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Field Evaluations of "ShapeAccelArray" In-place MEMS Inclinometer Strings for Subsurface Deformation Monitoring

FINAL REPORT
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16. Abstract

Continuous monitoring of subsurface ground movements is accomplished with in-place instruments utilizing automated data acquisition methods. These typically include TDR (Time Domain Reflectometry) or assemblies of several servo-accelerometer-based, electrolytic level transducer-based, or MEMS (Micro-Electro-Mechanical Systems) -accelerometer-based inclinometer probes that are usually aligned within special grooved casing. In-place inclinometers can determine the magnitude and direction of ground deformation, whereas TDR is primarily used to identify depths of active shearing only. Because the number of sensors in an in-place inclinometer chain may be somewhat limited due to cost or technological constraints, installation of in-place inclinometers on landslides has typically been preceded by the use of TDR or traversing probe inclinometers to target zones of interest.

The New York State Department of Transportation (NYSDOT) participated in prototype installations to evaluate long MEMS-inclinometer strings that do not utilize grooved casing or guide wheels. The new, guideless device and installation method is being used to achieve detailed deformation profiling to detect multiple zones of ground deformation. This approach can survive very large ground deformations and continue to collect measurements, and is able to be retrieved from severely distorted casing and redeployed.

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EXECUTIVE SUMMARY

The New York State Department of Transportation (NYSDOT) has participated in prototype installations to evaluate long MEMS-inclinometer strings. The "ShapeAccelArray" (SAA) is a device capable of measuring ground deformation with high accuracy every 0.305 meters and soil acceleration at 2.4 m intervals. This sensor array can be installed vertically, in a method similar to that used for traditional inclinometer casing, or horizontally. Each sensor array is connected to a wireless sensor node to enable real-time monitoring as well as remote sensor configuration. Unlike traditional traversing inclinometers, the SAA does not utilize grooved casing or guide wheels.

Noteworthy aspects of this particular system are that (1) it enables an exceptionally long zone of continuous monitoring using short sensor spacing to achieve detailed profiling, (2) it is potentially retrievable from highly deformed casings with the potential for re-use on other applications, and (3) the system can be adapted to fit into smaller diameter drill holes or cased holes not originally intended for inclinometers. While these attributes may represent significant potential benefits for landslide and construction monitoring, the guideless methodology also creates some practical challenges.

This report describes the prototype applications and issues that NYSDOT has experienced on two demonstration projects, explores some of the possible consequences of the SAA technology from a practitioner's perspective, and makes some suggestions for future improvements.

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INTRODUCTION

NYSDOT has performed and evaluated prototype installations of reusable guideless MEMS-inclinometer strings. The two instruments used by NYSDOT are early prototype versions developed by Measurand of New Brunswick, Canada *(1,2)*. NYSDOT has installed the MEMS-inclinometer strings on two projects, including both horizontal and vertical applications.

Recent MEMS technology may offer some distinct advantages over other types of tilt sensors *(3)*, and in fact many manufacturers are now offering MEMS-based inclinometer probes. The sensors may also be particularly well suited for in-place applications and networks employing multiple instruments *(1,4)*. The author's expertise is with installation methods and geotechnical interpretations but not with development or manufacture of sensing hardware. The motivation for this paper is to draw on recent experience to explore some of the possible consequences of this technology from a geotechnical practitioner perspective. What the authors believe are noteworthy aspects of the particular system described herein are that (1) it enables an exceptionally long zone of continuous monitoring, using short sensor spacing (1-ft (0.3m)) to achieve detailed profiling, and (2) it is potentially retrievable from highly deformed casings with the potential for re-use on other applications. While both these attributes may represent significant potential benefits in landslide monitoring, the guideless methodology also creates some practical challenges.

PROTOTYPE MEMS-INCLINOMETER STRINGS

The systems described in this paper consist of 104 rigid segments, each 1 foot (305 mm) long, connected end-to-end by torque-resistant flexible joints. Refer to Figure 1. Each segment contains three MEMS accelerometers to measure x, y, and z axis tilt. (Only the x and y sensors are needed to calculate the tilt of a segment in a near-vertical orientation; however, for a segment lying in a near-horizontal orientation, the z sensor becomes necessary to attain better accuracy.) By calculating and summing the displacements of segments from the bottom up, the shape of the entire string can be determined, which would resemble the deformed shape of the borehole axis. The system resolution reported by the manufacturer is +/- 0.05 mm/m. This is corroborated by NYSDOT field experience: variations of 0.9 mm in 17 m were observed over a period of six months at one site.

