Factors Contributing to Landslide Susceptibility of the Kope Formation, Cincinnati, Ohio

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ABSTRACT

The objective of this study was to evaluate the factors that contribute to the high frequency of landslides in the Kope Formation and the overlying colluvial soil present in the Cincinnati area, southwestern Ohio. The Kope Formation consists of approximately 80% shale inter-bedded with 20% limestone. The colluvium that forms from the weathering of the shale bedrock consists of a low plasticity clay. Based on field observations, liDAR (light detection and ranging) data, and information gathered from city and county agencies, we created a landslide inventory map for the Cincinnati area, identifying 842 landslides. From the inventory map, we selected ten landslides for detailed investigations that included seven rotational and three translational slides. Representative samples were collected from the landslide sites for determining natural water content, Atterberg limits, grain size distribution, shear strength parameters, and slake durability index. For the translational landslides, strength parameters were determined along the contact between the bedrock and the overlying colluvium. The results of the study indicate that multiple factors contribute to landslide susceptibility of the Kope Formation and the overlying colluvium including low shear strength of the colluvial soil, development of porewater pressure within the slope, human activity such as loading the top or cutting the toe of a slope, low to very low durability of the bedrock that allows rapid disintegration of the bedrock and accumulation of colluvial soil, undercutting of the slope toe by stream water, and steepness of the slopes.

Key Terms: *Kope Formation, Colluvial Soil, Landslide Susceptibility, Shear Strength, Pore Pressure, Slake Durability, Toe Undercutting.*

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INTRODUCTION

Landslide Problem in the Cincinnati Area

The Cincinnati area (Hamilton and Clermont counties) comprises the southwestern corner of Ohio and is one of the most landslide susceptible areas in the United States [Ohio Emergency Management Agency (EMA), 2011]. Most of the landslides occur in the Kope Formation and the overlying colluvial soil during late winter and early spring (Fleming, 1975). Landslide damage and mitigation cost the city millions of dollars each year (Rockaway, 2002). According to Schuster (1996), the annual per capita cost for landslide damage in the Cincinnati area was $5.80 in 1981 (equivalent to $17.27 in 2020). This does not include more than $22 million spent in 1981 (equivalent to $65.5 million in 2020) to stabilize a single landslide that occurred on Mount Adams during the construction of Interstate 471. One of the costliest time periods for landslide damage in the Cincinnati area occurred between 1973 and 1978 when, over a six-year period, an average of $5.1 million in 1981 dollars (equivalent to $15.2 million in 2020) was spent per year to repair landslide damage (Schuster, 1996).

Rotational and translational slides are the most frequently occurring slope movements associated with the Kope Formation and the overlying colluvial soil. Rapid earthflows, rockfalls, and complex slides (combination of rotational and translational slides), although present, are infrequent. Rotational slides are common where thick colluvium covers the bedrock. They are generally 2-15 m thick, 30-300 m wide (measured perpendicular to the direction of sliding), and 30 -150 m long (measured along the direction of sliding). Many rotational slides are associated with springs or marshy areas either beneath or within the slope toes (Fleming and Johnson, 1994). Translational slides are common where thin colluvial soils (2-3 m thick) cover relatively steep slopes (15°-30°). They occur along the colluvium-bedrock contact, are generally 10-150 m wide and 30–130 m long, and they vary in shape from long and narrow to wide and short (Richards, 1982). Translational slides generally occur during spring because the slide material is almost saturated between the months of January and May (Haneberg, 1991; 1992; Haneberg and Gokce, 1994). The dominant form of deformation in translational slides is longitudinal stretching resulting in a series of scarps. Complex landslides in the Cincinnati area consist of more than one layer of slide material. They are thinner near the slope crest and become thicker near the toe. Rapid earth flows in the Kope Formation (locally known as mudslides) occur on steeper slopes along the Columbia Parkway. They occur during wet periods in areas where the colluvium is < 2 m thick and is clayey in nature (Pohana, 1983). Rapid earthflows involve movement of the entire thickness of the colluvium, exposing the bedrock (Richards, 1982; Riestenberg and Sovonik-Dunford, 1983)

Geology of the Cincinnati Area

The Cincinnati area forms the western flank of the Cincinnati Arch where the bedrock dips gently at less than 1° (Fleming, 1975). The area represents an upland surface, enveloped by the Pre-Illinoian, Illinoian, and Wisconsinan age glacial deposits, that has been dissected by ancient drainage systems as well as the modern Ohio River and its tributaries (Pavey et al., 1992; Potter, 2007). Many of the tributaries have carved broad, terraced valleys with steep slopes. The relief between the Ohio River and the hilltops in the area is approximately 120 m (Baum and Johnson, 1996). Alluvium and glacial outwash cover the valley floors and colluvium covers most of the hillsides (Baum and Johnson, 1996).

The Kope Formation in the Cincinnati area is overlain by the Fairview Formation, both being Upper Ordovician in age. The contact between the two formations is at an elevation between 200 and 215 m (Gibbons, 1973). Figure 1 shows the extent of the Kope Formation in the Cincinnati area, as indicated by the surficial geology map. The formation is more than 60 m thick and consists of inter-bedded, medium to dark grey, shale (80%) and coarse-grained fossiliferous limestone (20%) (Fleming and Johnson, 1994). It should be noted that what is referred to as "shale" in the earlier studies is mudstone/claystone according to Potter et al. (1980) classification (Sarman, 1991; Dick, 1992; Hajdarwish, 2006). The shale (mudstone/claystone) consists of illite, chlorite, calcite, and quartz (Sarman, 1991; Dick, 1992; Hajdarwish, 2006). The limestone layers within the Kope Formation contain three sets of near-vertical joints, occurring at regular spacing. The orientations of the joints, however, vary between different locations (Hofman, 1966; Brett and Algeo, 2001; Brett et al., 2003). The shale also contains steeply dipping joints (Richards, 1982; Baum, 1983). The colluvium associated with the Kope Formation classifies as Eden silty clay loam according to the Hamilton County Soil Survey Report and as clay of low plasticity (CL) according to the Unified Soil Classification System (USCS) (Lerch et al., 1982; Glassmeyer, 2014). The colluvium covers most of the hillsides and generally ranges in thickness from a few centimeters up to 15 m (Fleming and Johnson, 1994), but can be much thicker at some places.

Study Objectives

Although landslides in the Cincinnati area have been studied extensively, a specific and detailed study regarding the susceptibility of the Kope Formation to landslide occurrence has not been conducted. Thus, the main objective of this study was to investigate the factors that contribute to high landslide susceptibility of the Kope Formation and the colluvium derived from it (Note: in this study, the colluvium is synonymous to the Kope Formation). This objective was accomplished by performing the following tasks:

1. Create a landslide inventory map for the Kope Formation and the associated colluvium.
2. Determine the engineering properties of the Kope Formation and the overlying colluvium.
3. Identify the types of slope movement that affect the Kope Formation.
4. Explain the landslide susceptibility of the Kope Formation and the overlying colluvium in terms of engineering properties, slope characteristics, and hydrologic conditions.

RESEARCH METHODS

Landslide Inventory

We developed a landslide inventory map for the Kope Formation and the overlying colluvial soil using LiDAR (light detection and ranging) data, field observations, and landslide-locations data from city and county governments (Figure 2). A total of 842 landslides were identified in the colluvial soil derived from the Kope Formation. Of these, 542 landslides were identified using the LiDAR-derived maps and 300 were identified through field observations and data obtained from city and county governments. The LiDAR data, with an accuracy of 0.33 m, was divided into tiles that were 1524 m by 1524 m square. Since the LiDAR data is a las (a blob point file or a collection of binary data stored as a single entity), the data were converted into usable maps using ArcGIS. The files were first converted from multipoint files to ASCII files. The ASCII files were then converted to raster files. Once the raster files were created, we developed a slope map, a hillshade map, a digital elevation map (DEM), and a topography map for the study area. These maps were used to identify landslide related features such as scarps and toe bulges. Randomly selected landslides from the inventory map were verified through field observations, using the GPS. Before mapping the landslides, three different layers were used to define the area of interest on LiDAR-derived maps: (i) the extent of the Kope Formation in the Cincinnati area as defined by the Ohio Department of Natural Resources (ODNR) bedrock geology map, (ii) the extent of the Kope Formation as defined by the ODNR surficial geology map, and (iii) the extent of the colluvium as defined by the ODNR soil survey division.

