Experience with the Installation and Performance of In-Place Slope Inclinometers

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ABSTRACT
The evolution of MEMS accelerometers has led to the development of several types of in-place slope inclinometer systems that can serve traditional geotechnical applications for monotonic ground movements, as well as being capable of measuring dynamic movements. The installation costs for the in-place system are somewhat higher than for conventional (slope inclinometer) SI casing, but over the duration of construction, the overall cost can be similar to, or lower than, conventional SIs. The in-place systems qualify for preferred use in applications requiring frequent data collection, difficult access, and/or where expected movements are high.

RÉSUMÉ
L'évolution des accéléromètres MEMS a engendré le développement de plusieurs types d'inclinomètres fixes qui peuvent mesurer des déplacements monotoniques du sol pour des applications géotechniques traditionnelles, et qui sont aussi capables de mesurer des déplacements dynamiques du sol. Les coûts d'installation pour les systèmes d'inclinomètres fixes sont plus ou moins supérieurs à ceux des tubes inclinométriques conventionnels, mais peuvent devenir très compétitifs sur la durée d'un projet de construction. Les systèmes d'inclinomètres fixes se distinguent comme instruments de choix dans des applications qui requièrent l'acquisition des données fréquentes, dans des endroits difficiles d'accès ou dans des cas où des déplacements importants sont prévus.

1 INTRODUCTION

The evolution of MEMS accelerometers has led to the development of several types of in-place slope inclinometer (SI) systems that can serve traditional geotechnical applications for monotonic ground movements, as well as being capable of measuring dynamic movements.

Typically in-place inclinometers are chosen over a standard slope inclinometer for remote reading or data logged applications, or where the required reading frequency is high. In the case of a construction site, there are additional benefits of in-place inclinometers: a) avoiding raising an inclinometer casing through fill, (and the associated problems of poor fill density and settlement of the inclinometer casing), and b) improving monitoring efficiency.

2 BACKGROUND ON GEODAQ INCLINOMETER

The Geodaq INC300 in-place inclinometer consists of a network of precisely spaced sensors capable of measuring acceleration, tilt, and temperature. The sensors are assembled at intervals of 152 mm (6 inches), 305 mm (1 ft), or 610 mm (2 ft) into modules 2.44 m (8 ft) long. The outer housing of the module consists of ABS plastic, and the sensors and electronics are encapsulated in a marine grade water sealant, forming a corrosion resistant, durable, and watertight system. The flexible plastic housing can tolerate significant bending, and will continue to measure deflection profiles in situations well beyond the capabilities of a conventional SI casing.

Adjacent modules are joined in the field using a plastic coupler that snaps onto the module and ensures correct alignment and spacing of adjacent modules. The cross-section dimension is largest at the location of the couplers, about 45 mm. Once all modules are connected, a complete network of sensors results. The system is grouted in-place creating a permanent in-place inclinometer installation. A relatively low cost controller module (GCM) is located at the end of the in-place inclinometer, providing a means to communicate with the network of inclinometer sensors.

3 CASE STUDY SITE

Four in-place slope inclinometers were installed in 2007 at a site in northern Alberta, to monitor the deformation of the foundation of a 30 m high earth fill dam during construction. Four conventional slope inclinometers were also installed, at various times during the construction, to supplement and verify the in-place inclinometer data.

The original ground elevation under the dam was around 390 m to 395 m (lowest at the toe). The dam crest elevation was 419.2 m and the average downstream slope was constructed at 10H:1V, to maintain stability through a weak foundation layer. The top of this layer also dipped in a downstream direction, dropping from about Elev. 387 m under the dam crest to about Elev. 382 m under the dam toe.

A schematic showing a portion of the downstream slope, and 4 inclinometers which will be discussed later in this paper, is given in Figure 1.