FIGURE 1: Inclinometer string on shipping reel.

The system is guideless in the sense that it does not utilize any special grooved casing or wheel assemblies, however traditional inclinometer casing with a manual servo-accelerometer-based inclinometer probe has been used to compare data results. This system can be adapted to fit into smaller diameter holes or holes not originally intended for inclinometers.

The simplified construction, as well as efficient data collection utilizing built-in multiplexing routines, makes very long chains of in-place sensors more practical and cost-effective. In landslide applications, this leads to the possibility that precise knowledge of the shear zone elevation would not be necessary prior to installation. Furthermore, this allows for simultaneous monitoring and detection of multiple shear zones at different depths. A limitation of manually-lowered inclinometer probes where multiple shear zones exist is that an upper deformation zone could cause the guide casing to bend excessively and obstruct the probe from being lowered to measure deeper shear zones. By virtue of the MEMS string's shorter segment length and smaller diameter (nominally 1-inch (25 mm)), the system is able to measure a larger bending deformation in the borehole and is easier to extract from significantly deformed casings.

While the guideless design may lead to certain advantages, there remain issues that include potential variability in lateral support provided by the loose sand backfill and the determination of the actual axial rotational alignment of any individual sensors in the event they may have deviated from their factory calibration, as will be discussed.

INSTALLATION PROCEDURES AND NYSDOT FIELD TRIALS

To date, NYSDOT has performed three installations (and subsequent extractions) of the inclinometer strings on two projects.

On the first project, a bridge replacement in the upstate New York town of Fort Ann, the two inclinometer strings were used in horizontal and vertical orientations to monitor consolidation settlement and lateral deformation, respectively, of soft soils beneath an embankment surcharge. The primary aim of this demonstration was to utilize the inclinometer strings in a relatively controlled environment, and in conjunction with more familiar geotechnical instrumentation to compare results and to test initial installation and extraction concepts.

FIGURE 2: Horizontal inclinometer string installation over wick drain field – Fort Ann.

FIGURE 3: Surcharge construction using geosynthetic reinforced earth wall – Fort Ann.

The vertical inclinometer string at Fort Ann was installed inside a borehole cased with 2-inch (51 mm) diameter PVC monitoring well casing. The annular space between the instrument and the casing was backfilled with clean sand in order to put the instrument in intimate contact with the ground. At the completion of the monitoring period, the inclinometer string was freed by flushing the sand out of the hole. The horizontal inclinometer string was directly inserted into a “snug”-fitting 1-inch (25 mm) diameter PVC pipe and buried in a small trench running transversely beneath the proposed embankment site. Refer to Figures 2 and 3.

For the second project, the vertical inclinometer string was extracted from Fort Ann and re-used to monitor an active landslide near Springville, New York. The instrument was inserted into a 1-inch (25 mm) PVC pipe before being installed within a borehole cased with ABS inclinometer casing (2.75-inch (70 mm) diameter). Refer to Figure 4. The gap was again backfilled with sand. This installation required inserting the 104-foot (31.7 m) long instrument to a depth of 140 feet (42.7 m) to detect a suspected deeper landslide shear zone. This meant that the 1-inch (25 mm) PVC pipe had to extend about 36 feet (11.0 m) above top of the inclinometer string to reach the ground surface. The field installation did not orient the instrument accurately; however this was simply a result of insufficient planning. It would have been possible to keep track of the instrument alignment by using the markings along the outside of the 1-inch (25 mm) PVC pipe.

