Deformation Measurements with Inclinometers

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Inclinometers have steadily gained widespread use for measuring deformations in landslides, natural slope creep, temporary excavations, earth and rock embankments, slurry walls, shafts, tunnels, lateral pile movements, and settlements beneath tanks, fills, and foundations. Inclinometer data can be used to determine displacement magnitude and rate and the location of the zone of displacement, as well as the absolute position of the inclinometer casing in the ground. High-precision inclinometers today utilize servo-accelerometer sensors in a uniaxial or biaxial configuration, mounted inside a waterproof wheel carriage. The most common is the traversing borehole type, where the wheels are oriented and guided by specially made grooved casing. Fixed-in-place inclinometers employ the same guide casing but are used infrequently due to high cost. Inclinometer monitoring is one of the most labor- and data-intensive geotechnical measuring activities. In addition to straightforward data reduction, many errors have to be identified and dealt with before results can be presented and correctly interpreted. In the authors' experience, many inclinometer monitoring programs have failed to yield good results because errors were not recognized. In this paper, guidance is given to the reader regarding inclinometer system design, installation, monitoring, data processing, and sources of errors and their resolution. Accuracy of the inclinometer is highly dependent on the equipment selected, the method by which it is installed in the ground, monitoring techniques, correct scrutiny of the data, and ability to correct instrument errors. A servo-accelerometer-type system is capable of a precision of ±0.05 to 0.25 in. over 100 ft when the casing is vertical or horizontal. The best results are achieved when cooperation and understanding between engineers, clients, and contractors provide continuity in the total monitoring process.

The measurement of ground movements is an essential part of many civil and mining engineering operations. Monitoring subsurface movements with inclinometers can be considered a direct extension of normal surface survey techniques. Inclinometer systems are used extensively to monitor the displacement magnitude, rate of displacement (i.e., accelerating or decelerating), and location of the movement zone. In many situations, where, how much, and whether or not the movement is increasing or decreasing are key issues. Inclinometer systems can be used to monitor displacements in landslides, natural slope creep, temporary excavations, earth and rockfill dams, slurry walls, shafts, tunnels, lateral pile movements, and settlement under tanks, fills, and foundations. Inclinometers are also used to determine the absolute position of boreholes prior to installing other instruments, for example, geophones or tieback tendons. They may also be used indirectly to measure moments and stresses in structures and can give good results with flexible steel structures where the deflection is large and the section modulus is known. Their value in composite concrete structures where the moment of inertia is uncertain is more limited.

The inclinometer commonly used today developed from a device built in 1952 by S. D. Wilson at Harvard University. It first became available commercially in the late 1950s from the Slope Indicator Company. Such an inclinometer consists of a probe, containing a gravity-actuated transducer, which is fitted with wheels and lowered on an electrical cable down a grooved casing to control orientation (*1, 2*) (see Figure 1). The cable is connected to a readout unit, and data can be recorded manually or automatically. The inclination of the casing with respect to gravity is measured at incremental depths, and the entire casing profile is obtained by numerical integration. Sets of readings taken periodically enable both the magnitude and rate of lateral casing movement to be calculated. The casing is normally set in vertical drillholes or attached to a structure in a vertical position to measure horizontal movements (Figure 2). It can also be set horizontally to measure heave or settlement (Figures 3–5) but will not measure movements in a horizontal plane. Movements of casings inclined up to 45 degrees may also be monitored but with considerably less accuracy (*7*).

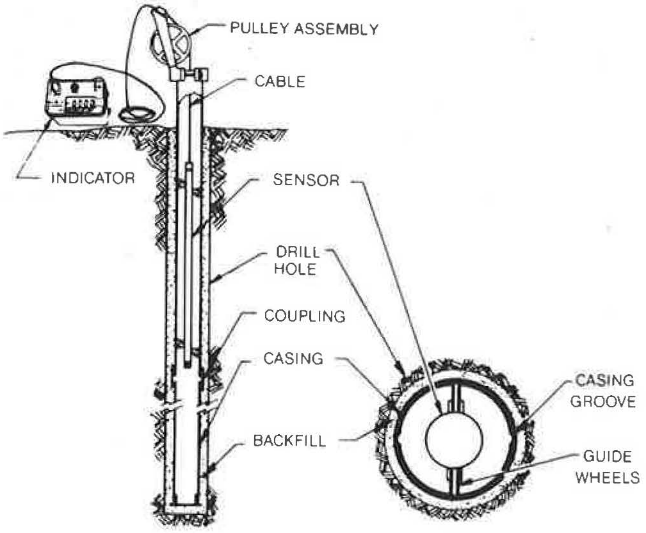

FIGURE 1 Principles of operation of probe inclinometer.

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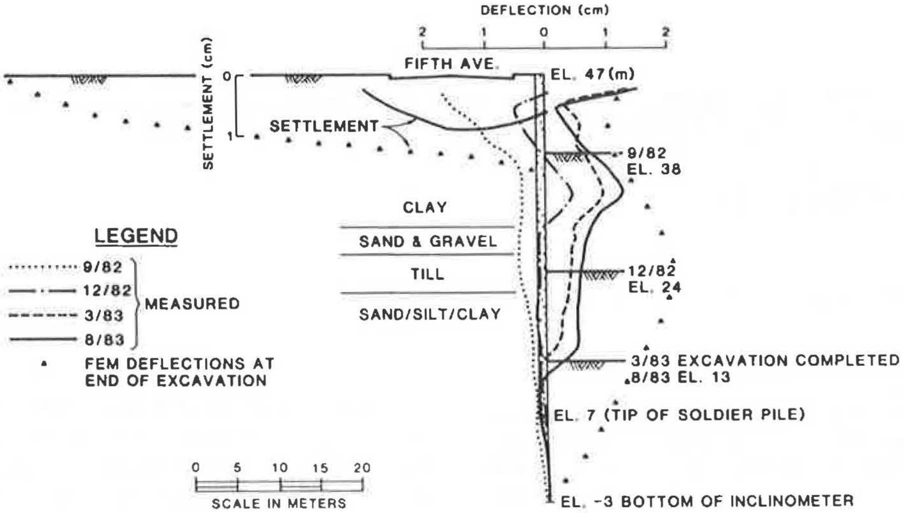


FIGURE 2 Shoring wall movements on the 34-m-deep Columbia Center excavation in Seattle, Washington (*3*).

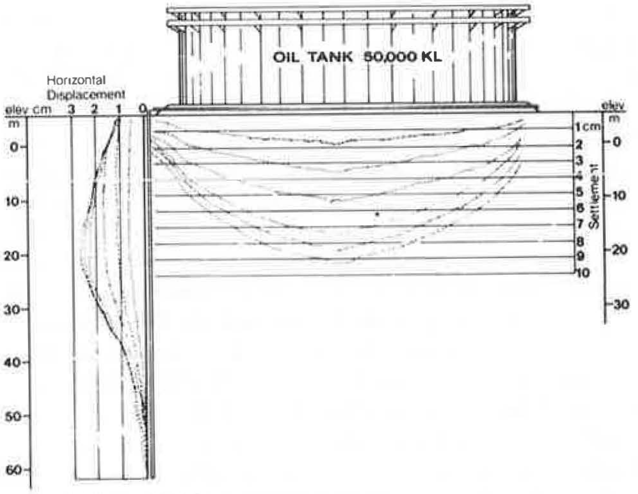


FIGURE 3 Vertical and horizontal monitoring of an oil tank foundation during water test loading (*4*).

Fixed-in-place inclinometers are available. They consist of a series of sensors with guide wheels, each containing a uniaxial or biaxial gravity-operated transducer that generates electrical signals. The sensors are joined by articulated rods and are suspended permanently in vertical grooved casing. Continuous or remote monitoring or both, by direct wire link, radio, or telephone modem, permit real-time data to be obtained in critical situations, in contrast to the manually read probe inclinometer system.

Other types of drillhole survey tools are also available. The oil well and geophysical logging industry use a variety of photographic, gyroscopic, and gravity-based electronic sensors that operate in unlined vertical drillholes and do not require casing with oriented grooves. Attempts have been made to develop versions of these tools (*8*) that are suitable for civil and mining use in boreholes 50- to 300-ft deep as an alternative to the probe inclinometer used inside grooved casings, but these efforts have been relatively unsuccessful to date due to cost, convenience, size, and accuracy. The rate gyro–based tools that have recently become available appear to be more promising (*9*).

Inclinometers may also be combined with probe extensometer systems that measure extension or compression along the axis of the inclinometer casing, a mechanical probe that locates casing joints, or an induction coil or magnet/reed switch sensor. When these devices are installed on vertical casings, they permit settlement or heave monitoring so that subsurface three-dimensional movements are monitored (*10*).

Inclinometer monitoring is one of the most labor-intensive geotechnical measurement activities. It generates large volumes of numerical data that must be correctly recorded, processed, scrutinized for errors, plotted, and interpreted. Experience indicates that many inclinometer measurement projects fail to achieve their intended aim because of a lack of appreciation of the many factors, both human and instrument, that need to be correctly implemented. Thus, in many cases, thick files of unplotted data are generated, or depth/displacement profiles wander mysteriously back and forth across a graph, or large movements are believed to be occurring when there may actually be little or none. More information concerning inclinometer systems and their use may be found elsewhere (*10–16*).

INCLINOMETER EQUIPMENT

The accuracy and reliability of the measured position or displacement profile is dependent on the quality of the casing, probe, cable, readout, and accessories selected. A poorly engineered probe, stretchy cable, faulty readout, or inferior casing will result in poor quality data at best, and an unhappy user.

