CHAPTER 12

MEASUREMENT OF DEFORMATION

12.1. INSTRUMENT CATEGORIES

Instruments for measuring deformation can be grouped in the categories listed in Table 12.1. Definitions of each category, together with an indication of typical applications, are given in later sections of this chapter. It can be seen that there is a vast array of instruments for monitoring deformation, but Peck (1972) warns:

> An instrument too often overlooked in our technical world is a human eye connected to the brain of an intelligent human being. It can detect most of what we need to know about subsurface construction. Only when the eye cannot directly obtain the necessary data is there a need to supplement it by more specialized instruments. Few are the instances in which measurements by themselves furnish a sufficiently complete picture to warrant useful conclusions.

12.2. SURVEYING METHODS*

Surveying methods are used to monitor the magnitude and rate of horizontal and vertical deformations of structures, the ground surface, and accessible parts of subsurface instruments in a wide variety of construction situations. Frequently, these methods are entirely adequate for performance monitoring, and geotechnical instruments are required only if greater accuracy is required or if measuring points are inaccessible to surveying methods, as is the case for subsurface measurements. In general, whenever geotechnical instruments are used to monitor deformation, surveying methods are also used to relate measurements to a reference datum.

Surveying methods are described briefly in the following subsections, and comparative information is given in Table 12.2. Reference datums and measuring points for monitoring surface deformation are also described in this section.

Surveyors who work on construction sites often have little experience with the accuracies required for deformation monitoring, and a well-trained survey crew is essential when maximum accuracy is required. Measurement accuracy is controlled by the choice and quality of surveying technique and by characteristics of reference datums and measuring points. Survey instrument technology is well established, and most reputable manufacturers include a statement of accuracy in their instrument specifications, which can be relied on if the instrument is calibrated and operated in accordance with instructions.

Discussions of surveying methods by Cording et al. (1975), Gould and Dunnicliff (1971), and Senne

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Table 12.1. Categories of Instruments for Measuring Deformation

Category	Type of Measured Deformation						Section
	↔	↕	⤢	↻	∸	⨪	
SURVEYING METHODS	●	●	●		●		12.2
Optical and other methods							
Benchmarks							
Horizontal control stations							
Surface measuring points							
SURFACE EXTENSOMETERS	●	●	●		●		12.3
Crack gages							
Convergence gages							
TILTMETERS				●	●	●	12.4
PROBE EXTENSOMETERS	●	●	●			●	12.5
Mechanical heave gage							
Mechanical probe gages							
Electrical probe gages							
Combined probe extensometers and inclinometer casings							
FIXED EMBANKMENT EXTENSOMETERS	●	●	●			●	12.6
Settlement platform							
Buried plate							
Mechanical gage with tensioned wires							
Gages with electrical linear displacement transducers							
Soil strain gage							
FIXED BOREHOLE EXTENSOMETERS	●	●	●			●	12.7
Single-point and multipoint extensometers							
Subsurface settlement points							
Rod settlement gage							
INCLINOMETERS	●	●	●	●		●	12.8
TRANSVERSE DEFORMATION GAGES	●	●	●			●	12.9
Shear plane indicators							
Plumb lines							
Inverted pendulums							
In-place inclinometers							
Deflectometers							
Borehole directional survey instruments							
LIQUID LEVEL GAGES		●				●	12.10
Single-point and multipoint gages							
Full-profile gages							
MISCELLANEOUS DEFORMATION GAGES							12.11
Telltales	●	●	●		●	●	
Convergence gages for slurry trenches	●					●	
Time domain reflectometry	●	●	●		●	●	
Fiber-optic sensors	●	●	●		●	●	
Acoustic emission monitoring	●	●	●			●	

Key: ↔ horizontal deformation ⤢ axial deformation (↔ or ↕ or in between) ∸ surface deformation
↕ vertical deformation ↻ rotational deformation ⨪ subsurface deformation.

Table 12.2. Surveying Methods

Method	Advantages	Limitations	Approximate Accuracy
Elevations by optical leveling	Fast, particularly with self-leveling instruments Uses widely available technology	First-order leveling requires high-grade equipment and careful adherence to standard procedures	Third order: ± 0.05 ft $\times \sqrt{mi}$ (± 12 mm $\times \sqrt{km}$)[a] Second order: ± 0.025–0.033 ft $\times \sqrt{mi}$ (± 6–8 mm $\times \sqrt{km}$) First order: ± 0.012–0.020 ft $\times \sqrt{mi}$ (± 3–5 mm $\times \sqrt{km}$)
Distance measurements by taping	Direct measurements	Requires clear, relatively flat surface between measuring points and reference datum Tape should be checked against a standard frequently	Third order: $\pm 1/3000$–$1/6000$ of distance Second order: $\pm 1/20{,}000$–$1/50{,}000$ of distance First order: $\pm 1/300{,}000$ of distance
Offsets from a baseline using theodolite and scale	Direct measurements	Requires baseline unaffected by movement	± 0.001–0.005 ft (± 0.3–2 mm)
Traverse lines	Usable where direct measurements are not possible	Accuracy decreases as number of legs in the traverse line increases If possible, traverse should be closed	$\pm 1/30{,}000$–$1/150{,}000$ of distance
Triangulation	Usable where direct measurements are not possible	Requires accurate measurement of angles and baseline length Very slow when compared with trilateration by EDM	$\pm 1/30{,}000$–$1/1{,}000{,}000$ of distance
Laser beam leveling and offsets	Faster than conventional optical methods Readings can be made by one person	Seriously affected by air turbulence, humidity, and temperature differential Requires curvature and refraction corrections beyond about 650 ft (200 m) Limited to about 0.25 mile (0.4 km)	± 0.01–0.03 ft (± 3–10 mm)
Electronic distance measurement (EDM)	Long range Fast and convenient Very accurate	Accuracy is influenced by atmospheric conditions	For distance: ± 0.001–0.03 ft (± 0.3–10 mm) ± 2–5 ppm For lateral position change by trilateration: ± 0.005–0.03 ft (± 2–10 mm) ± 2–5 ppm
Trigonometric leveling	Long range Fast and convenient Can be done simultaneously with traversing	Accuracy is influenced by atmospheric conditions Requires a very accurate measurement of zenith angle	Third order: ± 0.05 ft $\times \sqrt{mi}$ (± 12 mm $\times \sqrt{km}$)[a] Second order: ± 0.025–0.033 ft $\times \sqrt{mi}$ (± 6–8 mm $\times \sqrt{km}$)
Photogrammetric methods	Can record movement of hundreds of potential points at one time for determination of overall deformation pattern	Weather conditions can limit use Interpretation requires specialist skill For good accuracy the baseline should be not less than one-fifth of the sight distance	$\pm 1/5000$–$1/100{,}000$ of distance
Global positioning system	Operates with little attention from personnel Can be set to trigger a warning device Very accurate	Very expensive Availability very limited at present Requires special ephemeris and computer software	± 0.0005–3 ft (± 0.2 mm to 1 m); average accuracy is ± 0.03–0.1 ft (± 10–30 mm) with 1½ hours of observation per point

[a] mi = distance in miles; km = distance in kilometers.

Figure 12.1. Second-order automatic level, Kern Model GK2-A (courtesy of Kern Instruments, Inc., Brewster, NY).

(1980) have provided substantial material for preparation of this section. General texts describing surveying methods include Bouchard and Moffitt (1987) and Davis et al. (1981): these should be consulted by the reader who needs more detail.

12.2.1. Elevations by Optical Leveling

Construction site settlement surveys are usually carried out using engineer's levels (e.g., Figure 12.1) at second- or third-order accuracy.

Second-order leveling requires limiting sight distances, balancing foresight and backsight, carefully plumbing the rod, and reading on well-defined marks and stable turning points. The circuit should be closed on a benchmark and the apparent closing error distributed. A *two-peg test* should be made prior to measurements and the engineer's level adjusted if necessary.

First-order leveling requires an optical micrometer attachment and a pair of invar survey rods. Requirements for first-order leveling include very-high-quality equipment, careful adherence to standard procedures, a minimum of atmospheric disturbance, and minimum temperature variation.

12.2.2. Distance Measurements by Taping

Taping over distances greater than about 200 ft (60 m) has largely been superseded by electronic distance measurements (EDM). However, if no EDM is available, distance measurements can be made by taping. A thorough treatment of sources of error and methods of improving accuracy of tape measurements is given by Milner (1969).

12.2.3. Offsets from a Baseline Using Theodolite and Scale

Measurements are made from a baseline by simple right angle offset, using a scale or steel tape.

12.2.4. Traverse Lines

A traverse to determine change in lateral position is a survey made by measuring successive distances and angles. If the traverse returns to the starting point it is called a *closed traverse,* in which the sum of interior angles of the polygon can be calculated and adjusted. The sides can also be adjusted for error of closure, which gives a good indication of the overall precision of the traverse.

The accuracy of angular measurements depends on the theodolite, sighting target, and atmospheric turbulence. Theodolites reading to 1 arc-second generally do not have the resolving power to align on a target to that accuracy, but six to eight positions will yield a standard error within 1 arc-second.

12.2.5. Triangulation

Where direct taping is impracticable, triangulation can be used to determine change in lateral position. A fixed baseline is measured accurately by EDM or precise taping techniques, and two angles are determined between the baseline and the measuring points. It is vital that the reference baseline is established on stable ground outside the zone of movement. Once the baseline has been established, it is necessary only to determine angles to the measuring points and to calculate their positions and propagated errors. Use of equi-angular figures increases accuracy. Greatest accuracy, for example, when monitoring movements of the downstream face of an arch dam, requires first-order triangulation. Figure 12.2 shows a theodolite suitable for first-order triangulation.

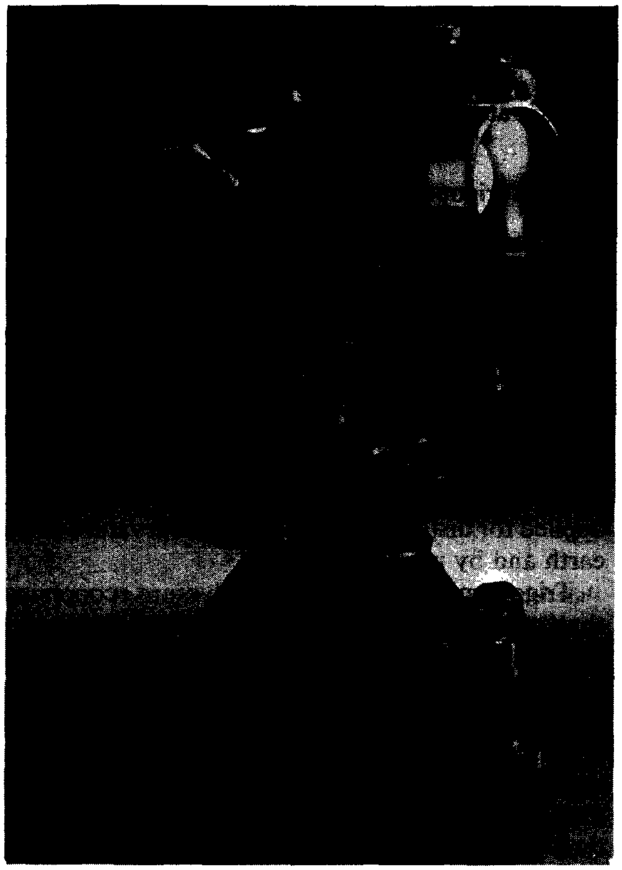


Figure 12.2. Precision theodolite, Wild Model T3 (courtesy of Wild Heerbrugg Instruments, Inc., Farmingdale, NY).

Most triangulation work is done at night or on cloudy days, since atmospheric turbulence and temperature variations are the limiting factors in making accurate observations.

12.2.6. Laser Beam Leveling and Offsets

The word *laser* is an acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. Lasers (e.g., Figure 12.3) can be used for alignment measurements and leveling, but the beam is deflected by air turbulence, humidity, and temperature differential. When these factors are small, measurement accuracy over distances of up to about 1000 ft (300 m) is about ±0.01 ft (±3 mm). Attempts have been made to increase accuracy by using split photocell detectors, but under typical field conditions accuracy is usually no better than ±0.01 ft (±3 mm) even over distances as small as 100 ft (30 m).

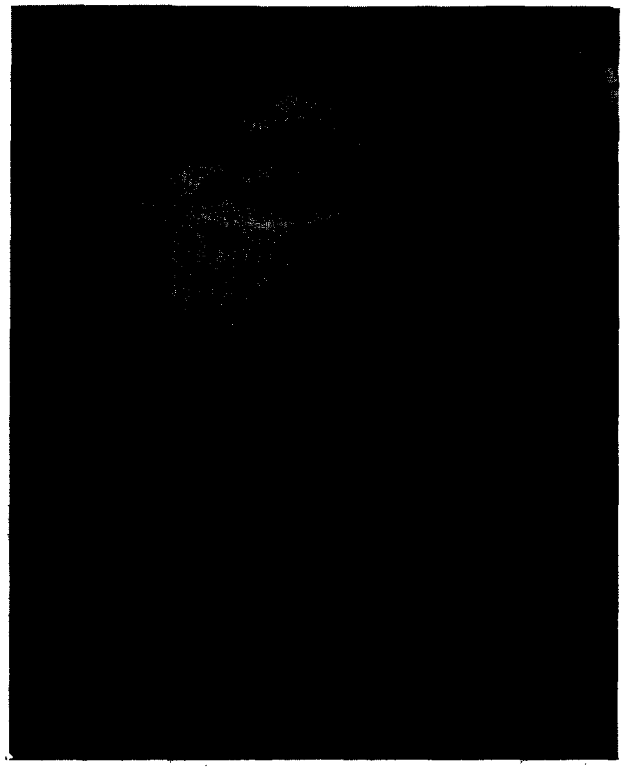


Figure 12.3. Electronic level, Spectra-Physics Model EL-1 (courtesy of Spectra-Physics, Dayton, OH).

12.2.7. Electronic Distance Measurement

Electronic distance measurement (EDM) equipment is used for measurement of distances, either for direct determination of distance change or for determination of lateral position change by trilateration. It is also used for trigonometric leveling, as discussed in the next section. Over the last 20 years the availability of increasingly reliable and accurate EDM equipment has radically changed conventional surveying practices. EDM devices require fewer personnel than conventional optical instruments, are faster to use, and are more accurate.

EDM equipment makes use of the velocity of electromagnetic radiation to measure the distance between the instrument and a reflector prism that is placed at the measuring point. Some equipment uses microwave radiation while others use infrared or visible light. Since air density has an effect on the velocity of light, air temperature, pressure, and humidity must be monitored. In the modern EDM, these factors are monitored and processed internally with a microcomputer.

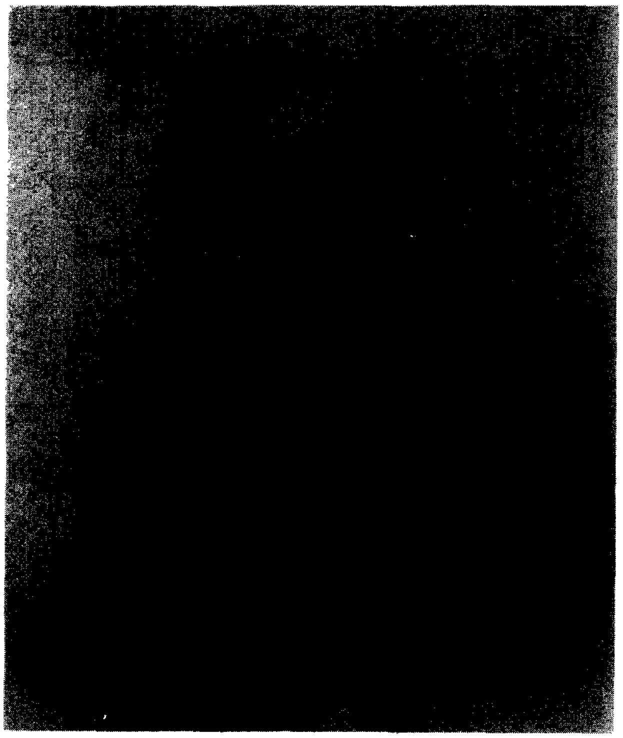


Figure 12.4. Electronic distance measurement equipment, Topcon Model GTS-2B (courtesy of Topcon Instrument Corporation of America, Paramus, NJ).

Depending on the model, an EDM can have a range of a few feet to several miles. Most instruments have two components of error: a random error plus a small percentage of the sight length. As an example of a highly accurate EDM, the Mekometer, developed in England in the late 1960s, has a range of 50–10,000 ft (15–3000 m) and an accuracy of ± 0.001 ft (± 0.3 mm) ± 2 parts per million (ppm). The Mekometer has been used for monitoring movements of embankment dams (Penman and Charles, 1973; Penman and Mitchell, 1970). A number of instruments, for example, the instrument shown in Figure 12.4, are widely available and in use at a more modest price and are capable of measuring distances to within ± 0.015 ft (± 5 mm). A list of available instruments is given by Hanna (1985).

K. Robertson (1977, 1979) describes the operating principle of EDM and discusses the usefulness of precision EDM in detecting small movements of large dams. He reports that surveys can detect movements within 0.01 ft (3 mm) when measurements are made during daylight hours, requiring about 5 minutes per measurement. In contrast, theodolite observations are usually made at night to minimize refraction effects and require the averaging of eight to twelve positions for each angle, involving at least ½ hour at each station.

12.2.8. Trigonometric Leveling

Trigonometric leveling uses EDM equipment to measure the slope distance from the instrument to a prism placed at the measuring point. The vertical angle between this sloping line and horizontal (the *zenith angle*) is measured with either a semi-precise (6 arc-seconds) or precise (2 or 1 arc-second) theodolite. The elevation difference between the instrument and measuring point is calculated from the measured distance and angle, and corrections are applied for distortion caused by the curvature of the earth and by refraction.

Trigonometric leveling is much more economical than conventional optical leveling when third-order accuracy is adequate and can be used when measuring points are physically inaccessible. Second-order trigonometric leveling requires use of special targets, sight distances not exceeding 1000 ft (300 m), more expensive equipment, and longer procedures. However, it is generally more economical than second-order optical leveling, especially in hilly terrain.