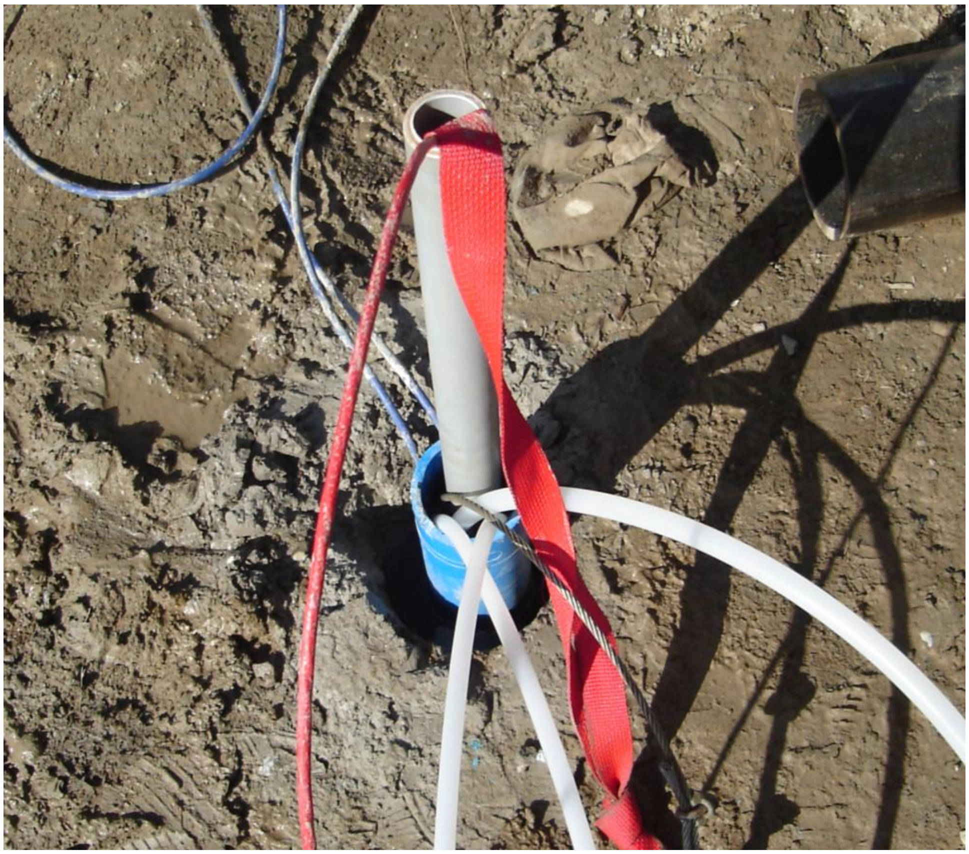

FIGURE 4: Inclinometer string installation showing 1-inch PVC pipe (gray), 2.75-inch inclinometer casing (blue), instrument lead wire (red), nylon strap (red), and three jetting tubes (white).

Overall, NYSDOT's first installations were considered successful. Results from the vertical inclinometer string at Fort Ann generally agreed well with an adjacent manual tracking inclinometer probe *(5,6)* and the string was successfully extracted at the end of the project using water injection to loosen the sand backfill. Similarly, the data from the horizontal inclinometer string agreed well with surface settlement gage readings and it was easily removed from its casing by manual pulling (even after experiencing nearly 1 ft (305 mm) of differential settlement). The installation at the Springville landslide site provided meaningful, near real-time data and helped to detect a deeper basal shear zone below a scarp that caused significant deformations in the casing (Figure 5). Traversing inclinometer probes may not have detected the deeper shear zone since the upper scarp deformation caused excessive bending and could have obstructed attempts to lower the probe deeper.

There were a number of issues and complications at both sites, however, as will be discussed.