Inclinometer casings may be plastic, aluminum alloy, or steel, with rigid or telescopic couplings (see Figure 6). Plastic casings may be ABS, PVC, or fiberglass and the grooves may be formed by broaching, extrusion, or moulding. ABS is flexible and easily cemented, PVC less so. The casing groove spiral should be less than 1 degree per 10 ft, and for plastics, a broached tube appears to be better than an extruded casing. Even so, hot sun and improper storage can warp and twist an initially straight casing. Casing diameters range from 1.9 to 3.8

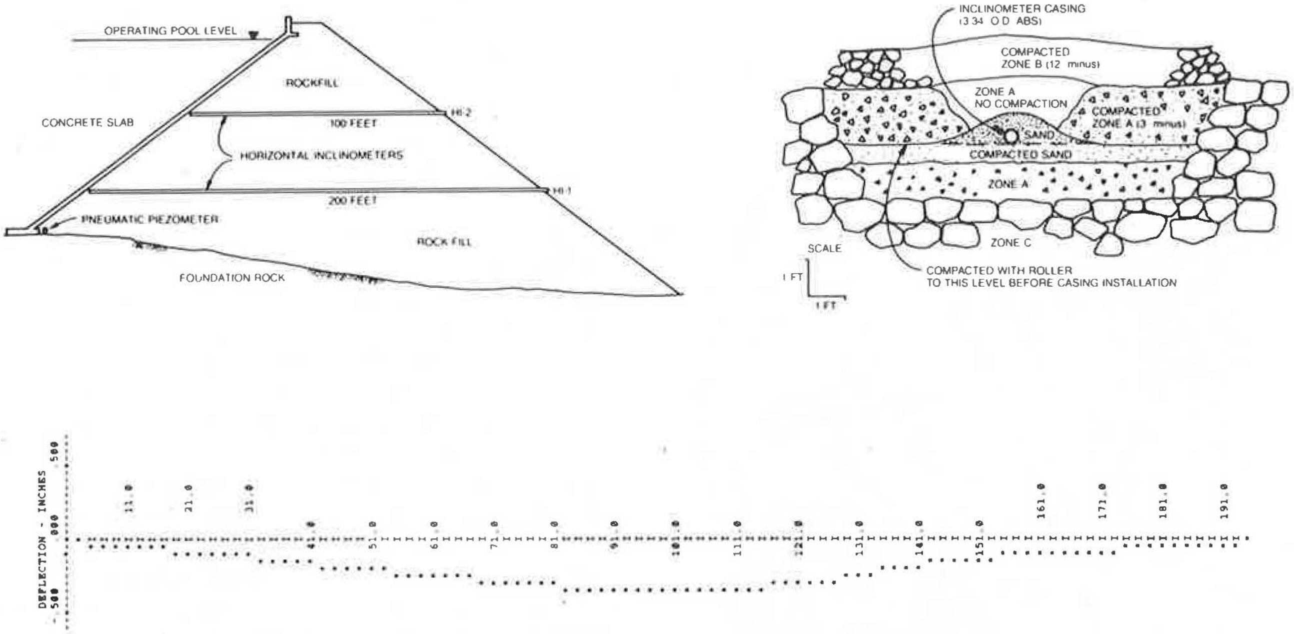


FIGURE 4 Horizontal inclinometer monitoring of a rockfill dam (*5*).

in., and the larger sizes are preferable where movements are large, thin shear zones are present, and drilling costs permit. Rigid couplings are available, with self-aligning features that include flush couplings for use where borehole space is tight. Connections may be made with rivets, plastic cement, or a self aligning Westbay coupling that incorporates an O-ring and nylon shear key that is very convenient. The aluminum alloy casing is extruded with grooves, and a close-fitting, similar second extrusion is employed for rigid or telescopic joints. Joints are riveted and must be sealed with mastic and tape. This aluminum alloy casing is subject to corrosion in alkaline environments. Some records have shown that in the presence of steel, electrolysis has caused a total loss in a few months. Baked-on epoxy paint offers the best protection, but even so,

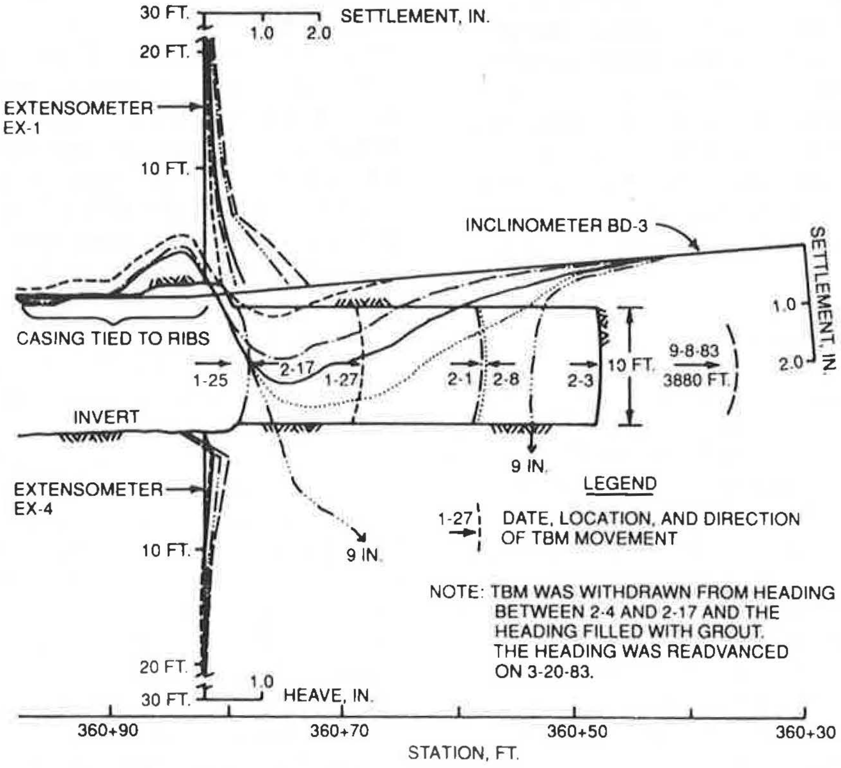


FIGURE 5 Vertical rock deformations in a tunnel in response to tunnel boring machine advance (*6*).

FIGURE 6 Digitilt inclinometer, manual readout, inclinometer casing, and couplings.

corrosion can occur, and ground conditions need to be carefully assessed before an aluminum alloy casing is selected. In benign environments, some users prefer aluminum casings over plastic (*17*). In some instances, seamless welded square steel tube can be used where great strength is required (e.g., attached to driven steel piles) or where the user wishes to attach strain gauges to the casing for axial strain measurements (e.g., in concrete piles). Otherwise, the steel tube is subject to corrosion and to loss of precision of probe location within the casing. Extruded steel tubing is usually twisted excessively and should not be used.

The gravity-actuated sensor may employ a rotary potentiometer, bonded resistance strain gauges, vibrating wire strain gauges, an electrolytic level, or a servo-accelerometer. The now discontinued Slope Indicator 200B employed a rotary potentiometer with a relay-operated contact to reduce friction. This sensor was stable and reliable but bulky. The Soil Instruments Mark II inclinometer, also discontinued, incorporated a strain gauge steel leaf spring with an oil-damped pendulum. The sensor was reasonably stable and reliable but subject to damage if it was not immobilized in transit. European manufacturers have incorporated the vibrating wire strain gauge on dual-axis pendulum devices, which are reliable but cumbersome. The electrolytic level has only been used in horizontal inclinometers because (a) it is currently too large to mount laterally in a vertical probe, (b) it has a more limited angular range, and (c) it is relatively sensitive to temperature. The servo-accelerometer is the sensor most widely used today. A product of the space program, the accelerometer can also be used in a static mode to measure angle. A very small, damped pendulous mass suspended by an elastic flexure is electrically nulled, with the voltage proportional to angle. The servo-accelerometer is accurate, reliable, reasonably robust, and compact, and two of them can be mounted in a slender biaxial probe for vertical casings.

The probe body (Figure 6) should be waterproof and preferably of stainless steel, with a well-engineered wheel carriage that has little or no side play in the wheels, axle, and swing arm assemblies. Preferably, the wheels should have double ball bearings and a wheel rim profile that is compatible with the casing groove geometry. Self-centering wheels are better than the earlier fixed-spring wheel assemblies. Wheel geometry and carriage design control the precision with which the probe can be relocated each time in the casing. This factor is particularly important with the currently used biaxial probes, which utilize only one pair of grooves and rely on the sides of the grooves for B-direction location. A sealed electrical connector should be located at the top of the vertical probe and at either end of a horizontal probe to permit it to be turned end for end. Inclined probes are available in which the sensor is set with its axis vertical and at an angle to the inclined probe (*18*), but these cannot be reversed end for end to eliminate zero errors and are less convenient and accurate in use. At the same time, it should be recognized that the accuracy of vertical or horizontal probes degrades severely when they are used in steeply inclined casings (*7*).

The electrical cable should be flexible, waterproof, untwisted, durable, easy to grip, and permanently and accurately graduated. It must not stretch under load or with time, and the outer sheath must not creep over the inner core or serious errors will result. These requirements are stringent and some inclinometer cables do not meet all of them. Connection to the probe requires a heavy-duty waterproof electrical connector, but a nonwaterproof connector is adequate at the readout end of the cable. For cable lengths up to 200 ft, a cable reel is not required because the cable is most easily handled in a manner similar to that used with a climbing rope. For cable lengths of 200–1,000 ft, a manual or powered reel is essential.

The readout unit should be robust, reliable, easy to read, portable, insensitive to temperature, and weather resistant (Figure 7). Traditionally, manual data recording on a field sheet is employed. Battery-powered digital readouts that display one or two sensor axes sequentially or simultaneously in a boxed or clipboard package are available. The amount of data that must be recorded is voluminous, and errors are easily made when manual transcription or computation is employed. Direct field reading to a solid-state memory unit with field data checking facilities is preferred. Field or office computer processing of the data recorded on magnetic tape or disk, including transmission by telephone modem (if needed) and automatic plotting reduce the labor, cost, and chance of errors. Most manufacturers now provide automated readouts of various types, of which the Slope Indicator Digitilt RPP (Recorder, Processor, Printer) is an example (see Figure 7). This instrument can record, store, file, and reduce inclinometer data, spiral data, and azimuth angle input. Built-in software allows the data to be corrected for systematic errors and permits spiral and inclination readings to be combined. This software also allows coordinate system rotation, and all of these procedures can be done on the spot, in

FIGURE 7 Digitilt inclinometer in use with recorder, processor, and printer (RPP).

the field, if needed. Results are tabulated and graphed on a built-in electrostatic printer, and data files are stored on magnetic tape. The Digitilt RPP can operate as a computer terminal and can send data via a telephone modem to a remote computer, or it can be connected to an external printer or plotter.

