Field Investigation of an Active Landslide In Kentucky: A Framework to Correlate Electrical Data and Shear Strength

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Field Investigation of an Active Landslide In Kentucky: A Framework to Correlate Electrical Data and Shear Strength

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Our mission is to increase knowledge and understanding of the mineral, energy, and water resources, geologic hazards, and geology of Kentucky for the benefit of the Commonwealth and Nation.

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Technical Level

General  Intermediate  Technical

Statement of Benefit to Kentucky
Landslides can cause great damage, but predicting where they’ll happen can be challenging. A new technique uses electrical properties of soil to study landslides and their causes.
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Field Investigation of An Active Landslide in Kentucky: A Framework to Correlate Electrical Data and Shear Strength

Matthew M. Crawford and L. Sebastian Bryson

Abstract
Landslide hazard assessments are best accomplished by a multidisciplinary approach that connects geologic processes with geotechnical behavior. Tools to accomplish this in the field include geologic characterization, hydrologic monitoring, and geophysical surveys, and in the laboratory, soil-strength testing. Volumetric water content, soil-water potential (suction), local rainfall, and in situ electrical conductivity were measured at a shallow colluvial landslide in Kentucky. Surface electrical-resistivity surveys were also conducted to support interpretations of depth to failure, lithologic differences, and changes in moisture content over time. Correlations of hydrologic data with electrical measurements and shear strength indicate that observed changes in the degree of saturation and soil-water potential for colluvial soils can be detected from inverted electrical-resistivity survey data. Subsurface electrical measurements, which are functions of moisture content and water potential, can be used to determine shear strength. Long-term observation data were used to develop a technical framework to assess landslide hazard and slope stability.

Introduction
The societal and economic impacts of landslides are significant, and reported occurrences are underestimated globally down to the local level. In the United States, landslides result in 25 to 50 fatalities annually and approximately $3 billion in damage (Highland and Bobrowsky, 2008; Lu and Godt, 2013). The deadliest landslide in the history of the conterminous United States occurred on March 22, 2014, near Oso, Wash., killing 43 people. In Kentucky, direct costs resulting from landslide mitigation along roadways and requests for Kentucky Emergency Management Hazard Mitigation grants for damaged homes are estimated to exceed a total of $10 million per year (Crawford, 2014; Overfield and others, 2015). State and county roads throughout Kentucky are continually closed because of landslides. Indirect costs such as road closures, utility interruption, decreasing property values, and litigation expenses are difficult to quantify.

Bedrock geology, slope angle, slope morphology, groundwater dynamics, soil type, and slope modification are some of the factors that influence slope instability. In addition, the majority of landslides, especially in the eastern United States, are triggered by rainfall. In order to connect several of these influencing factors, we adopted a multidisciplinary approach using geophysical and geotechnical techniques. Electrical resistivity is one such technique that has been proven to detect failure zones, slide geometry, soil composition, bedrock
lithology, and hydrologic conditions (De Bari and others, 2011; Travelletti and others, 2012; Van Dam, 2012; Perrone and others, 2014; Crawford and others, 2015). In addition, electrical data can be used to establish relationships with hydrologic conditions such as moisture content and water potential (suction). Once correlated to electrical resistivity (or its inverse, conductivity), these hydrologic parameters can then be used to calculate shear strength. The implication of these correlations is that field-based electrical resistivity can be used as a tool for assessing landslide hazards. The purpose of this study is therefore to combine geologic, geophysical, and geotechnical methods to characterize landslides and correlate several parameters that affect slope stability in order to evaluate whether electrical data can reveal hydrologic and stress conditions that lead to slope failure.

Geologic Setting

We investigated the shallow, colluvial Doe Run landslide in northern Kentucky, just south of Cincinnati (Fig. 1).

The geology of northern Kentucky and the Cincinnati area consists of interbedded shale (75 to 80 percent) and limestone (20 to 25 percent). Clay-rich colluvial soils of varying thickness cover steep slopes and result in high landslide occurrence (Haneberg, 1991; Fleming and Johnson, 1994; Baum and Johnson, 1996; Potter, 2007). A landslide inventory conducted by the Kentucky Geological Survey has documented approximately 400 landslides in Boone, Kenton, and Campbell Counties, just south of Cincinnati, although certainly more are yet to be documented. Generally, the landslides are of two types: thin translational slides and deeper-seated rotational slumps. The increased urban develop-
ment in this region increasingly encroaches on steep hillsides, thus increasing the area’s susceptibility to landslide hazards (Fleming and Johnson, 1994; Crawford, 2012).

