



Landslide Collides with Highway: Measuring Its Impact to Inform Future Mitigation – FINAL REPORT



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Frozen debris lobes (FDLs) are slow-moving landslides in permafrost. Recognizing the risk that FDL-A presented to the Dalton Highway, the Alaska Department of Transportation and Public Facilities realigned a portion of the highway about 400 ft downslope in 2018. The imminent collision of FDL-A with the abandoned section of embankment provided a unique opportunity to study the interaction between this landslide and highway in a safe and controlled way and on a somewhat predictable schedule. In August 2020, we conducted a subsurface investigation, drilling four boreholes, sampling the subsurface soils, and installing geotechnical instrumentation within the abandoned section of embankment. Analysis of the data indicated that FDL-A was shearing approximately 13 ft below the bottom of the Dalton Highway embankment before this project started and while the lobe was still tens of feet away. At the time of this report, FDL-A has horizontally displaced the embankment ~9 inches. Given the depth of shearing within the bedrock, and the weak nature of the bedrock, we postulate that the embankment will do little to stop FDL-A's downslope progression.				
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APPROXIMATE CONVERSIONS TO SI UNITS

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
<u>LENGTH</u>					<u>LENGTH</u>				
in	inches	25.4	mm	mm	millimeters	0.039	inches	in	
ft	feet	0.3048	m	m	meters	3.28	feet	ft	
yd	yards	0.914	m	m	meters	1.09	yards	yd	
mi	Miles (statute)	1.61	km	km	kilometers	0.621	Miles (statute)	mi	
<u>AREA</u>					<u>AREA</u>				
in ²	square inches	645.2	millimeters squared	cm ²	mm ²	millimeters squared	0.0016	square inches	in ²
ft ²	square feet	0.0929	meters squared	m ²	m ²	meters squared	10.764	square feet	ft ²
yd ²	square yards	0.836	meters squared	m ²	km ²	kilometers squared	0.39	square miles	mi ²
mi ²	square miles	2.59	kilometers squared	km ²	ha	hectares (10,000 m ²)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
<u>MASS (weight)</u>					<u>MASS (weight)</u>				
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
<u>VOLUME</u>					<u>VOLUME</u>				
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft ³	cubic feet	0.0283	meters cubed	m ³	m ³	meters cubed	35.315	cubic feet	ft ³
yd ³	cubic yards	0.765	meters cubed	m ³	m ³	meters cubed	1.308	cubic yards	yd ³
Note: Volumes greater than 1000 L shall be shown in m ³									
<u>TEMPERATURE (exact)</u>					<u>TEMPERATURE (exact)</u>				
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C	°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
<u>ILLUMINATION</u>					<u>ILLUMINATION</u>				
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m ²	cd/cm ²	cd/cm ²	candela/m ²	0.2919	foot-lamberts	fl
<u>FORCE and PRESSURE or STRESS</u>					<u>FORCE and PRESSURE or STRESS</u>				
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi
These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements									

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DEDICATION

The first author dedicates this report to her long-time colleague in FDL research and dear friend, Dr. Ronald (“Ronnie”) Daanen, who died in a helicopter crash while conducting field work on the North Slope of Alaska on July 20, 2023.

EXECUTIVE SUMMARY

Frozen debris lobes (FDLs) are slow-moving landslides in permafrost in the Brooks Range of Alaska. FDL-A is the largest and closest to the Dalton Highway, located at Milepost 219. Recognizing the risk associated with FDL-A, the Alaska Department of Transportation and Public Facilities realigned the Dalton Highway to a location about 400 ft downslope in 2018. The imminent collision of FDL-A with the abandoned section of embankment provided a unique opportunity to study the interaction between this landslide and highway in a safe and controlled way and on a somewhat predictable schedule. Through this project, we documented this collision by: 1) measuring the deformation of the abandoned Dalton Highway embankment and subsurface; 2) measuring earth pressure during the collision of FDL-A with the embankment; 3) testing subsurface material properties; and 4) observing the collision through repeat lidar scans and repeat photography. In August 2020, we conducted a subsurface investigation, drilling four 40-ft deep boreholes and sampling the subsurface soils, and installing geotechnical instrumentation within the abandoned highway embankment. Where drilled, the embankment was 10-12-ft thick, overlying non-plastic slightly organic silty sand with gravel to silty gravel with sand. We intercepted white mica schist bedrock in all boreholes, ranging from 14 to 32 ft below the embankment surface. We intercepted the permafrost table in three of the boreholes. We collected two split-spoon samples of the white mica schist bedrock, which we were able to test using the direct shear method. These samples yielded a friction angle of 30.8° and cohesion of 1.27 psi.

The geotechnical instrumentation indicated that FDL-A was shearing approximately 13 ft below the bottom of the Dalton Highway embankment before this project started in 2020 and while the lobe was still tens of feet away. As of the date of the last data download for this project (July 25, 2023), FDL-A had displaced the embankment approximately 9 inches horizontally. This horizontal displacement may be manifesting as cracks within the embankment surface. Through analysis of daily photographs taken of the toe, we observed evidence of rotational failure, shearing and buckling, and soil slumping at the surface. Field observations indicated that FDL-A started to overlap the side slope of the highway embankment at the ground surface in July 2022. Subsurface instrumentation indicated that the actual mass of FDL-A impacted the embankment at and above the original ground surface around June 1, 2023. So far during this collision, there have been no unusual changes in water pressure or temperature measured within the embankment. The progression of FDL-A's approach and collision with the abandoned Dalton Highway embankment can be viewed through time-lapse videos available on the webpage for FDL research (fdlalaska.org).

The annualized rate of movement for July 2022 to July 2023 was 26.1 ft yr^{-1} . This is a slight reduction in movement rate from a peak measured in 2020, which is attributed to cooling of the lobe caused by low and late snowfall during 2020/21. FDL-A, however, also has been interacting with the highway embankment since that time, which may be serving as an additional impediment to its downslope movement. Given the depth of shearing within the bedrock, however, we postulate that the embankment will do little to stop FDL-A's downslope progression.

1 INTRODUCTION AND PROBLEM STATEMENT

Part of the Alaska Department of Transportation and Public Facilities' (ADOT&PF) Strategic Plan is to “provide a safe and efficient transportation system for Alaska to thrive” and to “provide Alaskans with access to goods, services, economic opportunities, each other, and the world (ADOT&PF 2020).” Alaska’s extreme weather, difficult terrain, and ice-rich frozen ground make these goals sometimes difficult to obtain. For example, when geologic hazards impact major transportation corridors, these events may stop access, and reduce safety and efficiency until mitigated. As an example of geologic hazards, frozen debris lobes (FDLs) are landslides in permafrost, 23 of which are within a mile uphill of the Dalton Highway in the Brooks Range. The largest and closest FDL to the highway is FDL-A at Milepost (MP) 219 (Figure 1). Recognizing the risk associated with FDL-A, the ADOT&PF realigned the Dalton Highway to a location about 400 ft downslope of the existing alignment during the 2018 construction season (Figure 1), effectively “buying” time before FDL-A impacts the new alignment location; however, moving the highway, which cost over \$1M, was only a temporary solution.

The imminent collision of FDL-A with the abandoned section of embankment provided a unique opportunity to study a landslide impacting a roadway in a safe and controlled way and on a somewhat predictable schedule. The MP219 location represents an opportunity for an unprecedented, full-scale experiment to observe and measure how the FDL deforms the existing embankment. What is learned from this collision will be critical information in future mitigation plans for FDLs, and

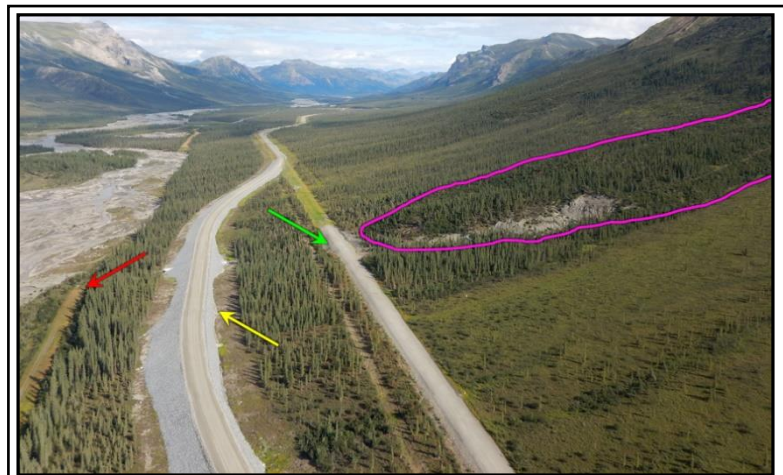


Figure 1. Oblique view of FDL-A (outlined in pink), the old (green arrow) and new Dalton Highway (yellow arrow) alignments, and the location of the buried Trans Alaska Pipeline System (red arrow), as seen in August 2019.

also can be applied to other mass movement events throughout the State of Alaska. ***Thus, our research objective was to obtain data from the collision of a landslide with an engineered structure in a full-scale field experiment.***

We proposed to achieve the project’s objective through the following tasks: 1) measure the deformation of the abandoned Dalton Highway embankment and subsurface; 2) measure earth pressure during the collision of FDL-A with the embankment; 3) measure soil strength properties of existing embankment and subsurface soils; and 4) document the collision through geomechanical instrumentation, repeat lidar scans, and repeat photography. Because of the nature of this full-scale experiment, meaningful results remain dependent on the timing of the collision of FDL-A with the abandoned Dalton Highway embankment. This report summarizes the work and analysis conducted on this project from July 2020 until September 2023.