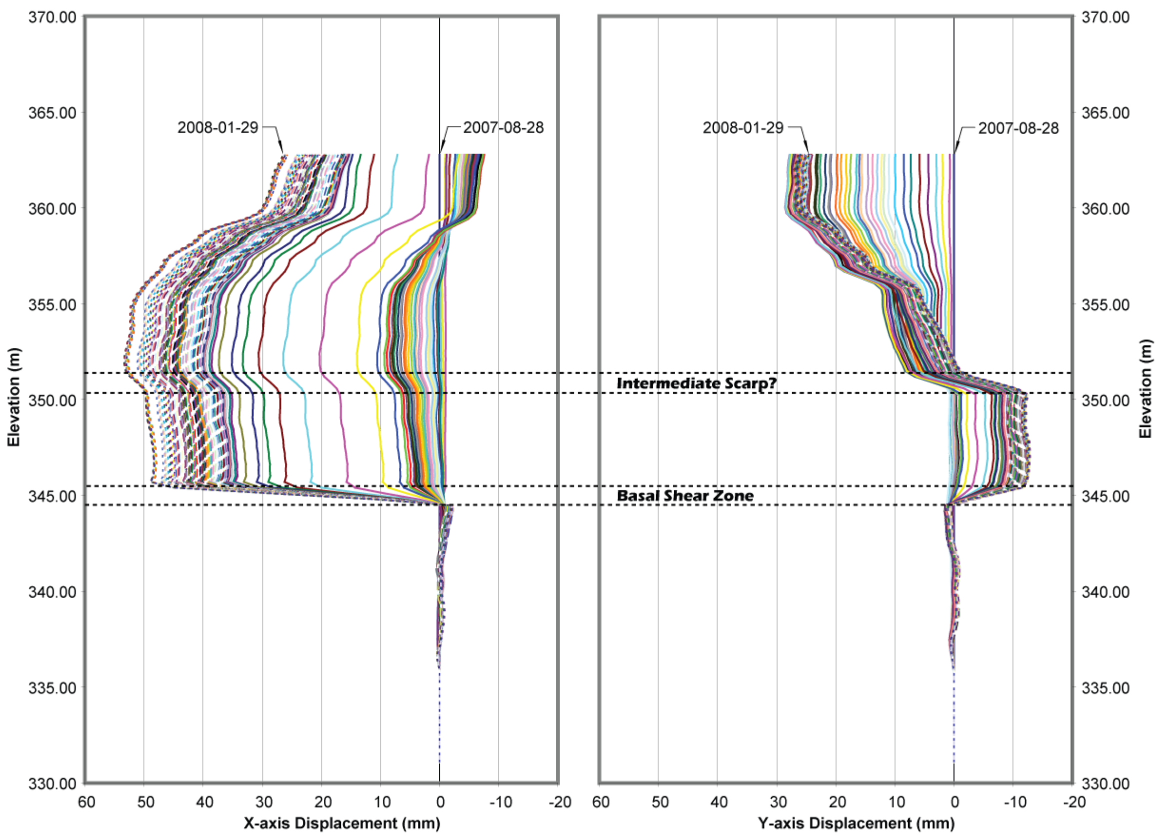

FIGURE 5: Average daily displacement profile – Springville

ISSUES

Installation and Sand Backfill

The vertical inclinometer string at the Fort Ann site was installed inside a 2-inch (51 mm) diameter PVC monitoring well casing, which had been grouted in place using a weak bentonite and cement mix. To suspend the instrument string in the hole prior to backfilling, a 0.125-inch diameter (3 mm) wire-wound steel cable was attached by taping it approximately every 5 feet (1.5 m). A plastic jetting tube (0.375-inch diameter (10 mm)) was also attached along the length of the string to facilitate later removal. After the inclinometer string was inserted, silica sand was slowly funneled into the top of the hole while the top of the casing was struck intermittently with a rubber mallet to prevent the sand from bridging. Refer to Figure 6. No tamping or compactive effort beyond this slight vibration was used.

FIGURE 6: Placing sand backfill by hand.

For retrieval, the sand backfill was loosened by pumping water through the bottom jetting tube and also using 0.5-inch (13 mm) PVC pipe for additional jetting from the top. Refer to Figure 7. However, extraction at the Fort Ann site ultimately required more pulling force and torque than recommended by the manufacturer, which will be a topic of further discussion.

FIGURE 7: Retrieval of inclinometer string by loosening sand backfill using water jetting.

During the first weeks of data collection at the Fort Ann site, the deflection plot of the vertical inclinometer string showed noticeable zigzag movements of many segments, presumably due to settlement of the sand within the casing. This might have been avoided by better planning of the borehole depth: the instrument could have been rested on the bottom, rather than hung in suspension. Over the following months, some minor additional deflections were measured (with magnitudes up to approximately 0.15-inch (4 mm)) along various portions of the inclinometer string. The various movements were in seemingly random directions and occurred either suddenly or at more modest rates. Since these differential deflections took place prior to placement of the surcharge load, it was concluded that they likely were due to backfill effects and not indicative of true ground deformation. Green and Mikkelsen *(7)*, point out that granular backfills around inclinometer casings are more prone to bridging than grout and that "incomplete backfilling or backfill settlement causes spurious casing movements that are best avoided." From the perspective of the project, it was fortunate that there was a several month gap between the instrument installation and the start of construction. By the time placement of the surcharge load began the spurious movements had ceased for the most part and the inclinometer string was "reinitialized" by simply disregarding the earlier data from the summation of movements.

The backfilling technique was improved at the Springville site by first inserting the inclinometer string, along with a flat nylon strap, directly into a 1-inch (25 mm) diameter PVC pipe. The nylon strap created a tighter fit and the PVC provided more rigidity to the string. Then the entire assembly (instrument string within PVC pipe) was inserted into the 2.75-inch (70 mm) diameter casing. To make the installation retrievable, the annular space between the 1-inch (25 mm) casing and the 2.75-inch (70 mm) inclinometer casing was backfilled with sand using similar procedures as for the Fort Ann site. The 1-inch PVC pipe seemed to eliminate much of the backfill settlement concern that was detected at the first site. It is possible that this change may have reduced the sensitivity of the instrument. However, since the 1-inch (25 mm) PVC pipe is a smaller diameter and less rigid than the 2.75-inch (70 mm) ABS inclinometer casing, the system would likely still behave relatively flexibly. In fact, the capability of this installation was subsequently verified by its detection of intermediate landslide shear zone displacements along scarps and the deeper basal sliding zone.