The Doe Run landslide is located in Doe Run Lake Park on a wooded slope and along the outside meander of Bullock Pen Creek, which flows into a reservoir (Fig. 2). The colluvium varies in thickness depending on slope angle and morphology. Near the lower parts of the slope, the colluvium thickness ranges from 4 to 5 m, then gradually thins to a meter or less midslope toward the ridgetops. The slope angle ranges from approximately 15° at the highest elevations to approximately 12° near the toe. The colluvium ranges from dark to light brown silty clay to grayish blue and soft greenish gray clayey silt. Weathered limestone slabs increase with depth toward a weathered rock zone.

The extent of the slide is difficult to discern, because the entire ridge can be classified as a large, active landslide complex. The headscarp and landslide flanks, which are difficult to observe, are visible only in a small distinct slump at the toe of the slope. This small feature has a headscarp height of approximately 1 m, distinct landslide flanks, and several rotated blocks, resulting in a hummocky surface. The length of the downslope axis of the monitored area is approximately 57 m.

One reason this site was chosen is because it is near another translational landslide that occurred in the fall of 2011. That landslide destroyed a hiking trail and partially flooded the creek.

**Field Measurements and Observations**

The primary field techniques in this study were in situ hydrologic measurement and intermittently conducted electrical resistivity surveys (Fig. 3).

**Hydrologic Data Collection**

Two types of sensors were used to determine long-term subsurface hydrologic conditions within the landslide. Water-content reflectometers monitored soil volumetric water content, bulk electrical conductivity, bulk dielectric permittivity, and temperature. Water-potential sensors measured soil-water potential (soil suction) and temperature. Water potential is the energy state of water in the soil, a determination of a stress state in the soil based on how water propagates through the matrix. The water-potential sensors consist of a ceramic disc made of a porous material with a static matrix of pores that is buried in the soil. The disc and the surrounding soil both adjust to a hydrologic equilibrium, and because the two mediums (disc and soil) are moving toward equilibrium, measuring the water potential of the disc gives the water potential of the soil.

The hydrologic sensors were installed in pits that were dug by hand. Two water-content reflectometers and two water-potential sensors were nested vertically in each pit and placed in the undisturbed, upslope face of the exposed soil in order to measure the natural transient wetting fronts in the soil (Fig. 4). After the sensors were placed
in the ground, the pits were backfilled. The pits are approximately 27.5 m apart, one upslope and one downslope. Table 1 presents the pit location and depths of the sensors. The sensors were installed May 5, 2015.

The data acquisition program used in the data logger was written to retrieve data in 15-min, hourly, and daily intervals. The hydrologic and electrical data presented in this report are the average daily values. Rainfall was measured on site using a tipping bucket and data logger. The logger has a 1-min resolution, and rainfall was logged at 0.25 mm/tip. Generally, 2015 and the first half of 2016 were wet in the study area. Cumulative rainfall from May 8, 2015, through September 2016 was 1,724.6 mm. In comparison, statewide average rainfall was 1,448 mm for 2015 and 1,168 mm for 2014 (www.kymesonet.org/summaries.html).

**General Observations**

- Data collected and presented here are from May 2015 to September 2016.
- Field measurements of volumetric water content, water potential, and electrical conductivity collected over 15 mo reveal periods of soil wetting and drying, and extended periods of nearly saturated or saturated soil.
- Volumetric water content and water potential change in response to rainfall.
- The magnitude of volumetric water content’s response to rainfall is greater for the shallow-
er sensors, both upslope and at the toe.

- Sensors in the toe of the landslide (in the slump feature) at the deeper location reacted minimally to rainfall.
- The water potential remained at or near saturation except for during two dry periods: late August to late October 2015 and mid-June to September 2016.
- From mid-June to September 2016, the water potential fluctuated because of less rainfall, increased temperature, and increased evapotranspiration.

**Parameter Correlation**

The water-potential sensors indicated that the colluvial soil was saturated or nearly saturated for much of the monitoring period (sensor limit of approximately –9 kilopascals), except for during the drying periods (Fig. 5). From early May to late August 2015, rainfall was approximately 350 mm, and several daily totals were greater than 37 mm. Water-potential values decreased during the drying period, from approximately late August until late October 2015; the lowest values (driest) were –450 and –350 kPa in the upslope pit and –318 and –43 kPa in the lower pit near the toe of the landslide. The sensors in the pit at the toe of the landslide are located in the scarp of the small slump. Significant amounts of water accumulate in this part of the slope, indicated by the lower suction values in the lower pit at the toe.

