The UBC Mini-inclinometer and settlement system

Campanella R G, Jackson S, Ortigao J A R & Crawford C B (1994) Design and installation of a new settlement•inclinometer device, Proc. Conf. *Settlement 94, Vertical and Horizontal Deformations of Foundations and Embankments*, Texas A & M University, College Station, ASCE Geotechnical Special Publication no. 40, vol 1, pp 911-922

Introduction

This report describes the construction, calibration and operation of a mini-inclinometer probe designed and manufactured by the UBC In Situ Testing and Instrumentation Group. The purpose of this new probe is to measure vertical and horizontal displacements simultaneously along the same access casing.

Description

The UBC mini-inclinometer comprises a 16 mm diameter, 360 mm long stainless steel probe (Fig 1), a cable and a read-out unit. It contains a liquid level tilt gauge (Fig. 2) which can measure angles simultaneously along two perpendicular axes. As the gauge is tilted, the lateral electrodes dip in and out of the electrolyte and their resistance changes with respect to the central electrode. The bridge circuit is designed to give an out-of-balance voltage proportional to the tilt.

This tilt gauge was selected on the basis of reliability, accuracy, dimensions and cost, after an extensive survey of different types of tilt gauges.

The gauge is connected to an electrical motor and a mechanical stopper enabling it to rotate precisely 180 degrees and to take opposite readings of tilt.

The probe has been designed to operate in standard SINCO ABS blue plastic casing 48 mm OD x 45 mm ID. A 14 strand electrical cable marked every 200mm, connects the instrument to the read-out unit.

The read-out box comprises the electrical circuit, rechargeable batteries and an 3.5 digit display to read tilt in both axis. A switch activates the motor for rotating the gauge and take opposite readings of inclination.

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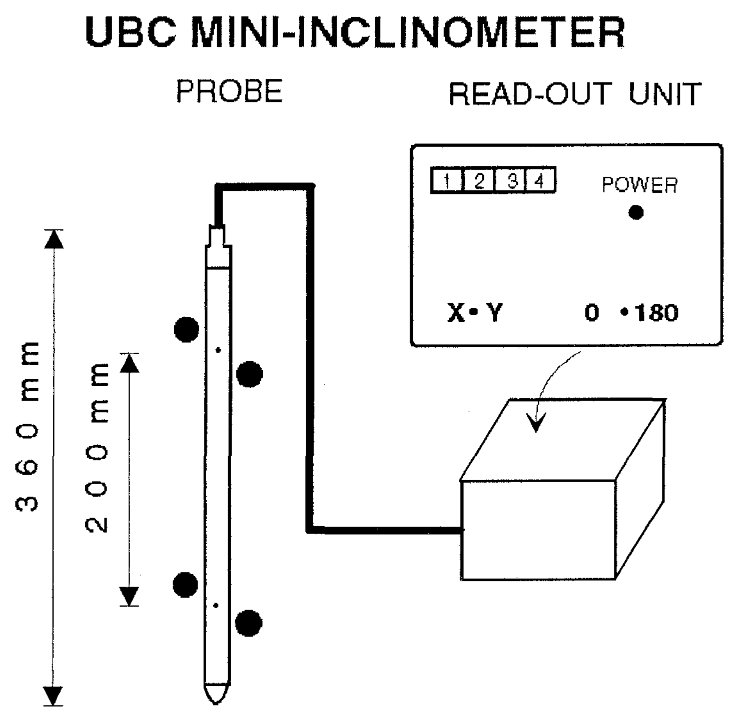

