Automated Landslide Instrumentation Programs on US Route 2 in Crookston, MN

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ABSTRACT: In September of 2003, a landslide occurred in downtown Crookston between US Route 2 and the Red Lake River, causing significant property damage. Movement in the slide area continues; in the summer of 2007 instrumentation was installed to monitor these movements. During the post-failure monitoring at this site, roadway and embankment distress was observed at a location just east of Crookston, also on US Route 2. A similar monitoring program was established at the site east of Crookston in the summer of 2008, just 3 months prior to a massive landslide. Based on visual observations and the monitoring data, a detour was put in place a week prior to the landslide. Both sites were instrumented with ShapeAccelArray (SAA) systems which provide automated monitoring and data transmission of slope movements. Significant deflections, far greater than are observable with traditional inclinometers, were recorded, providing significant insight into failure rates, magnitudes, and geometry. The instrumentation, monitoring, and stability analyses are discussed. The automated sensors have captured data at both sites that is of significant value in characterizing the slope behavior and providing an early warning system to ensure the safety of the traveling public.

1 INTRODUCTION

The Minnesota Department of Transportation (Mn/DOT) has been using traditional inclinometers for decades. These systems consist of a cased borehole where a portable probe can traverse the installation. Data is recorded on a portable logger and then downloaded on a computer to produce graphical plots of borehole movement. Recently, there has been increased interest in using remote sensing, where sensor arrays are installed and left in place; these systems employ automated data collection and cellular modem data uplink systems. A pilot project was designed to evaluate the use of automated slope monitoring equipment. An existing landside site in Crookston, MN was selected for the pilot project so that the new system information could be compared with existing data, obtained from a consultant study of stabilization alternatives, performed in 2006. Based on favorable results at this site, when another nearby roadway section was experiencing similar distress, a monitoring program was established at that site. Both sites were instrumented with ShapeAccelArray (SAA) systems, which differ somewhat from more common "in-place" inclinometers.

Both sites are on US Highway 2 in Crookston, MN. The first, Crookston West (CW) is just northwest of the main downtown areas; the second site, Crookston East (CE) is about 3 miles east of the CW site, about 1 mile east of the city near the junction of Minnesota Highway 9. Clay soils predominate both sites where the lacustrine clays of the Huot Formation overly the harder ground moraine tills of the Red Lake Falls Formation (BARR 2006). Figure 1 shows the location of the two landslide sites with respect to the city of Crookston and the meandering Red Lake River.

The instrumentation programs at these two landslide sites showed that the SAA systems provided a significantly improved level of detail as compared to the traditional systems, due principally to their sampling frequency and ductility. While data was still being assessed for the de-

velopment of a permanent remediation plan to protect US Highway 2 from further impact in downtown Crookston (the site of the 2003 slide), the second site (CE) became critical and failed. Based on visual observations and the SAA data at the CE site, the highway had been closed a week earlier, possibly preventing serious injury and property damage. This paper describes the SAA instrumentation at each site, results of the soil investigation and monitoring programs, usefulness of near-real-time monitoring systems, and how the new systems are providing valuable data and unexpected insight, with respect to very large deformation behavior, for the geotechnical analysis and remediation design at each of the two sites.

Figure 1. The two landside areas are both on the Red Lake River and adjacent to US Highway 2, about 3 miles apart in Crookston, MN. The western slide (CW) area is near the downtown; the eastern slide (CE) is east of the city near the intersection with Minnesota Highway 9.

2 SLOPE INSTABILITY IN CROOKSTON AREA

Rotational slump landslides are common along many rivers in northwestern Minnesota. The soils generally consist of granular sediments, clays, and tills associated with glacial Lake Agassiz. The Huot Formation underlies the Sherack formation, and overlies the Red Lake Falls formation in the Crookston area. The Huot is extremely clayey for glacial sediment, has a high natural water content, very low shear strength, and flows when subject to stress; it is responsible for bank and stability problems in the Crookston area (Harris 2003). The Sherack Formation is about 10 feet thick in the Crookston area, although it may be eroded in some areas, or overlain with additional fill.

The Red Lake River meanders through the weak lacustrine clay deposits of the Huot Formation (which are overconsolidated in some areas), causing slope failures, typically on the outside bends of the rivers where higher velocity water promotes erosion and removes soil at the toe of slopes, promoting instability (Schwert 2003). Erosion is not the only factor however, as one might expect, rainfall, river levels, and groundwater levels also appear to play a significant role in promoting riverbank instability. Failures are generally deep seated in nature, frequently ex-

tending to the contact between the lacustrine clay and the underlying glacial till, exiting in the river channel at or below the water level (Tallin and Thiessen 2009).

3 HISTORIC LANDSLIDE ACTIVITY

3.1 *Crookston West (CW)*

At both sites, there is evidence of ongoing slide activity and there are documents indicating significant events in the past. At the CW site, a massive landslide occurred in 1933 which destroyed Darkow's Hatchery and tourist cabins when the ground broke and dropped about seven feet (BARR 2006). Another significant landslide occurred in the early morning of September 4, 2003 when an approximately 1200 foot long scarp developed and the soils dropped up to six feet in places; more than half a million dollars in property damage resulted and several homes and buildings were total losses. The scarp was about 20 feet away from US Highway 2 at the nearest location (Zeng et al. 2007). This event prompted a significant investigation and monitoring program at this site. Several standard penetration test (SPT) borings, cone penetratration test (CPT) advances, pressuremeter (PMT) and flat plate dilatometer (DMT) tests were conducted. Monitoring locations, consisting of traditional inclinometers, and piezometers were established at 3 cross sections. The monitoring program showed that slow movement continued in the area.

3.2 *Crookston East (CE)*

At the CE site, a slide occurred in 1930 and more recent slides have been anecdotally reported, one damaging an entrance monument to a facility just northeast of the present slide area. In the fall of 2007, some minor settlement was noticed on US 2 and cracking in the embankment slope was observed. Embankment drainage was improved by installing a number of horizontal drains into the highway embankment and the highway was repaved in the distressed area. The drainage appeared to be functional as water was observed exiting the embankment after rain events. In the spring of 2008 additional settlement in the roadway occurred and additional patching was performed on a small section of both westbound lanes.

4 SHAPE ACCEL ARRAY (SAA) PILOT PROJECT

4.1 *Mn/DOT slope monitoring historic practice*

The Minnesota Department of Transportation (Mn/DOT) has been using inclinometers to measure slope movements for decades. Typical installations include a cased borehole, installed in regions of suspected or known instability, extending into firm ground at the base to provide a fixed reference point with which to compare the observed movements. The casing placed in the borehole has grooves to allow a portable, wheeled, probe to traverse the length of the borehole. The casing grooves are oriented in-line with the expected direction of movement (instability) at the time of installation. Data is acquired by periodically lowering the probe down the borehole and on returning it to the surface, pausing the probe at intervals to take readings which record the sensor inclination. The first survey established the baseline readings and acts as a reference for future surveys (DGSI 2009). Data is recorded on a portable logger and then downloaded on a computer to produce graphical plots of borehole movement.

4.2 *Automated slope monitoring pilot project*

Mn/DOT has recently started to use remote sensing whereby sensors or sensor arrays are installed, left in place, and are outfitted with automated data collection systems to periodically acquire and record data. Some of these systems have loggers that are manually downloaded every few weeks or months with field computers and others have cellular modem data uplink systems

which send the data automatically to a computer which hosts the data and allows for web based data downloading and viewing. The manually downloaded systems have been used on a number of projects to record data from piezometers, earth pressure cells, strain gages, and other vibrating-wire instruments.

The first successful Mn/DOT geotechnical application of the modem uplink and web-based monitoring system was used to evaluate the behavior of a portion of a pile-supported embankment project, on MN Highway 241 in St. Michael, MN, in near-real-time. The system was installed in the summer of 2006 and used Geocomp Corporation's *iSiteCentral* remote monitoring system. Another portion of the project was monitored using a manually downloaded system. Both systems performed well over the duration of the instrumentation and monitoring program.

Many of Mn/DOT's more active landslide and slope stability problem areas are some distance from the geotechnical offices in Maplewood, MN, and many are also some distance away from regional District offices as well. The time expended in collecting data has generally resulted in fewer datasets than may be desirable for a clear understanding of slope movements and responses to particular events, although long-term trend analysis is still valid.