Site Selection, Data Collection, and Sampling for Detailed Investigations

From the landslide inventory map, we selected ten landslide sites for detailed investigations (Figure 3). These included seven rotational landslide sites (Eight Mile Road landslide, Ten Mile Road landslide, Delhi Pike landslide complex, Elstun Road landslide, Nordyke Road landslide, Old US 52 landslide, Wagner Road landslide) and three translational landslide sites (Nine Mile Road landslide, Berkshire Road landslide, Columbia Parkway landslide). The selected sites represented a range of landslide sizes and geographic locations. The data collected at each site included slope geometry (slope height, slope angle, and slope length), thickness of the colluvium, type of slope movement, location of the failure plane with respect to slope face, whether the slide occurred in the colluvium or within the bedrock, and landslide dimensions (length and width). Where possible, information about the hydrogeologic conditions was obtained. We used Cruden and Varnes classification system (Cruden and Varnes, 1996) to identify the type of slope movement at each site. For describing landslide features and for measuring landslide dimensions at different sites, we used the standardized terminology recommended by the International Association of Engineering Geology (IAEG) Commission on Landslides (IAEG, 1990). Undisturbed chunk samples of colluvial soil, weighing approximately 5 kg, were collected from each site for laboratory testing. Additionally, bedrock samples were collected from the three translational landslide sites. The samples were immediately sealed in air-tight bags and stored in five-gallon plastic buckets to preserve natural water content of the soil samples and to prevent slaking of the bedrock samples.

Laboratory Investigations

Laboratory tests were conducted to determine natural water content, grain size distribution, Atterberg limits, shear strength parameters, and slake durability index. All tests were performed following the American Society for Testing and Materials (ASTM) specifications (ASTM, 2010). Natural water content, an indicator of the soil's void ratio, was determined as soon as the soil samples were brought to the laboratory. Both sieve analysis and hydrometer analysis were used to determine the grain soil distribution of the colluvial soil samples. The results of grain size distribution analysis helped classify the soil from each site according to the Unified Soil Classification System (USCS) (Casagrande, 1948; Holtz et al., 2011). Atterberg limits test was performed only on material passing the #200 sieve (0.074 mm) to determine liquid limit, plastic limit, and plasticity index. The test results were used to classify the fine-grained fraction of the soil according to the USCS. Two versions of the direct shear test were conducted to determine shear strength parameters. The purpose of the first version was to simulate failure conditions in case of rotational landslides with the failure plane located entirely within the soil whereas the second version simulated the failure conditions for the translational slides with the failure occurring along the contact between the bedrock and the overlying colluvial soil. The slake durability test was performed on the bedrock samples that were collected from the Nine Mile Road landslide, Berkshire Road landslide, and Columbia Parkway landslide sites where the bedrock is at shallow depths. The purpose of the slake durability test was to evaluate weathering potential of the bedrock. Two cycles of the test were performed on each sample and the 2^{nd}-cycle slake durability index (Id_2) was calculated. Based on Id_2 values, and using the International Society for Rock Mechanics (ISRM) classification (ISRM, 2007), the durability of the samples was classified as follows: high (Id2 > 95%); medium (Id2 = 85%-95%); low durability (Id2 = 60%-85%); and very low durability (Id2 = 0%- 60%).

Stability Analysis

The computer program Slide 6.0 (Rocscience, 2012) was used to perform stability analysis for the ten sites. The program identified the critical surface of failure and calculated the corresponding factor of safety (FS) for both dry and saturated conditions. We also used Slide to perform sensitivity analysis, i.e. variation of FS with respect to strength parameters and groundwater conditions.

RESULTS

Laboratory Test Results

The natural water content values for the colluvial soils from the ten landslides sites range from 13.1% to 27.1%, with a mean value of 20.4% (Table 1). The relatively high water content values suggest the presence of a high percentage of fine-grained clayey material in the colluvial soils at the landslide sites. This implies that even a small amount of precipitation can result in buildup of pore pressure and reduction in shear strength, leading to failure. The high water content values also indicate the potential for flow type movement.

The results of grain size distribution analysis indicated that, according to USCS, colluvial soils derived from the Kope Formation classify as clayey sand (SC). It should be noted that although the colluvial soil classifies as clayey sand, the sand size particles consist of broken pieces of shale bedrock and fossils, overall, the colluvium behaves as a clay of low plasticity during landslide activity.

Table 2 presents the Atterberg limits test results for the fine-grained fraction of the colluvium from the ten sites. A plot of Atterberg limits on Casagrande plasticity chart is shown in Figure 4. The plot shows that the fine-grained fraction of the colluvial soil classifies as clay of low plasticity (PL). Table 2 also lists the liquidity index (LI) values. The liquidity index compares the natural water content with the Atterberg limits and indicates how a soil will behave when sheared. If LI is > 1, the soil will behave as a viscous liquid when sheared, if it ranges from 0-1, the soil will behave as a plastic material on shearing, and if it is < 0, the soil will behave as a brittle material. The LI values in Table 2 indicate a plastic behavior of colluvial soil during landsliding.

The strength parameters of a soil (cohesion and friction angle) are the most important engineering property of a soil in terms of the stability of a slope. For the soil alone (rotational slides scenario), the peak cohesion and friction angle range from 24.5 kPa to 47.7 kPa and 22.8^o to 39.4^o, respectively, and the residual cohesion and friction angle from 22.2 kPa to 38.9 kPa and residual friction angle from 15.6^o to 20.8^o (Table 3). For soil-bedrock contact (translational slide scenario), the residual cohesion ranges from 6.8 kPa to 13.0 kPa, and the residual friction angle from 8.0^o to 14.6^o (Table 4) We provide only residual strength parameters for soil-bedrock contact because of the slow, continual movement of the thin soil layer over bedrock. These shear strength parameter values are inadequate to maintain stability with respect to both rotational and translational slides.

The second cycle slake durability index (Id_2) ranges from 7.1% (very low durability) for the Columbia Parkway landslide to 39.9% (low durability) for the 9 Mile Road landslide (Table 5). The low to very low durability of the Kope Formation explains the thick accumulation of colluvial soil at many locations. The durability properties of argillaceous rocks are important in slope stability because of the reduction in strength properties as a result of weathering (Dick and Shakoor, 1995).

Stability Analysis Results for Selected Slope Failures

Rotational landslides constitute the most common type of slope failure in the colluvial soil derived from the Kope Formation. All seven rotational landslides that were studied in detail occurred in colluvial soil. Rotational landslides occur where the colluvial soil is > 3 m thick.

Translational landslides are the second most common type of failure in the colluvial soil. Translational landslides tend to occur in complexes, affecting wide-spread areas. The failure plane for a translational slide is located along the contact between the colluvial soil and the underlying bedrock. The sliding mass for the three translational slides studied (Nine Mile Road landslide, Berkshire Road landslide, Columbia Parkway landslide) consists of colluvial soil. The thickness of colluvial soil at the locations of translational slides was found to be approximately 1.5 m to 3.0 m. Detailed descriptions of both rotational and landslides can be found in Glassmeyer (2014)

For the sake of brevity, we present stability analysis for one rotational landslide (Ten Mile Road landslide) and one translational landslide (Columbia Parkway landslide). For stability analyses for all ten landslides, see Glassmeyer (2014). The software program Slide (Rocscience, 2012) was used to perform the stability analysis, using residual strength parameters. For the Ten Mile Road landslide (Figure 5), the critical surface with the lowest factor of safety (FS) is shown in Figure 6, which matches the failure surface location observed in the field (Figure 5). The Slide program resulted in a FS of 0.83 for the dry condition and 0.79 for the saturated condition. The stability analysis indicated that for the FS to be >1, the cohesion of the soil should be > 61.2 kPa (instead of 22.5 kPa) if the friction angle were to remain constant at 15.6^o, or the friction angle needs to be > 33.8^o if the cohesion remains the same (22.5 kPa) (Table 3).

For the Columbia Parkway landslide (Figure 7), the critical surface, as determined by the

Slide program, is located along the contact between the colluvial soil and the underlying bedrock (Figure 8). It initiates at the top of the slope and emerges at the top of the retaining wall at the base of the slope (Figure 7). It should be noted that soil-bedrock contact may not be perfectly planar (Figure 8) but we assumed it to be planar for the purpose of stability analysis. Also, we assumed a uniform, average colluvium thickness. Locally, the landslide may change into earthflow/mudflow. The minimum FS for the dry condition is 1.04, when the colluvium is dry, and 0.68 when saturated. Stability analysis results show that the soil-rock friction angle needs to be >18^{o} instead of 14.8^{o} (Table 4) for the FS to be >1, if the cohesion were to remain constant at 6.8 kPa, or the cohesion should be >8.9 kPa if the friction angle remains constant (14.8^{o}) (Table 4). These results clearly suggest that strength parameters of the colluvial soil are lower than those required to maintain stability.