4 INSTALLATION

The in-place inclinometer system is watertight, and can be installed directly into an open hole and grouted into place using cement-bentonite grout. Two people are usually required to complete an installation, one to hold the instruments in the hole and the other to connect the

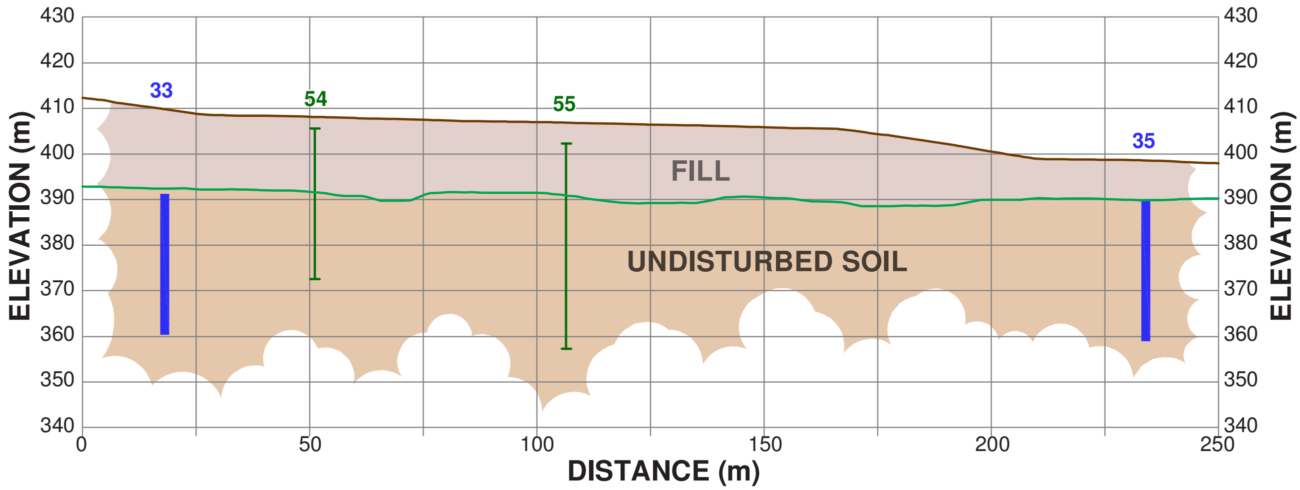

Figure 1 : Downstream slope of Dam Showing SI Locations (In-place SIs are Purple; Conventional SIs are Green)

next module. Filling the hole with water will offset the weight of the modules. As with all installations of instrumentation, it is prudent to verify that the modules are functional before, during and after installation. Readings are taken after the connection of each module to ensure that the installation is functional.

At the case study site, the in-place inclinometer's were installed inside a PVC casing, for ease of installation and to allow the string of instruments to be tested for a couple of days, prior to grouting.

For deep installations, additional torsional rigidity is required to avoid spiralling of the instrument; this can be achieved by attaching the modules to PVC or other casing.

Each in-place inclinometer module is marked with a directional tag, allowing the direction of movement to be set during installation.

Once an inclinometer is installed in the ground, its leads are attached to a GCM module (which requires a DC current source), and this in turn is connected to a laptop computer via a serial port. The data collection software, supplied by the manufacturer, requires a configuration and calibration file, which it uses to convert the raw data to displacements. Raw and processed data are automatically stored in a data file. The data collection software also has rudimentary features for viewing displacement plots with depth.

Data from the in-place inclinometer can also be read and processed by GTILT (Mitre Software), and hence can be presented in the same format as standard slope inclinometer plots.

5 PERFORMANCE

Figure 1 shows the location of two in-place inclinometers (SI33 and SI35, blue) and two standard inclinometers (SI54 and SI55, green) in relation to the original ground surface and final surface of the dam. The in-place SIs were installed prior to construction, and have the longest time record of foundation deformations. The conventional SIs were installed during construction, after some movement had been observed at SI33, to fill in the movement pattern under the entire dam slope.

Foundation movements as measured over the full recording period for SI 33 are shown in Figures 2 and 3. Note that the majority of construction (up to Elev. 416 m) occurred between the beginning of July and the end of October, 2007, with construction of the upper portion of the dyke ongoing to year end. Hence, the movements shown are a response to increasing load on the foundation.