Fig 1 - UBC mini-inclinometer

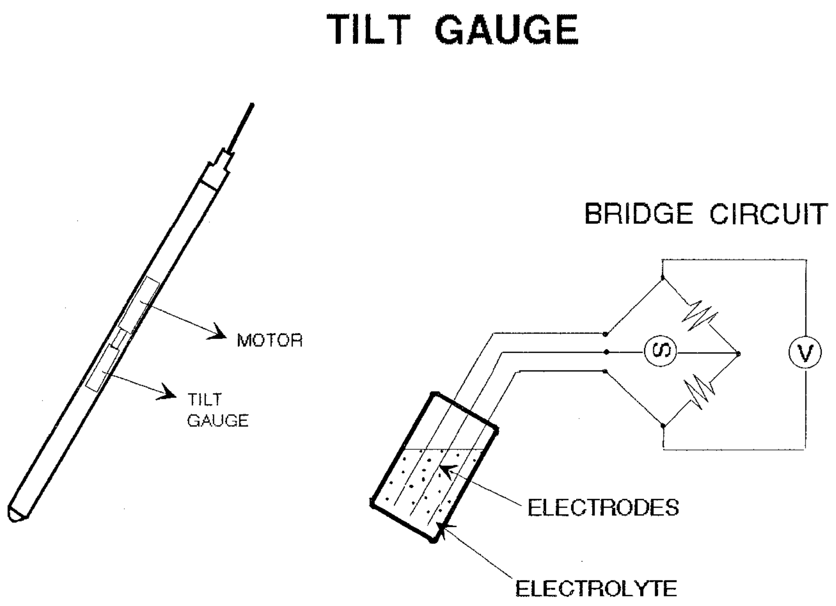

Fig 2 - Tilt gauge

The main difference of the UBC probe is its reduced dimensions as compared with commercially available probes (Fig. 3). The UBC probe is only 360 mm long, while standard commercial metric probes are typically 650 mm long. This feature allows much more bending in the casing before the probe gets stuck. Maximum allowable bending was evaluated and will be described later in this report.

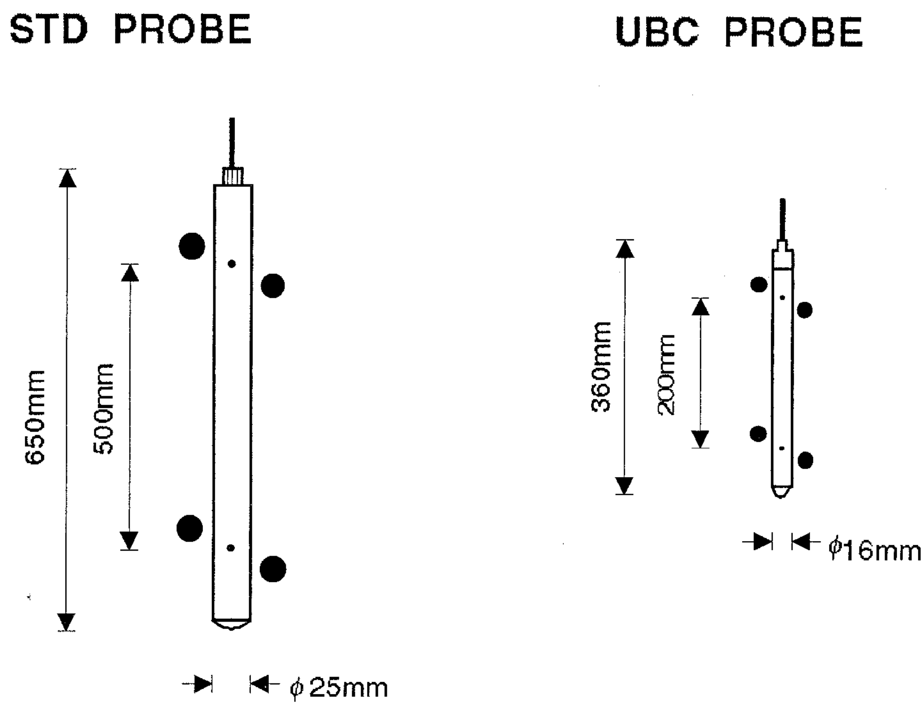

Fig 3 - Probe dimensions

Settlements can be measured by the UBC probe along the same access casing by means of the magnet *spiders* installed around the outside of the casing (Fig. 4). The spiders are PVC sleeves containing magnets that can move up and down freely along the casing. The leaf springs fix themselves to the surrounding soil. The position of the spiders is sensed by a pick-up installed in the probe which senses the magnetic field of each spider and allows the determination of its depth relative to the top of the casing.