A solution for collecting more frequent data, including data during flood events where access is sometimes impractical or impossible, is to employ automated systems, which are now becoming more widely available. A pilot project was proposed so that the technique would not be deployed on a 'program delivery' project without having first been tested at another site where any potential problems could be solved in a non-critical environment. Of particular interest was finding if increased reading frequency could lead to additional insights on how the rate of movement may change based on seasonal or rainfall impacts.

4.3 *Crookston West site selection*

The Crookston West site was selected for a variety of reasons: 1) This site had a large number of existing sensors, installed as part of an earlier Stabilization Alternative study (described in the next section), so the new data would complement the existing investigation and monitoring program, 2) the data could be compared with existing data to provide a side-by-side comparison with the traditional slope monitoring techniques, and 3) the site was known to be slowly moving and in need of continued monitoring, particularly as some existing inclinometer casings had sheared off and a probe was left unretrievable in an installation.

A scope of work was prepared and a consultant contract was awarded to American Engineering and Testing (AET) for the installation work and some monitoring and analysis of three 80 foot long ShapeAccelArray (SAA) systems (described in section 4.5). The systems were installed along cross section "A" of the Stabilization Alternative study area, just east of the intersection of US Highway 2 and Birch Street, and west of Pine Street (Refer to Figure 6).

4.4 *Original investigations, stabilization study, and CW site grading*

BARR Engineering prepared a report for Mn/DOT in 2006 which provided a detailed study of the site and recommendations for remediation of the landslide area to protect US Highway 2 from potential impacts if the slides were to continue and progress toward the roadway. The report was based on three different field investigations performed by Mn/DOT in September of 2003, Barr in November of 2005, and Mn/DOT in January of 2006. SPT soil borings, CPT advances, DMT tests, and PMT tests were conducted and multiple inclinometers and piezometers were installed. A comprehensive suite of lab tests (including direct simple shear (DSS), permeability, and index property tests) was performed on the samples obtained from the SPT borings.

Four preliminary alternatives were submitted for review; the preferred alternative at the time of the report was estimated to cost about 2.5 million dollars. Even with emergency money proved to the City of Crookston, this was considered a significant cost and further monitoring was proposed. The city purchased the landslide impacted properties and set about using some of the emergency funding to develop the impacted area into a green space. Unfortunately, as observed later, a construction plan to grade the area, remove the scarps, and smooth some of the existing landslide features appears to have done more harm to the slope stability than aesthetic good. Despite repeated efforts by Mn/DOT to ensure that material was removed from the whole area (thus reducing driving forces), there were some locations where fill was added to provide

uniform slopes where scarps had been. Figure 2 shows the area in April of 2008, prior to any clearing operations, Figure 3 shows the area during the clearing and grading construction project in September of 2008 and Figure 4 shows the same area again in April of 2009. It will be observed later that the construction project adversely impacted the site stability and substantially increased the rate of the slope movement, at least in the vicinity of the SAA instrumented cross section "A".

Figure 2. The CW site looking east; several of the protective casings for the traditional inclinometers can be seen in the photo (two at the left and one at the center right).

Figure 3. From approximately the same location as Figure 2, the CW site is now seen during the clearing and grading operations, conducted as part of a city project to remove trees, reconstruct area drainage, and smooth out the failure scarps. The 6 foot scarp has now been smoothed.

4.5 *ShapeAccelArray Displacement Monitoring System*

The SAA is a new geotechnical instrumentation device developed by Rensselaer Polytechnic Institute and Measurand Inc. An array unit is essentially a jointed flexible tube, containing arrays of MicroElectroMechanical (MEMS)-based sensors, spaced one foot apart. In this application the MEMS sensors are orthogonally aligned accelerometers which collect continuous three-

dimensional acceleration data, the gravity components of which can be used in conjunction with the known geometry of the array to compute displacements (Danisch et al. 2008) When installed in a borehole and connected to a data uplink device, soil deformations (and vibrations) can be monitored in real time at the site and periodically uploaded by a wireless (or fixed) connection to the internet where near-real-time observation is possible from any web accessible location. The on-site data acquisition systems can be configured to send a warning message to an engineer via e-mail or text message if certain movement or vibration thresholds are exceeded.

Figure 4. Months after the grading and clearing, in April of 2009, the CW site is again showing tension cracks, and some scarps that drop from two to six inches. The rate of movement also increased substantially after the construction operations. It appears that the driving forces were increased by the work (perhaps more than anticipated), effectively decreasing the overall factor of safety.

At site CW the entire system consists of three down-hole SAA instruments, cables and protective conduit running from the arrays to a central data acquisition cabinet, three data loggers (one per array), a multiplexer (needed if there is more than one array, as in this case), a cellular modem, a solar collector, a solar regulator, wiring back panel, a deep cycle marine battery, and the equipment cabinet. Each of the three 80 foot arrays has sensors mounted every foot, so each array has 240 MEMS accelerometers (X, Y, Z) acquiring information each time the array is polled for data.

The systems are similar to in-place inclinometers in that the SAA components are reusable at other sites once the work at a particular location is complete. The sensors can be automatically read and be set to upload data at preferred intervals as desired for the project work.

A ShapeAccelArray (SAA) system was selected for use as part of the project as it appeared to have a number of advantages over other 'in-place' inclinometer systems. Benefits appeared to include more economical (non-directional) casing, simple installation, integrated hardware and software system components, no exposed down-hole connections between sensor segments, a versatile and robust software user interface, improved coupling with site soils, and minimized field sensor setup and calibration. Mn/DOT became aware of the technology from technical publications and a Transportation Research Board workshop (held by the Committee on Exploration and Classification of Earth Materials).

Three 80 foot sensors were selected such that data could be compared with existing sensor data from the BARR Stabilization Alternative study. The new sensors were to be situated near existing inclinometers, which would provide redundant but independent data for direct comparison between the two systems.

4.6 *SAA Installation*

The three arrays were successfully installed in late June of 2007 and have been reporting data regularly since that time, with some early periodic lapses in data due to problems associated with the cellular modem uplink. Three borings were advanced by Mn/DOT crews. Personnel from Measurand Inc, AET, and Mn/DOT assisted with the array placement, trench digging (for cables leading to the data collection cabinet) and related installation activities. The web-based system for data viewing and reporting was configured by engineers at Measurand; within a few hours data was being acquired and was available for review. An advantage was that with this system the information could be easily viewed and monitored by department personnel at multiple locations using a computer on the internet, the appropriate software, and passwords. Figure 5 shows some of the components in various phases of the installation process. Figure 6 shows the location of the instrumented cross section "A" where the three SAA systems were installed at the CW site.

Figure 5. At left one of the 80 foot arrays is shown on its shipping spool. The center photo shows Mn/DOT, AET, and Measurand personnel in a team effort lowering the array into the flexible conduit used as a casing (so that it can be retrieved later if desired). The right photo shows the data acquisition cabinet with extra cable spooled in the lower right. The other components include a deep-cycle marine battery, solar regulator, cell modem, a multiplexer, and three data loggers.

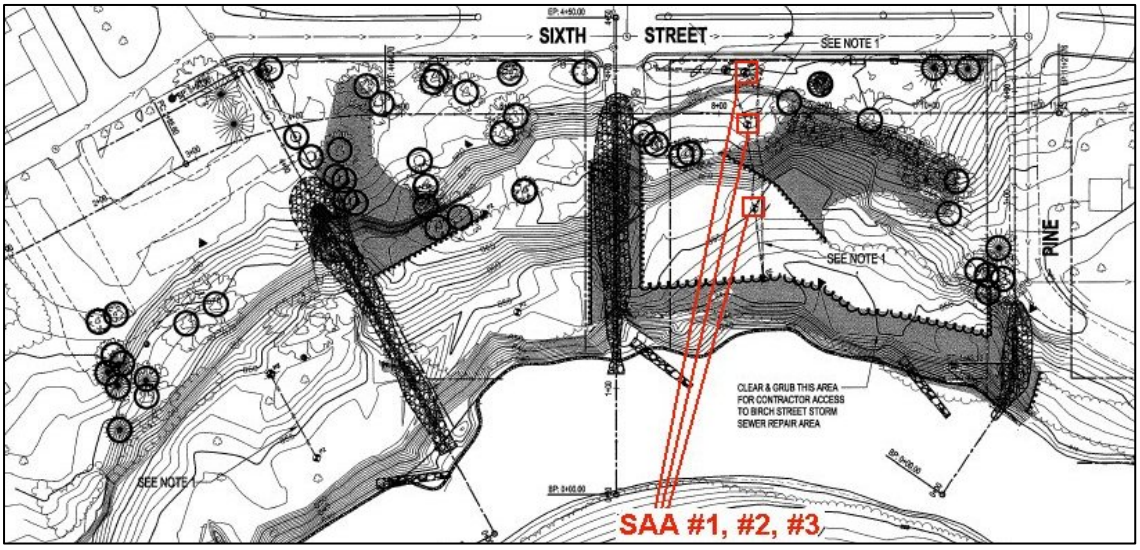

Figure 6. The SAA sensors were installed at cross section "A", as identified in the BARR Stabilization Alternatives study of the 2003 landslide area. The sensors were protected during the site grading operations of fall 2008 and continued to provide automated data on the slope movements at the site during the construction operations.

