PSEUDO THREE-DIMENSIONAL IMAGING OF CREEP FAILURE IN A HIGHWAY EMBANKMENT USING TWO-DIMENSIONAL ELECTRIC EARTH RESISTIVITY

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Abstract

In May 2017, we carried out an electrical resistivity tomography (ERT) survey of the downslope embankment of a state highway in central Illinois where creep failure has been observed for over 50 years. The fill is over 15 meters (~50 feet) at its deepest point and sits partially in an old stream bed. Water is currently conveyed through the channel in a box culvert underneath the embankment. The fill has been steadily creeping since initial construction and has caused severe damage to the highway above on several occasions. The purpose of this study was to image the failure associated with the subsurface creep in the fill and to identify the subsurface engineering works that may be interacting or moving with the creep.

We surveyed 10 parallel ERT profiles using an ABEM Terrameter SAS 4000. Nine profiles were 80 meters long and one was 40 meters long, with 10 meter spacing between each profile. We used an inline dipole-dipole array with electrodes spaced 2 meters apart (with a minimum 'a' spacing of 2 meters and a maximum was 4 meters; the minimum 'n' value was 1 and the maximum was 8). These 10 profiles were processed using Geotomo's Res2DInv software. Topographic corrections were made using GPS and elevation data collected the same day as the ERT survey. The data was interpolated between the survey lines using ArcScene to create a pseudo 3-dimensional model to identify key components of the slope creep.

Several underground objects were identified, including metal and plastic drainage pipes, a chimney drain, the box culvert, and possible groundwater plumes from recent rainfall events. The failure surface associated with the creep was also identified, and mapped in three dimensions.

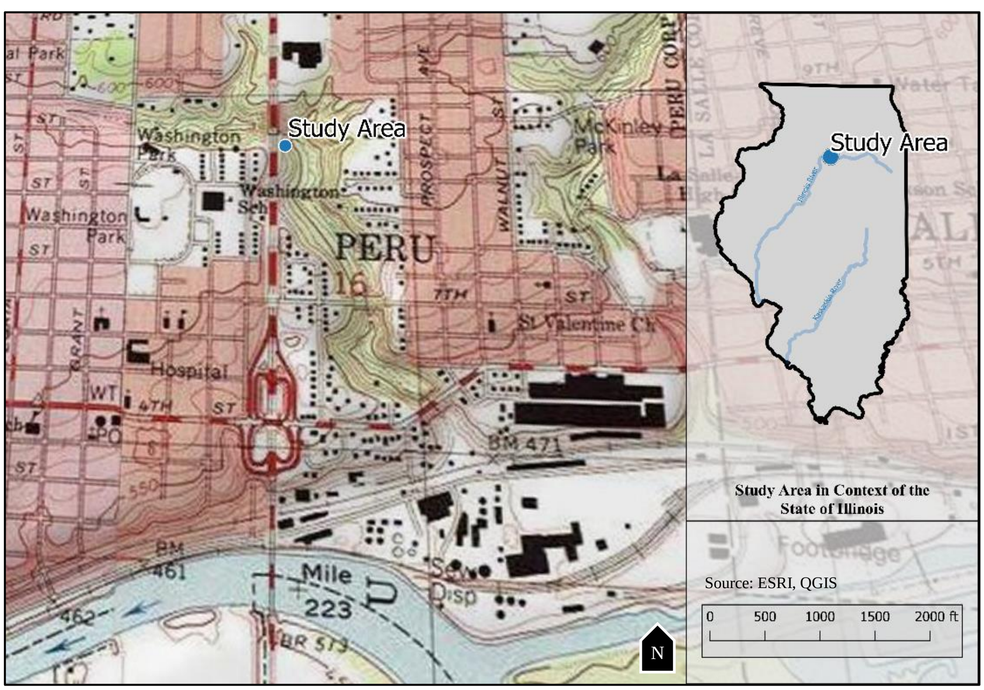

Figure 1: Study Area in Context. Elevation contours show elevation before construction of the embankment around 1961

Introduction

Background

Landslides of all types in the United States cost $3.5 billion per year in damage (Highland and Johnson, 2004), and the United States Geological Survey has identified "Real-Time Monitoring" of landslides as one of the key strategic elements to reduce losses from landslides and to provide new insights into landslide processes and triggering mechanisms (Spiker and Gori, 2003).

Our survey sought to investigate the site of a “debris flow” or soil creep failure in an engineered embankment beneath Illinois Route 251 where the road crosses a filled streambed. Illinois Route 251 is a major north-south road through Peru, Illinois, and the study area is less than a mile north of where Illinois Route 251 crosses the Illinois River (Figure 1).