2 SUBSURFACE INVESTIGATION AND EQUIPMENT INSTALLATION

2.1 Description of drilling program and instrumentation installation

The research team – consisting of M. Darrow and P. Presler (*University of Alaska Fairbanks (UAF)*); R. Daanen (*Alaska Division of Geological & Geophysical Surveys (DGGs)*); J. Simpson, S. Parker, and P. Lanigan (*ADOT&PF Northern Regions Materials Section (NRMS)*) – performed the subsurface investigation and equipment installation into the abandoned section of the Dalton Highway from August 12-17, 2020. First, ADOT&PF NRMS personnel dug a shallow trench into the embankment surface for burial of instrumentation cabling. All boreholes were advanced using a truck-mounted CME 55 drill rig, which was centered over the trench (Figure 2a). We completed four 40-ft deep (as measured from the embankment surface) boreholes using hollow-stem auger, which allowed for split-spoon sampling during drilling and served as a casing to keep each borehole open during instrument installation. We placed one MEMS-based in-place inclinometer (M-IPi), a temperature sensor cable, and one vibrating wire piezometer (VWP) into each boring (Table 1). All cabling was routed to the automated data acquisition system (ADAS) through the shallow trench and buried. We collected split-spoon samples at 2.5-ft intervals, providing near-continuous visualization of the subsurface materials. We collected representative samples from each borehole, which were sealed and transported to the Frozen Soil Testing (FROST) Laboratory at the University of Alaska Fairbanks (UAF) for laboratory testing (see Section 2.3).

Simultaneous with the drilling, the UAF-DGGs research team laid out tilt meters and pressure plates for installation on the east/uphill side of the embankment. For each borehole location, a 2 MPa pressure plate and tilt meter (both affixed to a single steel plate) were installed vertically into a slot dug into the edge of the embankment (Figure 2b). The exception was at TH20-02, where an additional 5MPa pressure plate on its own steel plate was installed within the embankment side slope. It was during this effort that we discovered that the tilt meter cables were provided to the specified length in feet instead of meters, and thus were too short to be installed where desired. To accommodate the short cables, we moved an automated data acquisition system (ADAS) associated with a 2018 subsurface investigation into the middle of the embankment, and dug an additional trench to route the remaining 2018 instrumentation cables, plus the tilt meter and pressure plate cabling, to this central ADAS (Figure 2c). Later, in summer 2022, we exposed the buried cables, extended them through splicing, routed the extended cables to the south, and moved the second ADAS out of the way of FDL-A's imminent impact with the embankment.

We installed two ADAS at the south end of the embankment section, one for the time-lapse camera system, and one to serve as the main ADAS for the majority of the instrumentation (Figure 2d). The time-lapse camera system (Nupoint Systems Inc.) was set up to deliver one photograph per day of the toe of FDL-A, which was transmitted to UAF via a satellite uplink. Additionally, we mounted two additional stand-alone field cameras (Reconyx) to acquire images of the landslide collision from different angles. The main ADAS consisted of a data logger, solar regulator, solar panel, battery bank, and the necessary instrumentation to serve as a weather station for the project area, including measurements of air temperature, precipitation, and snow



Figure 2. Images from the 2020 drilling program: a) drill truck centered on trench to drill TH20-03; b) looking down at the pressure plates and tilt meter embedded into the uphill side slope of the embankment near TH20-02; c) looking to the north at the 2020 location of the secondary ADAS moved to accommodate the short cables; d) all ADAS at the southern end of the project location in 2022; e) interpretative display installed as an outreach component.

Table 1. Summary of geomechanical instrumentation installed in the old Dalton Highway embankment.

Instrument	Manufacturer	Specifications
VW piezometer	Geokon	4500B (slim model), 700 kPa pressure range; cable length varies per installation
Temperature sensor string	---	re-used for this installation and failed to work properly; see text for explanation
M-IPi	Measurand	SAAV, 10-m long with 20 0.5-m long segments; cable length varies per installation
Pressure cell	Geokon	4815 (for granular soil); 4 at 2 MPa, 1 at 5 MPa; armored cable until centerline, transitioning to regular cable (length varies)
Tilt meter	Geokon	NEMA 4 enclosure; biaxial model; armored cable until centerline, transitioning to regular cable (length varies)

depth. ADAS components were mounted inside an enclosure or directly onto a rugged tripod that was anchored into the embankment surface.

As an outreach component, near the ADAS we installed an interpretive display made out of rugged materials to withstand the harsh weather conditions of the area (Figure 2e). This sign and research area have become a regular stop for tour companies and tourists. The PI has received many positive comments about the sign and its presentation of the research project. Figure 3 is a project map that includes the location of the ADAS and instrumentation.

2.2 Subsurface soils

Figure 4 contains schematics of the four boreholes. Where drilled, the embankment ranged from 10 to 12-ft thick, consisting of moist, brown, non-plastic silty gravel with sand to silty sand with gravel. The foundation soils typically consisted of brown, non-plastic slightly organic silty sand with gravel to silty gravel with sand. These soils were moist to wet where unfrozen. We intercepted gray, white mica schist bedrock in all boreholes, varying between 14.0 and 32.0 ft below the embankment surface. The highly weathered bedrock was moist to wet where unfrozen. We intercepted the permafrost table 19.8 to 25.0 ft below the ground surface in TH20-01 through TH20-03. A water table was perched on the permafrost table in TH20-01 and TH20-02. We also intercepted a water table in TH20-04.

2.3 Laboratory testing results

We transported all samples to the UAF FROST Laboratory for standard tests, including moisture content, Atterberg limits, and particle-size distribution including hydrometer tests and sieve analyses (ASTM D2216-19, D4318-17e1, D7928-21, D6913M-17, respectively (ASTM 2017b, 2017d, 2019, 2021)). We classified samples using the Unified Soil Classification System (USCS; ASTM D2487-17e1 (ASTM 2017a)). Test results are included in Figure 4, as well as in the appendix. One objective of the soil testing was to determine soil strength properties. We had difficulty in collecting intact samples with the split-spoon sampling method due to the coarse nature of the soils and their moisture content. We were able to collect three split-spoon samples of the bedrock material in TH20-04. The high moisture content and weathered