4.7 *SAA Data: new insight into rates and high strain behavior*

The SAA systems worked exceedingly well on the pilot project; the three systems are still working after more than 900 days, with readings taken at an average rate of every 6 hours on each array. The data on the array installed nearest US Highway 2 (SAA#1) showed almost no movement along the entire array (less than 0.25 inches over the entire array length) and is not shown here. The collection of data from the other two arrays, installed further down the slope, is more interesting and is shown in Figure 7. The two plots on the left side of Figure 7 are cumulative distribution plots, and the two graphs at the right are time rate of displacement plots (the time is in hours from installation x 10,000).

The cumulative deflection plot for SAA#2 indicates that at depth there is more displacement occurring than is seen at the surface, with about 12 inches of movement at the ground level and about 16 inches of maximum deflection at a depth of about 28 feet. The cumulative deflection plot for SAA#3 indicates that there appears to be a shear zone at a depth of about 45 feet and the material above that depth is deflecting more-or-less uniformly, with total deflections of about 25 inches over the 2.5 year observation period. It is interesting to note that the rate of deformation was fairly uniform at about 0.25mm/day (0.25 inch/month), as seen on the right hand graphs of Figure 7, for the first 10,000 hours of observation (up to the "1" on the graphs) and then the rate increased significantly. This increase in movement corresponds to the grading work conducted in September of 2008. The rate decreased somewhat after the completion of the work and continues to be somewhat variable based on the river level and rainfall events. The SAA systems capture the large deflections and the dramatic increase in rate (the post-construction rate is about 500% of the pre-construction rate) in detail. In Mn/DOT experience, traditional inclinometers have only successfully recorded a few inches of movement in a well defined failure plane before shearing and rendering the installation mostly if not wholly unusable (as the fixed reference end is no longer accessible). This is the first time that Mn/DOT has been able to resolve such large deformations, and is also the first time that very detailed rate information has also been gathered.

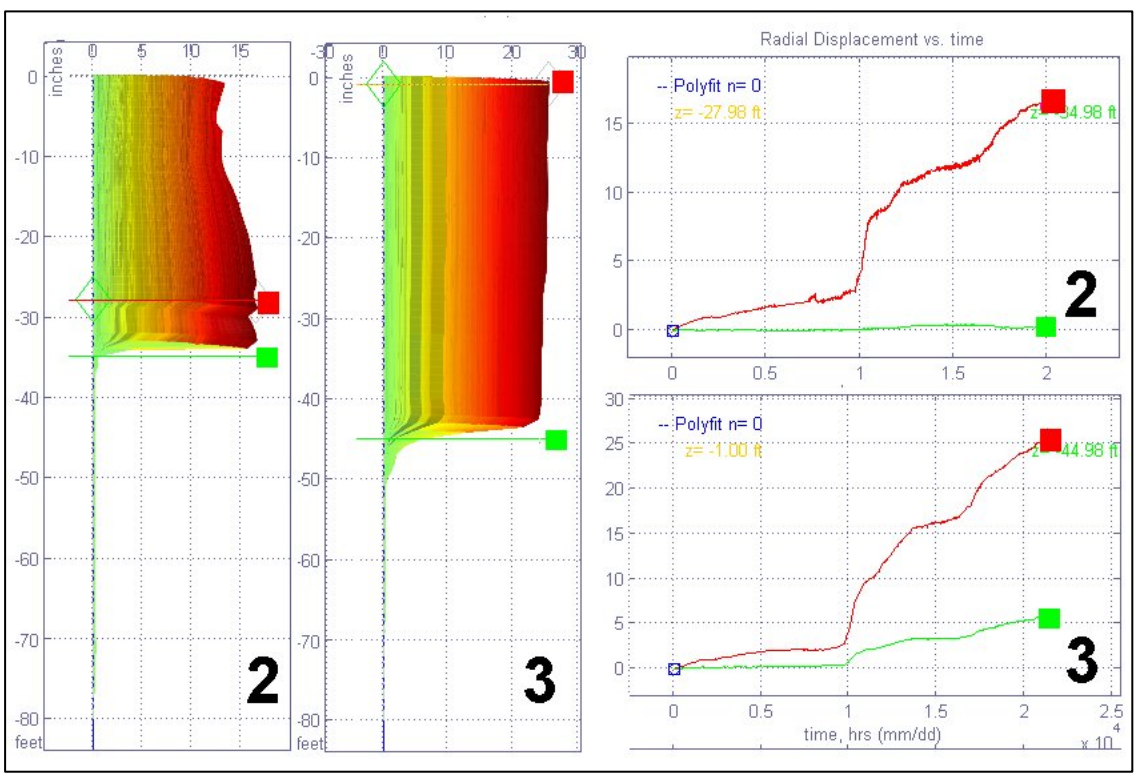

Figure 7. Cumulative displacement plots from SAA#2 and SAA#3 (at left) and rate plots for the same arrays (at right). A significant jump in the rate (over 500%) was observed during, and after the city grading project (at approximately 10,000 hours), implying that although an aesthetic improvement, it may not be long lasting. Rates are shown for 2 different depths on each SAA instrument.

4.8 *The CW site "low-cost" fix, new conclusions, and current site conditions*

Based on estimates of the cost of a full stabilization project at the CW site, money was not available for a complete stabilization initiative. Some of the emergency money earmarked for the site also had a spending deadline, and it was determined that improving the drainage and site appearance was a desirable way to use the available funding. Although the original BARR Stabilization Alternative report indicated that an early preliminary design to re-grade the area would result in lower factors of safety for long-term stability and rapid draw-down conditions due to increased driving and reduced resisting forces, this option was still undertaken by the city to improve the appearance of the site, improve drainage, and promote pedestrian safety.

It appears that the analysis indicating a reduced factor of safety, while not ever in question, is now supported by the instrumentation data. It was anticipated that the grading and storm water runoff improvements would only be a temporary "patch" although the deleterious impacts were probably not fully appreciated at the time this partial remediation project was designed. The homes and business have, however, been removed from the impact areas, the current movements no longer pose an immediate risk to private property.

Presently, the SAA data is being used to monitor the CW site conditions and ensure that US Highway 2 is not in any present danger of impact from the slide progression. The additional data on the slope behavior is being used to evaluate the area in consideration of a more appropriate long term solution to ensure that US Highway 2 can continue to safely accommodate traffic.

SAA#1 is still indicating no movement at a location near the sidewalk that runs alongside the highway and a sudden failure that would impact the driving lanes appears unlikely in the near future. Figure 8 shows the cross section of the failure area. Data from the SAA soil investigation and monitoring program suggests that the current failure is mostly coincident with the 2003 failure planes and zones of weakness. CPT and DMT data taken during the course of the 2007 investigations do suggest that the failure plane extends deeper than originally proposed, extending down to the contact with the much stiffer Red Lake Falls formation of overconsolidated till.