12.2.9. Photogrammetric Methods

Precise photography for measuring structural movements employs phototheodolites to take successive photographs from a fixed station along a fixed baseline. Movements are identified in a stereocomparator by steroscopic advance or recession of pairs of photographic plates in relation to stable background elements. The procedure defines components of movement taking place in the plane of the photograph. The method is similar to triangulation and involves the intersection of lines of sight, as shown in Figure 12.5. The film planes are usually parallel to each other and as nearly perpendicular as possible to a line joining the midpoints of the baseline and observation points. To calculate the position of a point, the focal length and orientation of the camera must be known, as well as the elevation of the ends and the length of the baseline. Once the control stations are established for the phototheodolite, the field work is minimal. The photogrammetric method has the advantage that hundreds of potential movements are recorded on a

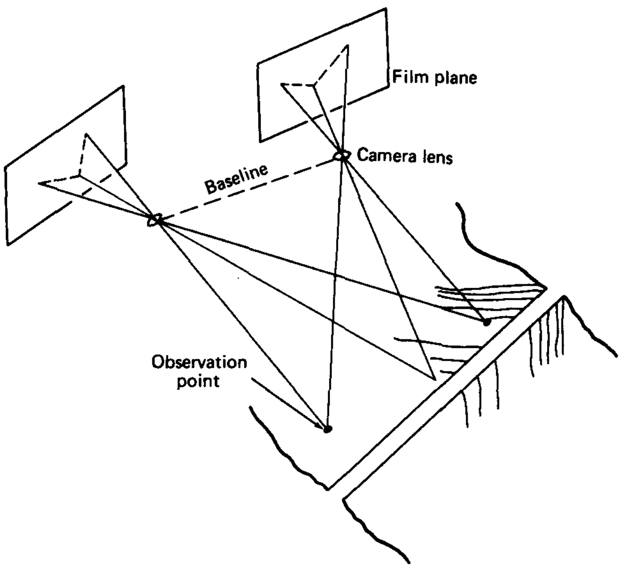


Figure 12.5. Photogrammetric arrangement using stereo pairs (after Senne, 1980).

single stereo photographic pair, allowing an appraisal of the overall displacement pattern in a minimum time. Figure 12.6 shows a stereoplotter system.

Measurement accuracy depends on many factors. Phototheodolites designed for this purpose should be used. The baseline should be as long as topography permits, not less than one-fifth the sight distance and nearly perpendicular to the line of sight. Stereocomparator measurements should be made to micron accuracy. In general, the standard error of measurement may vary from ±1/5000 to 1/100,000 of the sight distance, and accuracies as good as ±0.02 ft (±6 mm) have been reported for sight distances less than 200 ft (60 m). For longer sights up to 1600 ft (500 m), with baselines near 330 ft (100 m), accuracies of ±0.16 ft (±50 mm) have been obtained.

Moore (1973) describes photogrammetric measurements to determine deformations of a rockfill dam. A Wild P-30 phototheodolite was used and the data processed using a Wild A-7 Autograph. The standard deviations of the mean coordinates were in eastings ±20 mm (±0.07 ft), in northings ±40 mm (±0.13 ft), and in elevation ±10 mm (±0.03 ft).

Bozozuk et al. (1978) report on the use of photogrammetry for measuring pile head movements as surrounding piles were driven in a large pile group. Accuracy of measured horizontal deformations is reported as ±0.07 ft (±20 mm), of vertical deformations ±0.02 ft (±6 mm).

McVey et al. (1974) describe experiments with

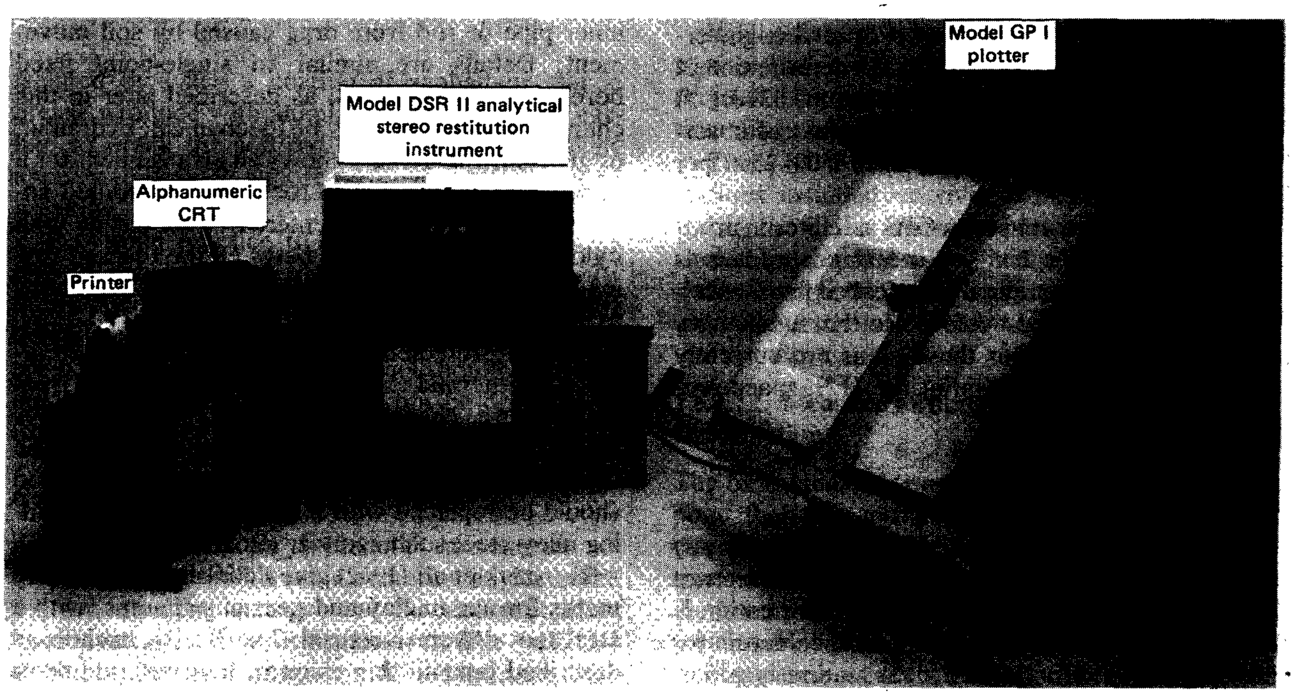


Figure 12.6. Analytical stereoplotter system for photogrammetric measurements (courtesy of Kern Instruments, Inc., Brewster, NY).

photogrammetric methods for monitoring deformation of underground openings, report on the difficulty of maintaining a suitable baseline, and suggest that an accuracy of ±0.002 ft (±0.6 mm) might be possible.

12.2.10. Global Positioning System

The *NAVSTAR Global Positioning System* (GPS) was originally conceived as a tool for military sea, land, and air navigation. The method is described by Hoar (1982) and Laurila (1983).

The system consists of three parts: satellites, a ground control network, and user equipment. Radio signals are used in an interferometric mode. Two or more GPS receivers simultaneously receive signals from the same set of satellites, and the resulting observations are subsequently processed to obtain the interstation difference in position. If one of the receivers is placed at a known position, the three-dimensional position of the second receiver may be determined, and the number of stations determined simultaneously is limited only by the number of receivers available. Calculations require use of a book of satellite positions as a function of time and earth position (an *ephemeris*) and special computer software. Accuracy of measurements is highly dependent on the time allowed for observations, and thus on the available funds, and submillimeter accuracy is possible in the extreme case. For civil engineering purposes, such as monitoring the deformation of dams, a more typical accuracy is ±0.03–0.1 ft (±10–30 mm), requiring about 1½ hours of observation per point, at a cost of U.S. $500–2500 per point.

At present there are seven GPS satellites in orbit, and availability for civil engineering purposes is somewhat limited. Original plans called for 18 satellites to be operational by 1989, so that availability would be unlimited, but these plans are currently delayed by the interruption of the U.S. space program.

12.2.11. Reference Datums

A stable reference datum is required for all survey measurements of absolute deformation. A reference datum for measurements of vertical deformation is referred to as a *benchmark*. A reference datum for measurements of horizontal deformation is generally referred to as a *horizontal control station* or a *reference monument*.

Benchmarks

Benchmarks established on substantial stable permanent structures ordinarily do not contribute error to settlement observations. However, a verification should first be made that the structure is not moving vertically owing to conditions such as groundwater lowering, seasonal thermal effects, or loading on piled foundations by negative skin friction.

The author suspects that many "benchmarks" used on construction projects are not as stable as the user thinks. If no suitable permanent structure is available that is **known** to be stable and remote from all possible vertical movement, a deep benchmark should be installed to a depth below the seat of vertical movement. Benchmarks placed at shallow depths in soil probably move to some extent and the movement may be sufficient to interfere with the desired accuracy of a survey. Apart from effects of frost heave, seasonal moisture changes, and nearby trees, construction activities may cause a near-surface benchmark to settle by subsoil densification from blasting or pile driving, by consolidation from nearby loading or drawdown, or as a result of extension strains directed toward an excavation.

A deep benchmark consists of a pipe or rod, anchored at depth, surrounded by and disconnected from a sleeve pipe. The sleeve pipe protects the inner pipe or rod from drag caused by soil movement. Details are similar to single-point fixed borehole extensometers, as described later in this chapter. The anchor may be mechanical, hydraulic, or grouted. Figure 12.7 shows an arrangement for a benchmark installation in rock, with a grouted anchor and the inner rod centered in the casing with nylon spacers. The space between the rod and casing may be filled with heavy oil or bentonite slurry to minimize friction.

Unless protected, exposed benchmarks are affected by thermal expansions and contractions from temperature changes. In high-precision surveys where these movements cannot be tolerated, the top 10–15 ft (3–4.5 m) of the deep benchmark rod should be replaced with a temperature compensating alloy steel such as invar (Bozozuk, 1984).

Bozozuk et al. (1962) give details of deep benchmarks for use in clay and permafrost areas, with a steel foot driven to refusal. The Borros anchor, as described later in this chapter, may be used for a benchmark if anchored in unyielding strata. Kjellman et al. (1955) describe a benchmark that is

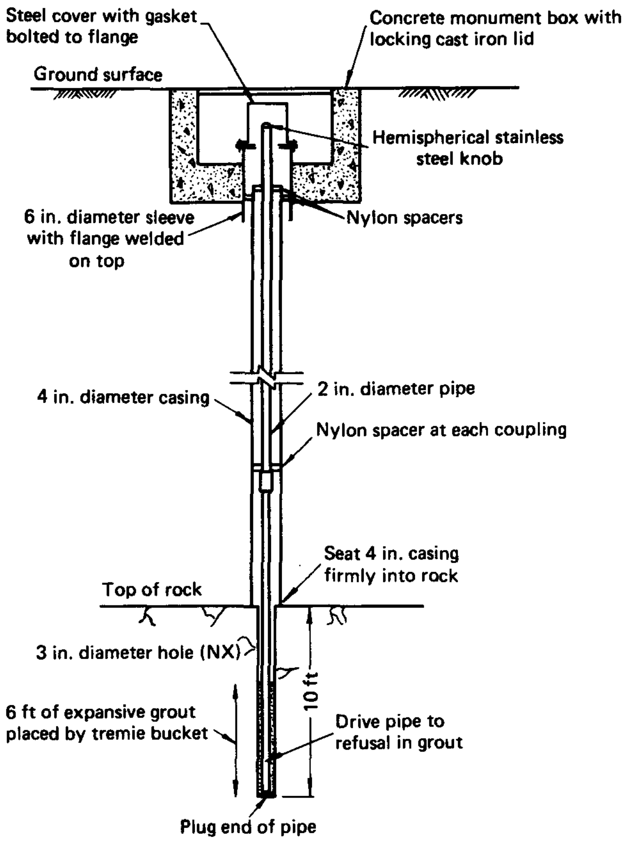


Figure 12.7. Benchmark installation in rock (after Cording et al., 1975).

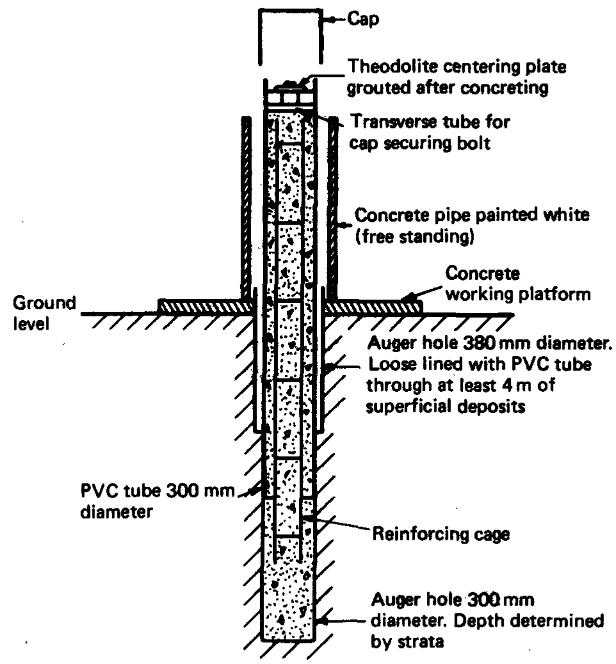


Figure 12.8. Horizontal control station for a theodolite (after Burland and Moore, 1974).

isolated by using a coating of asphalt or silicon grease wrapped with aluminum foil, instead of casing, to break the soil/rod bond. However, casing appears to provide a more positive method of bond breaking.

It is good practice to install three benchmarks and to survey between them on a regular basis, thereby identifying any vertical movement of a particular benchmark. If existing deep "benchmarks" are being considered, their details should be evaluated carefully, since they may not be designed to isolate the inner pipe or rod from soil movements.

Horizontal Control Stations

Reference datums for horizontal movements require a pedestal with a force centering device in the top for attaching a target and theodolite or electronic distance measuring device. The pedestal should be designed to prevent tilting and should be located below the seasonal movement zone. Figure 12.8 shows a horizontal control station with a force centering plate for the theodolite. The white concrete pipe around the upper part of the pillar shields it from the sun, since differential heating of the pillar can cause considerable apparent movement.

It is generally wise to use a horizontal control station that is at about the average elevation of the project. This eliminates the need for datum reduction computations.

There have been cases where horizontal control stations installed on river banks have moved inward; thus, the distance between such stations should be checked occasionally.

Inverted pendulums (Section 12.9.2) can also be used as horizontal control stations.

12.2.12. Measuring Points for Monitoring Surface Deformation

The term *measuring point* is used in this book for a point that may move. The term *observation point* can also be used. The word *benchmark* is sometimes used for a point that may move, but this use is incorrect: as discussed in the previous section, a benchmark is an immovable reference datum.

Measuring points may be located on structures or on the ground surface. The primary requirement is for stable and robust points that will survive throughout their required life. Temporary points that are later replaced by permanent points should be avoided, as they tend to be easily damaged and errors may occur when converting to the permanent points. Measuring points must have a clearly identified mark or surface to which each measurement is made. For example, for optical leveling, a machined hemispherical corrosion-free seat should be provided for the rod. Measurements of horizontal deformation may require filed cross-lines on the head of the measuring point. For procedures using a theodolite, force centering trivets may be used to produce repeatable centering of the instrument.

Various surface measuring points are described in this section. Measuring points for monitoring subsurface deformation are described in later sections of this chapter.

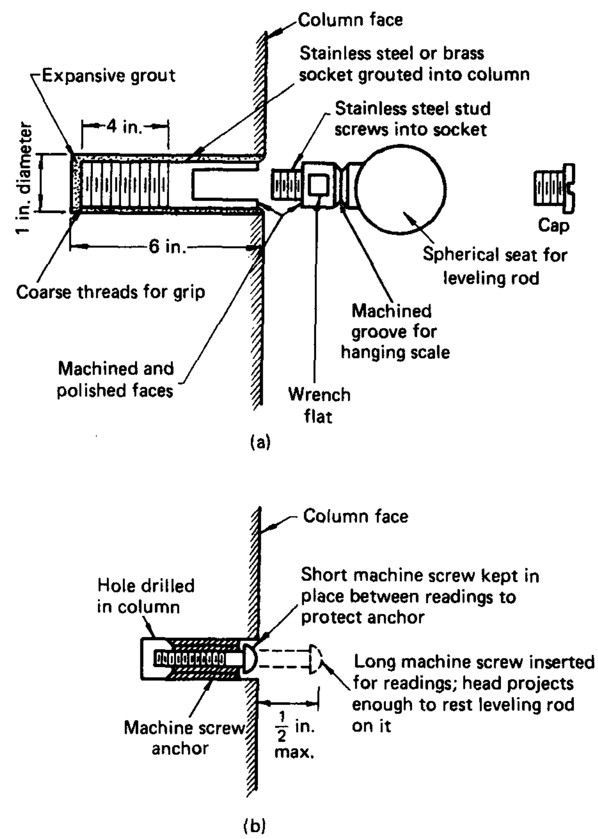


Figure 12.9. Measuring points on structures, suitable for use with optical leveling: (a) for precise work and (b) for less precise work (after Cording et al., 1975).

Measuring Points on Structures

Measuring points on structures may be simple 0.375 in. (10 mm) diameter by 2 in. (50 mm) long nickel plated steel carriage bolts cemented into shallow holes, using an epoxy-bonded patching compound. They can be used for both horizontal and vertical deformation measurements. Alternatively, bolts can be attached by using one of the proprietary powder actuated or expansion anchoring systems.

Figure 12.9 shows two types of measuring point for use while optical leveling on vertical surfaces. Permanent scales may also be attached to structures for elevation or offset measurements.

Measuring Points on Surface of Ground

When measurements of ground surface movement are required, it is generally necessary to seat the measuring point below the zone of frost heave and seasonal moisture changes. Cycles of shrinkage and swell in clay under grass-covered fields have been observed to cause vertical movements to depths of 15 ft (5 m) or more in severe climates and in expansive soils. Bozozuk et al. (1962) indicate that in the plastic Leda clay near large elm trees, vertical movements have been measured varying from 3 in. (80 mm) at the ground surface to 0.5 in. (13 mm) at a depth of 14 ft (4 m).

If the purpose is to monitor surface settlement caused by excavation, and the surface has structural strength, the measuring point must be seated below the surface. For example, when monitoring the settlement trough caused by tunneling below a concrete pavement, use of paint marks on the pavement can be misleading.

A typical measuring point for monitoring settlement of the ground surface is shown in Figure 12.10. Alternatively, a shallow subsurface settlement point (Section 12.7.6) can be used. Figure 12.11 shows a typical measuring point for monitoring settlement on the surfaces of embankment dams. Wilson (1967) describes a measuring point (Figure 12.12) with a vernier gage and movable target for use with a theodolite when measuring horizontal deformation of the surfaces of embankment dams. Other ground surface measuring points are described by Burland and Moore (1974).

Control stakes, also referred to as *alignment stakes, displacement stakes, toe stakes, reference stakes,* and *slope monitoring stakes,* are used in highway and other work for monitoring offsets from a baseline. An example is shown in Figure 12.13. A more rugged steel construction can be used in an

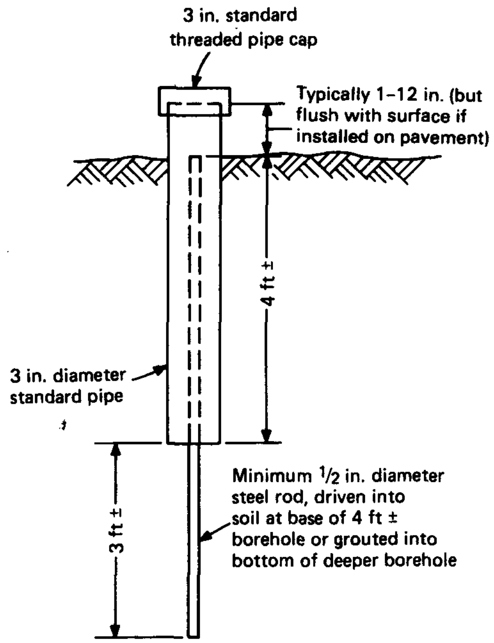


Figure 12.10. Measuring point on ground surface, suitable for use with optical leveling.