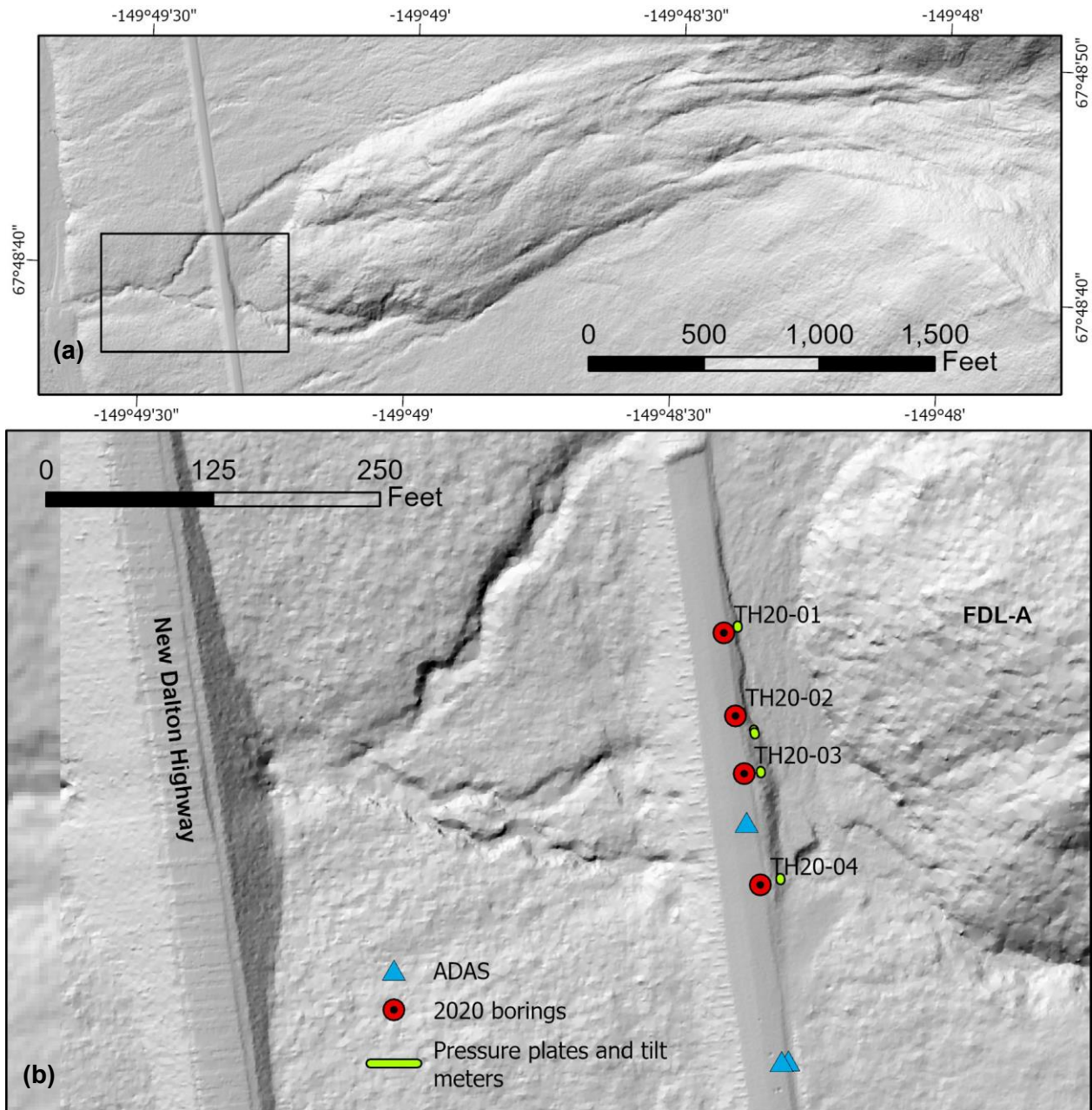
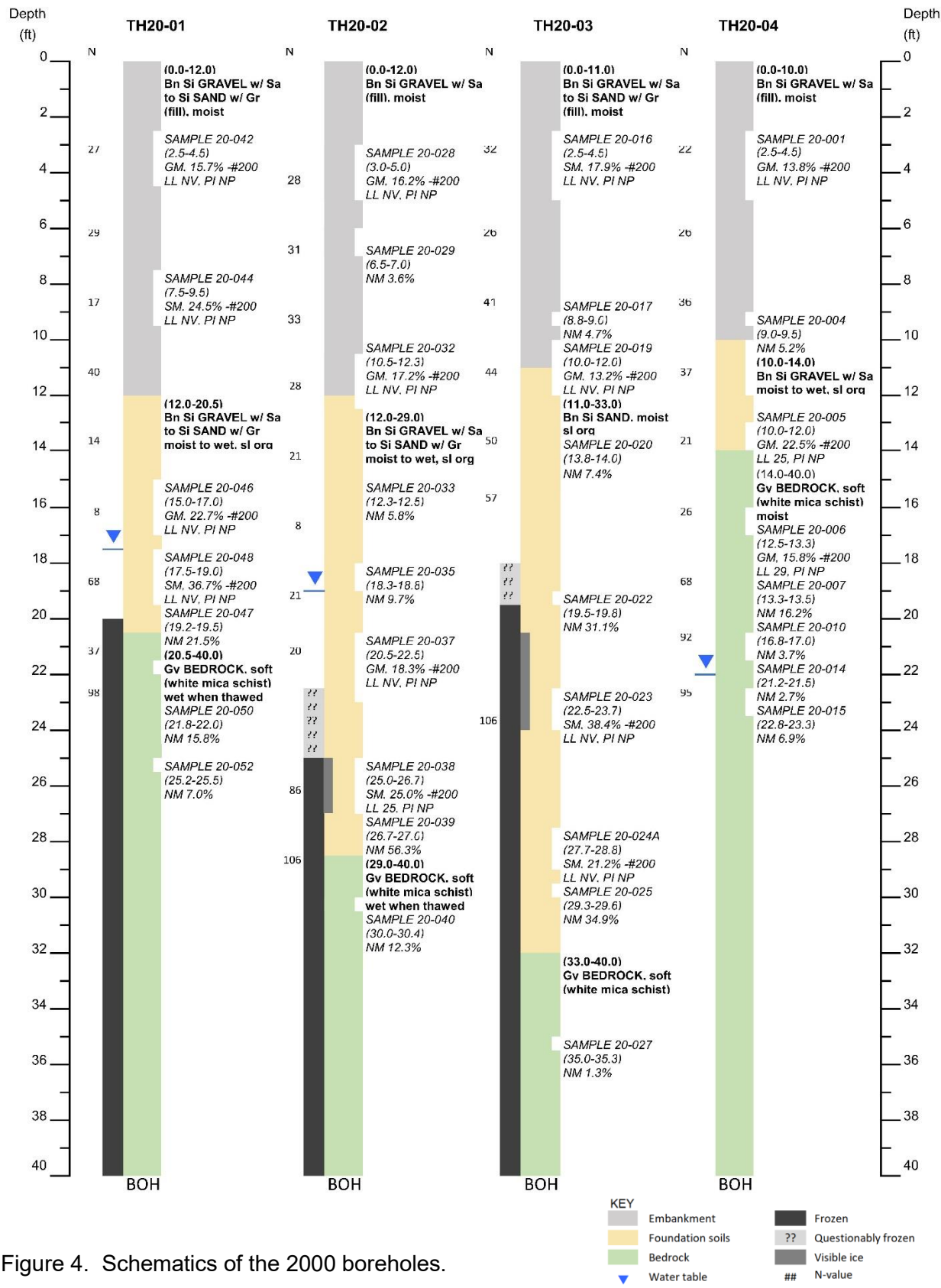


Figure 3. Project location: (a) FDL-A to the east of the original Dalton Highway alignment (background imagery is unpublished 2015 lidar); (b) location of borings and instrumentation relative to the toe of FDL-A, and the original and new Dalton Highway embankments (background imagery is unpublished 2020 lidar).



condition of the bedrock samples allowed us to prepare test specimens for direct shear tests (ASTM D6528-17; ASTM 2017c). We tested two sets of three samples of the weathered white mica schist bedrock at above-freezing conditions. The average values of those tests are as follows: moist unit weight of 113.5 lb/ft³, moisture content of 6.4%, friction angle of 30.8°, and cohesion of 1.27 psi.

3 SUMMARY AND INTERPRETATION OF FIELD DATA

3.1 Real-time Kinematic Global Positioning System (RTK-GPS) measurements and field observations

We collected RTK-GPS measurements of surface marker pins on eight FDLs. Seven FDLs are accessible by foot from the Dalton Highway. The eighth monitored FDL is across the Dietrich River from the highway and required the use of a helicopter for access, which was generously provided by the Alyeska Pipeline Service Company (APSC).