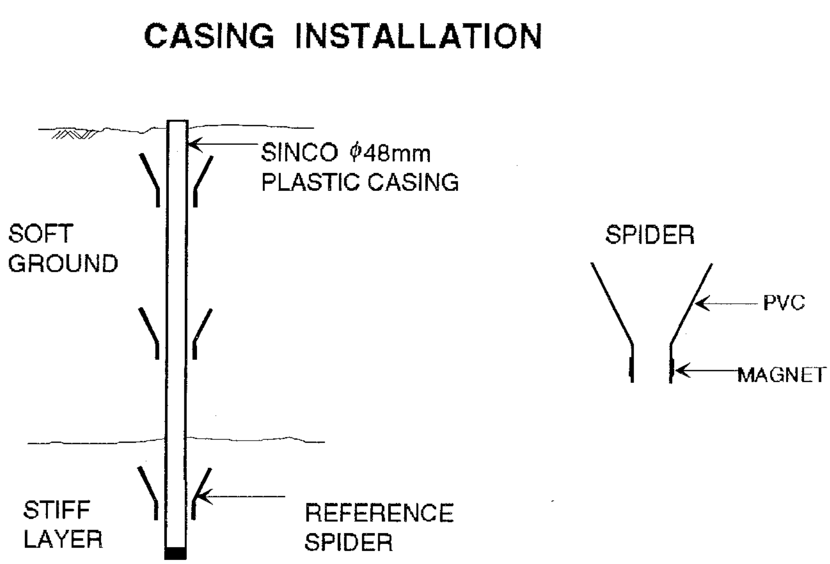

Fig 4 - Casing installation

Installation in soft soils

The system was designed to be installed by means of the UBC In Situ Testing truck by pushing and/or jetting into the ground.

Firstly, a steel *HQ* casing, 75 mm ID, 87mm OD is pushed into the ground. A disposable plastic conical shoe is used to plug the bottom of the casing and allow installation into a harder soil layer. Jetting of the point can be also be carried out as shown in Fig. 5 to allow penetration through resistant soil layers. A quick connector links this shoe to a hose and allows water to be pumped to the tip. At the end of the installation the quick-connector is disengaged by means of a wire line (not shown) and the hose is removed.

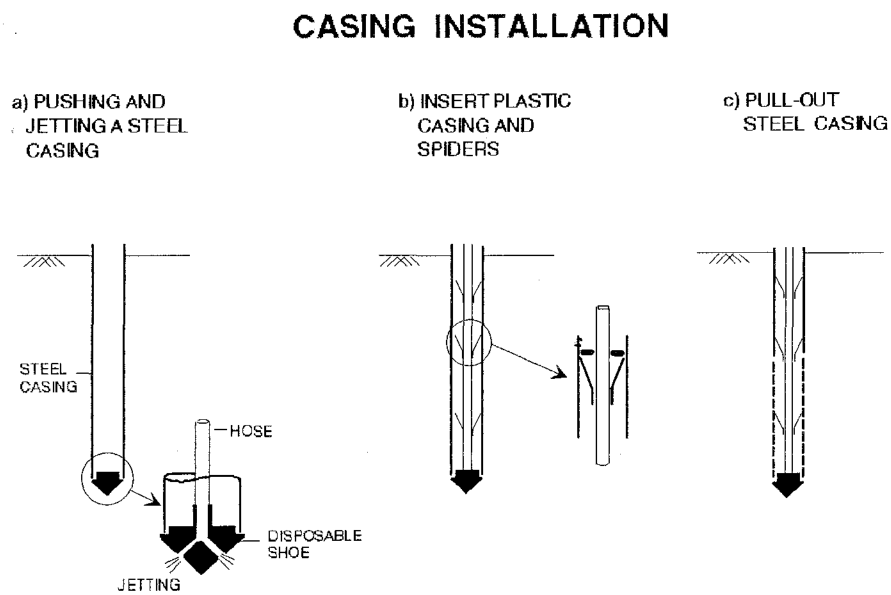

Fig 5 - Casing installation using the UBC site investigation truck

The grooved inclinometer casing and the spiders are then inserted into the steel casing. The inclinometer casing is oriented to have its grooves aligned according to the main deformation axis of the structure to be monitored.