The Columbia Parkway landslide is currently being stabilized at an estimated cost of $17 million (City of Cincinnati – Transportation & Engineering, 2020). The stabilization project extends from Bains Street (Mt. Adams area) on the west side to beyond Torrence Parkway (East Walnut Hills area) on the east side, a nearly two-mile long stretch of the Parkway. Within this stretch, 12 landslide locations have been chosen for stabilization with the stabilization method, involving either metal mesh and soil nails or retaining walls (Figure 9), varying from location to location (City of Cincinnati – Transportation & Engineering, 2020). The construction started towards the end of 2019 and is expected to be completed by summer 2021 (City of Cincinnati – Transportation & Engineering, 2020).

FACTORS CONTRIBUTING TO LANDSLIDE SUSCEPTIBILITY OF THE KOPE FORMATION

Low Shear Strength

We believe the residual strength parameters are more important than the peak strength parameters for the long-term stability of slopes comprised of colluvial soil derived from the Kope Formation. This is because many of the landslides in the Kope Formation develop progressively over a long period of time. Figures 10 and 11 show the relationships between factor of safety and the residual strength parameters for the Ten Mile Road and Columbia Parkway landslides, respectively. A comparison of these plots with the residual strength parameters (Tables 3 and 4) shows that the residual cohesion and residual friction angle values for both rotational and translational slides are not high enough to support the slopes (i.e. the values in the tables are lower than those required to provide a FS > 1). Therefore, the low shear strength of the colluvial soil and soil-bedrock contact is an important factor contributing to landslide susceptibility of the Kope Formation.

Porewater Pressure

The presence of water within a slope can significantly decrease the stability of a slope. The average amount of precipitation in the Cincinnati area is 107 cm (US Climate Data, 2014). Since the colluvial soil classifies as a clayey sand for all landslides studied, it can be assumed that the material has low permeability and poor drainage characteristics (Holtz et al., 2011). This can lead to buildup of porewater pressure within the slope during prolonged periods of rainfall and snow melt, reducing shear strength and contributing to slope failure. Figure 12 shows the relationship between the location of the water table and the FS for the slopes at the Ten Mile Road and Columbia Parkway landslide sites. In this figure, 0 (along the vertical axis) represents the water table located at the bedrock level and 1 represents the water table at the ground surface, and values in between represent the relative elevations of the water table from the bedrock to the ground surface. The plots in Figure 12 show that, as the water table within the slope rises, the FS of the slope gradually decreases. The FS is at its lowest value when the water table is at the ground surface. i.e. the soil is completely saturated. Only a partial saturation of the colluvial slopes is required to cause failure, as several other factors also contribute to instability. Many of the slopes in the study area show either continually flowing water or water seeps throughout the year. Thus, development of pore pressure is another important factor that explains the high susceptibility of the Kope Formation to landsliding.

Human Activity

Human activity is an important factor influencing the stability of many slopes in the Cincinnati area (Behringer, 1992). Construction activities alter the stability of a slope in two ways: (i) by adding weight to the top of the slope, and (ii) by removing lateral support at the toe of the slope. Due to the topography of the Cincinnati area, many of the roads are built on tops of hillsides, cut into hillsides, or built in the toe areas by partial removal of the slope toes. By building on top of a slope, the driving forces acting on the slope increase and tend to cause failure. By cutting out the hillsides and the toes of the slopes, the resisting forces decrease.

Low to Very Low Durability of the Bedrock

The Kope Formation is a clay-bearing rock of low to very low durability against slaking (Id_2 = 7.1% - 39.9%) because of which it easily disintegrates and erodes rapidly. It is the easy disintegration of the Kope Formation that leads to thick accumulation of the colluvial soil on top of bedrock. The nondurable nature of the Kope Formation and the colluvial soil derived from it make these materials susceptible to landsliding.

Undercutting of the Slope Toe

Many slopes in the Cincinnati area are subject to undercutting of the slope toe by stream erosion (Figure 5). This removes the lateral support, thereby reducing the resisting forces. Undercutting of the slope toe, facilitated by the low durability of the Kope Formation, is a very important factor contributing to high susceptibility of the Kope Formation to landsliding.

Steepness of Slopes

The steepness of natural slopes in the Cincinnati area is another contributing factor to landslide susceptibility of the colluvium that is associated with the Kope Formation. The low to very low durability of the bedrock results in rapid down cutting of the valleys, giving rise to steep slopes. Although the bedrock slopes may reach a state of equilibrium at relatively steeper angles, the colluvial soils that cover the bedrock are not strong enough to maintain stability at those angles. Furthermore, many slopes have been over-steepened because of the rapidly eroding streams or human activity. The slope angles in the Cincinnati area range between 20^{o} and 40^{o}, which is generally higher than the residual friction angle values. The results of the stability analysis show that slopes steeper than 15^{o} will not have an adequate factor of safety against failure under wet conditions.

The above discussion shows that multiple factors, either individually or in combination, contribute to the high susceptibility of the Kope Formation to landsliding.

CONCLUSIONS

Based on the results of this study, the following conclusion can be drawn:

1. Rotational and translational landslides are the main types of movement affecting the slopes comprised of colluvial soil derived from the Kope Formation. Once a failure has been initiated, both types of movement may transform into earthflows, and occasionally into mudflows, with the addition of water.
2. The factors that contribute to the high susceptibility of the colluvial soil to landslides include low shear strength parameters of the soil or soil/bedrock contact, development of porewater pressure, human activity, low to very low durability of the bedrock,

undercutting of the slope toe by stream water, and steepness of the slopes.

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Table 3: Shear strength parameters for failure surface through the colluvial soil.

Table 4: Shear strength parameters for failure surface along the soil-bedrock contact.

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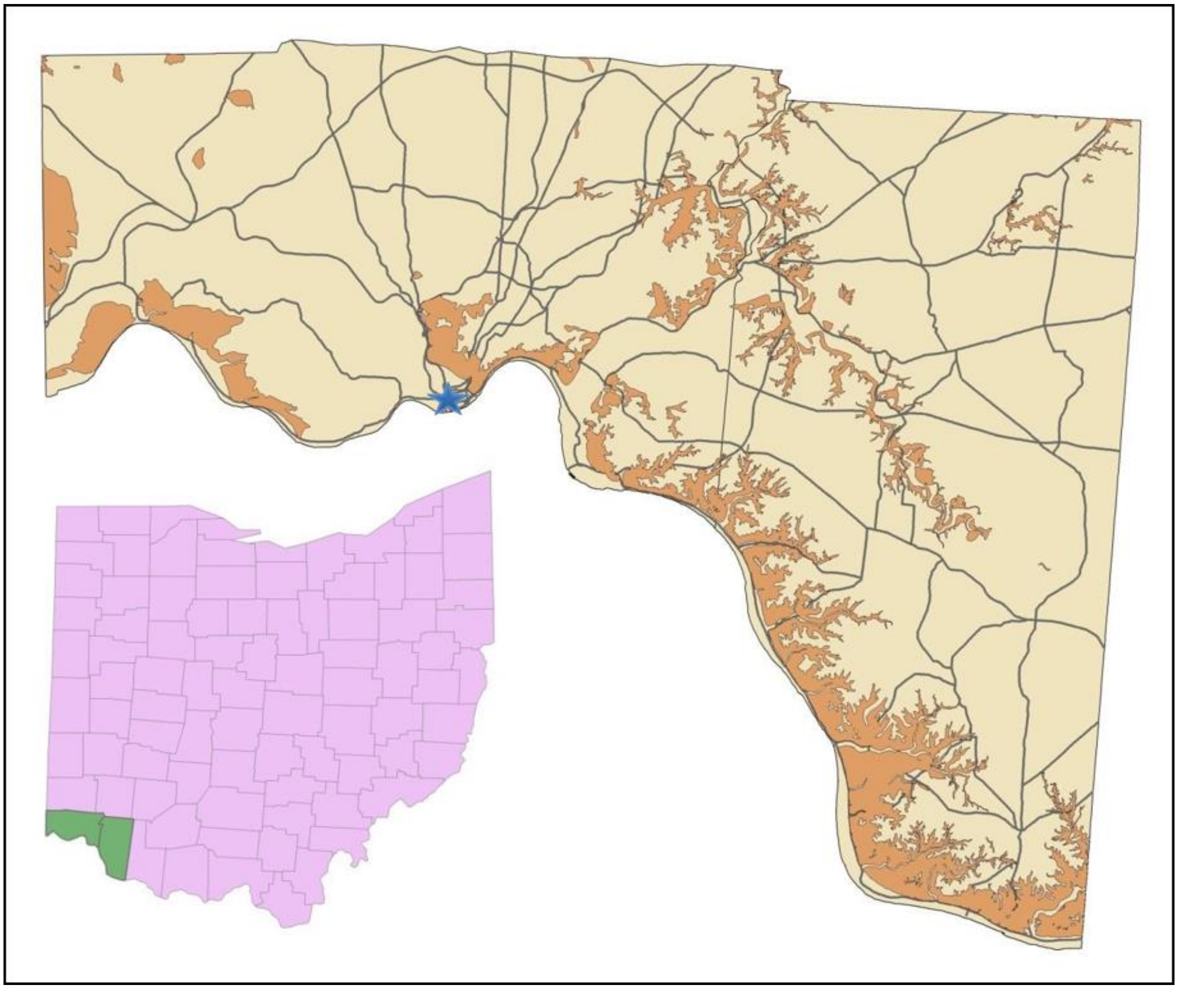


Figure 1: Map showing the extent of the Kope Formation (darker brown) in the Cincinnati area. The blue star indicates the location of downtown Cincinnati. The shaded area in the southwest corner of the Ohio map shows Hamilton (left) and Clermont (right) counties.

