press).

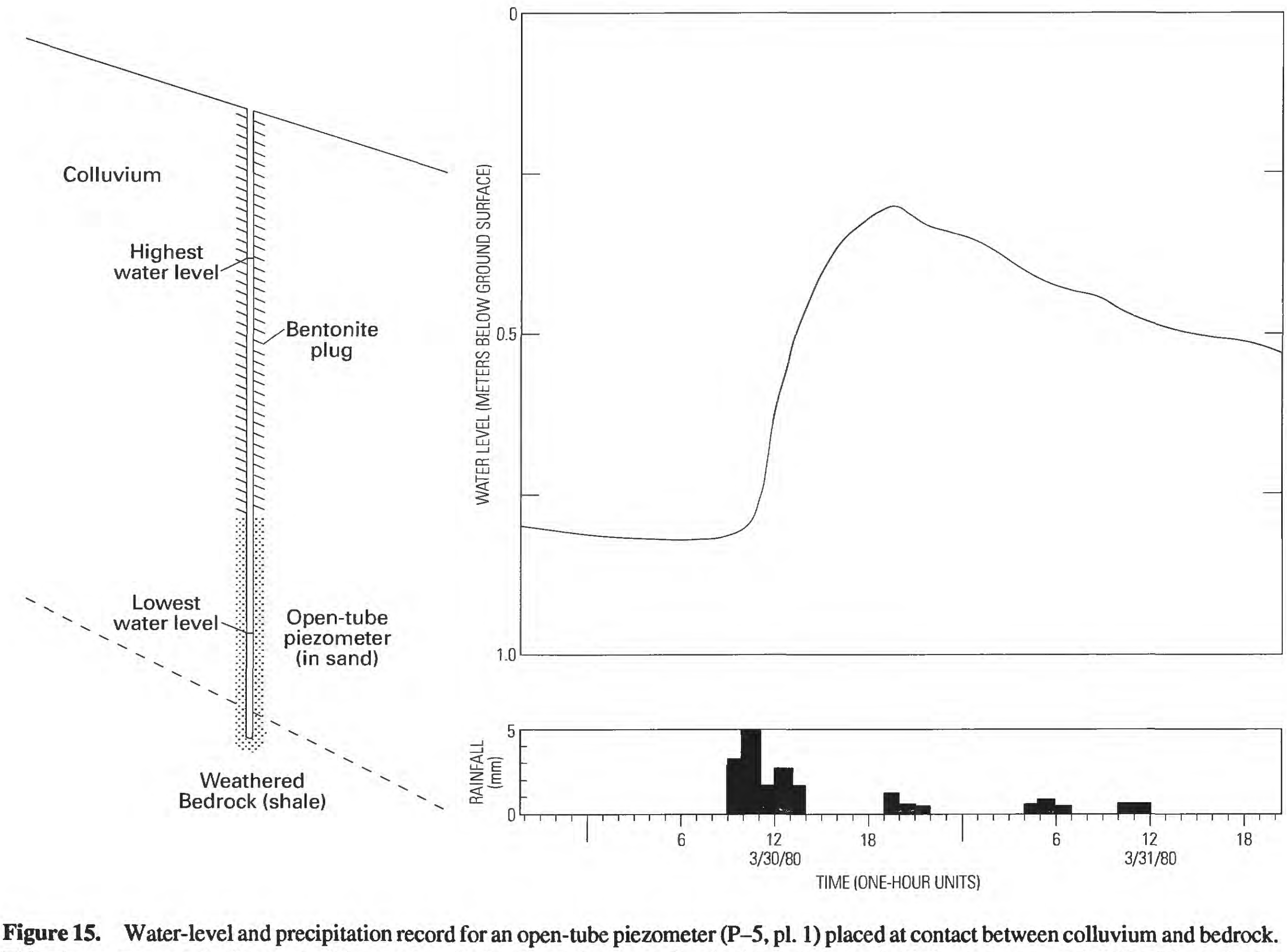

Figure 15. Water-level and precipitation record for an open-tube piezometer (P–5, pl. 1) placed at contact between colluvium and bedrock. This piezometer was dry for most of the year but, during the spring, water levels changed dramatically in response to rainfall. This particular record shows water-level response to a 1.7-cm rainfall on March 30–31, 1980. Sketch to the left of the water record shows location of piezometer relative to colluvium and weathered bedrock. (From Fleming and others, 1981.)