Specifically, the goals of the survey were to delineate the creeping material relative to the intact embankment; locate wet areas (groundwater seepage) within the fill; locate drains and other subsurface structures from previous repairs; and, if possible, map the interface between the fill and the original ground surface.

Figure 2: Failure in the subsurface of the embankment is causing damage along the roadway. This photo (facing south) was taken the month prior to the ERT survey.

Study Area

The streambed channel was filled during the original construction of the road, creating an embankment over 15 meters (50 feet) tall at its highest point. The fill used in the embankment is composed of clay and reworked shale, and it overlies Pennsylvanian bedrock. The stream is now routed through a box culvert beneath the embankment.

Problems with this embankment have been evident ever since it was first constructed in 1962, with creep failure occurring in the subsurface along the roadway as it crosses the stream channel. The failure has reached the shoulder of the roadway causing a hazard (Figure 2). The topography in 1962 prior to construction—along with the study area and the planned road—are shown as a three-dimensional model in Figure 3.

Methods

ERT surveying is a geophysical technique that takes advantage of the contrast in electrical properties of natural materials, and there are several methods (i.e. arrays) used to measure these properties. In this project, we chose to use the inline dipole-dipole array. Advantages of the dipole-dipole array over the Wenner array (another common method) include relatively high horizontal sensitivity and relatively wide horizontal data coverage. Disadvantages include a relatively poor vertical sensitivity and a relatively shallow area of investigation (Loke, 2016). Given the relatively small electrode spacings and the primary importance of delineating the horizontal boundaries of the mass movement, the dipole-dipole array was chosen.

For the ERT measurements conducted in this survey, 40 metal electrodes were pushed into the ground at intervals of 2 meters along each survey line. Nine survey profiles were taken, each measuring 80 meters long; a tenth survey profile was also taken with only 20 electrodes, measuring 40 meters long (Figure 4). The stakes were connected through multi-core cable to a computer-controlled resistivity meter (ABEM Terrameter 4000) and switching system (LUND imaging system). A control program sequentially switched various combinations of electrodes, operated the instrument, and stored the data.

Profiles of resistivity measurements were obtained at 2 m spaces and up to about 8 m (25 ft) deep. Topographical information was then added to the data using information obtained by Illinois Department of Transportation (IDOT) surveyors as we collected our data. A two-dimensional resistivity model was calculated for each profile from the electrical data using a finite element inversion program (Res2dInv). Resistivity profiles plotted in Figure 6 are shown at the same horizontal and depth scales and with identical resistivity scales. In general, the resistivity values measured in this study were low, but consistent with moist, silty clay to fine sand. The resistivities are depicted using a logarithmic scale ranging from 1 ohm-m to 181 ohm-m.

Several months after the initial survey, inclinometers were installed to verify the depth of the failure.

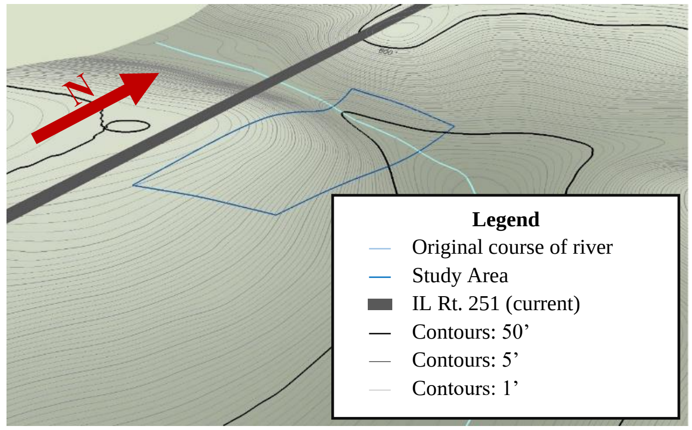

Figure 3: Three dimensional rendering of study area overlaid on the original elevation contours.