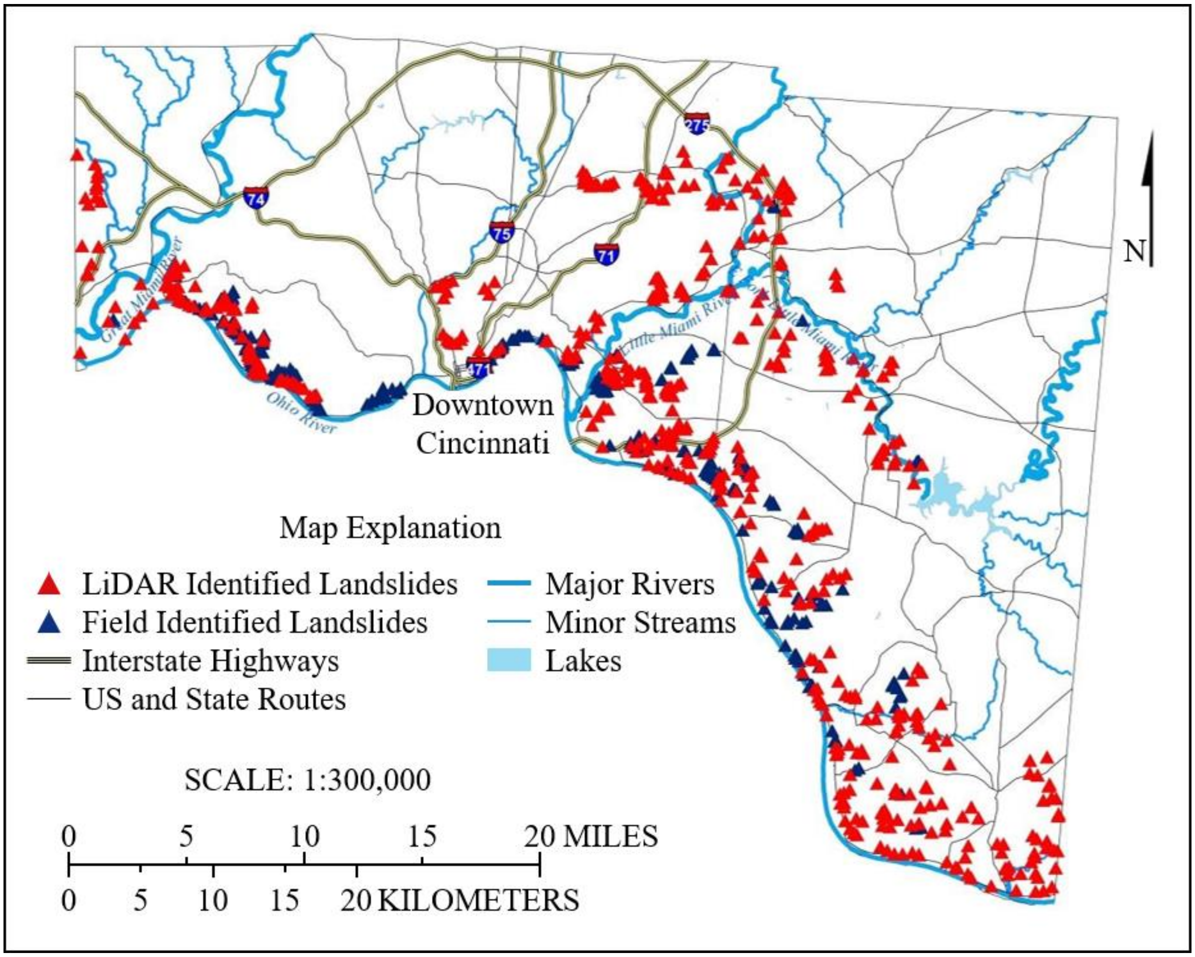


Figure 2: Landslide inventory map for the Kope Formation and the overlying colluvial soil within the Cincinnati area.

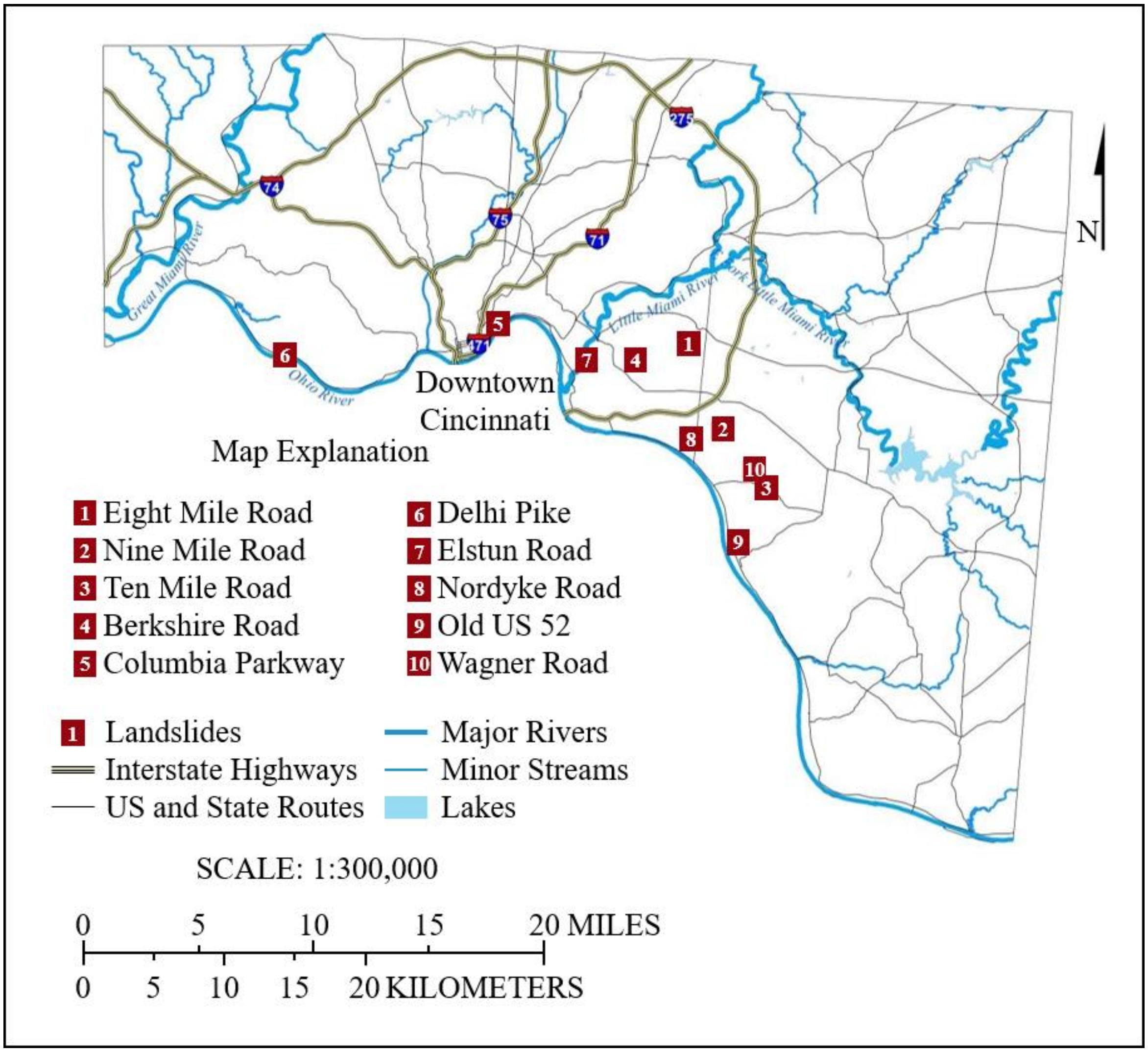


Figure 3: Locations of the landslide sites selected for detailed study.