Figure 5 is a summary of the annualized rates of movement since 2013, when monitoring of all eight FDLs began. Note that the annual variations of movement have been removed from this figure for simplicity. Seven of the FDLs have demonstrated an ongoing increase in their movement rates over the period of observation. With the 2023 data, FDL-D demonstrates a downward trend in its overall movement rate for the first time since monitoring began. Figure 6 is a summary of FDL-A's rate of motion, including rates obtained from analysis of historic imagery (see Darrow et al. 2016) and recent RTK-GPS measurements; note that the vertical scale in this graph is in m yr⁻¹. A linear trend is the best-fit for the historic rate of motion, with an R² of 0.95 (blue series, Figure 6). When the recent RTK-GPS rates are added, the best-fit is no longer linear (orange series with R² of 0.62), but is exponential (red series with R² of 0.82). The recent measurements demonstrate slower rates after 2020. We attribute this slowing mainly to snowfall. The winter of 2020/21 had a late snowfall that also resulted in about half of the accumulation typical for the area (i.e., ~15 inches versus ~30 inches, based on Coldfoot data; SNOTEL site 958). The lack of insulation provided by the snow had the effect of cooling the subsurface, which slowed movement. The annualized rate of movement for July 2022 to July 2023 was 26.1 ft yr⁻¹.

3.2 Lidar data acquisition and change detection analysis

We conducted lidar scanning of the FDL-A toe area in May 2021 and June 2022, using a Riegle VUX-LR integrated into a fully dynamic lidar system by Phoenix lidar. We used a backpack to transport the lidar system, which allowed scanning of the small toe area. The system is setup with RTK-GPS for accurate location information at 10 points per second. Between RTK-GPS readings, the system relies on a Northrop Grumman Inertial Momentum Unit (IMU) at a rate of 100 times per second. The combination of these two devices makes it possible to know the location and orientation of the device with an accuracy of about 1 cm. We produced digital elevation models (DEM) at a resolution of 10 cm from each lidar scan.

We took the difference between the 2021 dataset and a previously-collected 2020 dataset (not part of this project), and between the 2022 and 2021 datasets, producing DEMs of Difference (DoDs). Figure 7 contains these DoDs; note that the data presented here are in meters. Each has been masked to exclude differences less than 0.5 m. Differencing between the datasets

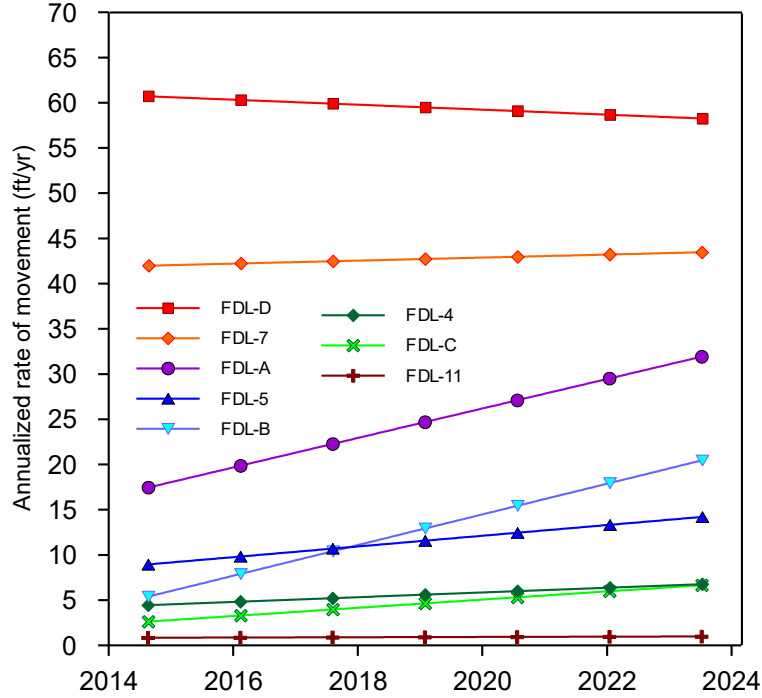


Figure 5. Annualized rate of movement summary for the eight investigated FDLs from 2013 to July 2023. Symbolized lines represent linear fits to average annualized rates for each FDL. Note that annual variations in movement have been removed for simplicity.

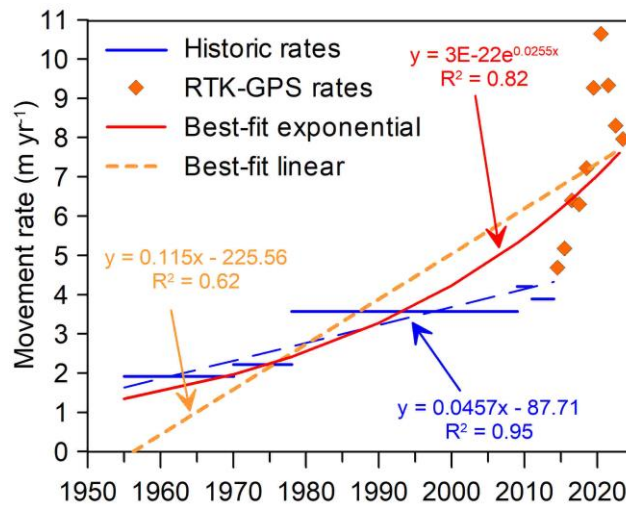


Figure 6. Integration of historic and recent movement rates of FDL-A. Note that the vertical scale is in m yr^{-1} .

collected for this project and the 2020 lidar indicated movement in areas for which there should be none (e.g., areas of light green color west of the embankment in Figure 7a). We attribute this to lidar collected after leaf out in 2020. There was better agreement between the 2021 and 2022 data sets, resulting in error of less than 0.43 m (Figure 7b); however, the 2021 dataset demonstrated pixelated areas that produced artifacts along the eastern part of the embankment (i.e., light orange area in Figure 7b). Field observations indicated that there is no bulging within the abandoned Dalton Highway embankment in this area. Despite these discrepancies, these datasets illustrate dramatic changes in the position of the toe of FDL-A, with vertical changes up to 8.2 m.

3.3 Time-lapse imagery

The camera system worked well, with a few exceptions. The solar panel controller malfunctioned in the fall of 2020, causing excess voltage to the camera. Members of the research team traveled to the site in November 2020 to replace the camera and the solar controller, and to download data. The replacement camera worked well; however, it did not have a defrost option so some images were not useable due to the frosted lens during some periods of the winter. Additionally, there were a few periods during the project when the satellite array did not allow for transmission from the site; thus, some photographs were not received.

Despite the lost or unusable images, we successfully received enough daily images to build a time-lapse video beginning in January of 2021. Through analysis of these images, we can discern daily movement and gage qualitative changes in velocity at the toe. When the images are viewed as a time-lapse movie, the movement of FDL-A becomes obvious, even in the winter months.

We also made a time-lapse video from one of the Reconyx cameras, which we mounted at the north end of the study site. This camera provided daily images, although the tree to which it was mounted was knocked out of plumb by movement of FDL-A. In July 2023, the camera was threatened by the toe of FDL-A. We repositioned the camera to the west, downhill side of the abandoned Dalton Highway embankment in an attempt to capture evidence of shearing within the embankment. We direct the reader to the FDL website (fdlalaska.org) to view these videos.

3.4 Data integration and analysis

3.4.1 Borehole temperature measurements

We were not able to acquire useful data from the digital temperature cables due to issues with hardware and programming. While occasional temperature readings most likely were accurate, they were not frequent enough to be useful. During multiple field visits, we tried to troubleshoot and reprogram the data logger, while in communication with company representatives via satellite phone. Despite these efforts, we could not establish proper and consistent readings. We disconnected the digital temperature cables in early 2022 because we suspected that they were interfering with the M-IPI readings, which we deemed the most important component of this research. Fortunately, the M-IPI contain temperature sensors in each of their instrumented segments. Although uncalibrated, these sensors can serve as a back-up for temperature

