Landslide Monitoring Methods: Application of Existing Technologies to Long-Term and Real-Time Monitoring of Slope Movements

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16. Abstract

Various landslide monitoring techniques were applied concurrently to a known cut-slope landslide and a previously unknown fill slope failure, both on the Ozark Mountain Highroad (Missouri Route 76) near Branson, Missouri. Both subsurface and drone-based monitoring techniques were employed so that the strengths and weaknesses of the various monitoring techniques could be compared. Slope inclinometer casings and vibrating wire piezometers were installed at the three borings drilled in the project area. An in-place inclinometer was installed in one boring to demonstrate the effectiveness of instrumented landslide monitoring. Dataloggers were connected to a cellular modem to enable real-time monitoring of the instruments through a web-based interface. LiDAR data was collected by drone annually. The research team developed a subsurface geometry for both slides and identified movement triggering events. The team also compared the various monitoring techniques to provide guidance for future selection of long-term monitoring methods at other unstable slopes.

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LANDSLIDE
TECHNOLOGY
A DIVISION OF CORNFORTH CONSULTANTS

LANDSLIDE MONITORING METHODS: APPLICATION OF EXISTING TECHNOLOGIES TO LONG-TERM AND REAL-TIME MONITORING OF SLOPE MOVEMENTS

MONITORING LANDSLIDE ON ROUTE 465 NEAR BRANSON
BRANSON, MISSOURI

MoDOT Project Number TR202016

November 23, 2022

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ABSTRACT

Various landslide monitoring techniques were applied concurrently to a known cut-slope landslide and a previously unknown fill slope failure, both on the Ozark Mountain Highroad (Missouri Route 76) near Branson, Missouri. Both subsurface and drone-based monitoring techniques were employed so that the strengths and weaknesses of the various monitoring techniques could be compared. Slope inclinometer casings and vibrating wire piezometers were installed at the three borings drilled in the project area. An in-place inclinometer was installed in one boring to demonstrate the effectiveness of instrumented landslide monitoring. Dataloggers were connected to a cellular modem to enable real-time monitoring of the instruments through a web-based interface. LiDAR data was collected by drone annually. The research team developed a subsurface geometry for both slides and identified movement triggering events. The team also compared the various monitoring techniques to provide guidance for future selection of long-term monitoring methods at other unstable slopes.

EXECUTIVE SUMMARY

This report documents research conducted as part of MoDOT research project 202016, *"Monitoring Landslide on Route 465 Near Branson."* Since the start of the research project, the original *Route 465* nomenclature has been renamed *Missouri Route 76*. The overall roadway is still referred to as the Ozark Mountain Highroad. The highway is consistently referred to as the Ozark Mountain Highroad or Route 76 throughout this report to be consistent with the current roadway designations, if not with the original RFP.

The objective of this research project was to monitor the previously identified slow-moving slide in the cut slope above the roadway using various remote sensing techniques for a minimum of 12 months. Subsurface information would be paired with surface mapping to develop detailed maps of the landslide surface along with subsurface profiles. To complete this objective, the research team used a combination of LiDAR surveys and subsurface instrumentation connected to an automated data acquisition system (ADAS). The ADAS used a modem and cellular connection to regularly upload data collected by the on-site dataloggers to a website for routine monitoring from an off-site location. A weather station was also installed onsite to help identify triggering events for landslide movement. Subsurface instrumentation included slope inclinometers, an in-place-inclinometer, and vibrating wire piezometers. The boreholes were also logged by a representative of the research team during drilling to determine the geologic profile at the site.

A site reconnaissance of the landslide was completed in May 2020 and identified a second landslide in the embankment supporting the northbound lanes. This slide was also incorporated into the investigation and monitoring program. A LiDAR scan was completed in June 2020 to generate a high-resolution ground surface. Subsurface investigation, instrumentation installation, and installation of the remote monitoring system was completed in September 2020. The in-place inclinometer was installed in the embankment landslide in June 2021 following measurement of a reliable, well-defined shear zone. This landslide was coincident with pavement cracking and following coordination with the MoDOT Technical Committee, MoDOT maintenance personnel sealed the cracks in December 2021. The objective of this work was to see if this routine maintenance activity had an impact on the amount of water infiltrating into the slide through the damaged pavement and a subsequent impact on landslide stability. The monitoring period was extended through September 2022 to permit evaluation of crack sealing effectiveness and to better identify triggering movements in the slow-moving landslide. In total, remote monitoring was enabled at the landslide site for 24 months. Additional LiDAR surveys and manual readings of the slope inclinometers that did not have in-place inclinometers installed also occurred during this period.

At the close of the monitoring period, the research team concluded that both slides are impacted by seasonal precipitation patterns, with most measured movement occurring between the beginning of April and the end of June. The cut slope slide at the location of one of the borings is moving on a shear zone approximately 10 feet below the ground surface in the native clay soils. The embankment slide is moving on a pair of shear zones bracketing the contact between the embankment fill and the native slope, both of which are clay materials. Using the instrumented boring in the embankment landslide, groundwater data, precipitation data, and displacement data were correlated to determine triggering events for the landslide. For this slide, movement is triggered by precipitation events that deliver four or more inches of rainfall to the site between the months of April and June. Based on review of the rainfall data collected onsite, precipitation events are most frequent during these months, increasing ambient pore water pressures and making the slide more likely to move in larger storm events. Movement was measured at other times of the year and in other storm events, but larger precipitation quantities were necessary to achieve similar displacements to those measured after smaller storms in the spring.

The impact of crack sealing on stability of the embankment landslide was also assessed, and no improvement to landslide stability was identified. It appears that the cracked and damaged pavement is not a significant conduit for rainfall into the slide mass at this location. The research team suspects that most water is entering the slide mass from the median east of the landslide, where bedrock is known to be shallow.

At the conclusion of the monitoring period, the various methods used during the project to monitor landslide deformation were compared in a monitoring methods analysis. This analysis incorporated the sensitivity of the various monitoring techniques, their approximate cost, and their ease of use, including both set-up in the field, and post-data collection processing. In this analysis, the in-place inclinometer was the most sensitive to subsurface deformation, measuring displacements as small as 0.01 inch. Manual slope inclinometer surveys identified shear zone displacement as small as 0.1 inch. LiDAR scans required surface deformation of at least 12 inches to register change in the ground surface. The benefits and constraints of dataloggers in real time as opposed to quarterly or biannual data downloads is also discussed. The various costs and considerations involved in selecting an instrumentation and monitoring plan are summarized in the methods analysis for use as a reference and decision support tool in future MoDOT projects monitoring long-term landslide deformation.

All of the on-site monitoring equipment discussed in this research project remains onsite, and the dataloggers continue to collect data. The cellular connection and IP subscription that enabled remote monitoring were allowed to lapse at the end of the research project, but MoDOT intends to continue manually downloading data from the loggers on an annual basis. In the future, this expanded dataset may lead to a better understanding of the triggering events for the Ozark Mountain Highroad landslides. It may also help support the implementation of multi-year monitoring periods for slow moving slides, to help make risk assessments more reliable and mitigation work more cost-effective.

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1 INTRODUCTION

Many Departments of Transportation (DOTs) throughout the United States are challenged by slow-moving landslides within their right of ways. Because these slides creep over many years, their effects can often be addressed in the short-term by additional maintenance, but these repairs rarely address the root causes of the landslide and do not reduce slide movement or long-term risks to the travelling public. Using modern technology to improve monitoring of these slopes allows DOTs to make more informed decisions as they develop long-term mitigation solutions for a problematic slide area.

Over the past decade, advances in instrumentation and the expansion of cellular networks have made remote near-real time monitoring a realistic option throughout much of the United States. In addition, site-specific photogrammetry or LiDAR data collection via unmanned aerial vehicles (UAVs) has become an affordable method for detecting change across project sites. These new technologies do not displace the traditional methods for collecting subsurface data, but rather complement them to provide a more complete picture.

The rapid rate of change in slope monitoring tools creates uncertainty on how to best integrate all the new tools into a cost-effective monitoring program. The purpose of this study is to test selected methods of long-term landslide monitoring on a known slow-moving landslide in southwestern Missouri. By proactively targeting a known slow-moving landslide for this research project, Missouri Department of Transportation (MoDOT) is positioned to better understand the strengths and weaknesses of the different monitoring methods currently available.

The selected landslide is located along Missouri Route 76, otherwise known as the Ozark Mountain Highroad, near its intersection with Route 76/76 Country Blvd west of Branson. The landslide is on an east-facing, 2H:1V, 75-foot-tall cut slope above the southbound lanes of Route 76. Site reconnaissance in May 2020 identified a second, less active landslide in the embankment fill slope opposite the cut, which was also instrumented.

The instrumented monitoring program for this research project extended over 24 months, from September 2020 to September 2022. The research program incorporated subsurface explorations and instrumentation installation, in addition to conducting regular LiDAR surveys to track surface deformation in the project area and compare this to the subsurface deformations measured by instruments installed in the landslide. During the research project, the researchers were also able to assess the impact of crack sealing on the stability of the landslide in the embankment slide. The team also identified seasonal movements and movement triggering events.

At the end of the research period, the different monitoring methods were compared in a methods analysis that is intended to help guide MoDOT in applying these different monitoring techniques throughout the state. The insights gained from this study would allow MoDOT to more confidently develop site-specific monitoring programs for other slow-moving landslides. Over time, this data would in turn allow a more realistic interpretation of the long-term risks posed by these landslides and result in more cost-effective mitigation designs.

2 SITE HISTORY

2.1 Regional Geologic Setting

The study area is located in southeast Missouri's Ozark Plateau region. Previous geologic mapping completed by the Missouri Department of Natural Resources mapped the site as underlain by Mississippian limestone and Ordovician dolomite (Whitfield, 2004). The contact between these two units is an unconformity. Bedrock is typically overlain by quaternary alluvium, and rock outcrops are concentrated along roadway excavations. Springs and caves are common on the regional level, but none are mapped within the project area.

The larger bedrock geologic map shows the Roark Creek Fault north of the project area and the Ten-O'Clock Run Fault to the south and west. The portion of the Ten-O'Clock Run Fault closest to the study area is shown in Figure 1. However, no faults are mapped within the project area that would have contributed to the observed slope instability.

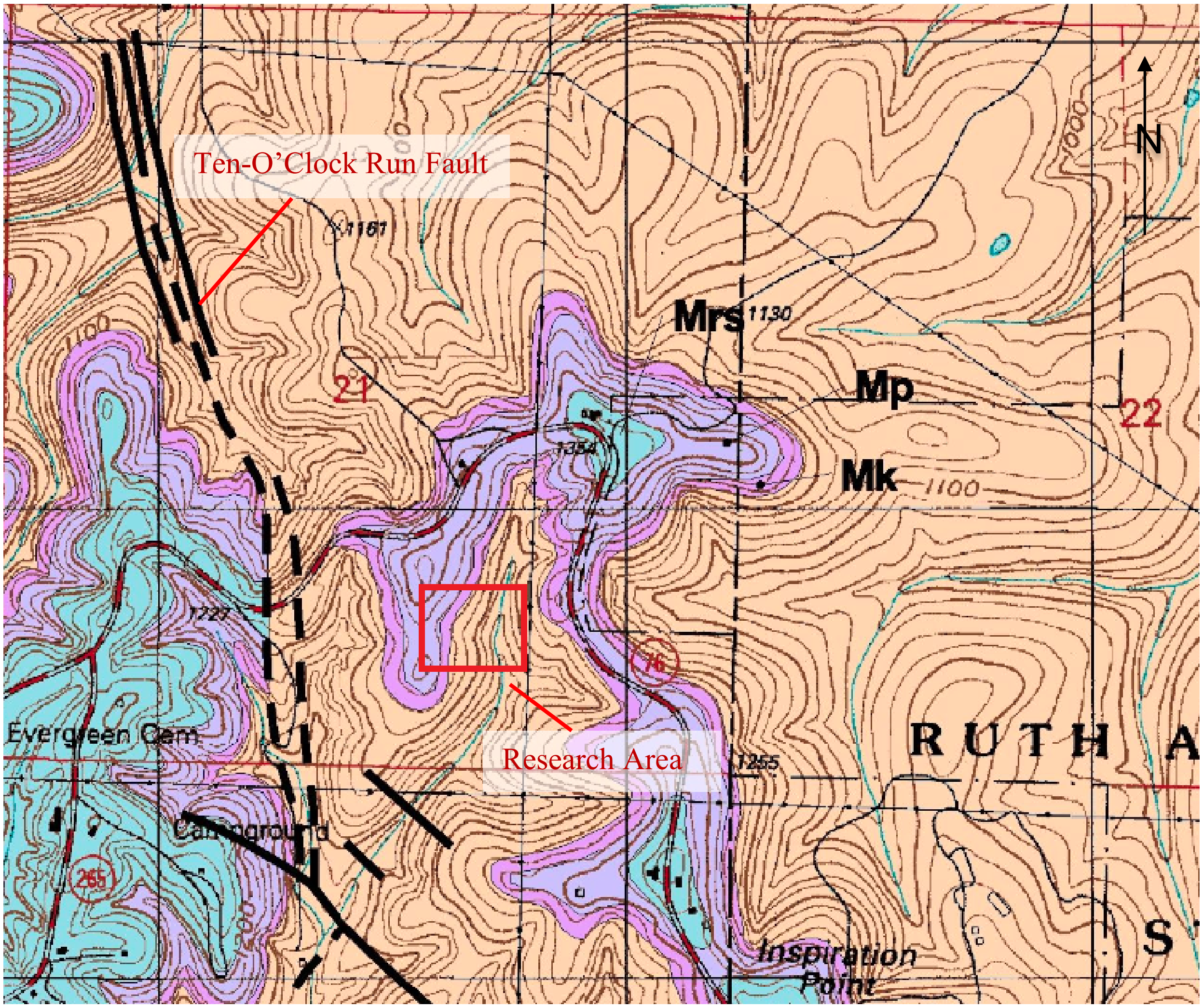


Figure 1: Segment of 2004 geologic map with the research area outlined in red. Scale of this excerpt is approximately 1in = 1,250ft. Pierson Limestone (Mp, light purple), Kinderhookian Series (Mk, purple), and Cotter Dolomite (Oc, beige) are expected to be encountered within the research area. (Whitfield, 2004).

2.2 Construction History and Previous Slope Movement

The Ozark Mountain Highroad is a four-lane, divided highway that was conceived as part of a long-term plan to relieve traffic congestion in downtown Branson. It connects Missouri Route 76 to US Route 65 north of Branson. This allows drivers to bypass downtown Branson, where Route 76 was the main throughfare. The northern section of the Ozark Mountain Highroad, from Route 76 to US 65, opened to traffic in 2003. MoDOT owns right of way to complete a southern portion that would extend the Highroad to connect to US 65 south of Branson as well, but there is currently no plan to complete that work. As shown in Figure 1, Route 76 originally curved north of the project area to contour around a steep draw with a seasonal creek. Construction of the Ozark Mountain High Road required construction of a steep cut slope to accommodate the southbound lanes and an embankment fill up to 30 feet thick to support the northbound lanes.

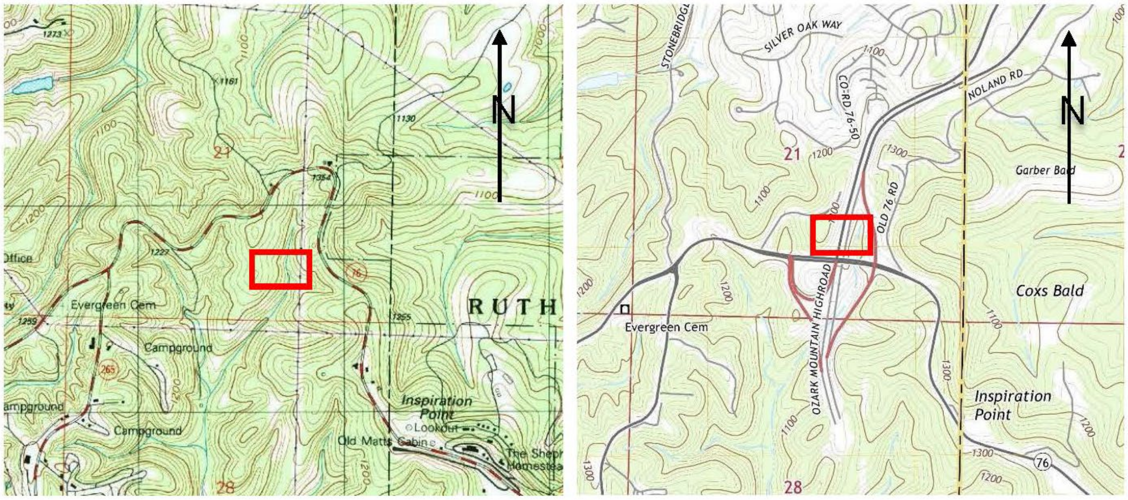


Figure 2: Excerpts from USGS topographic maps from 1989 (left) and 2021 (right) showing the project area (in red) before and after construction of the Ozark Mountain Highroad.

Construction drawings and historical satellite images indicate that the cut slope was partially excavated in 1993 during the construction of the overpass that supported realignment of old Route 76, as shown in Figure 3. By 2001, final slope excavation was completed, and a set of nested gabion walls was constructed in the opposite embankment prior to the 2003 opening of the Ozark Mountain Highroad. A rockfill drain was constructed in the cut slope near the south end, aligned with a low spot in the ridge. No instability in the cut slope was noted at this time. The final cut slope in the study area was 2H:1V and approximately 75-feet tall, with height increasing from south to north. The site plans provided by MoDOT are included in Appendix A for reference.

No documentation of when landslide movement in the cut slope began has been located. MoDOT personnel described it as an ongoing, slow-moving landslide that had not yet impacted roadway performance. Publicly available satellite images were obtained from Google Earth and used to constrain the start of landslide movement. A subset of these images is shown in Figure 3. Initial landslide movement in cut slope is visible in the August 2008 image. The landslide appeared to continue to expand slowly in subsequent images, with the head scarp retrogressing up the cut slope.

The slide does not appear to have progressed south of the rockfill drain, although the drain has gradually been filled in by slide debris is some locations.

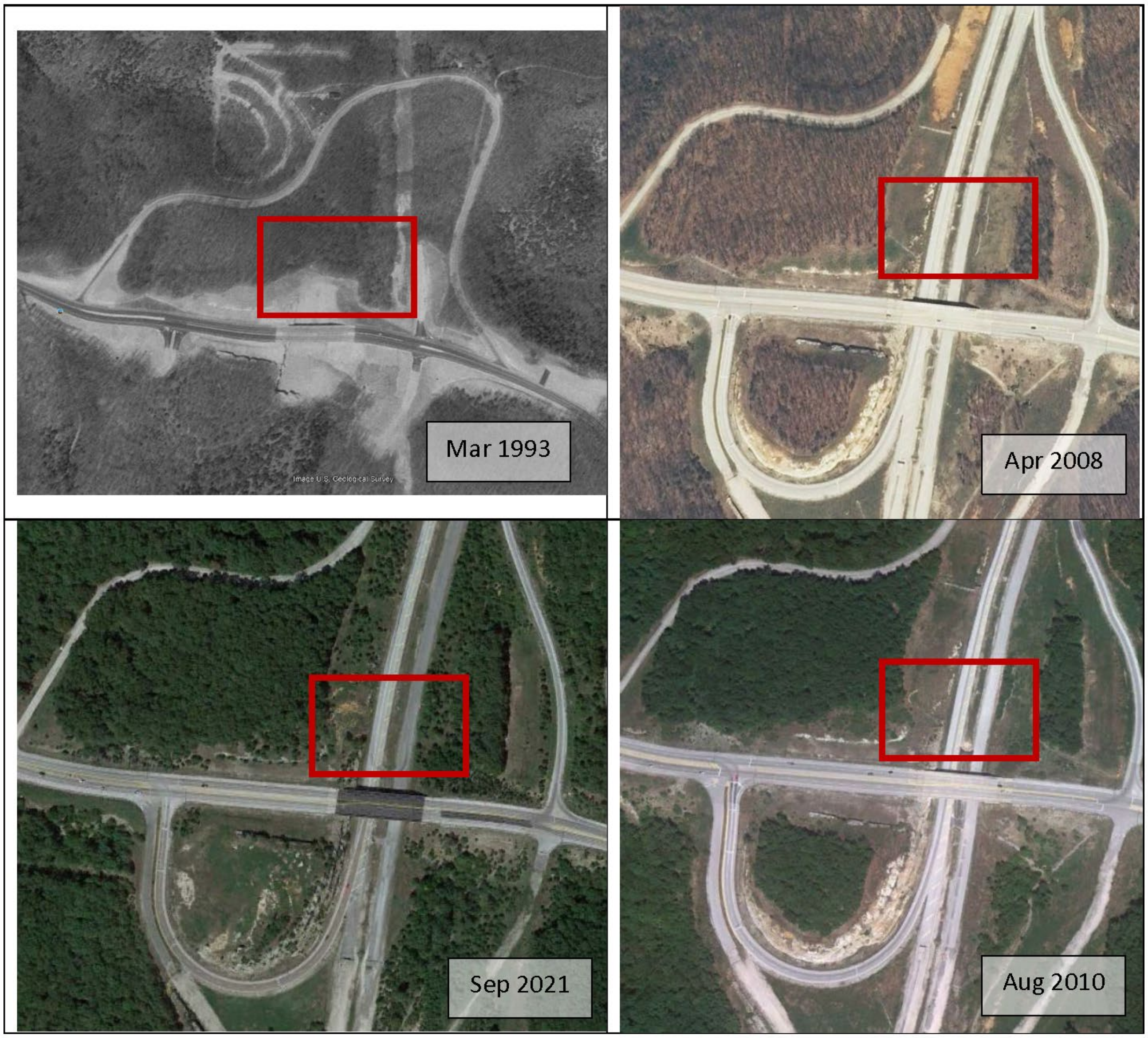


Figure 3: Selection of satellite images showing progression of slope instability at the study area over time. Movement appears to initiate between 2008 and 2010. All images courtesy of Google Earth.

The gabion basket retaining wall system is north of the cut slope landslide partway down the embankment slope. The location of these walls in the plan sheet appears to be a response to geometric constrains in the final rockfill drainage design at the base of the draw. The wall system is constructed of three overlapping segments, each consisting of two three-foot tall baskets filled with angular rock. The middle wall supports the ends of the adjacent segments. Based on Figure 3, the wall system was not constructed during initial excavation for the overpass. They are not visible in the lower resolution 1993 photo but are clearly visible in 2008. By 2021, the walls have been overgrown with black locust trees and are no longer clearly visible.

2.3 Previous Investigations

This landslide was the site of several overlapping research projects completed by students and faculty from the Missouri Institute of Science and Technology (MST) between 2013 and 2017 (Maerz N. , 2014; Maerz N. , 2014; Herries, 2017). It is our understanding that MST faculty approached MoDOT for help in identifying landslides that could be imaged for this project, and MoDOT directed them to the Ozark Highroad slide. These research projects used repeated LiDAR surveys collected from a total station to track landslide deformation and to attempt to define subsurface geomorphology without a subsurface investigation. The project placed a target grid across the entire landslide to allow researchers to pick out relative rates of movement within the landslide mass in an effort to gain more detailed surface and near-surface movement data (Maerz N. B., 2016).

Reflective targets constructed of 6-inch diameter Styrofoam balls mounted on steel rods of different lengths driven into the landslide in an approximate grid pattern (Maerz N. , 2014). Using the targets, scans could be tied together, and individual data points compared. Rotation of the targets relative to landslide movement was proposed to be used as a proxy for identifying depth to the shear zone. This work relied on a site-specific algorithm that attempted to account for the individual rod length, relative displacement, and rotational shift (Maerz N. B., 2016).

The first set of targets was installed in 2013, but little movement was detected between the initial 2013 work and the start of the 2015-2017 monitoring period (Maerz N. B., 2016). Between July 2015 and July 12, 2017, 17 scans were completed as part of a Masters' Thesis project (Herries, 2017). In July 2015, the landslide was roughly 120 feet wide with a roughly 140-foot axial length. The 18-month research period reported 36 inches of movement between December 2015 and March 2016, with slower creep movement between scans for the rest of the monitoring period. Movement was concentrated in the lower left portion of the slide mass and in areas that were unvegetated. Most targets moved in parallel with the landslide or deformed in ways that could not be resolved to rotation above a slip plane. The MST research team was not able to determine the geometry of the slip surface but did capture useful insight on the seasonality of slide movement in this cut slope. (Herries, 2017).

The reflective targets from the MST investigation remain onsite, as shown in Figure 4 below. Significant slide movement and growth occurred in May 2020 following an extended period of heavy precipitation. The landslide expanded to the north (right side of frame) and reflective targets that were previously intended to be control points are now within the slide mass.

Figure 4: Reflective monitoring stations from previous research on the Ozark Mountain Highroad Slide in May 2020.

3 SITE INVESTIGATION

The site investigation at the Ozark Mountain Highroad landslide consisted of several components. After reviewing the construction history and results of previous investigations, Landslide Technology located pre-existing LiDAR data. This data was used to support the site reconnaissance that mapped the surface expression of the existing landslide and sited recommended boring locations. After the site reconnaissance was completed, a subsurface investigation was completed to install monitoring instrumentation.