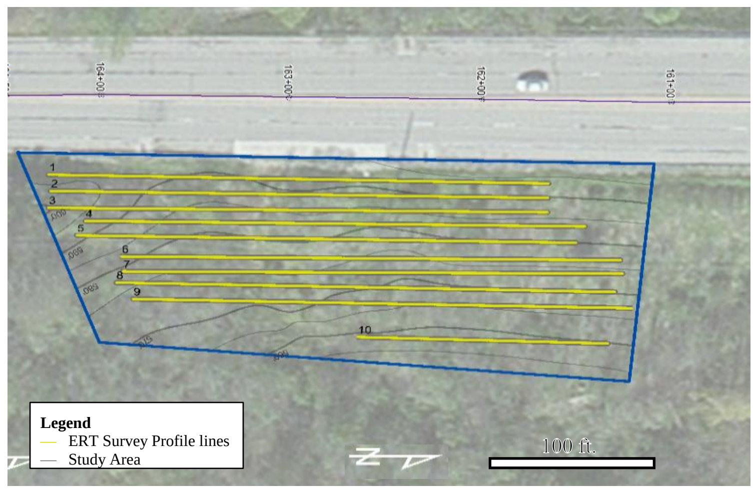

Figure 4: A) The 10 ERT profiles overlaid on elevation contours (feet) taken from the day of the measurement. IDOT markers (e.g., 161+00) are shown along the centerline of the road.

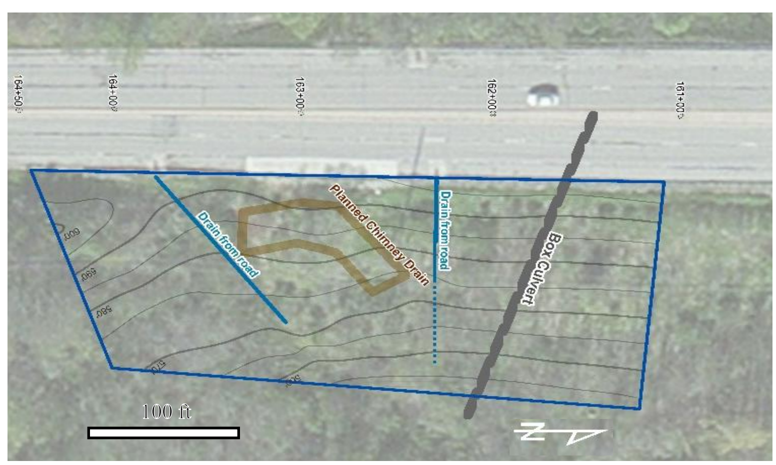

Figure 5: Subsurface structures in the study area. The chimney drain is shown in its planned location. The dotted line in the drain may be where the pipe transitions from metal to plastic, as indicated by relatively higher resistivity values.