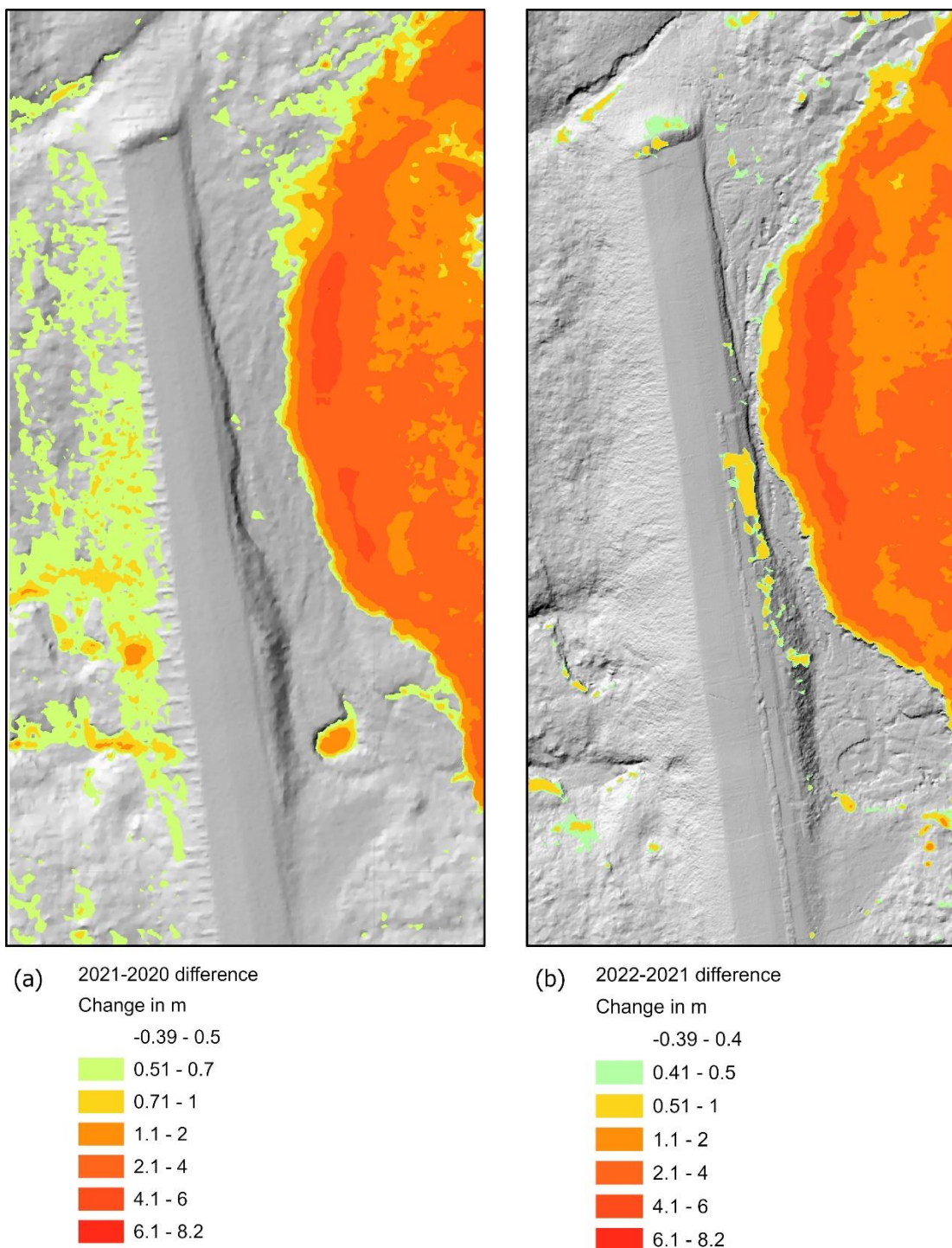


Figure 7. DEMs of difference for the toe area of FDL-A: (a) between 2020 and 2021; (b) between 2021 and 2022. Base map data are 2020 and 2022 lidar, respectively, both unpublished.

measurements (Darrow and Jensen 2012). Figure 8 contains an example of the temperature profiles for TH20-01 for months for which we have complete data (note that this figure is in SI units).

3.4.2 Borehole water pressure measurements

Figure 9 contains the VWP water pressure and temperature readings over the project measurement period. The southern VWP (TH20-04) was located close to the pre-existing culvert, and thus is interpreted as experiencing groundwater pulses within the old drainage channel. This location demonstrated two yearly peaks in groundwater, which represents snowmelt (late May/early June) and the summer rainy period (July). The VWPs in TH20-01 and TH20-02 also demonstrated increases in groundwater pressure in the late summer but with slower response times.

All VWP temperatures dropped after installation, most likely reflecting the dissipation of the heat due to drilling. The southern VWP (TH20-04) recorded the warmest temperature, with the adjacent VWP in TH20-03 recording the coldest temperatures. In fact, the VWP in TH20-03 froze around April 24, 2021, which is reflected by smooth water pressure measurements. This VWP recorded above-freezing temperatures on September 7, 2021; however, the smooth water pressure measurements continued until February 24, 2022, possibly indicating the amount of time for the grout at that depth to thaw completely to allow transmission of water pressure.

3.4.3 Pressure plate and tilt meter measurements

Figure 10 contains graphs of (a) the temperatures recorded by the tilt meters and pressure plates, (b) the pressure plate readings, and (c) the tilt meter readings. As all of these devices were buried within 2 ft of the surface, the temperatures are closely dependent on air temperature and demonstrate the seasonal temperature fluctuations. All of these temperatures generally follow each other well. Thus, it is notable that the temperatures from pressure plate 1

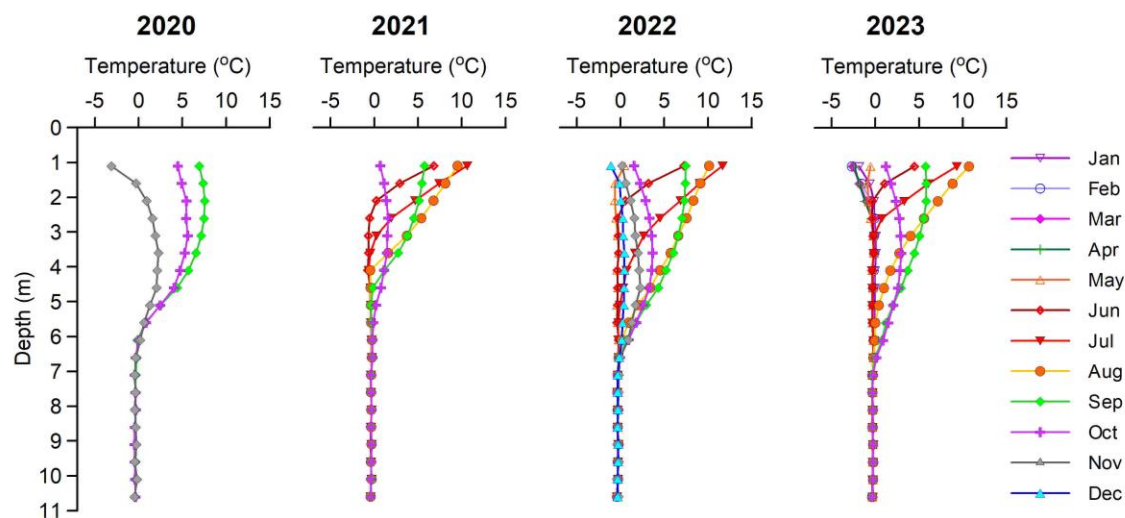


Figure 8. Temperature profiles from TH20-01.