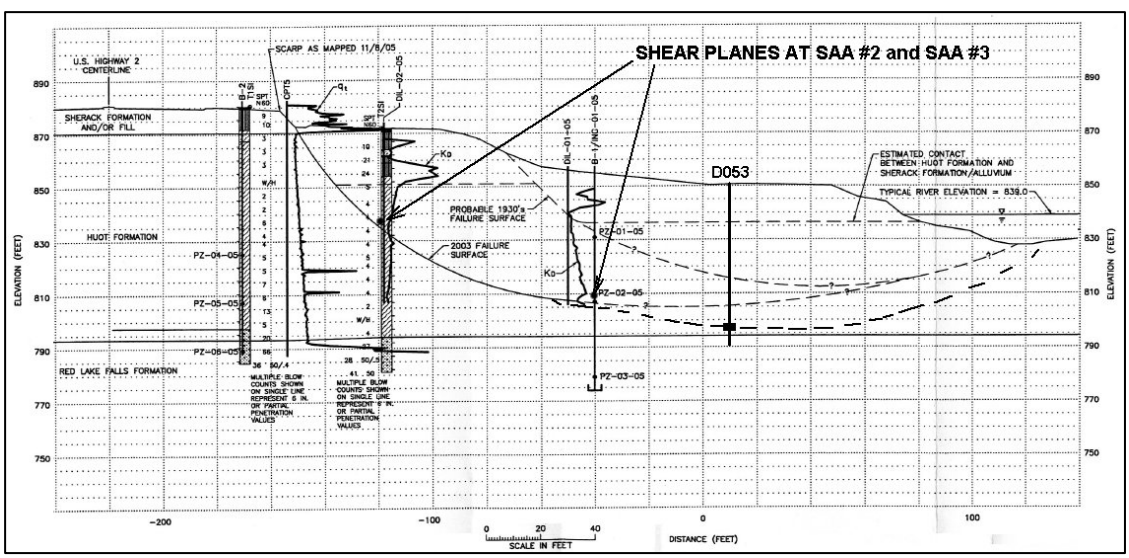

Figure 8. Cross section "A" diagram showing some soil boring information, and theoretical failure surfaces based on the instrumentation programs at the CW site. Recent SAA data has shown that the movements are fairly slow, uniform, and well-behaved. The slope appears to move faster when the water levels are low (a decrease in resisting force) or when fill is added at the top of the slope (an increase in driving forces). The diagram was originally prepared by BARR for Mn/DOT; recent data has been added.

4.9 *An insightful near-real-time observation*

An interesting observation made in late March of 2009 was that during the spring flood period, when readings with traditional inclinometers would be impossible, the rate of movement observed at SAA#3 slowed, stopped, and slightly reversed, for a short time. It is believed that the water pressure on the slope provided enough resisting force to bring the slide area into temporary equilibrium and even cause a slight reversal of movement. Nearby USGS Gage station data showed that the peak gage height of 25.12 feet occurred on March 25, 2009 which corresponds almost exactly with the rate information recorded by the array. The 20 feet of water pressure (above the normal 5 foot stage) would be loosely equivalent to about 10 feet of 'resisting' earth pressure. The flood event quickly subsided and the slope movement returned to normal following the flooding. The capture of this sort of information would not have been possible with traditional manually-read installations. The fact that about 10 feet of equivalent earth pressure was needed to establish a temporary equilibrium also appears to be in good agreement with the observations that several feet of additional fill, in places, from the grading work has been promoting accelerated movements over the previously more stable state.

5 A SECOND FAILURE AREA, A SECOND SAA SYSTEM, AND A SECOND SUCCESS

5.1 *Crookston east*

Based on favorable results at the CW site, when another nearby roadway section was experiencing similar distress, a second independent monitoring program was established at that site. This second site is also on US Highway 2, between the westbound lanes of the highway and the Red Lake River. At this site the highway is a rural 4-lane divided highway; distress had been noted in the two westbound lanes and the right hand (north) roadway shoulder and the embankment. The site is located just east of Crookston (refer to Figure 1), near the junction with Minnesota Highway 9. Figure 9 shows the CE site, looking west.

Figure 9. The roadway patch can be seen as the darker pavement area on the left side of the photo. The embankment on the right gradually drops down to the Red Lake River. The water surface is about 45 feet below the pavement surface.

The second site was instrumented with a similar ShapeAccelArray (SAA) system; two arrays, each with a length of 120 feet, were installed to help characterize the slope behavior. To distinguish the site more easily from the CW site, the new arrays were named SAA#4 and SAA#5. The two arrays were successfully installed in late May and early June of 2008, several months later than originally intended due to scheduling problems and a heavy spring workload. By this time another roadway patch had been applied to maintain a smooth pavement surface.

Mn/DOT personnel did the complete installation of the two arrays and the set up of the data collection equipment in a utility cabinet on-site. The configuration of the sensors and equipment, as at site CW, was done during the manufacturing process, making the actual installation fairly straightforward. As at the first site, most of the technical issues which arose were related to the cellular modem and not the actual slope monitoring equipment. After some minor connection difficulties, data was being uploaded to the Measurand web-servers and would be available for review within a day of installing the sensors.

5.2 *Monitoring Plan*

The monitoring plan at this site, which became known as "Crookston East" (CE), was similar to the downtown monitoring plan, where the arrays would be read several times a day and the data collected until enough movement had been observed to characterize the shear zones within the highway embankment. Figure 9 shows the CE site looking west.

Soils at this site were similar to those at the CW site, although somewhat more clayey in overall character. A CPT sounding was advanced in the westbound shoulder. Triaxial tests were conducted on samples obtained from the SAA installation borings. Undrained shear strength values ranged from 60 to 700 psf. Effective stress friction angles generally ranged from 8 degrees to 22 degrees (refer to Table 1). With testing underway in the lab, data was progressively obtained by the automated SAA systems. Before long, some additional pavement distress was observed and District personnel were becoming concerned about the need for a larger scale fix.

5.3 *Alarming observations and responses*

From the initial installation of the SAA sensors at this site, the movements observed were larger than those observed at the CW site and the observed shear zones were considerably deeper than anticipated. Movement as deep as 100 feet was observed on SAA#4. In early September of 2008, just 2 months after the sensors were installed and put on-line, movements were already exceeding 6 inches at the top of the arrays. Shortly thereafter, larger pavement distresses were being observed and the rate of movement began steadily increasing.

A meeting was held at the District offices in Crookston on September 10, 2008 to review the site and assess the SAA sensor data at the CE site. It was determined that the slope was no longer creeping, but instead was beginning to fail catastrophically. As a result, the District let an emergency contract to construct highway crossovers which would allow traffic to be diverted from westbound US 2 onto the eastbound lanes- where traffic would then be one-lane in each direction around the affected areas- should it become necessary to do so.

On the weekend of September 13, 2008 additional cracking defining a future scarp was noticed after rain passed through the area. The rates of slope movement were now increasing on very well defined failure planes according to data from both SAA#4 and SAA#5. A decision was made to detour traffic around the area using a longer bypass, as the construction for the crossovers had yet to begin. The westbound lanes of US 2 were closed and westbound traffic was detoured to the north of the city on Monday September 15, 2008. Eastbound traffic continued to use both eastbound lanes, which appeared unimpacted, based on visual observations. Figure 10 shows the distress that began on the weekend of September 25, 2008 when a large progressive landslide occurred, ripping apart a 500 foot section of the westbound lanes of US 2 and sinking them down about 10 feet. Figures 11 and 12 show the continuation of the failure until equilibrium is reestablished several days later. The rate of drop was about 3 feet per day. By

September 29, 2008 most of the movement had occurred and a substantial amount of material was observed uplifted into the Red Lake River at the toe of the slide area (Figure 20).

The SAA systems continued to record data during and after the event, but lost information on the direction of the slide when segments of the arrays directly in the shear zone became horizontal, rendering the 3D calculations based on the gravity acceleration components invalid. The systems remain in place today and still provide valuable data on the shape of each of the down-hole SAA instruments. The data collection cabinet "rode out" the slide and although it translated several feet north and downward, it is still nearly vertical; data collection and transmission was not compromised at any time during the event, even though an estimated 400,000 cubic yards of material below it failed and moved northward toward the river. The intact cabinet can be seen in Figure 10 (before the slide) and Figure 12 (after the slide).

Figure 10. The roadway patch provides a good reference for the roadway impact from the slope failure. The equipment cabinet for the up-hole SAA sensor components can be seen at the right side of the photo. The sensors are located about 15 feet upslope and down slope from the cabinet location.

Figure 11. One day later (than Figure 10), the westbound lanes are now clearly impassable and the pavement is being ripped apart as the embankment drops and the active slide progresses to the north.

Figure 12. By October 1, 2008 the slide had made the local and regional news. Mn/DOT Foundations crews were on-site to install new instrumentation in order to monitor the stability of the, as yet unimpacted, eastbound lanes. The emergency contract highway crossovers had recently been completed and the longer westbound US Highway 2 traffic detour was replaced by two-way traffic (one lane each direction) on the former eastbound lanes. The thick asphalt pavement overlays can be seen over the original concrete paving at the left side of the photo.