Volumetric water content also indicates wetting and drying periods (Fig. 6). Collecting both volumetric water content and water potential allowed field soil-water characteristic curves to be created. SWCCs help define the stress state and general behavior within the unsaturated zone of the soil mass, and are a fundamental part of assessing material strength (Abramson and others, 2002). A decrease in water potential increases the effective stress within a soil mass, thereby improving slope stability. The field SWCCs collected at the Doe Run landslide demonstrate these varying hydrologic conditions (Fig. 7).

**Table 1.** Type and location of hydrologic sensors at the Doe Run landslide. \( \Theta = \) volumetric water content. \( \psi = \) water potential. Two of each sensor type were nested vertically in the upslope and downslope pits.

<table>
<thead>
<tr>
<th>Pit and Sensor</th>
<th>Sensor Depths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upslope ( \Theta )</td>
<td>30 cm, 70 cm</td>
</tr>
<tr>
<td>Upslope ( \psi )</td>
<td>30 cm, 65 cm</td>
</tr>
<tr>
<td>Downslope ( \Theta )</td>
<td>75 cm, 1.3 m</td>
</tr>
<tr>
<td>Downslope ( \psi )</td>
<td>55 cm, 1.2 m</td>
</tr>
</tbody>
</table>
Field Measurements and Observations

Figure 5. Water potential (suction) versus rainfall at the Doe Run landslide.

Figure 6. Volumetric water content over time measured at the upslope sensor at a depth of 70 cm. Each dot represents an average daily value.
against water potential ($\psi$) from saturated to dry conditions. Because the electrical conductivity and volumetric water content have a linear relationship (Fig. 8), electrical conductivity can be used in the logistic power equation of $\Theta$ versus $\psi$. Using Eq. 1, we can model electrical conductivity versus water potential from saturation to dry (Fig. 9):

$$y = \frac{a}{1 + \left(\frac{x}{b}\right)^c} \quad EC = EC_s + \frac{EC_r - EC_s}{1 + \left(\frac{\psi}{b}\right)^c} \quad \text{Eq. 1}$$

where $EC_s$ is electrical conductivity corresponding to residual volumetric water content ($\approx 0\,\text{dS/m}$), $EC_r$ is electrical conductivity corresponding to the saturated volumetric water content ($\approx 0.495\,\text{dS/m}$), $\psi$ is water potential, $a$ is saturated electrical conductivity, and $b$ and $c$ are fitting parameters (Table 2).

The fitting parameters were optimized using the Microsoft Excel equation solver. Figure 8 shows a linear model for a range of volumetric water contents versus electrical conductivity. Figure 9 plots the result of using Eq. 1 to model water-potential values from saturation to dry versus electrical conductivity. We show the data and model for the upslope location at the sensor depth of 70 cm.
Field Measurements and Observations

Figure 8. Linear model for the upslope pit of volumetric water content versus electrical conductivity. See Table 2 for the fitting parameters.

Figure 9. Water potential (log-scale) versus electrical conductivity in the upslope pit at a depth of 70 cm, modeled using Eq. 1. See Table 2 for the fitting parameters.
because of the large range of values in the drying curve from the field SWCC. The linear correlations and drying curves for the downslope location and other depths are similar (see Appendix 1).

### Shear-Strength Models

To expand the correlation between hydrology and electrical conductivity, shear-strength parameters were compiled from the hydrologic correlations and shear-strength triaxial tests. Triaxial equipment at the University of Kentucky was used to conduct consolidated, undrained triaxial tests on three remolded samples from the Doe Run landslide. Samples were taken from the soil-bedrock interface at a depth of 70 cm and compacted in the lab to the in situ unit weight.

The hydrologic sensor measurements, SWCC parameters, and shear-strength data were used in an extended Mohr-Coulomb failure criterion to calculate shear strength. The shear-strength model by Vanapalli and others (1996) (Eq. 2) was used as the shear-strength criterion for this study. The shear-strength values were calculated by inputting the measured in situ water potential and volumetric water content data and the cohesion, net normal stress, and friction angle determined from the triaxial test (Table 3):

\[
\tau_f = c' + (\sigma - u)\tan \phi' + \frac{\theta_s - \theta_r}{\theta_s - \theta_r} (u_s - u_w)\tan \phi'
\]

where \(\tau_f\) is shear strength, \(c'\) is cohesion at zero matric suction (water potential) and zero net normal stress (effective cohesion), \((\sigma - u)\) is net normal stress, \((u_s - u_w)\) is matric suction (water potential), \(\theta_s\) is saturated volumetric water content, \(\theta_r\) is residual volumetric water content, \(u_s\) is pore-air pressure, \(u_w\) is porewater pressure, and \(\phi'\) is angle of internal friction associated with net normal stress.