Fixed-in-place inclinometers (*13*) consist of a series of long-gauge length probes (Figure 8) permanently installed to provide continuous automatic and remote deformation data at critical locations and where the relatively high cost is justified. These instruments will not provide a detailed profile of ground movements unless sensors are closely spaced. Sensor zero drift with time can be difficult to detect and is not eliminated as it is with the portable probe inclinometer, which can be reversed through 180 degrees. Available accelerometer sensors are fairly reliable, and fixed-in-place inclinometer systems have been reasonably successful (*19*). Fixed-in-place inclinometers can be installed permanently in casings adjacent to probe inclinometer casings or may be installed during a critical period in a probe inclinometer casing and then removed. Even a single sensor fixed-in-place unit can be installed across an identified thin shear zone.

As noted, a casing spiral or twist can occur due to manufacturing, storage, or installation deficiencies. Serious spiraling has, on occasion, been identified in the field. Spiral should be measured (a) on deep casings, (b) where measured movements are in suspect directions, (c) where absolute casing position is required to good accuracy, or (d) where installation difficulties have occurred. A spiral survey is normally required only once, and computerized data reduction is essential. One type of spiral survey tool consists of a long torque rod mounted between wheel assemblies with a rotary displacement transducer.

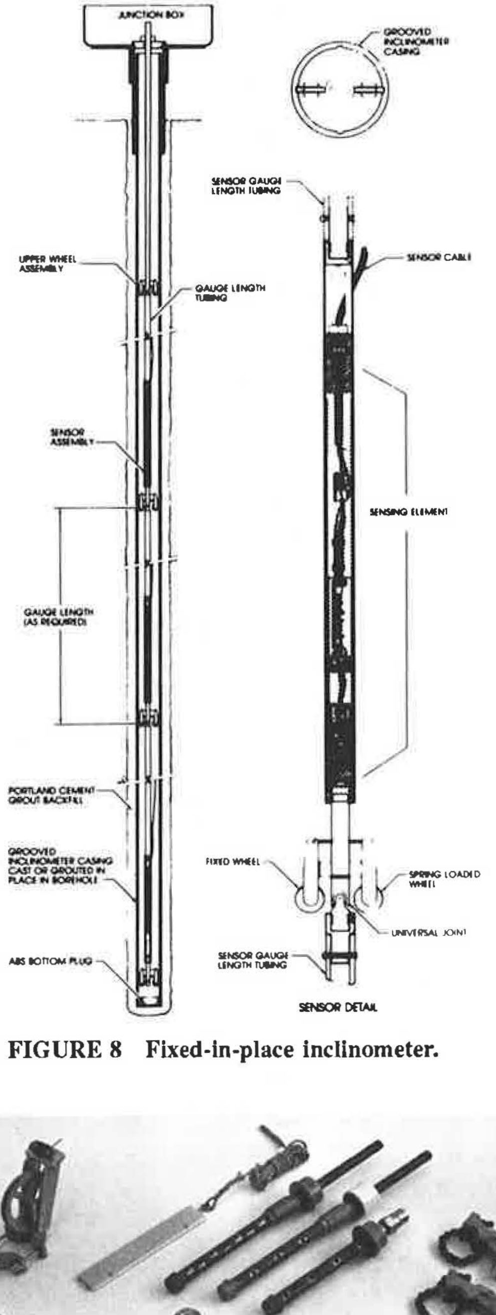


FIGURE 8 Fixed-in-place inclinometer.

FIGURE 9 Installation tools and accessories.

Accessories are needed to install and operate inclinometer systems (Figure 9), including installation tools, pulley wheel and cable clamp, grout valves, and end caps. Protective enclosures, a calibration facility, instructional material including videotapes, data sheets, software package, calculator or computer, telephone modem, and printer are also available. The calibration of the probe inclinometer may change with time, and calibration frames that provide a functional check are available from some manufacturers. On-site limited calibration checks may also be performed by using short lengths of fixed casing cast into an immobile concrete block or by extending some casings to well below the movement zone so that regular surveys of immobile casing are performed. Otherwise, calibration should be done periodically by the manufacturer on a dividing head. Inclinometer system accuracy is dependent on a number of factors, including sensor design and construction, installation technique, casing quality and orientation, care and attention given when taking readings, and instrument maintenance (*10*). True independent checks on system accuracy are difficult to perform and rarely done. An inclinometer system check test setup (*12*) is shown in Figure 10, but this excludes field related factors that can degrade measurement accuracy (*20*).

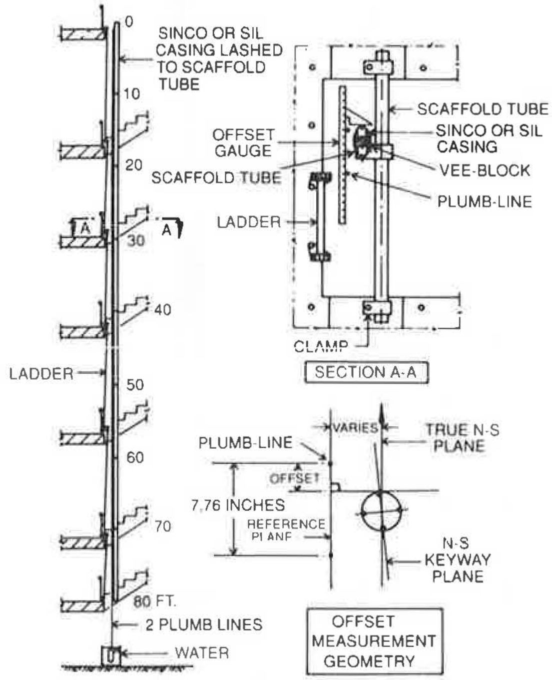
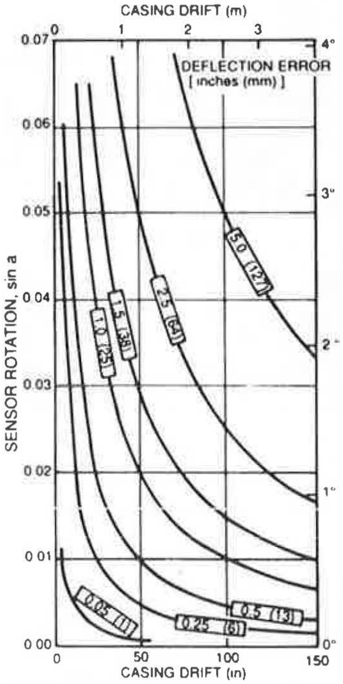


FIGURE 10 Inclinometer casing test set up in a stairwell (*12*).

In selecting appropriate equipment for inclinometer measurement, instrument accuracy, quality, reliability, manufacturer reputation, and availability of service, manuals, and software should be the prime considerations. Hardware costs are only a small proportion of the total measurement cost, which includes drilling, installation, data processing, and evaluation. Accurate, reliable instruments are essential. Many have discovered this too late, and low cost is a poor basis of choice.

INSTALLATION PRACTICE

Casing installation procedures are described in detail in manufacturer's instruction manuals (*13, 15*) and discussed elsewhere (*10, 14, 21*). The inclinometer casing is commonly installed in soil or rock in vertical boreholes drilled by a variety of methods, depending on the material type, borehole stability, amount of water present, drilling equipment available, casing size, and cost. For observational accuracy, the borehole should be as close to vertical as practicable. Errors in inclinometer surveys are proportional to the product of casing inclination and angular changes in sensor alignment. For inclined casings, sensor alignment changes of 1 to 2 degrees may produce errors in the measured displacement of several inches per 100 ft of casing (Figure 11). Sensor alignment change occurs with time due to wheel play in a groove, wheel carriage wear, internal changes in the sensor, and changes in alignment between the sensor and wheel carriage. Thus tight specifications on borehole verticality and quality drilling techniques are preferable.



NOTE CASING DRIFT OVER ANY DEPTH INCREMENT IS MEASURED AS HORIZONTAL DEVIATION FROM TRUE VERTICAL AXIS IN TWO MUTUALLY PERPENDICULAR PLANES DEFLECTION ERROR IN ONE PLANE IS RESULT OF DRIFT IN OTHER PERPENDICULAR PLANE

FIGURE 11 Measurement error as a result of casing inclination and sensor rotation (*14*).

The largest inclinometer casing size should be used where hole size permits, because this size will accommodate the largest movement before probe access is obstructed. Drilling costs or structural constraints may necessitate using smaller sizes, for example, the 1.9-in. O.D. plastic flush coupled casing in an NX-borehole. The casing is coupled together (typically in 5- to 10- ft lengths), the joints are sealed (including the bottom of the casing), and the casing is lowered into the borehole. If the borehole is filled with water or drilling mud, water must be added inside the casing, and extra weight may be needed to over come buoyancy. The casing should be oriented so that grooves are aligned in the anticipated predominant movement direction, and twisting of the casing should be avoided during insertion. Groove alignment at couplings is maintained by keyways of varying types (Figure 12). Where settlement or heave in excess of 1 percent is anticipated, telescopic couplings are required and should be set during installation at the appropriate position for the anticipated movement direction. Telescopic couplings complicate both installation and reading procedures