5.4 *CE Site SAA Data: further new insight into rates and very high strain behavior*

As noted earlier, the SAA systems worked exceedingly well on the pilot project; here the systems provided exceptional performance given the fast rate of movement and the very large lateral deformations of nearly 10 feet. By adjusting the options for the data presentation in the reporting software it was possible to discern a number of nuances with respect to the slope behavior. The data provided by SAA#4 was the most interesting and remarkable. After only two weeks in service two different shear zones were clearly becoming apparent. One was relatively shallow at a depth of about 25 feet, the second shear zone was at a depth of about 103 feet. As the slide progressed, two additional shear zones at depths of 66 feet and 74 feet appeared to initiate. These new zones would eventually fail at a comparatively fast rate and experience very large lateral deformations- much larger than the deformations seen at the 25 and 103 foot depths. Figure 13 shows the progression of cumulative displacement plots on SAA#4.

On September 1, 2008 a total of about 5 inches of movement was observed on SAA#4, with more than half of the movement occurring at the interface with the stiffer soils at a depth of about 103 feet. By September 25, 2008, the slide had progressed to a maximum deflection of over 30 inches with much of the movement occurring along two distinct shear zones at depths of 66 and 74 feet. By October 1, 2008, the slide area had translated laterally over 100 inches and data from both SAA systems was still accurately recording the failure process.

Figure 14 shows a progression of strain plots which clearly indicate the locations of the shear zones and shows how they change somewhat as the landslide evolved. The shear zones at depths of 24 feet, 66 feet, 74 feet and 103 feet, are readily identifiable. It can also be seen that in the early stages of the slide the 103 foot depth zone was more active and deformations at this interface were later dwarfed by those seen at the 66 and 74 foot interfaces.

The cumulative displacement data from SAA#5 is shown in Figure 15. Here the behavior is markedly different from that seen on SAA#4 although the two arrays are only about 40 feet from one another. A distinct shear zone can be seen at a depth of about 79 feet; above this layer there is a thick layer where displacements are nearly uniform, suggesting a shear zone nearly 75 feet thick. The data also shows some unusual movement in the upper 5 feet, which appears to be the result of near-surface scarping and local ground movement based on site photos (there is a large scarp adjacent to the instrument location). Figure 16 shows the remains of westbound US Highway 2, and the uneven scarping ground surface near SAA#5 and the equipment cabinet.

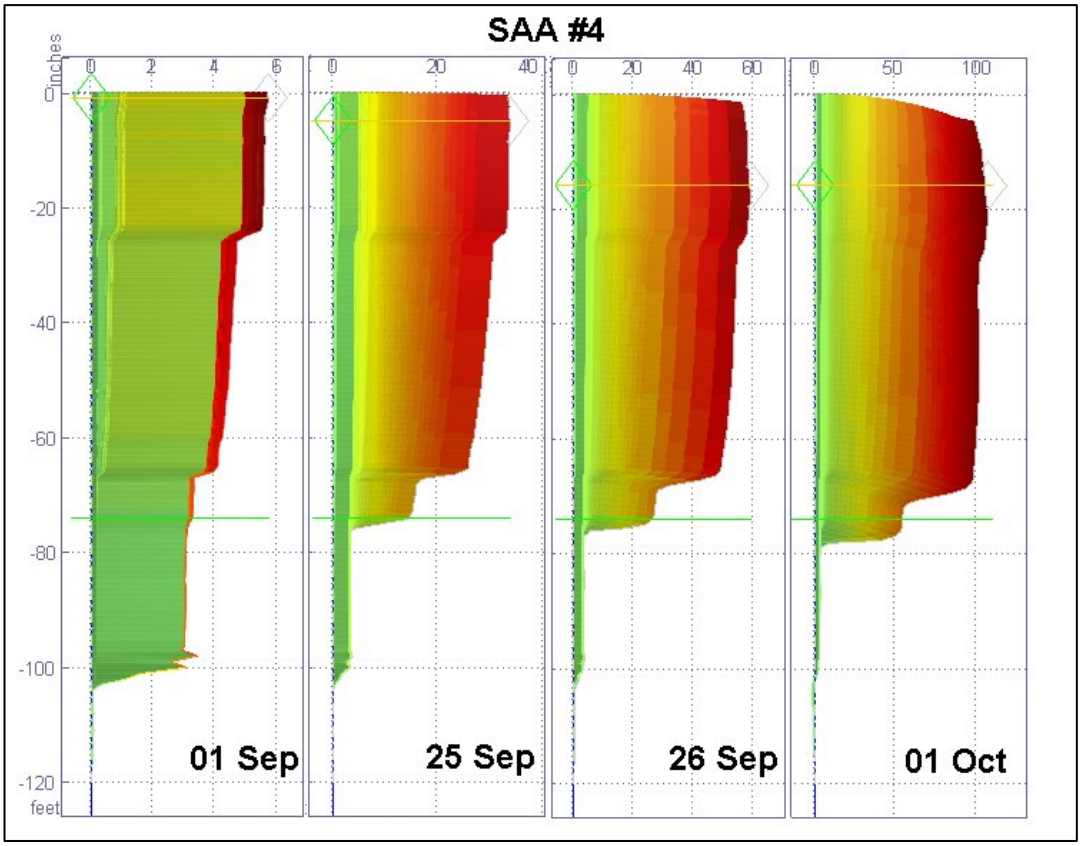

Figure 13. Cumulative displacement plots from SAA #4 showing the progression of deflection from early in the study period through the slope failure. Over 100 inches of lateral deflection was recorded.

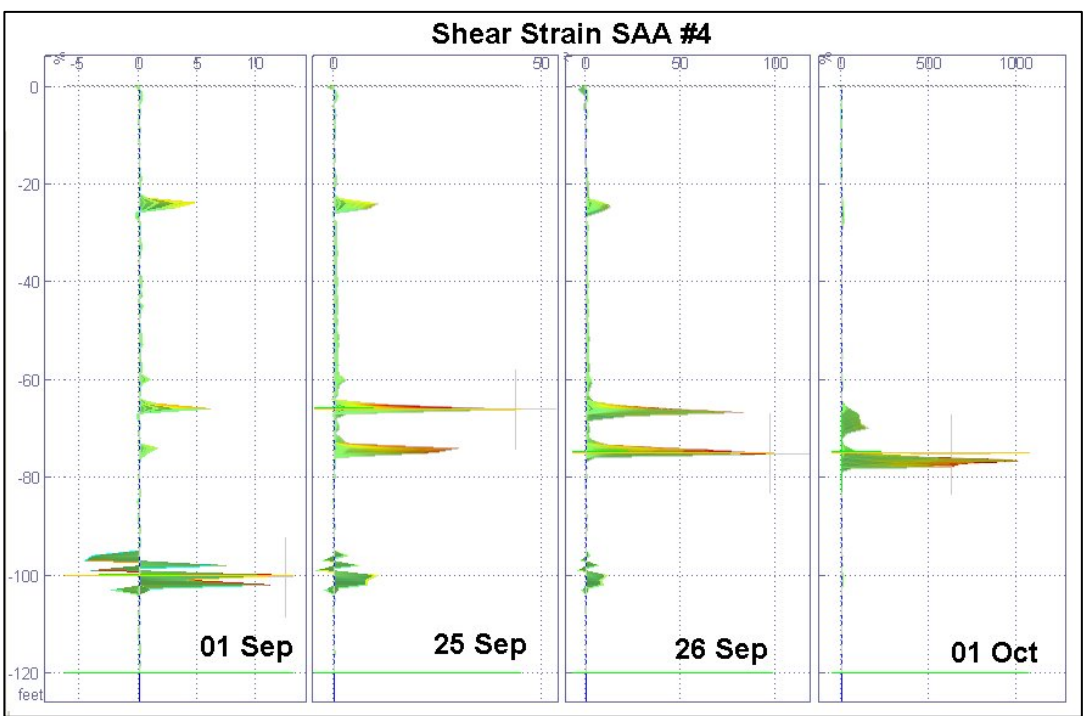

Figure 14. An output option available from the SAA reporting software is the shear strain. This provides an easy way to determine where the largest deformations are occurring and how thick the shear zones are; narrow bands imply thin shear planes, where wider bands indicate thicker shear zones.