The location of SI54, near to SI33, provides an opportunity to compare the two types of slope inclinometers, in regards to both the displacement versus depth profile, and the measurement of displacement (over a particular interval) versus time. Figure 4 shows the former comparison. It is clear from this figure that the two types of instruments provide similar results as to movement pattern and time response (note that the depth scale for SI33 is more compressed, as it is a longer SI). The amount of displacement across the shear plane is about 50-60 mm from October 19 to November 19, and about 80-90 mm from October 19 to December 1, for both SIs.

6 AVANTAGES OF, AND POTENTIAL ISSUES WITH, IN-PLACE SLOPE INCLINOMETERS

The in-place SIs delivered several benefits to the project, which were not apparent at the start of the work:

- Total costs were less than for a series of conventional SIs reading the same amount of displacement.
- Instrument reading was quick compared to a conventional SI (about ¼ of the reading time).
- The in-place SI leads can be trenched to any convenient location, away from construction traffic or other interference.
- The in-place SIs have the potential to be read more frequently by a data logger, or to be read remotely. Because this location was an active construction site, the client elected not to take advantage of this potential benefit.

- The in-place SIs endured up to 400 mm of movement across a ½ m zone, which allowed monitoring over the entire construction period, without replacement.
- Even if one accelerometer fails due to excessive ground movement, other accelerometers may continue to operate.

The following potential issues should be recognized and allowed for in the design of these installations:

- The in-place SI is less rigid than a conventional SI casing (perpendicular to the SI, as well as torsionally about the vertical axis). Spiralling can thus be an issue, unless the string of in-place SIs is strapped to a more rigid casing.
- Failure of an individual accelerometer will cause a "blind spot" in the monitoring profile. This is not a common or expected occurrence, but does point out the need for diligence in checking the SI at several stages during installation, when damage is most likely to occur.
- Each accelerometer is calibrated separately and thus care must be taken to record the order of installation and ensure this is reflected properly in the calibration file.

7 REFERENCES

Dunnicliff, J. and Green, G.E. 1988. *Geotechnical Instrumentation for Monitoring Field Performance*, John Wiley & Sons, Inc., New York, NY, USA.

Fell, R., MacGregor, P., Stapledon, D. and Bell, G. 2005. *Geotechnical Engineering of Dams*, Taylor & Francis Group plc, London, UK, p. 858.