Sensor Alignments

Maintaining the rotational alignment of the many segments of the inclinometer string is crucial in the same respect that avoiding (or identifying) a spiraled inclinometer casing is. After it is assembled, each segment is calibrated at the factory to a "zero azimuth" (analogous to the A+ direction in traditional wheel-based inclinometer probe systems) which is then marked near the top of the instrument. Any twists between segments would lead to incorrect directional readings and incorrect summation of displacements (as with an uncorrected spiraled inclinometer casing). The elastic rotational "play" in the inclinometer string joints is at least 0.3 degrees per segment when torqued with 7.4 ft-lbs (10 kN-m) moment *(5)*. However, based on a forensic analysis of the Springville inclinometer string by the manufacturer, it appears that this elastic range was inadvertently well exceeded.

Movement directions recorded by sensors at different elevations were significantly different from each other, (see Figure 8), and therefore twists in the inclinometer string were suspected during the monitoring of the Springville slide. However, there were neither insitu means to measure actual alignments nor means to determine whether damage or twists had occurred at the joints without removing the instrument from the borehole casing. After its extraction, the lower half of the instrument was found to be out of alignment by 3 to 4 degrees per joint. The cumulative effect was that the lower sensors were over 180 degrees out of alignment from the upper! It is postulated that the damage to the joints most likely occurred during prior extraction at the Fort Ann site, which required more pulling force than originally intended (the manufacturer's recommendation was 500 lbs (2.2 kN)). One lesson to be learned is that a field check should be performed on a retrieved instrument prior to each additional installation to verify sensor alignment and that all the components are functioning as originally intended. The manufacturer is reportedly now providing software for performing a field calibration of rotational alignment, although the authors have not yet had the opportunity to evaluate it. System improvements could also be made to provide improved durability. To this end, the manufacturer is now encasing the inclinometer string with steel braid to improve torque resistance.