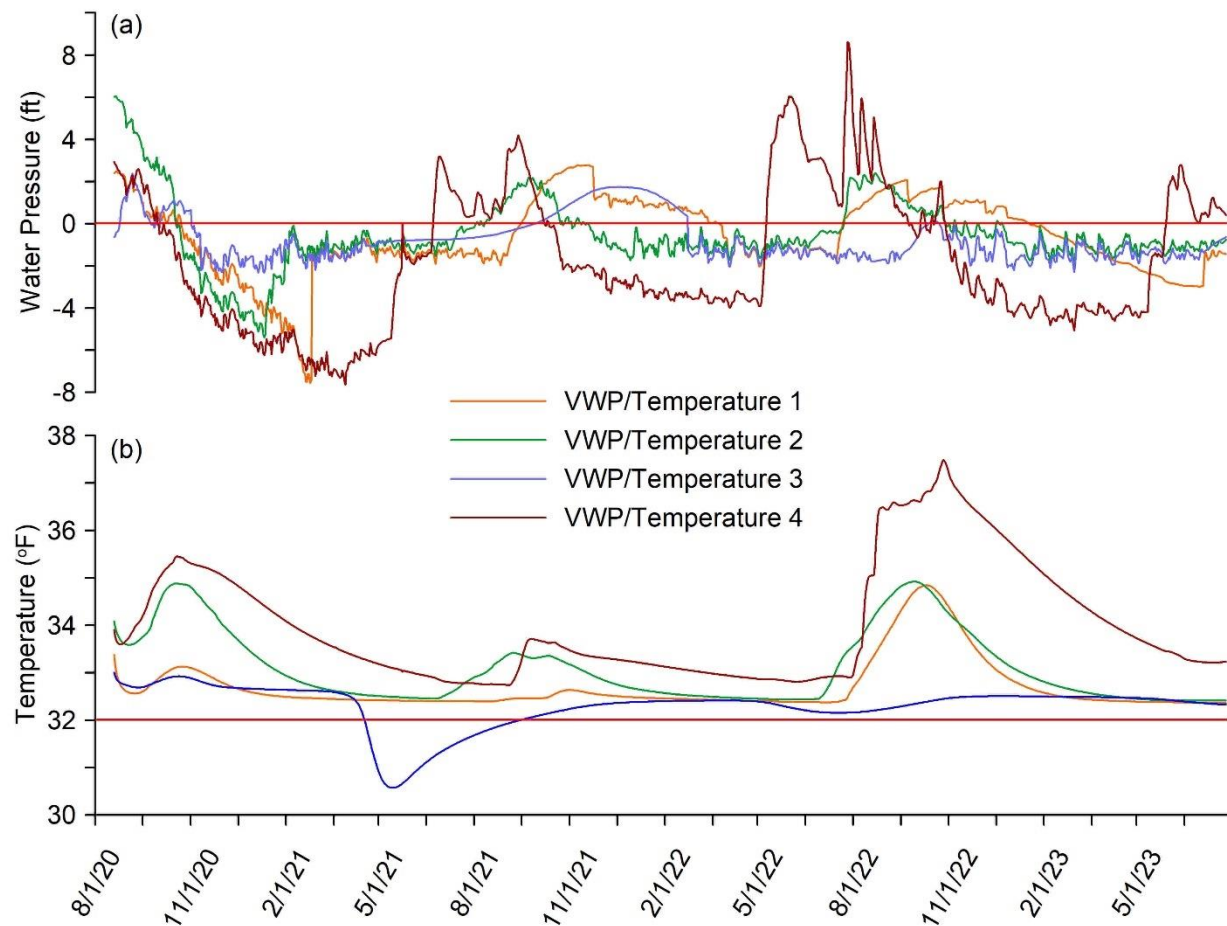


Figure 9. VWP data (a) and their associated temperatures (b) over the project measurement period. Red horizontal lines represent 0 ft and 32°F in (a) and (b), respectively.

(PP 1) and tilt meter 1 (Tilt 1; both installed near TH20-01) are about 4.3°F warmer in the winter of 2022/23 and about 7.6°F cooler in the summer of 2023 than the other readings. We attribute this to the fact that toe of FDL-A covered this part of the embankment in the late summer of 2022.

As we attached the pressure plates to steel plates to make them more robust against the impact of FDL-A, the steel plates may be adding additional temperature sensitivity to the pressure plate readings (Figure 10b), as the readings increase with sub-freezing temperatures, and then decrease as the embankment thaws in the spring. The pressure plate readings near TH20-01 (PP 1) increased during the winters of 2021/22 and 2022/23; however, the readings also dropped back down to the average values during the summer. We suspect that these elevated values indicate that FDL-A is beginning to push on the plate. One of the tilt sensors at the TH20-01 location (Tilt 1A) also started to deviate from the other readings on August 2, 2022. This is most likely due to the impact of FDL-A. We recommend on-going monitoring to obtain proof of concept for the tilt meter and pressure plate instrumentation.

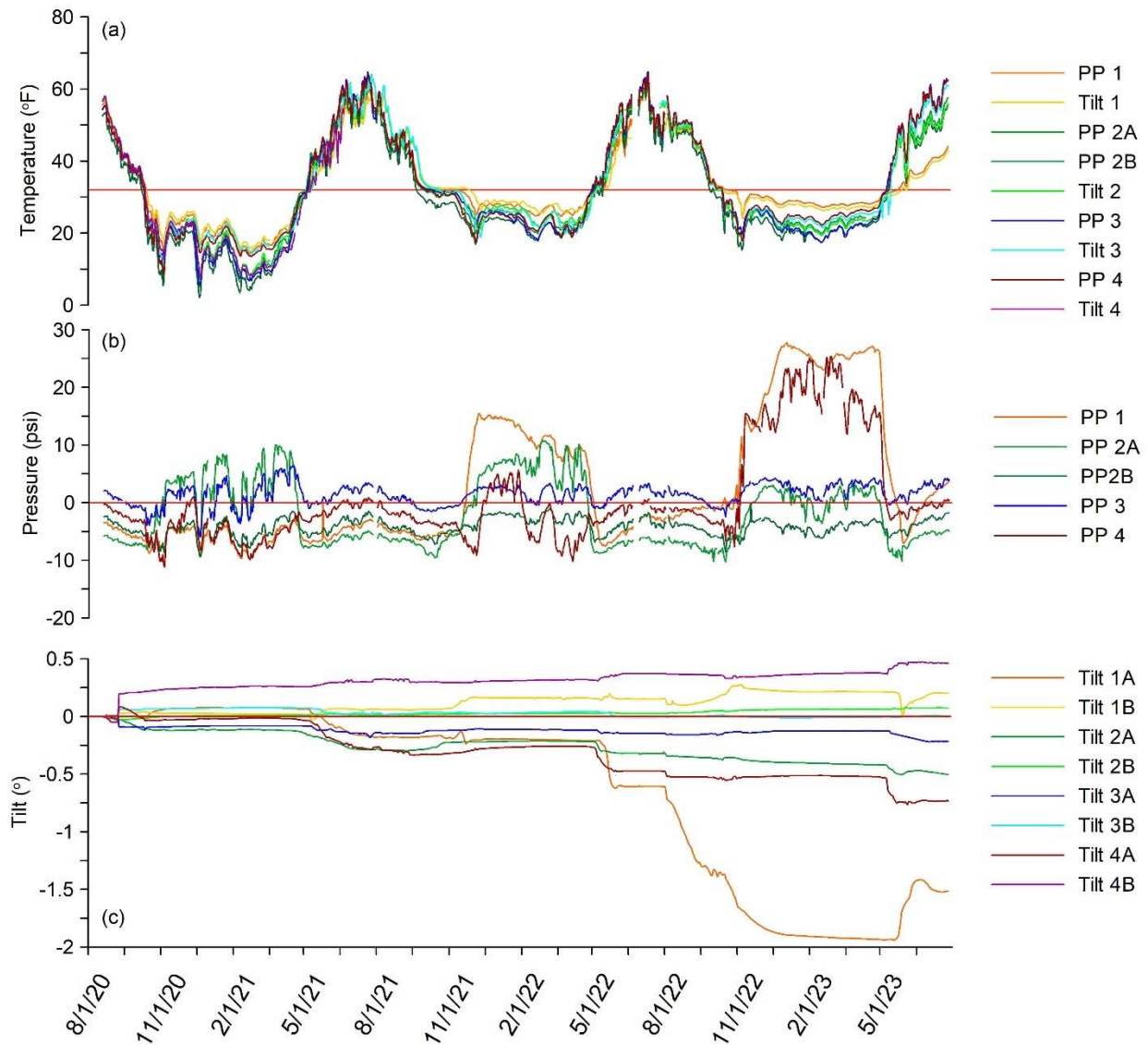


Figure 10. Pressure plate and tilt meter measurements over the project measurement period: (a) temperatures from all pressure plate and tilt meter devices; (b) pressure plate readings; (c) tilt meter readings.