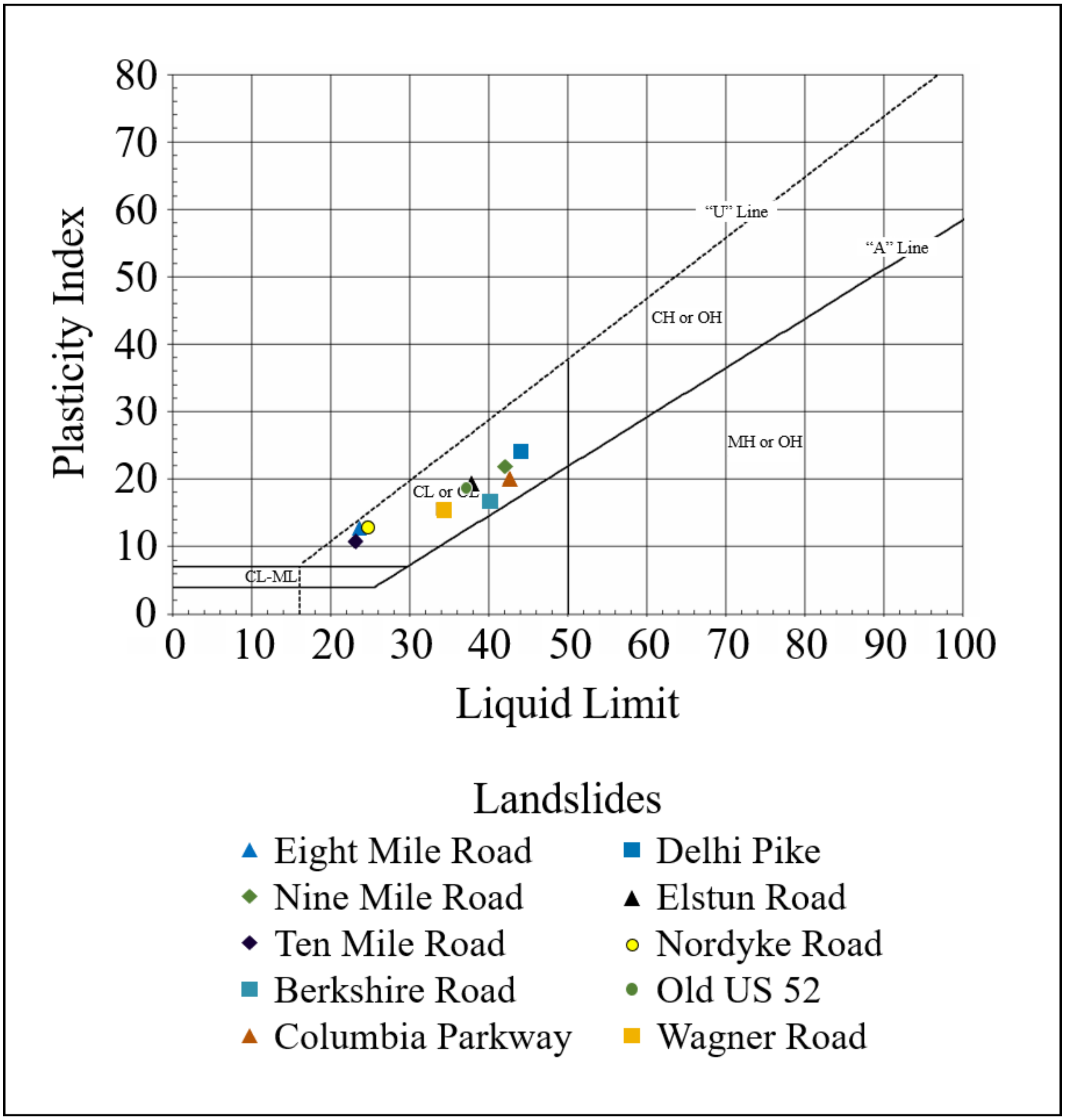


Figure 4: Plot of Atterberg limits of the fine-grained fraction of the colluvial soils from the landslide sites on the Casagrande plasticity chart.

Figure 5: The Ten Mile Road landslide with well-developed head scarp. Notice the undercutting of the toe by a stream.

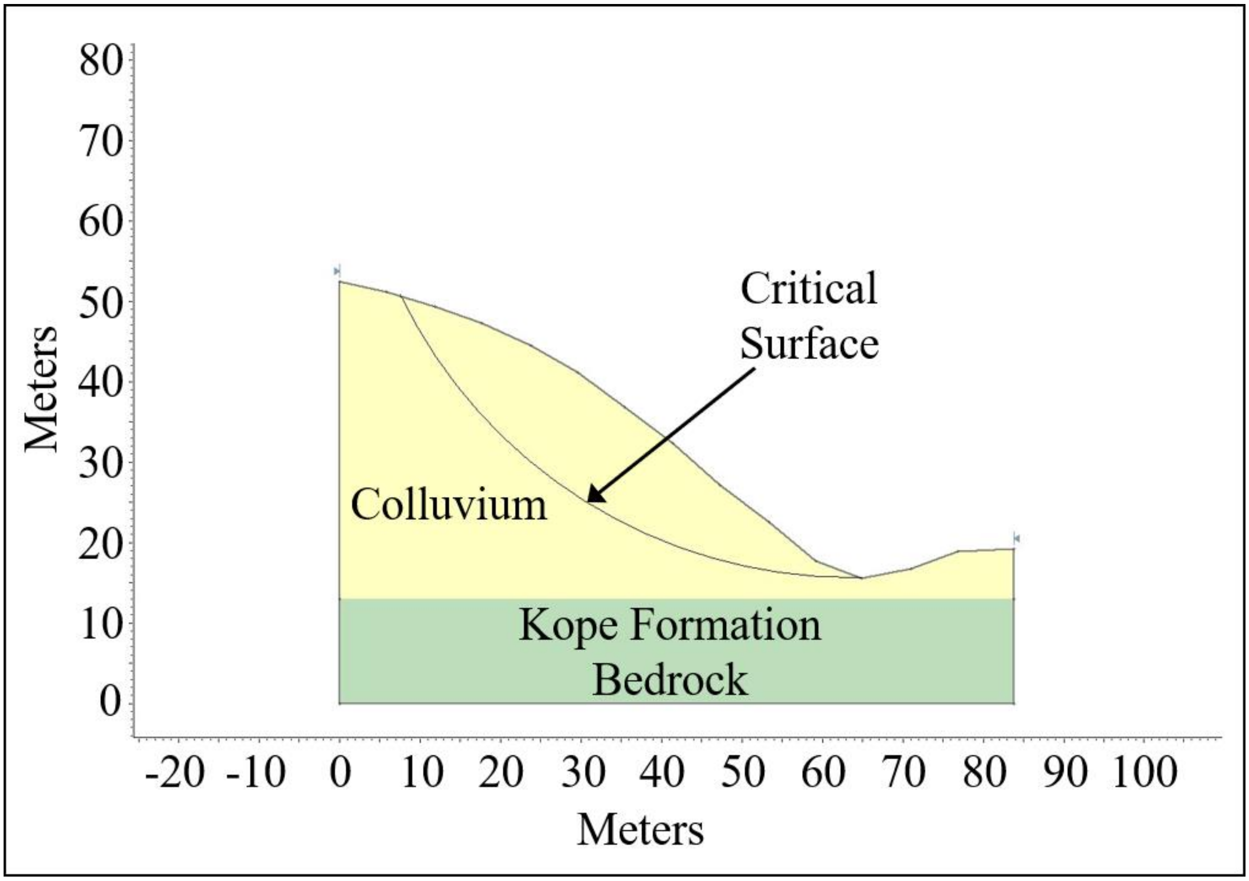


Figure 6: Critical surface for the minimum factor of safety for dry and saturated conditions for the Ten Mile Road landslide, as determined by the Slide program.

(a)

(b)

Figure 7: (a) Head scarp of the Columbia Parkway landslide and (b) toe of the Columbia Parkway landslide, emerging on the top of the retaining wall.