3.1 Pre-Existing LiDAR Data

Landslide Technology searched for publicly available LiDAR data that could be used to create a reconnaissance site map prior to the first round of site-specific data collection. The Missouri Spatial Data Information Service had aerial LiDAR collected for Stone County in 2010. This LiDAR survey had a 3-foot pixel resolution, which is typical for airborne LiDAR data (Missorui LiDAR Data, 2022). The 2010 landslide extent is apparent on the bare earth data, as shown in Figure 5, but the raster resolution is 3-feet pixels. At this resolution, significant landslide movement must occur before it can be captured in a change detection program.

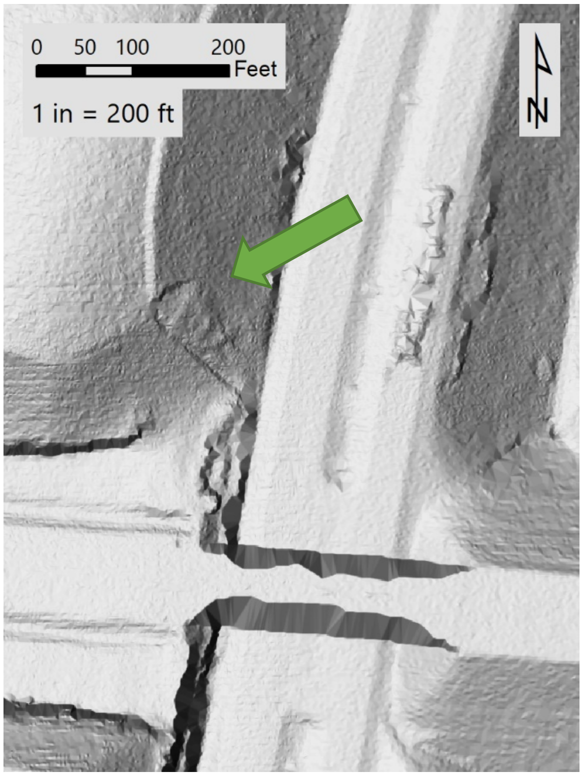


Figure 5: Bare earth LiDAR data from 2010 aerial LiDAR survey, with green arrow pointing to the landslide area.

Although insufficiently detailed for long-term monitoring, the 2010 LIDAR was used to develop an initial site map with contours for field use, shown in Figure 6 below. The site map was created by processing the downloaded 2010 raster DEM with the ArcGIS Contour Tool. Extents of the final site map were based on an estimate of the likely area that would be covered during the site reconnaissance and a useful scale for field work.

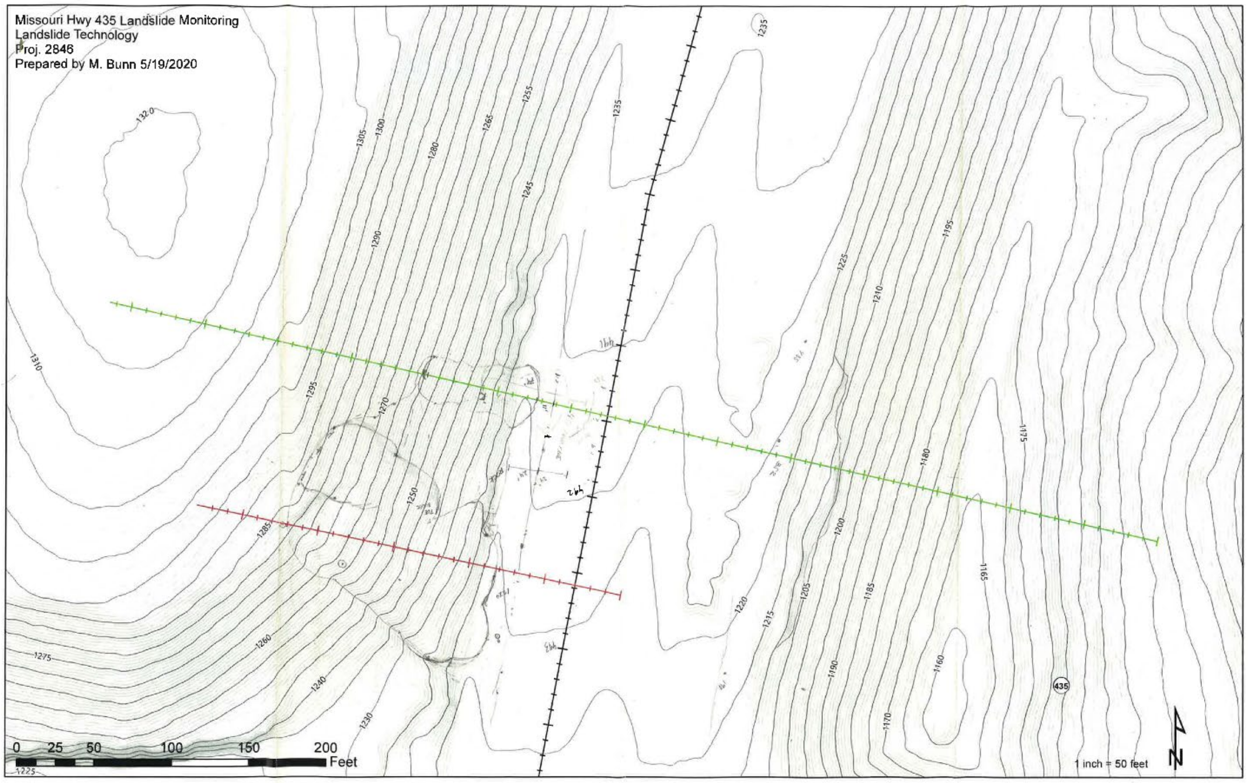


Figure 6: Site map with contours made from 2010 Stone County LiDAR data. This is a scan of the map was used during the field reconnaissance and includes notes taken in the field.

3.2 Site Reconnaissance

On May 21, 2020, Landslide Technology staff performed a site reconnaissance of the landslide and surrounding area. The purpose was to develop preliminary interpretations of the landslide's behavior and to select possible locations for test boreholes. During this visit, Landslide Technology collected observations on materials involved in the landslide, surface hydrologic conditions, and vegetation. The team also mapped the extent of primary landslide features.

Key features mapped during the 2020 field visit, and from high-resolution LIDAR data collected by Aerial Insights in June 2020, are displayed in Figure 7 on the following page.

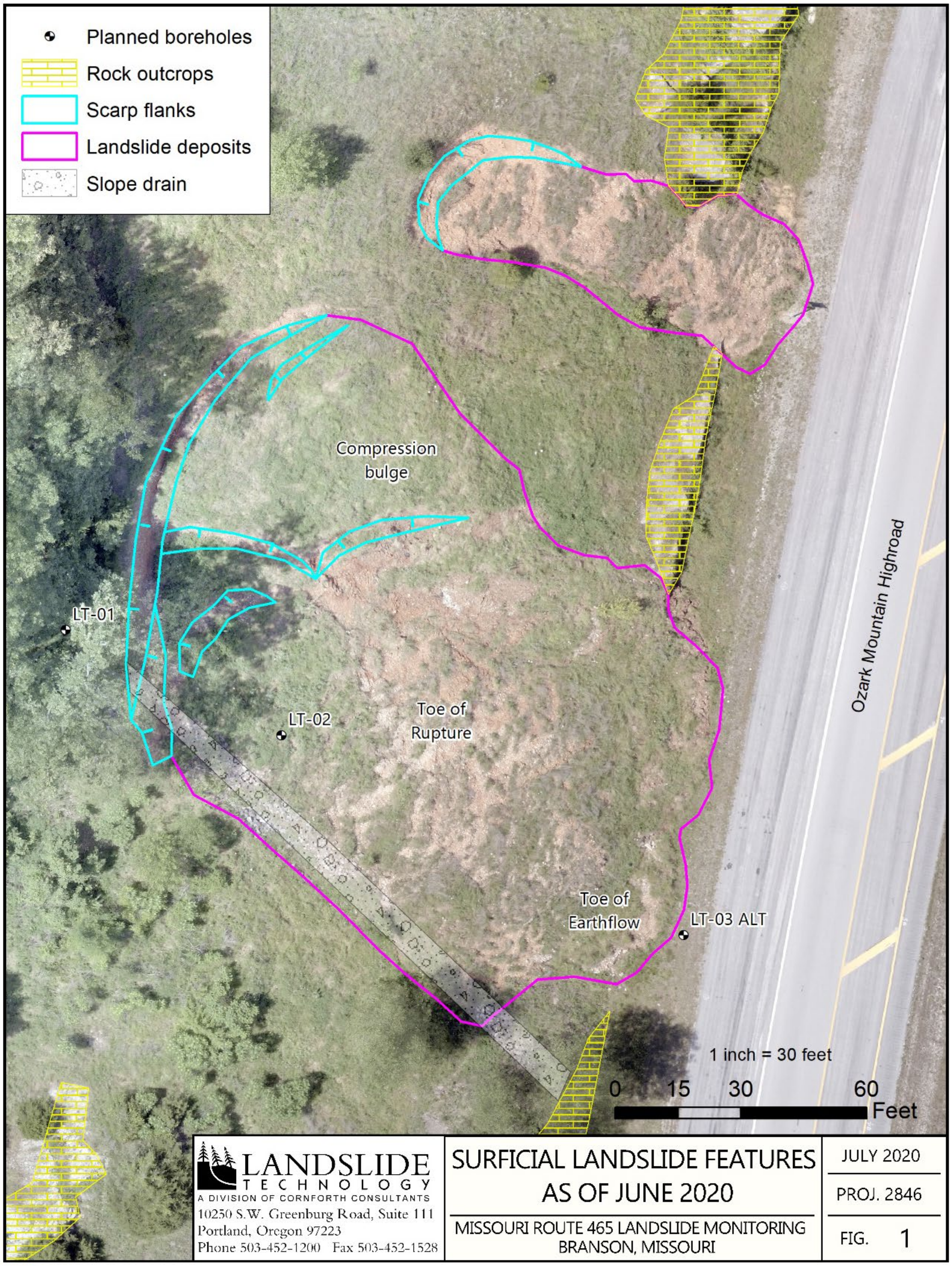


Figure 7: Finalized landslide map incorporating the site reconnaissance observations from May 2020, the LiDAR imagery from June 2020, and proposed boring locations.

3.2.1 Main Landslide and Adjacent Slump

On May 14, shortly before the planned site visit, MoDOT personnel notified the team that the slide had recently moved and expanded following a period of heavy rain. Evidence of recent movement was easily discernable and widespread during the site visit, as indicated in Figure 8 below. This photo taken from the Route 76 overpass provides an overview of the cut slope, with the original slide on the left, and the newly activated May 2020 flow slide on the right. The rockfill drain that appears to control the southern extent of the landslide is hidden behind the trees on the left side of the photo.

Figure 8: View of cut slope landslide complex taken from the Route 76 overpass May 2020.

Based on measurements collected during the site visit, the existing landslide head scarp had expanded northward roughly 50 feet in May 2020. The southern end of the landslide remained defined by the rock drain, although landslide debris had been deposited onto it, as shown in Figure 9. A new, smaller slide originating roughly halfway up the slope had developed roughly 100 linear feet north of the original slide. A low rock cut, approximately four feet tall, separated the two slides. Both slides appeared to be exiting the cut slope above the elevation of the rock cut. Saturated landslide debris then spilled down the slope and collected in the roadside ditch. Although the landslide mass was saturated and difficult to traverse, no springs or other drainage features feeding water to the slope were noted. Saturation of the soils appeared to be caused by extended precipitation or changes in groundwater level. In Cruden Varnes landslide terminology, both slides would be more properly referred to as earth spreads or earth flows based on their observed behavior, as opposed to landslides. (Cruden & Varnes, 1996). However, previous studies and the research proposal referred to this cut slope instability as a landslide, and that nomenclature is retained in this report to avoid confusion.

A selection of photos taken during the site reconnaissance are compiled in Figure 9. These photos show the nested head scarps associated with the slides, along with the landslide toes and internal deformation. The clay in the slide was saturated and moisture was actively seeping from the slide debris in multiple locations. Both slides appeared to have moved as saturated masses, with further internal deformation occurring as the slides moved downslope. No landslide movement was observed during the site visit.

Figure 9: Slide features from May 2020. Clockwise from left, toe deposit in the roadway ditch, nested scarps at the head of the slide, an internal toe in the slide mass, and water seeping from the recently mobilized slide debris.

Because the research project included subsurface investigation, a key component of the site reconnaissance was determining borehole locations. A representative from the Kansas City office of Geotechnology, LLC joined the Landslide Technology team for part of the site reconnaissance. Together they traversed the landslide slope to site borehole locations that would provide valuable information about landslide geometry while maintaining safe drill rig access and operation. One borehole was staked immediately above the landslide scarp to help characterize in place native material and provide insight into possible landslide retrogression. A second borehole was planned within the landslide deposits, with the goal of characterizing the landslide material, shear zone depth, and measuring future landslide movements. Access for both boreholes required access improvements. For the boring above the landslide, access improvements consisted of minor tree clearing, so that the drill rig could track along the crest of the road cut. For the boring inside the landslide, an access path was constructed from Route 76 to the proposed boring location so that the drill rig could track to the staked boring location. A work pad for the drill rig and associated equipment was also constructed at the end of the access path. Geotechnology suggested scheduling drilling for late summer, to allow the slide mass time to dry out and further improve drill rig access.

A third borehole had been initially planned for the highway shoulder below the landslide, to confirm that movement did not extend below the roadway. However, observations from the site reconnaissance indicate that the slide toes out above rock cut, depositing material on the lower part of the slope and in the highway ditch. A borehole in the ditch was unlikely to provide valuable information on potential roadway distress from a rotational toe. The landslide debris being deposited in the ditch also restricted the available work area. After considering these candidate locations, Landslide Technology and MoDOT decided to install the third borehole in an area of cracking and deformation in the currently unused northbound lanes of Route 465, above the gabion wall system. The observations of this area are described in the following section.

3.2.2 Roadway Deformation Associated with Retaining Wall

The site reconnaissance also extended across the road, looking for possible indications of global instability. Two areas of pavement deformation were noted in the unused northbound lanes of Route 465, opposite of the landslides. Neither area of deformation appeared to be related to a landslide that extended across the roadway to the cut slope.

The first segment involved subsidence of the east lane and shoulder, located approximately 275 to 365 feet north of the Route 76 overpass bridge. A crescent shaped crack extended from the east shoulder at the south end of subsidence to 15 feet from the east shoulder, approximately 60 feet north of the starting point. A pair of photos of the pavement distress are shown in Figure 10.

This embankment deformation is within the set of walls shown in the original design plans and the 2010 LiDAR data. Both data sources illustrate wall segments supporting the northbound lanes from approximately 190 to 435 feet north of the Route 76 overpass bridge, roughly 10 feet lower than top of the embankment. The 6-foot-tall retaining wall is comprised of three overlapping segments. Each segment is constructed from two 3-foot-tall gabion baskets with angular rock backfill. The segments were constructed similarly, with the north and south sections built above the middle segment. At their ends, the north and south segments rested upon the ends of the middle segment. Settlement of the north and south segments could be observed relative to portions of each wall that overlapped the center segment. For approximately half the length of each segment, the lower rock basket was battered away from the slope and the upper rock basket had a batter toward the slope. Batter away from the slope is generally an indicator of poor wall performance, but due to the flexibility of the rock baskets, it is unclear if the observed condition reflected long-term wall deformation or if the damage occurred during construction. No evidence of a landslide toe or other slope failure was observed in the embankment slope. However, the embankment is thickly vegetated, and minor deformations could have been obscured.

Figure 10: Arcuate cracking and minor deformation of the shoulder in the northbound lanes upslope from the gabion basket retaining wall system.

The second area of deformed pavement was located between 560 and 650 feet north of the Route 76 overpass bridge, north of the gabion wall system. It involved apparent subsidence of the entire paved northbound roadway, with increased subsidence to the east side of the embankment, as shown in Figure 11. No pavement damage or arcuate cracking was observed.

Figure 11: Deformation in shoulder of northbound lanes evidenced by the observed pavement down drop.

Based on the observed pavement distress, retaining wall extents, and possible retaining wall deformation, the site reconnaissance team recommended treating the deformation in the northbound lanes as a separate slope instability. No pavement cracking or deformation extended across the northbound and southbound lanes to tie the two slides together to indicate a global slope instability problem.

The third boring that had been initially planned for the southbound highway shoulder was expected to provide minimal insight to landslide geometry, as previously described. Balancing this observation with the previously unidentified cracking and deformation in the northbound lanes of Route 465, the planned third boring was moved to the shoulder of the northbound lanes to investigate continued deformation of the embankment and roadway supported by the gabion basket retaining walls.

3.3 Subsurface Investigation

Geotechnology, LLC, of St. Louis, Missouri was subcontracted to the borehole drilling equipment and operators. Drilling used a Central Mine Equipment (CME) 550X rubber tire drill rig, which could access borehole locations off the roadway with limited access improvements. Geotechnology retained a local excavating company to construct an access path and work pad for the drill rig to reach LT-1 and LT-2. These access improvements were completed on August 24 and 25, 2020 using a Caterpillar 440 backhoe. Access improvements occurred during drilling work at LT-3, so that Geotechnology and Landslide Technology could provide feedback to the excavator operator without delaying the drilling schedule. All drilling explorations were completed between August 24 and August 29, 2020.

The program consisted of three exploratory borings, as shown on the site plan in Figure 12. Borings LT-1 and LT-2 were located above the southbound lanes. LT-1 was located above the crest of the cut slope, outside of known landslide movement. LT-2 was located roughly halfway up the cut slope, within the body of the main slide mass. These two borings are aligned to enable creation of a cross section of the landslide. Boring LT-3 is located in the shoulder of the northbound lanes, just beyond the edge of pavement but within the area of cracking and pavement deformation. The coordinates of the boring locations, presented in Table 1, were estimated by a field representative from LT using a GPS-capable smartphone and then refined based on later LiDAR surveys.

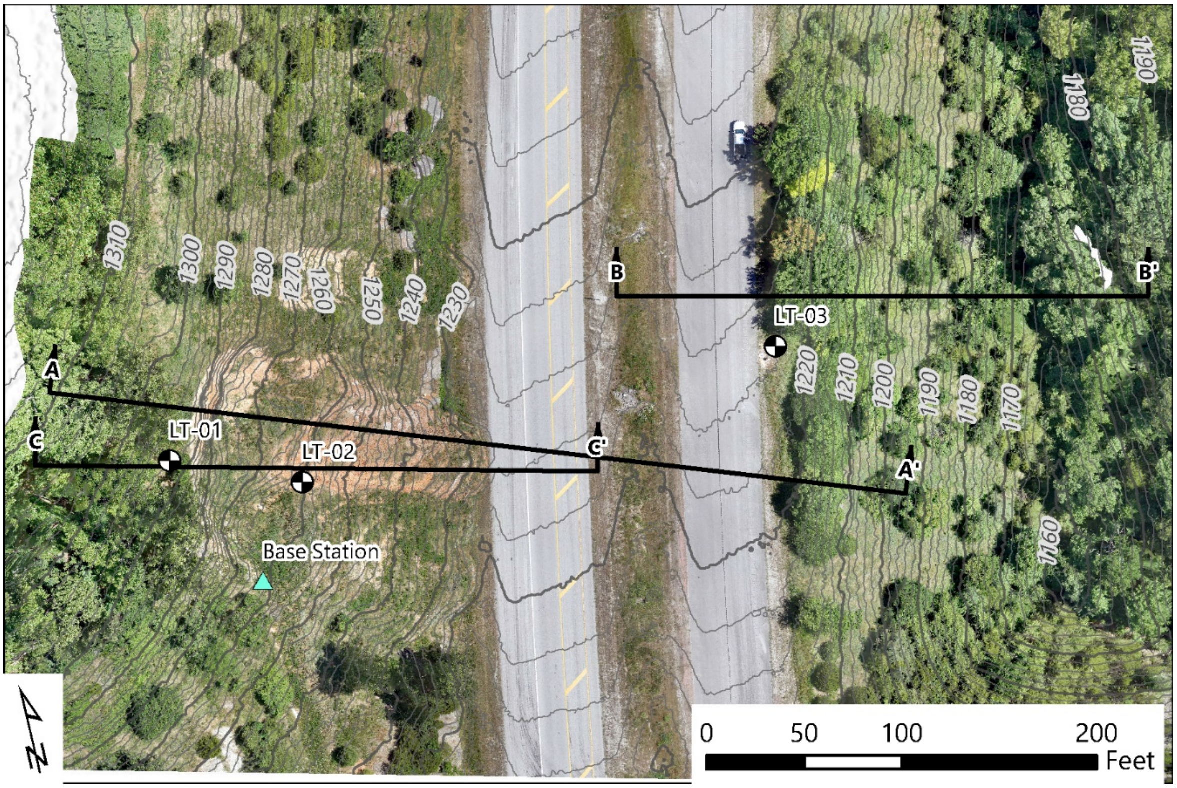


Figure 12: Site Plan showing location of borings and weather station installed at Ozark Mountain Highroad landslide.

The exploratory boring depths ranged from 46 to 55 feet. The borings extended between 12 and 21 feet into rock. This ensures that the slope inclinometer casing was installed in competent rock below any projected slide plane in the soil slopes. Hollow-stem auger methods were used for drilling to the top of rock or refusal. Split spoon samples were typically taken at approximately 5-foot intervals using a calibrated 140-lb hammer dropping 30 inches to perform Standard Penetration Tests (SPT). Once drilling encountered to top of rock, the drill rig switched over to coring with HQ rods and triple-tube coring techniques. All exploratory borings were backfilled with cement-bentonite grout.

Table 1: Summary of Borings at the Branson Landslide Study Area

Boring Name	Northing[1]	Easting[1]	Elevation[2]	Boring Depth
LT-1	307943.4	1400501.0	1290.8	55
LT-2	307917.6	1400564.9	1260.9	46
LT-3	307930.6	1400817.2	1223.5	50.5

Notes:

1. *Boring locations in Missouri State Plane Central*
2. *Elevations estimated from LiDAR survey and boring locations*

Slope inclinometer casing and a vibrating wire piezometer were installed in all three borings. The slope inclinometer casing extended to the bottom of the borehole. The location of the vibrating wire piezometer was determined in the field based on observations made by the field engineer during drilling.

A field engineer from Landslide Technology was present throughout the field explorations to collect and log the recovered soil and rock samples, prepare a descriptive field log of the subsurface conditions encountered by the drilling, and to document the instrument installation project. Landslide Technology's field representative also coordinated backfilling and clean-up efforts at each boring with the driller.

A summary log of the subsurface conditions encountered in each boring is shown on Summary Boring Logs, Figures A2 through A4 in Appendix A. The Summary Boring Logs describe the drilling methods, materials encountered, depths and types of samples, a plot of SPT blow counts, interpreted geologic layer thicknesses, and a plot of natural water contents of collected samples. The elevations on the Summary Boring Logs were obtained from the LiDAR data collected in the 2010 aerial LiDAR survey.

3.3.1 Boring LT-1

LT-1 is located in a bench above the cut slope. Based on review of the pre-construction topography, grading impacts in this area were minimal. Drilling progress through roughly 34 feet of stiff red clay (CH) with scattered limestone rock fragments before encountering limestone bedrock. Within the bedrock, a zone of stiff red clay was encountered from roughly 41.5 and 43.6 below the ground surface and interpreted as a dissolution and infilling feature.

3.3.2 Boring LT-2

LT-2 is located in the slide mass, roughly halfway up the cut slope. The boring extended through soft red clay with gravel-sized angular limestone fragments to a depth of approximately 9.5 feet below the ground surface, before transitioning to a very stiff red clay (CH). Soil stiffness dropped to medium stiff between roughly 24 feet below the ground surface and the top of rock at 32.5 feet below the ground surface. Once bedrock was encountered, the boring was extended through the limestone bedrock to a final drilled depth of 46 feet.

3.3.3 Boring LT-3

LT-3 is located off the paved shoulder on the eastern side of the northbound lanes, within the area of pavement cracking and deformation associated with the gabion wall system. This boring extended through embankment fill before encountering native soil roughly 27 feet below the ground surface. This was very close to where we expected to encounter the fill/native soil transition based on pre-construction topography in the construction plan set. Both the embankment fill and native soil were composed of a medium stiff to stiff red clay (CH). Limestone bedrock was encountered at 38 feet below the ground surface and dolomite bedrock was encountered at 40.5 feet below the ground surface.

3.4 Groundwater Conditions

During the May site visit the clay in the landslide mass was so soft that walking across the slide mass was difficult. By late August, the landslide mass had dried out, and the surface soils were very hard and difficult to excavate. Soils encountered during drilling were dry with water content increasing with depth, and no standing water developed in boreholes left open overnight.