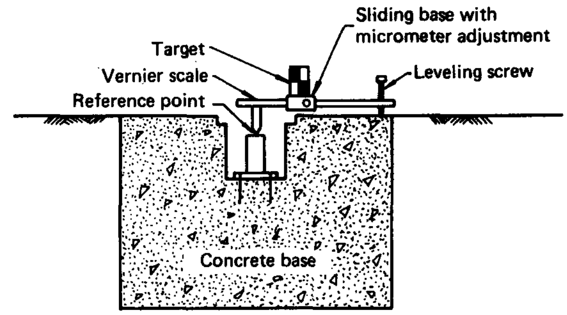


Figure 12.12. Measuring point on surface of embankment dam, with vernier gage and target, for monitoring horizontal deformation (after Wilson, 1967).

attempt to resist vandalism, and stakes can be set in concrete below frost penetration depth to minimize frost-induced movements. Wherever feasible, stakes should be installed in a straight line, so that significant movements can be detected easily and approximate measurements of offsets made by reading the scale with binoculars or a survey instrument. A scale can also be marked on or attached to the vertical lumber for monitoring settlement. Problems in using control stakes include vandalism, disturbance owing to construction activities, and lack of precision. In addition, when movement is discerned it is often "too late." Therefore, control stakes should be used with caution.

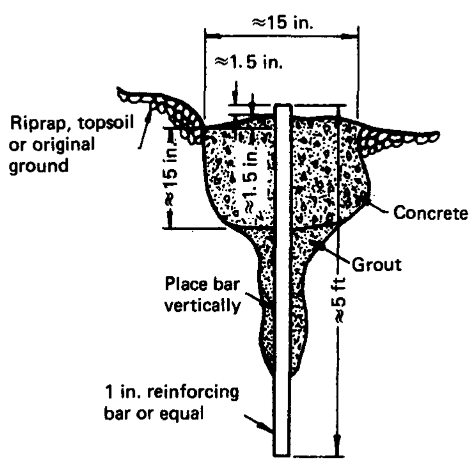


Figure 12.11. Measuring point suitable for monitoring settlement on surfaces of embankment dams (after USBR, 1974; courtesy of Bureau of Reclamation).

12.3. SURFACE EXTENSOMETERS

Surface extensometers are defined in this book as devices for monitoring the changing distance between two points on the surface of the ground or a structure. They may also be used for monitoring changing distances between two points on the surface of an excavation. Surface extensometers can be divided into two categories: *crack gages* and *convergence gages*.

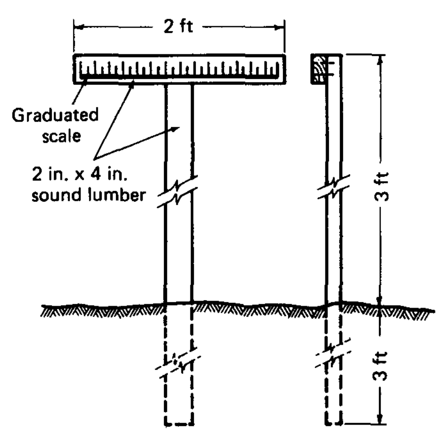


Figure 12.13. Typical control stake.

Table 12.3. Mechanical Crack Gages

Method	Advantages	Limitations	Approximate Precision
Wooden wedges	Inexpensive Can be used by all personnel	Qualitative only Interpretation unreliable	Crude
Glass plates or plaster patches	Inexpensive	Usually qualitative only	±0.05 in. (±1 mm)
Pins and tape	Inexpensive		±0.1 in. (±3 mm)
Pins and steel rule	Inexpensive	Span limited	±0.02 in. (±0.5 mm)
Pins and calipers	Inexpensive	Span limited	±0.01 in. (±0.3 mm)
Pins and tensioned wire, using weight	Inexpensive Can be adapted to trigger alarm		±0.1 in. (±3 mm)
Pins and mechanical extensometer			±0.005 in. (±0.1 mm)
Convergence gages	See Section 12.3.3	See Section 12.3.3	±0.001–0.1 in. (±0.03–3 mm)
Grid crack monitor	Inexpensive	Span limited	±0.05 in. (±1 mm)
Mechanical strain gage		Span limited	±0.0001–0.002 in. (±0.003–0.05 mm)
Dial indicator	Inexpensive	Span limited	±0.0001–0.001 in. (±0.003–0.03 mm)

Crack gages (sometimes called *jointmeters* or *strainmeters*) are typically used for monitoring tension cracks behind slopes and for monitoring cracks in concrete or other structures, pavements or tunnel linings, or joints or faults in rock. Observations of fracturing on a rock surface can provide useful information concerning behavior at depth, and surficial monitoring is usually far less expensive than borehole instrumentation or other techniques for subsurface monitoring.

Convergence gages are typically used for monitoring convergence within tunnels, braced excavations, and mines.

12.3.1. Mechanical Crack Gages

There are numerous mechanical devices available for monitoring the width of discontinuities (e.g., cracks, faults, and joints). The most common methods are described in the following subsections, and comparative information is given in Table 12.3. All methods require access to the gage location for monitoring.

Wooden Wedges

The use of wooden wedges driven into open fractures, and observing when wedges loosen, has been a traditional method used by mining personnel to indicate deformation, but more definitive techniques are usually required.

Glass Plates

The method consists essentially of cementing glass plates across discontinuities and observing breakages. Glass plates, usually about 3 × 1 × 0.1 in. (76 × 25 × 2.5 mm) thick, are cemented to the cleaned and roughened surface using epoxy resin adhesive. The observations are supplemented as necessary by measurement and recording of crack separation and direction of relative movement. Details of the procedure are described by ISRM (1984).

Plaster Patches

Gypsum plaster, which is brittle, is applied across discontinuities with a flat trowel, and observations are made as described above for glass plates.

Pins and Tape

A pin is set on each side of a discontinuity and separation monitored using a steel tape. The type and dimensions of the pins and the fixing system to be used should be appropriate to the condition of the ground or structure to be monitored, to ensure that the pins are rigidly attached to the surface and will remain attached throughout the monitoring program.

When the surface is strong rock or concrete, unaffected by local cracking, pins are typically 1 in. (25 mm) long and 0.25 in. (6 mm) in diameter with a tapered point at one end and a welded base at the other. Epoxy resin is used to fix the base to the surface, or holes can be drilled in the base and a concrete rivet gun used.

For soils or soft rocks, pins 20 in. (500 mm) long and 0.5 in. (13 mm) in diameter are typically used where they are to be driven into the formation. Alternatively, pins may be installed by grouting into a drilled hole. The exposed ends should be pointed or alternatively have filed cross-lines on flat heads.

Details of the installation methods are given by ISRM (1984), including equipment description, installation of pins, and reading and calculation procedures.

Pins and Steel Rule or Calipers

Pins are set as described previously and separation monitored using a steel rule or calipers. Measurements are more precise than when using a tape, but the span is limited.

Pins and Tensioned Wire, Using Weight

Figure 12.14 illustrates the use of a pin and tensioned wire gage for monitoring tension cracks at the top of a rock slope. A wire is stretched across the discontinuities between an anchor on one side and a pulley mounted on a measurement station on the other side. A weight on the wire below the pulley maintains tension. A scale is attached to the measurement station behind the wire, and a measurement block is fixed to the wire. Observation of the position of the measurement block with respect to the scale provides movement data. A trip block can be added to the wire, arranged to contact a trip switch on the scale when a predetermined movement occurs. This can be connected to an alarm if required.

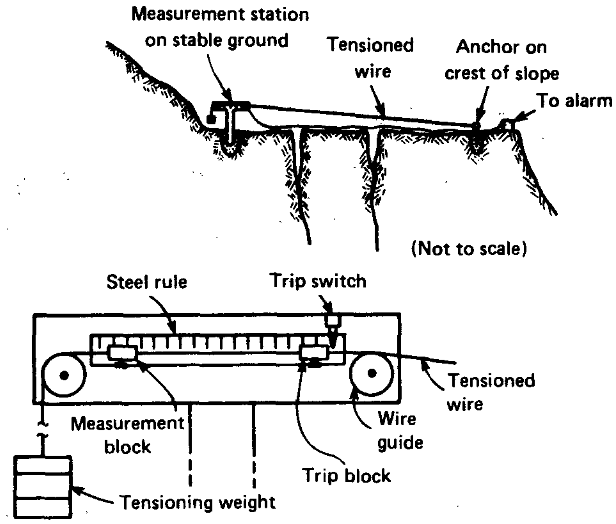


Figure 12.14. Mechanical crack gage, using pins and tensioned wire (after Hoek and Bray, 1981).

Pins and Mechanical Extensometer

Where greater precision is required and the span is too large for a steel rule or calipers, a *slack-wire* mechanical extensometer indicator (Section 12.7.4) can be used to measure the distance between pins, as shown in Figure 12.15. A 100 ft (30 m) steel tape with punched holes 1.5 in. (38 mm) apart can be used for measurement of any span. Alternatively, a length of 0.05 in. (1.3 mm) diameter stainless steel wire can be used for measuring a designated span, with a stainless steel button attached at each end of the wire by stainless steel set screws.

Convergence Gages

Mechanical tape, wire, rod, or tube convergence gages (Section 12.3.3) can be used as mechanical crack gages by attaching anchors to either side of the discontinuity.

Grid Crack Monitor

The *grid crack monitor,* also called a *calibrated crack monitor* and *calibrated telltale,* consists of two overlapping transparent plastic plates, one mounted on each side of the discontinuity. As shown in Figure 12.16, crossed cursor lines on the upper plate overlay a graduated grid on the lower plate. Movement is determined by observing the position of the cross on the upper plate with respect to the grid.

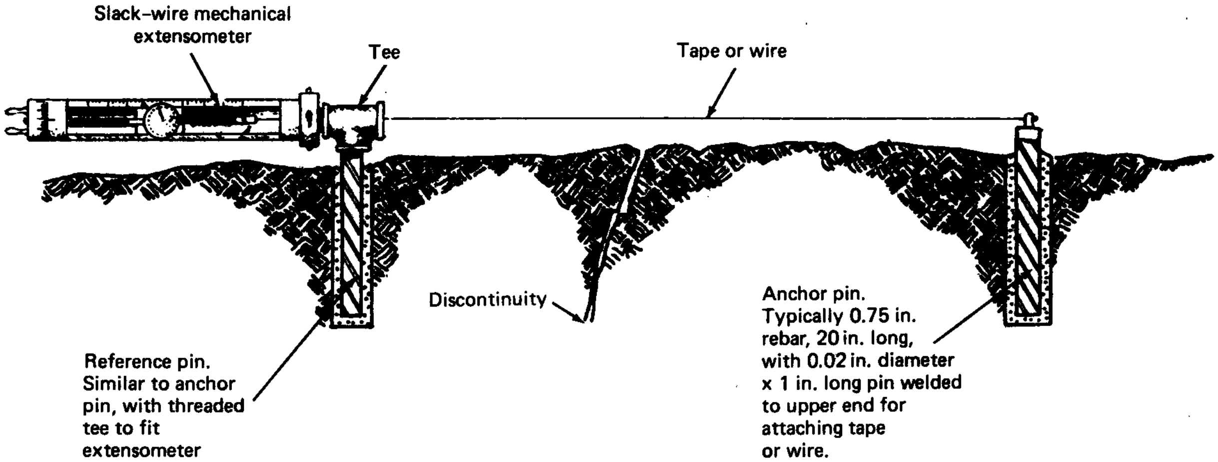


Figure 12.15. Mechanical crack gage, using pins and mechanical extensometer (after Yu, 1983; courtesy of *Canadian Mining Journal* and Kidd Creek Mines Ltd.).

Mechanical Strain Gage

Surface-mounted mechanical strain gages (Chapter 13) can be used for measurements across discontinuities.

Dial Indicator

A dial indicator can be attached temporarily or permanently to a bracket on one side of the discontinuity and arranged to bear against a machined reference surface on the other side. Three-axis versions are also available for measurements in orthogonal directions. Portable micrometers can be used instead of dial indicators.

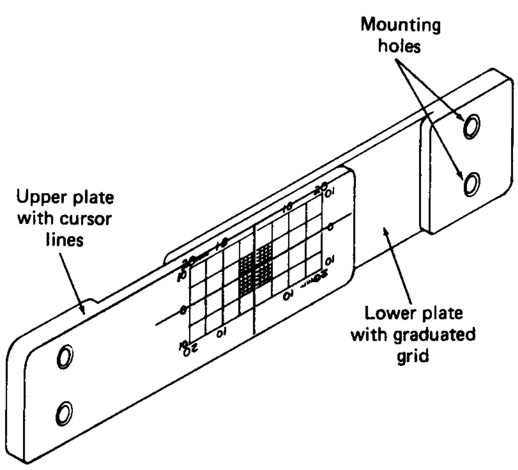


Figure 12.16. Grid crack monitor (courtesy of Avongard Products, U.S.A. Ltd., Waukegan, IL).

12.3.2. Electrical Crack Gages

When access to the gage location is not available for monitoring, or when continuous monitoring is needed, a remote reading electrical gage is required.

Three general arrangements are possible. First, an electrical linear displacement transducer can be attached to a bracket on one side of the discontinuity and arranged to bear against a machined reference surface on the other side. Second, anchor points can be located on either side of a discontinuity and the transducer attached to the anchor points via ball joints, as shown in Figure 12.17. Details of this arrangement, including instrument description, anchor point installation procedure, and reading and calculation procedures, are given by ISRM (1984). Third, an electrical linear displacement transducer can be incorporated in the mechanical system shown in Figure 12.14.

Available transducers (Chapter 8) include linear potentiometers, linear variable differential transformers (LVDTs), direct current differential transformers (DCDTs), variable reluctance transducers (VRTs), vibrating wire transducers, bonded and unbonded resistance strain gage transducers, and transducers with frequency-displacement induction coils. A magnetostrictive convergence gage, described in Section 12.3.3, can also be used as an electrical crack gage.

A single gage can be installed to monitor deformation perpendicular to the discontinuity, or a three-axis version can be used for measurements in orthogonal directions.

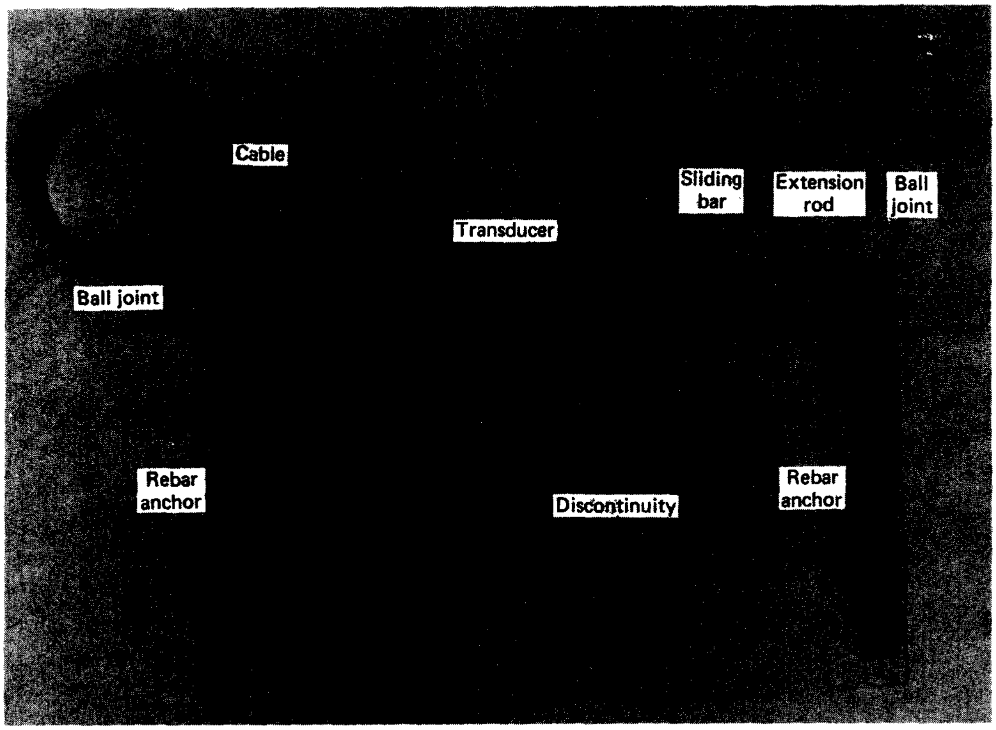


Figure 12.17. Electrical crack gage (courtesy of Irad Gage, a Division of Klein Associates, Inc., Salem, NH).

Electrical crack gages are more expensive than mechanical gages, and their range is limited. However, range can usually be extended by resetting. Precision is between ±0.0001 and 0.005 in. (±0.003 and 0.13 mm), depending on the transducer. Also depending on the transducer, readings can be affected by lead wire changes and by temperature and other environmental conditions.

12.3.3. Convergence Gages

A *convergence gage* usually consists of a tape, wire, rod, or tube in series with a deformation indicator. The gage is usually portable and is attached at the time of reading to permanent anchors mounted at each end of the measuring span. The most common gage types are described below.

Protective covers should be provided for anchors. The stability of all gages should be checked on a regular schedule, either by using a calibration frame supplied by the manufacturer or by reading a span that is known to be stable. The latter is preferable, because it provides a check on the complete gage rather than merely the part containing the deformation indicator.

Tape Convergence Gages

A typical *tape convergence gage,* often called a *tape extensometer,* is shown in Figure 12.18. The tape has punched holes at 2 in. (50 mm) intervals. Grouted rebar and expansion shell anchors are shown, but anchors can be welded or bolted. The tension in the tape is controlled by a compression spring, and to standardize tension the collar is rotated until the scribed lines are in alignment. After attachment of the extensometer to the anchors and standardizing the tension, readings of distance are made by adding the dial indicator reading to the tape reading. Precision is typically ±0.005 in. (±0.13 mm) in a 30 ft (10 m) span, decreasing with increasing span. Maximum span is approximately 200 ft (60 m).

Wire Convergence Gages

Conventional portable *wire convergence gages,* or *wire extensometers,* are similar to portable tape convergence gages. Either a separate wire can be used for each span or the wire can be equipped with a series of collars to accommodate variation in span. Precision with conventional steel wires is

Figure 12.18. Tape extensometer (courtesy of Slope Indicator Company, Seattle, WA).

similar to precision of tape convergence gages and can be improved by using an invar wire: a 10°C temperature increase causes an expansion in a 10 ft (3 m) invar wire of approximately 0.002 in. (0.05 mm).