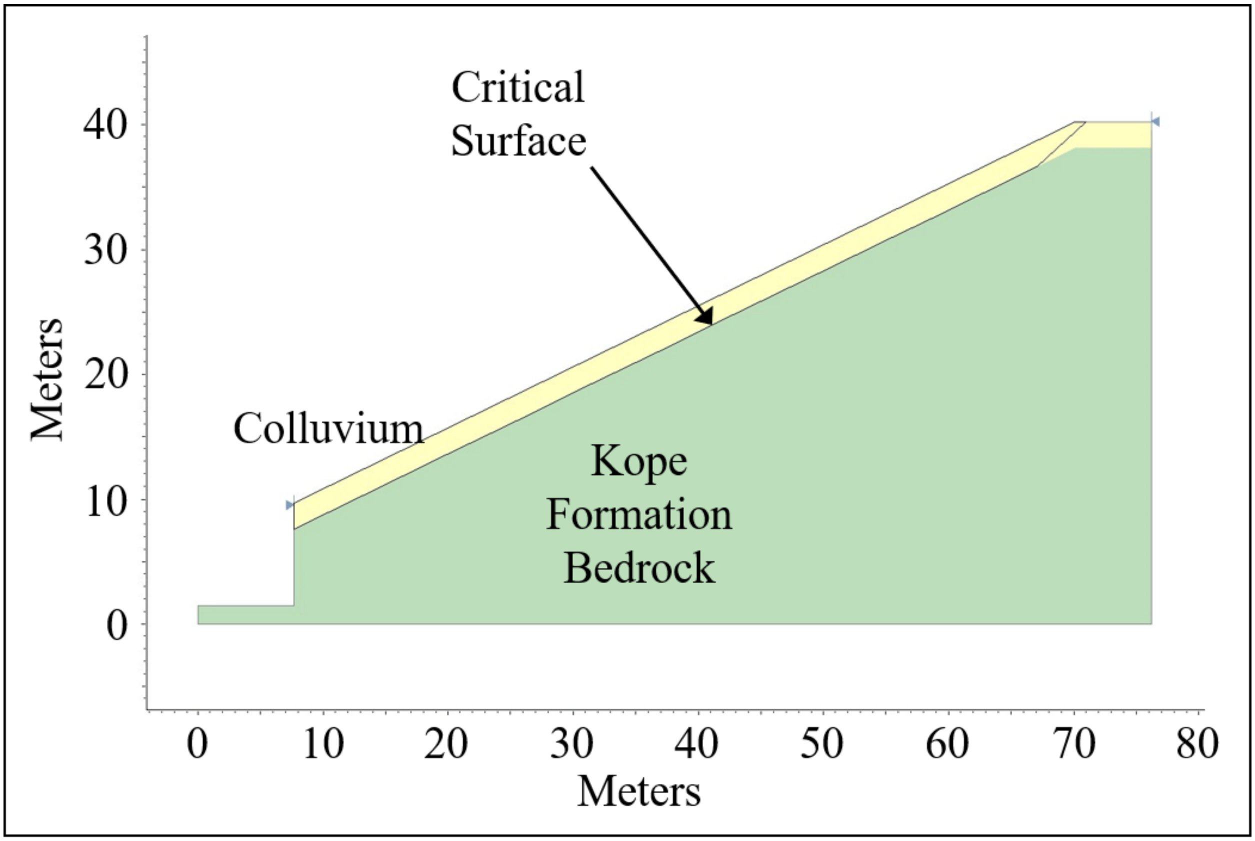
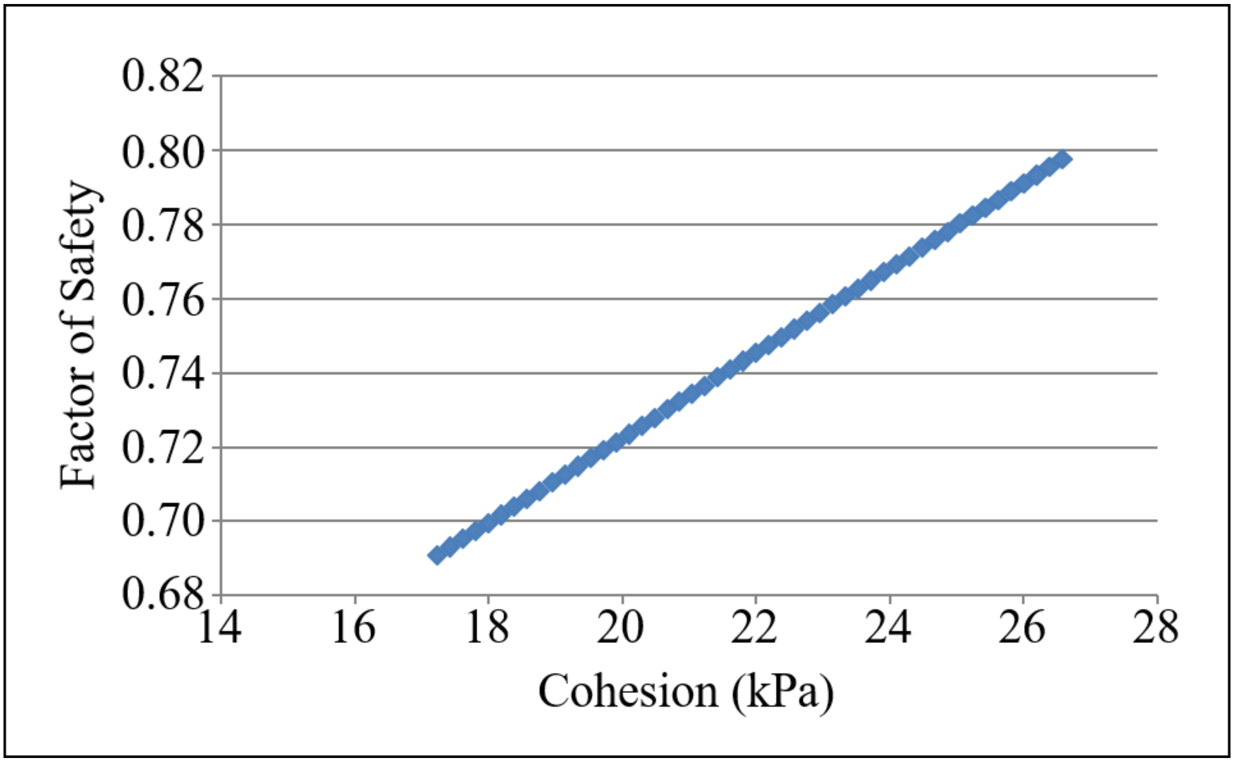


Figure 8: Critical Surface for the minimum factor of safety for the Columbia Parkway landslide, as determined by the Slide program.

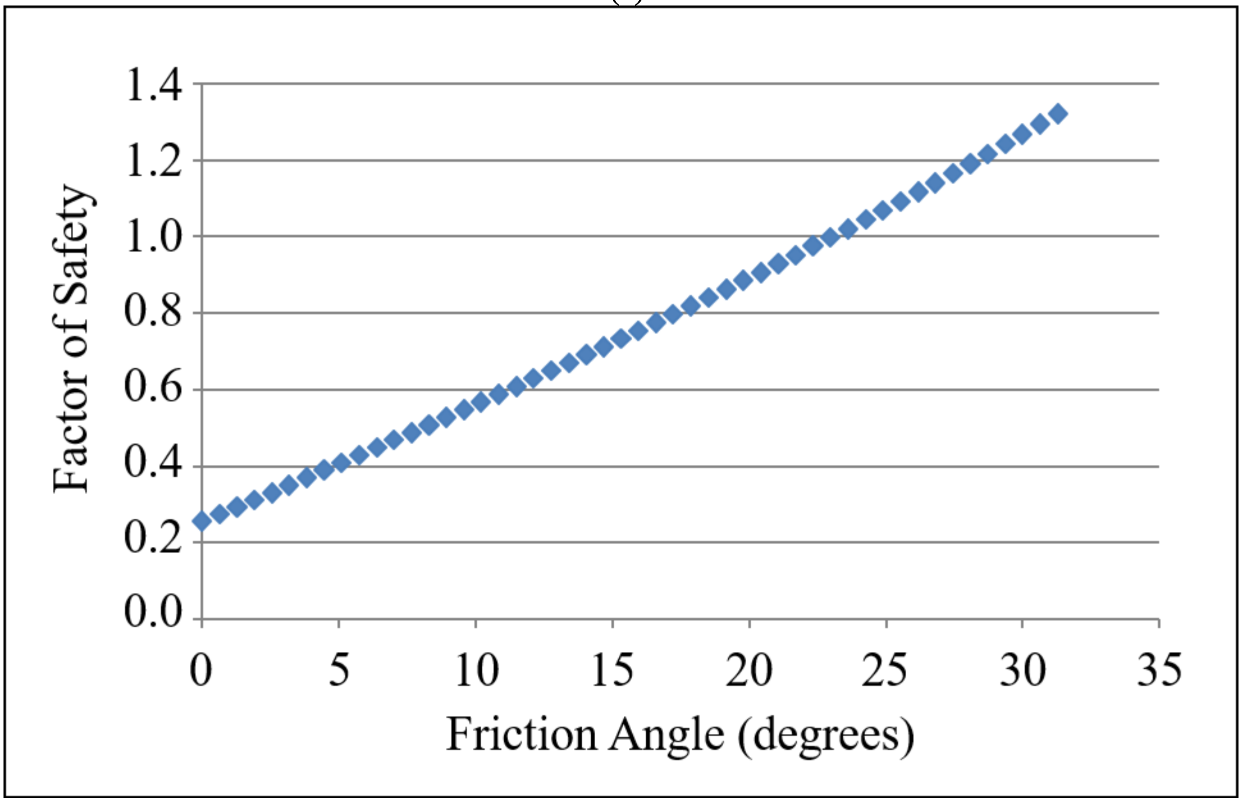
(a)

(b)

Figure 9: (a) Installation of metal mesh and soil nails and (b) section of a new soldier beam retaining wall (photos courtesy of Dr. John Rockaway).