TRENCHES AND THE FAILURE SURFACES

All three trenches into the thin landslides (trenches 2, 3, and 4 on pl. 1) extended through the colluvium and into bedrock. There was no evidence that sliding extended into the bedrock, but virtually all the colluvium overlying the bedrock has failed. In all the trenches, one or more failure surfaces were present in the colluvium and (or) in the thin transitional zone to bedrock. Trenches 2 and 3 were short trenches into the toes of the thin landslides. Trench 4 extended nearly 60 m from a topographic bench near boring P–5 to Delhi Pike.

The colluvium is separable into two units on the basis of color. At the surface, the colluvium is a brown to dark-brown, stony, silty clay. The dark clay overlies a yellow-brown silty clay. The underlying bedrock is a mottled olive-gray shale with a few scattered beds of limestone in the shale. The thin transitional zone between the colluvium and bedrock contains abundant small chips of shale in a clayey matrix.

A few open tension cracks were found in the colluvium. Some of these cracks occurred at the edges of benches, where arching of the colluvium over the edges would produce stretching.

The positions and shapes of the failure surfaces are simple where the landslide geometry is simple and complex where large stones or bedrock ledges interfere with the sliding. Where the slope is smooth (for example, between 25 and 35 m on the trench 4 profile on pl. 1), the failure surface is a simple planar surface at the contact with weathered bedrock. A bumpy or hummocky ground surface typically coincides with more complex failure surfaces. A bench in the bedrock abruptly steepens the slope of the failure surface at the colluvium-bedrock contact. One to two meters downslope from the bedrock bench, one or more listric faults intersect the basal shear surface (as seen, for example, at 44 and 47 m on the trench 4 profile). The listric faults, in part, accommodate the change in slope of the basal failure surface, where it passes over the ledge, and also allow stretching of the landslide.

These landslides apparently undergo a significant amount of internal deformation as they move. The flagstones of limestone are haphazardly oriented near the ground surface. With increasing depth, the large dimensions of the stones become parallel to the failure surface. Voids are under or upslope from some of the stones and, in a few places, we noted that a layer of soft clay had been deposited in the void space.

The failure surfaces are typically paper thin, glossy, and abundantly striated. At all scales of observation, the surfaces show roughness. Roughness was produced by small stones or fossil fragments projecting into the surface. Small steps, 2–3 mm high, are common where the colluvium breaks from one shiny surface to another. These steps have the same appearance as chatter marks on fault surfaces in rock.

At a slightly larger scale, the failure surfaces commonly bifurcate around rock fragments. Also, multiple surfaces occur where the slope of the failure surface is changing over a short distance. Still larger undulations in the failure surface occur where a limestone layer produces a bench on the top of the bedrock. When multiple failure surfaces are present, as in trench 3 (pl. 1), the material between the surfaces is softer and more moist than that outside the failed zone.

Figure 16 shows two scanning electron micrographs of fragments of the failure surface. Figure 16*A*, magnified at 16×, is a view normal to a major failure surface. Direction of sliding was from right to left. For the most part, the surface is streamlined in the direction of sliding and contains discontinuous ridges and furrows parallel to the direction of sliding.

The light-gray circular spots on the failure surface that are about 0.2 mm in diameter are aggregates of calcium sulfate crystals. We observed clear water on the surfaces of soil peds from the pedologic B horizon but did not directly observe water along the failure surface. The crystal aggregates are indirect evidence that free water exists seasonally along the surface of sliding. The crystal aggregates were not found in the interiors of the blocks or on smaller, subordinate shiny surfaces such as the one shown in figure 16*B*.