A precise invar wire convergence gage, the

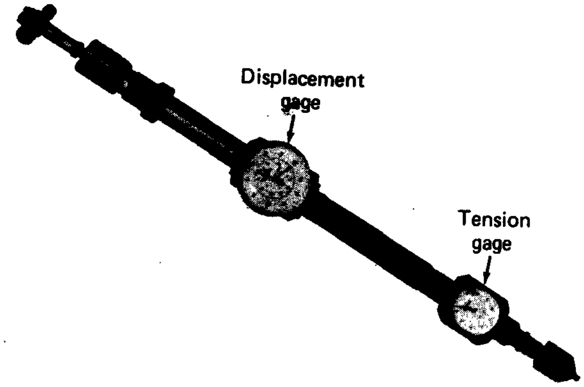


Figure 12.19. ISETH Distometer (courtesy of Kern Instruments, Inc., Brewster, NY).

ISETH Distometer (Figure 12.19), has been developed in Switzerland by the Federal Institute of Technology, Zürich (Kovari et al., 1974). Individual lengths of invar wire are used for each span. Precision is ±0.001 in. (±0.03 mm) for spans up to 60 ft (20 m) and ±1/1,000,000 of the distance for longer spans up to 150 ft (50 m). An alternative invar wire convergence gage, the *Distomatic* (Figure 12.20), is widely used in France (Londe, 1977). The wire is tensioned by an electric motor, actuating an electronic limit switch at the required standard tension. The motor is geared to a counter and the reading displayed digitally. Precision is reported to be ±0.001 in. (±0.03 mm) over a 20 ft (6 m) span and ±0.002 in. (±0.05 mm) over an 80 ft (25 m) span.

All the wire convergence gages described above

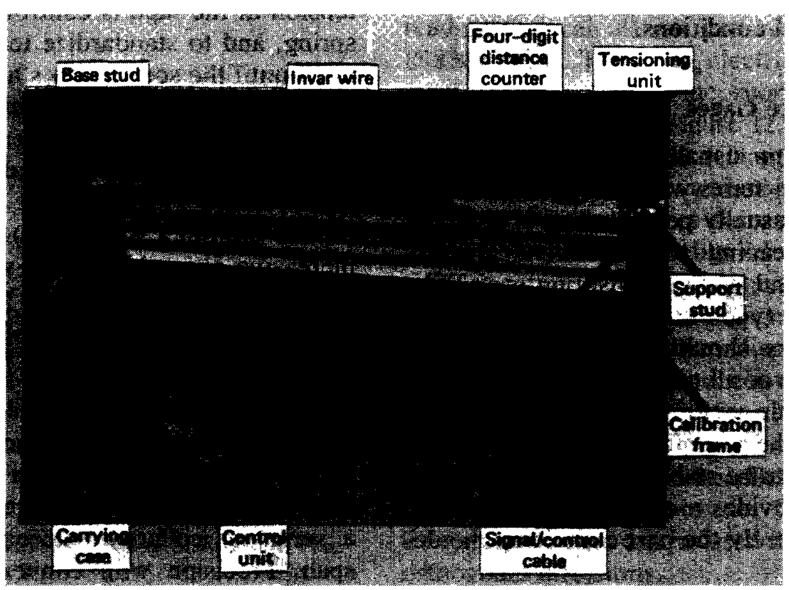


Figure 12.20. *Distomatic* convergence gage (courtesy of Telemac, Asnières, France).

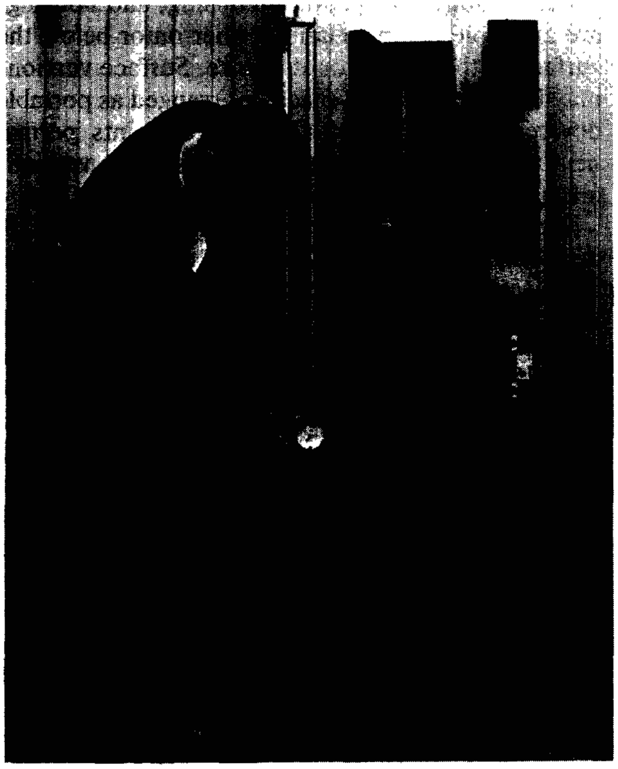


Figure 12.21. Invar tube convergence gage (courtesy of Soiltest, Inc., Evanston, IL).

are portable. The arrangement shown in Figure 12.14, using a tensioned wire and a pulley, can be adapted for use as a convergence gage, using either a mechanical or electrical transducer.

Rod and Tube Convergence Gages

Rod and *rigid tube convergence gages* generally consist of telescoping rods or rigid tubes, a dial indicator or micrometer, and contact seats that mate with anchors. Some gages have invar rods or tubes, others have aluminum or galvanized or stainless steel for which a temperature correction can be applied to maximize precision. Range of span, depending on the model, is 6 in. to 25 ft (150 mm to 8 m). The telescoping arrangement is often spring loaded. Figure 12.21 shows a gage with telescoping invar tubes, placed in its calibration frame. Stacey and Wrench (1985) describe a gage with telescoping stainless steel tubes and a vernier scale.

These gages are alternatives to tape or wire gages for vertical spans in tunnels and mines where access to the upper anchor is inconvenient, and for vertical spans precision is typically ± 0.005 in. (± 0.13 mm).

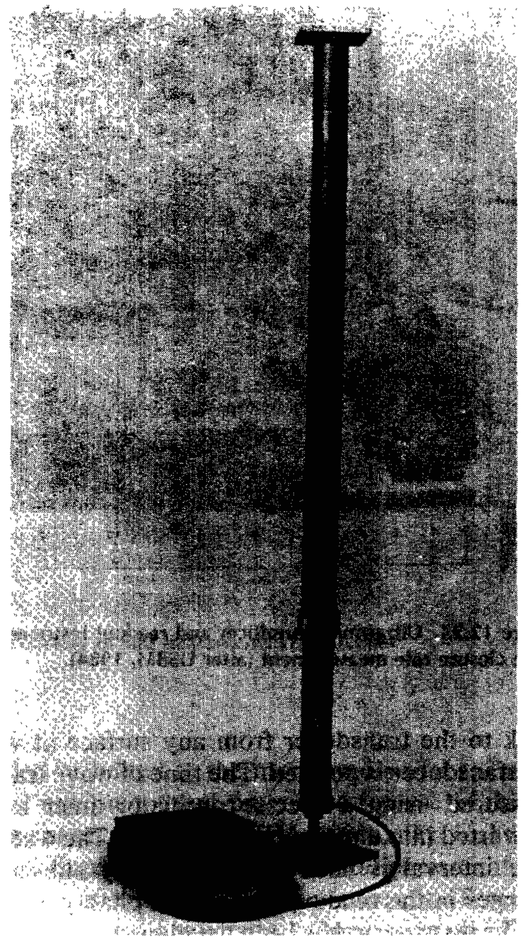


Figure 12.22. Fixed-in-place tube convergence gage (courtesy of Roctest Ltd., Montreal, Canada).

However, precision of horizontal or inclined spans is reduced by sag and for spans greater than 10 ft (3 m) may be as low as ± 0.1 in. (± 3 mm).

Rod and tube convergence gages are also available with electrical displacement transducers for remote reading, both as fixed-in-place and portable instruments. Figure 12.22 shows a fixed-in-place instrument.

Ultrasonic Convergence Gage

USBM (1984) reports on the recent development of an *ultrasonic convergence gage*. As shown in Figure 12.23, the gage consists of a transducer and a readout device. The small ultrasonic transducer, similar to an audio speaker diaphragm, is plucked with an ultrasonic frequency every 6 seconds. This frequency wave is sent through the air and reflected

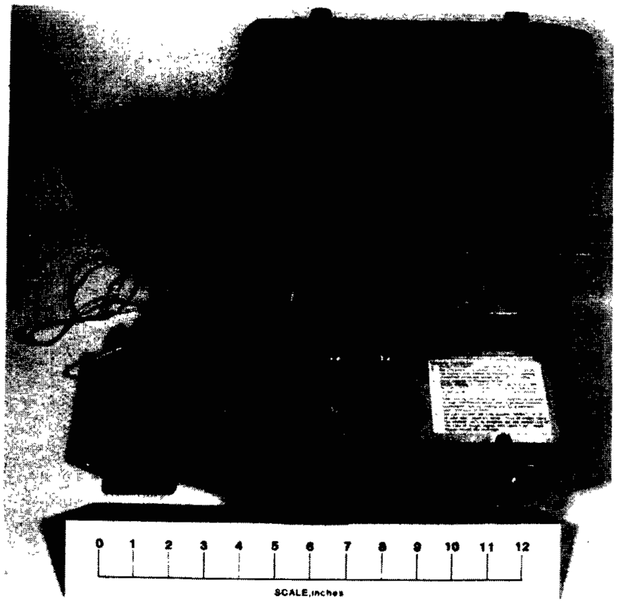


Figure 12.23. Ultrasonic transducer and readout instrument for mine closure rate measurement (after USBM, 1984).

back to the transducer from any surface at which the transducer is pointed. The time of wave travel is measured using a precise oscillator/timer and is converted into a measure of distance. The 6 second time interval is used to convert any subsequent changes in the reading to a rate of change.

The instrument has been developed to provide an unobstructive means of measuring changes in distance from roof to floor or from rib to rib of a mine opening and to indicate the rate of closure so that operators of underground mines can detect hazardous ground conditions. Based on use to date, USBM comments that a convergence of 0.5 in. (13 mm) can readily be measured, but the instrument is not capable of measuring a convergence of less than 0.05 in. (1.3 mm). Range is 1–35 ft (0.3–11 m), and alarm settings can be included. The device is therefore most applicable for measuring convergence during longwall mining, pillar robbing, and other mining operations resulting in large ground movements.

12.4. TILTMETERS

Tiltmeters, also referred to as *clinometers,* are used to monitor the change in inclination (rotation) of points on or in the ground or a structure.

A tiltmeter consists of a gravity-sensing transducer within an appropriate housing, and housings are available for installation either on or below the surface of the ground or structure. Surface versions may be either fixed-in-place or arranged as portable devices by mating with reference points permanently attached to the surface. Subsurface versions are usually fixed-in-place within boreholes.

Applications of tiltmeters include monitoring tilt of retaining walls and concrete dams and monitoring landslides in which the failure mode can be expected to contain a rotational component. Very precise tiltmeters can sometimes be used during a short time period to provide a rapid indication of deformation trends. They are also used for monitoring ground subsidence over mined areas, and tiltmeters are available for detecting earthtides and other geodetic or seismic events. Tiltmeters have been used for monitoring safety of buildings alongside excavations in an attempt to provide forewarning of distress, but unless a rotational component of deformation is expected, settlement measurements are likely to be more meaningful.

The precision of a tiltmeter is normally expressed in radians, arc-seconds, or gons. Conversion factors are given in Appendix H.

12.4.1. Mechanical Tiltmeters

Figure 12.24 shows a mechanical tiltmeter consisting of a beam and bubble level, similar to a builder's level, with a leveling adjustment at one end of the beam. The beam is located on two anchored reference balls, the leveling adjustment turned until the bubble level indicates that the beam is in a horizontal plane, and a dial indicator or micrometer inserted through the leveling adjustment to bear on the reference ball. Relative movements in the vertical plane are recorded as changes in dial indicator readings. Errors caused by zero shift are accounted for by reversing the tiltmeter, repeating the readings, and averaging. Precision is approximately ± 0.0005 in. (± 0.013 mm) for beams up to 8 in. (200 mm) long, decreasing to ± 0.005 in. (± 0.13 mm) for beams 3 ft (900 mm) long. These figures correspond to ± 13 and 29 arc-seconds. Similar tiltmeters are available for monitoring tilt of near-vertical surfaces.

12.4.2. Tiltmeters with Accelerometer Transducer

A portable tiltmeter for measuring tilt in both a horizontal and vertical plane is shown in Figure 12.25.

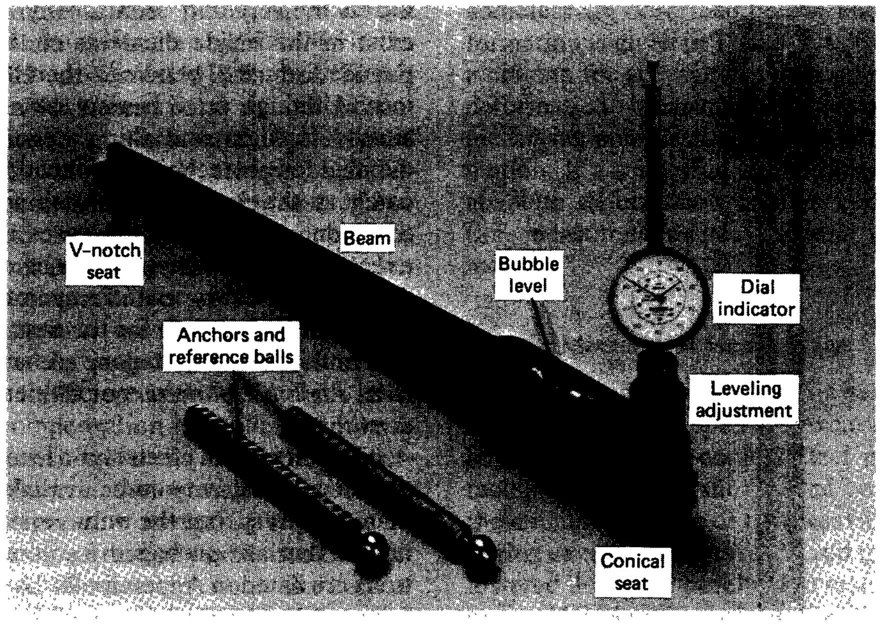


Figure 12.24. Mechanical tiltmeter (*portable clinometer*) (courtesy of Soil Instruments Ltd., Uckfield, England).

A measurement is made by placing the tiltmeter in an exactly reproducible position on a reference plate, taking a reading, turning the tiltmeter 180 degrees, and again taking a reading. This method allows use of the *check-sum* procedure described for inclinometers in Section 12.8. The reference plate is either metallic or ceramic and must be securely bonded or bolted to the monitored surface. Details of the equipment and procedure for use of this instrument are given by ISRM (1981a). Typical range is ±30 degrees from the horizontal or vertical, and precision is typically ±50 arc-seconds. Temperature sensitivity is typically 2–3 arc-seconds/°F.

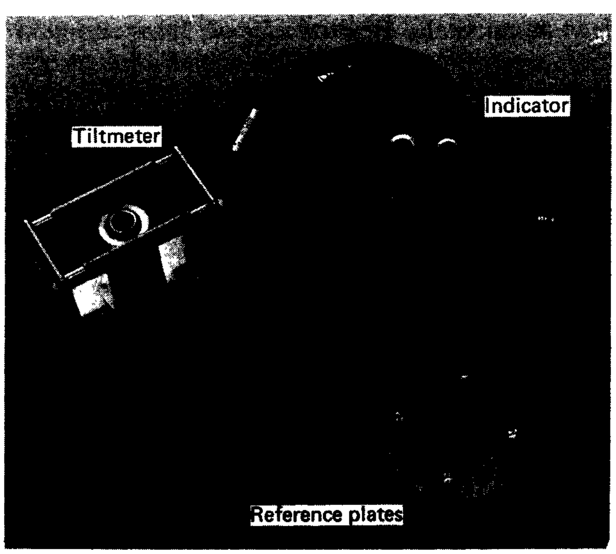


Figure 12.25. Tiltmeter with accelerometer transducer (courtesy of Slope Indicator Company, Seattle, WA).

A more precise portable tiltmeter with accelerometer transducer, referred to as a *clinometer*, is available from Solexperts AG. The instrument is used for measuring tilt in both horizontal and vertical planes, and measurements are made using the *check-sum* procedure. The standard range is approximately ±3 degrees from the horizontal or vertical, and tests by Thut (1987) indicate a precision of less than ±1 arc-second. It is believed that this high precision can be attributed to the highly repeatable mating arrangement between the portable instrument and the reference plate.

12.4.3. Tiltmeters with Vibrating Wire Transducer

Pendulum-actuated vibrating wire transducers are available for attachment to the face of a structure or for embedment below the surface of the ground or structure.

Two configurations are available. First, a pendulum is rigidly attached to the top of the tiltmeter such that tilt causes bending strains in the pen-

Figure 12.26. Tiltmeter with vibrating wire transducers (courtesy of Telemac, Asnières, France).

dulum, and the strains are monitored by two vibrating wire transducers, one on each side of the pendulum in the plane of tilting. Figure 12.26 shows an example. Alternatively, four transducers can be spaced around the pendulum for monitoring tilt in two vertical planes 90 degrees apart. In the second configuration the vibrating wire transducers span between the pendulum and the instrument housing. Whenever transducers are mounted on opposite sides of the pendulum, in either configuration, tilting causes equal and opposite strains in the two transducers, and temperature effects are eliminated. However, the instruments are usually bulky and heavy. Ranges of available tiltmeters typically vary from ±0.1 to 1 degree, with precision approximately 0.5% of range, that is, ±2–20 arc-seconds

12.4.4. Tiltmeters with Electrolytic Level Transducer*

Electrolytic level transducers (Chapter 8) can be grouped into two categories. In the first category the glass vial is made simply by sealing the ends of a standard glass tube, softening the glass, and bending to the required radius. Any irregularities that exist in the inside diameter of the tube are compounded during bending; therefore, accuracy is low. Although price is also low, temperature sensitivity is high, and this category is not recommended for geotechnical applications. In the second category the vial is made with a vacuum forming technique that greatly increases accuracy because exact internal dimensions can be controlled and reproduced in every vial. Temperature sensitivity is significantly less than for the first category. Tiltmeters in this second category are sometimes referred to as *earthtide tiltmeters* or tiltmeters with *geodetic sensitivity*.