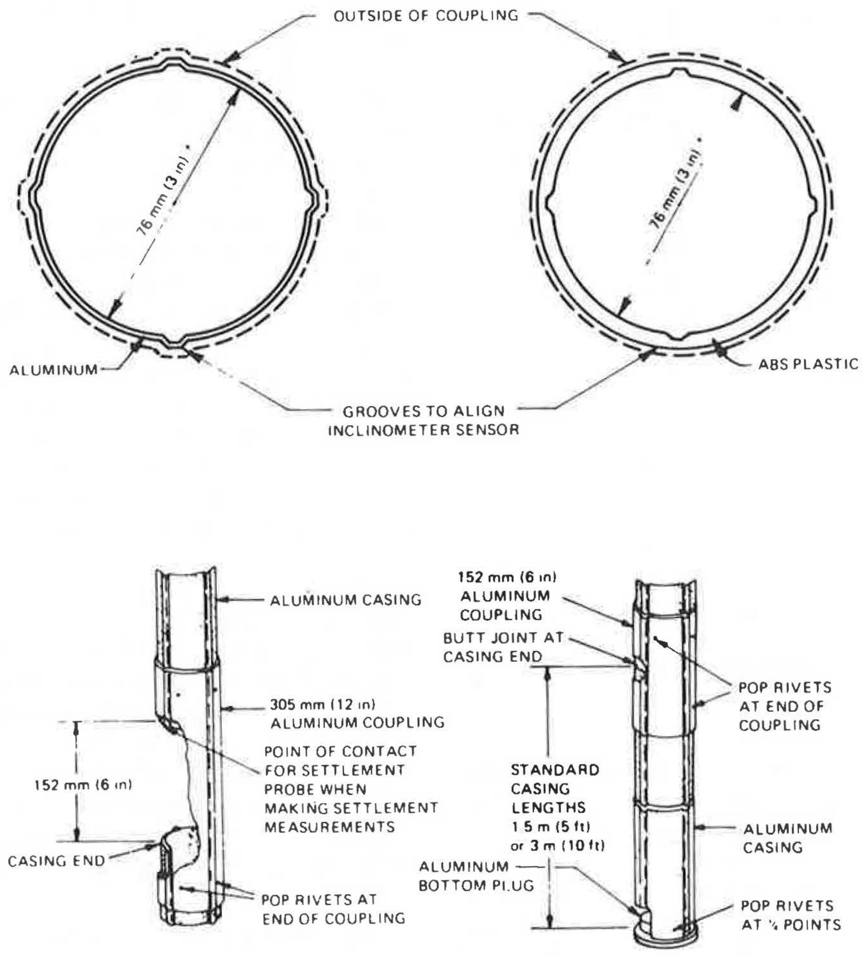
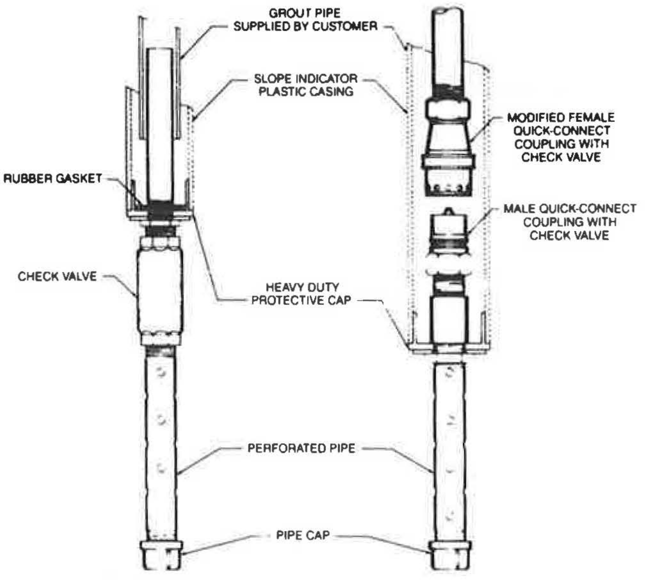


FIGURE 12 Inclinometer casing details (*14*).

and should be used only when required. Care is needed during installation to avoid extending or collapsing the preset assembled joints. All casings should extend 10 to 20 ft below the zone of anticipated movement to provide a stable reference section. Inclinometer measurements are usually more accurate and reliable than surface survey check measurements made on the tops of the casings, and reliable casing base fixity is vital.

A casing installation in a borehole must be backfilled around the casing with sand, pea gravel, or grout (Figure 1) to ensure conformity with the surrounding ground movements. Incomplete backfilling or backfill settlement causes spurious casing movements that are best avoided. In some cases, for instance, soft ground, the backfill strength should be matched to the ground strength so that conformity is achieved. Uniform, coarse clean sand or pea gravel can be used to backfill the annular space in stable shallow holes, and clean sand can be sedimented through water or flushed through a tremie pipe. Granular backfill is more prone to bridging and settlement. Grout pumped through a tremie pipe extending to the bottom of the borehole is the preferred method, but this may not work in open granular materials. An external grout pipe along side the casing can be used if the borehole is large. It is more convenient to grout through a drill rod inside the inclinometer casing, connected temporarily to a one-way grout valve attached to the bottom of the casing (Figure 13). The drill rod also serves to keep the casing straight and helps overcome buoyancy effects until the grout sets. Where large movements on well-defined shear zones are anticipated, a large borehole and weak grout backfill should be used so that the casing will shear locally through the backfill, maintain probe access longer, and provide continuity of readings. The localized shear movements will be redistributed over a larger casing length, but this is preferable to getting no data. Completed installations should be washed out to clean the casing, and adequate surface protection should be installed and locked, if appropriate, to guard against damage or vandalism. Casings can be successfully installed in deep holes (200 to 1,000 ft) by using a safety cable attached to the bottom of the casing and multistage grouting with an external tremie pipe.

Vertical inclinometer casings installed during construction of earth or rockfill dams must (a) incorporate telescopic couplings, (b) be adequately protected from damage by construction traffic, (c) be extended section by section as the embankment rises, (d) avoid providing a zone of increased permeability, and (e) settle by the same amount as the surrounding production machine-placed fill. These needs are often difficult to achieve, and great care and quality control are required. This is particularly true if other instruments are also being installed, as is often the case (*7*).



GASKET SEAL TYPE "QUICK-CONNECT" TYPE

FIGURE 13 Grout valve for inclinometer casing installation.

Horizontal inclinometer casing is usually placed in compacted fill beneath an embankment or structure (*4, 5*). The casing must be straight, with one pair of grooves vertical and preferably on a constant flat, free-draining grade so that the casing can be washed out. The instrument is pulled into the casing with a steel cable. If access is available only at one end, the cable should be passed around a dead-end pulley and returned in a second small PVC pipe alongside the casing.

Inclinometer casings can be cast into concrete piles, grouted into hollow core concrete piles after driving, attached to steel sheet, H, or pipe piles, installed after driving in steel tubes, or grouted into slurry walls. When the inclinometer is being used to monitor wall deflections of any type, it is advisable to extend some, if not all, of the casings beyond the base of the wall. This usually requires drilling 10 to 15 ft beyond the base of the installed wall through a steel pipe.

Inclined inclinometer installations are used in sloping cores and concrete membranes in dams and for drillhole alignment surveys with temporarily installed casing. Examples and methods for dams are discussed by Penman and Hussain (*22*) and errors are analyzed by Mikkelsen and Wilson (*7*). Inclined installations in drillholes should be avoided where possible because measurement errors are too great, due to casing groove alignment uncertainties and sensor errors. With care, short holes can be surveyed with modest accuracy, and position surveys of tieback holes can sometimes be obtained with sufficient accuracy. Where inclined installations on sloping cores are required, groove alignment must be very closely controlled. The trolley and track described by Penman and Hussain (*22*) is an elegant, if complicated, technique that uses a conventional vertical probe that can be reversed (Figure 14).

Fixed-in-place inclinometers are installed in vertical casing, which should be installed as described previously. The fixed-in-place inclinometer assembly is suspended in the casing, and a waterproof electrical cable from each sensor is connected to a junction box at the surface. A conveniently located automatic data acquisition system (ADAS) monitors each sensor sequentially. The system may be hard wired or radio telemetered to the ADAS, which can be accessed by telephone as required. Fixed-in-place inclinometers can be transferred from one casing to another and can be salvaged at the end of the project.

MONITORING PROCEDURES

Installed casings should be monitored regularly by a trained two-person crew who are thoroughly familiar with correct procedures and have read and digested the manufacturer's instruction manual. Inappropriate procedures produce poor-quality data and a disillusioned client. A reading interval equal to the distance between the probe wheel carriages is usually

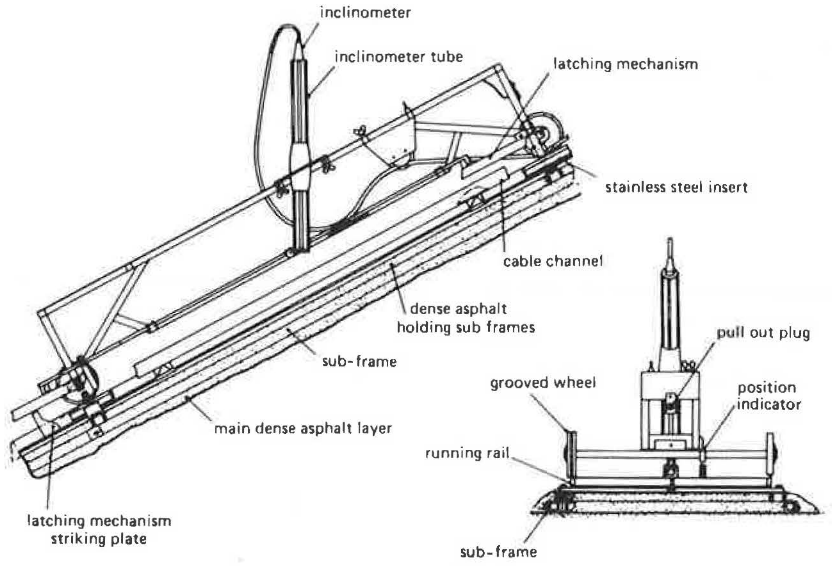


FIGURE 14 Inclinometer trolley/track used on an inclined upstream membrane on a dam (*22*).