Figure 16*B* is an oblique view, at about 40× magnification, of a short slickensided surface in a sample containing several slickensided surfaces. The left and right sides of the sample (out of view in this image) are both slickensided surfaces. The flat, slickensided surface in the middle of the view does not visibly extend through the sample, which is only about 1 cm thick. The edge of another smooth surface, subparallel to the first, is exposed about 150 μm to the left of it. None of these surfaces appear to be parallel to the others, but neither are they grossly out of alignment with each other, as might be expected if they were conjugate shear fractures. Our supposition is that the complex fracture zones occur where the failure surface is changing shape either by passing over an asperity or emerging to the ground surface. These particular samples are from near the downslope end of trench 4, where shortening deformation was occurring and material was pushed onto Delhi Pike.

The continuous, well-developed failure surface traceable in trench 4 (pl. 1, profile) indicates that the strength is at a residual value (Skempton, 1964, 1985). However, three other observations suggest that the strength mobilized in the field might be larger than the laboratory-measured residual strength. One observation, already mentioned, is roughness on the failure surfaces that could contribute to increased strength. The roughness was observed over a scale of about six orders of magnitude, from micrometers to meters. We also noted that sliding is accompanied by deformation of the colluvium over a zone that extends to about a half meter above the failure surface. Large limestone clasts within this zone are preferentially oriented parallel to the failure

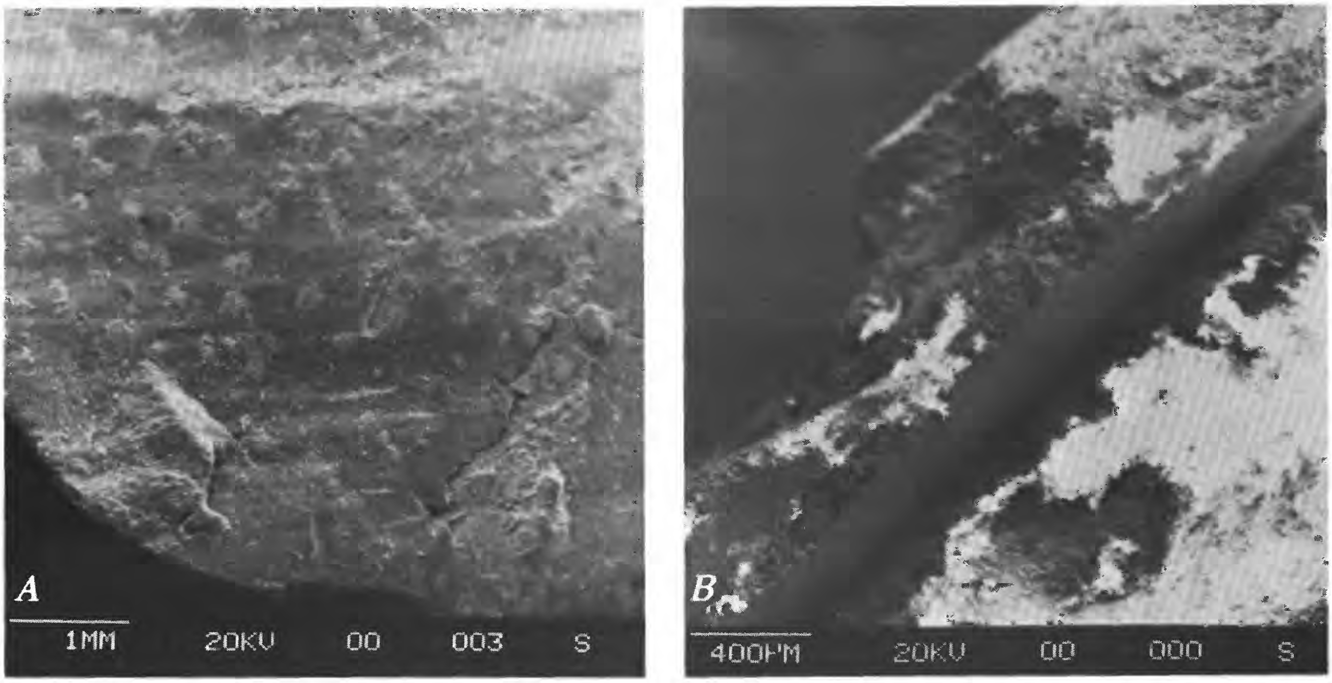

Figure 16. Scanning-electron micrographs of portions of the failure surface. *A*, View normal to a slickensided surface. *B*, View oblique to several subparallel slickensided surfaces.