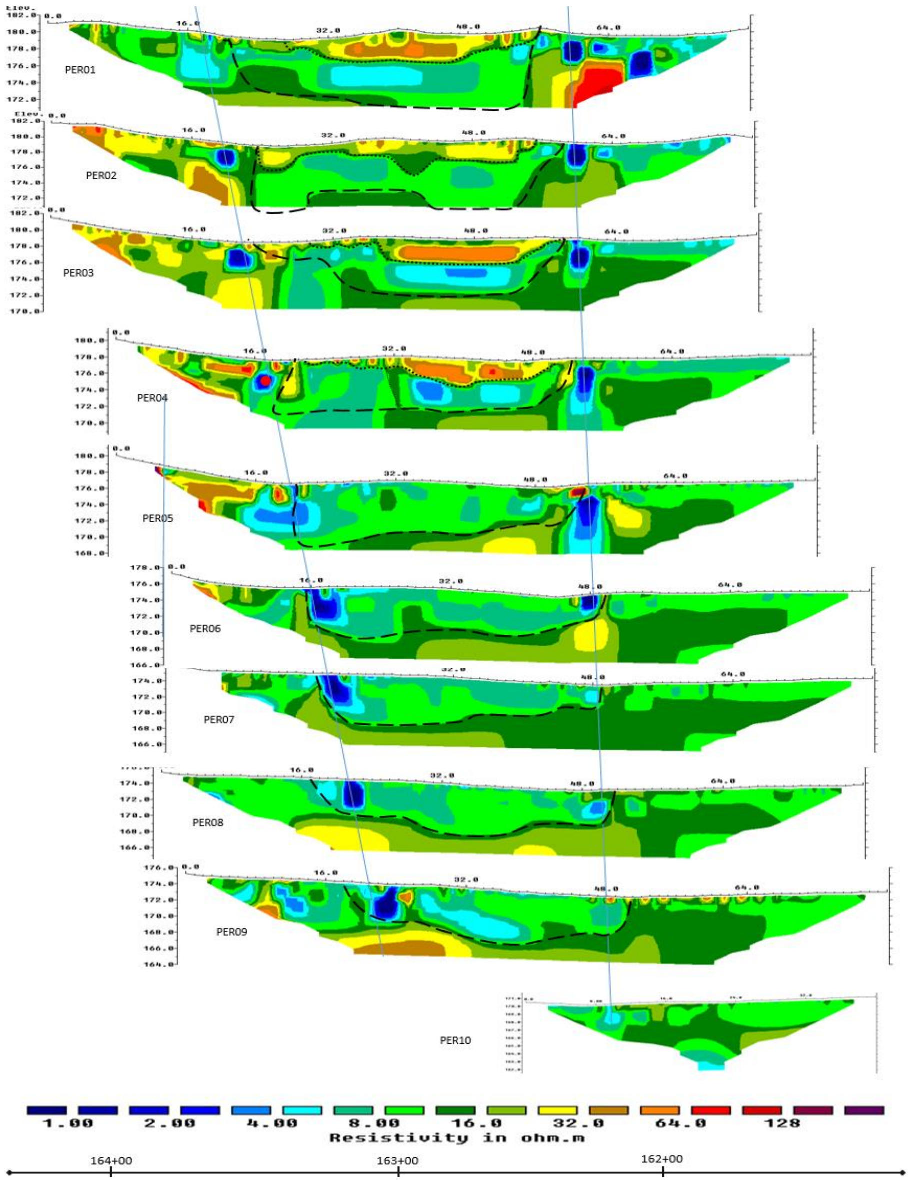

Figure 7: The 10 resistivity profiles in this project, laid out to scale horizontally and vertically. IDOT markers are shown along the bottom of the profiles. Drain pipes are delineated by blue lines, the estimated failure surface is shown by large dotted lines, and a high resistivity area believed to be a chimney drain is shown by small dotted lines.