3.5 Site Geology

Broadly speaking, the soils on site consist of a clay colluvium overlying limestone and dolomite bedrocks. The embankment fill appears to have used the adjacent cut slope for borrow, because the native clay colluvium and the embankment fill are nearly identical in composition. Referring to the regional geologic map, the limestone encountered on site was interpreted to be part of the Kinderhookian Series, while the dolomite was interpreted as being part of the Cotter Dolomite. The contact between the two units was at a lower elevation than expected from the regional geologic map. Contact between the rock units did not appear to correlate with landslide location or activity.

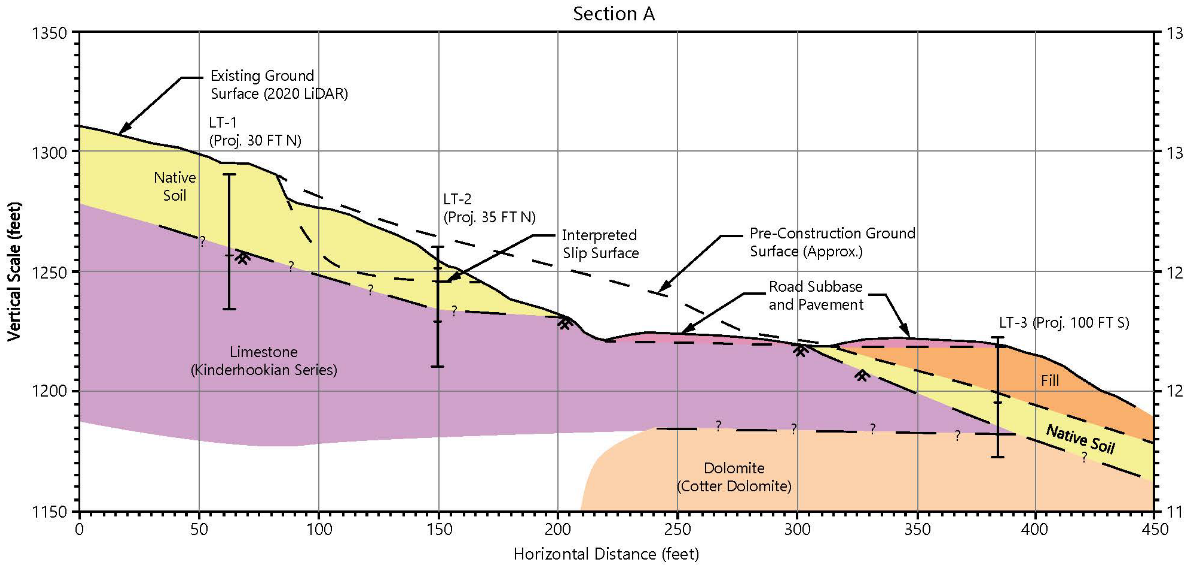


Figure 13: Geologic cross section through body of main slide showing cut-fill construction for this portion of the Ozark Mountain Highroad.

4 LABORATORY TESTING

Laboratory testing was performed to determine soil index and engineering properties of landslide and shear zone materials. Testing was performed at Landslide Technology's soil laboratory in Portland, Oregon in general accordance with ASTM laboratory testing methods. Tests were performed on select samples collected during field explorations to verify field classification and determine the following:

- Soil classification
- Natural moisture content
- Atterberg limits
- Torsional Ring Shear (Residual Shear Strength)

Soil samples obtained from the field exploration program were visually re-examined in the laboratory to refine field classifications. Results of additional laboratory testing, final soil descriptions and classification are presented on the Summary Boring Logs, Figures A2 to A4 in Appendix A.

4.1 Natural Moisture Content

All soil samples collected from the borings were tested to determine their natural moisture contents in general accordance with ASTM D2216-10. The results of these tests are plotted graphically on the Summary Boring Logs, Figures A2 to A4 in Appendix A.

4.2 Atterberg Limit

Liquid and plastic limits (Atterberg limits) were determined for selected soil samples collected during the field investigations. Both samples were from the cut-slope soils. Test procedures were in general accordance with ASTM D4318-10. Results of this testing are summarized in Table 2 below and plotted graphically on the Plasticity Chart, Figure 14. Natural moisture contents determined from field samples during drilling was at or near the plastic limit.

Table 2: Summary of Atterberg Limit tests performed on selected soil samples from the Rout 465 Landslide Investigation

Boring No.	Sample No.	Depth (ft)	Natural Moisture (%)	LL (%)	PL (%)	PI (%)	Atterberg Limit Classification
LT-1	S-6	28.5-30	20	79	20	59	CH
LT-2	S-2	9.5-11	34	81	29	52	CH

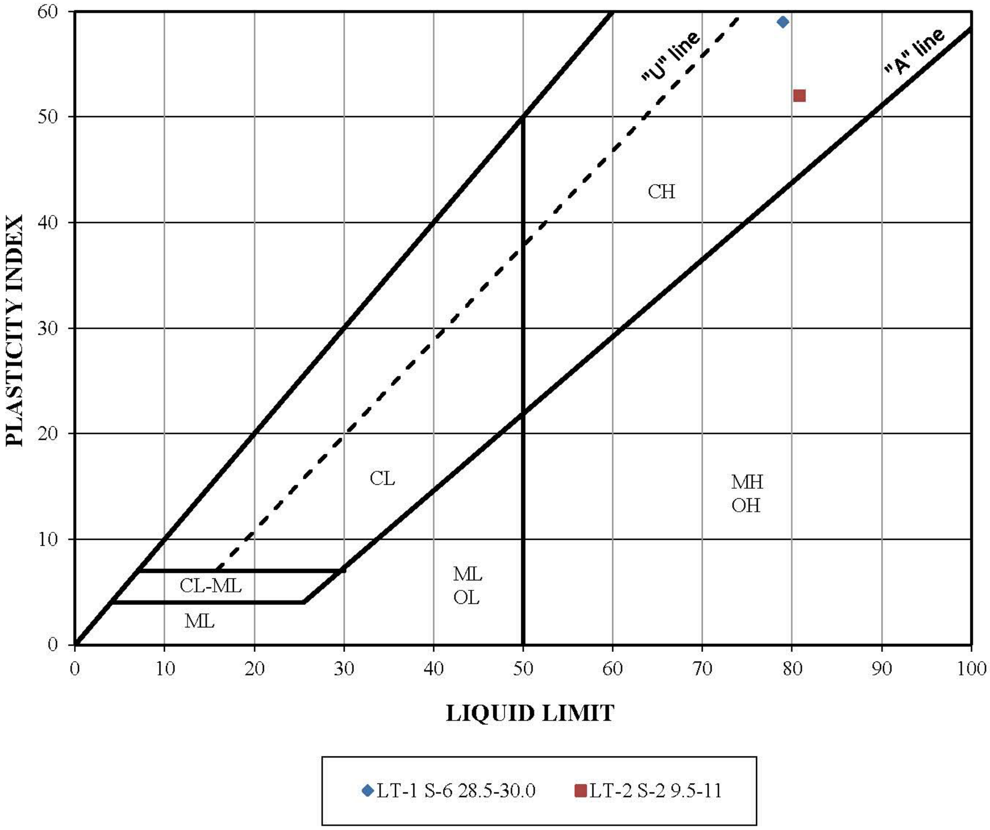


Figure 14: Plot of Atterberg Limit results for selected native soil samples.

Like the moisture contents described in the previous section, the results of these tests are also plotted graphically on the Summary Boring Logs, Figures A2 to A4 in Appendix A.

4.3 Ring Shear Test

A torsional ring shear strength test was conducted on sample S-2 from LT-2. This sample of red fat clay (CH) was collected between 9.5 and 11 feet below the ground surface, at the base of the observed slide movement. The test was performed in accordance with ASTM D 6467 standard testing procedure to determine the residual strength of the landslide shear zone materials. The soil was selected from sampled material and remolded into the ring-shear apparatus.

Ring shear testing of LT-2, S-2, was conducted at consolidation normal pressures of approximately 6,200, and 12,340 pounds per square foot (psf). Following consolidation, the sample was pre-sheared at a rate of 0.088 inches/minute (in/min) at a normal stress of 12,340 psf for approximately 7 minutes. Following pre-shear, the displacement rate was reduced to 0.0007 in/min (1 inch/day) and allowed to run until reaching residual shear strength at each consolidation pressure. Residual shear strength tests indicate an effective residual angle of internal friction (ϕ'_r) of 7.2°.

Plotted ring shear testing results are presented in Figure 15 below.

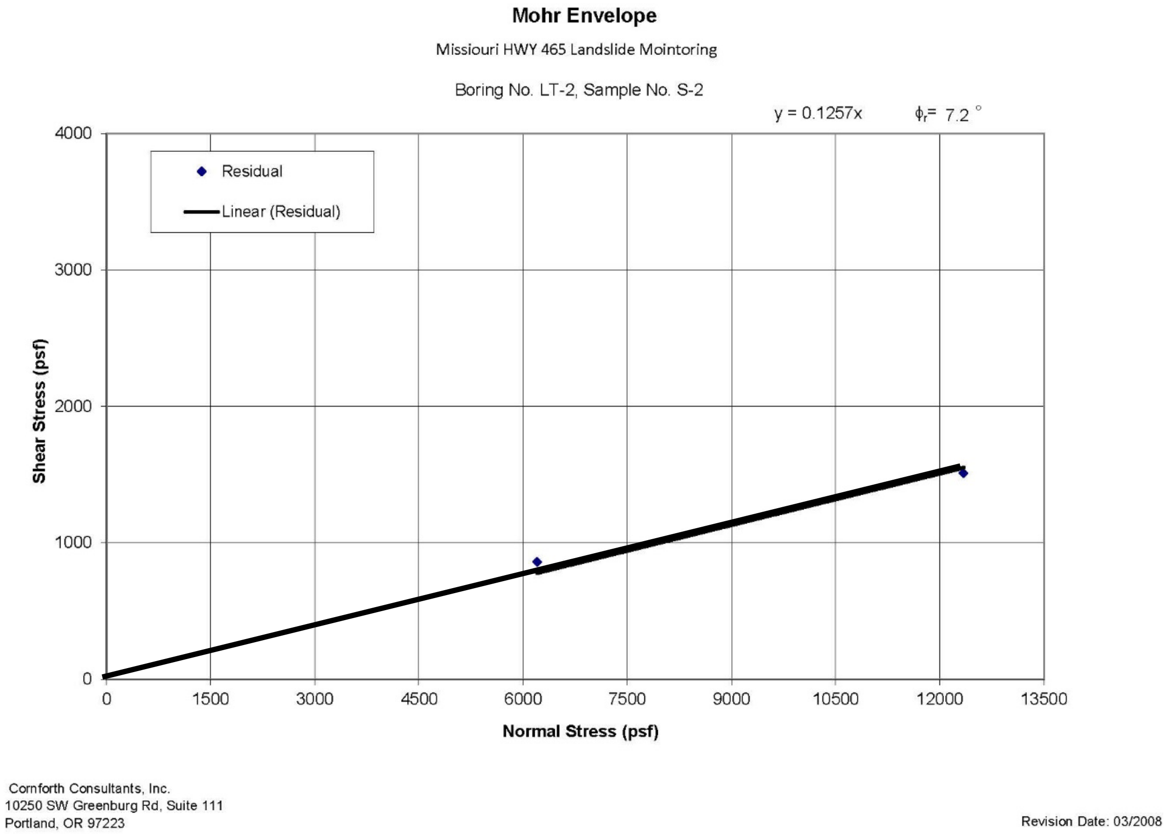


Figure 15: Plot showing the results of ring-shear testing on a sample of clay from LT-2, near the zone of maximum observed deformation.

5 INSTRUMENTATION AND MONITORING EQUIPMENT

5.1 Site Instrumentation

5.1.1 Slope Inclinometers

Slope Indicator inclinometer casing measuring 2.75 inches in diameter was installed in all three borings, so that manual readings of subsurface deformation could be conducted over the course of the research project. Casing was installed to within six inches of the bottom of each boring. Top and bottom reading depths and the azimuth of the A0 measurement groove are summarized in Table 3 below. Photos of the three inclinometers are assembled in Figure 16.

Table 3: Summary of slope inclinometers installed in the Branson Landslide Study Area

Boring Name	Top Depth[1] (ft)	Bottom Depth[1] (ft)	Casing Stickup (ft)	Reading Interval (ft)	A0 Azimuth	Monument Type
LT-1	2	56	3.0	2	102	Above-ground
LT-2	2	46	3.0	2	102	Above-ground
LT-3	2	48	1.0	2	106	Flush-mount

Notes:

1. *All depths measured from top of slope inclinometer casing.*

Figure 16: SI Monuments at Branson Landslide. Clockwise from top left: LT-1 above-ground monument, LT-1 open showing inclinometer pipe, LT-2 above-ground monument, and LT-3 flush mount.

5.1.2 *Vibrating Wire Piezometers*

A GEOKON 4500S vibrating wire piezometer is installed in each boring, attached to inclinometer casing's exterior during installation. Piezometer depth was determined in the field after drilling was completed, based on where the field engineer suspected slide movement would be most likely, or where groundwater movement might be concentrated by a change in soil permeability. Piezometer depths and targeted zones are summarized in Table 4 and the constants used in reducing the data are summarized in Table 5. Copies of the instrument calibration sheets are also provided in Appendix A.

Table 4: Summary of vibrating wire piezometers installed in the Branson Landslide Study Area

Boring Name	Piezometer Serial No.	Depth below ground surface[1]	Elevation[2] (ft)	Zone of Interest
LT-1	2028925	32	1258.8	Soil/rock contact in natural slope above the slide area
LT-2	2028927	29.1	1231.8	Potential slide plane in weaker zone of native soil
LT-3	2028926	27	1196.5	Fill/Native soil contact

Notes:

1. *All depths measured from ground surface at time of instruction installation.*
2. *Elevations calculated from the estimated ground surface elevations from LiDAR survey and boring locations and the measured installation depth*

Table 5: Constants used in reducing vibrating wire piezometer data in the Branson Landslide Study Area

Boring Name	Piezometer Serial No.	R_0[1]	T_0[1]	G[2]	K[2]	A[2]	B[2]	C[3]
LT-1	2028925	9076.043	25.5	-0.01647	-0.01289	-1.509E-08	-0.01624	148.638
LT-2	2028927	9000.561	24.4	-0.01583	-0.01086	1.399E-09	-0.01585	142.546
LT-3	2028926	9030.789	26.3	-0.01573	-0.01293	2.029E-09	-0.01576	142.160

Notes:

1. *Zero reading collected immediately prior to installation in the boring.*
2. *Constants are for psi/digit*
3. *Calculated using polynomial equation and field zero readings*

5.1.3 *In Place Inclinometers*

After collecting manual slope inclinometer readings from September 2020 to April 2021, the research team installed an in-place inclinometer (IPI) in LT-3 on June 25, 2021. The IPI is a Model

6300-1 uniaxial in-place inclinometer produced by GEOKON. A schematic of an IPI is shown in Figure 17 below (Geokon, 2019). The instrument uses a tilt sensor to measure precise inclination of the instrument assembly within the SI casing, and when combined with the known gage length, this returns a net displacement over the shear zone from the date of IPI installation. Because it connects to a vibrating wire datalogger, tilt data can be collected at any time interval the datalogger will support. Instead of the weeks that typically pass between manual readings, the datalogger at Branson was programmed to collect data from the IPI at 10-minute intervals. This supported identification of triggering events and long-term slide behavior.

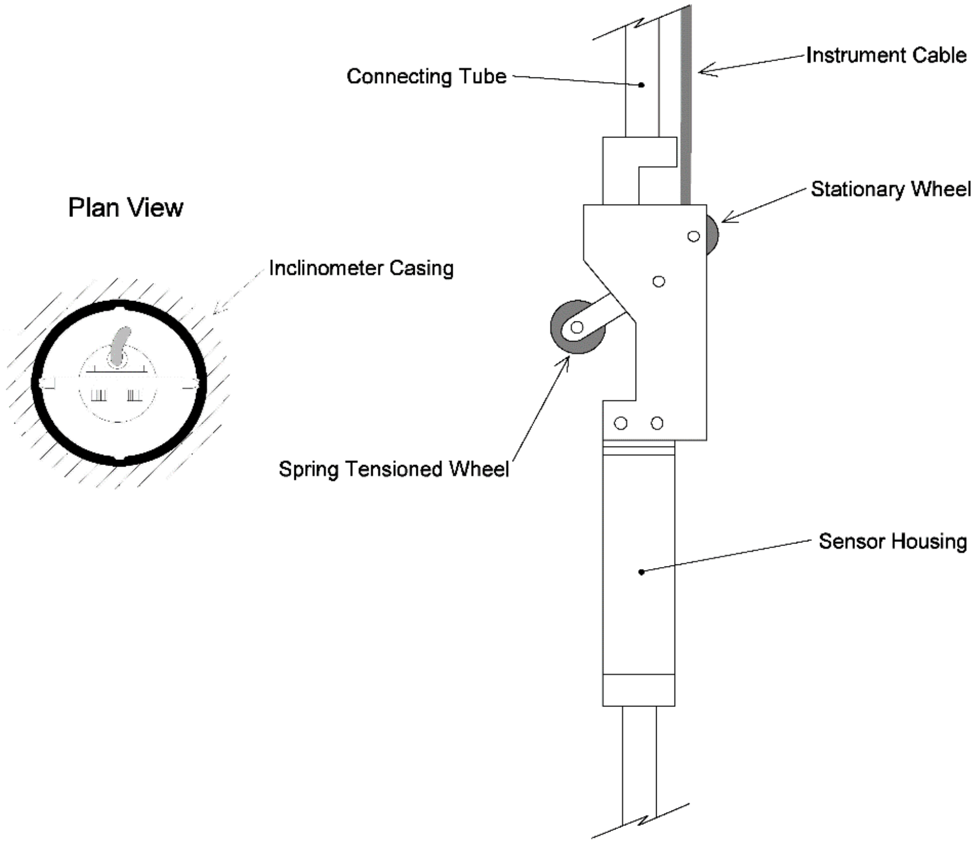


Figure 17: Schematic of GEOKON Modal 6300-1 In-Place Inclinometer (Courtesy of GEOKON).

The IPI was originally slated for installation in the cut-slope landslide, LT-2, but the combination of shallow movement over a broad zone of deformation made IPI installation ineffective with the constraints of the research project budget. Determination of this monitoring depth and calculated total displacement is described in greater detail in Section 6.7. Once installed, the tilt sensor data was processed using the linear equation on the IPI calibration sheet from GEOKON, included in Appendix A. Instrument constants, gauge length, and installation depth are summarized in Table 6 below.

Table 6: Constants used in reducing data from in-place inclinometer installed in LT-3

Serial Number	Gauge Length (ft)	Top Depth[1] (ft)	Bottom Depth[1] (ft)	R0	T0	G
2110115	5	20	25	7800.8828	15.9	0.002312

Notes:

1. *All depths measured from top of slope inclinometer casing.*

5.1.4 Weather Station

Seasonal landslide movement typically correlates with precipitation and seasonal groundwater level fluctuations. The vibrating wire inclinometers collected groundwater data, but a weather station was required to collect precipitation data on site. The research team installed a ClimaVUE50 weather sensor, photos of which are shown in Figure 18 below. The station measures rainfall using a drip counter. Water collected in the funnel at the top of the weather sensor is released in drops of a known size, which generate an electrical pulse between a pair of pins as they exit the funnel. Although rainfall data was the primary data of interest for the research team, the weather station also collects temperature, relative humidity, solar radiation, and wind speed and directional data.

Figure 18: Pair of photos showing weather station as installed at base station (left) and a close up of the weather station and sensor (right).

Because the rain funnel must be level to work properly, the weather station also includes a tilt sensor. The weather station was installed at the southern edge of the known landslide. The tilt sensor was used as an additional proxy for landslide movement. Increased tilt of the weather station would have indicated that the landslide movement was expanding to the south and that ground deformation was causing the pole supporting the weather station to tilt out of alignment.

5.2 Automated Data Collection Equipment

5.2.1 Dataloggers

Two types of dataloggers are installed at the site, both manufactured by Campbell Scientific, Inc. (CSI) of Logan, Utah. Both of the programmable dataloggers query the sensors, log and process raw data, tabulate and store raw data and engineering units, and manage site and remote communications. The dataloggers and components are described below. A list of all the instrumentation and system components installed at the Ozark Mountain Highroad are compiled in Appendix B.

Base Station. The base station is built around CSI's CR6 datalogger with a built-in RF407 0.25W 900mHz radio to facilitate site communications. A Sierra Wireless Raven RV50 cellular gateway modem is connected to the CR6 via a short network cable for remote data collection. The modem's cellular connection was provisioned by CSI's subscription service with Verizon cellular service. The vibrating wire piezometers from LT-1 and LT-2 are connected directly to the CR6. The ClimaVUE50 weather station connected to the CR6. The CR6's solar controller manages the 20W 12V solar panel and 50ampHr battery. The modem's power was shut down via programming instructions at night to manage excess power drawdown while the site radio was always powered on. The site never lost power over the monitoring period with these power controls implemented. The code currently managing data collection and processing at the CR6 logger is included as Appendix C.

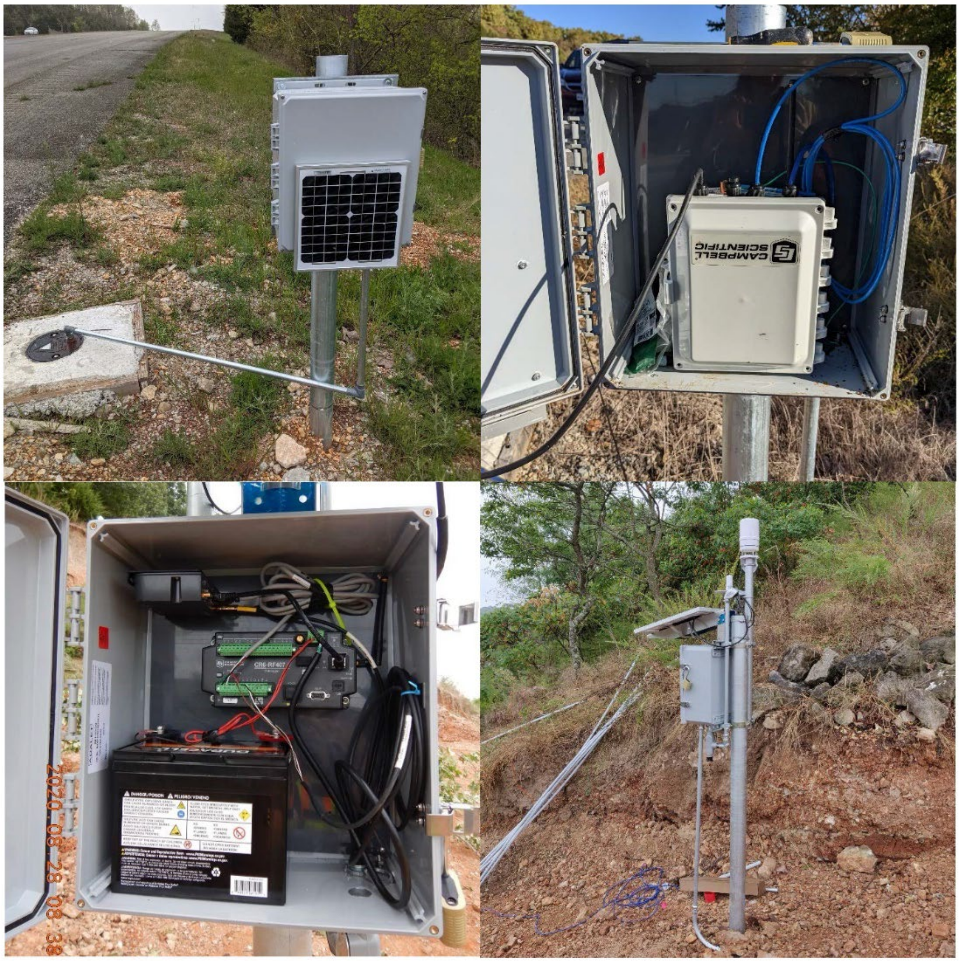


Figure 19: Clockwise from left: weatherproof box and solar panel at LT-3; enclosure with a CRVW3-407 datalogger at LT-3; weather station, solar panel, and weatherproof box at base station; and interior of base station with CR6 logger, peripherals, and rechargeable battery.