surface, whereas clasts outside this zone appear to be haphazardly oriented. The deformation that creates parallel clasts is work done by the landslide in the process of sliding and contributes to resistance to sliding. And, finally, the presence of multiple failure surfaces is evidence that the failure geometry is less than optimum for sliding. Presumably, multiple slip surfaces are also an indication of internal deformation of landslide material.

We do not know if the internal remolding of material and the creation of multiple slickensided surfaces occur simultaneously during landslide movement. If they do, the residual strength of the soil, as back-calculated from field conditions, might be significantly larger than the strength measured on a single failure surface in the laboratory.

There is evidence that landslide movement may be limited to only one of the slickensided surfaces during a movement episode. The roots that extended into bedrock near the downslope end of trench 4 were kinked at only one level even though they penetrated at least two slickensided surfaces (fig. 17). Perhaps multiple failure surfaces are created during the first-time failure of the slope and subsequent movement involves a more simple geometry.

Figure 17. Kinked roots on an exposed failure surface. The abrupt kinks in the roots formed at the position of the failure surface. There were at least two failure surfaces at this position near the toe of the landslide, but the roots were deformed only along the surface exposed in the photographs. (Photograph by Mary Riestenberg, College of Mount St. Joseph.)

PROPERTIES OF THE COLLUVIUM

The colluvium is a stony, silty clay containing variable amounts of sand to boulder-size fragments of limestone. Within the colluvium, soil scientists recognize two soil series whose distributions roughly correspond to areas containing thin and thick landslides (Lerch and others, 1982). These soils are named the Pate Series, representative of thick colluvium, and the Eden Series, representative of thin colluvium. In general, the colluvium consists of dark-brown silty clay (10YR4/3) overlying yellow-brown silty

Table 1. Summary of selected physical properties of Eden and Pate Soil Series

Data from Soil Conservation Service (1978)

Soil series	Depth (cm)	Soil horizon	Liquid limit	Plasticity index	Permeability (μm/s)	Moist bulk density (g/cm³)	Gradation (percent)			
							Coarse (>76 μm)		Fine (< 76 μm)	
							Gravel	Sand	Silt	Clay
Eden	0–15	A	35–65	12–25	0.4–4	1.35–1.65	0–40	0–25	0–30	27–60
	15–61	B	45–75	20–45	0.4–1	1.45–1.65	10–45	0–35	5–35	40–60
Pate	0–15	A	25–35	8–20	1 –4	1.35–1.60	0–10	0–20	5–35	20–40
	15–91	Bt	40–60	15–30	0.4	1.50–1.70	0–10	0–20	5–30	35–55
	91–183	B_3	40–60	20–35	0.4	1.60–1.80	15–50	0–30	10–35	35–55

Data from Norton (1979)

Soil series	Depth (cm)	Soil horizon	Composition of clay minerals in clay-size fraction (percent)			Clay fraction (percent)
			Vermiculite	Micas and illite	Kaolinite	
Pate	0–30	A	9	77	15	23
	30–95	Bt [1]	30	47	23	31
	95–144	B_3	34	48	17	20

[1] The Bt horizons contain 2–5 percent montmorillonite. Other horizons contain only trace amounts of montmorillonite.

clay (10YR4/4). Within a given soil profile, the thicknesses of both the dark and yellow-brown colluvium are highly variable. And, although the dark colluvium in most places occurs near the ground surface, it occurs locally as wedges or layers within the yellow-brown colluvium. The burial of surficial layers may be due in some cases to root throw from overturning of trees (Hack and Goodlett, 1960) and in other cases to the overriding of surficial materials by landslides. We noted overridden soil in trench 1 (pl. 1). The pedologic B horizon contains translocated clay and has a prismatic blocky structure. Free water was observed on the surfaces of soil peds in the B horizon shortly after rain storms.