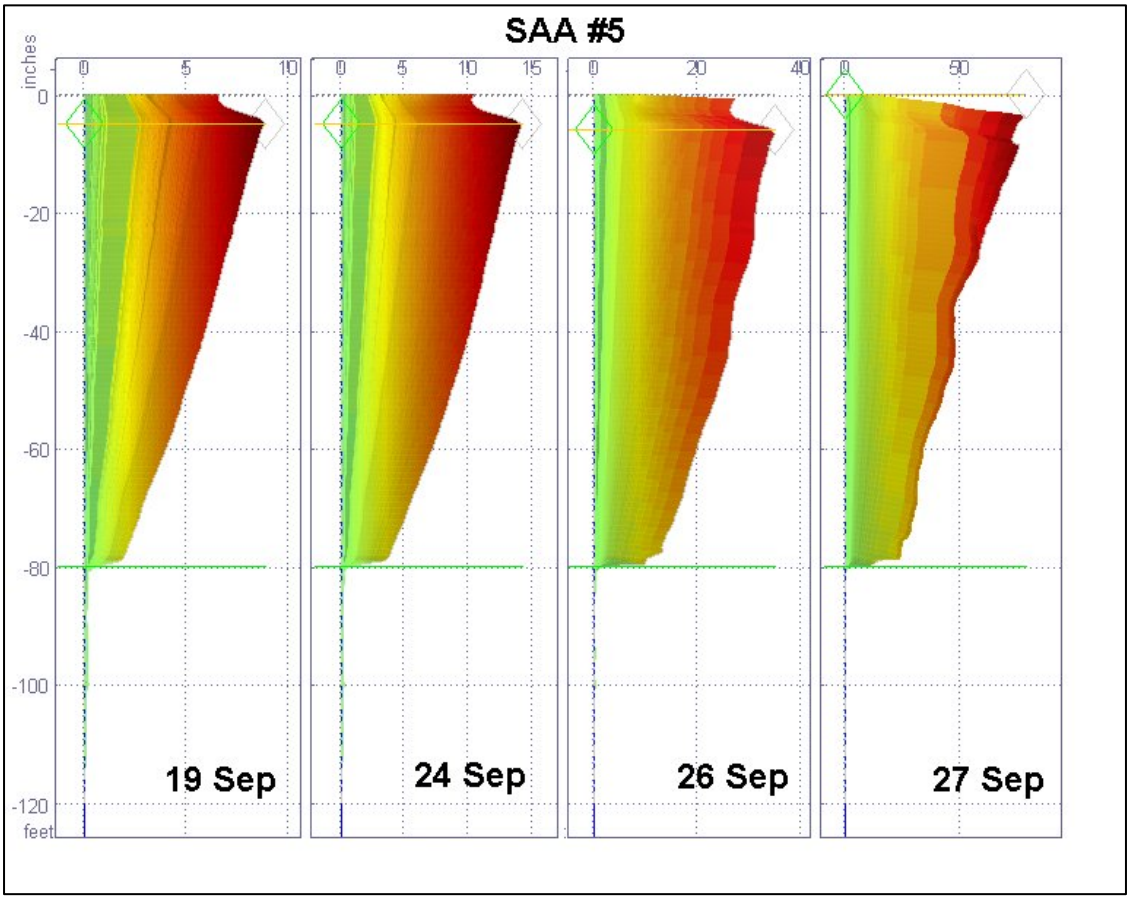

Figure 15. Cumulative displacement plots from SAA#5 show the deformation progression. Movement appears to initiate along a narrow shear zone at 79 feet; more evenly distributed deflections are seen above this layer, indicating an unusually thick shear band and a uniform 'tilting' of the soil toward the north. This differs from the observed motions at SAA#4 where movements appeared more purely translational in nature. The maximum observed deflection at SAA#5 was about 75 inches.

Figure 16. The six foot scarp immediately adjacent to SAA#5 is likely responsible for the unusual readings near the top of the array. SAA#4 is located just off the photo to the right of the equipment cabinet. The data cable from the array to the cabinet was stretched taut after the event; some of the scarp was dug out to provide strain relief. Data continues to be acquired along the entire length of both arrays; the data is uploaded daily to the web-server.

5.5 *Soil testing and failure analysis*

The difference in apparent behavior between SAA#4 and SAA#5 was of interest. Several isotropically consolidated-undrained triaxial test series were performed from samples from borings taken at the CE site. Some of the samples were taken from additional borings taken after the failure. Two additional SAA systems (SAA#6 and SAA#7) and two traditional inclinometers were installed to monitor possible impacts to the eastbound embankment. The triaxial test results are summarized in Table 1. Table 2 presents the results of hydrometer testing on samples from the CE site. The soils at this site have a higher clay content than those at the CW site.

Mn/DOT surveyors collected survey data along the cross section where the SAA systems were installed. This data combined with the triaxial test data, information from a CPT sounding, and the data from the SAA systems was used to develop a FLAC slope stability model.

Table 1. SP 6003-30 Isotropically Consolidated Undrained Triaxial Shear Strength (s_u) Data*

Boring	Sample Depth (ft.)	Sample Depth (ft.)	s_u (psf)	σ (degrees)	$s_{u'}$ (psf)	σ ‘ (degrees)	Soil type
T4SAA	13	31	710	8.3	520	17.6	Clay
T4SAA	15	41	620	8.5	590	15.1	Clay
T4SAA	24	71	800	6.0	930	8.1	Clay
T6SAA	2	19	260	14.3	660	7.1	Clay
T6SAA	3	29	820	4.0	450	14.9	Clay
T6SAA	5	49	610	7.7	240	18.7	Clay
T6SAA	7	69	410	9.0	288	17.1	Clay
T7SAA	8	89	10	3.7	130	2.5	Clay
T10SI	4	51	40	11.3	90	20.1	Clay

*two or three triaxial tests were run in each test series to determine the failure envelope and derive the total stress and effective stress parameters.

Table 2. SP 6003-30 Hydrometer Test Data

Boring	Sample #	Sample Depth (ft.)	% Clay	% Silt	%Sand
T6SAA	3	29	56	36.4	7.6
T6SAA	6	59	53.1	36.2	10.7
T7SAA	8	89	65.6	32.8	1.6

5.6 *FLAC model*

A FLAC model was created which had good agreement among the site geometry, strength, and observed behavioral characteristics. The model agrees with a number of observed features: 1) a failure initiation point in the median of US Highway 2, 2) large deformations near those observed on the SAA sensors, 3) a weak zone as observed on a CPT sounding taken through the north shoulder of westbound US 2, 4) an exit point somewhere in the base of the Red Lake River, 5) a secondary zone of weakness nearer the surface with an exit point near the base of the upper tier of the slope (to the south of the relatively flat area in the mid-slope).

The movement vectors also appear to be in good agreement with the directions of movement observed on the SAA sensors. The FLAC model suggested that SAA#5 would be in a broad shear zone with movement both down and north. The model also suggested that SAA#4 would see higher strain in a particular zone (about 70 feet deep) with lesser movements above this layer, with the exception of another possible shear band. This behavior appears to agree well with the observed data. Figure 17 presents an overlay of the observed areas of weakness and

movement on the FLAC factor of safety model results. Depending on the range of soil strengths and traffic loads, as well as other input parameters, the stability generally ranged from 0.9 to 1.1. It appears that the slide was deep seated in nature (although not extending to the Red Lake Falls Formation) and involved the movement of more than 400,000 cubic yards of material.