Tiltmeters with electrolytic level transducers and geodetic sensitivity are available from several manufacturers, but the only versions known to the author that are packaged for geotechnical applications are listed in Appendix D. The tiltmeters manufactured by Applied Geomechanics, Inc. (for surface and downhole use), Sperry Corporation (for surface use), and G + G Technics (for surface and undersea use) all incorporate a transducer manufactured by Spectron Glass and Electronics, Inc., Hauppauge, NY. The *Sperry Tilt Sensing System,* shown in Figure 12.27, is manufactured with ranges from ±20 arc-minutes to ±45 degrees. A console and recorder are available for monitoring multiple tiltmeters, and threshold levels can be set individually to provide hazard warning. Use of the Sperry Tilt Sensing System is described by Cape (1984) and ENR (1984).

Tests made on the Sperry Tilt Sensing System by New York State Department of Transportation

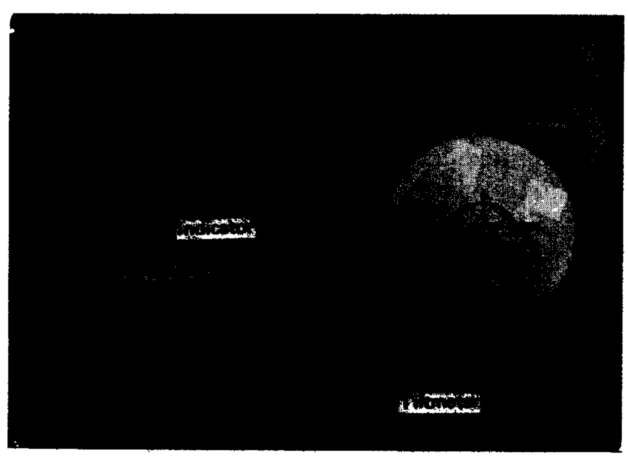


Figure 12.27. Sperry Tilt Sensing System (courtesy of Sperry Corporation, Phoenix, AZ).

*Written with the assistance of Robert S. Marshall, President, Spectron Glass and Electronics, Inc., Hauppauge, NY.

(Gemme, 1984) indicate that the version with a range of ±20 arc-minutes has a repeatability in the laboratory of ±0.3 arc-seconds. Holhauzen (1985) states that in stable underground vault environments, the tiltmeter manufactured by Applied Geomechanics, Inc. consistently achieves a stability of ±0.3 arc-seconds or better during tests of 3 or 4 days. Firm figures for longer-term repeatability in a field environment do not appear to be available.

Temperature compensation of tiltmeters with electrolytic level transducers and geodetic sensitivity can be provided by including a thermistor with the same thermal coefficient as the electrolytic level transducer, but compensation is applicable only to uniform temperature conditions. When the temperature of the transducer and mounting arrangements is nonuniform, temperature sensitivity is greatly increased, and mounting arrangements should therefore be designed to average any nonuniformity of temperature or to allow temperatures to equalize quickly.

12.5. PROBE EXTENSOMETERS

Probe extensometers are defined in this book as devices for monitoring the changing distance between two or more points along a common axis, by passing a probe through a pipe. Measuring points along the pipe are identified mechanically or electrically by the probe, and the distance between points is determined by measurements of probe position. For determination of absolute deformation data, either one measuring point must be at a location not subject to deformation or its position with respect to a reference datum must be determined by surveying methods. The pipe may be vertical, providing measurements of settlement or heave, may be horizontal, providing lateral deformation measurements, or may be inclined.

Typical applications of probe extensometers are monitoring vertical compression within embankments or embankment foundations, settlement alongside excavations, heave at the base of open cut excavations, and lateral deformation of embankments. In general, they are alternatives to fixed borehole extensometers (Section 12.7), allowing for more measuring points and minimizing the cost of permanently installed materials, but generally measurements are less precise than fixed borehole extensometer measurements.

Various mechanical and electrical probe extensometers are described below, and comparative information is given in Table 12.4. Table 12.4 includes a column for accuracy, which refers to accuracy of deformation measurements, assuming that one measuring point is at a location not subject to deformation. If a surveying method is used to determine absolute deformation data, accuracy of deformation measurements may depend on the surveying method.

12.5.1. Mechanical Heave Gage

The gage is used for monitoring heave at the bottom of braced or other open cut excavations. As shown in Figure 12.28, a conical steel point is installed, facing upward, in a slurry-filled borehole just below the eventual bottom of the excavation. At any time during excavation, a probing rod of known length is lowered down the borehole to mate with the conical point. The elevation of the top of the rod is determined by surveying methods, giving the elevation of the conical point. The borehole can be located readily during construction by coloring the slurry with ethrysene dye. The gage is described by Swiger (1972). Bozozuk (1970) gives details of a similar gage, using a four-bladed steel vane at the bottom of the borehole.

12.5.2. Crossarm Gage

The crossarm gage was developed by the U.S. Bureau of Reclamation (Bartholomew et al., 1987; USBR, 1974) for installation during construction of embankment dams. As shown in Figure 12.29, it consists of a series of telescoping pipe sections with alternate sections anchored to the embankment by horizontal steel channel crossarms at 5–10 ft (1.5–3m) intervals. The crossarms ensure that the pipes move together an amount equal to compression of the intervening fill. Depths to the measuring point at the lower end of each interior pipe are sounded to the nearest 0.01 ft (3 mm) by a probe with spring-loaded sensing pawls, lowered on a steel tape. The probe is lowered just beyond each interior pipe in turn and raised until the pawls latch against the lower end. On reaching the bottom of the pipes, the pawls retract and lock within the body of the probe.

Installation details are described by USBR (1974) and require that most of the soil immediately surrounding the pipes be excavated and replaced by hand-compacted backfill. As each successive crossarm is placed, the elevation of a reference point on

Table 12.4. Probe Extensometers

Method	Advantages	Limitations	Approximate Accuracy[a]
Mechanical heave gage (Figure 12.28)	Inexpensive	Requires survey crew Risk of borehole caving during excavation	±0.2–1.0 in. (±5–25 mm)
Crossarm gage (Figure 12.29)	Crossarms ensure that axial deformations of pipe conform with deformations of soil Can accommodate large compression	Pawls in probe may jam Cannot be installed in boreholes Steel pipes can corrode Probe may become wedged if large lateral deformations occur Laborious to read Compaction difficult[b]	±0.05–0.2 in. (±1–5 mm)
Mechanical probe within inclinometer casing (e.g., Figure 12.30)	Simple When installed in fill, collars provide positive driving force to slide pipe Both vertical and horizontal deformations may be monitored[c]	Pawls in probe may jam If used in boreholes, axial deformations of casing may not conform with deformations of soil Laborious to read Compaction difficult[b]	±0.05–0.2 in. (±1–5 mm)
Sliding micrometer (Figure 12.31)	Very accurate Installation can be vertical or horizontal[c,d]	Very expensive Laborious to read	±0.0001 in. in 39 in. (±0.002 mm in 1 m)
Gage with current-displacement induction coil (e.g., Figures 12.32, 12.34)	Versions available for all site conditions Various installations possible[c,d,e]	Readings somewhat subjective Accuracy reduced by stray electric currents Compaction difficult[b]	±0.02–0.2 in. (±0.5–5 mm) for vertical installations ±0.02–1.0 in. (±0.5–25 mm) for horizontal installations
Gage with frequency-displacement induction coil (e.g., Figure 12.37)	Very accurate Various installations possible[c,d,e]	Compaction difficult[b]	±0.001 in. (±0.03 mm)
Magnet/reed switch gage (Figure 12.38)	Versions available for all site conditions Can be used as a heave gage at base of open cut excavations without interference to excavation Various installations possible[c,d,e]	Compaction difficult[b]	±0.02–0.2 in. (±0.5–5 mm) for vertical installations ±0.1–1.0 in. (±3–25 mm) for horizontal installations
Bellow-hose gage		Readings subjective No positive anchorage at measuring points Compaction difficult[b]	±0.1–0.3 in. (±3–8 mm)
Magnetostrictive gage (e.g., Figure 12.41)	Suitable for boreholes at all inclinations, including upward[d]	Reading depth limited to 25 ft (7.6 m) Requires careful handling	±0.002–0.01 in. (±0.05–0.3 mm)

[a] Accuracy refers to accuracy of deformation measurements, assuming that one measuring point is at a location not subject to deformation. If a surveying method is used to determine absolute deformation data, accuracy of deformation measurements may depend on the surveying method.
[b] When installed vertically through fill, large compaction equipment cannot be used near the pipe; thus, compaction tends to be inferior. Interruption to normal filling is costly, and damage by construction equipment is possible. Liquid level gages (Section 12.10) sometimes provide a preferable measurement method.
[c] Vertical installations can be combined with an inclinometer casing (Section 12.8) for monitoring both vertical and horizontal deformations.
[d] The instrument can be installed either horizontally or vertically.
[e] Horizontal installations can be combined with a full-profile liquid level gage (Section 12.10) for monitoring both horizontal and vertical deformations.

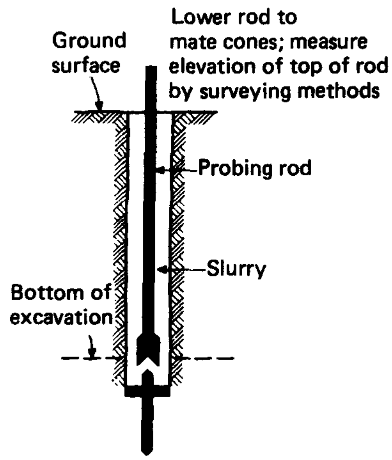


Figure 12.28. Schematic of mechanical heave gage.

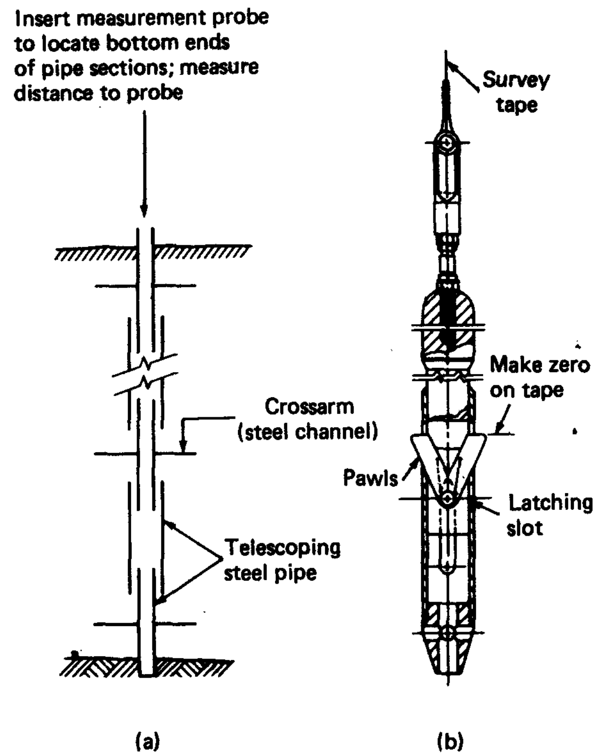


Figure 12.29. Crossarm gage: (a) Schematic of pipe arrangement and (b) measurement probe (after USBR, 1974; courtesy of Bureau of Reclamation).

the uppermost pipe section is determined to the nearest 0.01 ft (3 mm) by optical leveling.

For determination of compression between crossarms, the optical leveling error is eliminated and a precision of ±0.05 in. (±1.3 mm) can be obtained by applying a constant tension to the tape, using a pulley and counterweight.

The original version of the gage used 1.5 and 2 in. (38 and 51 mm) pipes, requiring a slender probe somewhat prone to malfunction and to becoming wedged in the pipes. Recent improvements include the use of 3–4 in. (76–102 mm) pipes, thus permitting the passage of a larger and more rugged probe than the original. Corrosion of the steel pipes has caused problems in some older installations, usually near the phreatic surface and especially in warmer climates and where soil conditions produce corrosive seepage water. Use of plastic pipe with a stainless steel ring at the measuring point on the lower end of each interior pipe could obviate the difficulty. Poor alignment of pipes or large lateral deformations have caused malfunctioning (Peters and Long, 1981), but a shorter probe can be tried if the standard probe will not pass down the pipes.

12.5.3. Mechanical Probe Within Inclinometer Casing

Measurements with a mechanical probe can be made in inclinometer casing connected with telescoping couplings (Section 12.8.3).

Vertical deformations are measured either with a probe similar to the crossarm gage probe or with a special hook supplied by some manufacturers of inclinometer casing (Figure 12.30). In embankments, the casing is forced to follow the pattern of soil compression by attaching settlement collars to its outside. If these are omitted, the telescoping action relies solely on friction between soil and the surface of the casing, and precision will be decreased if soil slips with respect to the section of casing it surrounds (Rosati and Esquivel, 1981). Settlement collars are not possible for borehole installations; thus, the telescoping of casing will not necessarily conform with soil compression, and data may not be correct.

12.5.4. Sliding Micrometer

A recent development by the Federal Institute of Technology, Zürich (Kovari and Amstad, 1982; Kovari et al., 1979), allows very accurate measurements of axial deformation to be made within a pipe. Measurements in soil and rock do not often merit such accuracy, and the primary application is for determination of axial and bending strains in

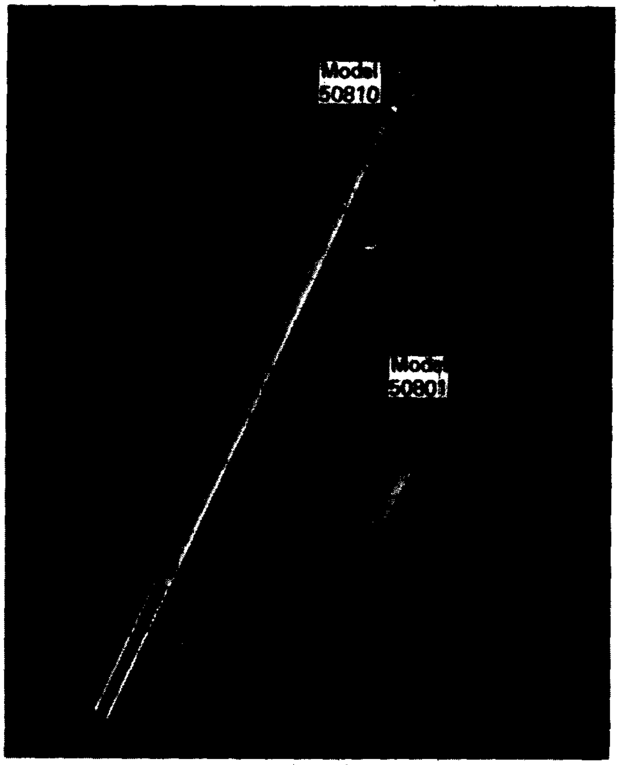


Figure 12.30. Mechanical probes for use within inclinometer casing (courtesy of Slope Indicator Company, Seattle, WA).

slurry walls, concrete piles, drilled shafts, and other concrete structures.

Figure 12.31 shows the basic arrangement. The pipe casing is either embedded directly within the concrete or grouted within a borehole. Cone-shaped measuring points are attached to the pipe casing at 1 m (39 in.) intervals, and the cones are fluted to allow passage of the probe. The probe (the *micrometer*) consists of a waterproof spring-loaded protective sleeve with fluted spherical ends and an invar tube and linear displacement transducer for measuring the distance between spherical ends. To take a set of measurements, the probe is attached to an installation rod, inserted within the pipe casing, the spherical ends mated with the first two cone-shaped measuring points, and a reading made. The probe is then rotated 45 degrees to allow the fluted spheres to pass through the fluted cones and relocated on the next pair of measuring points. The procedure is repeated to the end of the pipe casing, and a further set of readings is made during withdrawal, thus providing a check.

Precision of measurement between adjacent measuring points 1 m (39 in.) apart is reported to be ±0.0001 in. (±0.002 mm, ±2 microns), corresponding to ±2 microstrain. Temperature change problems have reportedly been eliminated through

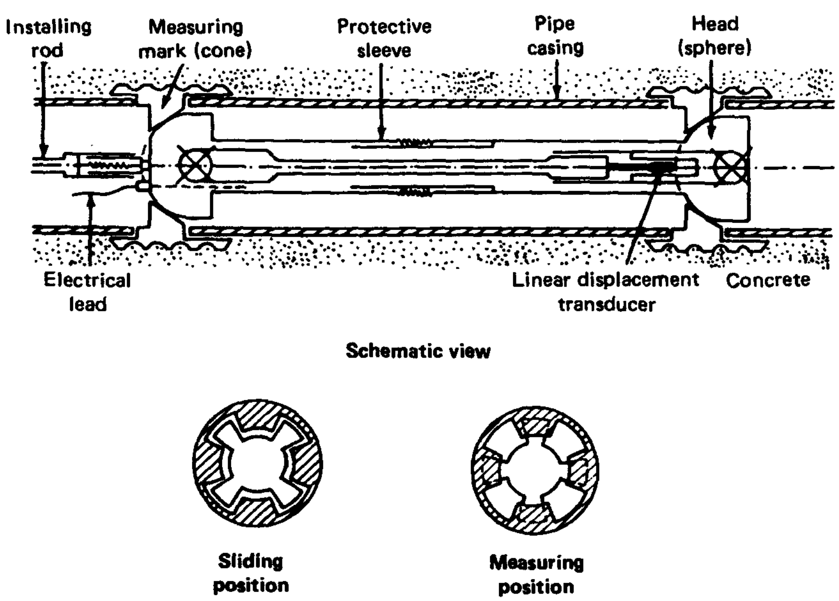


Figure 12.31. Sliding micrometer (after Kovari and Amstad, 1982). Reprinted by permission of the Institution of Civil Engineers, London.

self-temperature compensation, and the system is usable at any pipe orientation. A portable invar steel calibration frame is available to check the proper functioning of the instrument and its long-term stability.

The sliding micrometer is also available with a gravity-sensing transducer mounted within the probe, so that the system can also be used as an inclinometer (Section 12.8) for determination of the three orthogonal displacement vector components along a near-vertical borehole (Köppel et al., 1983). The instrument is supplied by Solexperts AG under the trade name *Trivec*.

12.5.5. Gage with Current-Displacement Induction Coil

Induction coil transducers with current output, described in Chapter 8, are used by several manufacturers of probe extensometers. The embedded part of the instrument consists of a telescoping pipe surrounded by steel rings or plates at the required measuring points. The reading device consists of a primary coil housed within a probe and an attached signal cable connected to a current indicator.

Depth measurements are made either with a survey tape attached to the probe or by using graduations on the signal cable: the former is very preferable because the cable can experience significant change in length during its life (Robinson, 1985). Use of a composite survey tape and signal cable is preferable (similar to the composite tape and cable shown in Figure 9.4 for use with an electrical dipmeter when reading open standpipe piezometers), allowing accurate measurements to be made without the need for dual lines running along the pipe. Readings are made by traversing the probe along the pipe and noting the tape graduation when output current is a maximum. Various arrangements for traversing the probe along horizontal pipes are described in Chapter 17. Changes in reading with time provide deformation or strain data, either in the horizontal or vertical direction.