Other than small variations in color and texture, the physical properties are the same for both soil series. The routine engineering properties of the colluvium are reported in tables 1 and 2. Data in table 1 are from the Soil Conservation Service (SCS) (1977, 1978) and Norton (1979) for the entire range of the Pate and Eden Soil Series and thus are representative of the colluvium over a wide geographical area.

The principal difference in properties between the Pate and Eden Series is in the amount of coarse fraction. Eden soils, which occur on the higher, steeper reaches of the slopes, contain more rock fragments than the Pate soils. The amount of increase is illustrated by the increase in rock fragments larger than about 10 cm exposed in the walls of the trenches. In trench 1, the most downhill trench, rock fragments occupied just 1.4 percent of the exposed trench wall. In trenches 2 and 3, just uphill from Delhi Pike, rock fragments compose 3.5 and 2.6 percent, respectively, of the trench walls. In trench 4, 6–12 m farther uphill than trenches

Table 2. Summary of physical properties of colluvium and shale from the Delhi Pike study area

[All tests performed according to American Society for Testing and Materials standards]

Physical property	Average	Range
Atterburg limits (20 tests):		
Liquid limit	45	36–52
Plastic limit	23	19–26
Plasticity index	22	15–27
Gradation (20 tests; percent):		
Sand	10	4–18
Silt	32	22–44
Clay	59	47–68
Permeability (8 tests; cm/s)*	1.4×10^{-3}	4×10^{-3}–3×10^{-4}
Field density (9 tests; g/cm³)	2.01	1.74–2.13
Specific gravity of solids (1 test)	2.79	

*Nine samples tested, undisturbed in the trench; data from one sample (8×10^{-6}) not included in range or average.

2 and 3, rock fragments compose 4.6 percent of the trench wall. And, at the upper end of trench 4, rock fragments compose 9 percent of the trench wall. While these amounts of coarse fraction might influence the physical properties of the colluvium somewhat, nowhere is the coarse fraction large enough to dominate the behavior of the soil. The mechanical behavior of the soil is dominated by the properties of the fine fraction.

We tested 20 samples from the borings and trenches—including dark-brown colluvium, yellow-brown colluvium, and weathered shale—for Atterberg limits, gradation, permeability, field density, and specific gravity of the solids. Results are summarized in table 2. We did not quantify the composition of clay minerals in the clay-size fraction, but they are predominantly illite and mixed-layer clays and have subordinate amounts of kaolinite.

The only significant difference between our data in table 2 (which are specifically for the Delhi Pike site) and the SCS data in table 1 (which represent a large geographic area) is in the values of permeability. We consistently obtained values more than 10 times larger than those in the SCS data. These discrepancies are probably due more to differences in the test methods than to differences in the materials. Our tested samples were trimmed from block samples obtained from the trench walls using the falling-head method (Lambe and Whitman, 1969), whereas the SCS measurements were based on percolation tests in the field.

The most important physical property of the soil, with respect to slope stability, is its strength. Among the several methods used to measure the strength of a soil, engineering practice has demonstrated that the relevant measure of resistance to sliding is the residual strength (Skempton, 1964). Residual strength is commonly measured in a direct- or ring-shear device that accumulates large displacements on a well-developed failure surface. The residual strength is the minimum strength measured under fully drained conditions for at least three different normal loads.

We conducted five separate tests of residual strength on samples collected from the trench walls. Three of the tests were by repeated direct shear and two by ring shear. One of the direct-shear tests was on a remolded total sample that contained coarse sand and fossil fragments. The other two direct-shear tests and both of the ring-shear tests had various coarse fractions removed: the +230 mesh (>63 μm) fraction was removed for one test of each type, and the +30 mesh (>600 μm) fraction was removed for the other test of each type. All the tests were conducted under three different normal loads equivalent to burial at depths of 1, 2, and 4 m. The results of the tests are in table 3.