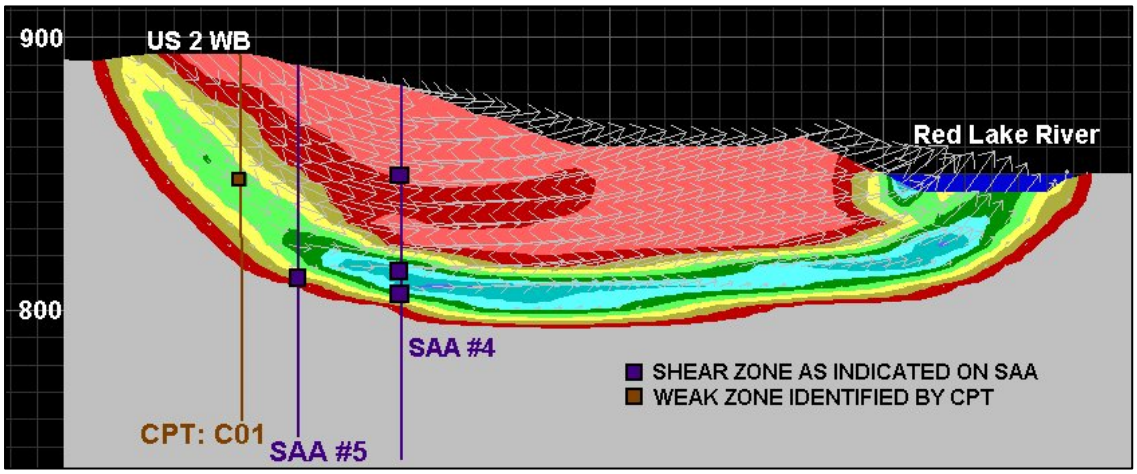

Figure 17. The FLAC model agreed well with the surface observations, CPT test data, and the SAA monitoring data. The model also provided some insight into the difference in the observed deformation behavior between SAA#4 and SAA#5.

5.7 *Long term monitoring and system performance*

The two systems at the CE site continue to provide data after 550 days in place, although data quality has been compromised since early October of 2008 when the large deflections caused a loss of directional (azimuth) data from both SAA systems. This was due to some segments being horizontal (it is impossible to calculate the azimuth of near-horizontal segments). However, data is still being acquired along the entire length of both 120 foot arrays. Despite the loss of the azimuth information, data is still being uploaded regularly and the arrays continue to provide an opportunity to observe the high-strain post-failure slope behavior, similar to the original monitoring at the CW site. Without an accurate direction component, the standard software reporting graphs appear awkward and difficult to interpret. However, the reporting software allows a selection for "ignore direction." Figure 18 shows the "absolute shape" of the CE arrays with the direction ignored. The information on these current plots (after the loss of the azimuth data) agrees well with the information presented on the more typical cumulative deformation plots presented earlier in Figures 13 and 15.

Recent data from SAA#4 shows that there has been about 6 inches to 8 inches of additional movement occurring equally along the two shear zones at depths of 66 feet and 74 feet. Recent data from SAA#5 shows that only about 2 inches to 4 inches of additional movement has been recorded in the failure zone above a depth of 79 feet; there has been no movement below that depth. The rate of movement has been stabilizing since the major landslide event and the shape of the sensors appears to be in good agreement with the conditions before the directional data was lost.

Although it was originally anticipated that these systems would be recovered and reused at another site after the monitoring period was over, they will likely be left in place to record subsequent slope movements. Due to the exceptionally large deformations, removing them appears impractical or impossible without causing catastrophic damage to the sensors.

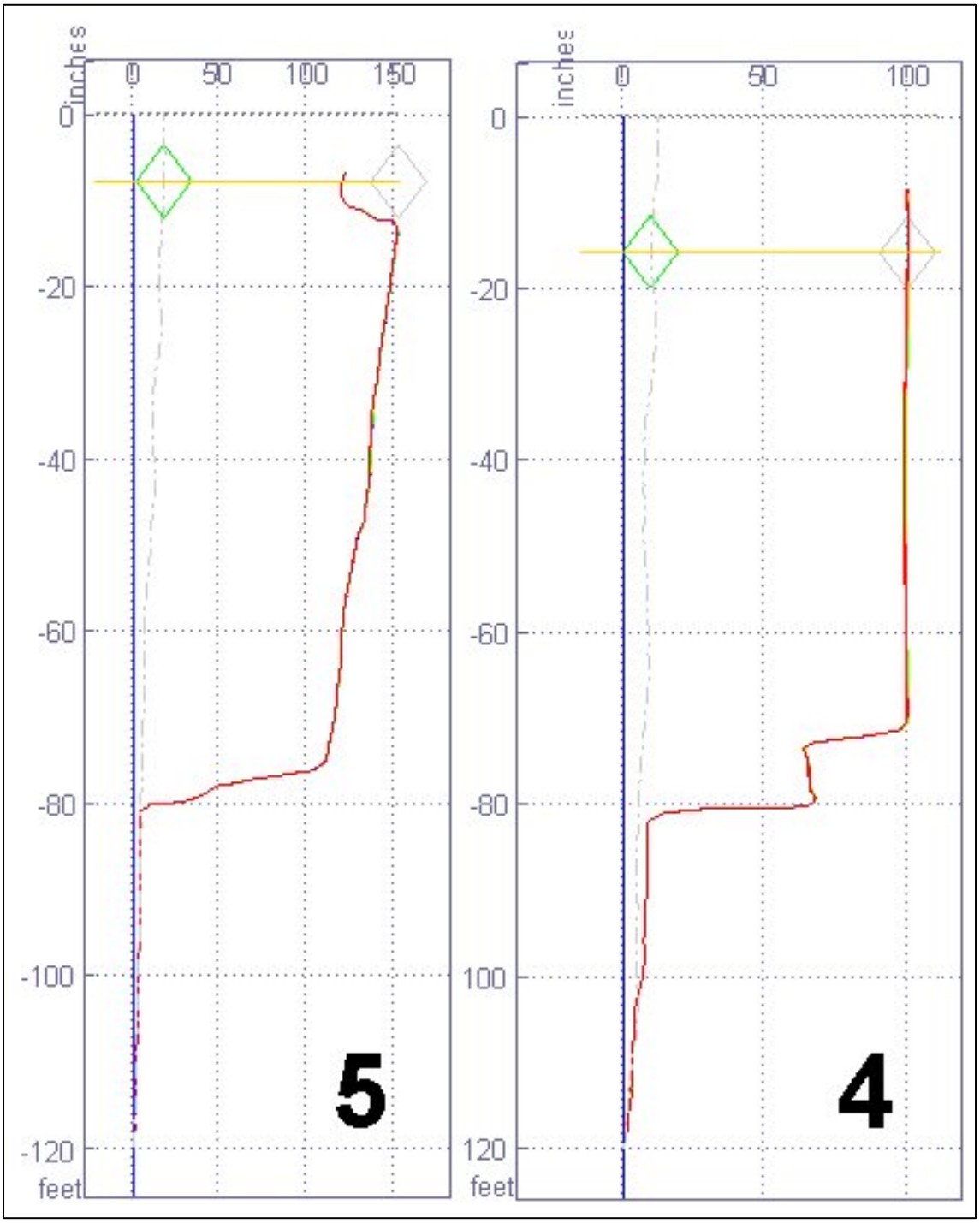

Figure 18. The SAA software allows the user to view the absolute shape of the sensor arrays and ignore the direction information. This feature is used to evaluate the high deformation long-term data

5.8 *Remediation*

Although the information at the original CW site is still under study for a long-term solution, there was a more immediate need for a solution at the CE site. Several concepts for remediating the site were quickly considered including 1) soil stabilization and ground improvement, 2) a bridge 3) lightweight fill, and 4) changing the alignment of the highway to avoid the area. After

some relatively fast calculations and cost estimates it was determined that rerouting all 4 lanes of US Highway 2 on a more southerly alignment would be the easiest to design and build, and be the least expensive.

The ground improvement, bridge, and lightweight fill alternatives were all expected to have costs upward of $4 million dollars, with the roadway realignment more likely costing only about $2 million dollars. The District elected to proceed with design plans to move the 4-lane roadway section about 400 feet to the south. Shortly after the landslide, the pavement in the slide area was removed, the area was graded to improve drainage, and turf establishment fabrics were placed. Traffic continues to be routed on the former eastbound lanes with a single lane in each direction. Monitoring on the original sensors, SAA#4 and SAA#5 continues, as well as monitoring on two additional arrays, SAA#6 and SAA#7 which were installed in the median area shortly after the failure to ascertain if there was any threat to the remaining lanes of US Highway 2, now carrying both traffic directions. These two new systems both show less than 2.5 inches of new movement, most of which occurred soon after installation. The realignment project is scheduled to be awarded for construction in the spring of 2010.

Figure 19 shows the proposed design plan for the realignment of US Highway 2 to the south of the failure area. Monitoring will continue as the river can still continue to meander and erode material at the slope, although the offset is expected to provide a n adequate margin of safety for the foreseeable future. Figure 20 shows two drill rigs on the site installing two additional manual inclinometers and two additional SAA systems for the continued monitoring of the unimpacted portion of US Highway 2.