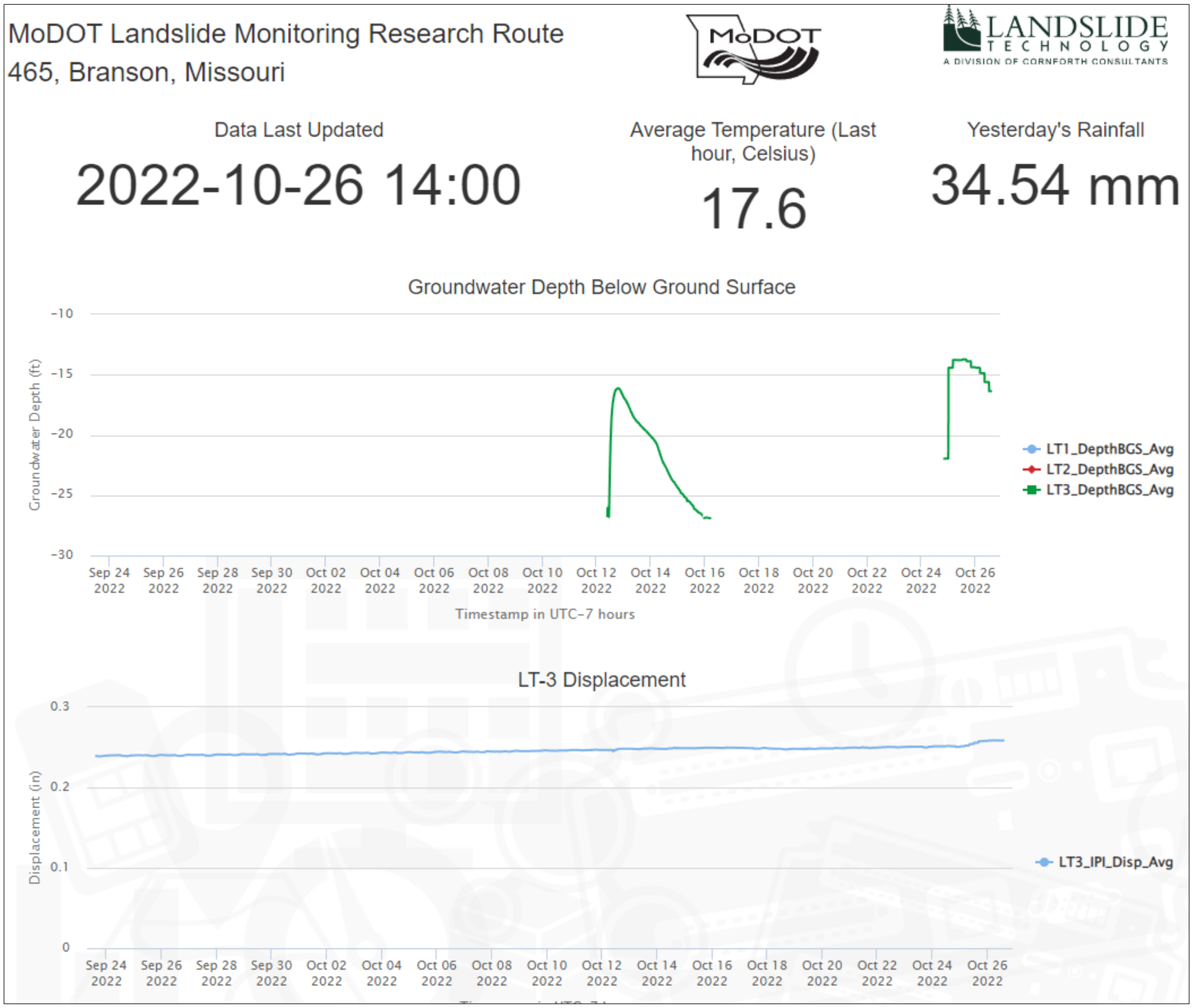
LT-3 Datalogger. LT-3 was installed across the divided highway to monitor landslide movement and porewater pressures. Site constraints prohibited the direct wiring of the VWP and IPI to the base station logger. Communications between LT-3 and the base station were facilitated by the 0.25W RF407 900mhz radios integrated into each datalogger. The LT-3 datalogger only needed to read two vibrating wire sensors, thus a simpler datalogging solution was permitted. CSI's CRVW3-RF407 three-channel datalogger built for vibrating wire sensors with an integrated 7 ampHr battery monitors the sensors and communicates with the base station. The 10W 12V solar panel is connected to the datalogger's solar controller. The vertically mounted solar panel sheds snow and therefore did not lose power during the monitoring period despite the radio always being on with a frequent reading interval.

5.3 Initiation of Real-Time Monitoring

5.3.1 Konect GDS System

Landslide Technology contracted with CSI's Konect GDS service for both cellular provisioning and data presentation. The cellular network utilized by Konect GDS for this site was Verizon. The

SIM card was provided by CSI and installed in the Sierra Wireless RV50 modem installed at the base station. A data management platform and website (Figure 20) was configured to obtain data on a daily basis and present plots of groundwater level and sensor temperatures, IPI displacement, and weather station values. The website is available at the time of writing, but communications were discontinued remotely October 26, 2022. No new data is being uploaded to the website, although the data loggers are continuing to collect and store data.



MoDOT Landslide Monitoring Research Route 465, Branson, Missouri

Data Last Updated
2022-10-26 14:00

Average Temperature (Last hour, Celsius)
17.6

Yesterday's Rainfall
34.54 mm

Figure 20: Konect GDS Data Management Website.

The website plotted the following site variables generally over a 4-week timespan:

- Groundwater depth below ground surface,
- IPI displacement in LT-3,
- Groundwater temperature at the sensor depth,
- Hourly & daily rainfall,
- Hourly air temperature and relative humidity,
- Solar radiation,
- Wind speed, direction, and 24-hour history,

- Battery charge and station temperatures at both loggers, and
- Tilt of the weather station.

5.3.2 Other Connection Options

Real time monitoring can be performed with multiple types of configurations. To display data using the Konect GDS website used in this research project, the only requirement is that the logger connects to the website using a static naming convention. This static naming convention is either an IP address or a domain from a data service. Both Verizon and AT&T provide data services that can be used to connect a logger to a Konect GDS website or to interface with the logger directly from the office. Selecting which commercial carrier to use depends primarily on which company provides better cellular coverage in the project area.

Konect GDS relies on either Verizon or AT&T cellular service, both of which rely on cellular coverage being available at the project site, or at least at the location of the modem station. If cellular coverage is not available, a satellite modem can also be used. As cellular coverage has improved nationwide, use of satellite modems has become less common, but may still be the only option on some remote sites.

6 LONG-TERM MONITORING OF BRANSON CUT SLOPE LANDSLIDE

Long-term monitoring of the two slides used the instrumentation and monitoring equipment described above, as well LiDAR data collected annually via unmanned aerial vehicle (UAV). The monitoring results are summarized in the following subsections. The effectiveness of the different types of monitoring and potential considerations when developing a monitoring program are discussed in Section 8. All subsurface monitoring equipment installed at the Ozark Mountain Highroad remains in place. MoDOT has expressed interest in continuing to maintain and monitor that equipment, and a quick guide for that work has been compiled and included in Appendix D.

6.1 LiDAR Data Collection

LiDAR collection from unmanned aerial vehicles (UAVs) has become increasingly affordable over the last decade, as high precision laser scanners have become less costly and light enough to be carried by UAVs. Using multiple low elevation passes, UAV-mounted LiDAR units can produce high-density point clouds with sufficient data penetrating vegetation to produce bare earth elevation models and detect small scale movements on vegetated slopes, such as the one in the Ozark Mountain Highroad cut slope. Photos can also be collected during these passes and later tied together to produce an orthophoto or a structure-from-motion digital surface model. The orthophoto provides high-resolution color imagery that can provide additional information on material types exposed in the project area and they may also help end users orient themselves in the project area. Digital surface models produced using photogrammetric methods can be useful datasets for some applications, but they are not capable of seeing through the vegetation, making them a less desirable alternative to LiDAR for this study.

6.1.1 Quantifying Previous Surface Deformation

As previously discussed in Section 3.1, Landslide Technology evaluated the publicly available 2010 bare earth LiDAR data that covered the project site, shown in Figure 5. Although the lower point density limits the use of airborne LiDAR in detecting minor movement common in creeping landslides, the 2010 LiDAR data provided a ground surface that could be used for approximate comparison with the UAV LiDAR dataset collected by our subcontractor, ROCK Robotic (formerly Aerial Insights), on June 4, 2020. The comparison between these two data sets is shown in Figure 21. Because the two surveys are separated by about a decade, slope activity was apparent despite the low resolution of the 2010 survey.

The change detection analysis shown in Figure 21, confirmed that Landslide Technology had sited borings LT-1 and LT-2 along the approximate center axis of the most active portion of the landslide. In the 1-foot contour intervals shown in the change detection map, green is areas of material loss at the head of the slides, while red shows areas of material deposition at the slide toes. The limited change in elevation in the main body of the slide, between the landslide head and toe, indicated that the main slide mass in this zone is moving parallel to the cut slope, with displaced material being deposited in the ditch. The cross-section comparison also shows the loss of ditch capacity since 2010, as the toe of the slide has deposited material in the ditch. The cross section also shows how much more fine resolution is available in the 2020 UAV survey, which has a more textured ground surface that the 2010 ground line.

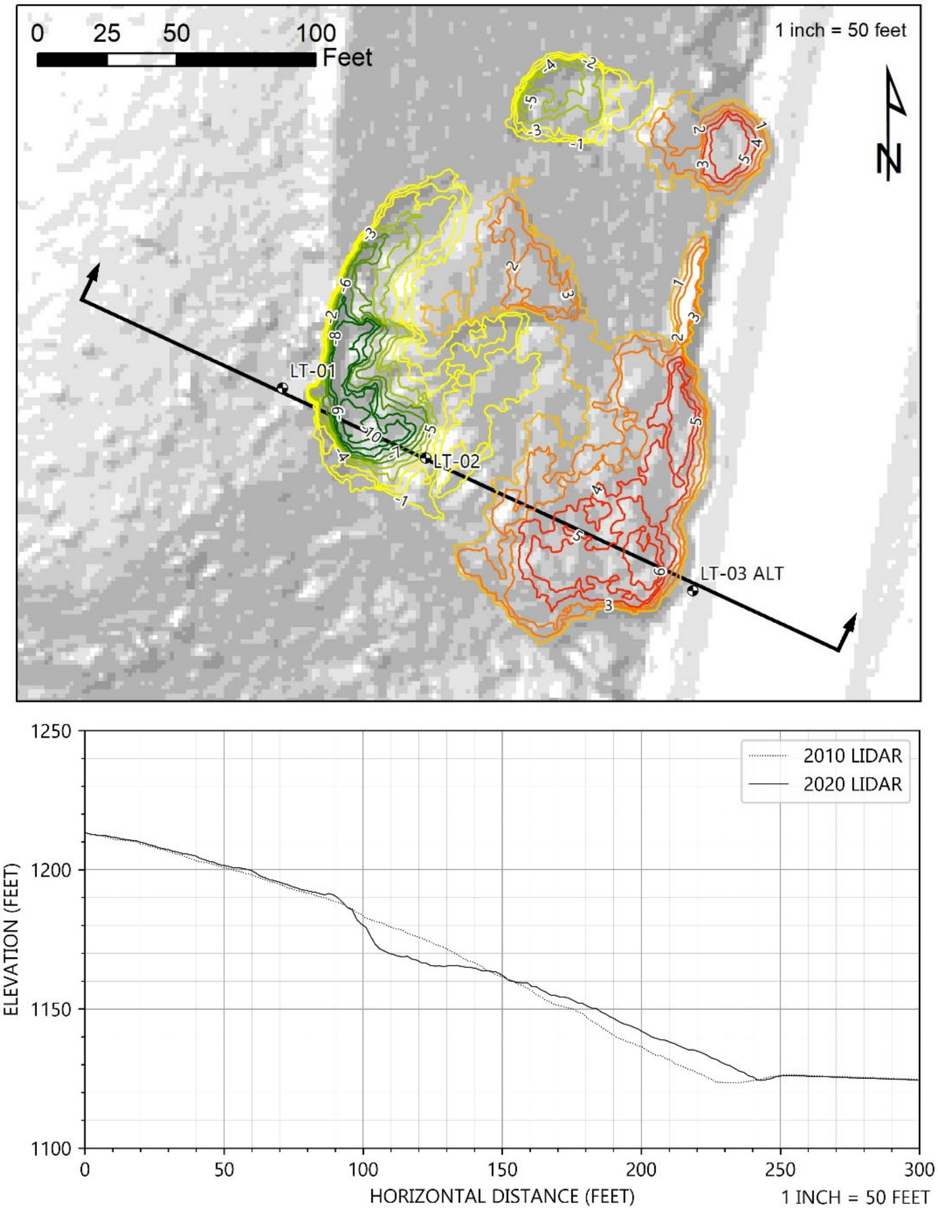


Figure 21: Comparison of 2010 Stone County LiDAR data with this project's initial dataset collected in June 2020. Contour intervals are 1-foot, with green indicating a decrease in surface elevation and red indicating an increase in surface elevation.

6.1.2 Research Project Monitoring

Over the course of the Ozark Mountain Highroad research project, annual drone-based surveys were performed by ROCK Robotic three times: June 2020, April 2021, and June 2022. All three surveys used a UAV to collect lidar and photographic data. ROCK Robotic provided Landslide Technology with classified, georeferenced lidar point clouds and georeferenced orthophotos constructed by assembling numerous individual high-resolution photos. Classified lidar point clouds include point data that has been labeled as ground surface, vegetation, or one of several other classes, which allows for the ground surface beneath vegetation to be filtered away, producing a bare-earth model that shows only topography.

Survey grade ground control was not used for the LiDAR surveys, which saved on survey costs, but increased post-processing requirements. The three lidar point clouds had imperfect horizontal and vertical alignment. When compared to the 2010 airborne lidar dataset for Stone County and existing USGS topographic maps, the elevations of the drone datasets were between 80 and 94 feet lower than reality. Because the airborne lidar dataset elevations matched USGS topographic maps, Landslide Technology aligned each of the three ROCK Robotic datasets to the 2010 dataset to correct their elevations. Alignment was performed using iterative closest point (ICP) registration in the open-source software application Cloud Compare (https://www.cloudcompare.org/). Starting with 2020, which was registered to the 2010 data, each dataset was registered to the prior dataset. Alignment was verified by comparing cross sections of the aligned datasets. In some cases, multiple ICP alignments were performed. After registration, each dataset was converted into a raster digital elevation model with a 1-foot grid size using the Rasterize tool in Cloud Compare.

Once aligned and converted into raster digital elevation models, the data was ready for use in ArcGIS, which has tools that support multiple types of data comparison. Lidar datasets from 2020 to 2022 were compared by performing elevation differencing, which is where the earlier dataset's elevations are subtracted from the later dataset's elevations. The resulting product is a raster with values representing the vertical difference between the two datasets. Differences near zero generally indicated no change. Positive differences generally indicate accumulation or deposition, and negative changes generally indicate erosion or subsidence. Changes detected during the three LiDAR passes are visually summarized in Figure 22 below. The June 2022 topography is the base hillshade for all four figures. Figure 22 illustrates a project site map with contour intervals in the upper left, and the remaining maps show year-to-year change and total change detected over the course of the project. Red indicated areas where the ground elevation has decreased as displacement lowers the ground surface, and green indicates area of increased ground surface elevation, or material deposition. Translational ground movement that does not change the ground surface elevation is not strongly detected, though small ground shape changes are discernible in this dataset.

The net masses of calculated material loss and displacement are summarized in Table 7 below. These volumes are calculated by computing the change in surface elevation between the June 2020 and June 2022 surveys. The overall mobilized mass of the slides is expected to be larger, because the slide mass includes all material above the slip plane, while the calculated mass displacement in 2022 only includes material above or below the 2020 ground surface. The volume estimates are influenced by how the analysis areas are selected, and by noise within the data sets. For this project site, they are estimated to be within 10% of total volume change between the two datasets. Based on available data, the net gain in material at the North Slide is interpreted as swelling of the native cut slope material as it deformed and moved downhill. This material expansion effect was not observed at the main slide. After examining the LiDAR surveys, Landslide Technology noted that the toe of the main slide is closer to the edge of pavement than the toe of the north slide. A composite cross section from the LiDAR surveys along Section A-A' (Figure 23) shows the toe of the slide at the edge of the shoulder. The research team suspects that MoDOT maintenance crews have removed or reworked minor amounts of material at the toe of the main slide to maintain ditch capacity, and that this has impacted the calculated volume of material deposited within the slide area. No significant amount of material appears to have been removed from the study area over the course of the project. The access improvements for drilling also noticeably shifted material around the slide area. The access path and drill pad are clearly visible in the 2022 hillshade.

Table 7: Summary of estimated mass displacement in the cut slope landslides between June 2020 and June 2022.

Area	Volume Loss (cubic yards)	Volume Gain (cubic yards)
Main	-515	425
North Slide (minor)	-20	30
Drilling Access Path	-50	50

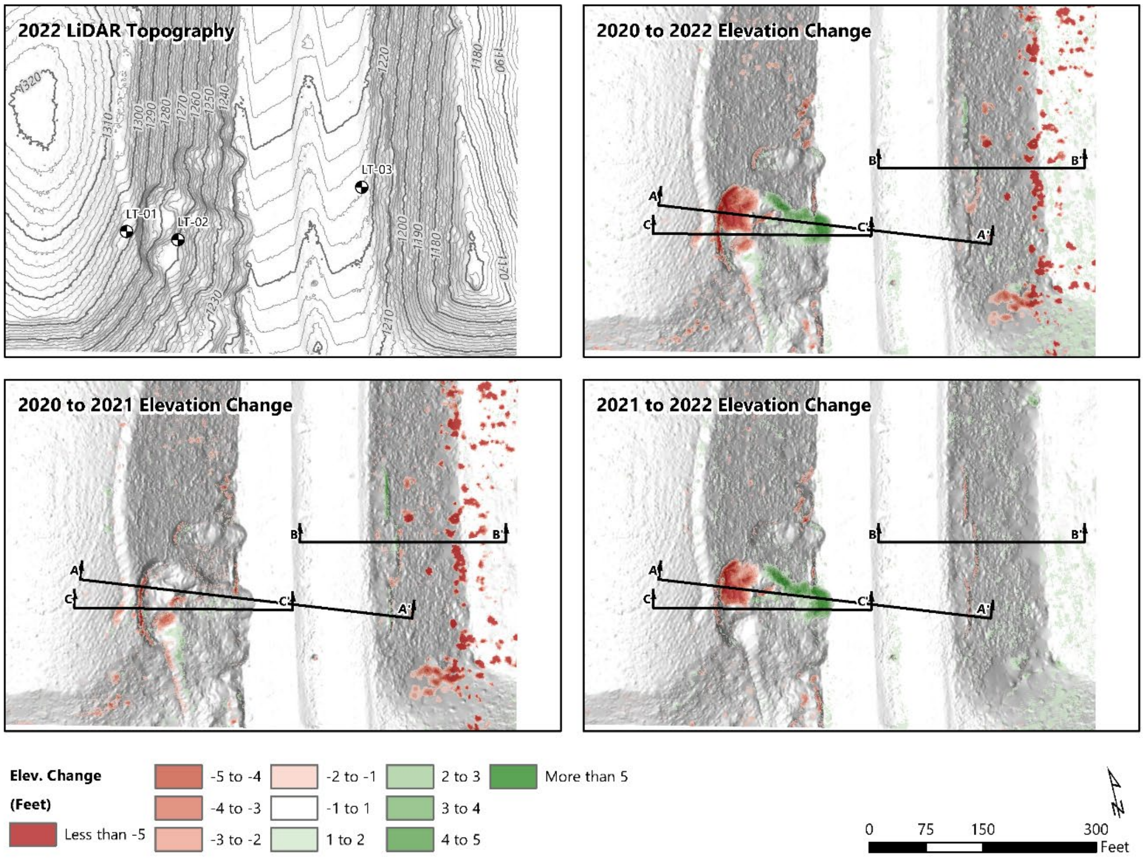


Figure 22: Change detection over the monitoring period using the three high-resolution LiDAR data sets. Red dots visible in the 2020 to 2021 and 2020 to 2022 images are caused by vegetation that was not removed from the 2020 dataset.

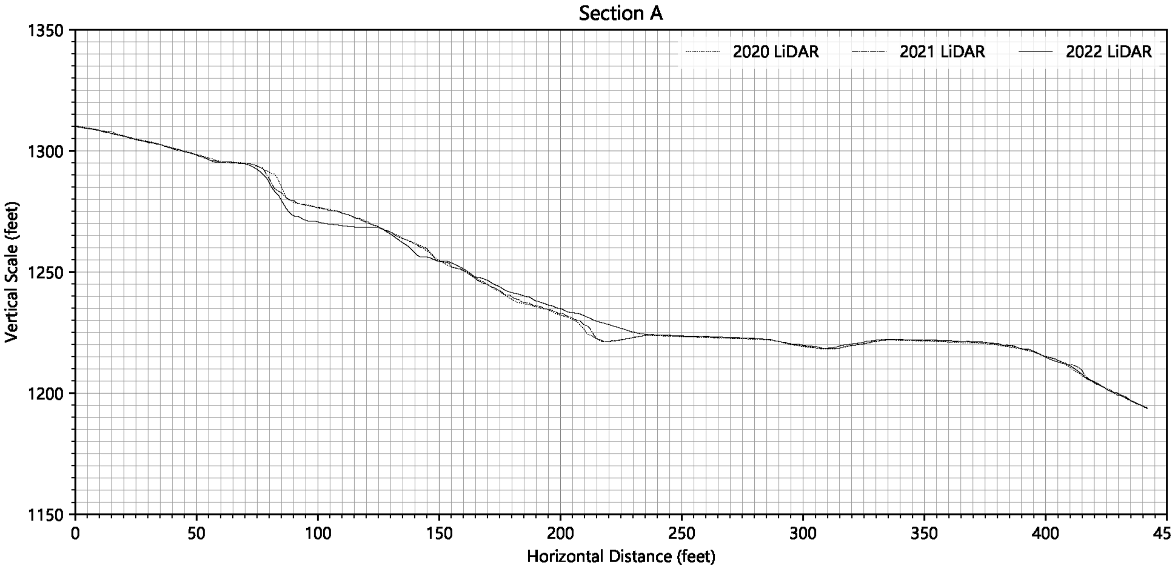


Figure 23: Cross section A-A' showing ground surfaces from 2020, 2021, and 2022 LiDAR surveys. Note encroachment of landslide deposits onto the edge of roadway.

Comparison of the three annual datasets aligns with other data recorded by subsurface monitoring instruments and the weather station. There was significant movement in May 2020, before the first LiDAR flight in June 2020. No appreciable movement was collected between June 2020 and April 2021, but movement was detected in June 2022. This supports the seasonal nature of the slide, with most deformation occurring in late spring and early summer. No movement was observed in the embankment slide under the northbound lanes, although, as described in Section 6.4, the IPI recorded subsurface movement during this period. Based on the LiDAR data, construction of the access path and drill pad also appears to have stabilized the southern portion of the main slide by removing mass from the scarp, with movement now concentrated on the northern portion of the slide. However, as described in Section 6.4, subsurface movement was measured in the slope inclinometer installed in the drill pad that may not yet be expressed at the ground surface. Also, since activation in May 2020, the minor slide north of the main slide does not appear to have continued to move discernably.

Reviewing the collected data, surface deformation of roughly one foot is necessary to confidently detect slide movement. This is especially true if surveys are collected at different times of year, since fast growing vegetation can have a significant impact on quality of the bare earth dataset, thick grass, in particular, is very difficult to penetrate with LiDAR and develop a true bare-earth surface. Likewise, choices made when processing one data set may not be apparent until future comparisons with new sets. For example, the points of red “material loss” at the base of the embankment when comparing the 2021 to 2020 correspond with tree trunks that were not removed from the 2020 data set during post-processing.

6.2 Precipitation Monitoring

The weather station and pore water pressures from the vibrating wire piezometers were both collected through the modem connection at the base station. Data collection started September 1, 2020, after the subsurface instrumentation had been installed. Water years, or cumulative precipitation over a twelve-month period starting on October 1, is a standard approach to compare how similar precipitation was over the research period. Figure 24 below shows the two water years recorded at the project site. Precipitation data for the 2019-2020 water year, collected by the Army Corps of Engineers at Table Rock Dam, is also included. Table Rock Dam is located roughly 5.5 miles south of the project site and demonstrates how much more rainfall there was in spring of 2020, the last period of major slide development on the cut slope. By contrast, precipitation in the two years after subsurface instrumentation was installed was 10 to 12 inches less.