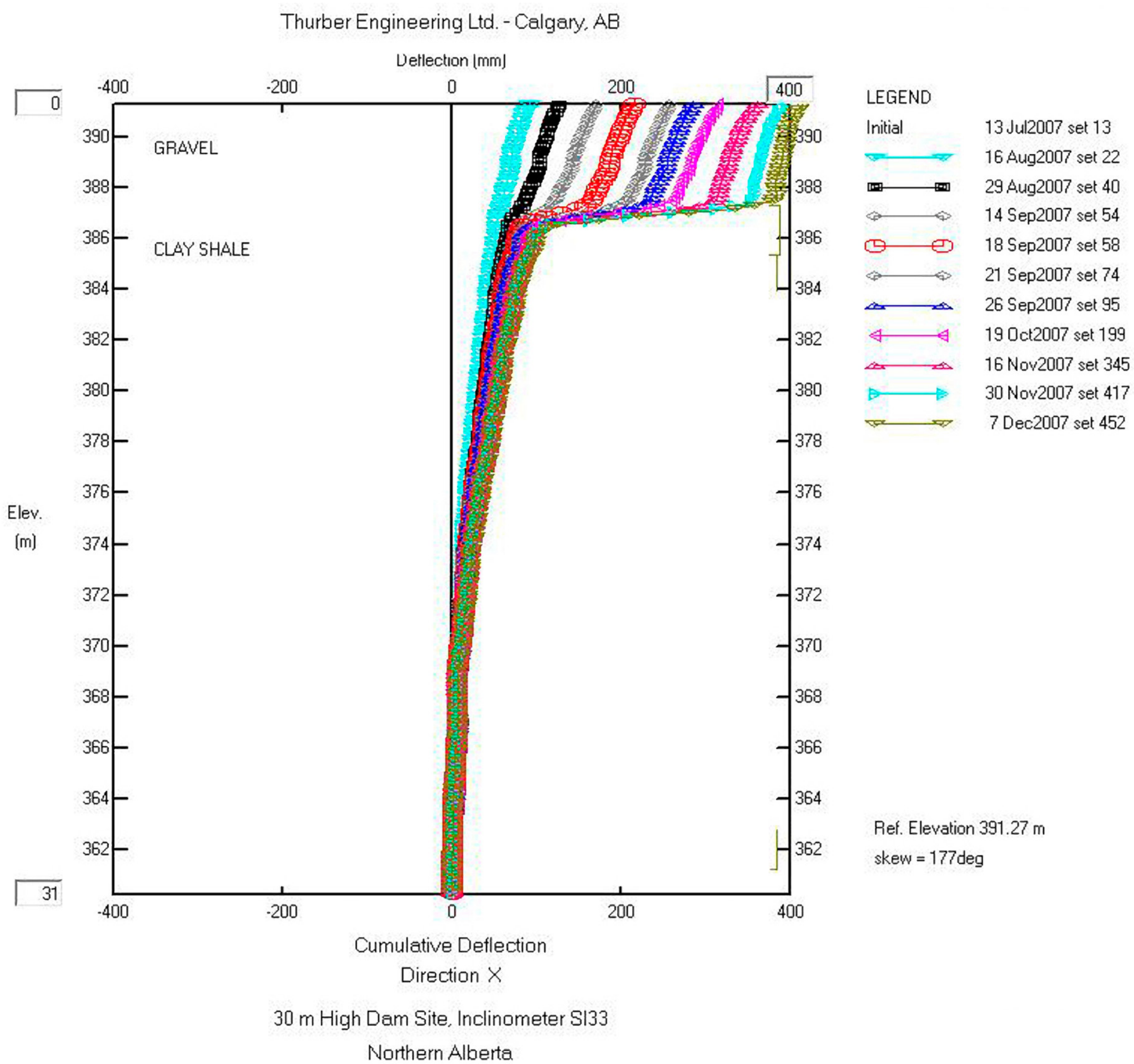

Figure 2 – Displacements observed in SI33 over the construction period.