Plastic collars are fixed to the inclinometer casing to position the spiders during the extraction of the steel casing. The spiders are, however, free to move downward with soil settlement.

The inclinometer casing can be filled with clean water to reduce buoyancy. The steel casing is pulled out by the hydraulic jack of the truck, but the inclinometer casing and spiders are held in place.

The annular space between the soft soil and the inclinometer casing can be filled with drilling mud but usually and the soil is allowed to squeeze against the casing.

Probe calibration

The probe was calibrated at UBC under a controlled conditions. A mechanical instrument known as a *dividing head,* commonly used in mechanical workshops, was used to incline the probe at precise angles, accurate to 6" The instrument was mounted on a very stable base and levelled precisely. Readings were taken at 2° intervals between 20° (anti clockwise) and -20° (clockwise). At each inclination a set of four readings, namely *X0, X180, Y0 and Y180* are obtained. *X0* and *X180* correspond to opposite (180 degrees) readings according to the main instrument axis in the direction of the wheels (Fig. 6). Y0 and Y180 are the corresponding readings in the secondary axis of the instrument.

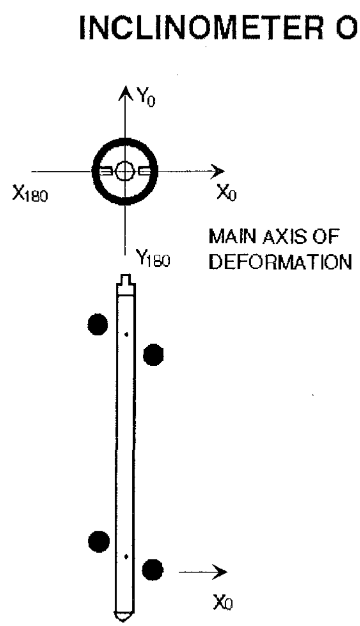

Fig 6 - Inclinometer orientation

At each inclination the *SUM* and the *DIF* of the *X* and *Y* axis readings were obtained through:

$$XSUM = X0 + X180 \quad (1)$$

$$XDIF = X0 - X180 \quad (2)$$

Analogous *YSUM* and *YDIF* values were obtained for the *Y* axis.

Calibration results are shown in Figs. 7 and 8 for axis *X* and *Y*, respectively. Fig. 7a shows DIF values in mV plotted against angle. The resulting relation appears to be approximately linear. However, attempts to fit a linear regression resulted in large residuals as compared to polynomial curve fitting. Polynomial orders from 2 to 8 were used. The third order polynomial yielded the least sum of the square of the residuals. Therefore, the following equation was adopted:

$$\theta = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \quad (3)$$

where: θ = angle in degrees
x = DIF in mV

The curve fitting resulted in the following calibration parameters:

TABLE 1 CURVE FITTING PARAMETERS

PARAMETER	X AXIS	Y AXIS
a_0	0.01042	0.049481
a_1	-0.0027188	-0.00268525
a_2	2.7085 e-011	1.8021e-011
a_3	2.1217e-012	1.8332e-012

SUM data is presented in Figs. 7b and 8b. This parameter is useful as a quick field check of the quality of the data. According to this data, opposite readings yield *SUM* data less than 60 mV for the *X* axis and less than 300 mV for the *Y* axis. If these values are exceeded, the operator should take the readings again at this location.

Residuals for the *X* axis relative to the calculated values are presented in Figs. 7c and 7d. The standard deviation of the residuals is 25". Assuming a normal distribution, there is a 95% chance that the error is less than ±2 x 25"=50".