For determination of absolute deformation data, either one steel ring or plate must be at a location not subject to deformation or its position with respect to a reference datum must be determined by surveying methods. The first option maximizes precision and is preferable. For borehole installations, the lowest measuring point should be placed at sufficient depth to serve as the reference datum, and precision can be maximized by installing three such measuring points and averaging readings.

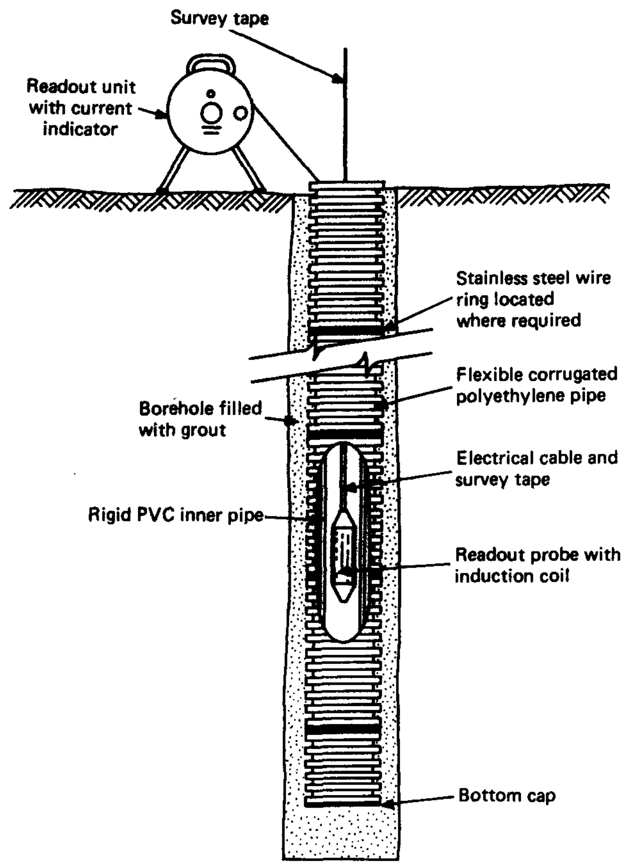


Figure 12.32. Schematic of Slope Indicator Company *Sondex* probe extensometer, installed in a borehole.

Two arrangements are possible for the embedded part of the instrument and are described in the following subsections.

Instrument with Corrugated Pipe and Steel Wire Rings

A corrugated polyethylene pipe, typically of 3 or 4 in. (76 or 102 mm) inside diameter, is surrounded by rings of stainless steel wire. A schematic of a borehole installation is shown in Figure 12.32 and a photograph in Figure 12.33. This arrangement can be installed either in a borehole or in fill but, as discussed later, the alternative arrangement with rigid plastic pipe, telescoping couplings, and steel plates is preferable for installations in fill.

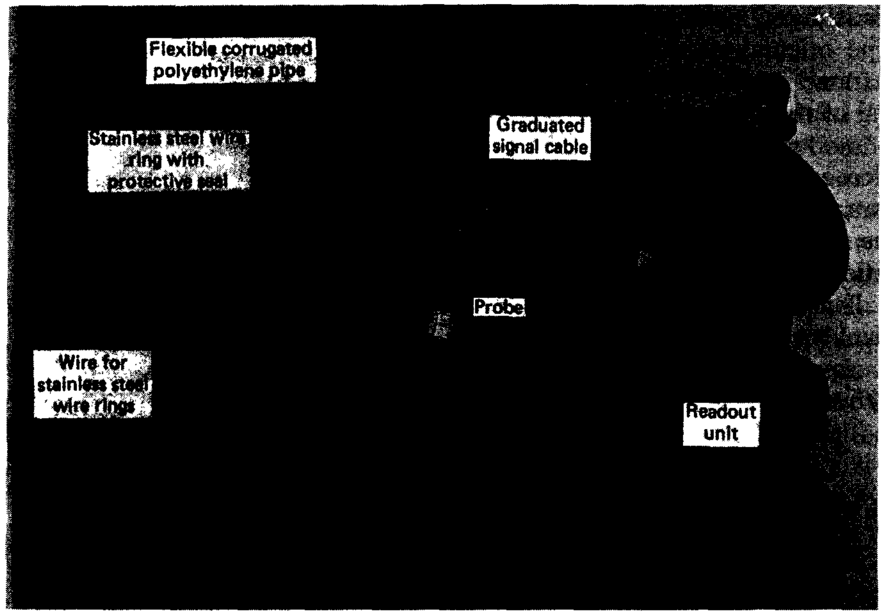


Figure 12.33. *Sondex* probe extensometer (courtesy of Slope Indicator Company, Seattle, WA).

Instrument with Rigid Plastic Pipe, Telescoping Couplings, and Steel Plates

Rigid PVC pipe, typically of 2.5 in. (63 mm) nominal diameter with telescoping couplings, is surrounded by steel plates when installed horizontally or vertically in fill or by expanding anchors when installed in a borehole. The steel plates are typically 12 in. (300 mm) square and 0.2 in. (5 mm) thick, each with a central hole. The version for horizontal installation in fill is described by Penman and Charles (1973), who refer to it as a *horizontal plate gage* (Figure 12.34).

For horizontal or vertical installations in fill, this arrangement is preferable to corrugated polyethylene pipe, because PVC pipe is more resistant to crushing and allows passage of the probe more easily. Steel plates are preferable to steel wire rings, as conformance with soil deformation is ensured.

A version of the gage, the *Idel Sonde,* uses a radio transmitter housed within the probe to transmit a signal when the probe passes a steel ring or plate. The primary use of the device has been in embankment dams, and it has generally not performed as well as the simpler and less expensive conventional version.

Precision

The gage is electrically very sensitive and can locate a steel ring or plate to within ±0.02 in. (±0.5 mm).

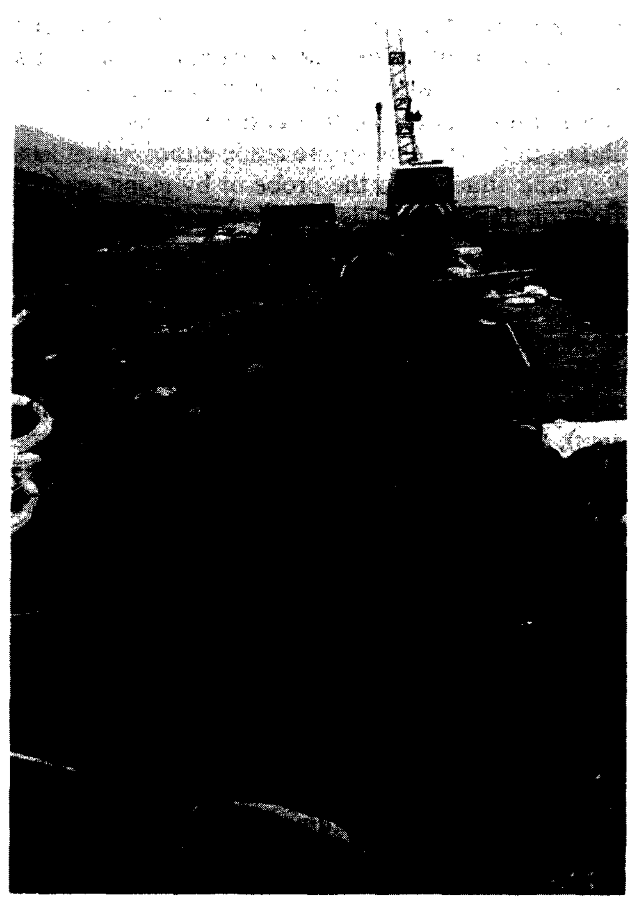


Figure 12.34. Horizontal plate gage (courtesy of Building Research Establishment, Watford, England; Crown copyright, 1987).

Table 12.5. Methods for Borehole Installation of Probe Extensometer with Current-Displacement Induction Coil

Method	Applications and Typical Minimum Borehole Diameter[a]	Method for Attempting Conformance	Outer Pipe	Inner Pipe	Anchors	Installation Sequence
1	Widely used in United States Uniform soils Predicted vertical compression up to about 2% 4 in. (100 mm)	Grout	Corrugated polyethylene, continuous or coupled	Flush-coupled or belled-end PVC	Steel wire rings mounted on corrugated pipe	Drill, insert double pipe system length-by-length, grout; *or* drill, insert corrugated pipe, insert inner pipe, grout
2	Uniform soils Predicted vertical compression up to about 5% 4 in. (100 mm)	Grout	Corrugated polyethylene, with telescoping couplings	Flush-coupled or belled-end PVC	Steel wire rings mounted on corrugated pipe	Drill, insert double pipe system length-by-length, grout
3	Widely used in England All soils Small and large predicted vertical compression 8 in. (200 mm)	Positive anchorage	None	PVC with telescoping couplings	Pneumatically actuated arrowheads	Drill, grout, insert coupled pipe with surrounding anchors, actuate anchors
4	Very large predicted vertical compression (up to 30%) 6 in. (150 mm)	Positive anchorage	PVC with telescoping couplings	PVC with standard socket couplings or belled ends	Spring-actuated anchors	Drill, insert outer coupled pipe with surrounding anchors, insert inner coupled pipe, grout, actuate anchors, withdraw inner pipe

[a] If drill casing is used, borehole diameter is inside diameter of casing.

When a vertical installation is read by using a survey tape and noting the tape reading at which output current is a maximum, precision with respect to the deep measuring point will generally be ±0.1–0.2 in. (±3–5 mm). If greater precision is required, a long-range dial height gage or micrometer reading head can be placed on a reference surface at the top of the installation, the sliding arm inserted within one of a series of holes punched in the survey tape, and precision with respect to the deep measuring point can be ±0.02 in. (±0.5 mm). If the deep measuring point is not a reference datum and optical leveling is required, precision will also depend on the accuracy of the optical leveling.

Measurement precision in horizontal installations, with respect to a steel plate at one end, generally ranges from ±0.1 to 1.0 in. (±3–25 mm). If greater precision is required, a rod containing a primary induction coil near the position of each steel plate can be installed permanently within the telescoping pipe (Penman and Charles, 1982). Each plate can then be located horizontally by switching to the appropriate coil along the rod and inching the rod along with a rack and pinion mechanism until the coil coincides exactly with the plate. With this system, it is only necessary to move the rod over a short distance, and a precision of ±0.02 in. (±0.5 mm) is possible.

Installation in Boreholes

Installations in boreholes should follow the general guidelines given in Chapter 17. Four methods are in use, the preferred method depending on the predicted vertical compression, the stratigraphy, other site-specific conditions and needs, instrument availability, and experience of installation personnel. The four methods are described in the following subsections and summarized in Table 12.5.

Installation in Boreholes, First Method: Corrugated Plastic Pipe and Steel Wire Rings. Conventional Method

Corrugated pipe and steel wire rings are arranged as shown in Figure 12.32: this arrangement is widely used in the United States for installing the *Sondex* instrument, manufactured by Slope Indicator Company.

The rigid PVC inner pipe is included to prevent the possibility of the corrugated pipe becoming crushed, and it also centers the probe for maximum reading precision. This installation method relies on conformance between the soil and corrugated pipe via the grout and, as discussed in Chapter 17, very careful attention must be paid to selection of grout mix. The grout should ideally have a modulus and undrained shear strength as similar as possible to that of the subsoil. If the grout is either excessively stiff or soft, or if measurements are required in strata having differing compressibilities, conformance is questionable. The method has been used satisfactorily in uniform soils where vertical compression has not exceeded about 2%, but conformance is open to question for greater compressions. Pea gravel has been used as a backfill instead of grout, but a granular backfill should only be used if it satisfies the conformance criteria discussed in Chapter 17: it should never be used for installations in clay.

The system can be installed by working with 10 ft (3 m) lengths of corrugated and rigid pipe, coupling them and installing the two together, length-by-length, filling the annular space between the two pipes with a bentonite slurry to minimize friction, and finally grouting the space outside the corrugated pipe. If this method is used, the couplings in the corrugated pipe **must** be sealed against intrusion of grout, normally by generous use of mastic filler and sealing tape.

As an alternative for installations less than 100 ft (30 m) deep, a continuous length of corrugated pipe can be installed first, followed by installation of the inner pipe. A typical installation procedure for this alternative, which supplements the guidelines given in Chapter 17, is as follows:

1. Drill a vertical hole using HW drill casing to the depth required, allowing length for the weight on the bottom cap (required to overcome buoyancy while grouting), and flush with clean water.
2. Stretch out the corrugated pipe and securely connect the weighted bottom cap with its attached male check valve.
3. Lower the corrugated pipe into the cased borehole, using a safety line, always keeping the pipe filled with clean water. Tie the top of the corrugated pipe to the top of the drill casing.
4. After the weight comes to rest on the bottom of the borehole, install the rigid inner pipe within the corrugated pipe until it rests on the bottom cap. The rigid pipe may be flush coupled Sch. 40 PVC or belled end Class 200 PVC, installed with female down if settlement is anticipated.
5. Lower 1 in. (25 mm) Sch. 40 steel pipe inside the rigid inner pipe, with female check valve attached, filling with water prior to mating with the bottom cap check valve. Pump a small amount of water to ensure proper mating.
6. Mix grout and pump enough grout to fill approximately 30 ft (10 m) of annular space between the corrugated pipe and drill casing. Pull 30 ft (10 m) of drill casing.
7. Continue step (6) until all drill casing is removed and an undiluted grout return is observed at the top of the borehole.
8. Remove the steel grout pipe and flush the inside of the rigid inner pipe with clean water.
9. Install a protective top cap and secure the corrugated pipe while the grout sets.

The above procedure uses the double shutoff check valve arrangement for grouting, as described for inclinometers in Section 12.8. Alternatively, the annular space can be grouted via a tremie pipe lowered to the bottom of the borehole. The single shutoff arrangement cannot be used for installation of corrugated pipe by this method; because the inner pipe is installed after installation of a continuous length of corrugated pipe, there is no seal between the bottoms of the two pipes, and grout might enter the annular space between the two pipes at the bottom of the borehole.

Installation in Boreholes, Second Method: Corrugated Plastic Pipe with Telescoping Couplings and Steel Wire Rings

The second installation method is similar to the first, installing the two pipes length-by-length, except that telescoping couplings are provided in the corrugated pipe. The couplings are typically made from PVC, with O-rings, and they encourage conformance. This method appears suitable for vertical compressions up to about 5%, but for larger compressions a positive soil anchorage is recommended.

Installation in Boreholes, Third Method: Rigid Plastic Pipe with Telescoping Couplings and Pneumatic Anchors

The third installation method, developed by the Building Research Establishment in England, uses rigid PVC pipe with telescoping couplings, and expanding anchors at the measuring points.

The expanding anchors have two arrowheads attached to pistons in two small cylinders and are placed around the PVC pipe as it is lowered into the borehole. They are later driven into the sides of the borehole by applying pneumatic pressure to the cylinders via small-bore nylon tubing. Use of expanding anchors requires an 8 in. (200 mm) diameter borehole. The annular space between the soil and pipe should be filled with a grout designed to keep the borehole open but soft enough so that it does not impede telescoping of the pipe.

Installation in Boreholes, Fourth Method: Rigid Plastic Pipe with Telescoping Couplings and Spring Anchors

The fourth installation method has recently been developed by Slope Indicator Company for use in very soft clays with their *Sondex* probe extensometer. It is based on anchor systems developed earlier by the Building Research Establishment in England (Marsland, 1974a), which use explosive cutters to release spring anchors. The system uses rigid plastic pipe with telescoping couplings and spring anchors. An anchor consists of a length of PVC pipe, sized to fit over the telescoping pipe, cut, heated, and allowed to cool as shown in Figure 12.35. A stainless steel wire ring is mounted around the anchor to form the measuring point. Shortly before installation, anchors are held in a retracted position by a nylon line with slip knots, passing through a cutting block as shown in Figure 12.36. The system is installed in a cased borehole as follows:

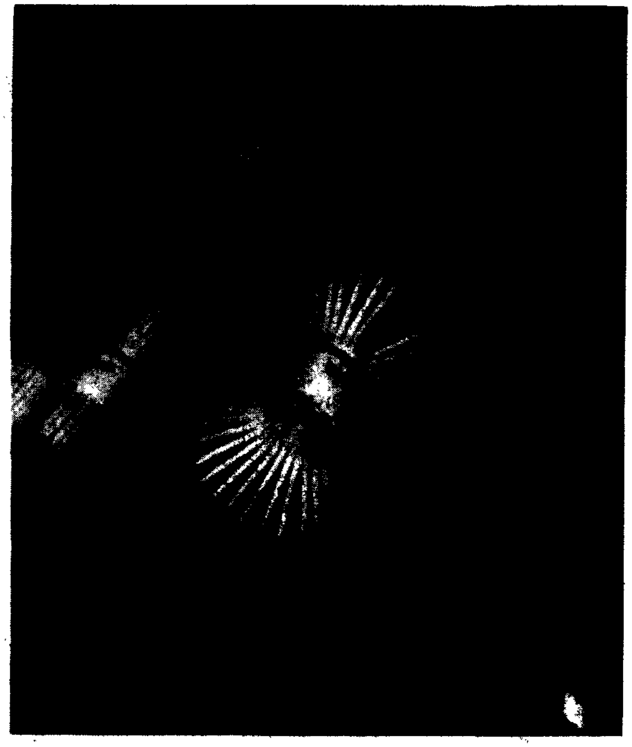


Figure 12.35. Spring anchor for use with Slope Indicator Company *Sondex* probe extensometer.

1. Place anchors over the telescoping pipe and prevent them from slipping along the pipe by tying with a second nylon line. This second line passes through the cutting block and anchor and partly through the wall of the telescoping pipe.
2. Install the telescoping pipe and anchors through the drill casing as described above for the alternative first installation method, with grout pipe and double shutoff arrangement. Insert a trip rod with bottom cutter head through the cutting blocks as installation proceeds. Great care is needed to avoid premature anchor tripping as the system is lowered, and the inside profile of the drill casing must be smooth and the anchor ends beveled.
3. After lowering to the bottom of the borehole, verify correct wire ring locations by using the probe, and insert a rigid PVC stiffening pipe within the telescoping pipe to bear on the bottom cap. The purpose of this stiffening pipe is to ensure that all telescoping joints remain in their open position during grouting. Fasten the stiffening pipe and telescoping pipe together at the top, and grout.
4. Withdraw all drill casing entirely, top up with grout, and withdraw grout pipe.