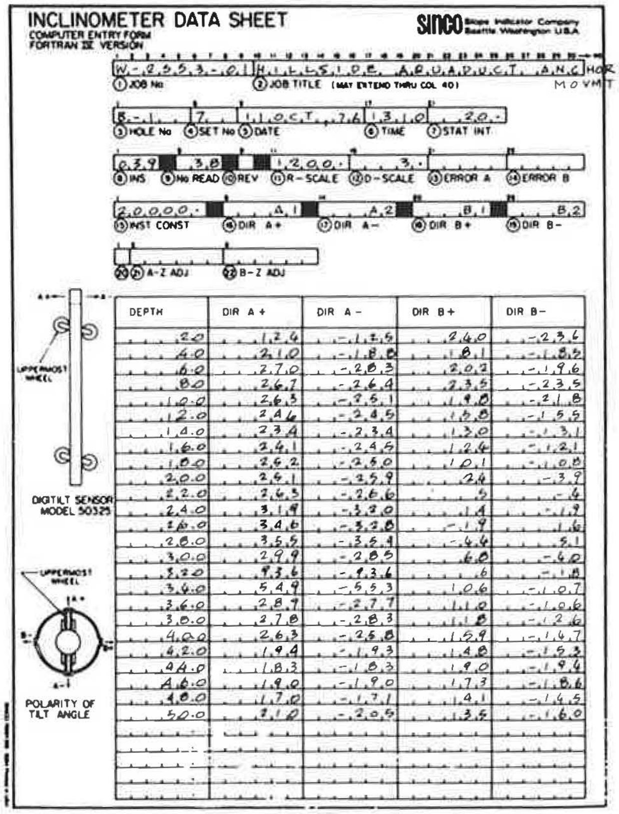
most appropriate, although a greater interval may sometimes be used with little loss of accuracy, provided that thin shear zones are absent. Preferably, the same instrument should be used throughout the job because probes are not interchangeable without generating systematic errors. Instrument damage or manufacturer recalibration may necessitate reinitialization of the readings. Readings should be taken from the bottom of the casing up, with close depth control (±1/4 in.), by using a pulley wheel and cable clamp or similar device attached to the casing collar. In vertical casings, a uniaxial probe requires four passes up the casing, whereas only two passes are needed with a biaxial probe, which saves field time. The B-sensor data obtained with the biaxial probe are less accurate than those of the A-sensor (i.e., parallel to the wheels) because the side of the casing groove controls the B-axis sensor alignment. It is essential to obtain readings on both faces, that is, with the probe turned 180 degrees, to eliminate zero shift errors and enable data quality "checksums" to be computed. Checksums must always be computed and scrutinized for errors in the field. Where errors are suspected, repeat readings must be taken on the spot. In horizontal casings, the uniaxial probe must be disconnected from the cable and reconnected to the second socket at the other end of the probe to reverse the probe, and only two passes are needed.

If casing spiral is suspected to be of significance, a spiral survey tool should be used to survey the casings. All portable equipment should be handled with care and protected during day-to-day use. The back of a pickup truck is no place for a delicate instrument on a rough site; instruments require "tender loving care" for good results. The cable should be protected from nicks, and connectors must be kept clean and dry. Although most probes and readouts are rated for a reasonably broad temperature range, neither should be left unshaded in hot climates or exposed to prolonged temperatures close to or below freezing point. Battery life at low temperatures is considerably reduced, dependent on type (*23*). Electronic component malfunction is more likely under extreme environmental conditions.

Function checks on the instrument are necessary. Hanging the probe freely on 6 ft of cable gives a quick daily zero check, and regular readings in fixed short casings are desirable. Manufacturer adjustment, maintenance, and recalibration are advisable once per year or if instrument performance is suspect. The instrument must be cleaned and wheels checked for excessive wear and oiled daily. Where practicable, periodically washing out the casing will remove grit that can collect in the grooves and cause increased groove wear, degrading data quality. Periodic surface surveys of both line and level at the casing collar provide an important check on measured ground movements and should always be made. If possible, where high accuracy is needed, duplicate sets of inclinometer readings should be taken and an average data set determined.

Data should be reported in an initial installation report, followed by monitoring reports (*13*). The installation report should include equipment model and serial numbers, calibration, description of installation, site plan with casing location, elevation, groove orientation, convention adopted for the sign of the movement and probe orientation, initial data sets, and a spiral survey, if one was taken. Each monitoring report should include equipment model and serial number, data set, a diary of field activities, and observations related to the installation. Jobs may extend over many months or years, and detailed records can be crucial when personnel changes or problems arise.

Where manual readings are taken, data are recorded on a field sheet formatted for computation or computer key entry (Figure 15). Face errors for pairs of corresponding readings (i.e., A+, A- and B+, B-) must be determined and should be relatively constant at each depth. This provides a critical field check on data reliability. A similar procedure must be followed with an electronic notebook or a computer-based readout, such as the Digitilt RPP. Field equipment or procedures that do not permit on-the-spot data quality checks should never be used. Two or three initial data sets should be obtained on a casing before any construction activity to ensure reliable baseline data and confirm that backfill movements are absent.



INCLINOMETER DATA SHEET
COMPUTER ENTRY FORM
FORTRAN IV VERSION

SINCO Slope Indicator Company Seattle Washington U.S.A.

① JOB No: W-2553-01
② JOB TITLE (MAY EXTEND THRU COL 40): HILLSIDE AQUADUCT ANC HOR MOVMT
③ HOLE No: B-1
④ SET No: 7
⑤ DATE: 11OCT76
⑥ TIME: 1310
⑦ STAT INT: 20.
⑧ INS: 039
⑨ No READ: 38
⑩ REV:
⑪ R-SCALE: 1200.
⑫ D-SCALE: 3.
⑬ ERROR A:
⑭ ERROR B:
⑮ INST CONST: 20000.
⑯ DIR A+: A1
⑰ DIR A-: A2
⑱ DIR B+: B1
⑲ DIR B-: B2
⑳ ㉑ A-Z ADJ:
㉒ B-Z ADJ:

DEPTH	DIR A+	DIR A-	DIR B+	DIR B-
2.0	124	-125	240	-236
4.0	210	-188	81	-185
6.0	270	-203	202	-196
8.0	267	-264	235	-235
10.0	263	-251	148	-218
12.0	246	-245	158	-155
14.0	234	-234	130	-131
16.0	241	-245	124	-121
18.0	262	-250	101	-108
20.0	261	-259	24	-39
22.0	263	-266	5	-6
24.0	319	-320	14	-19
26.0	346	-338	-19	16
28.0	355	-354	-44	51
30.0	299	-285	60	-60
32.0	436	-436	6	-18
34.0	549	-553	106	-107
36.0	289	-277	110	-106
38.0	278	-283	118	-126
40.0	263	-258	159	-147
42.0	194	-193	148	-153
44.0	183	-183	190	-194
46.0	190	-190	173	-186
48.0	170	-171	141	-145
50.0	210	-205	135	-160

FIGURE 15 Field data sheet formatted for keypunch data entry.

Computer-based field readouts are being used more widely because they provide convenience, reliability, elimination of data transcription errors, on-the-spot computation of casing position or displacement, and cost savings. A recent cost comparison (*24*) indicated a tenfold reduction in monitoring costs when use of a Digitilt RPP was compared with use of manual equipment.

Monitoring telescopic casing where large axial displacements occur poses difficulties in repositioning the probe in the casing. If readings are made in the normal way at uniform depth intervals, the absolute profiles must be compared graphically. If a separate settlement survey is performed, computational techniques can be used to compare the two data sets.

Alternatively, the probe may be relocated at the same position in a casing section by "feeling" the casing coupling as the wheels pass through. Again, a separate settlement survey is required. Additional bookkeeping complications occur when casing is built into an earth or rockfill dam because the reference point from which measurements are made is constantly changing (*25*) and reliance is placed on surface surveys. As yet, there is no better solution to this problem.

Fixed-in-place inclinometers should be read daily after installation to check for zero drift of a bad sensor. Depending on the readout arrangements, threshold readings and alarms may be set and telemetry systems may be checked. Automatically collected data should be scrutinized periodically for errors, particularly drift, and periodic probe inclinometer surveys should be made on an adjacent casing (Figure 16).

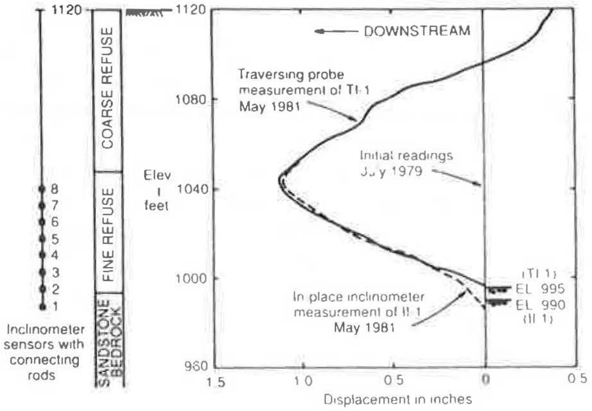


FIGURE 16 **Horizontal movements measured with probe inclinometer and with fixed-in-place inclinometer in adjacent casings (*26*).**

DATA PROCESSING, ERROR SOURCES, AND ACCURACY

Data checksums (i.e., algebraic sum of pairs of readings 180 degrees apart) must be computed and scrutinized in the field, and data should be processed as soon as possible. Manual data reduction is tedious even with the help of a programmable calculator, and many users recognize the advantages of computerized analysis (*24, 27*). IBM-PC software is now available; for example, Slope Indicator/Geo-Slope PC-SLIN, with keyboard or RS-232C serial input, tabular and graphic output, error