The frequency distribution of the residuals is shown in Fig. 7d, together with a gaussian distribution. The error peak is not centered as a result of the non-linearity of the sensor response. This leads to the conclusion that the assumption of a normal distribution is not met.

Cross-sensitivity

The cross-sensitivity was evaluated by taking measurements on the *Y* axis while only the *X* axis was tilted. The results are plotted in Fig. 7e. The *DIF* values show a maximum cross-sensitivity of 200 mV when the probe was inclined at 20^o on the X axis. Therefore, the maximum cross-sensitivity is 200 mV divided by the maximum DIF reading in the X axis, which is approximately 8000 mV, thus:

200 mV / 8000 mV = 2.5%

Equivalent calibration data corresponding to the *Y* axis is portrayed in Fig. 8. The residuals for this axis are about twice of the *X* axis, the 95% probability error band (Fig. 8c) is ± 100". The frequency distribution for those residuals (Fig.. 8d) shows a *pdf (probability density function)* close to the gaussian curve. The cross-sensitivity data is presented in Fig.. 8e. The same approximate 2.5% value is obtained for the cross-sensitivity.

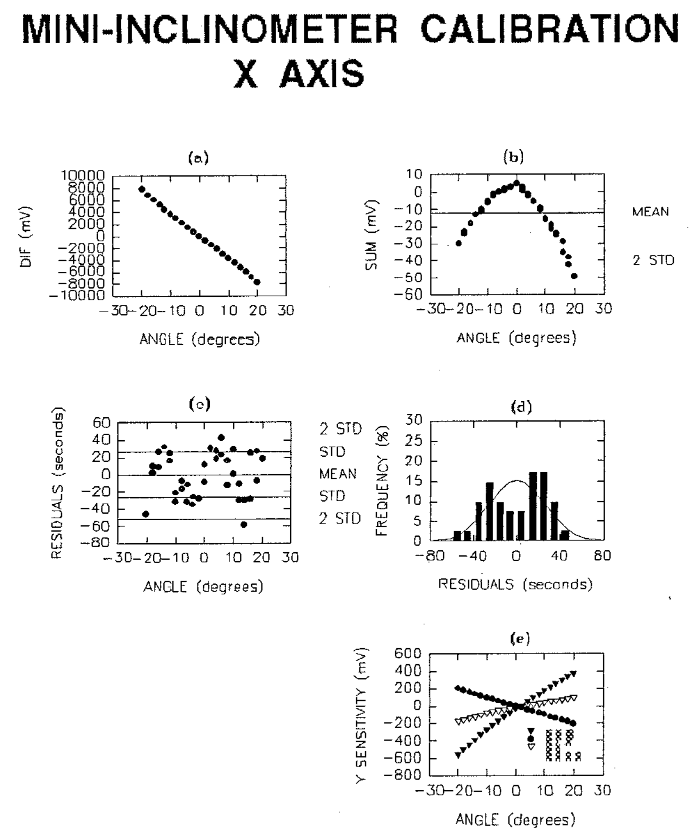

Fig 7 - Mini-inclinometer calibration X axis

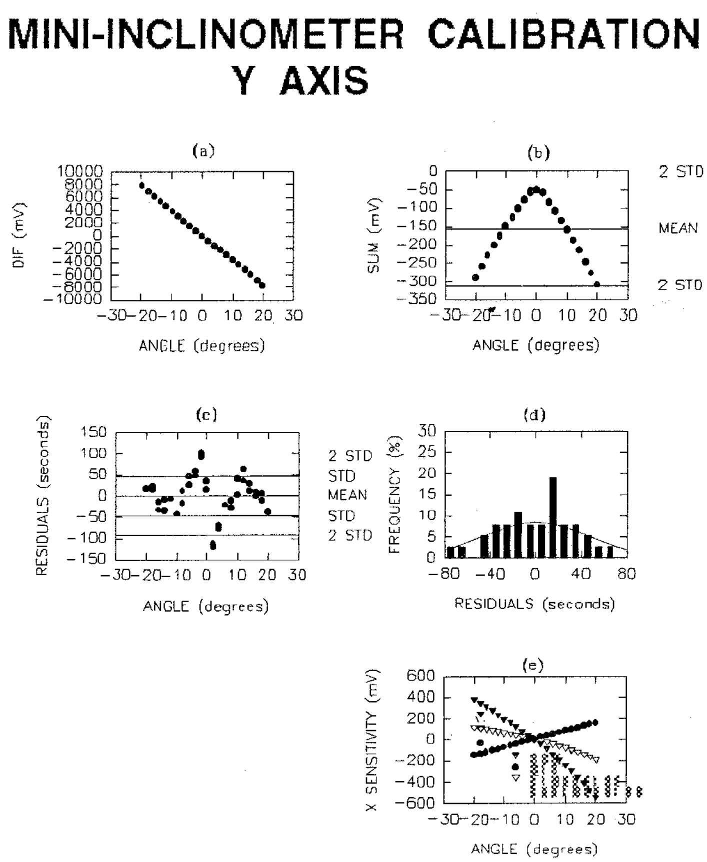

Fig 8 - Mini-inclinometer calibration Y axis

Temperature calibration

Temperature calibration was carried out by immersing the probe in a bucket of water and varying the water temperature from 5 to 45°C. The probe was kept at a known constant inclination by means of the diving head. At the end of a temperature cycle, the probe was moved to another inclination. The temperature was measured by means of a precise thermometer accurate to 0.2°C.