Residual strength parameters, expressed as the slope of the best-fit line through the three data points, are angles of internal friction ranging between 12° and 24°. The largest value was obtained for the sample that did not have the coarse fraction removed. Smallest values, 12°–17°, were consistently obtained with the ring-shear device on samples that had the coarse fraction removed. Whether the fraction removed was +30 mesh or +230 mesh made only a slight difference in the strength parameters.

Table 3. Residual strength of colluvium from the Delhi Pike study area

[All tests performed according to American Society for Testing and Materials standards]

Test conditions	Strength parameters	
	Residual friction (degrees)	Residual cohesion (kPa)
Direct-shear test		
Total sample:		
Cohesion assumed zero	24	0
"Best fit"	21	3
+30-mesh fraction removed:		
Cohesion assumed zero	21	0
"Best fit"	18.5	8
Minimal friction	12	16
+230-mesh fraction removed:		
Cohesion assumed zero	21	0
"Best fit"	20	5
Minimal friction	11	16
Ring-shear test		
+30-mesh fraction removed:		
Cohesion assumed zero	17.5	0
"Best fit"	12	5.5
+230-mesh fraction removed:		
Cohesion assumed zero	16	0
"Best fit"	12.5	3

The best-fit straight line through the data points for each test had a small cohesion intercept that ranged from 3 to 16 kPa. There has been much discussion in the literature about whether a sample at residual strength can have a small cohesion intercept as part of its total strength parameters. The data obtained here are not relevant to that issue, and interested readers are referred to Skempton (1985) and to the references that he cites relative to residual strength.

Shannon and Wilson, Inc. (oral commun., 1980) studied a large landslide in colluvium in the Mt. Adams section of Cincinnati (fig. 1). Their laboratory measurements showed that the colluvium had residual friction angles of 15° and zero cohesion. Back-calculation of strength parameters for the landslide produced a residual friction angle of 13° and a cohesion of 96 kPa.

STABILITY ANALYSES

We performed stability analyses for both thin and thick landslides at the Delhi Pike site. For the thin landslides, we used the geometry revealed by trench 4 (pl. 1) and averages of measured properties. Figure 15 shows the response for water levels in thin slides to even a moderate-size spring rainstorm. Storms large enough to raise the unconfined water surface as high as the ground surface are likely even in years of average precipitation. We back-calculated strength parameters for the above conditions using the method of Janbu (1973). At equilibrium, a frictional resistance of 39° is necessary to support the slope. This value is much larger than the strength we would expect to find along the well-developed failure surfaces exposed in trench 4.

Skempton (1964, 1985) reports measurements of residual strength on clays of similar physical properties in the range of 13° to 15°. Results of our measurements of residual friction angles of the colluvium varied from about 24° to 12° for different types of tests and methods of sample preparation (table 3). The largest values were obtained from untreated but remolded samples tested in a direct-shear machine. The smallest values were obtained on samples that had the coarse fraction (>30 and >230 mesh) removed and were tested in a ring-shear device. After the tests, we inspected the failure surfaces developed during shearing. Samples having larger residual strength invariably contained sand-size particles along the planes of failure.

Even assuming the maximum value of residual strength that we measured, the colluvium is only marginally strong enough to resist failure by thin landsliding. Therefore, some additional factor(s) must have enhanced the resistance to sliding. Possible factors mentioned earlier include tree roots, roughness of the failure surface, and (or) small residual cohesion.

The factor of safety of slopes underlain by thick landslides is apparently consistent with laboratory measurements of strength. We back-calculated the stability of the slope that we studied on the downhill side of Delhi Pike, using the same properties as for the thin slides. The computed effective residual friction angles necessary for equilibrium range from 23° for a slope saturated to the ground surface to 12° for a slope with the water level below the failure surface. Both extreme values appear to be unrealistic. We measured saturated conditions to a level of 1 m above the failure surface at the toe and noted the presence of springs locally within the failed mass. On the other hand, near the middle of the landslide, we did not find saturated conditions in the colluvium anywhere above the bedrock; the failure surface in the colluvium was at least 2 m above the bedrock-colluvium contact. Thus, an estimated average residual friction in the range of 16° to 20° would be consistent with field and laboratory data.