3.4.4 MEMS-based in-place inclinometer (M-IPI) measurements

Figure 11 contains plots of the M-IPI measurements for the four test holes shown in Figures 3b and 4. We detected movement in TH20-01, -02, and -03 immediately upon installation in 2020 while the toe of FDL-A was still more than 30 ft away. These data indicate that the base of FDL-A is shearing into the weathered bedrock (TH20-01) and below the permafrost table (TH20-01 through TH20-03). These data also indicate that FDL-A has displaced TH20-01 approximately 9 inches horizontally. This amount of deformation is not discernable in the lidar (see Section 3.2), in careful viewing of the timelapse movie (see Section 3.3), or through field observations;

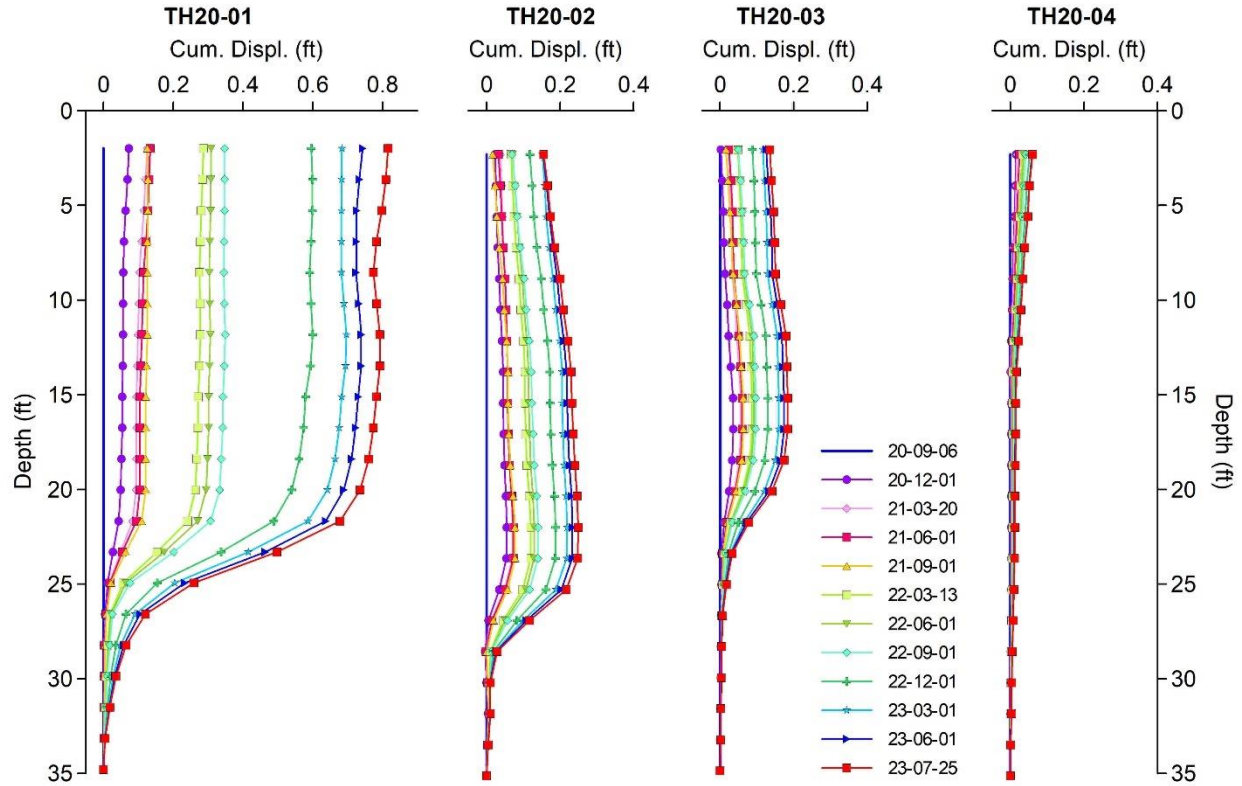


Figure 11. M-IPI measurements from selected months over the project measurement period.

however, the horizontal displacement may be manifesting in cracks within the embankment surface. In 2022, we noticed persistent cracks in the embankment surface, and mapped their positions using the RTK-GPS device in May 2023 (see Figure 12). It is possible that these cracks formed through thaw settlement, as this portion of the embankment is no longer maintained; however, their locations and orientations also suggest that they could be due to horizontal shearing from FDL-A. We recommend on-going monitoring to determine the cause of the cracking.

3.4.5 Data integration

Based on the M-IPI data, FDL-A was shearing approximately 13 ft below the bottom of the Dalton Highway embankment before this project started in 2020 and while the lobe was still tens of feet away. Based on field observations, and comparison of RTK-GPS measurements of FDL-A's toe and previously-developed shapefiles of the toe of the embankment, FDL-A started to overlap the side slope of the highway embankment in July 2022. During a trip to the site to download data and collect toe measurements in October 2021, we observed a mound of uplifted soil between FDL-A and the highway embankment in the vicinity of TH20-01 (Figure 13a). Analysis of the daily photographs taken of the toe indicates that this mound first appeared on September 19, 2021 (Figure 13b), becoming more prevalent by November 30, 2021 (Figure 13c). We interpret this mound to be soil trapped between FDL-A and the embankment forced upwards due to rotational shearing and buckling as FDL-A approached the embankment.

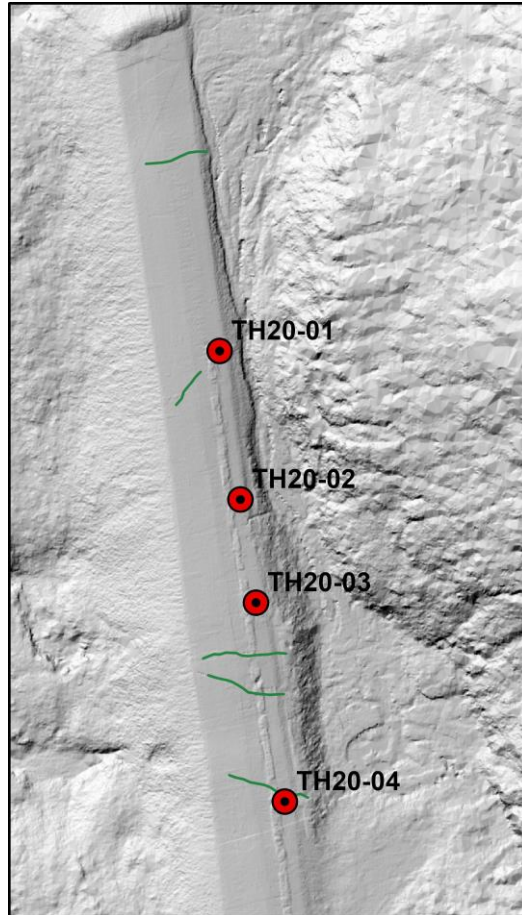


Figure 12. Persistent cracks (in green) in the embankment surface mapped in May 2023. Background data is 2022 lidar (unpublished).



Figure 13. Sequence of deformation at the toe of FDL-A: (a) soil mound noted during a field visit on October 2, 2021; location (red ellipses) of the soil mound in (a) on (b) September 19, 2021 and (c) November 30, 2021; (d) back-tilted trees (red arrow) along toe on March 1, 2023; (e) slumping of previous back-tilted trees (red arrow) on September 9, 2023.

During the fall of 2021, there was no change in the M-IPI data at TH20-01, which continued to demonstrate steady horizontal displacement within the upper few feet of the bedrock.

The next noteworthy change in the westward progression of FDL-A was the back-tilting of trees that became visible in the daily images on March 1, 2023 (Figure 13d). This suggests a shallow rotational failure of the toe, possibly along the shear surface developed during the fall of 2021. During a field visit in June 2023, we noted the presence of scarps and down-dropped blocks in the vicinity of the trees shown in Figure 13d, supplying more evidence of rotational failure. By September 2023, there were several pulses of soil slumping down the toe, causing the trees to rotate forward towards the embankment (Figure 13e). We last downloaded data from the site on July 25, 2023. The last reading of the M-IPI in TH20-01 indicates an outward leaning of the device beginning at about 7 ft below the embankment surface; previous readings suggest this leaning began around June 1, 2023 (Figure 11). We interpret this as the actual mass of FDL-A impacting the embankment at and above the original ground surface, and suspect that the pressure plate and tilt meter at TH20-01 also will indicate this impact through a significant increase in earth pressure and change in tilt in the future. So far during this collision, there have been no unusual changes in water pressure or temperature measured within the embankment. As previously mentioned, the progression of FDL-A's approach and collision with the abandoned Dalton Highway embankment can be viewed through time-lapse videos available on the webpage for FDL research (fdlalaska.org).

In Section 3.1, we presented movement rates for FDL-A, which demonstrated a reduction in movement rate since 2020. As previously mentioned, we attribute the majority of this rate reduction due to cooling of the lobe caused by low snowfall during 2020/21, since nearly all of the monitored FDLs also demonstrated a slowing after that winter. FDL-A, however, also has been interacting with the highway embankment since that time, which may be serving as an additional impediment to its downslope movement. Given the depth of shearing within the bedrock, however, we postulate that the embankment will do little to stop FDL-A's downslope progression.

The data collected through this project have been instrumental in determining the nature of the interaction of FDL-A with the abandoned highway embankment. Due to the on-going movement of this frozen debris lobe and its proximity to the current Dalton Highway alignment, we recommend continued monitoring of the existing instrumentation. Updated rates and pressure plate readings, for example, may be used in mitigation strategies to protect the new Dalton Highway embankment and adjacent infrastructure.