The *DIF* of opposite readings on the *X* axis was transformed to angles by mean of the calibration equation (Table. 1). Then, the apparent angle shift was obtained as the difference between the angle at any temperature minus the angle at 20°C.

The results plotted in Fig. 9 and show that there is no influence of temperature when the probe is vertical, but it can be significant, up to 600", if the probe is warmed to 45°C and inclined at 20°. Temperatures less than 20°C seem to have little influence on the results when the probe is inclined less than 15°.

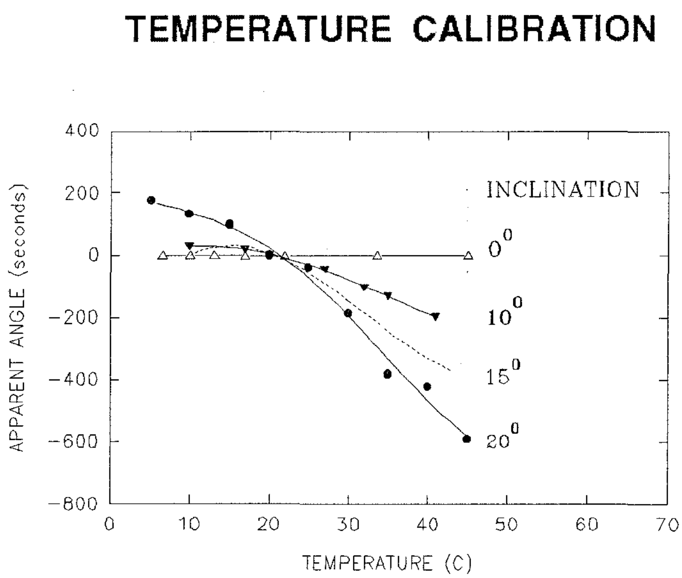

Fig 9 - Temperature calibration

Maximum casing bend

A significant improvement of the UBC mini-inclinometer results from its reduced dimensions that allow more bending of the casing than standard commercially available probes.

The maximum allowable bending for the Sinco 48mm diameter casing was evaluated by means of two dummy rods, having the same length and diameter of the probes shown in Fig. 3. The rods were slid through a section of bent casing until they got stuck (Fig. 10). A 1.5m section of casing, supported from its ends, was progressively bent by applying lateral displacements to its centre. The displacement was recorded and the bending radius was measured from point O, at selected intervals from the casing until a circle could be fitted to the maximum bent shape of the casing.