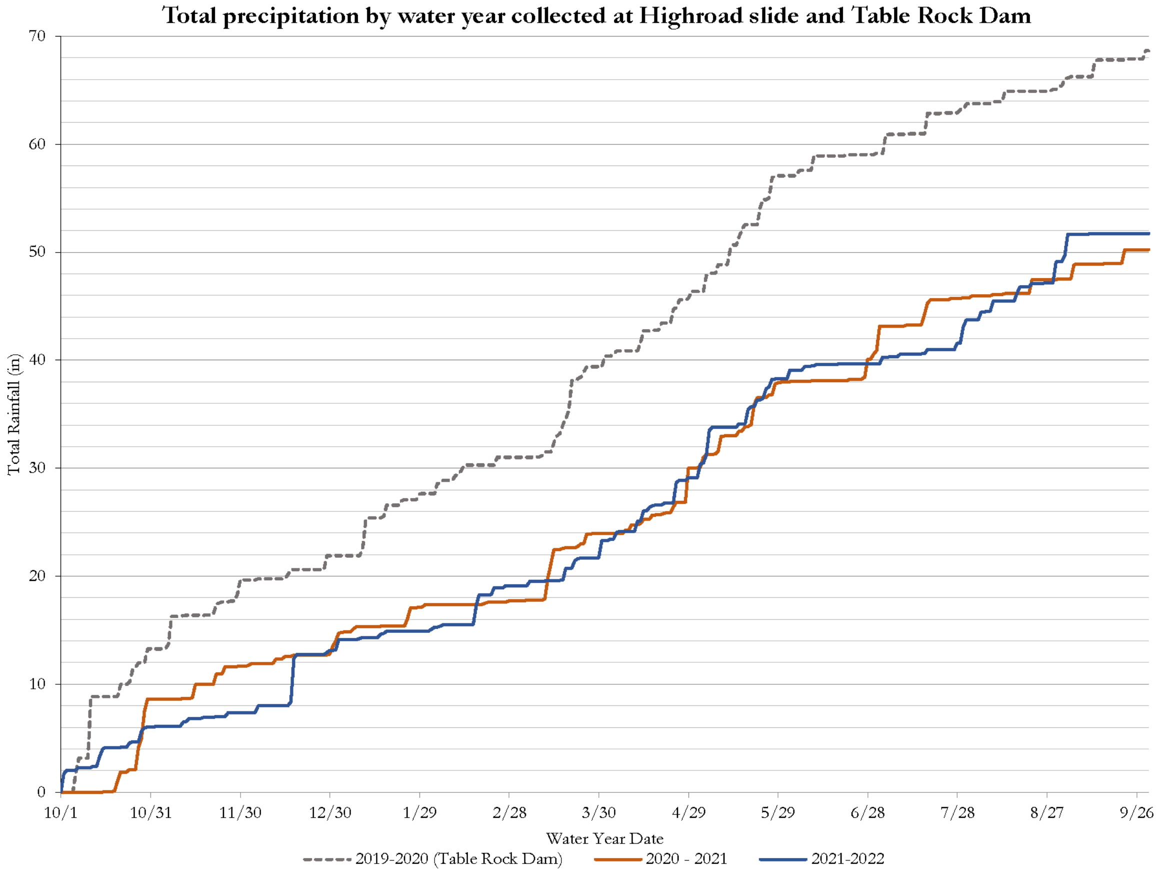


Figure 24: Cumulative precipitation collected in the project area and nearby Table Rock Dam during the study period.

As discussed in 6.1, the LiDAR survey collected in April 2021 did not detect any surface deformation that the research team could link to landslide movement with confidence. Combining the site observations from spring 2020 with a closer view of the cumulative precipitation between April 1 and June 30, shown in Figure 25, it appears likely that the LiDAR was collected too early in the year. The April data collection missed the initiation of seasonal creep in late spring, when the rate of precipitation accumulation increased. With additional data collection between 2020 and spring 2022, the next UAV flight was scheduled for June 2022, likely capturing two years' worth of seasonal creep on the cut slope.

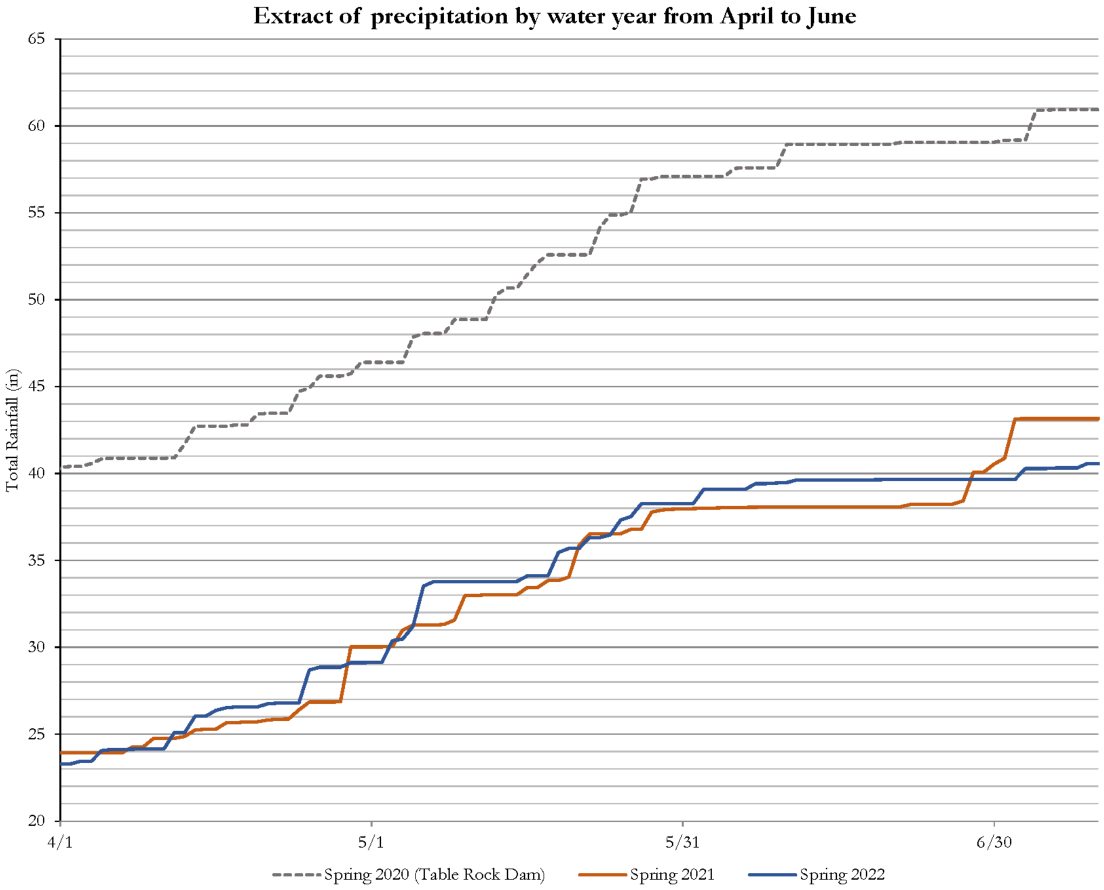


Figure 25: Extract of water year plot comparing April to June precipitation during the study period.

The precipitation data collected at the Ozark Mountain Highroad covered 25 months. The monthly precipitation collected from the weather station on site was also compared to the 20-year regional normals provided by the National Weather Service (NWS) for the regional office in Springfield, Missouri, as plotted in Figure 26. Compared to the 20-year normal, spring 2021 and spring 2022 were both wetter than average, as were July and October. Limited movement was detected after May 2020, even in wetter than average years. This implies that after doubling in size during the series of storms in 2020, the slide is now marginally stable, and should be expected to creep seasonally under average or slightly wetter than average conditions. Additional slide expansion similar to that observed in 2020 requires a much wetter than average spring. The precise tipping point could not be determined from the data collected so far, but the 20 inches collected in spring 2020 at Table Rock Dam provide an approximate ballpark of the seasonal precipitation required to initiate slide growth.

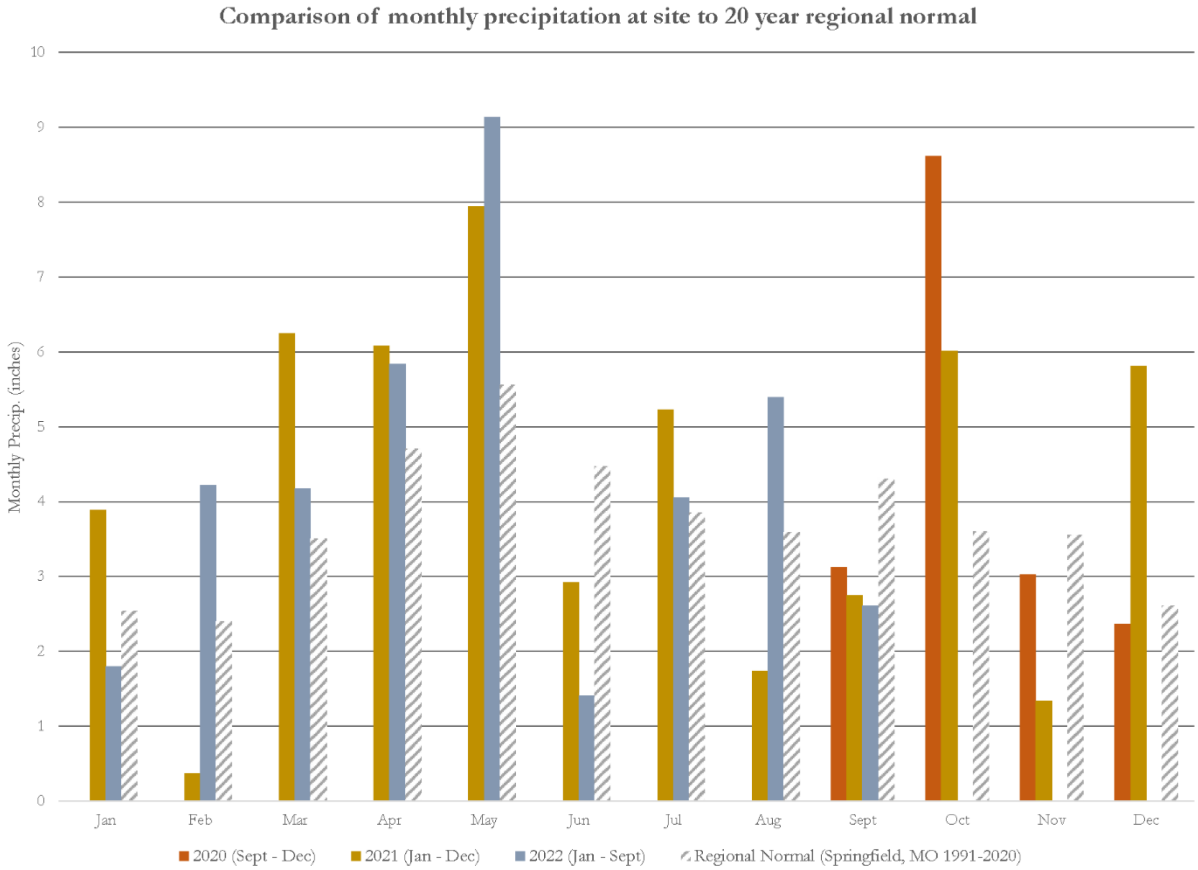


Figure 26: Monthly Precipitation collected at the project site compared to the 20-year normal from the Springfield, MO regional office for the National Weather Service for water years 2020 through 2022.

6.3 Groundwater Monitoring

Pore water pressure data was collected at the three vibrating wire piezometers installed onsite and compared with the rainfall data from the weather station. A combined data plot is shown in Figure 27. There is no common groundwater elevation observed in all three instruments that would support a regional groundwater table in the project area contributing to observed landslide movements.

The two piezometers in the cut slope, installed near the top of rock, were dry for most of the monitoring period. Both recorded maximum pore water pressures on the order of 0.5 feet and were most likely to be dry in spring and summer. Response to precipitation events in these two piezometers was muted. LT-1 was intentionally installed in a stable native slope. LT-2 was installed at what was assumed to be the base of the slide during drilling but is roughly 20 feet below the base of the slide movement observed in the LT-2 inclinometer to date. This indicates that the destabilizing pore pressures are perched well above the top of rock and that fracture flow from bedrock is not likely to destabilize the overburden.

The piezometer in LT-3, which was installed near the base of the embankment fill just above the contact with native soil, was also frequently dry, particularly in summer. It is the closet piezometer to a known shear zone, being roughly 2 feet below the base of the main observed shear zone in LT-3. The piezometer in LT-3 is very responsive to precipitation events, with a rapid rise in pressure as the surge in pore water pressure moved through the system followed by a gradual decline. Regardless of the size of the storm event, maximum pore water pressure measured at the piezometer tip following rain events was typically around 12 feet. The response of LT-3 to precipitation events and its proximity to the shear zone were leading factors in selecting LT-3 for IPI placement. One of the goals of the research program was to try and develop triggering conditions for landslides, an achievable goal if precipitation, groundwater elevations, and movement can all be compared to each other. The triggering conditions identified for the embankment slide are discussed in more detail in sections 6.7and 6.8.

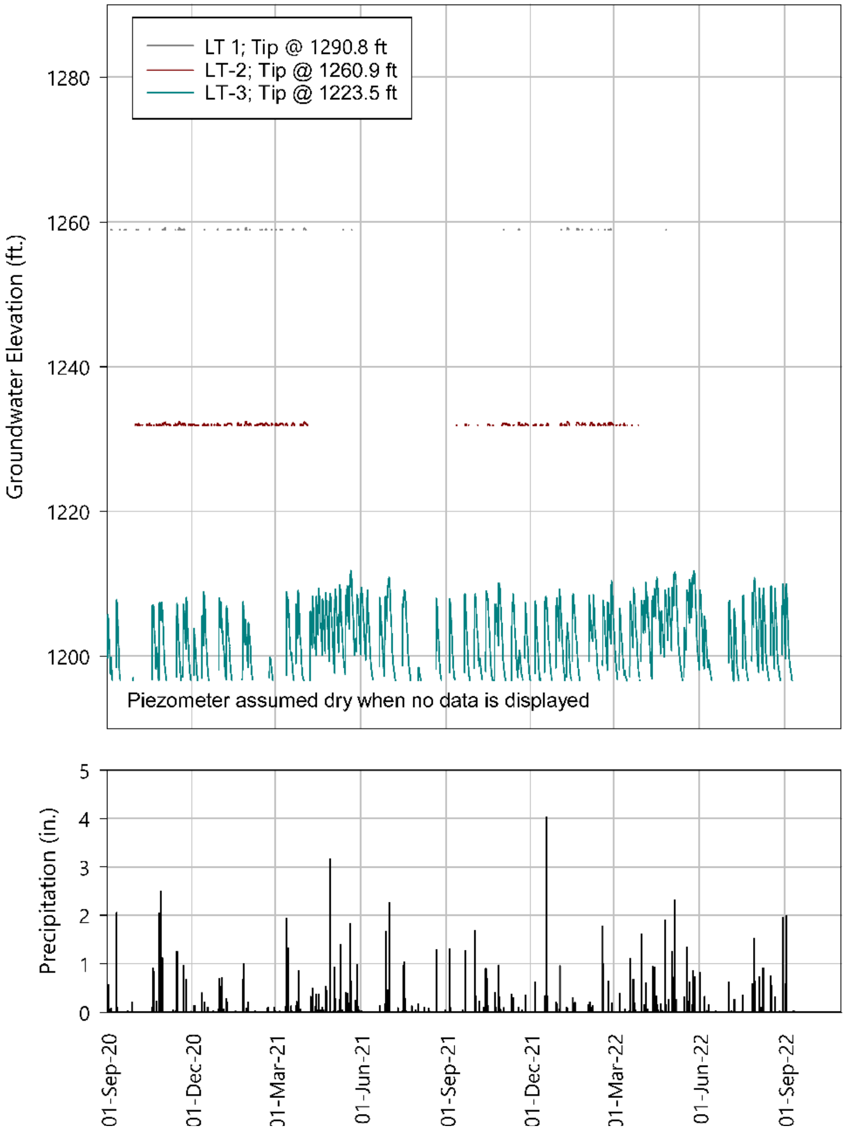


Figure 27: Summary of groundwater data collected at all three vibrating wire piezometers and daily precipitation collected by the weather station over the research project period.

6.4 Slope Inclinometer Data Collection

The three slope inclinometers were initialized on September 9, 2020. Additional surveys were collected on December 7, 2020, April 20, 2021, June 25, 2021, and October 21, 2022. All readings were conducted using a GEOKON probe with a two-foot measurement interval. During processing, the readings were adjusted for stickup, so that movement depths reference the top of the ground surface and not the top of the casing. Shear zones, net displacement, and estimated movement azimuth are summarized in Table 8 below. More detailed descriptions of the data collected for each instrument are included in the following subsections.

Table 8: Summary of identified shear zones, measured displacement, and movement azimuths.

Boring No.	Shear Zone A[1]	Net Displacement (in)	Movement Azimuth (deg)	Shear Zone B[1]	Net Displacement (in)	Movement Azimuth (deg)
LT-1	--	--	--	--	--	--
LT-2	5-9	1.87	138	--	--	--
LT-3	21-23	0.1	129	29-31	0.01	110

Notes:

[1] *Shear Zones are in depth below the ground surface*

6.4.1 LT-1

LT-1 was installed in the natural slope above the cut slope. The boring was difficult to backfill with the fractured formation requiring more grout than anticipated. Based on subsequent casing deformation, grout loss occurred near the contract between bedrock and native soil, around 34 feet below the ground surface. A small grout bridge of set grout prevented drill operators and inspectors from observing and correcting this zone of grout loss during drilling activities. Without the support of full grout encapsulation, the casing deformed within the available annulus space between subsequent surveys, as shown in Figure 28 below. None of the movement appeared to be associated with movement along a shear zone

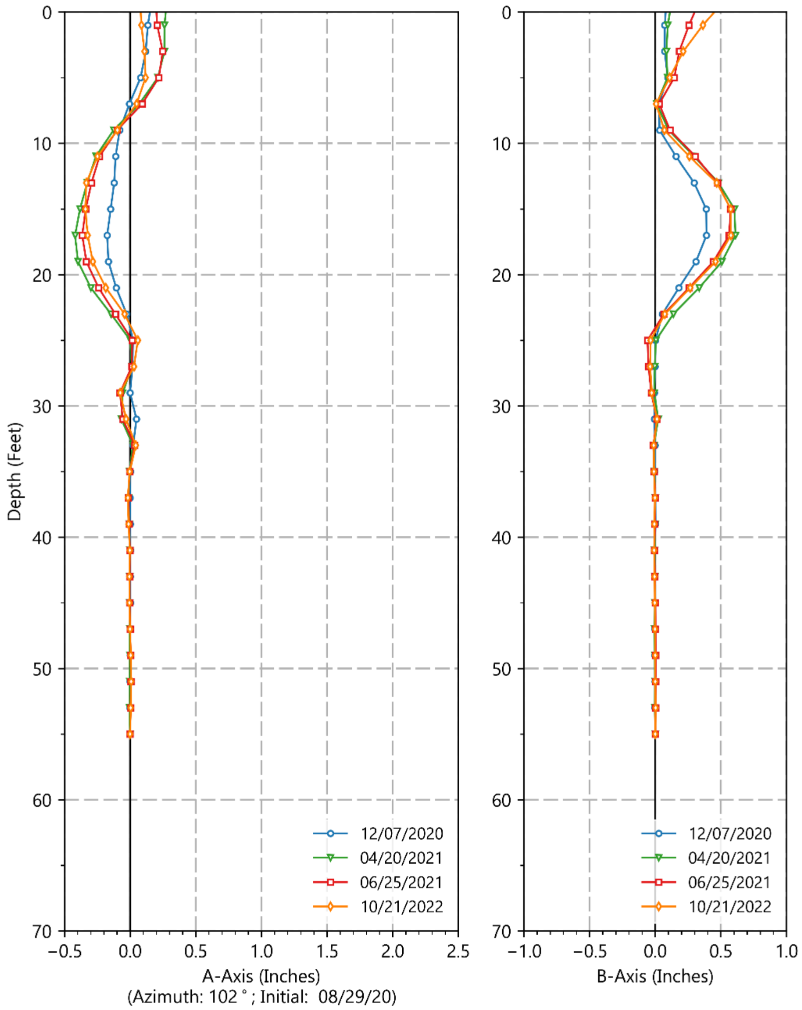


Figure 28: Cumulative displacement plot of LT-1 over the monitoring period, located on the natural slope above the cut.

6.4.2 LT-2

This inclinometer was installed in the body of the main landslide mass. A plot of cumulative displacement is presented in Figure 29 and the time displacement plot for the identified shear zone is presented in Figure 30.

During drilling, a softer zone of clay was encountered between approximately 25 feet below ground surface and the top of rock. Based on landslide size, this zone of weaker clay was interpreted as being the base of the slide, and the piezometer was installed within this interpreted shear zone. Subsequent monitoring identified movement between roughly 5 and 9 feet below the ground surface. The largest displacement between surveys, 1.2 inches, occurred between April 2021 and June 2021. These two readings bracketed the wet spring season. However, net displacement between June 2021 and October 2022 was only 0.5 inches, even though spring precipitation was similar in both years. It is possible that movement was larger in spring 2021 because the slide was adjusting to the local grading work performed in August 2020 when the drill pad and access route were constructed. Alternatively, spring slide movements may be decreasing as the slide adjusts to the last round of major expansion in May 2020.

None of the movement detected in LT-2 could be corroborated in the LiDAR scans. The fact that the LiDAR scans identified continued movement on the northern part of the slide suggests that the grading improvements for drill rig access slowed movement rates on this portion of the slide by removing mass and thus reducing destabilizing driving forces from the landslide. Apparent slight backwards displacement may be interpreted at a depth of 29 feet, however its magnitude of under 0.10 inches is below the threshold that typically is considered reliable in manual SI surveys. Further surveys, if the upper shear zone remains passable, may permit additional insight regarding possible displacement at this depth.

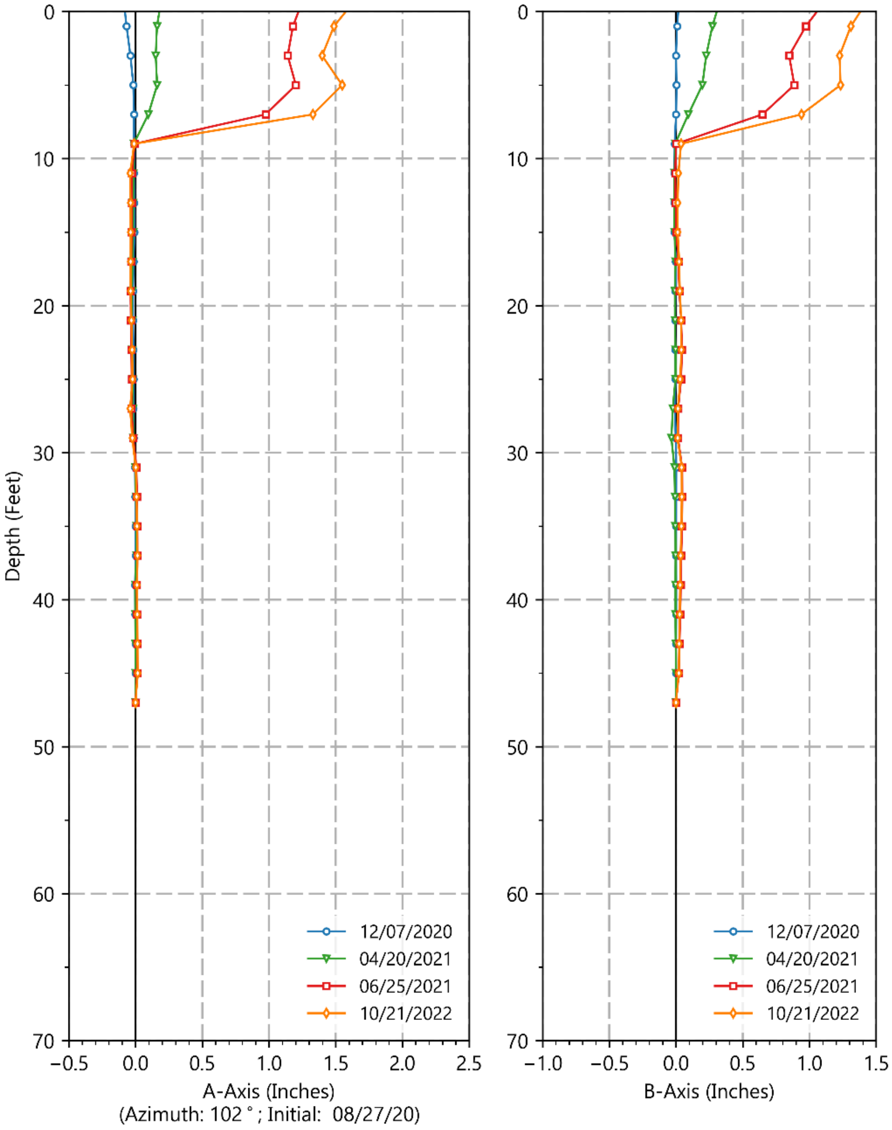


Figure 29: Cumulative displacement plot of LT-2, located in the cut slope instability, over the monitoring period.