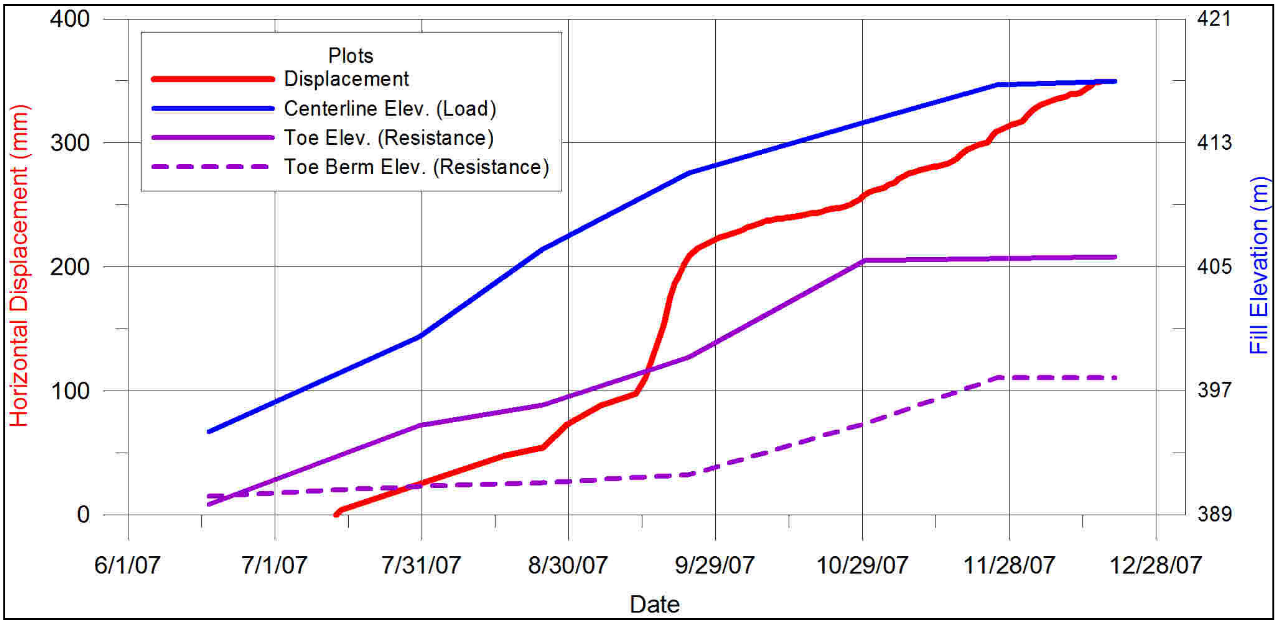

Figure 3 – Horizontal (Downstream) Displacement for SI33 (also showing Fill Elev. at Dam Centerline, near toe, and for top of Toe Berm)

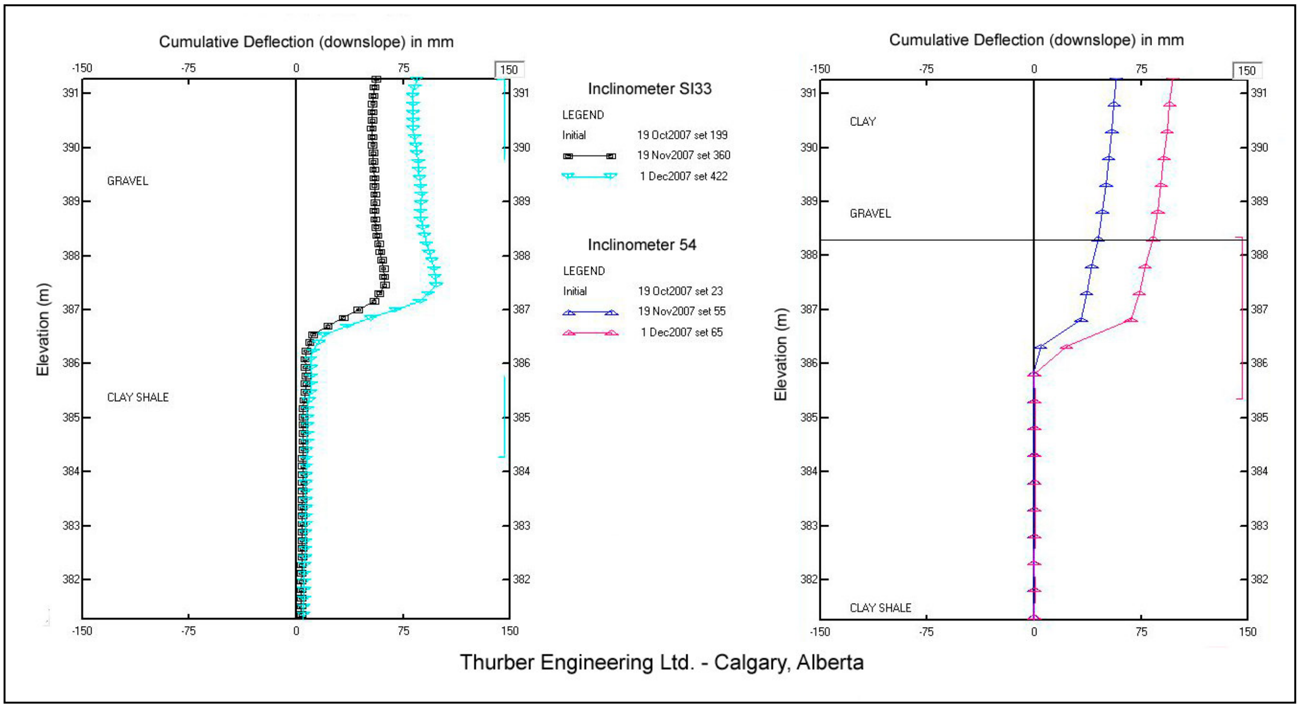

Figure 4 – Comparison of SI33 (on left) and SI54 (on right), for same time intervals.
(A 10 m portion of each SI has been selected, over the same depth interval,
to make comparison of plots easier).
(Note that measuring interval is much more frequent for the in-place SI33
than the conventional SI54).