The calculated shear strength (Eq. 2) correlates with the in situ water potential for wetting and drying curves (Fig. 10). Shear strength was then correlated with the in situ electrical conductivity (Fig. 11). The strength model (red line) is derived from combining the linear model (using the predicted \(\theta\)) and the logistic power model (predicted electrical conductivity), which demonstrates the potential for predicting strength behavior if the hydrologic conditions and electrical conductivity within the slope are known.

### Surface Electrical-Resistivity Measurements

Two-dimensional surface electrical-resistivity profiles were conducted along two lines at the Doe Run landslide (Fig. 2). Each array was repeated at the same spot on five different dates, using an eight-channel resistivity meter with 84 electrodes. One array measured 56.7 m parallel to the downslope direction and the second measured 31 m transverse to the downslope direction. The resistivity measurements were conducted July 1, Sept. 2, and Nov. 16, 2015, and Feb. 5 and June 14, 2016. A dipole-dipole electrode configuration was used for all measurements and Earth Imager 2D software to invert the apparent resistivity and create the 2D resistivity profiles (Fig. 12). For all profiles see Appendix 2.

#### General Observations
- Each resistivity profile exhibits contrasts that have been interpreted to be the landslide failure surface, landslide type, areas of excess moisture, and bedrock depth.
- The inverted resistivity profiles image the landslide failure surface and the deeper-seated small slump feature at the toe of the slide.
- Differences in the inverted profiles and resistivity contrasts over time reflect recent rainfall events.
Figure 10. Shear strength versus water potential in the upslope pit at a depth of 70 cm.

Figure 11. Shear-strength model fit with the upslope drying curve plotted versus electrical conductivity in the upslope pit at a depth of 70 cm.
Surface Electrical-Resistivity Measurements

Figure 12. Inverted resistivity profiles measured in the downslope direction of the Doe Run landslide. The top and bottom profiles were measured July 1 and Sept. 2, 2015, respectively.

amounts and the soil-moisture conditions in the slope.

The surface electrical-resistivity measurement for the July 1 profile was collected after 45 mm of rain the previous five days. The measurement for the Sept. 2 profile was collected after five days of no rain, as reflected by the decreasing water potential (Fig. 5). Generally, compared to the July profile, the September profile shows higher-resistivity (drier) values throughout. The September profile shows the low-resistivity zone near the surface (blue colors, interpreted to be the failure surface) as a less continuous layer than in the July profile, indicating drier conditions. Resistivity values in the slump are lower in September than in July, also indicating drier conditions. Continued surface electrical-resistivity measurements over time will reflect the hydrologic conditions measured within the slope and potentially identify the conditions that lead to failure.

Comparison of Electrical Resistivity and Sensor Electrical Conductivity

In order to apply the surface electrical-resistivity measurements to the shear-strength calculations, the electrical conductivity from the water-content reflectometers was compared to the surface electrical-resistivity data from the resistivity meter. The electrical-resistivity values from the resistivity meter were extracted from the inverted profiles from the same place the sensors are buried. Figure 13 shows the variability of values measured by the resistivity meter to a depth of 20 m over time at the upslope pit location. The black dashed lines show the depth of the in situ sensors. The resistivity values were converted to conductivity to compare with the conductivity data from the water-content reflectometer. There is a difference in conductivity between the July and September measurements, which supports the interpretations from the 2D profiles. At the sensor locations in both the upslope and downslope pits, the resistiv-
Figure 13. Variable electrical-conductivity values from the resistivity meter at the upslope pit for July 1 and Sept. 2, 2015. The black dashed lines show the depth of the in situ sensors. Resistivity values were converted to conductivity.

Comparing measurements from the in situ sensors with those from the resistivity meter is challenging for several reasons, however. The moisture conditions and moisture gradient are dictated by soil type, slope morphology, and depth from the surface. Comparing the same data (electrical conductivity, in this case) measured from two different devices is a challenge. Therefore, in order to make predictive interpretations about electrical conductivity/resistivity measurements and the hydrologic conditions and shear strength of a slope, a multiplying factor is used to correlate the sensor and electrical-resistivity measurements. Figure 14 shows that the electrical-resistivity measurements can be calibrated to the subsurface sensor data by multiplying the resistivity measurements by 1.45. This multiplying factor calibrates the two data sets only for the upslope pit at 70 cm. This adjustment is not universal and applies only to this specific landslide.