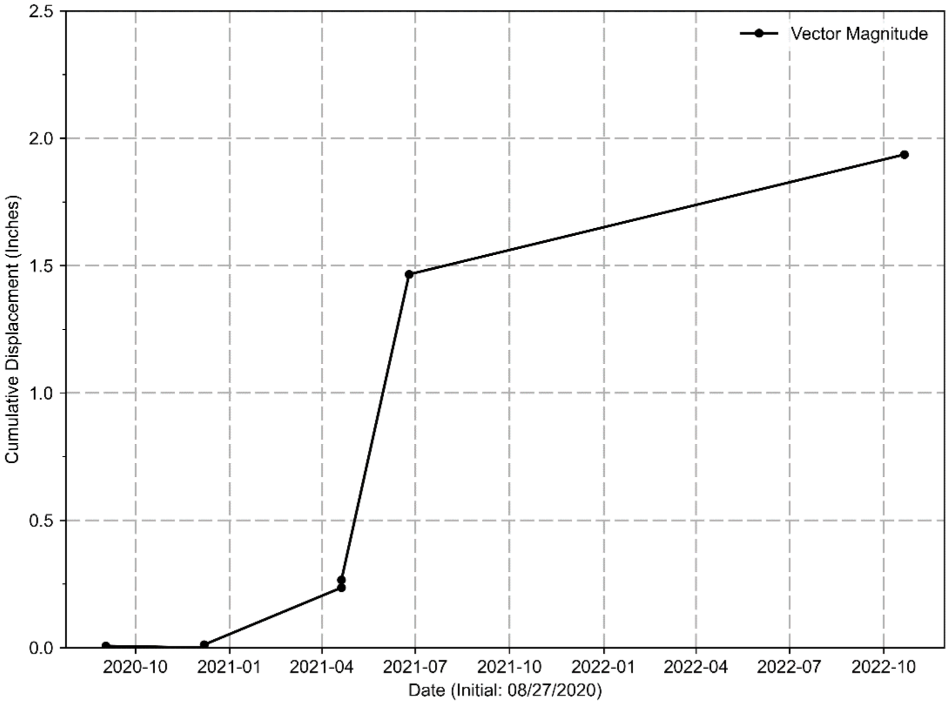


Figure 30: Time Displacement plot of observed displacement between 5 and 9.5 feet below ground surface in LT-2.

6.4.3 LT-3

This inclinometer was installed in the shoulder of the northbound lanes, within the arcuate cracking and deformation associated with the embankment failure. An in-place inclinometer (IPI) was installed in this instrument on June 25, 2021. The results of the IPI monitoring are discussed in sections 6.7 and 6.8. This section summarizes the results of the manual readings collected between September 2020 and June 2021. A plot of cumulative displacement over this period is presented in Figure 31 and the time displacement plot for the two identified shear zones are presented in Figure 32 and Figure 33.

During drilling, the contact between the native clay slope and the clay embankment fill was encountered at approximately 27 feet. The vibrating wire piezometer was installed at this depth, to capture pore water pressures at this contact. Subsequent monitoring identified two zones of movement: one between approximately 21 and 23 feet below ground surface, and a smaller one between approximately 29 and 31 feet below the ground surface. The more active, shallower zone is roughly seven feet above the base of the embankment. At a depth of roughly 25 feet, the embankment transitions from stiff to very stiff clay, so movement in the embankment is occurring above this stiffer zone.

The lower shear zone is in the native soil, roughly 2 feet below the base of the fill. Measured displacement in this zone was much smaller than in the upper shear zone.

None of the movement detected in this inclinometer could confidently be identified in the LiDAR scans. This is not surprising given that the cumulative displacements over both shear zones was less than a quarter inch.

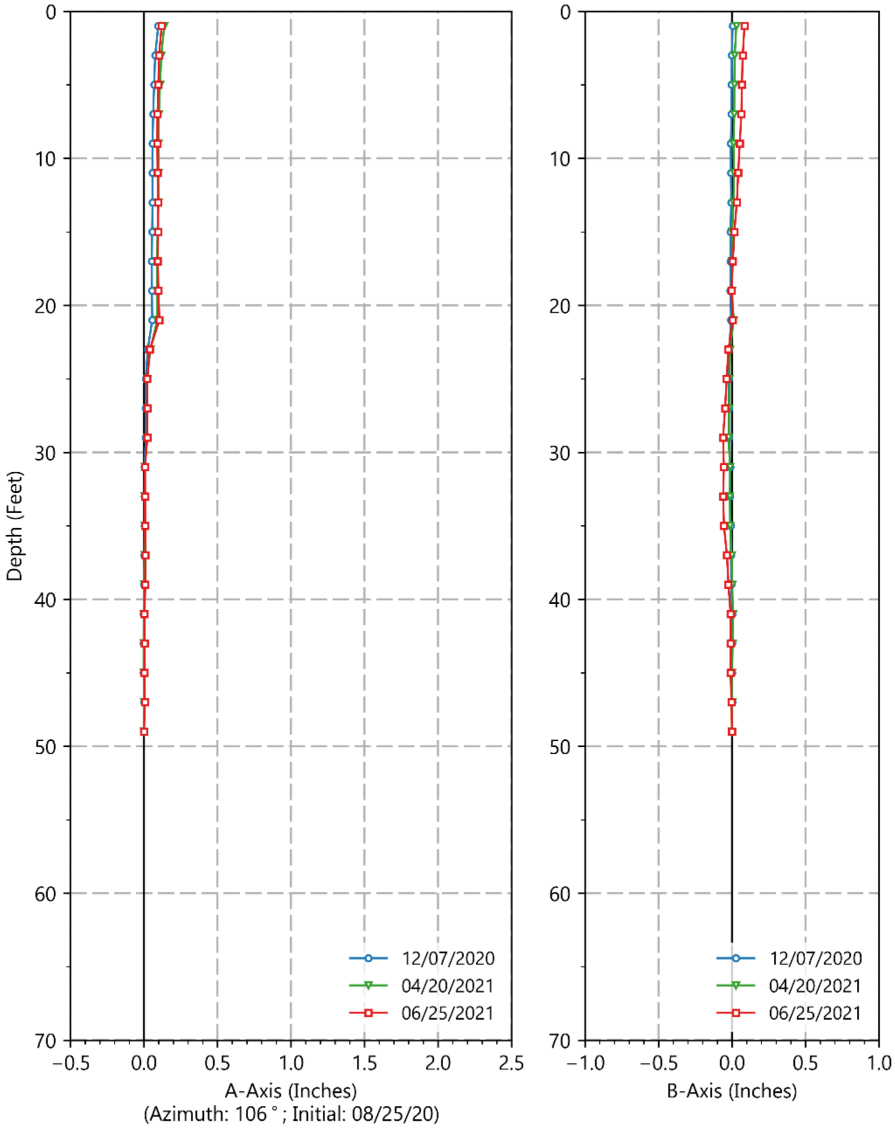


Figure 31: Cumulative displacement plot of LT-3, located in the observed northbound embankment slide, over the monitoring period.

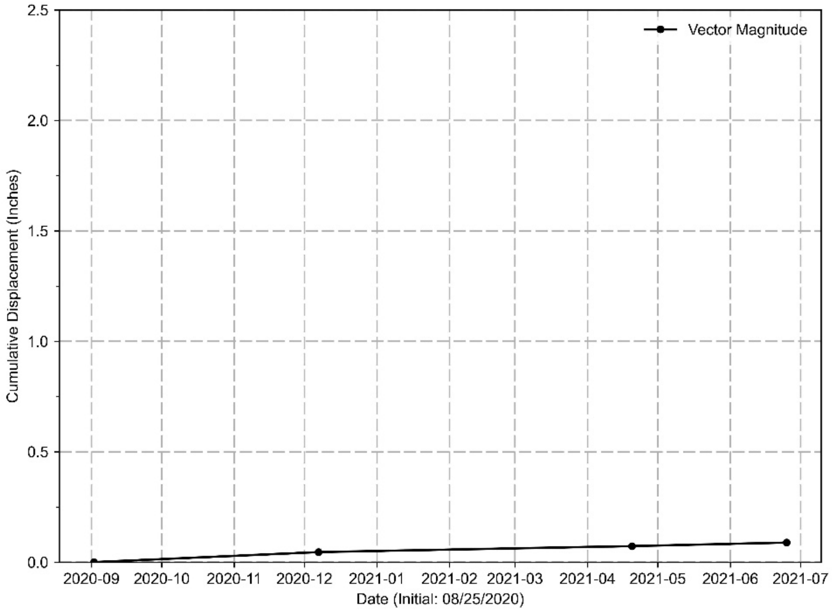


Figure 32: Time displacement plot for the upper shear zone of LT-3 between September 2020 and June 2021, prior to IPI placement.

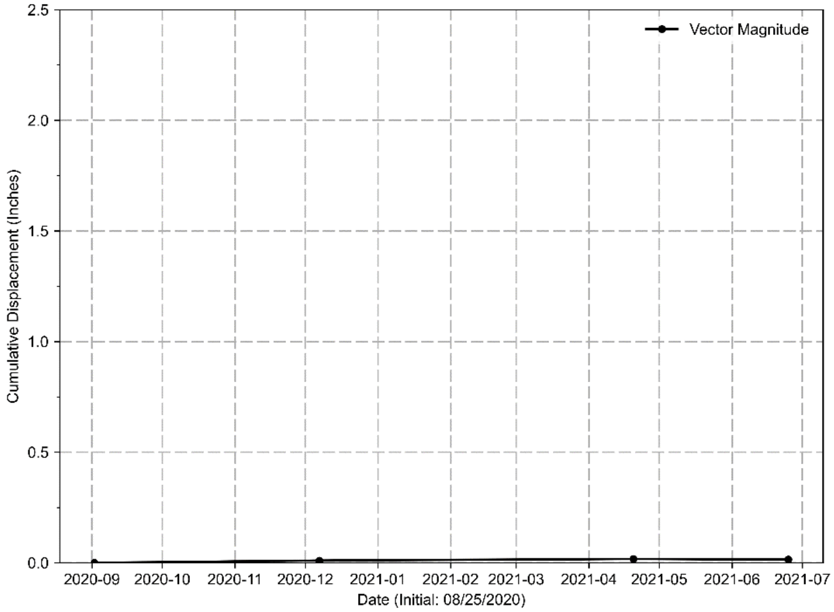


Figure 33: Time displacement plot for the lower shear zone of LT-3 between September 2020 and June 2021, prior to IPI placement.

6.5 Geologic Profile of Highroad Cut Slope Slide

During the original site investigation, the research team collected data on past movements and current observations and estimated that the cut slope slide was a rotational slide occurring in the clayey overburden slope above the soil-bedrock contact, as sketched in Figure 34. Based on these assumptions, Landslide Technology developed a site investigation plan that extended all three inclinometers through the overlying soil into bedrock.

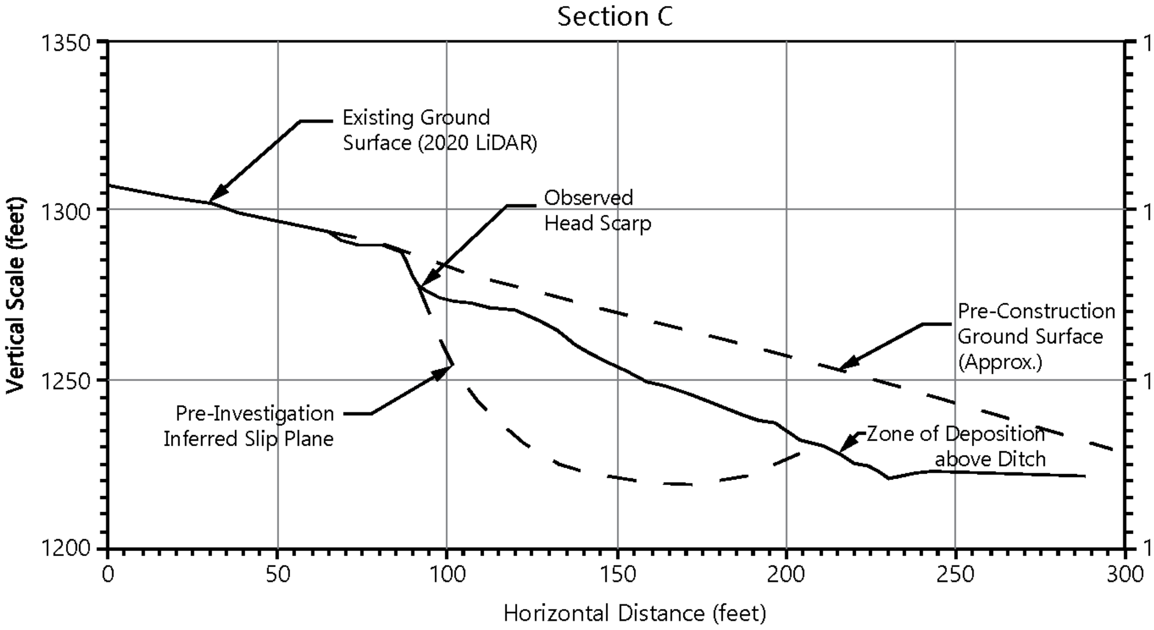


Figure 34: Estimate of slip surface geometry of the cut slope slide prior to subsurface investigation.

After monitoring the inclinometers in LT-2 for aprproximately two years, the deflection data does not support that initial assumption. A shear zone was identified between roughly 5 feet and 9 feet below the ground surface, much shallower than originally assumed. Based on the cross section developed over the course of the monitoring period and presented in Figure 35, the actual cut slope slide is interpreted as a rotational failure translating to a slumping earth flow where the slide toes out of the slope. This could explain the steep slope of the headscarp, the relatively shallow movement in the slope inclinometer, and the inflation and quanitity of the material deposited on the lower slope and roadside ditch. As the clay soil in the cut slope becomes saturated over the spring, it loses cohesive strength and, once movement initiaties and peak shear strengths are surpassed, the 7° residual shear strength (described in Section 4.3) permits the observed movements. The cut slope slide also shares some of the features of an earth spread or earth flow, particularly in lower parts of the slide that are more saturated.

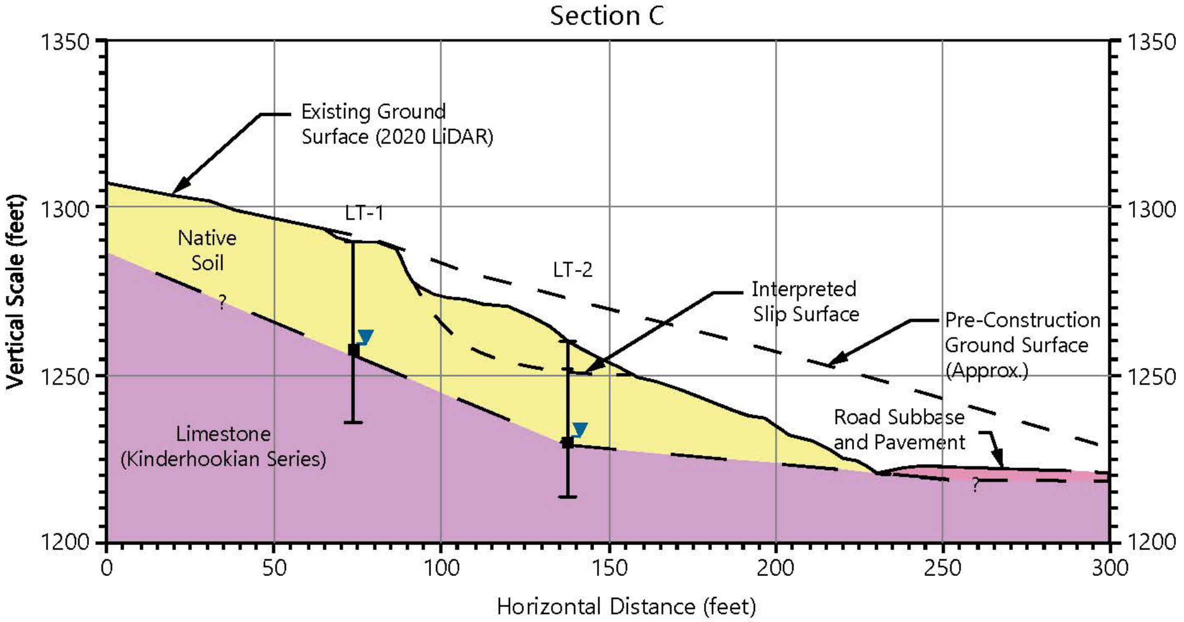


Figure 35: Geologic profile and subsurface geometry of the cut slope landslide based on subsurface samples and long-term monitoring.

Although the LT-2 inclinometer turned out to be installed to a much greater depth than necessary, extending the subsurface investigation through the native soil to bedrock had research benefits. It allowed the research team to conclude that the slide was shallow, and that a less converstative, more cost effective mitigation may be viable for this site in the future, if desired by MoDOT.

6.6 Geologic Profile of the Highroad Embankment Slide

The southbound lanes of the Ozark Mountain Highroad are in a cut, but the northbound lanes rest on a fill embankment placed on a steep native slope. Based on the pre-existing topography, maximum fill thickness was expected to be approximately 30 feet. Using borings, site observations, and pre- and post-construction topography, a geologic cross section of the slide was developed and is shown in Figure 36 below. The embankment fill is constructed of the same fat clay as the native soil and is assumed to be reworked spoils from the cut slope excavation.

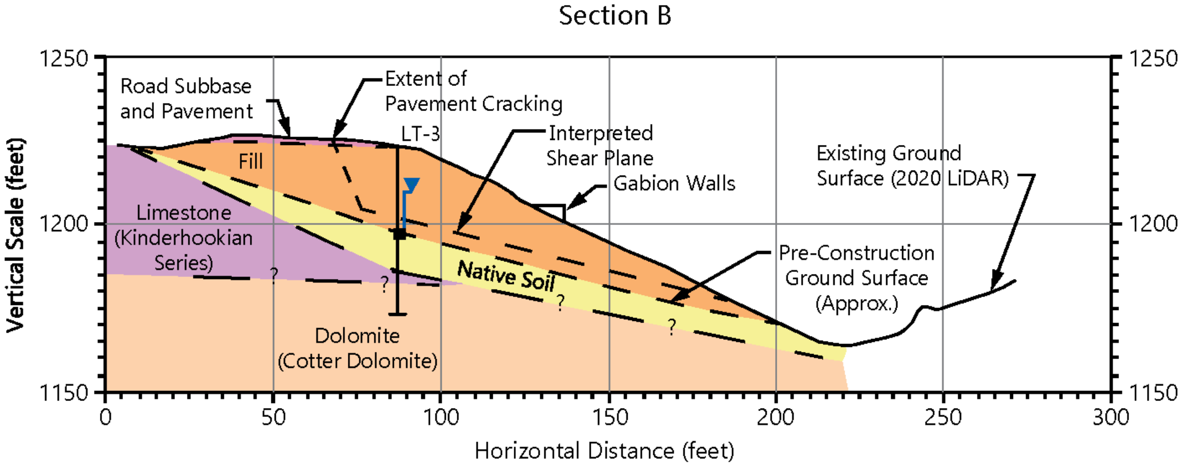


Figure 36: Geologic profile and subsurface geometry of the embankment fill landslide based on subsurface samples and long-term monitoring.

Prior to installation of the slope inclinometer, the research team formed the hypothesis that the base of landslide movement would be at the fill – native soil contact. Because landslide movement in the roadway was only observed above the gabion walls, the team theorized that the additional fill placement in the upper portion of the slope enabled by the gabion walls triggered the local slope instability. No toe or deformation of the embankment slope was noted during the site reconnaissance or interpreted from the LiDAR surveys.

After collecting manual and IPI readings over the course of the project, the data supports the initial hypothesis with some additional detail. The main slide movement is occurring in the embankment fill, approximately 5 feet above the fill-native soil contact. Additional minor movement is occurring in parallel in the native soil roughly 4 feet below the fill-native contact. Taken together, this suggests that the additional fill retained by the gabion walls and the fill it retains is a driving factor in the slide, but that good construction practices were followed during placement of the embankment fill that prevented the actual embankment fill – native soil contact from developing into a weak zone that would be the preferential location of a shear zone.

6.7 Long Term Monitoring of LT-3

The original research plan for the project included installation of an in-place inclinometer for real-time monitoring once the shear zone was identified. This real-time monitoring would give the research team a better chance of identifying the conditions that triggered landslide movement. By spring of 2021, the research team had identified shear zones in both slide areas: one in LT-2 in the cut slope and two in LT-3 in the embankment slide. The cut slope slide is the original focus of the research study. However, the observed shear zone in LT-2 was between 5 and 9 feet BGS, and the piezometer the team had planned to use when identifying triggering events was over 20 feet below the shear zone and typically dry. The shear zones identified in LT-3 was closer to the piezometer, and that piezometer also responded to precipitation events. In consultation with MoDOT's Technical Committee, the research team opted to install the IPI in LT-3.

The challenge in LT-3 was that the two shear zones spanned approximately 10 feet, and the standard gauge length for an IPI is 5 feet. It is possible to instrument multiple shear zones by installing multiple IPIs in an inclinometer casing and monitoring the different shear zones independently. However, this was outside the budget constraints of this research project. Instead, because both instruments were moving in a similar direction and on a similar pattern, the research team used a factor to estimate movement on the lower shear zone based on movement in the upper shear zone and combine the two. Movement in the deeper shear zone, from 29 to 31 feet below the shear zone, was much less than the movement in the upper shear zone, as seen in Figure 33. The IPI was placed to miss this lower zone and collect accurate measurements only for the upper shear zone. Because movement in the upper shear zone is concentrated between 21 and 23 feet BGS, the IPI was installed from 20 to 25 feet BGS.

Combined displacement for both shear zones was calculated using the equation below

$$\text{LT-3 IPI Displacement (in.)} = 0.10 + 1.2 * 60\left(\sin\left(G * (R_1 - R_0) * \frac{\pi}{180}\right)\right)$$

Where:

0.10 = total displacement measured between 20 and 31 feet BGS by the manual readings completed between September 2020 and June 2021

1.2 = factor to extend the displacement measured on the 21 to 25 ft shear zone over the whole zone. As of June 2021, the shear zone between 29 and 31 represented 20% of the total movement over both zones, and this was assumed to remain the same in future monitoring.

G = 0.002312, gauge factor in degrees of tilt per digit, constant provided by GEOKON

R_1 = current vibrating wire tilt sensor reading in the IPI

R_0= the initial IPI reading collected in the field immediately after installation (7800 for the IPI in LT-3)

All displacement and groundwater monitoring data collected at LT-3 over the course of the research project is presented in Figure 37 on the following page. The rate of movement in the inclinometer increases in the spring and early summer, before slowing over the rest of the year. Because overall movement measured over the course of the research period was roughly 0.25 inches, the routine noise in the IPI signal is harder to filter out. Intervals in the late summer and fall where the IPI is showing no movement or displacement appears to decrease are both interpreted as periods of no measurable landslide movement.

The IPI was left in place at the end of the research project, and the data logger installed at LT-3 is continuing to collect data for the IPI and the vibrating wire piezometer, transmitting it to the base station on the cut slope.

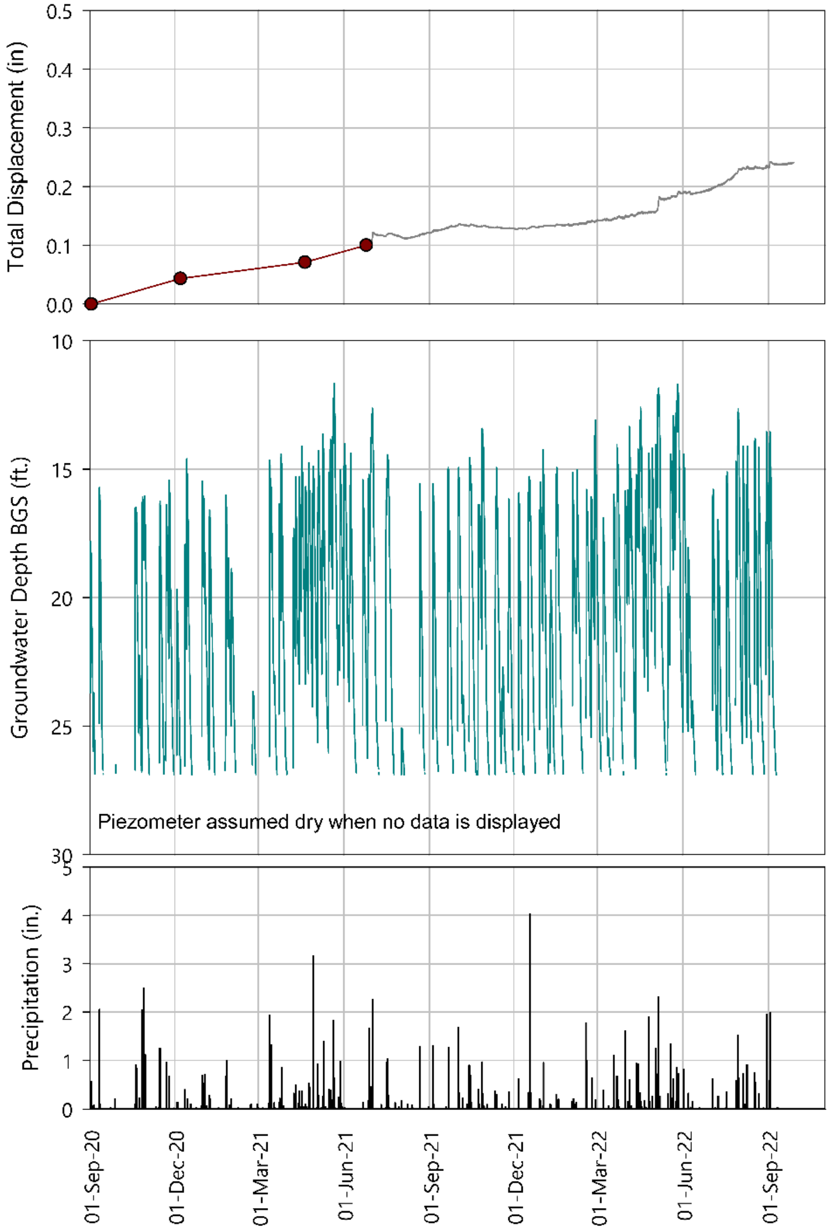


Figure 37: Plot summarizing all data collected at LT-3 - manual deflection measurements, IPI displacement, and groundwater elevation - combined with daily precipitation data collected at the weather station on the cut slope.