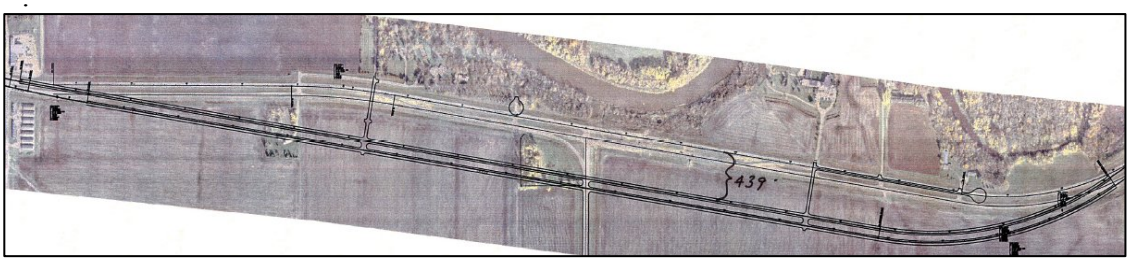

Figure 19. The river bend and failure area are at the center top of the figure. The proposed realignment of the highway will offset the 4 travel lanes approximately 440 feet to the south. The roadway realignment required the purchase of new right-of-way and the realignment of several utility towers.

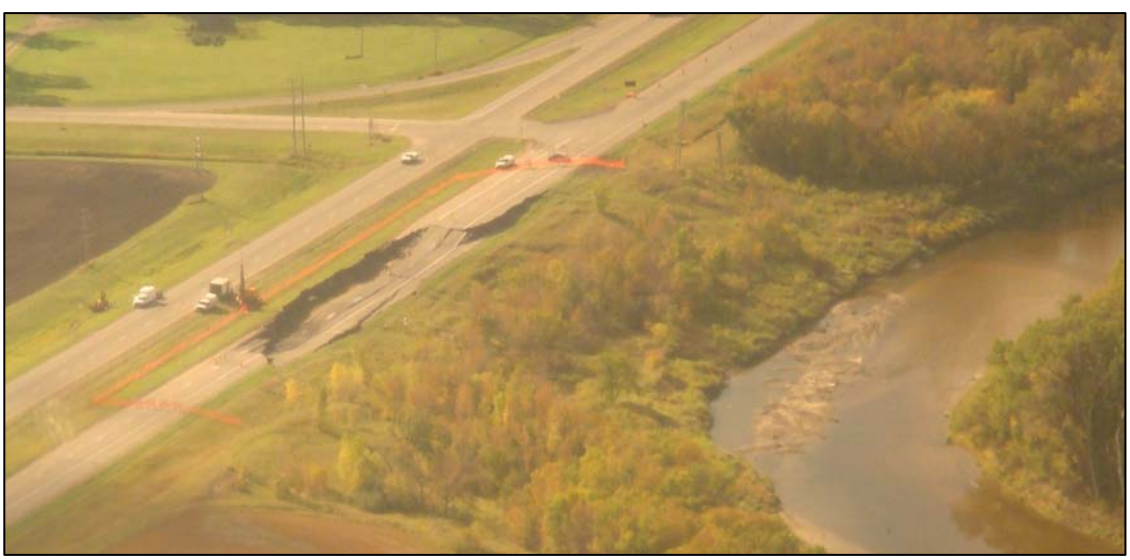

Figure 20. Although there had been some minor distresses observed on the mainline paving and the embankment for many months, this large a failure was unexpected. This aerial photo shows the main scarp, the uplifted material at the toe in the Red Lake River, and the drilling operations to install additional post-failure monitoring. The failure area has been marked off with orange snow fencing.

5.9 *Landslide Summary*

Both landslides appear to be rotational in nature, where most of the displaced mass is moving as a coherent unit along the rupture surface with relatively little internal deformation. At both slides the head moved more-or-less vertically downward, with the upper surface areas tilting backward toward the scarp in some areas. The triggering mechanisms at both the CW and CE sites appear to be combinations of rainfall, hydraulic erosion at the toe of the slopes, and low water levels in the Red Lake River. Both slides occurred in the autumn when water levels were near their lowest seasonal levels. The USGS defines a slide as a "down slope movement of a soil or rock mass occurring on surfaces of rupture or on relatively thin zones of intense shear strain" (Highland and Bobrowsky 2008); these two slide areas fit that definition well and are fairly typical of the slides seen in northwestern Minnesota, although perhaps on a larger scale with more visible impact than many. Both landslides are progressive failures; there is a history of movement at both locations. The sites are also on the outside bends of river meanders, suggesting that the slide activity will continue unless countermeasures are taken. A long-term solution at the CW site is still pending further analysis and review; large soil dowels and caissons are being considered, as are ground improvement methods. The long-term solution for the CE site consists of changing the roadway alignment and "moving out of the way."

Thanks in some part to random chance, the pilot program to evaluate the SAA sensors created the opportunity to expand the initiative at the CE site and lead to the timely monitoring of that site just months prior to a catastrophic failure event. The data captured at that site was striking and has provided several new insights about the rates, magnitudes, and geometry of landslides in northwest Minnesota's clayey soils. The nature of the failure at both sites has also resulted in a new appreciation for the impact of low water levels, as well as the high water levels more commonly associated with roadway failures, on account of flooding and scour.

6 IMPACTS OF THE SAA PILOT PROJECT

Based on the favorable results of the original pilot project, at the CW site, and the subsequent work at the CE site, several additional systems have been ordered and installed at other landslide sites and in a horizontal application monitoring settlement below a bridge abutment. At these additional projects, the ease of installation, remote monitoring, and frequent sampling intervals have proved to be very useful in high quality assessment of site behaviors.

It is anticipated that the regular use of these systems will continue, especially where frequent sampling or assessment of large deformations is required. The systems have also proven to save a large amount of time with respect to both the acquisition of the data (getting to and from sites and recording data at the site) and the data processing and reduction, which is fully automated with the SAA systems. Whereas a noticeable amount of time has been spent editing and manipulating traditional inclinometer data in the past, due to acquisition difficulties (usually by multiple people), this is almost totally absent with the SAA systems.

7 CONCLUSIONS

The pilot project was a larger success than originally anticipated. The automated landslide instrumentation performed so well on the first project, that even before that study was complete, the Mn/DOT Northwest District elected to install a second system to monitor a landslide that was soon to have a much larger impact on Mn/DOT infrastructure than the original slide area.

The SAA systems provided a wealth of information that, at the CE site, proved invaluable to confirm that major roadway distress was not only possible, but probable- if not certain, in the very near term. Before the situation at the CE site became critical, the data from the SAA installations provided engineers with enough confidence to let an emergency contract for a traffic detour, maintain traffic on the eastbound highway lanes and close the westbound roadway in sufficient time to prevent any loss of personal property or life.

The near-real-time monitoring systems allowed data to be collected at rates far in excess of what would be practical using traditional manual systems. In some cases, such as at site CW during the spring flooding, data acquisition would have been impossible. In addition, the web-based data downloading system allowed local engineers in Crookston, geotechnical engineers in Maplewood, and other interested staff and personnel to review the data at any workstation with an internet connection, the system software, and site passwords. This feature has been particularly advantageous for data review, collaboration, and sharing among multiple parties.

Perhaps the most unexpected benefit of using the SAA systems is the amazing resilience and overall ductility of the down-hole sensors. While in the past, traditional inclinometers have sheared with only a few inches of deformation along a shear plane, the SAA sensors have successfully recorded over 100 inches of lateral deformation and still remain in useful service, although somewhat degraded in performance. The ability to tolerate large deformations and still provide engineering data on the soil behavior has provided new insight into the existence of multiple high-strain shear zones and how the rate and magnitude of movement within these zones varies during the evolution of a landslide event. The SAA sensors are exceptionally robust, the installation is relatively straightforward, and the monitoring and reporting software is easy to learn and manipulate. A variety of data presentation options also make it possible to examine slope behavior in a variety of ways. The automated sensors have captured data at both sites that is of significant value in characterizing the slope behavior. After the failure events, the existing and newly installed systems are providing data for further analysis and acting as early warning systems for future instability, ensuring the continued safety of the traveling public.

Based on our experience in the pilot study, the benefits of these systems, particularly in reduced labor, travel, and error evaluation- even in non-critical applications- make them a highly desirable alternative, even on typical projects. The SAA systems provide outstanding performance where there is interest in precision evaluation of the rates of movement, a need for frequent readings, or a need for monitoring of large deformations.

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