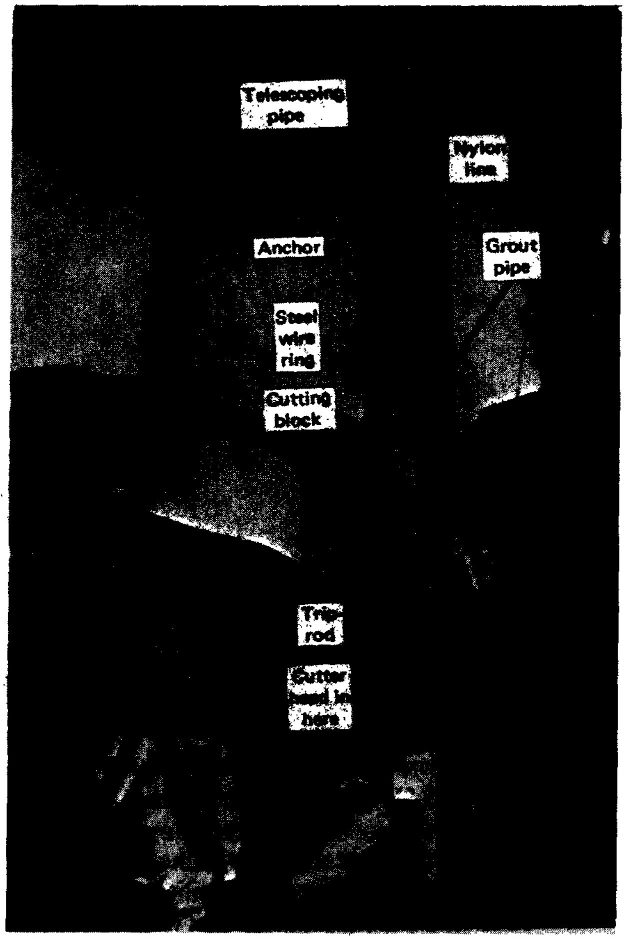


Figure 12.36. Installation of spring anchors for use with Slope Indicator Company *Sondex* probe extensometer.

5. Pull the trip rod to cut the pair of nylon lines at each anchor such that anchors positively grip the soil and are free to slide with respect to the telescoping pipe.
6. Allow the grout to set, and remove the stiffening pipe.

It must be emphasized that this fourth installation method requires great skill and care and should not be undertaken by inexperienced personnel. The system has recently been installed in very soft marine clays that form the foundation of a test embankment for a new airport in Hong Kong. Consolidation of the clays was accelerated by using vertical drains, and predicted vertical compression was greater than 30% (Handfelt et al., 1987). To date, maximum vertical compression has reached this value, and settlement data appear excellent. Plastic inclinometer casing with special long-range telescoping couplings was used instead of conventional telescoping pipe, so that both settlement and horizontal deformation could be measured (Section 12.5.10). Since the work in Hong Kong, Syncrude Canada Ltd. has simplified the installation procedure by eliminating the external cutting block and trip rod. The first and second nylon lines were replaced by two identical lines, one at each end of the anchor. Each line passed around the end of the anchor and through small-diameter holes drilled at opposite ends of the diameter through the anchor and telescoping pipe. Each line therefore held the anchor in its retracted position and also prevented it from slipping along the telescoping pipe. After installation in the borehole, the nylon lines were cut by lowering a dummy probe with a cutting blade fastened to its lower end, and the lines were drawn out of the drilled holes by the anchor spring action. The holes were not large enough to allow grout to pass through. This modification, although a simplification, prevents use of the internal stiffening pipe, and the author is reluctant to recommend it for all applications unless it can be shown that the stiffening pipe is unnecessary.

Installation in Fill

Installations in fill should follow the guidelines given in Chapter 17. Installations in boreholes that are later extended upward through fill should be converted to the telescoping pipe and steel plate system at the ground surface.

12.5.6. Gage with Frequency-Displacement Induction Coil

Induction coil transducers with frequency output, described in Chapter 8, are used by Telemac in their *Extensofor* probe extensometer (Bellier and Debreuille, 1977; Bordes and Debreuille, 1983), shown in Figure 12.37. The instrument consists of a 6 ft (2 m) long probe with a primary coil at each end. Steel rings or plates are installed around telescoping PVC pipe, generally as described previously for the gage with a current-displacement induction coil, at about 6 ft (2 m) spacing. The center-to-center distance between adjacent pairs of steel rings or plates is derived from the frequency output, using a conversion table, with a measurement precision of ±0.001 in. (±0.03 mm). The probe carries two inflatable packers to hold it steady while readings are

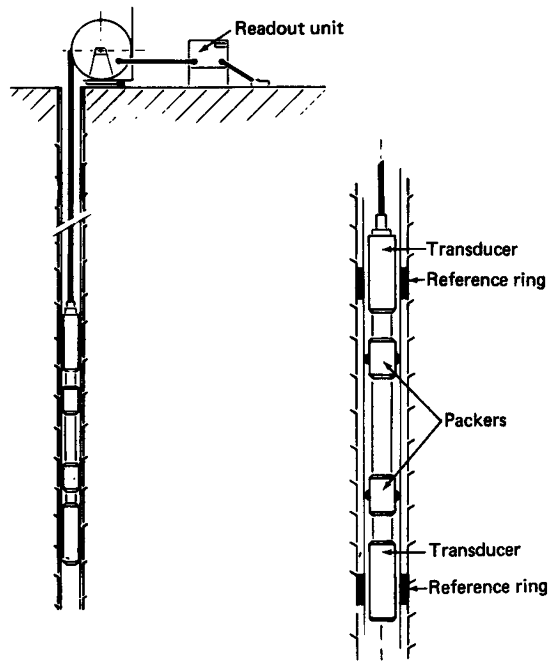


Figure 12.37. ***Extensofor*** **probe extensometer (courtesy of Telemac, Asnières, France).**

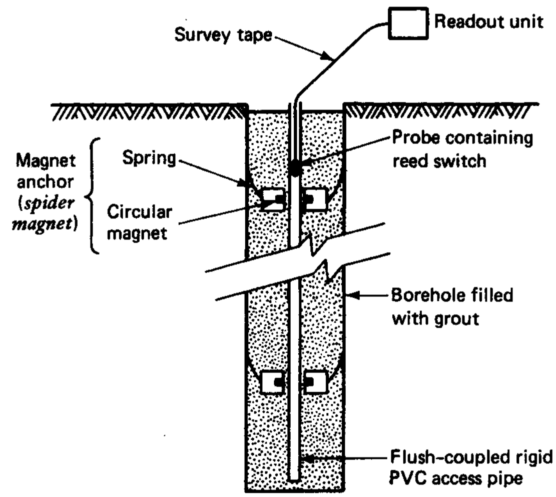


Figure 12.38. Schematic of probe extensometer with magnet/reed switch transducer, installed in a borehole.

taken, and the measurement range is about ± 1.5 in. (± 38 mm). The primary application is for monitoring axial deformations along boreholes in rock.

12.5.7. Magnet/Reed Switch Gage

The *magnet/reed switch gage* was developed by the Building Research Establishment in England (Burland et al., 1972; Marsland, 1974a) and incorporates the magnet/reed switch transducer described in Chapter 8. When used as a probe extensometer, the device consists of a series of circular magnetic anchors surrounding a rigid or telescoping plastic access pipe and is referred to as a *magnetic probe extensometer* or *magnetic extensometer.* A schematic of a borehole installation is shown in Figure 12.38 and various components in Figure 12.39.

An improved probe has been developed in Brazil (Figueiredo and Negro, 1981) that uses a different method of signal transmission when the reed switch is closed by a magnet. When closure occurs, a coupled oscillator in the probe is activated, generating square waves that are conducted through a steel survey tape up to the surface. The oscillator signal is received and amplified at the surface, enabling the operator to detect the signal through headphones. This improved probe avoids the use of a

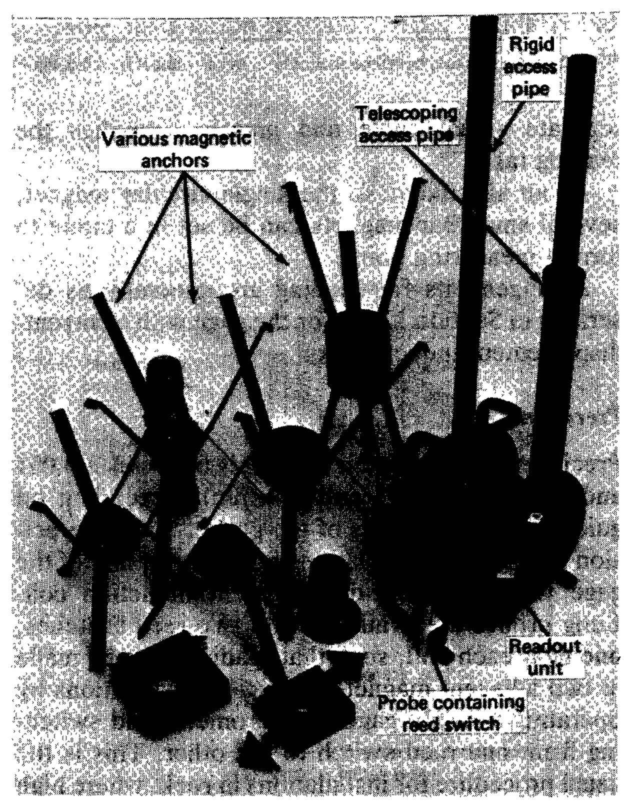


Figure 12.39. Magnet/reed switch probe extensometer (*magnetic extensometer*) (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England).

Table 12.6. Methods for Borehole Installation of Probe Extensometer with Magnet/Reed Switch Transducer

Method	Applications and Typical Minimum Borehole Diameter[a]	Method for Attempting Conformance	Outer Pipe	Inner Pipe	Anchors	Installation Sequence
1	Predicted vertical compression up to about 1% 3.5 in. (90 mm)	Positive anchorage (but may be inhibited by grout)	None	PVC with flush couplings	*Spider magnet* with three leaf springs	Drill, grout, insert coupled pipe, insert anchors
2	All soils Small and large predicted vertical compressions 6 in. (150 mm)	Positive anchorage	None	PVC with telescoping couplings	Pneumatically actuated arrowheads	Drill, grout, insert coupled pipe with surrounding anchors, actuate anchors
3	All soils Small and large predicted vertical compressions 3.5 in. (90 mm)	Positive anchorage	Corrugated, coupled to anchors	PVC with flush couplings	*Spider magnet* with six leaf springs	Drill, grout, insert double pipe and anchor system length-by-length, actuate anchors
4	Rock 3.5 in. (90 mm)	Contact between leaf springs and rock, *or* grout	None	PVC with flush couplings	Either attached to pipe; *or spider magnet* with three leaf springs	Drill, insert coupled pipe, insert *spider magnet; or* drill, grout, insert coupled pipe with attached magnets

[a] If drill casing is used, borehole diameter is inside diameter of casing.

separate signal cable and greatly simplifies the reading task.

As an alternative to the single circular magnet, several small bar magnets can be set in a circle to form a measuring point.

Arrangements for reading are generally as described in Section 12.5.5 for the gage with a current-displacement induction coil.

Precision

Precision of reed switch closure is between ± 0.001 and 0.01 in. (± 0.03 and 0.3 mm), depending on guidance arrangements of the probe. System precision for vertical installations is similar to that of the gage with a current-displacement induction coil. Long probes are available with two reed switches, one near each end, such that readings can be made at two adjacent magnets in vertical installations by operating a height gage or micrometer and switching from one reed switch to the other. This is the usual procedure for installations in rock, where high precision is often required, and the entire system can be traversed by reading magnets in pairs. For maximum precision in horizontal installations, the twin reed switch probe can also be used. Alternatively, a rod containing a reed switch near the position of each magnet can be installed permanently within the telescoping pipe, making micrometer measurements of the movement of the rod that is required to align switches and magnets.

Installation in Boreholes

Installations in boreholes should follow the general guidelines given in Chapter 17. Four methods are in use, the preferred method depending on the predicted vertical compression, the stratigraphy, other site-specific conditions and needs, instrument availability, and experience of installation personnel. The four methods are described in the following subsections and summarized in Table 12.6

Installation in Boreholes, First Method: Rigid Plastic Pipe with Conventional Spider Magnets

Rigid flush-coupled PVC access pipe and *spider magnets* are installed as shown in Figure 12.38. Each anchor has three upward leaf springs, mounted at 120 degrees around the anchor. The borehole is usually cased and filled with a suitable grout, the access pipe is greased and inserted, the casing is raised to a level just above the lowest spider magnet, and a magnet is pushed downward over the access pipe until the leaf springs snap out of the casing bottom and bite into the soil. The procedure is repeated until all anchors are installed and casing withdrawn. While this is a simple installation method, there appears to be a possibility that anchors may become grouted to the access pipe, thereby inhibiting conformance. The method should therefore be used only for monitoring small vertical compressions, up to about 1%.

Installation in Boreholes, Second Method: Rigid Plastic Pipe with Telescoping Couplings and Pneumatic Anchors

The second method uses expanding anchors with arrowheads, as described in Section 12.5.5 for the induction coil gage. Because the reed switch probe can be of smaller diameter than the induction coil probe, arrowhead anchors can be installed in a smaller diameter borehole, and 6 in. (150 mm) is typical. This method overcomes the conformance concerns raised for the first method but entails more expensive anchors and a larger diameter borehole.

Installation in Boreholes, Third Method: Rigid and Corrugated Plastic Pipes and Spring Anchors

The third method consists of *spider magnets* around a rigid PVC access pipe, with lengths of plastic corrugated pipe linking adjacent pairs of spider magnets. The spider magnets are set with a pneumatic or explosive cutter, and the corrugated pipe ensures that spider magnets are free to slide along the rigid pipe, thereby ensuring conformance. The system is assembled and inserted in the borehole length-by-length and can be installed in a 3.5 in. (90 mm) borehole.

Three additional leaf springs are mounted on each *spider magnet,* at 120 degrees, pointing downward, and the six springs are held in a retracted position by loops of nylon twine. A pneumatic cutter is placed on each anchor such that when anchors are in position they can be actuated from the ground surface by applying pneumatic pressure via 0.19 in. (5 mm) air lines. The lowest anchor is actuated first, the air line pulled in an attempt to recover the lowest cutter, and the other anchors actuated in turn. Typically about 75% of cutters are recovered.

Installation in Boreholes, Fourth Method: Boreholes in Rock with Rigid Plastic Pipe

The magnet/reed switch gage can also be used for monitoring axial deformation in boreholes in rock. Magnets are either attached directly to the rigid PVC access pipe and the system grouted in place, or the rigid PVC access pipe/*spider magnet* arrangement is used.

Installation in Fill

For installations in fill, magnets are attached to rectangular or circular PVC or aluminum plates and installed around rigid PVC pipe with telescoping joints.

Installation for Monitoring Heave at Bottom of Open Cut Excavations

The magnet/reed switch gage can be arranged to provide measurements of heave at the bottom of braced or other open cut excavations, in a way that does not interfere with excavation work. As shown in Figure 12.40, the installation is made prior to the start of excavation, using one of the first three borehole installation methods. After taking initial readings, the access pipe is sealed 5–10 ft (1.5–3 m)

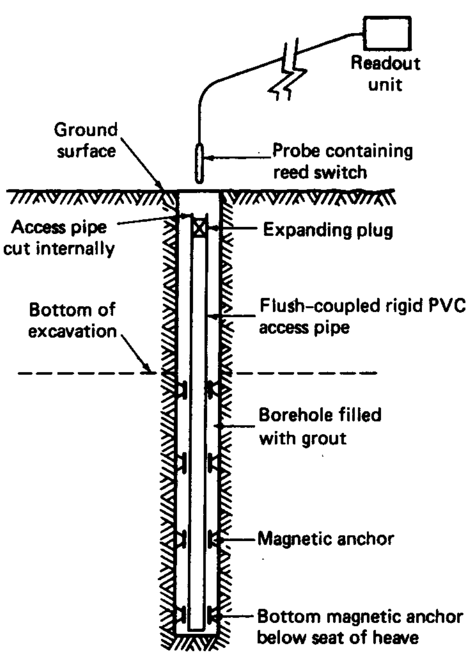


Figure 12.40. Schematic of probe extensometer with magnet/reed switch transducer, arranged for monitoring heave at the bottom of open cut excavations.

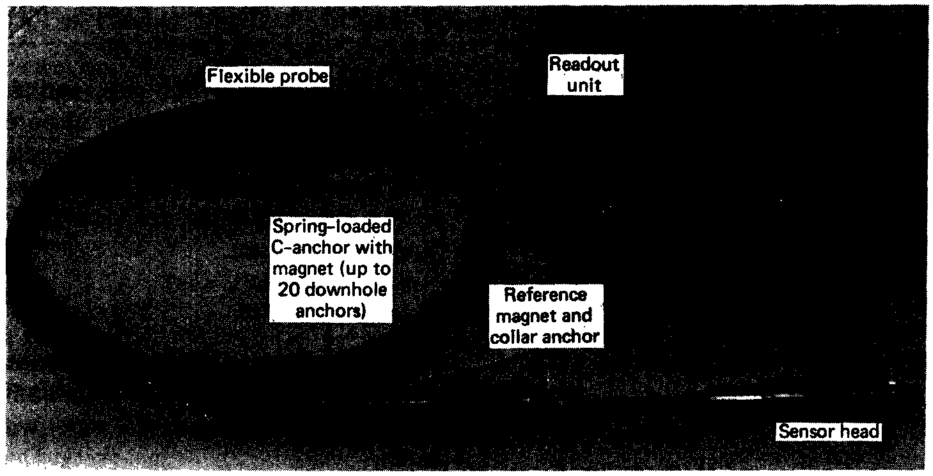


Figure 12.41. Flexible sonic probe (courtesy of Irad Gage, a Division of Klein Associates, Inc., Salem, NH).

below the ground surface, using an expanding plug set with an insertion tool, and the pipe is cut with an internal cutter just above the plug. A good survey fix is made on the plan position and, just before general excavation reaches the top of the pipe, the pipe is carefully located, a reading made, and the pipe again sealed and cut. The procedure is repeated until excavation is complete. Clearly, vigilance on the part of supervisory personnel is required, but the method is far less prone to damage and malfunction than use of fixed borehole extensometers with electrical transducers.

12.5.8. Bellow-Hose Gage

The *bellow-hose gage* (Bozozuk and Fellenius, 1979) consists of flexible polyethylene tube with short lengths of copper pipe mounted at predetermined locations to serve as measuring points. A probe with three protruding steel spring contact arms is lowered within the tube on the end of a survey tape. The steel springs are electrically insulated from each other, but two are connected to a cable leading from the probe to a voltmeter. When the probe contacts a copper pipe, the electrical circuit is closed, activating the voltmeter, and a tape reading is made alongside the top of the tube. The system is installed in a borehole by grouting, using the first method described above for the gage with a current-displacement induction coil (Section 12.5.5). When compared with the induction coil gage, readings are more subjective, no positive anchor arrangement is available to ensure conformance, and there appear to be no advantages.

12.5.9. Magnetostrictive Gage

The *magnetostrictive gage (sonic probe)* described in Section 12.7.4 is available in a removable flexible probe version and is shown in Figure 12.41. A magnet is attached directly to each anchor and a central access tube (not shown in the figure) is installed throughout the borehole. The flexible probe is inserted to the deepest magnet, and distances between magnets are displayed at the readout unit. The system has its primary application in underground rock excavations, where more elaborate permanently installed components would be subject to damage, and can be used in upward holes. The current version has an anchor depth limitation of 25 ft (7.6 m).