6.8 Triggering Conditions for Embankment Slide

The IPI was installed in LT-3 for approximately 14 months, but only captured one spring season. Since movement rates at both the cut slope and the embankment slide are seasonal, it was difficult to refine triggering events. By visual inspection, IPI movement appeared to correlate with rain events, but not all rain events triggered movement, as shown in Figure 38 below.

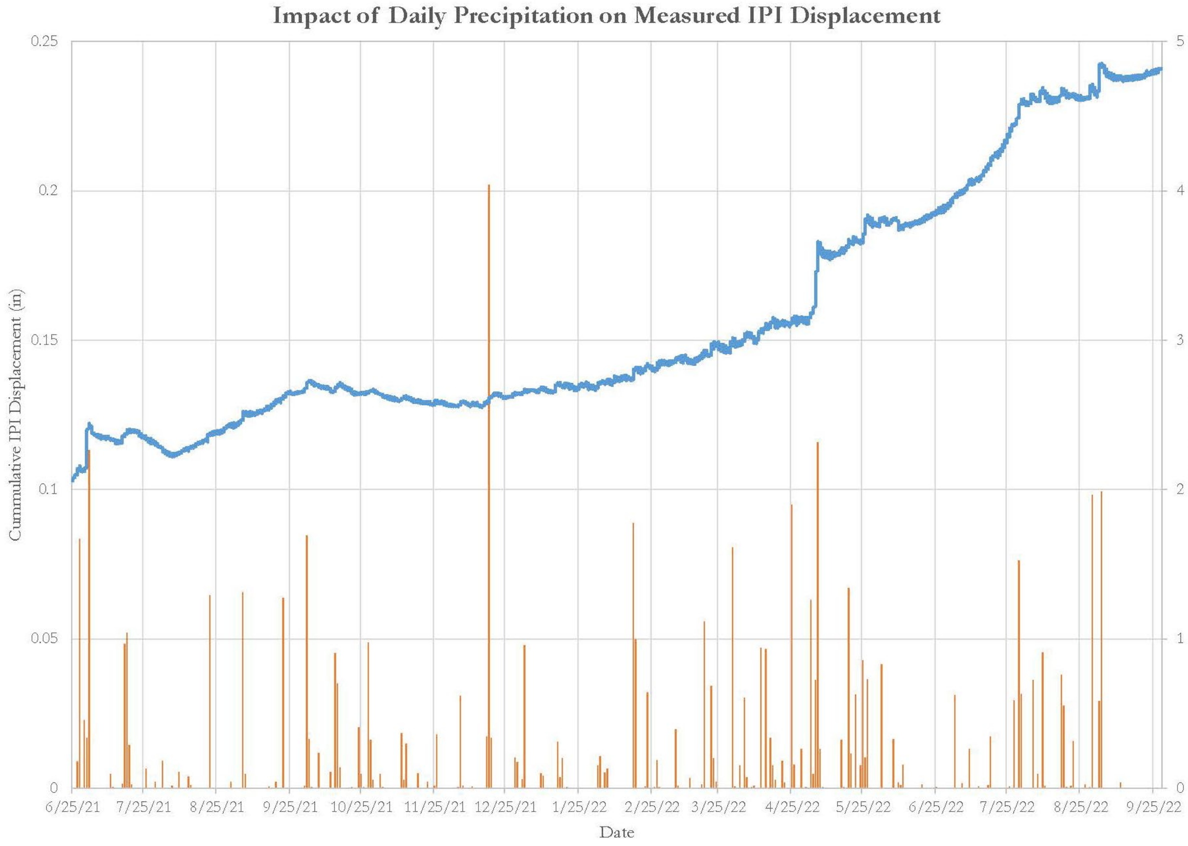


Figure 38: Comparison of IPI displacement and daily precipitation totals.

Because precipitation events had an impact on IPI movement but did not determine it, the next theory was that, because groundwater elevation responded to precipitation events, there was a triggering groundwater elevation that determined the rate of landslide movement. Hourly groundwater levels are plotted against hourly cumulative displacement rates in Figure 39. There is no clear correlation between the head measured at the piezometer tip and the rate of movement recorded by the IPI. The highest recorded pore water pressures are more likely to be associated with higher movement rates, but not to a degree that could be used in a statistical prediction.

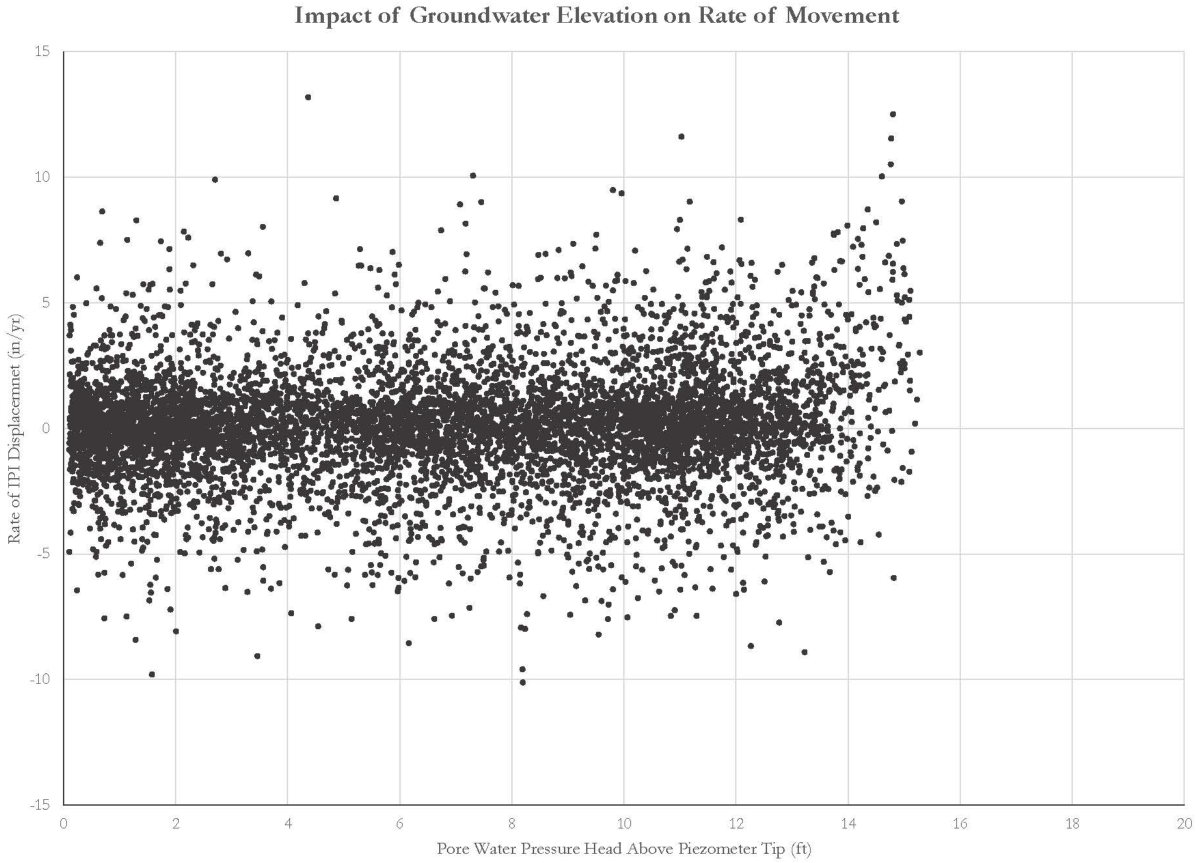


Figure 39: Rate of IPI displacement vs pore water pressure head measured at the piezometer tip.

Individual groundwater elevations did not correlate with increased rates of movement, but the duration of measurable groundwater did, as shown in Figure 40 below. This graph shows both cumultaive IPI displacment and the number of days of measureable groundwater at the piezometer tip. Groundwater in LT-3 typically rose sharply after a precipitation event, then gradually declined as the pore water pressure dissapated. In the summer, the piezometer frequently went dry between storm events, but in the spring, frequent smaller storm events maintained groundwater levels above the tip. In spring of 2022, the piezometer recorded groundwater levels above the tip from March 30 to June 14, 2022, with only two dry days during this 76-day period period. This also corresponds with the largest individual displacement recorded by the IPI during the monitoring period. It was followed by a period of 0.04 inches of sustained creep over the following 6 weeks. In the other seasons in the monitoring period, measureable groundwater was typically present at the sensor tip for less than two weeks, which likely contributed to slide stability during those seasons.

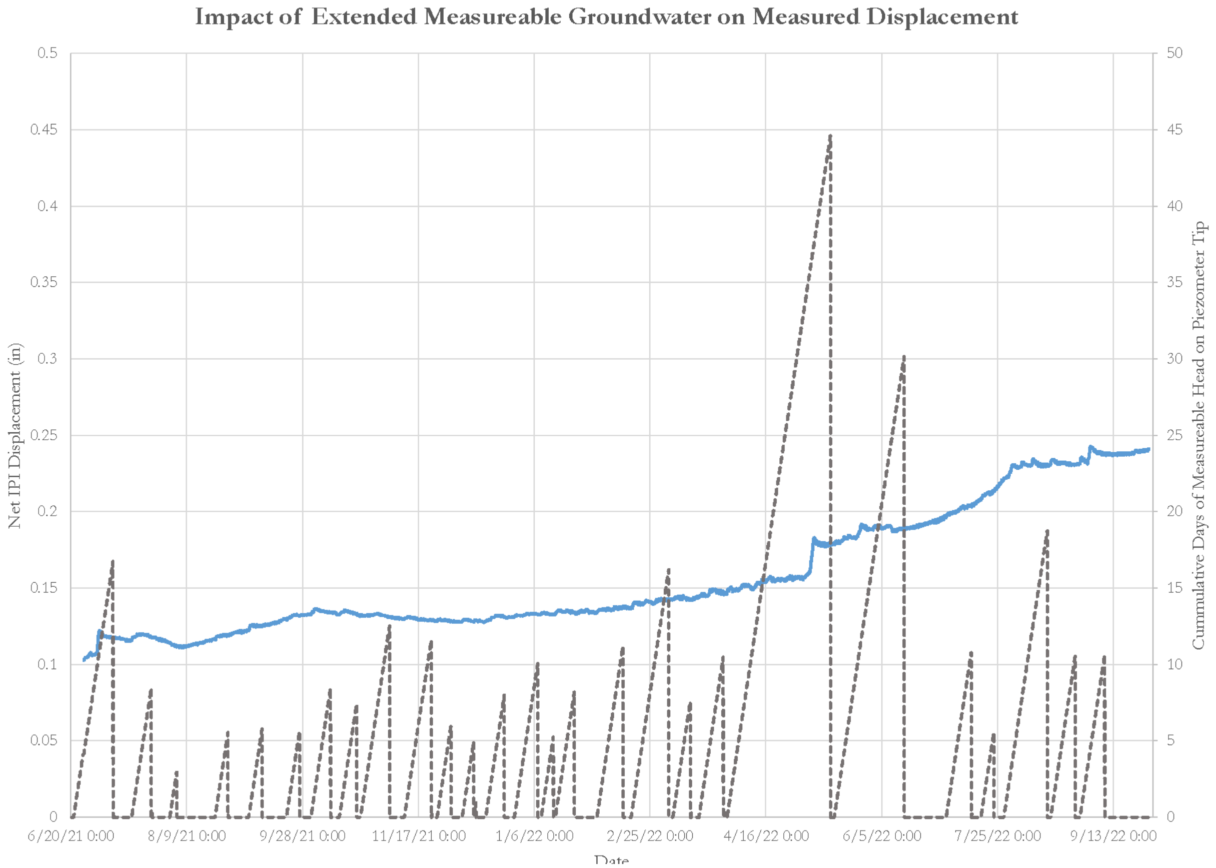


Figure 40: Net IPI displacement and the number of days of measurable groundwater.

The number of days of measureable groundwater has an impact on the rate of movement, but there was no triggering length of time that determined movement rate. For example, groundwater was present for more days in June 2022 than in June 2021, but was associated with less movement. Based on the data available to date, it appears that the the sustained presence of groundwater provides a precondition for renewed movement, but individual storm events are still necessary to trigger movement. Individual storm events associated with measureable IPI displacement are summarized in Table 8 below. A storm event was defined as days of measureable rainfall at the project weather station. To overcome noise from the the vibrating wire sensor, measureable IPI displacement was defined as net displacement greater than 0.01 inches. From this table, it is apparent that the groundwater conditions present at the start of the storm event contributed to the movement associated with the storm event. Storm events in summer, fall, and winter seasons had to be larger than storms in the spring and early summer in order to generate comperable displacements.

Table 9: Summary of storm events with more than 0.01 inches of movement and associated movement with preceding days of groundwater.

Storm Start	Storm End	Total Precipitation (in)	Net Displacement of IPI	Cumulative Days of measurable groundwater prior to storm
6/25/2021	7/3/2021	4.91	0.014	4
5/3/2022	5/8/2022	4.66	0.022	34
5/24/2022	5/27/2022	1.94	0.007	12
7/28/2022	8/2/2022	2.75	0.007	0
9/2/2022	9/3/2022	2.56	0.009	3

Both the embankment slide and the cut slope slide are occurring in similar materials and displayed similar seasonal movement patterns. Although real-time monitoring was not implemented in the cut slope, the research team is confident that the triggering conditions identified in the embankment slide are broadly transferable to the cut slope slide as well. One of the original goals of the research task was to identify triggering conditions that could be used to set up an alarm. Once the triggering threshold was reached, a notification would be sent from the Konect GDS modem to select people of interest. Based on the data collected to date, if the research was continuing for another year, Landslide Technology would program an alarm notification to go out when more than 4.5 inches of rain fell in a multi-day period between April 1 and June 30. This would have captured movement events greater that 0.1 inch for LT-3 during the research period. It is the opinion of the research team that it also would have correlated with movement in LT-2, and increased likelihood of activation of new slides in the cut slope area.

7 INVESTIGATION OF CRACK SEALING IMPACTS

7.1 December 2021 Crack Sealing

Because the no significant movement at depth was detected on the cut slope landslide, and because the recorded movements in the embankment slide were also very small, the MoDOT Technical Committee and Landslide Technology discussed extending the landslide monitoring period in the April 2021 interim meeting, prior to the installation of the IPI in LT-3. At that time, future crack-sealing of damaged pavement behind the retaining wall was also discussed. The theory was to test if the crack sealing reduced water infiltration into the slide mass and slowed the rate of deformation.

The IPI was installed in LT-3 on June 25, 2021, and picked up repeated minor movements over the summer in response to multiple rainfall events. In October 2021, Landslide Technology and the MoDOT Technical Committee decided to ask the Branson maintenance shed to crack seal the damaged pavement behind the retaining wall. The goal was to see if there was any reduction in recorded movements during storm events after crack sealing. Crack sealing in the center of the northbound lane was completed in December 2021. Figure 41 contains a photo of the crack sealing area below, with the monitoring station for LT-3 visible to the right of the shoulder.

Figure 41: Crack sealing in northbound lane. Photo taken October 2022. LT-3 data logger is visible left of the shoulder.

7.2 Impact of Crack-Sealing on LT-3 Movement

After crack sealing was completed, the research team continued collecting displacement and piezometer data to compare with the data collected at the weather station. As previously discussed in Section 6.8 the embankment slide appeared responsive to the amount of time measurable groundwater was present, as opposed to a specific triggering groundwater elevation. As shown in Figure 42 below, the crack sealing did not have a noticeable impact on the rate at which groundwater moved through the embankment fills after a storm event. It also did not reduce the overall head measured at the piezometric tip following rain events. The cracking in the roadway did not apparently provide a pathway for water into the subbase, so there was no discernable impact on movement rates or piezometer levels when the cracks were sealed.

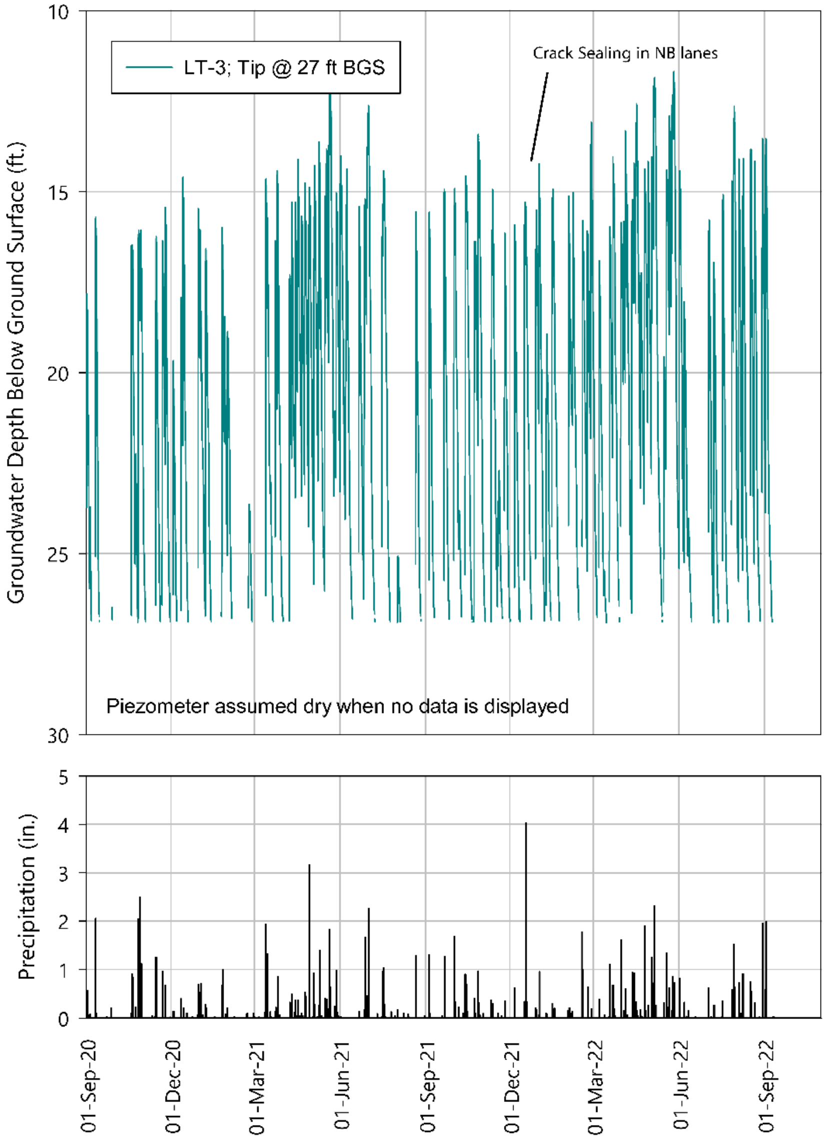


Figure 42: Pair of plots showing patterns of precipitation and groundwater elevation response before and after crack sealing.

Revisiting Figure 38 from Section 6.8, the rate of cumulative displacement did not change in the winter after the crack seal was applied. Movement rates increased in the spring as precipitation increased, as shown in Figure 43, and also increased in response to specific storm events.

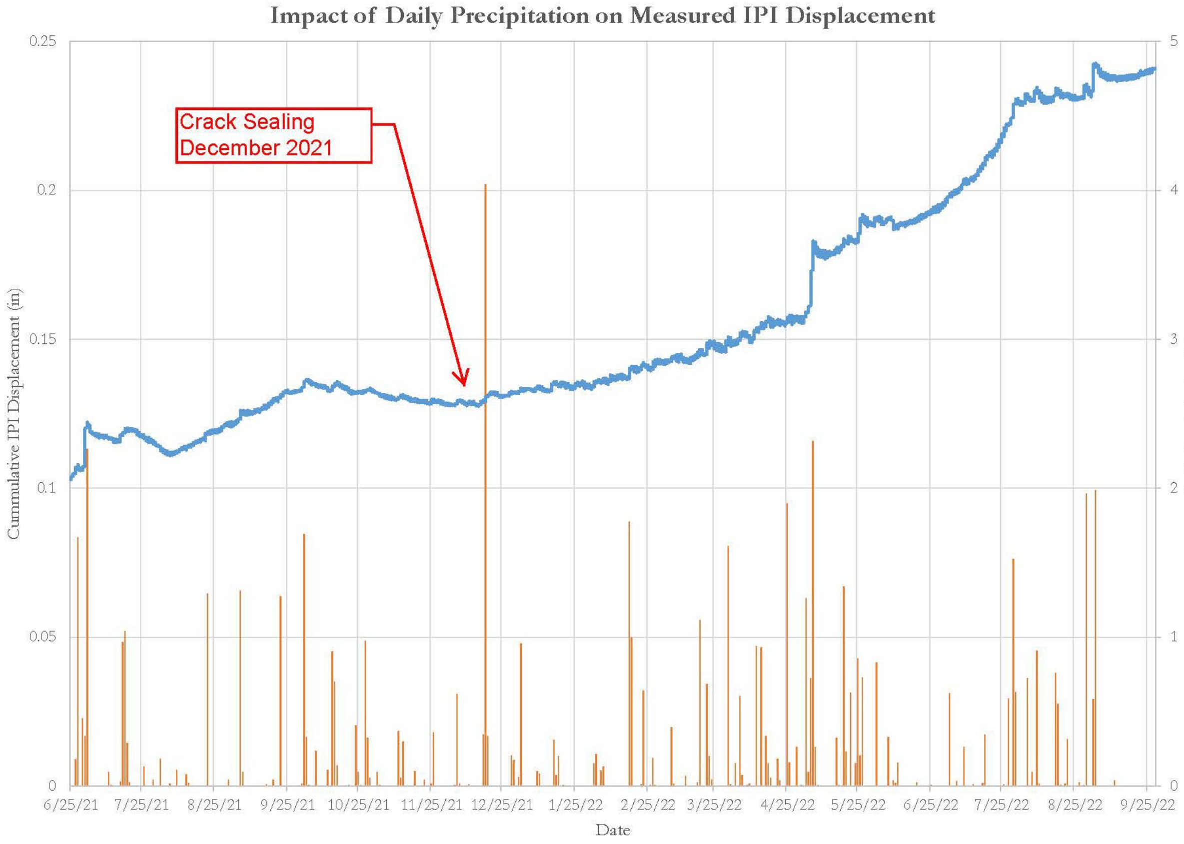


Figure 43: Comparison of precipitation and measured displacement at the LT-3 IPI.

Because the size and timing of storm events varies over the course of the year, Landslide Technology compared net displacement to both the size of the storm and to the time of year the storm occurred. The storm events were grouped by those that occurred before crack sealing and after crack sealing. As shown in Figure 44, storms with less than two inches total precipitation have a negligible impact on slide movement. In larger storms, crack sealing did not appear to reduce the amount of displacement measured in a given storm event. The IPI was installed in late June 2021, and this did not fully capture slide movement in the spring and early summer season, when, according to past observation, landslide movement is most likely. Therefore, it was not possible to compare storm displacements during the seasons when movement is most likely. Once the measured displacement during a storm was compared to the time of year the storm occurred, as shown in Figure 45, it became clear that the time of year and its corresponding preconditions that a storm occurs has a large impact on movement. Storms that occur in the spring and early summer are associated with higher rates of movement, although individual storms in the summer months are frequently larger. In summer and fall, where pre- and post-crack sealing data can be compared, there is no discernible difference between net displacement during storm events before and after crack sealing.

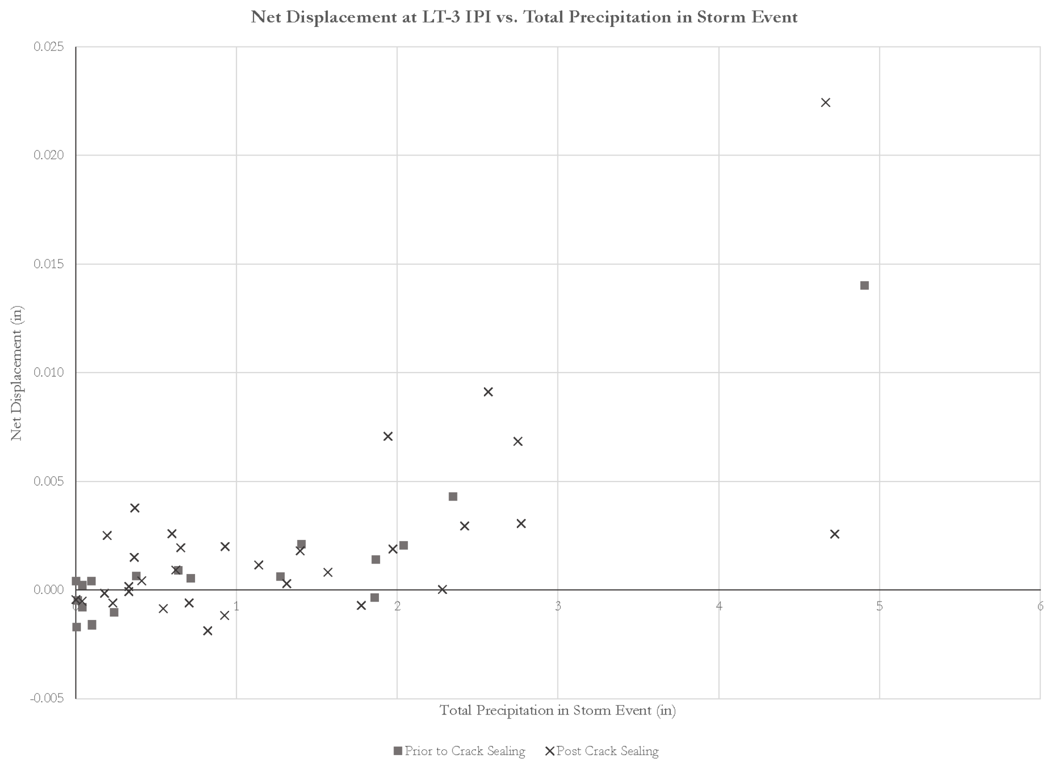


Figure 44: Comparison of measured net displacement and storm event size before and after crack sealing at LT-3.