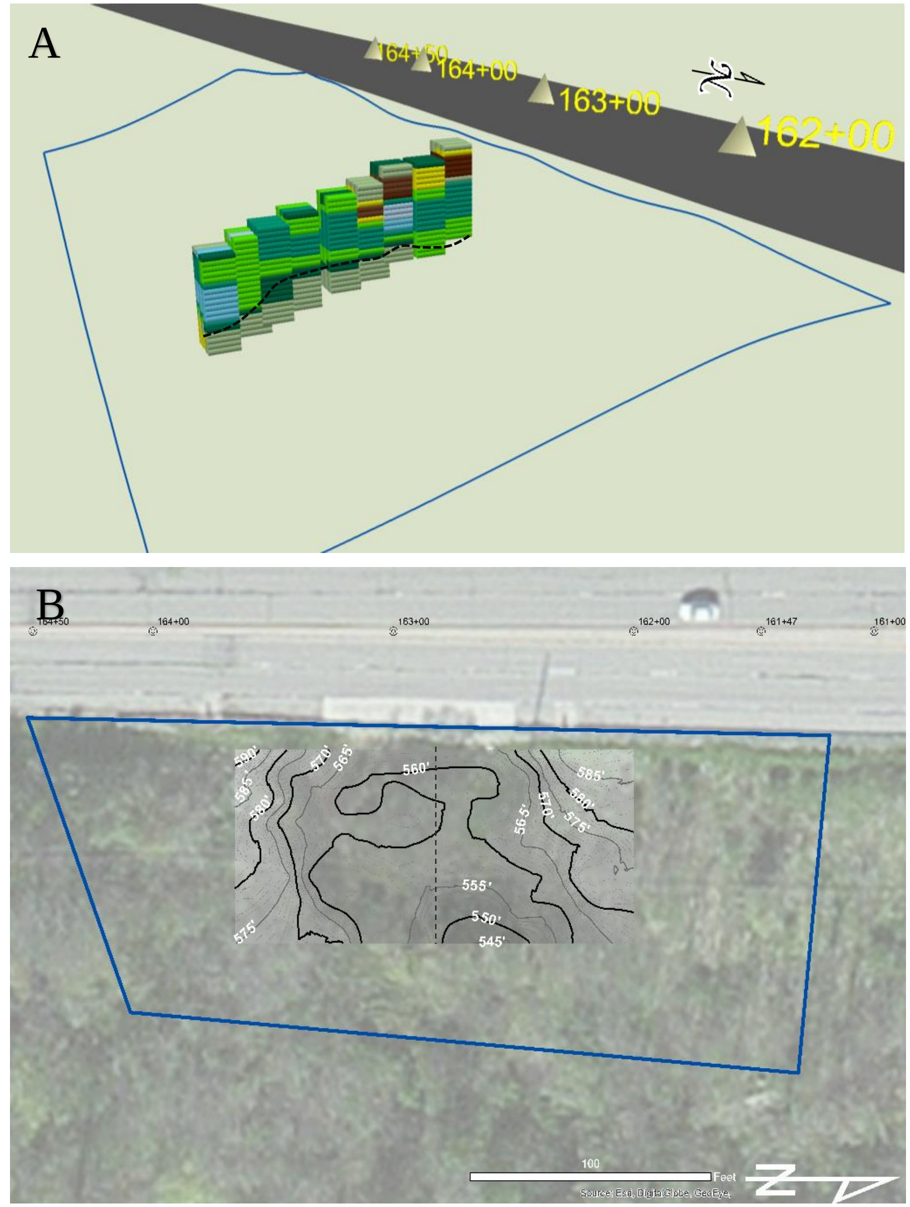

Figure 6: A) A 2-D profile of the subsurface using a single column of points from each profile 1-9, with a dotted line indicating the estimated failure surface. B) A contoured image of the failure surface. The dotted line shows the location of the profile in 6A.

Results

Figure 6 shows the 10 resistivity profiles at their relative locations at the site. Two shoulder drains had been installed during previous repairs. Because no as-built drawings exist, it was not clear where the drains led away from the roadway. The two drainpipes are clearly imaged on the resistivity profiles (the two blue lines/red dots). The northern pipe is perpendicular to the roadway. The southern pipe angles to the north as it proceeds downslope. This, in itself, is an important result of the survey as it provides precise information to IDOT for planning future repairs. In addition, the low-resistivity anomalies at two locations on nearly every line provided us a means to confirm alignment of the resistivity profiles one-to-another. Unfortunately, the very low resistivity values of the pipes distort the rest of the image and various artifacts can be seen in the inverted resistivity profiles. This makes interpretation of the creep failure surface difficult because the pipes seem to be very near important interfaces in the failure and thus obscure the imaging of the failure. The northern drain pipe appears to transition to a material with higher resistance between profiles 6 and 7—perhaps plastic or another non-metal. The low resistivity zone at the base of the tenth profile is consistent with the box culvert carrying the re-routed stream. However, this interpretation is far from definitive. These and other subsurface features are also shown in Figure 5.

The shallow, relatively high-resistivity material imaged on profiles 1-4 appears to be a more recent fill material. It is in the same general area as a chimney drain which appears in IDOT repair plans, but whose construction was not confirmed. Two areas of relatively high resistivity just north (Profile 5) or just below (Profile 6) the northern drain pipe are interpreted as artifacts related to the drain pipe, but they may also be a northern continuation of the fill material imaged on profiles 1 through 4. The features described above are fairly well-imaged on the resistivity profiles. Based on the consistent resistivity values and locations of the features we are relatively confident in our interpretations.

The primary purpose of this survey was to delineate the elevation at which the failure is occurring. Because the resistivity profiles are close together, we were able to compare them for features, which may be subtle on any one profile, but when repeated on adjoining profiles suggest the presence of a physical interface and not merely noise in the resistivity data. In particular, a linear feature can be seen near the center of the base of most of the profiles (Figure 6). It separates a zone of relatively higher resistivity material below from a zone of relatively lower resistivity material above. The north and south boundaries of this feature are often obscured by artifacts from the buried drain pipes; however, we believe we can trace the edges with some confidence in most of the profiles.

We also show this feature in profile on Figure 7a. We create a contoured surface, shown in Figure 6 and Figure 7b. This surface is consistent with a slip surface between the competent slope (higher resistivity material) and a mass creep of the lower resistivity material. The southern edge of this surface, though difficult to precisely image because of the presence of the drain pipe, appears to be fairly steep and to abut the zone of the relatively highly resistive undisturbed material on the far south end of profiles 2 through 6. On the north, the surface gradually moves farther north as it moves downslope.

In response to these findings, IDOT installed inclinometers at the site to verify these results and further delineate the slip-face. According to the inclinometers, at the location of greatest movement, the ground has been moving at a rate of 0.025 inches/day (1.1 inches over 6 weeks). The interface between the stable ground and the creeping ground was within 1 foot of our estimation at all the recorded points except one (where it was within 3 feet of our estimation). Where we had predicted no movement in the subsurface, the inclinometers confirmed that the subsurface was stable.

Conclusions

We were able to image several features (drain pipes, box culvert) from previous work at the site. A small area of fill material in the center of the embankment was also imaged (perhaps a chimney drain). We were also able to image a very subtle feature consistent with a slip-face. The very low resistivity of the drain pipes limit the resolution of this feature, but the general shape and location are confirmed both by the surface manifestations of the creep and by the inclinometers that were installed following our survey.

Acknowledgements

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