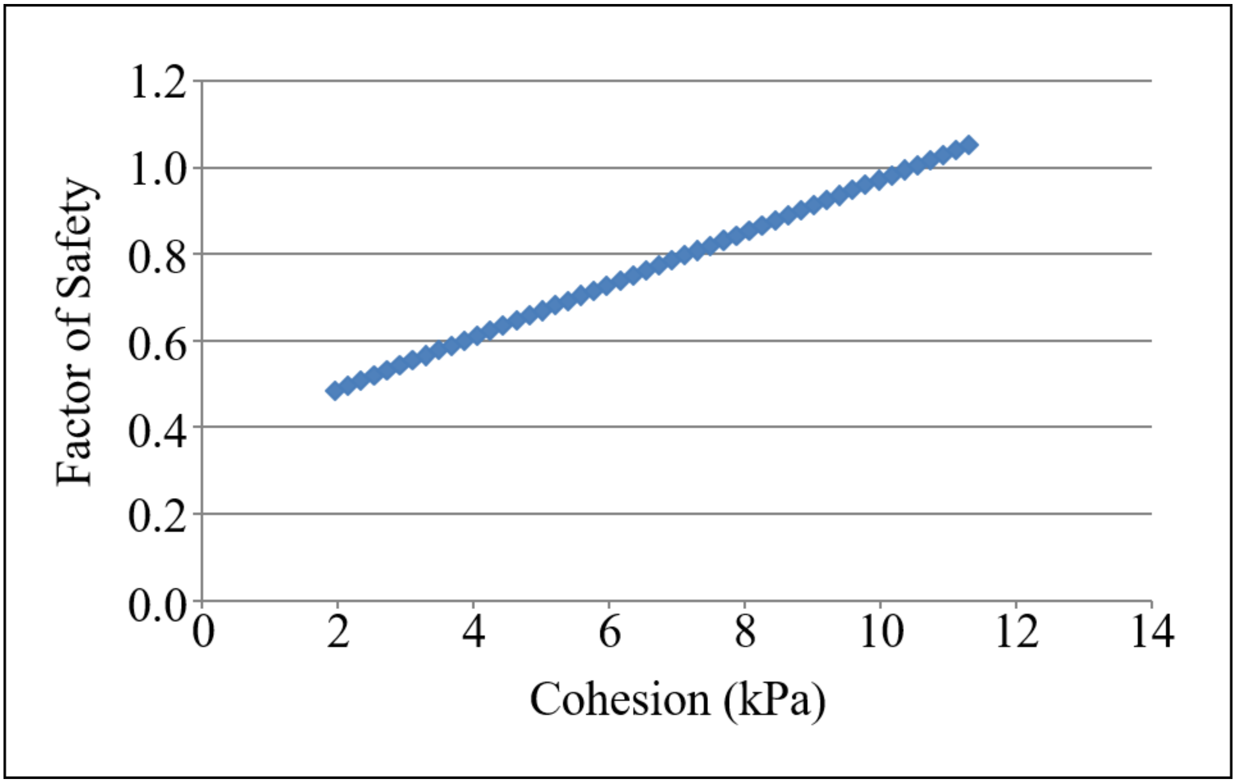


(a)

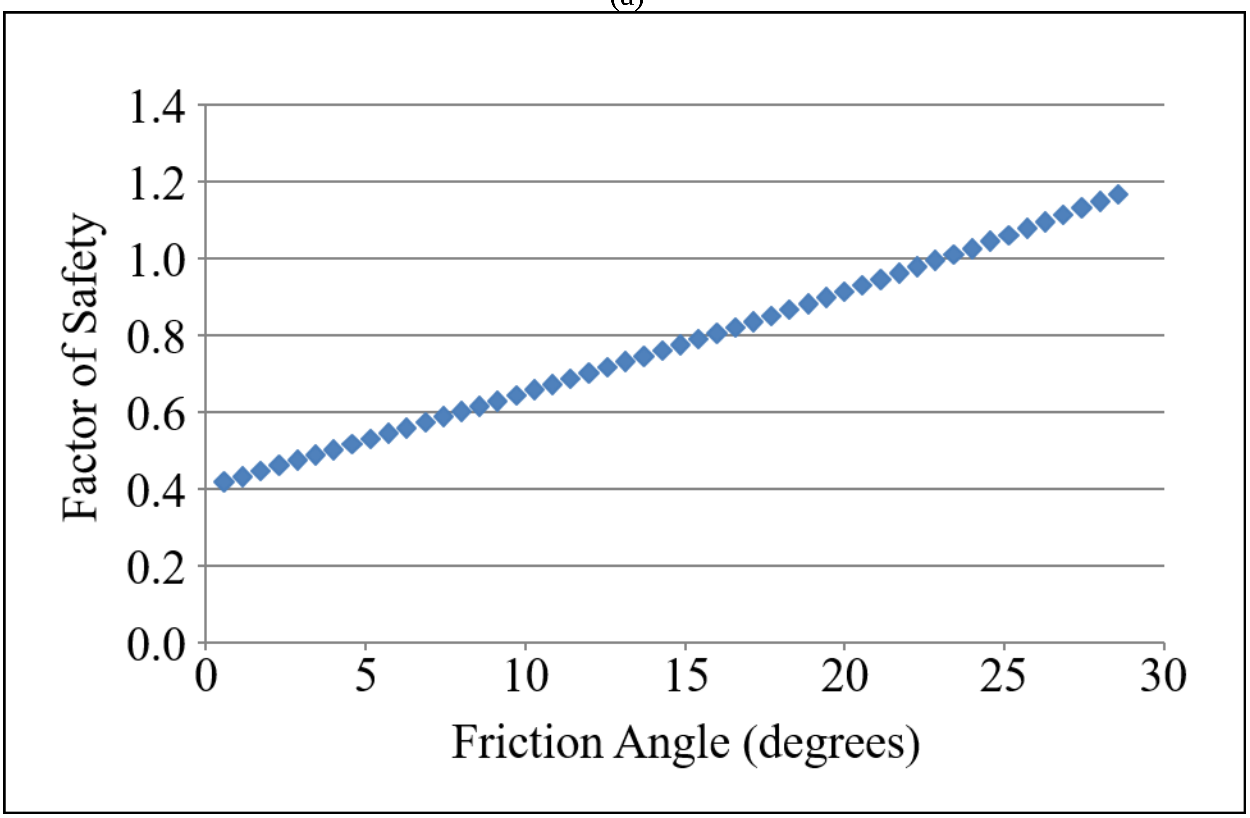


(b)

Figure 10: Relationship between strength parameters and factor of safety for the Ten Mile Road landslide: (a) cohesion vs FS and (b) friction angle vs FS.