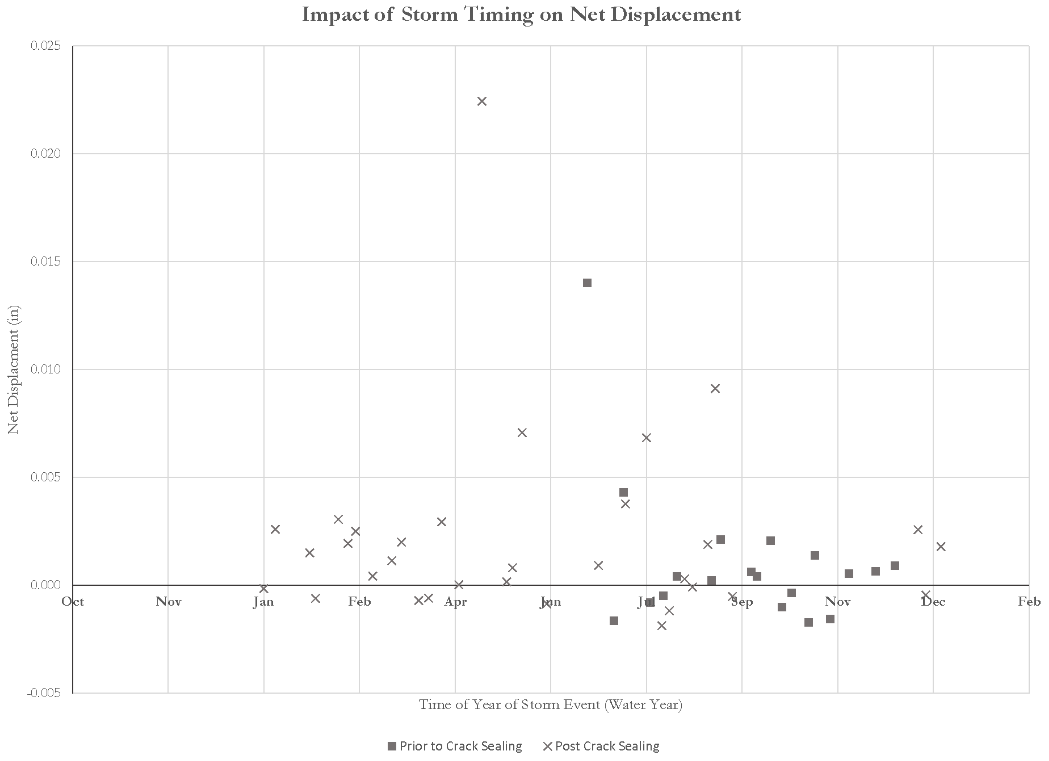


Figure 45: Impact of storm season on measured displacement, with data further sorted before and after crack sealing.

The crack sealing work did not have any measurable impact on embankment slide movement. This does not mean that crack sealing is not a good maintenance practice or that it would not be a cost-effective option for surface water control. Instead, it is likely that most of the water pulsing through the landslide after a storm is collecting in the median ditch between the two travel lanes and entering the slide from that location, as opposed to infiltrating through the damaged pavement. Top of rock in the median is close to the ground surface, with several minor rock outcrops observed within the project area. With limited infiltration capacity in the ditch, runoff may develop a preferential seepage path along the native soil – embankment fill contact, where it contributes to slide movement. Based on the information collected from LT-3 so far, reducing slide movement by changing precipitation infiltration through the pavement or pavement damage will be difficult and have limited practicality.

The cellular subscription for remote data collection has been discontinued in anticipation of project completion. However, the IPI is still in place in LT-3, and the datalogger is still collecting data, although it must now be downloaded manually during a site visit. Collecting data over the coming spring season could provide additional insight about the impact of crack sealing on landslide displacement after storm events.

8 MONITORING METHODS ANALYSIS

Landslide Technology incorporated lessons learned into a methods analysis following review of the various monitoring methods employed at the Ozark Mountain Highroad slides. This analysis incorporated both economic considerations and user expectations. It was further separated into a method analysis for selecting monitoring tools (Section 8.1) and a method analysis for data acquisition equipment (Section 8.2). Both analyses are intended for use as a reference when selecting monitoring equipment for other sites requiring long-term monitoring.

8.1 Method Analysis for Monitoring Instrumentation

The research project at Ozark Mountain Highroad used UAV LiDAR scans and subsurface instrumentation to monitor two landslides. The following subsections summarize strengths, considerations, and lessons learned when using the various monitoring methods. The results of this analysis are summarized in Table 10 at the end of this section.

8.1.1 LiDAR and Orthomosaic

Three LiDAR flights were conducted by UAV over the course of the research project. Each flight cost approximately $7,000. This cost included some post-processing of the scans by the subcontractor, ROCK Robotics. The final data set they delivered included a DEM with a one-foot raster pixel resolution and an orthomosaic, both standard files that intermediate and advanced GIS users are familiar with manipulating. Both files could be imported into CloudCompare or ArcGIS. Surfaces could be generated from tools in both programs and compared to other surveys. In the three datasets collected, the research team was able to detect movements of +/- one foot with confidence. Vegetation, particularly thick grass, adds a significant amount of noise to the data collected at a finer than 1-foot interval. One way to correct for this in the future would be to conduct LiDAR surveys at a consistent time each year, so that seasonal vegetation changes between surveys are minimal.

To reduce costs on this project, survey grade control was not performed for the UAV data acquisition. This meant Landslide Technology personnel had to complete some additional data processing work before comparing the data sets. Including ground control or accuracy requirements in future projects would reduce that processing time and would make estimates in elevation changes more reliable, which could in turn make it possible to detect movements less than one foot with confidence. However, this would increase upfront data collection costs, and detection of surface deformation of less than 0.5 feet is unlikely, even with improved survey grade control. Other site treatments, such as grass trimming with handheld equipment prior to surveys, may have a similar improvement effect on the minimum detection threshold.

Because none of the equipment used to complete the LiDAR scan is permanently installed, no maintenance is required beyond staying abreast of work completed onsite that may have impacted the bare earth ground surface.

8.1.2 Slope Inclinometer

To collect data on subsurface deformation, slope inclinometers were installed at three locations on site. The average cost of installation, including drilling costs, was approximately $130 per foot of casing in 2020. After installation, manual readings were collected at intervals, and each of these reading sets required a day of labor, including travel time from a nearby regional office, at an approximate cost of $1,450. Reading the slope inclinometer casings requires an inclinometer probe, and all surveys must use the same reference point to be compatible. Provided that is known before going out in the field to collect the reading, the process is straightforward and user-friendly. Routine maintenance is required for the slope inclinometer system used to collect the survey, but no maintenance is required on the casing itself, beyond ensuring that the monument and casing are not damaged.

Between repeated surveys, landslide displacements of 0.1 inches or more are typically reliable. Time plays a large role for achieving a high-quality investigation of a slow-moving landslide. Monitoring a known slide over several years while developing a plan for repair that correctly incorporates the depth to movement and the landslide's internal forces is the primary benefit to DOTs. An engineering design that correctly addresses the landslide's driving mechanisms provides value by making the repair more cost-effective in the long run.

Highly effective for long-term monitoring, manual slope inclinometer surveys are however of limited usefulness for real-time monitoring of a high-risk slide. Each reading requires time to collect and process, and personnel typically schedule site trips in advance. Scheduling multiple manual readings during a construction period or wet season can quickly make the manual readings less cost-effective than installation of an in-place inclinometer, described in the following section.

8.1.3 In Place Inclinometer

An in-place inclinometer was installed in LT-3 for a total cost of approximately $2,850, including instrument and installation costs. The IPI uses a vibrating wire tilt sensor and a known gauge length to calculate movement over the shear zone. It needs to be installed in an inclinometer where the shear zone has already been identified, so one where at least two manual readings have been completed. The installation and connection to a datalogger is straightforward. User friendliness is comparable to installing other vibrating wire sensors, like piezometers, crack meters, or tilt meters. The vibrating wire tilt sensors are more vulnerable to rough handling due to its internal mechanisms sensitivity to tilting beyond its range. To remedy this, a set screw is installed during shipping and handling that provides mechanical support to prevent damage.

Over the course of the research program, the IPI consistently measured displacements on the order of 0.01 inches. There was more noise in the readings when the rate of movement was low. Interpretation of movement and triggering events in a more active shear zone likewise would have been less susceptible to noise in the collected data.

Once the IPI is installed, no maintenance is required on the tilt meter, but the logger will need regular visits to check battery charge when not attached to a remote ADAS and/or solar panel. The IPI also supports remote monitoring, something that is not possible with manual slope inclinometer readings. Manual readings can no longer be conducted in the SI casing, because the IPI prevents passage of the probe. As movement continues on the shear zone, the IPI will eventually get stuck in the casing, and will ultimately shear. Data near the end of the instrument's lifespan should be reviewed carefully before being included in monitoring reports.

Because an IPI must be installed in a preexisting inclinometer casing, and because installation prevents future manual surveys of the whole casing, these instruments are best for determining triggering events for landslide movements, monitoring deformation in remote sites, or for high-risk monitoring. Because the IPI tilt sensor is constantly measuring, the vibrating wire datalogger can be set to record over a much shorter time interval than the weeks to months that typically elapse between manual readings. A tighter data interval helps resolve changes in movement rates in response to different external events, such as precipitation or excavation at the toe of the slope due to construction work. Installing an IPI in a remote site can also reduce the number of annual visits required to a long-term monitoring site, since the data can be downloaded manually on an annual basis, or remotely from the office if an ADAS system is enabled. Finally, IPI installation can be particularly cost effective in monitoring earth movements around construction sites, particularly in areas of known slope instability. Real-time data acquisition can support implementation of a monitoring system that sends an alarm to the project manager when displacement rates or net displacements increase above a certain threshold.

8.1.4 Vibrating Wire Piezometer

A vibrating wire piezometer with a 50-foot cable, attached to the outside of the slope inclinometer casing, adds approximately $500 to the cost of each boring. Since landslides are typically driven by the interaction of soil and groundwater, installing a piezometer with the slope inclinometer installation is a cost-effective way to obtain measurements critical to engineering design. Vibrating wire piezometers can be monitored by individual dataloggers or routed to a central base station. Both methods were employed at this project. Depending on the type of datalogger (discussed in the following section) groundwater data from the piezometer can also be monitored in real time and incorporated into alarm warnings for a project.

The vibrating wire piezometers do not measure shear movement, but if placed at the shear zone, they can help answer questions about groundwater conditions at the time of movement. This helps identify water levels and rates of groundwater elevation change that preceded movement events and evaluate mitigation options. For example, dewatering is unlikely to reduce the rate of movement on a slide that is dry, but may significantly slow or halt a slide where movement is driven by seasonal and/or storm-related groundwater changes on the order of feet.

8.1.5 Weather Station

A weather station was used at this site, at a cost of $1,800 in 2020. Knowing precipitation rates can help identify triggering events in a landslide. However, this data can also frequently be obtained from the Climate Data Online (CDO) interface managed by the National Oceanic and Atmospheric Administration (NOAA) at https://www.ncdc.noaa.gov/cdo-web/ when representative weather stations are nearby. Weather data on this site has been QC-ed by NOAA before being made available for downloading. The data from Table Rock Dam referenced in this report was obtained through this website. Note that highly localized precipitation events common with thunderstorms may not be correctly represented when using an offsite weather station. In areas where CDO coverage is poor, and determination of triggering events is critical to monitoring and long-term mitigation, purchase and installation of a weather station at a project site may be required.

Table 10: Comparison of Monitoring Methods for the Ozark Mountain Highroad Landslide

Monitoring Method	Min. Detection Limits(in)	Installation Cost	Annual Cost	Advantages	Constraints
Slope Inclinometer	0.1	\$130/ft[1]	\$5,800[2]	-Uses readily available monitoring system -Records deformation over the entire casing - Readable for decades of use, depending on shear rates	- Typically completed once every few months - Best for collecting seasonal displacement data -Require in-person site visit to collect data
In-Place Inclinometer	0.005	\$2,850[3] (+ cost of SI casing installation)	N/A	- Enables near real-time data collection with a datalogger - Can be integrated into a remote monitoring system, reducing the frequency of site visits - Enables better identification of movement triggering events - Supports integration with ADAS system to trigger an alarm based on measured movements	- Requires data logger - Requires purchase of additional instrumentation - Must be installed in existing slope inclinometer casing that displays a discrete shear zone - Survey of entire casing cannot be completed while IPI is installed - Most effective in shear zone less than 2/3 the length of the total IPI gauge length (e.g., less than 3.5 ft for a 5 ft IPI)
LiDAR Scan	12	N/A	\$7,000[4]	- Similar in annual cost to quarterly slope inclinometer monitoring - Covers larger project area - Detect expansion of slide or new areas of movement - Identify different movement rates within slide mass	-Requires GIS experience to process and interpret data - Does not detect depth of slide movement -Survey quality can be reduced by vegetation density, especially thick grass -Necessary time lapse between surveys makes it difficult to identify single

Notes:

[1] *Approximate cost of installed casing, including drilling costs and instrumentation component costs. Does not include inspection costs*

[2] *Assumes quarterly surveys (4x per year) and a full day spent on traveling to the site and collecting data*

[3] *Combines approximate costs of instrument and installation, assumes a full day spent travelling to site, installing, and programing the IPI*

[4] *Assumes one survey per year*

8.2 Method Analysis for Data Acquisition

There are multiple options for logging and retrieving data from a site, and comparison of different equipment manufacturers was not part of this research project. Instead, this section describes the decision-making process behind the equipment selected for use at Ozark Mountain Highroad.

The data acquisition system used in this project was selected based on Landslide Technology's experience in past projects. It used Campbell Scientific equipment, including dataloggers, a weather station, and the modem connection. Additional supporting components, such as solar panels and rechargeable batteries, were purchased from others. A complete "parts list" for the monitoring system constructed at the Ozark Mountain Highroad is included in Appendix B.

Campbell Scientific is one of many companies making vibrating wire dataloggers, including RST, GEOKON, and DGSI. These dataloggers also support the addition of radio antennas to enable data transmission within a job site. These other dataloggers have some advantages over the CRVW-3 and CR6, like a smaller size and an ability to run for a long duration on small batteries, instead of the solar-panel and rechargeable battery setup employed at the Ozark Mountain Highroad. Single or double vibrating wire dataloggers are typically as easy to program and install as the Campbell Scientific loggers, and typically cost less on a per-logger basis. The CRVW-3 and CR6 were selected for use on this project because the CR6 can integrate with both vibrating wire piezometers from LT-1 and LT-2 and the weather station installed at the base station, which required connection through a control terminal as opposed to a vibrating wire terminal. It also supports data acquisition from the radio at LT-3 and the modem connection necessary to make remote data acquisition possible from the office.

All data logger manufacturers have their own software programs to communicate with loggers in the field and configure loggers to collect data. Campbell Scientific's program is Loggernet and comprises a suite of software for programming, configuration, communications, and etcetera. Some modules, like Loggernet DevConfig, are free. Others, like Loggernet Connect, must be purchased as part of the Loggernet suite. The CRWV3 can be configured and deployed in the field using DevConfig. This module is a tabbed interface prompting the user to enter information on the vibrating wire sensors, type of data output desired, and logging interval. Barriers to use are low, and it is user friendly.

Programming the CR6 requires coding be uploaded through the Loggernet Connect module and requires users to develop, have, or hire programming expertise. The CR6 accepts custom CRBasic code, which is developed in the office and the uploaded either remotely or in the field. Drafting this code typically requires either previous experience with CRBasic, or a resource of someone who does. Campbell Scientific provides the Loggernet module Short Cut to assemble a program for basic data acquisition. However, more advanced functions, such as alarming, are not possible with Short Cut. When remote monitoring is enabled, the upfront coding process provides the benefit of providing formatted tables with engineering units suitable for straightforward processing, plotting, and online presentation.

An additional consideration when choosing loggers for this project was the focus on remote monitoring of landslide movement. The tables generated by the CR6 after it was programed could be easily queried by the Konect service for display on the project website. Landslide Technology also expected logging intervals and other table calculations to require updating over the course of the project. Using Loggernet's Connect and a CR6 datalogger equipped with a modem made those updates possible to complete remotely.

The results of this analysis and points for consideration when purchasing data acquisition equipment for future projects are summarized in Table 11.

Table 11: Comparison of Data Monitoring Equipment used for the Ozark Mountain Highroad Landslide

Datalogger	Unit Cost[1]	Number of Instruments Supported	Advantages	Constraints
CRVW3-407	$1400 (logger) + $200 (supporting components)	3 (6 channels total)	- Uses readily available USB Micro-B cable for field data connection - Can be reconfigured in the field - Supports radio communication between logger and base station, and incorporation into ADAS system	- Will not fit in a standard above-ground or flush-mount monument, requires additional mounting post - Does not support a weather station or other non-vibrating wire type sensors
CR6-407	$2300 (logger) + $350 (supporting components)	12 universal inputs that must be programed based on instrument type	- Supports both vibrating wire, weather station, and other sensors - Supports communication with other loggers on site - Supports modem connection for communication with web-based data applications	- Programming is more complex than CRVW-3 - Difficult to reconfigure without use of proprietary LoggerNet software
ADAS System with remote communication capabilities	$1,100 (components) + $250 (annual IP subscription) + $50 (monthly cell service)	N/A	- Enables remote data downloads and remote updates of logger program code - Allows implementation of an alarm when trigger conditions are identified - Vandalism or damage to an instrument can be identified before a scheduled site visit - Reduces number of site visits to an annual or biannual maintenance visit	- Additional equipment required to implement - Subscription cost of cellular data connection - Additional programing skills required to set up the ADAS system

Notes:
[1] Does not include cost of logger and associated supplies (solar panel, battery, enclosure, modem, etc.)

9 CONCLUSIONS AND RECOMMENDATIONS

The research team hopes the work completed on this project is beneficial to MoDOT for developing monitoring programs at other slow-moving or seasonally active landslides in the state. Although the conclusions on landslide geometry and triggering events are specific to the Ozark Mountain Highroad, the methods used to reach these conclusions could be employed at other slides.

9.1 Additional Considerations

Regardless of the conclusions on the monitoring methods analysis in Section 8, site constraints may ultimately make some monitoring techniques more feasible than others. Because the top of the cut slope slide was accessed from old Route 76 and the main body of the slide was accessible from Route 76, the drilling and access at Ozark Mountain Highroad occurred entirely in MoDOT's right of way (ROW). As a result of the overlapping ROWs from these three roads, MoDOT had access to the entire slide from all directions. This is not always the case, and there are likely other slides that are located partially on neighboring private or public property or properties. Instrumenting these slides will require coordination with the adjacent property owner(s). Landslide Technology recommends making every effort possible to gain access when needed as incomplete and/or erroneous information can often lead to increased rates of movement, incorrect engineering calculations, inadequate or overbuilt stabilization measures, and the accompanying risks of managerial and public perception.

Instrumentation and dataloggers that have been paid for and installed are one-time costs, but remote access to view and download data or receive a notification of a triggering event relies on data subscriptions. For example, the Konect GDS system used at the Ozark Mountain Highroad had a monthly cellular and website service subscription of $50 per month. Maintaining these subscriptions through multiple budget cycles will require on going coordination within the department. Likewise, LiDAR scans collected by others are a one-time cost, and getting budget allocated to ensure they are conducted at the same general time each year will require additional effort from the project manager.

9.2 Considerations in Program Development

When expanding this research to other sites, we recommend that, in addition to completing the monitoring methods analysis in Section 8, the team responsible for developing the landslide monitoring program also collect the following information:

Site History. There is often a lag between when a slow-moving landslide is initiated, and when it is perceived as a threat to the roadway. Review of construction documents and historic satellite photos can provide information on original conditions, the approximate time that movement initiated, and the relative rate of growth. In this project, Google Earth was an excellent resource for publicly available historic images, but only went back to the early 1990s. Taken together, these data sources on past slide behavior, even if anecdotal, can help estimate how long the monitoring period will need to be in order to identify slide geometry and triggering events, which is critical for budgeting purposes.

Monitoring Duration. Planning and implementing a sufficient duration for monitoring is critical for understanding slide behavior prior to designing a repair. Very limited movement was recorded at the Ozark Mountain Highroad for the first 12 months of the project, leading to a monitoring extension for the project. Such periods of inactivity are common for slowly moving landslides. Minor movements were recorded in the second year of monitoring and used to identify triggering conditions. However, a repeat of the May 2020 event, with conditions that led to the slide doubling in size and a new earth flow initiating, all immediately prior to the start of monitoring, were not encountered during the two-year monitoring period. The Ozark Mountain Highroad demonstrates that benefit of having multiple seasons of monitoring completed before attempting to identify triggering events, particularly for slow-moving landslides.

Access. This project confirmed the importance of getting a boring through the slide mass to identify the subsurface materials and define site geometry. At Ozark Mountain Highroad, drilling in the embankment slide was straightforward, because the head scarp of the slide was in the paved roadway, and the borehole could be installed just beyond the paved shoulder. In contrast, drilling on the cut slope slide required additional effort, planning, and work for drill rig access. Drilling planned for early June also had to be delayed until late summer, to allow the cut slope soils to dry out. At the time of the site reconnaissance in May, the clay was so soft and saturated that it was difficult to traverse the slide area on foot. Working with the driller on what the minimum improvements necessary for site access also requires coordination and clear communication of the project goals. For example, the improvements made for the drill rig in this project improved local stability in that part of the landslide, although it did not stop subsurface movement.

In-House Expertise. Regardless of the type of data collected, evaluating it and drawing reasonable conclusions is only possible if the geotechnical engineer or engineering geologist has experience and is either personally familiar with the associated data analysis or is getting guidance from someone who does. This is true when reducing manual survey data and identifying shear zones or when comparing LiDAR data sets with GIS tools. Where in-house expertise becomes critical is in the development and programing of remote data acquisition systems. These coding programs have a steep learning curve, and implementation of an automated data acquisition system (ADAS) that can be accessed through the web is likely to require coordination with multiple groups within the department. If MoDOT wants to develop in-house expertise in bringing ADAS online for multiple sites, we recommend selecting a champion from within the group and support them through the first ADAS implementation, knowing that setting up and programing all subsequent systems will be much easier. Note that training classes are available from Campbell Scientific for system design and basic programming.

Regardless of the monitoring method or methods selected for the slow-moving landslide, long-term monitoring continues to provide benefits. This research program, for example, cost $150,000 but identified a previously unknown landslide on the northbound lanes, determined the depth of movement at both slides, and identified likely triggering events. Should a mitigation future mitigation plan be developed for these landslides, the design team is now in a better position to determine if, for example, a shallow rock inlay would be sufficient to halt the cut slope slides or if installing horizontal drains along the embankment fill – native soil contact would be sufficient to prevent additional pavement damage above the embankment slide.

9.3 Closing

There are numerous benefits to long-term landslide monitoring. First and foremost, it permits the design team to characterize the subsurface materials, groundwater conditions, define landslide geometry, and understand movement rates and triggers. This information is required for cost effective and functional mitigation measures that will stabilize the investigated landslide. Acknowledgement that an investigatory period may last several years for slow moving landslides is important for setting budgets, timelines, and managing expectations. Performing focused landslide investigation programs during early, multi-year planning studies in corridors known for unstable slopes would allow MoDOT the time needed to detect and measure landslide geometry prior to preliminary and final design efforts.

This research project has provided MoDOT a toolbox for using a variety of long-term remote monitoring techniques and has reaffirmed that site investigations incorporating long-term monitoring are a critical component of responsible management. Applying research results by developing investigation and accompanying monitoring programs will help MoDOT ensure success during the planning, investigation, design, and construction process for landslide mitigation and within landslide-prone corridors.

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Appendix A: Site Plans, Boring Logs, Instrument Calibration Sheets

Appendix B: Monitoring Equipment and System Component List

Appendix C: Current CRBasic Code for CR6 Datalogger

Appendix D: Instrumentation Maintenance Guide