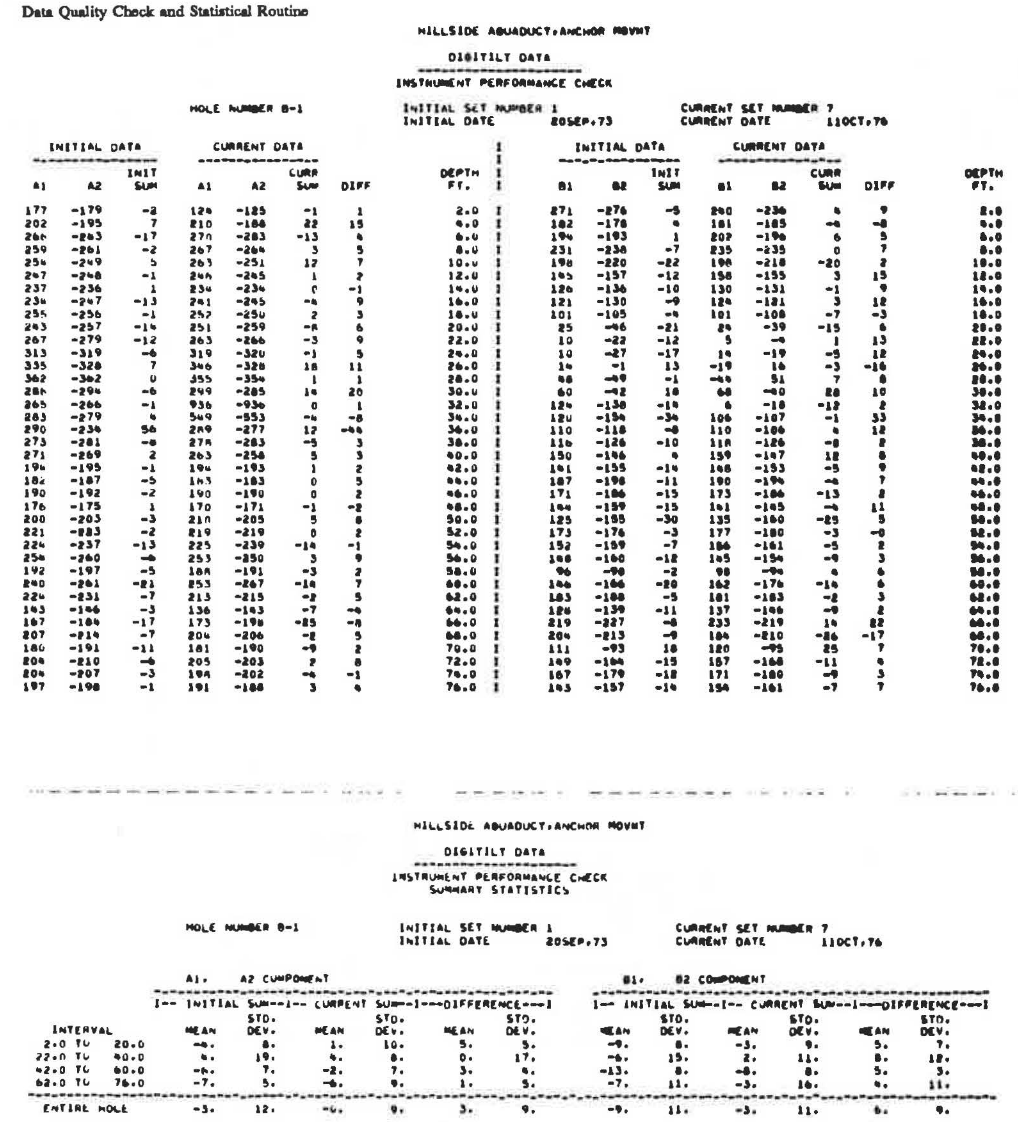
Field Data and Displacements

```
-----------------------------------------------------
  GEO-SLOPE                  :  P C - S L I N  :
-------------------------------------------------80526--------------------
                BENCHMARK EXAMPLE NO. 1
                       DIGITILT DATA
                         PAST            PRESENT
                        ------ .         -------
FILE NAMES               A:SI1.SN         A:SI11.SN
JOB NUMBER               W-2553-01        W-2553-01
HOLE NUMBER              B-1              B-1
DATA SET NUMBER          7                7
DATE                     SEPT 20/73       OCT. 11/76
TIME                     13:10            12:30
READINGS PER DIRECTION   2                2
INSTRUMENT NUMBER        039              039
CONSTANT                     20000.           20000.
ERROR ANGLE - A COMP.          .000             .000
ERROR ANGLE - B COMP.          .000             .000
ZERO SHIFT - A COMP.                        0
ZERO SHIFT - B COMP.                        0

       PAST DATA           PRESENT DATA
     ---------------     ---------------
                  PAST                   PRESENT            DEFL.     DEPTH
    A+       A-   DIFF.    A+       A-    DIFF.   CHANGE     IN.       FT.
--------------------------------------------------------------------------
   177     -179    356    124     -125     249     -107    1.0149      2.0
   202     -195    397    210     -188     398        1    1.1112      4.0
   266     -283    549    270     -283     553        4    1.1106      6.0
   259     -261    520    267     -264     531       11    1.1082      8.0
   254     -249    503    263     -251     514       11    1.1016     10.0
   247     -248    495    246     -245     491       -4    1.0950     12.0
   237     -236    473    234     -234     468       -5    1.0974     14.0
   234     -247    481    241     -245     486        5    1.1004     16.0
   255     -256    511    252     -250     502       -9    1.0974     18.0
   243     -257    500    251     -259     510       10    1.1028     20.0
   267     -279    546    263     -266     529      -17    1.0968     22.0
   313     -319    632    319     -320     639        7    1.1070     24.0
   335     -328    663    346     -328     674       11    1.1028     26.0
   362     -362    724    355     -354     709      -15    1.0962     28.0
   288     -294    582    299     -285     584        2    1.1052     30.0
   265     -266    531    936     -936    1872     1341    1.1040     32.0
   283     -279    562    549     -553    1102      540     .2994     34.0
   290     -234    524    289     -277     566       42    -.0246     36.0
   273     -281    554    278     -283     561        7    -.0498     38.0
   271     -269    540    263     -258     521      -19    -.0540     40.0
   194     -195    389    194     -193     387       -2    -.0426     42.0
   182     -187    369    183     -183     366       -3    -.0414     44.0
   190     -192    382    190     -190     380       -2    -.0396     46.0
   176     -175    351    170     -171     341      -10    -.0384     48.0
   200     -203    403    210     -205     415       12    -.0324     50.0
   221     -223    444    219     -219     438       -6    -.0396     52.0
   224     -237    461    225     -239     464        3    -.0360     54.0
   254     -260    514    253     -250     503      -11    -.0378     56.0
   192     -197    389    188     -191     379      -10    -.0312     58.0
   240     -261    501    253     -267     520       19    -.0252     60.0
   224     -231    455    213     -215     428      -27    -.0366     62.0
```

Total Deflection between the PAST and PRESENT sets of data

FIGURE 17 **Tabulated computer output.**



Data Quality Check and Statistical Routine

```
                                          HILLSIDE AQUADUCT,ANCHOR MOVMT

                                               DIGITILT DATA
                                          ----------------------
                                          INSTRUMENT PERFORMANCE CHECK

                      HOLE NUMBER B-1      INITIAL SET NUMBER 1                CURRENT SET NUMBER 7
                                           INITIAL DATE       20SEP,73         CURRENT DATE       11OCT,76

    INITIAL DATA          CURRENT DATA                   I      INITIAL DATA          CURRENT DATA
  ----------------     ----------------                  I   ----------------      ----------------
              INIT                 CURR          DEPTH   I                INIT                  CURR             DEPTH
  A1     A2    SUM     A1     A2    SUM   DIFF    FT.    I    B1     B2    SUM     B1     B2     SUM   DIFF        FT.

 177   -179     -2    124   -125     -1     1     2.0   I   271   -276     -5    240   -236      4     9          2.0
 202   -195      7    210   -188     22    15     4.0   I   182   -178      4    181   -185     -4    -8          4.0
 266   -283    -17    270   -283    -13     4     6.0   I   194   -193      1    202   -196      6     5          6.0
 259   -261     -2    267   -264      3     5     8.0   I   231   -238     -7    235   -235      0     7          8.0
 254   -249      5    263   -251     12     7    10.0   I   198   -220    -22    198   -218    -20     2         10.0
 247   -248     -1    246   -245      1     2    12.0   I   145   -157    -12    158   -155      3    15         12.0
 237   -236      1    234   -234      0    -1    14.0   I   126   -136    -10    130   -131     -1     9         14.0
 234   -247    -13    241   -245     -4     9    16.0   I   121   -130     -9    124   -121      3    12         16.0
 255   -256     -1    252   -250      2     3    18.0   I   101   -105     -4    101   -108     -7    -3         18.0
 243   -257    -14    251   -259     -8     6    20.0   I    25    -46    -21     24    -39    -15     6         20.0
 267   -279    -12    263   -266     -3     9    22.0   I    10    -22    -12      5     -4      1    13         22.0
 313   -319     -6    319   -320     -1     5    24.0   I    10    -27    -17     14    -19     -5    12         24.0
 335   -328      7    346   -328     18    11    26.0   I    14     -1     13    -19     16     -3   -16         26.0
 362   -362      0    355   -354      1     1    28.0   I    48    -49     -1    -44     51      7     8         28.0
 288   -294     -6    299   -285     14    20    30.0   I    60    -42     18     68    -40     28    10         30.0
 265   -266     -1    936   -936      0     1    32.0   I   124   -138    -14      6    -18    -12     2         32.0
 283   -279      4    549   -553     -4    -8    34.0   I   120   -154    -34    106   -107     -1    33         34.0
 290   -234     56    289   -277     12   -44    36.0   I   110   -118     -8    110   -106      4    12         36.0
 273   -281     -8    278   -283     -5     3    38.0   I   116   -126    -10    118   -126     -8     2         38.0
 271   -269      2    263   -258      5     3    40.0   I   150   -146      4    159   -147     12     8         40.0
 194   -195     -1    194   -193      1     2    42.0   I   141   -155    -14    148   -153     -5     9         42.0
 182   -187     -5    183   -183      0     5    44.0   I   187   -198    -11    190   -194     -4     7         44.0
 190   -192     -2    190   -190      0     2    46.0   I   171   -186    -15    173   -186    -13     2         46.0
 176   -175      1    170   -171     -1    -2    48.0   I   144   -159    -15    141   -145     -4    11         48.0
 200   -203     -3    210   -205      5     8    50.0   I   125   -155    -30    135   -160    -25     5         50.0
 221   -223     -2    219   -219      0     2    52.0   I   173   -176     -3    177   -180     -3     0         52.0
 224   -237    -13    225   -239    -14    -1    54.0   I   152   -159     -7    156   -161     -5     2         54.0
 254   -260     -6    253   -250      3     9    56.0   I   148   -160    -12    145   -154     -9     3         56.0
 192   -197     -5    188   -191     -3     2    58.0   I    96    -98     -2     98    -94      4     6         58.0
 240   -261    -21    253   -267    -14     7    60.0   I   146   -166    -20    162   -176    -14     6         60.0
 224   -231     -7    213   -215     -2     5    62.0   I   183   -188     -5    181   -183     -2     3         62.0
 143   -146     -3    136   -143     -7    -4    64.0   I   128   -139    -11    137   -146     -9     2         64.0
 167   -184    -17    173   -198    -25    -8    66.0   I   219   -227     -8    233   -219     14    22         66.0
 207   -214     -7    204   -206     -2     5    68.0   I   204   -213     -9    184   -210    -26   -17         68.0
 180   -191    -11    181   -190     -9     2    70.0   I   111    -93     18    120    -95     25     7         70.0
 204   -210     -6    205   -203      2     8    72.0   I   149   -164    -15    157   -168    -11     4         72.0
 204   -207     -3    198   -202     -4    -1    74.0   I   167   -179    -12    171   -180     -9     3         74.0
 197   -198     -1    191   -188      3     4    76.0   I   143   -157    -14    154   -161     -7     7         76.0
```

```
                                          HILLSIDE AQUADUCT,ANCHOR MOVMT

                                               DIGITILT DATA
                                          ----------------------
                                          INSTRUMENT PERFORMANCE CHECK
                                              SUMMARY STATISTICS

                      HOLE NUMBER B-1      INITIAL SET NUMBER 1                CURRENT SET NUMBER 7
                                           INITIAL DATE       20SEP,73         CURRENT DATE       11OCT,76

                     A1,   A2 COMPONENT                                  B1,   B2 COMPONENT
                ---------------------------------------------------   ---------------------------------------------------
                I-- INITIAL SUM--I-- CURRENT SUM--I---DIFFERENCE---I   I-- INITIAL SUM--I-- CURRENT SUM--I---DIFFERENCE---I
                        STD.             STD.              STD.               STD.             STD.              STD.
   INTERVAL      MEAN   DEV.     MEAN    DEV.     MEAN     DEV.        MEAN   DEV.     MEAN    DEV.     MEAN     DEV.
  2.0 TO  20.0    -4.     8.       1.     10.       5.       5.         -9.     8.      -3.      9.       5.       7.
 22.0 TO  40.0     4.    19.       4.      8.       0.      17.         -6.    15.       2.     11.       8.      12.
 42.0 TO  60.0    -6.     7.      -2.      7.       3.       4.        -13.     8.      -8.      8.       5.       3.
 62.0 TO  76.0    -7.     5.      -6.      9.       1.       5.         -7.    11.      -3.     16.       4.      11.
-----------------------------------------------------------------------------------------------------------------------
  ENTIRE HOLE     -3.    12.      -0.      9.       3.       9.         -9.    11.      -3.     11.       6.       9.
```