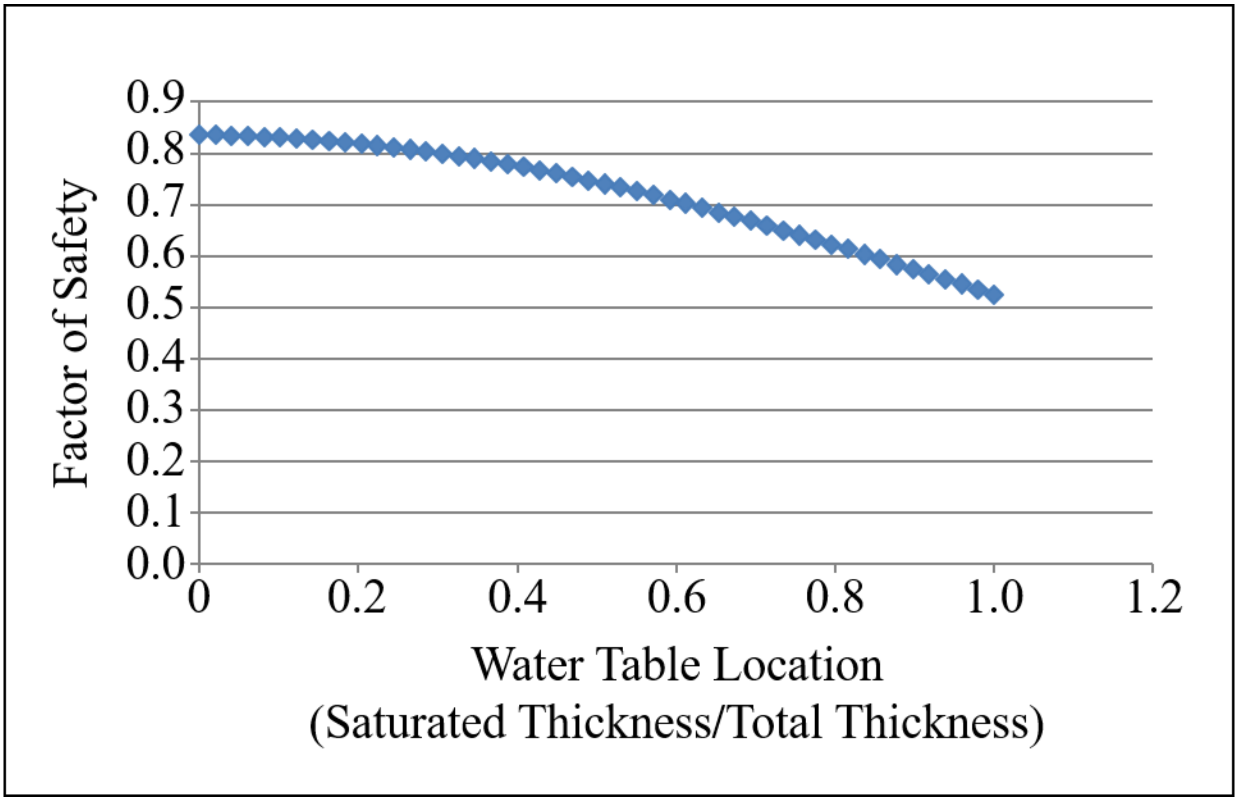


(a)

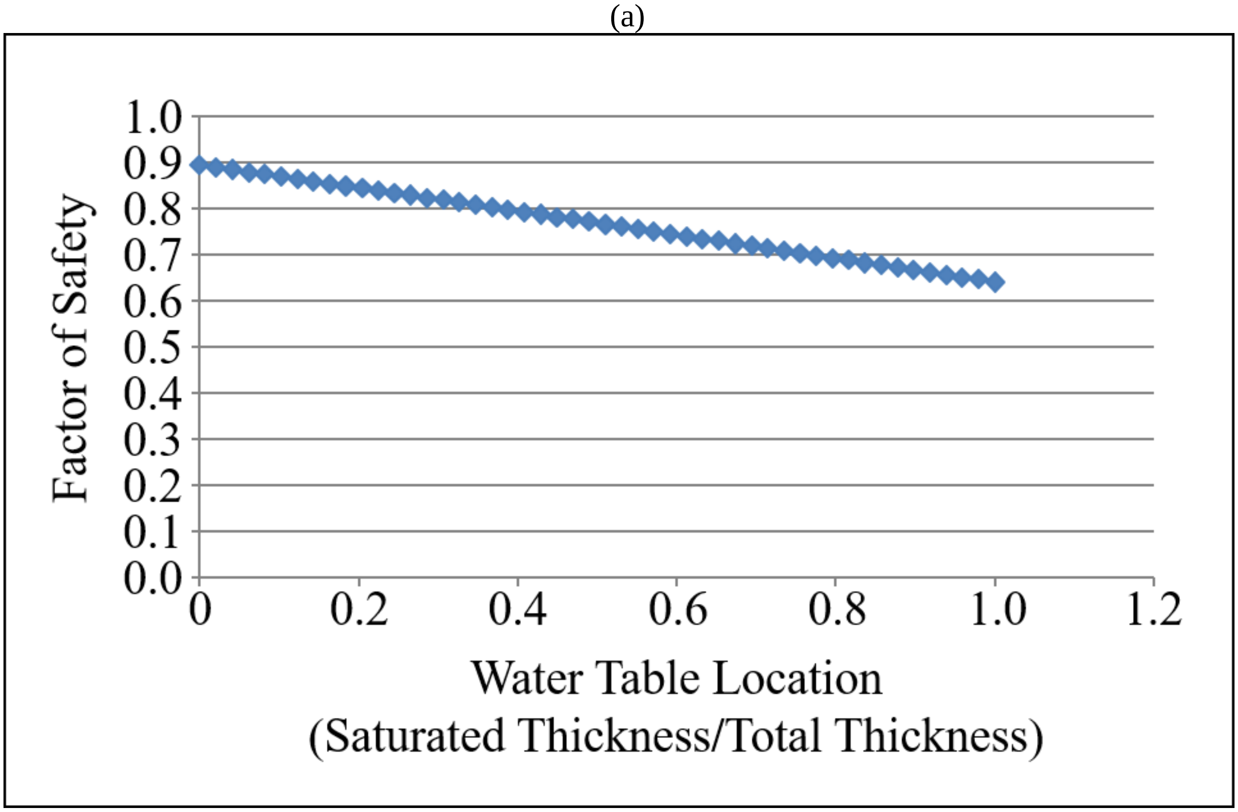


(b)

Figure 11: Relationship between shear strength parameters and factor of safety for the Columbia Parkway landslide: (a) cohesion vs FS and (b) friction angle vs FS.



(a)



(b)

Figure 12: Relationship between water table location and factor of safety for the: (a) Ten Mile Road landslide and (b) Columbia Parkway landslide.

Table 1: Natural water content values for the colluvial soil samples from the landslide sites.

Sample Location	Natural Water Content
Eight Mile Road Landslide	13.1%
Nine Mile Road Landslide	27.1%
Ten Mile Road Landslide	13.9%
Berkshire Road Landslide	23.8%
Columbia Parkway Landslide	23.0%
Delhi Pike Landslide	25.6%
Elstun Road Landslide	18.9%
Nordyke Road Landslide	13.6%
Old US 52 Landslide	21.1%
Wagner Road Landslide	23.5%
Mean	20.4%
Median	22.0%

Table 2: Atterberg limits of the fine-grained fraction of the colluvial soil from the landslide sites.

Sample Location	Liquid Limit	Plastic Limit	Plasticity Index	Liquidity Index
Eight Mile Road Landslide	23.6	10.9	12.7	0.2
Nine Mile Road Landslide	41.9	20.1	21.8	0.3
Ten Mile Road Landslide	23.0	12.3	10.7	0.2
Berkshire Road Landslide	40.0	23.3	16.8	0.03
Columbia Parkway Landslide	42.6	22.5	20.1	0.02
Delhi Pike Landslide	44.0	19.8	24.2	0.2
Elstun Road Landslide	37.8	18.5	19.3	0.02
Nordyke Road Landslide	24.4	11.6	12.8	0.2
Old US 52 Landslide	37.2	18.5	18.7	0.1
Wagner Road Landslide	34.1	18.4	15.7	0.3
Mean	34.9	17.6	17.3	0.2
Median	37.5	18.5	17.8	0.2

Table 3: Shear strength parameters for failure surface through the colluvial soil.

Sample Locations	Peak Cohesion (Kpa)	Residual Cohesion (Kpa)	Peak Friction Angle (degrees)	Residual Friction Angle (degrees)
Eight Mile Road Landslide	24.5	23.3	31.0	20.8
Ten Mile Road Landslide	27.5	22.5	33.8	15.6
Delhi Pike Landslide	33.4	24.0	23.8	17.8
Elstun Road Landslide	26.4	24.5	50.4	19.8
Nordyke Road Landslide	47.7	38.9	22.8	17.8
Old US 52 Landslide	35.2	32.7	39.4	20.3
Wagner Road Landslide	27.7	22.2	27.5	18.3
Mean	31.8	26.9	32.7	18.6
Median	27.7	24.0	31.0	18.3

Table 4: Shear strength parameters for failure surface along the soil-bedrock contact.

Sample Locations	Residual Cohesion (Kpa)	Residual Friction Angle (degrees)
Nine Mile Road Landslide	11.8	14.0
Berkshire Road Landslide	13.0	8.0
Columbia Parkway Landslide	6.8	14.6
Mean	10.5	12.2
Median	11.8	14.0

Table 5: Slake durability index test results for the bedrock samples from the translational landslide sites.

Location	Slake Durability Index (Id2) (%)	Durability Rating
Berkshire Road Landslide	28.5%	Very Low
Columbia Parkway Landslide	7.1%	Very Low
Nine Mile Road Landslide	39.9%	Low