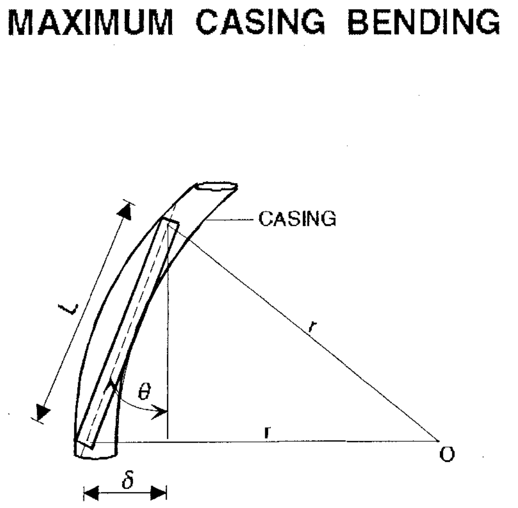

Fig 10 - Maximum casing bending

These measurements led to the following data:

TABLE 2 CASING BEND COMPARISON

DESCRIPTION	UBC PROBE	STANDARD COMMERCIAL PROBE
Probe diameter (mm)	16	25
Probe gauge length (mm)	200	500
Probe total length (mm)	360	650
Minimum bending radius for a 48mm plastic casing (mm)	1200	4200
Maximum angle deflection over a gauge length (degrees)	4.78	2.40

Comparison between two probes

A comparison between the UBC probe and a commercial one was carried out using a calibration frame available at Powertech Laboratories Inc, a division of the BC Hydro Inc, Surrey, BC. This frame comprises two 5m long inclinometer casings attached side by side and both fixed at the bottom to the wall. The UBC probe was used in one casing, and the commercial probe in the other, simultaneously.

Readings were taken before and after a horizontal displacement of 0.5m was applied at a depth of 1.6m from the top of the casings. Fig. 11a compares the recorded inclination versus depth, and Fig. 11b shows the calculated displacements. The agreement between both probes is good. However, the reading of the commercial probe at 4.5m depth showed excessive drift, probably because the guide wheels were in a joint. This may have also influenced the maximum calculated displacement, which is slightly different for the two probes.

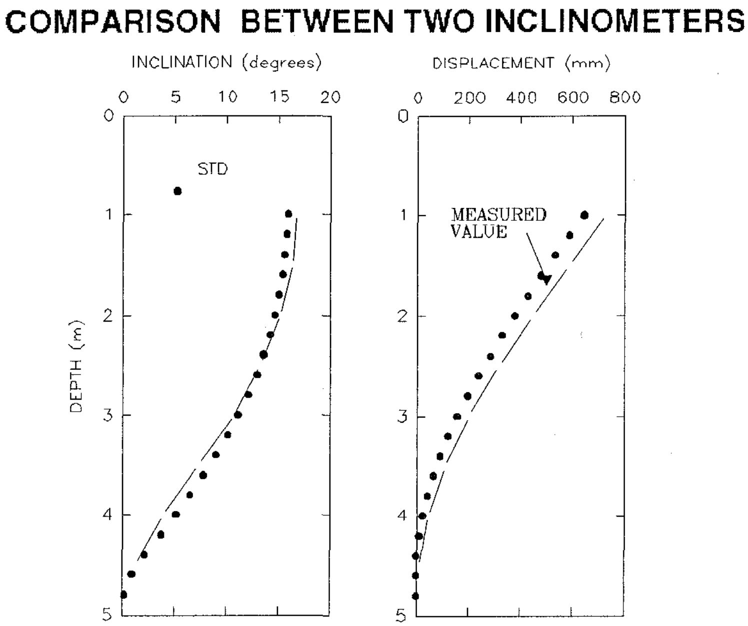

Fig 11 - Comparison between two inclinometers

Conclusions

Limited experience with the UBC inclinometer and settlement system leads to the conclusion that this probe is a significant cost-effective improvement relative to existing commercial inclinometers. Both horizontal and vertical displacements can be monitored in the same tube.