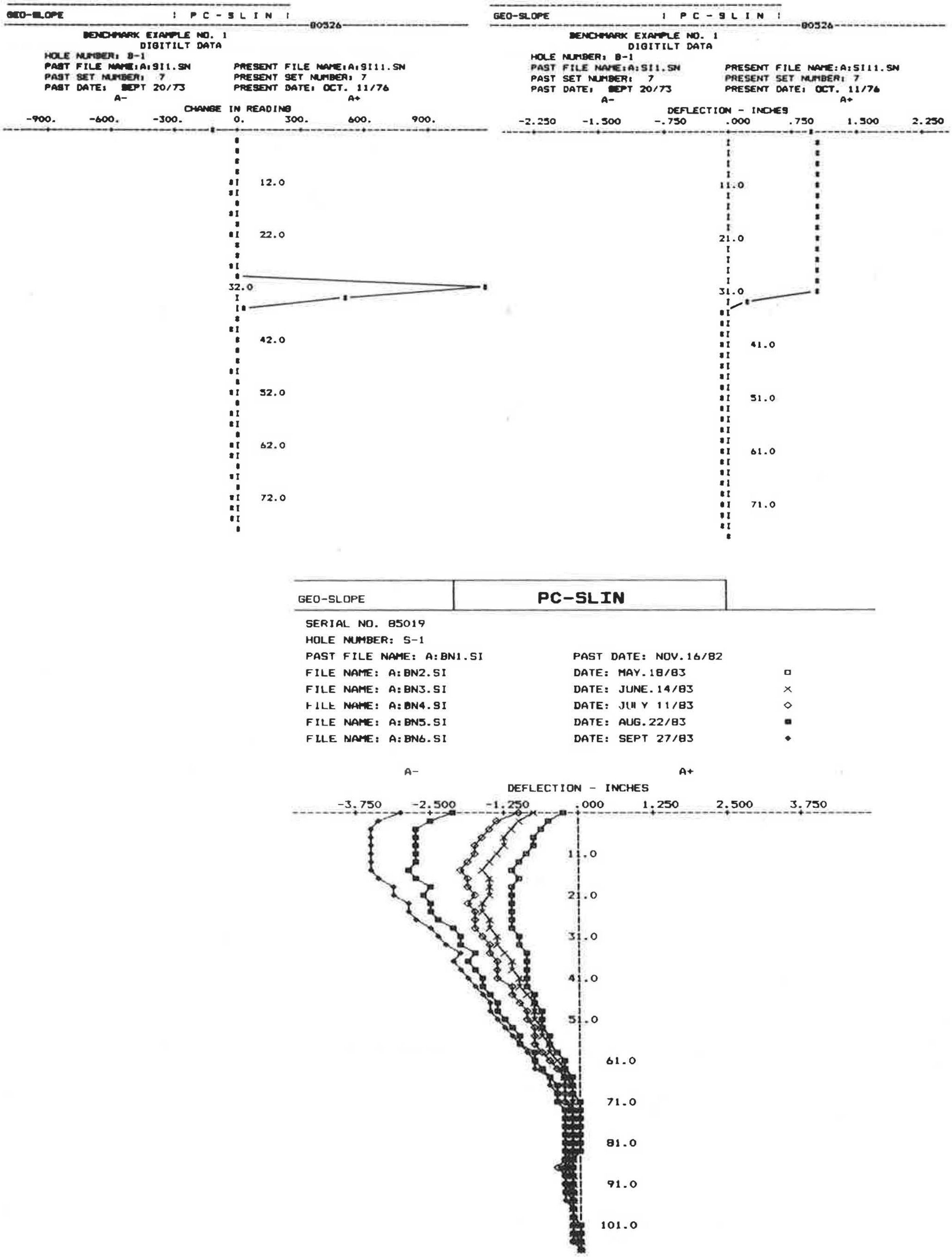
FIGURE 17 continued.

detection routines, and systematic error correction features. Readings can be input manually from hand-recorded data sheets or by RS-232C serial input from magnetic tape when recorded automatically, as with the Digitilt RPP.

Processed data (Figure 17) should be scrutinized by using error detection and correction routines to optimize the data quality and enable correct interpretation of engineering behavior. Graphical data presentation is essential and may include (a) slope change/depth, (b) displacement/depth, (c) displacement/time for a specific depth interval, and (d) displacement vector plots on a site plan, in that order (Figures 18, 19, and 20). Construction activities and instrument field crew observations should be noted on the plots to aid interpretation. Ground movements are usually progressive and continuous in one direction, although the rate of displacement will generally not be constant. Erratic displacement/time plots should always be carefully investigated. Figure 20 shows steady state creep in a reactivated ancient slide, whereas Figure 21 presents a decreasing deep-seated movement rate, that is, a more stable condition developing.

A wide range of random or systematic errors can occur, both obvious or subtle. Experience indicates that data interpretation is often difficult and that wrong conclusions are drawn concerning magnitude and locations of movement. Both authors have extensive experience in trying to diagnose errors and draw rational engineering conclusions from conflicting and inexplicable data, not always as successfully as desired. Errors arise due to equipment faults, user misuse, or mistakes, as well as recognized system limitations.

Equipment problems include sensor malfunction, wheel bearing wear, low batteries, moisture ingress to cable connections or readout, mechanical shock damage, nicked cables, improper casing installation, calibration changes inherent in manufacturer servicing, and cable stretch or marker movement with use. User errors arise due to reading errors and data



```
GEO-SLOPE                  : P C - S L I N :
---------------------------------------------80526-----------------
          BENCHMARK EXAMPLE NO. 1
                 DIGITILT DATA
    HOLE NUMBER: B-1
    PAST FILE NAME:A:SI1.SN        PRESENT FILE NAME:A:SI11.SN
    PAST SET NUMBER:  7            PRESENT SET NUMBER: 7
    PAST DATE:  SEPT 20/73         PRESENT DATE: OCT. 11/76
```

```
GEO-SLOPE                  : P C - S L I N :
---------------------------------------------00526-----------------
          BENCHMARK EXAMPLE NO. 1
                 DIGITILT DATA
    HOLE NUMBER: B-1
    PAST FILE NAME:A:SI1.SN        PRESENT FILE NAME:A:SI11.SN
    PAST SET NUMBER:  7            PRESENT SET NUMBER: 7
    PAST DATE:  SEPT 20/73         PRESENT DATE: OCT. 11/76
```

```
GEO-SLOPE    PC-SLIN
 SERIAL NO. 85019
 HOLE NUMBER: S-1
 PAST FILE NAME: A:BN1.SI        PAST DATE: NOV.16/82
 FILE NAME: A:BN2.SI             DATE: MAY.18/83        □
 FILE NAME: A:BN3.SI             DATE: JUNE.14/83       ×
 FILE NAME: A:BN4.SI             DATE: JULY 11/83       ◇
 FILE NAME: A:BN5.SI             DATE: AUG.22/83        ■
 FILE NAME: A:BN6.SI             DATE: SEPT 27/83       ◆
```

FIGURE 18 Graphical computer output: (top) single data set, (bottom) multiple data set.

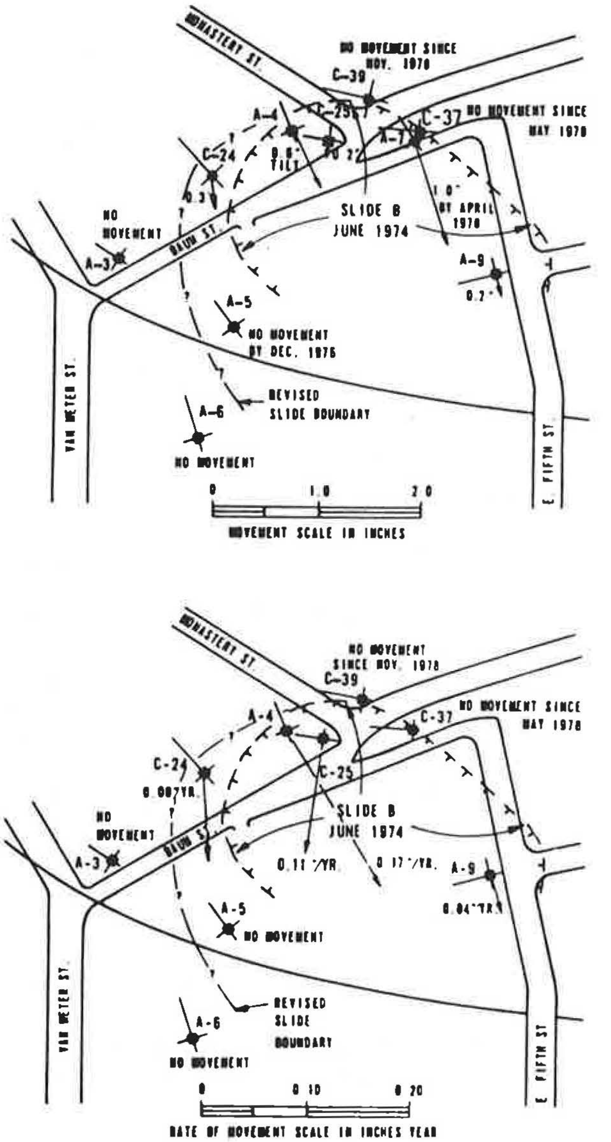


FIGURE 19 Vector plots of slide movements showing magnitude of movement January 1976–April 1979 and average rate of movement January 1978–April 1979.

transcription errors where manual methods are used; incorrect probe orientation in the casing grooves; probe depth position errors due to careless reading techniques, surface casing disturbance, or incorrect matching of readings 180 degrees apart; incorrect assumption of casing base fixity; unrecognized settlement or heave; improper reading techniques; or lack of survey control when telescopic couplings are used or when large settlements or heave must be accounted for. This is a formidable list of problems that can and do occur, and good project planning, equipment selection, training, data scrutiny, and awareness of the pitfalls are needed to avoid them.