After calibration, the resistivity-meter profiles can be used to correlate with shear strength calculated from the in situ hydrologic data.

Spatial shear-strength data can then be obtained from the surface electrical-resistivity survey by:

1. Adjusting the surface electrical-resistivity data using a calibration factor
Figure 14. Calibration of the surface electrical measurements from the resistivity meter and subsurface sensor conductivity for the upslope location. A multiplying factor adjusted the resistivity values to the in situ electrical conductivity from the water-content reflectometers. The shapes of the curves are similar, suggesting that the data sets can be calibrated to one another.

(2) Inputting the calibrated electrical-resistivity data into the hydrologic models (linear and logistic power equations) and then the shear-strength model (extended Mohr-Coulomb)

(3) Creating spatial shear-strength contour maps by using the calculated shear strengths and corresponding spatial coordinates. Figure 15 shows the shear strength presented as a 2D profile normalized to the maximum value. The contouring software Surfer was used to create this profile.

Summary

Geologic, geophysical, and geotechnical data were collected from a shallow colluvial landslide in northern Kentucky. Volumetric water content, water potential, and bulk electrical conductivity were collected from in situ sensors. The hydrologic conditions were correlated with rainfall. SWCCs were plotted from the field volumetric water content and water-potential data. Electrical conductivity and hydrologic parameters were then correlated and modeled. The unsaturated soil parameters were then used to calculate shear strength using an extended Mohr-Coulomb failure criterion, so that shear strength could be correlated to water potential and electrical conductivity over time. This technique allowed shear strength to be inferred from the electrical-conductivity data. Surface electrical resistivity was also measured in order to interpret depth to failure and areas of excess moisture. The surface electrical-resistivity data can be correlated to the hydrologic data and shear strength, and used to provide information about the stability of the slope. Repeated surveys over time will show differences in resistivity values that can be correlated to the hydrologic data, and potentially show the slope conditions that lead to failure.

Landslide behavior and stability of preexisting, often old landslides depend on fluctuating water content and stresses in the unsaturated zone that contribute to subsequent landslides (Abramson and others, 2002; Godt and others, 2009). Partially saturated soils fluctuate from the reduction in negative pore pressures (water potential/suction) to positive pore pressures when there is increased rainfall. These suction stresses, along with excess moisture, porosity, and clay-rich rocks and soils, affect slope stability. These factors also affect the physics of electrical-current flow in the
subsurface, thus controlling electrical resistance of geologic materials. Using electrical resistivity to determine wet and dry soils based on repeatable measurements of large volumes in the landslide mass, rather than a small, intrusive single sample, is a great advantage for geologic and geotechnical investigations in terms of cost, time, and slope disturbance.

Collecting data about transient water fluctuations within shallow colluvial landslides and analyzing them is a key to addressing slope stability. These hydrologic conditions are pertinent to investigating landslides that are triggered or reactivated by rainfall. Comparing hydrologic and electrical-conductivity measurements with surface electrical resistivity can provide information about the shear strength of soils, ultimately showing that electrical data can be an indicator of shear strength.

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**Figure 15.** Shear-strength profile calculated from field hydrologic conditions and a combination of electrical measurements, including surface electrical resistivity.
References Cited
Appendix 1. Linear regression and logistic power models correlating hydrologic parameters for upslope and downslope locations within the Doe Run landslide.

### Upslope 30 cm—Drying

\[
y = 1.4202x + 0.0303 \\
R^2 = 0.9631
\]

### Upslope 70 cm—Drying

\[
y = 0.4693x + 0.2014 \\
R^2 = 0.9944
\]
Downslope 75 cm—Drying

\[ y = 0.5551x + 0.1784 \]
\[ R^2 = 0.9863 \]

Downslope 1.3 m—Drying

\[ y = 0.4656x + 0.2137 \]
\[ R^2 = 0.9627 \]
Appendix 2. Electrical-resistivity profiles of all lines at the Doe Run landslide. Electrical-resistivity inversion was calculated using Advanced Geosciences software AGI Earth Imager 2D.

**July 1, 2015—Parallel to downslope direction**

**July 1, 2015—Transverse to downslope direction**

**September 2, 2015—Parallel to downslope direction**

**September 2, 2015—Transverse to downslope direction**
November 16, 2015—Parallel to downslope direction

November 16, 2015—Transverse to downslope direction

February 5, 2016—Parallel to downslope direction
February 5, 2016—Transverse to downslope direction

June 14, 2016—Parallel to downslope direction

June 14, 2016—Transverse to downslope direction