CONCLUDING REMARKS

In summary, slopes in thin colluvium appear to be more stable than we would predict from laboratory measurements of residual strength of the colluvium. The puzzling question about thin landslides, then, is not why some slopes have failed, but rather why failure is not more extensive. Observations of episodes of movement of typical thin landslides (fig. 18) suggest that a type of stick-slip phenomenon may contribute to larger-than-measured initial strength. We observed that a small displacement causes a large loss of resistance, and a thin landslide commonly accelerates out of the slide scar. The situation, shown schematically in figure 18, may be equivalent to the abrupt loss of strength in first-time failures of slopes compared to reactivation of previously failed slopes. For thin colluvium, however, the slope has previously failed and yet retains greater resistance to sliding than predicted by laboratory measurements.

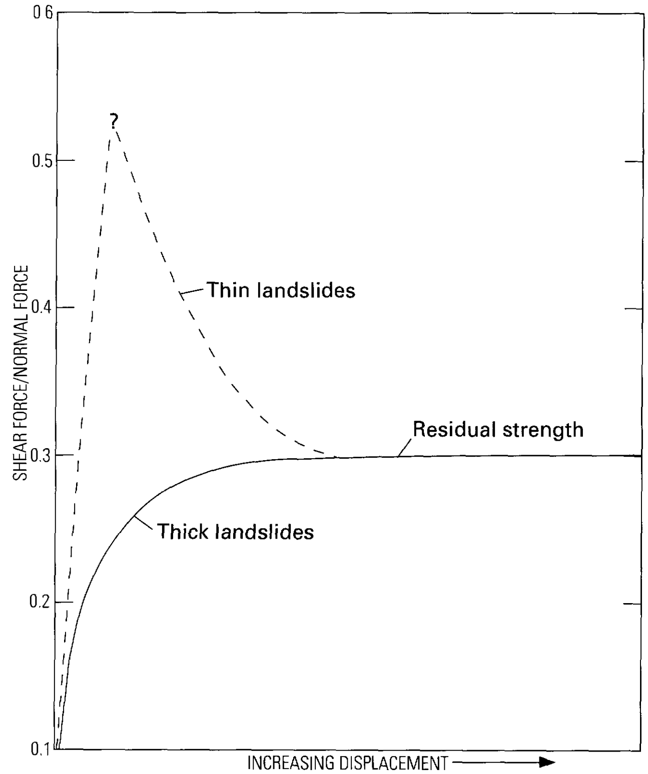

Figure 18. Hypothetical force-ratio-displacement models for thin and thick landslides. Back-calculation of stability of thin colluvium reveals that the residual strength is insufficient to support the slope. Field behavior indicates that some form of stick-slip behavior produces large initial strength that is lost after a small amount of displacement. The back-calculation of stability of thick colluvium reveals that failure is consistent with the measured value of residual strength.

The landslides in the thick colluvium behave more or less as we would predict from laboratory measurements of residual strength of the colluvium. We know of no examples in which thick landslides have moved more than a few meters during any given episode of movement. More commonly, the total displacement during a movement episode is only a few centimeters. A force-displacement diagram for the thick landslides (fig. 18) illustrates the concept that the maximum mobilized resistance to sliding is residual friction. The cause of the difference in behavior between the two landslide types could be due to a small amount of residual cohesion and/or roughness of the failure surface and perhaps tree roots.

The presence of multiple failure surfaces is an interesting aspect of the thick landslides. The history of failure at the Schmale residence indicated that the failure surfaces formed progressively from a common headscarp along Delhi Pike. Our stability analysis is relevant only to the deepest of the failure surfaces. The tree rings and constricted inclinometer casings are evidence that movement continues to occur on the more shallow failure surfaces.

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