If it is assumed that equipment and user related errors can be recognized and controlled, measurement errors also exist because of the inherent limitations of the best available instrument and casing. The data quality tabulation (Figure 17) is an essential aid and should always be used. Variation in checksums can be quickly scanned, errors detected, and data quality assessed. The statistical analysis provides a useful comparative instrument performance rating. If opposite walls of the inclinometer casing are not quite parallel, if any wheel is in a coupling, or if depth control is imprecise, the checksum may vary randomly. Small variations are tolerable.

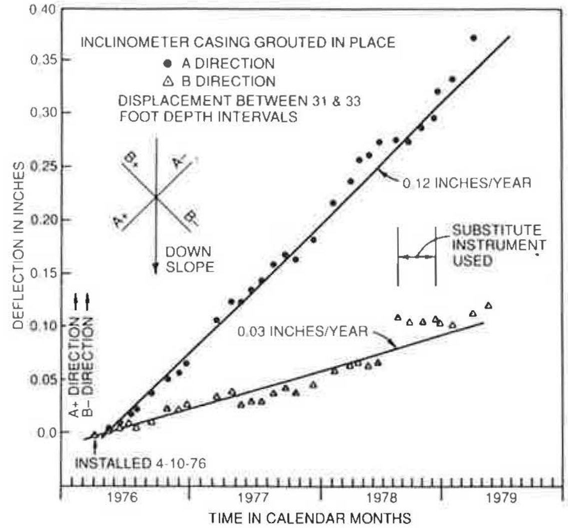


FIGURE 20 Creep movements on a thin shear zone in a reactivated ancient slide.

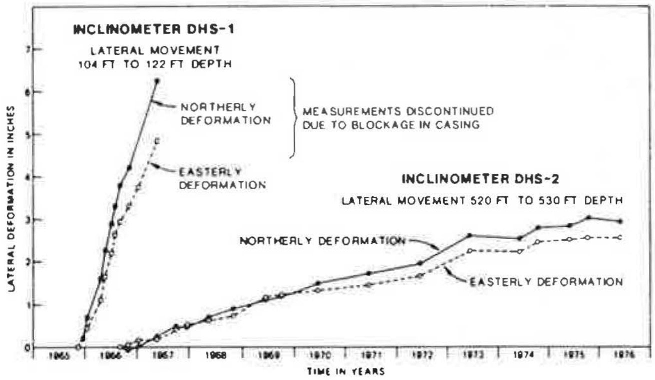


FIGURE 21 Deformations measured on deep shear zones on a landslide in Canada.

Ideally, checksums should remain constant with depth within a given data set for both A and B sensors. If a change in the zero offset occurs between sets of readings, the checksum will change, but this does not matter. If a change occurs in the zero offset during a particular set of readings, either during a traverse or between opposite traverses due to temperature or shock-induced changes to the sensor suspension, the result will be errors that can only be eliminated by careful scrutiny and computerized error detection routines (Figure 22). When readings are obtained in slightly inclined casing, a correction for changes in the servo-accelerometer azimuth orientation may be required. Slight changes in the sensor due to shock occur from time to time. These changes show up as irregular rotation of the displacement/depth profile (Figure 22) and can mask shear occurring at discrete zones. The combination of sensor azimuth rotation with inclined casing causes systematic errors. Individual correction angles can be applied to the A and B sensors of each data set by using computerized routines and shear zone movement correctly identified (Figure 21). Although sensor zero shifts are a significant problem and must be properly dealt with during data processing, the scale span or slope of currently available servo-accelerometers is fairly stable, and errors due to this source appear to be less serious. They cannot be eliminated by routine procedures and require instrument recalibration by the manufacturer. Some manufacturers provide simple field calibration frames, but these appear to be of limited value.

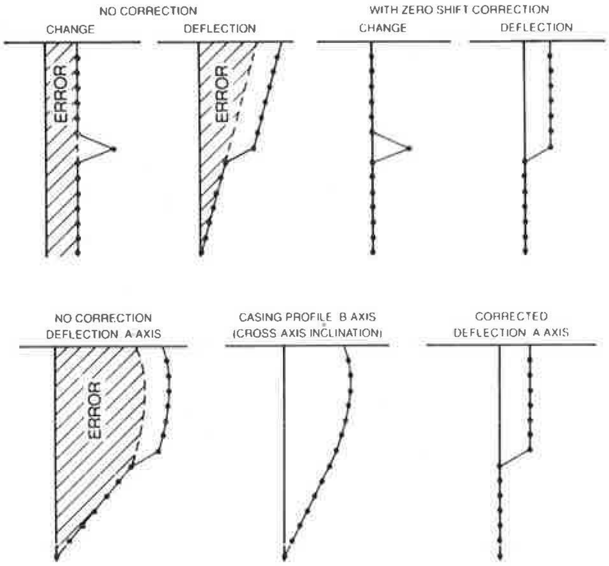


FIGURE 22 Typical zero shift and rotation errors.

Errors can arise immediately after installation due to settlement of the backfill. Erratic casing movements develop but usually cease with time. An extreme type of error can occur where drilling and grouting upset the stress and thermal regime of the surrounding material. Casings installed on a permafrost slope to monitor slope creep have shown extraneous movements due to recovery of thermal equilibrium around the casing, effects of stratigraphy and settlement, and heave of the casing (*28, 29*). High-quality monitoring procedures and painstaking analysis were employed that enabled definitive slope velocities of 0.30 cm/yr to be established. Other data filter techniques have been suggested (*30*); however, caution is urged in using statistical techniques.

Similar principles to the foregoing apply to horizontal inclinometer casings. Where access is available at both ends of the casing, first-order leveling is used to convert the inclinometer survey to a closed traverse, and settlement measurement accuracy is greatly increased. Inclined casings used to monitor displacement pose special problems (*7*) that require consideration of (a) groove spiral, (b) initial groove roll angle at the casing collar, and (c) sensor azimuth changes. In addition, if absolute position is desired, the azimuth of the vertical reference plane is determined by surveying the casing collar. Fixed-in-place inclinometers are subject primarily to sensor drift errors, and slope change/time plots for individual sensors should be scrutinized.

Measurement accuracy achieved with inclinometer systems is highly dependent on (a) the equipment selected, (b) the installation and monitoring procedures used, and (c) correct data scrutiny and processing. The system accuracy or precision achieved is quite different from the quoted resolution or sensitivity of the probe and readout. The inclinometer measures relative movements, so it may be more appropriate to discuss performance in terms of precision, that is, the repeatability with which the instrument can determine the position of one end of the casing relative to the other. A servo-accelerometer-type inclinometer system is capable of a precision of ±0.05 to 0.25 in. over 100 ft in vertical and horizontal casings but much less in inclined casings (*7*). It is, of course, rare for an accurate independent check to be possible (*12*), and estimates of precision or accuracy achievable are based on a combination of direct measurement, experience, and reasonableness of the data.

PLANNING AND EXECUTION OF INCLINOMETER MONITORING PROGRAMS

As with all geotechnical monitoring programs, inclinometer measurements must be properly planned and executed. Too often instruments are installed for ill-defined reasons, and data are collected and filed away, unused (*10, 31*). Instrumentation has become fashionable. In contrast, real needs should be assessed, behavior predicted, and tasks assigned following a systematic approach. What needs to be measured, the accuracy required, and if and how this can be achieved should be considered. Specialist advice on instrumentation system design should be sought where in-house skills are lacking. The engineer is usually the party most interested in obtaining reliable monitoring data and should retain as great a control as is possible. In general, instrumentation should not be left up to the contractor.

Descriptive or performance specifications for instrument procurement may be used (*10, 31, 32*). Too often a single lump sum bid item appears in a specification for supply and installation of a variety of instruments, and the low bidder wins (*7*). Under these conditions the engineer often ends up with something far less than is needed, even though considerable sums of money have been expended. It is preferable for the engineer to select the make and model number of instrument believed to be most suitable and to specify with no substitution allowed. Sole source justification may be required and can be used (*33*). The inclusion of "or equal" leads to excessive emphasis on low cost so that high-quality instruments are excluded (*34, 35*). There is often no good, legally defensible way of excluding substitute instruments. An entire inclinometer monitoring program may fail if an inferior instrument is selected. This is not an acceptable risk and hence must be avoided. Detailed procedures for minimizing these risks are discussed elsewhere (*10, 31*).

CONCLUSION

The inclinometer is widely and successfully used to measure ground movements and is capable of considerable accuracy. Successful projects require good planning, high-quality and appropriate instruments, proper installation, diligent reading, correct data processing, and intelligent scrutiny and interpretation. Cooperation and understanding between engineers, clients, and contractors is essential for success.

ACKNOWLEDGMENTS

We are indebted to our colleagues for support. We are also grateful to our clients, through whose projects we have come to better understand many of the problems of instrument performance and subtleties of data analysis. These experiences led to the improvements discussed in this paper. The substance of this paper was originally presented at a symposium on field instrumentation organized by the Nanyang Technological Institute, Singapore, in November 1986.

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Publication of this paper sponsored by Committee on Soils and Rock Instrumentation.