The authors have included the contents of this report, as well as analysis and interpretation from additional sources of data, into a journal paper entitled "Documenting the collision of a landslide in permafrost with an engineered structure," submitted to the *Environmental and Engineering Geoscience* journal. We direct the reader to that article for more details.

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APPENDIX: LABORATORY TESTING DATA

PROJECT NAME: FDL-A Impact Study
 LOCATION: FDL-A, Dalton Highway, MP219
 SAMPLED BY: M. Darrow
 DATE: 8/13/2020-8/16/2020

TEST HOLE NO.	20-04	20-04	20-04	20-04	20-04	20-04	20-04
DEPTH (ft.)	2.5-4.5	9.0-9.5	10.0-12.0	12.5-13.3	13.3-13.5	16.5-17.0	21.2-21.5
LAB NO.	001	004	005	006	007	010	014
DATE SAMPLED	8/13/20	8/13/20	8/13/20	8/13/20	8/13/20	8/13/20	8/13/20
% Passing 2"	100		100	100			
1.5"	86		100	78			
1"	79		98	65			
Gravel 3/4"	73		88	62			
1/2"	67		78	57			
3/8"	60		72	53			
#4	47		58	45			
#10	36		46	36			
Sand #20	28		38	28			
#40	23		33	24			
#60	19		29	21			
Silt/Clay #100	17		27	19			
#200	13.8		22.5	15.8			
Hydro* 0.02	8.6		12.9	10.0			
0.005	3.2		5.5	4.5			
0.002	1.5		3.0	2.8			
LIQUID LIMIT	NV		25	29			
PLASTIC INDEX	NP		NP	NP			
SOIL CLASSIFICATION	GM		GM	GM-			
SOIL DESCRIPTION	Si Gr w/ Sa		Si Gr w/ Sa	Si Gr w/ Sa			
NATURAL MOISTURE		5.2			16.2	3.7	2.7
SP. GR. (FINE)	2.74		2.71	2.72			

*Note: These values are interpolated from hydrometer test results.

PROJECT NAME: FDL-A Impact Study
 LOCATION: FDL-A, Dalton Highway, MP219
 SAMPLED BY: M. Darrow
 DATE: 8/13/2020-8/16/2020

TEST HOLE NO.	20-04	20-03	20-03	20-03	20-03	20-03	20-03
DEPTH	22.8-23.3	2.5-4.5	8.8-9.0	10.0-12.0	13.8-14.0	19.5-19.8	22.5-23.7
LAB NO.	015	016	017	019	020	022	023
DATE SAMPLED	8/13/20	8/14/20	8/14/20	8/14/20	8/14/20	8/14/20	8/14/20
% Passing 2"		100		100			100
1.5"		100		89			100
1"		94		79			100
3/4"		87		74			100
Gravel 1/2"		77		67			99
3/8"		71		61			97
#4		59		47			92
#10		44		34			84
Sand #20		34		26			73
#40		28		21			64
#60		24		18			56
#100		21		16			48
Silt/Clay #200		17.9		13.2			38.4
0.02		12.4		8.6			25.0
Hydro* 0.005		5.2		3.2			11.0
0.002		3.0		1.8			7.0
LIQUID LIMIT		NV		NV			NV
PLASTIC INDEX		NP		NP			NP
SOIL CLASSIFICATION		SM		GM			SM
SOIL DESCRIPTION		Si Sa w/ Gr		Si Gr w/ Sa			Si Sa
NATURAL MOISTURE	6.9		4.7		7.4	31.1	
SP. GR. (FINE)		2.73		2.73			2.74

*Note: These values are interpolated from hydrometer test results.

PROJECT NAME: FDL-A Impact Study
 LOCATION: FDL-A, Dalton Highway, MP219
 SAMPLED BY: M. Darrow
 DATE: 8/13/2020-8/16/2020

TEST HOLE NO.	20-03	20-03	20-03	20-02	20-02	20-02	20-02
DEPTH	27.7-28.8	29.3-29.6	35.0-35.3	3.0-5.0	6.5-7.0	10.5-12.3	12.3-12.5
LAB NO.	024A	025	027	028	029	032	033
DATE SAMPLED	8/14/20	8/14/20	8/14/20	8/15/20	8/15/20	8/15/20	8/15/20
% Passing 2"	100			88		90	
1.5"	100			78		90	
1"	98			76		84	
3/4"	96			73		81	
Gravel 1/2"	87			68		73	
3/8"	83			61		68	
#4	70			50		56	
#10	52			39		42	
#20	40			31		32	
Sand #40	33			25		26	
#60	28			22		23	
#100	25			19		20	
Silt/Clay #200	21.2			16.2		17.2	
0.02	15.0			11.0		10.5	
Hydro* 0.005	6.0			5.0		4.0	
0.002	3.6			3.0		2.0	
LIQUID LIMIT	NV			NV		NV	
PLASTIC INDEX	NP			NP		NP	
SOIL CLASSIFICATION	SM			GM		GM	
SOIL DESCRIPTION	Si Sa w/ Gr			Si Gr w/ Sa		Si Gr w/ Sa	
NATURAL MOISTURE		34.9	1.3		3.6		5.8
SP. GR. (FINE)	2.75			2.76		2.73	

*Note: These values are interpolated from hydrometer test results.

PROJECT NAME: FDL-A Impact Study
LOCATION: FDL-A, Dalton Highway, MP219
SAMPLED BY: M. Darrow
DATE: 8/13/2020-8/16/2020

TEST HOLE NO.	20-02	20-02	20-02	20-02	20-02	20-01	20-01
DEPTH	18.3-18.8	20.5-22.5	25.0-26.7	26.7-27.0	30.0-30.4	2.5-4.5	7.5-9.5
LAB NO.	035	037	038	039	040	042	044
DATE SAMPLED	8/15/20	8/15/20	8/15/20	8/15/20	8/15/20	8/15/20	8/15/20
% Passing 2"		100	100			100	100
1.5"		90	95			96	96
1"		87	91			90	91
3/4"		79	89			85	87
Gravel 1/2"		70	85			74	81
3/8"		64	80			68	76
#4		51	70			53	64
#10		40	56			39	51
#20		32	46			30	43
Sand #40		27	39			25	37
#60		24	34			21	33
#100		22	30			19	29
Silt/Clay #200		18.3	25.0			15.7	24.5
0.02		10.2	15.2			11.2	14.2
Hydro* 0.005		3.6	6.9			5.0	5.8
0.002		1.5	3.0			2.5	2.1
LIQUID LIMIT		NV	25			NV	NV
PLASTIC INDEX		NP	NP			NP	NP
SOIL CLASSIFICATION		GM	SM			GM	SM
SOIL DESCRIPTION		Si Gr w/ Sa	Si Sa w/ Gr			Si Gr w/ Sa	Si Sa w/ Gr
NATURAL MOISTURE	9.7			56.3	12.3		
SP. GR. (FINE)		2.74	2.76			2.70	2.71

*Note: These values are interpolated from hydrometer test results.

PROJECT NAME: FDL-A Impact Study
 LOCATION: FDL-A, Dalton Highway, MP219
 SAMPLED BY: M. Darrow
 DATE: 8/13/2020-8/16/2020

TEST HOLE NO.		20-01	20-01	20-01	20-01	20-01		
DEPTH		15.0-17.0	19.2-19.5	17.5-19.0	21.8-22.0	25.2-25.5		
LAB NO.		046	047	048	050	052		
DATE SAMPLED		8/16/20	8/16/20	8/16/20	8/16/20	8/16/20		
% Passing	2"	100		100				
	1.5"	100		100				
	1"	88		99				
Gravel	3/4"	79		96				
	1/2"	70		90				
	3/8"	65		87				
	#4	54		80				
Sand	#10	44		69				
	#20	38		57				
	#40	33		51				
	#60	30		47				
	#100	27		43				
Silt/Clay	#200	22.7		36.7				
Hydro*	0.02	13.8		27.0				
	0.005	5.0		12.9				
	0.002	2.8		7.9				
LIQUID LIMIT		NV		NV				
PLASTIC INDEX		NP		NP				
SOIL CLASSIFICATION		GM		SM				
SOIL DESCRIPTION		Si Gr w/ Sa		Si Sa w/ Gr				
NATURAL MOISTURE			21.5		15.8	7.0		
SP. GR. (FINE)		2.69		2.70				

*Note: These values are interpolated from hydrometer test results.