Reduced probe dimensions enable the instrument to be used in limited space and allows much more bending to take place in the inclinometer casing. It is envisaged that this probe can be employed in existing casings in which the commercial inclinometers can no longer pass.

The use of the electric motor for rotating the gauge allows opposite readings to be obtained at the time, saving overall survey time.

Further improvement to the system will include an automatic data acquisition system and dedicated software for data reduction.

Acknowledgments

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Mr H Schrempp carefully designed and machined the probe and Rod Ortigao, teenager son of the first author, carried out all the lengthy calibrations his daddy obliged him to.

Thanks are due to Mr L Terriaux of Sinca Inc., to Mr J Wong of Powertech Inc for the use of their calibration frame, and to Mr G Jolly, of Adara Systems Ltd, for lending the temperature bath for the calibrations.

Appendix

Surveying inclinometer casings for lateral displacements

1. Turn the instrument on and insert it into the casing as shown in Fig. 6. Make sure that the wheels are correctly positioned relatively to the *X0* direction.

2. Slide the probe down to the bottom of the borehole.

3. Record instrument depth relative to the top of the casing and take *X0, X180, Y0* and *Y180* readings (Table A1).

TABLE A1 Field data sheet

Depth (m)	*X0* (mV)	*X180* (mV)	*XDIF = X0-X180* (mV)	*XSUM = X0+X180* (mV)	*Y0* (mV)	*Y180* (mV)	*YDIF = Y0-Y180* (mV)	*YSUM = Y0-Y180* (mV)
0	-145	190	-335	45	-151	145	-296	6
0.2	-107	120	-227	13	-90	77	-167	-13
0.4	-45	24	-69	-21	-97	50	-147	-47
.	.	.	.	.	.	.	.	.
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18.2	6	-3	9	3	79	-122	201	-43
18.4	48	-48	96	0	78	-90	168	-12

4. Raise the probe a distance equivalent to a gauge length (200mm), take readings again as explained in item 1. Repeat this procedure until the probe reaches the top of the casing.

5. *Before you leave the site* calculate *XSUM* and *YSUM* data for checking the quality of the readings. Good quality readings have *XSUM*<60 mV and *YSUM*<600 mV. If these limiting values are exceeded, check for errors and repeat the readings at the depth it occurred.

6. Obtain *XDIF* and *YDIF* as the difference between the 0 reading and the 180 reading: *XDIF = X0-X180*; *YDIF = Y0-Y180,* as shown in table A1.

7. Lateral displacement calculations are performed over values of the *VAR* (Variation) values corresponding to the difference between the *initial* set of readings, also known as *baselines*, and the *actual* readings, as indicated in Table A2: *VAR=actual - baseline*

8. The inclination θ in degrees is obtained by equation 2. The results should be represented graphically as shown in Fig. 11.

9. The lateral displacements δ are obtained by equation 4, as shown in the last two columns of table A2. First, values of $\sin\theta$ are added from the bottom (*ie,* starting at the maximum depth $z=z_{max}$, where zero lateral displacement is assumed) upwards. Then, these values are multiplyed by the gauge length L, giving the displacements δ, as shown in the last column in

table A2.

$$\delta = L \sum_{z_{max}}^{z=0} \sin\theta \qquad (4)$$

where: L is the gauge length of the probe, equal to 200mm.

TABLE A2 Calculation of lateral displacements on X axis

Depth (m)	BASELINE *XDIF* (mV)	ACTUAL *XDIF* (mV)	*XVAR* (mV)	θ (degrees)	$\sin\theta$	$\Sigma\sin\theta$	δ (mm)
0	-335	2450	2785	-7.515	-0.131	-0.277	-55
0.2	-227	2350	2577	-6.959	-0.121	-0.146	-29
0.4	-69	430	499	-1.346	-0.023	-2.51×10^{-2}	-5
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
18.2	9	25	16	-0.033	-5.76×10^{-4}	-8.20×10^{-4}	-0
18.4	96	105	9	-0.014	-2.44×10^{-4}	-2.44×10^{-4}	-0