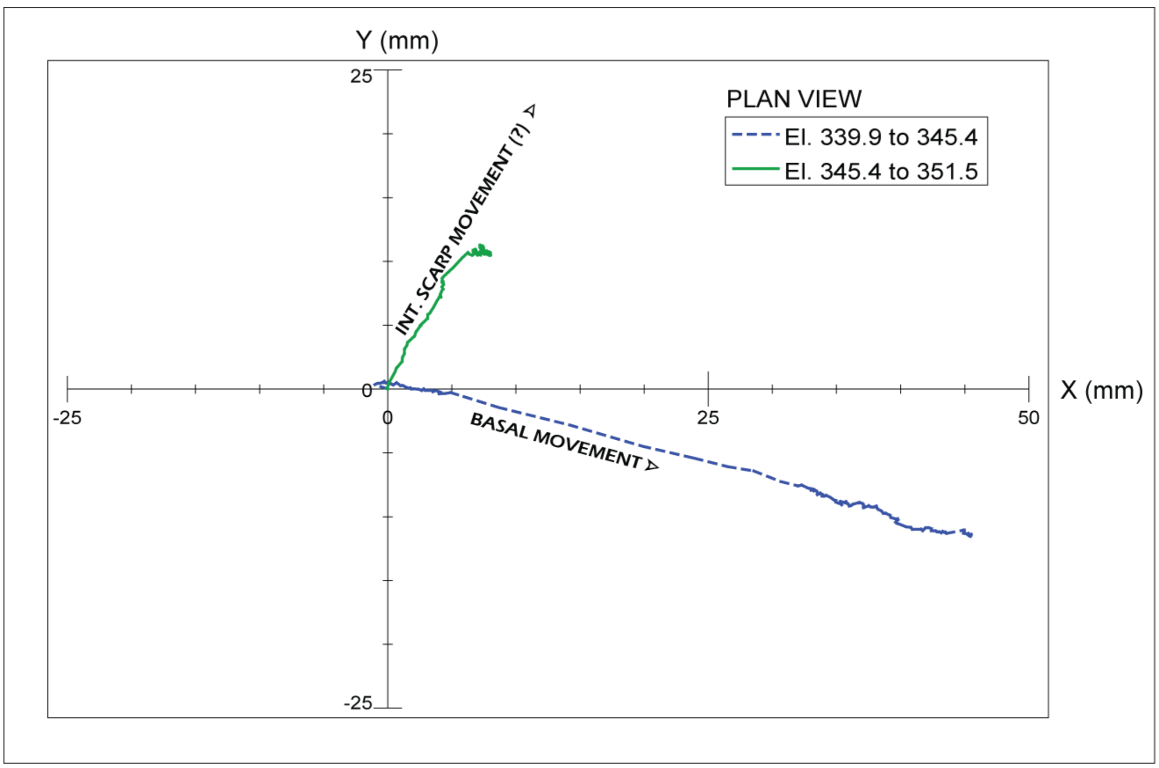

FIGURE 8: Resultant direction of movement over selected elevation ranges – Springville

It might be possible to develop mathematical methods to correct known rotation errors, provided that the actual amount of rotation can be determined. For guide casing applications, Mikkelson *(8)* describes methodology for correcting rotation errors. Special calibration procedures or additional instrumentation may need to be incorporated with the inclinometer string to measure orientations. The manufacturer reports that they are installing triaxial magnetometers in some newer models so that twists may be identified insitu.

Malfunctioning Sensors

After approximately three months in the ground at the Springville landslide, one of the lower sensors began to behave erratically. In the following weeks, several more sensors began to malfunction. Because the malfunctions occurred on a deeper sensor first and seemed to work their way up in elevation, it was suspected that water may have infiltrated the protective sheath and was short-circuiting connections as it rose. This was later confirmed upon retrieval and dissection of the instrument by the manufacturer. Two possible explanations are a) that the polyolefin sheath was nicked at some point during field handling and groundwater seeped in, or b) that the water pressure used to expel the sand at the Fort Ann site (up to roughly 300 psi (2070 kPa) – approximately twice the manufacturer’s approved limit) was too high and that water may have entered then. Based on the observation that the 1-inch (25 mm) casing was still dry inside upon extraction, the later explanation would seem most likely. Fortunately, the malfunctioning sensors were well below the depth of the landslide basal shear zone and therefore those segments could simply be excluded from the summation of readings so that useful data could still be plotted and interpreted. However, approximately five months after installation, further complications associated with the water-damaged circuits created current demands that resulted in an inability to download any further readings.

The extraction at the Springville site was accomplished with much lower water pressure (less than 50 psi (345 kPa)) by using three jetting hoses installed at various depths within the borehole casing. The manufacturer is now including waterproof bulkheads in their newer inclinometer string systems at every eighth joint as a backup to the protective sheath.

CONCLUSIONS

This paper describes prototype applications and issues that NYSDOT has experienced on two projects. The guideless MEMS-based inclinometer string instrument is in its infancy, but has demonstrated several benefits, as well as issues to resolve.

The NYSDOT installation method has succeeded in retrieval and re-use, thus increasing the instrument’s cost-effectiveness. Ground deformations measured by this installation method have proven to be reasonable and compared favorably with conventional manual inclinometers in guide casings. The deformation profiles may have been slightly altered due to the use of loose sand backfill, but similar magnitudes and rates of movement were measured.

The installation of a guideless (wheel-less) inclinometer string below grade requires proper planning to align the instrument in the direction of anticipated primary deformation. Additionally, the individual sensor orientations should be verified by appropriate measurements (due to the potential for misalignment and spiraling or twisting).

Additional field tests are needed alongside standard inclinometers where recognizable deformations are occurring to confirm system accuracy and use of diagnostics and data corrections to achieve matching deformation profiles.

It appears that field diagnostic methods are needed to verify instrument performance and to identify potential issues. Since the instrument remains in place during the monitoring period, diagnostic devices may need to be manufactured directly into the inclinometer string system and the readout software possibly modified in order to make diagnostic recordings and evaluations.

Additional field tests and laboratory bench tests should be performed to develop recommended practices for installation of retrievable in-place inclinometer string systems. Items to consider include:

- Casing types/sizes. Simple tests involving 'S' bends in various sized casings may be used to determine the maximum radii of bending that could be tolerated before rendering the instrument string irretrievable.
- Backfill. Tests to determination fill types and installation methods that will achieve preferred densities (compatible with the ground being monitored) and reduce or eliminate voids.
- Extraction. Further development of methods that can remove the instrument without significant harm, and procedures for post-retrieval inspection, testing, repairs and calibration to provide confidence in reusing the system.

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