12.5.10. Combined Probe Extensometers and Inclinometer Casings

As indicated in Table 12.4, several of the probe extensometers can be used in conjunction with inclinometer casing in a vertical borehole, thereby obtaining both horizontal and vertical deformation data from one installation.

If a mechanical probe is used within inclinometer casing, no additional permanently installed features are required. However, use of this combination

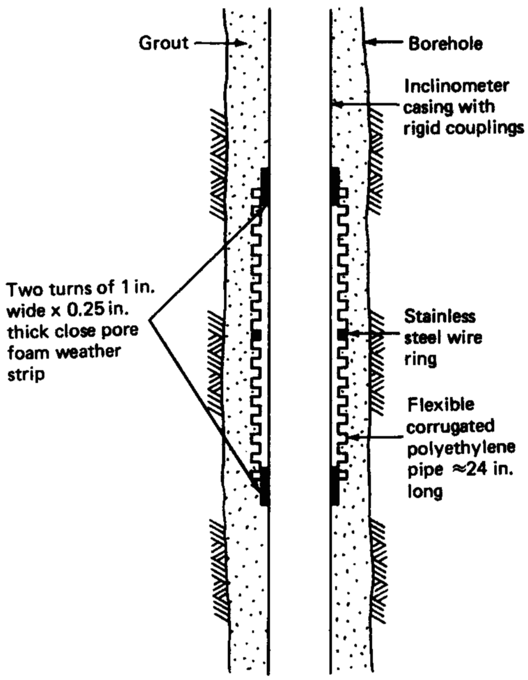


Figure 12.42. Schematic of induction coil ring combined with inclinometer casing.

should be limited to installations in fill, when settlement collars can be added. If the induction coil gage or the magnet/reed switch gage is installed vertically in fill or in a borehole, inclinometer casing with appropriate couplings can replace the inner pipe. If inclinometer casing is surrounded by corrugated plastic pipe, the intervening space must be well lubricated, and careful relative sizing of casing and pipe is required so that the casing is not free to move laterally with respect to the pipe. It is also important to fix the inclinometer casing so that it is not free to rotate.

Available installation methods are similar to those summarized in Tables 12.5 and 12.6, with the exception of the fourth method in Table 12.6. If the gage with current-displacement induction coil is used, the arrangement shown in Figure 12.42 provides an alternative simpler installation method for applications where less than about 2% vertical compression is anticipated. The thickness of weather strip is selected so that the polyethylene pipe can be pushed over the strip. The strip is intended to hold the corrugated pipe in place during installation, to prevent grout entering the annular space between the casing and pipe and to allow the corrugated pipe to break free as needed when settlement occurs.

If the user is concerned that the combined arrangement may reduce the reliability of either vertical or horizontal deformation measurements, the author recommends separate installations.

12.5.11. Combined Probe Extensometers and Open Standpipe Piezometers

The induction coil and magnet/reed switch instruments can also be combined with the standpipe of an open standpipe piezometer, so that both groundwater pressure and settlement can be monitored.

12.5.12. Recommendations for Choice of Probe Extensometer

It is not possible to make definitive recommendations for the choice of a probe extensometer. The author does not favor use of the bellow-hose gage, but all the others may on occasion be the instrument of choice. The selection depends on the application, the predicted axial compression, the ground conditions, other site-specific conditions and needs, the skill and experience of installation personnel, availability of hardware, the general factors for selection of instruments that are given in Section 4.9, and the more specific factors given in this section.

When reliable deformation data are essential, the author recommends use of a positive anchorage, rather than reliance on grout for ensuring conformance.

12.6. FIXED EMBANKMENT EXTENSOMETERS

Fixed embankment extensometers are defined in this book as devices placed in embankment fill as filling proceeds for monitoring the changing distance between two or more points along a common axis without use of a movable probe. They are used for monitoring settlement, horizontal deformation, or strain.

12.6.1. Settlement Platform

Settlement platforms are typically used for monitoring settlement below embankments on soft ground.

A settlement platform consists of a square plate of steel, wood, or concrete placed on the original ground surface, to which a riser pipe is attached (Figure 12.43). Optical leveling measurements to

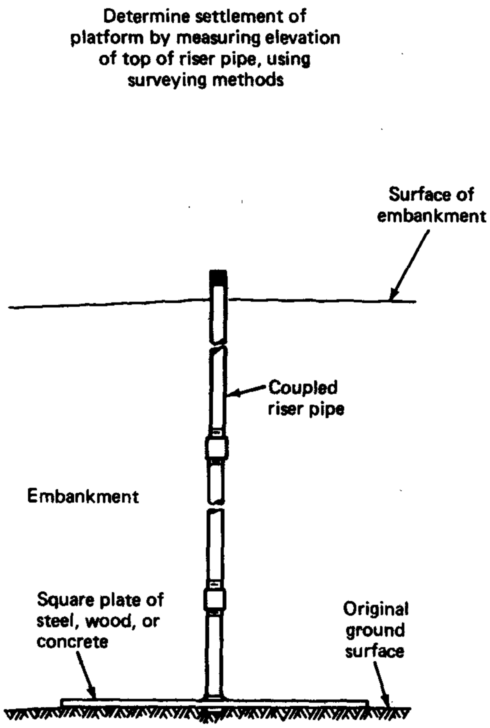


Figure 12.43. Typical settlement platform.

the top of the riser provide a record of plate elevations. The plate is typically 3 or 4 ft (1 or 1.2 m) square, and the riser pipe is typically 2 in. (50 mm) standard black iron pipe with threaded couplings. Either the pipe and plate are welded together or a floor flange is bolted to a wooden plate or embedded in a concrete plate. A sleeve pipe is sometimes placed around the riser pipe, with a gap between the bottom of the sleeve pipe and the plate to prevent downdrag forces on the riser pipe from being transmitted to the plate. Reasonable practice appears to require a sleeve pipe only if the embankment is over about 25 ft (8 m) high or if the plate is seated on highly compressible material such that downdrag forces might punch the plate below the original ground surface.

Care must be taken to maintain pipe verticality, and a record of added pipe length must be made as fill is placed. At the time of plate installation, an initial reference mark should be scribed on the riser pipe and its elevation determined and recorded. The pipe should be scribed to an accuracy of 0.01 ft (3 mm) at maximum intervals of 5 ft (1.5 m), measured from the initial mark. Immediately after the pipe is scribed, the graduations should be numbered to reflect the distance from the initial scribe. When pipe lengths are added, the extensions should b scribed in a similar way by tape measurement fro scribes on the lower pipe. An adjustable hose clam can be placed around the pipe at the highest scrib mark to provide a place to rest the survey rod whe determining the elevation of the scribe mark. Th clamp is loosened and moved upward as fill placed.

The primary advantage of settlement platforms i their simplicity. Limitations include their tendenc to be damaged by construction equipment and th difficulty in compacting around the riser pipe: case have occurred in which a highway pavement ha settled directly over a settlement platform, indica ing inadequate compaction. These problems ca sometimes be avoided by using liquid level gage (Section 12.10) instead of settlement platform Other limitations are the potential for measuremen errors caused by additions of pipe lengths an caused by non-vertical sections of pipe, and the re quirement for a survey crew when taking reading However, with proper care, they can provide rel able data of adequate precision, generally in th range ±0.1–1.0 in. (±3–25 mm).

Where an unyielding layer exists at shallo depth, economy can sometimes be achieved by in stalling a subsurface settlement point (Sectio 12.7.6) through a hole in the plate as shown in Fig ure 12.44. The arrangement allows measurement

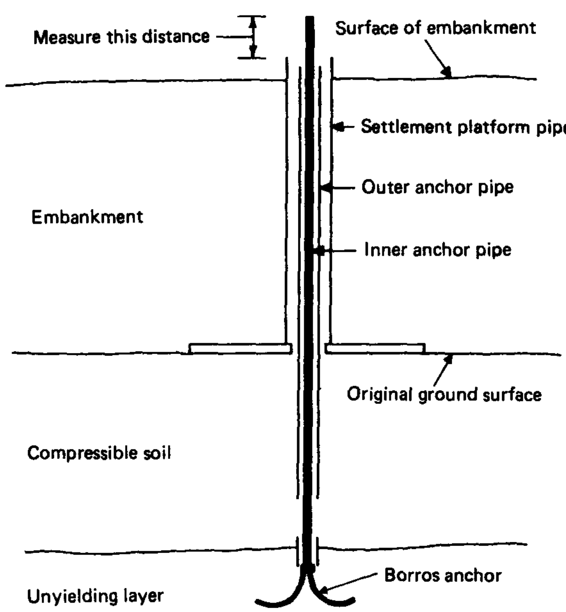


Figure 12.44. Schematic of combined settlement platform an Borros anchor.

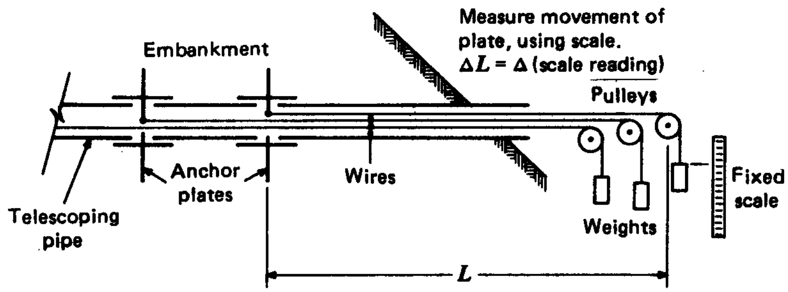


Figure 12.45. Schematic of typical mechanical gage with tensioned wires.

of absolute settlement to be made—without using a survey crew—by using a scale or mechanical gage to measure the distance shown.

12.6.2. Buried Plate

A *buried plate* is identical to the steel or concrete base plate of a settlement platform, and its use overcomes problems associated with the coupled riser pipe. To take an elevation reading on the plate, a vertical borehole is drilled, jetted, or augered from an accurately surveyed surface position, the plate located, and a depth measurement made. An accurate record must of course be made of the initial location of the plate in plan and elevation, and the plate must be large and level. The primary application for buried plates is for monitoring settlement below embankments on soft ground in cases where accuracy requirements are not great and where a boring rig is readily available.

Rózsa and Vidacs (1983) illustrate the application of buried plates, installed below an embankment on soft ground, in a row across an entire cross section.

12.6.3. Mechanical Gage with Tensioned Wires

Tensioned wire gages are used horizontally within an embankment or along the ground line at the base of an embankment to measure absolute horizontal deformation or horizontal strain.

As shown in Figure 12.45, the gage consists of vertical anchor plates attached to couplings in telescoping pipe laid horizontally. Steel wires or cables attached to each anchor plate are brought through the pipe to a measuring point where movement of a mark on the wire is observed relative to a fixed reference, while a standard tension is applied to the wire. Hosking and Hilton (1963) used at least ten wires in each pipe and 20 lb (9 kg) tension. Two different but standard weights can be used, as described in Section 12.7 for fixed borehole extensometers, to examine downhole friction characteristics. Additional guidelines are given in Section 12.7.

The pipe is normally installed in a shallow trench, as described in Chapter 17, and a terminal enclosure is required to house the pulleys, weights, and scale. Precision is generally ±0.2–0.8 in. (±5–20 mm). When absolute deformation data are required, the system must be located with respect to a horizontal control station, using surveying methods, and precision may be reduced.

12.6.4. Gage with Electrical Linear Displacement Transducers

These instruments consist of an electrical linear displacement transducer (LVDT, DCDT, linear potentiometer, vibrating wire transducer, variable reluctance transducer, or induction coil transducer with frequency output) mounted in line with a rod that connects two anchors, and cabled to an accessible location (Figure 12.46). An oil-filled telescoping

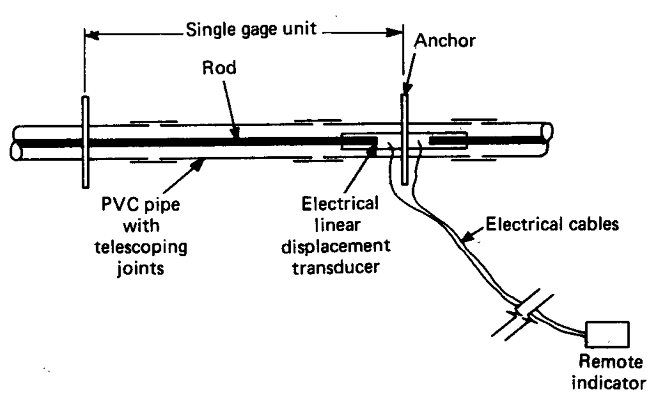


Figure 12.46. Schematic of fixed embankment extensometer with electrical linear displacement transducers.

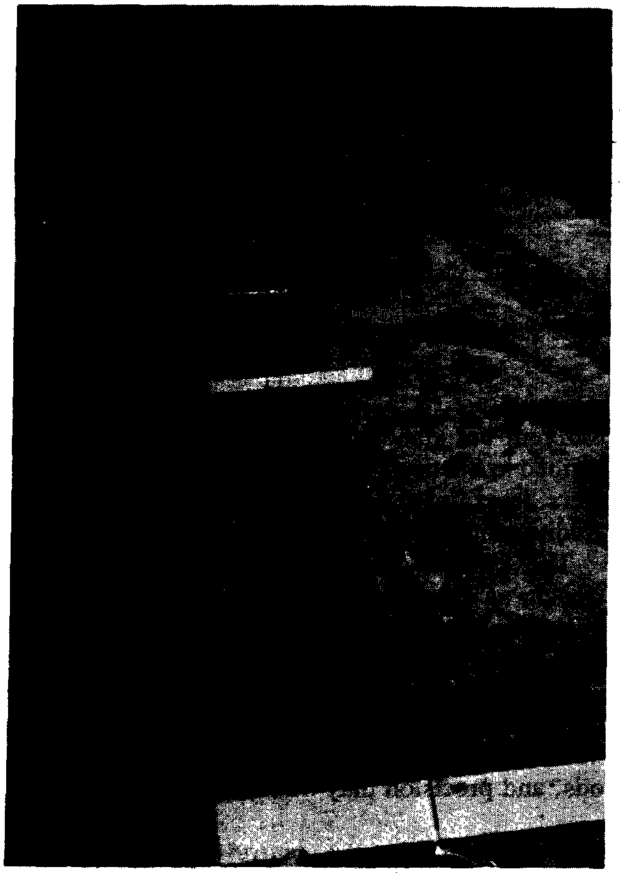


Figure 12.47. Installation of fixed embankment extensometer, with linear potentiometer transducers, in embankment dam.

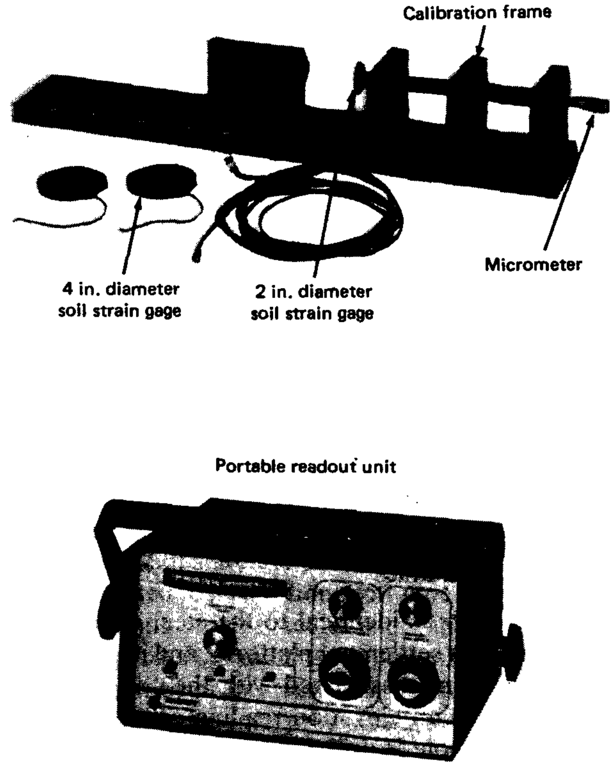


Figure 12.48. Soil strain gage (courtesy of Bison Instrument Inc., Minneapolis, MN).

PVC pipe usually surrounds the rod and transducer, with O-rings in the couplings, to provide physical protection and waterproofing.

Their use is primarily for measuring horizontal strain in embankment dams, and the instruments are sometimes referred to as *horizontal strainmeters*. If the distance between anchors is too small, local variations may produce nonrepresentative data, whereas too long a distance will integrate true variations into an "average" value (Wilson, 1967). An appropriate anchor spacing is usually 10–20 ft (3–6 m). Gages can be installed singly or several can be coupled in series as shown in Figure 12.47. They can be grouped in different alignments to provide complete strain data in a horizontal plane.

Typical precision is ±0.01 in. (±0.3 mm), corresponding to a strain of ±0.005% with an anchor spacing of 16 ft (5 m).

12.6.5. Soil Strain Gage

The soil strain gage (Selig, 1975a) is described i Chapter 8 and is used for measurement of strain i any direction in earth fills. Components are show in Figure 12.48.

Gages have been used extensively to measur vertical and horizontal strain beneath moving vehi cles, as input to research studies on highway bas and subbase materials, and on railroad ballast. Seli (1975b) describes strain determination around larg buried culverts. They have also been used as con vergence gages for monitoring the width of th trench during a full-scale test of a slurry trench ex cavation: this application is described in Sectio 12.11.2.

As shown in Figure 12.49, the two coils may b related to each other in an orthogonal, coaxial, o coplanar configuration. Strain is determined fro the change in spacing between the coils after instal lation. The system is designed to operate with th two coils separated at a distance of less than fiv coil diameters, and coils are commercially availabl with diameters from 1 to 4 in. (25–100 mm). How

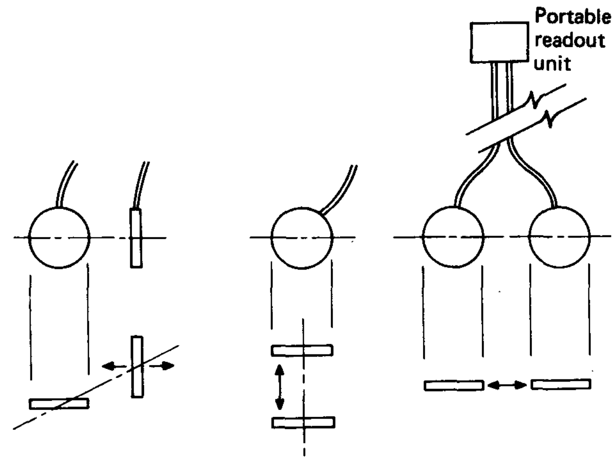


Figure 12.49. Soil strain gage configurations.

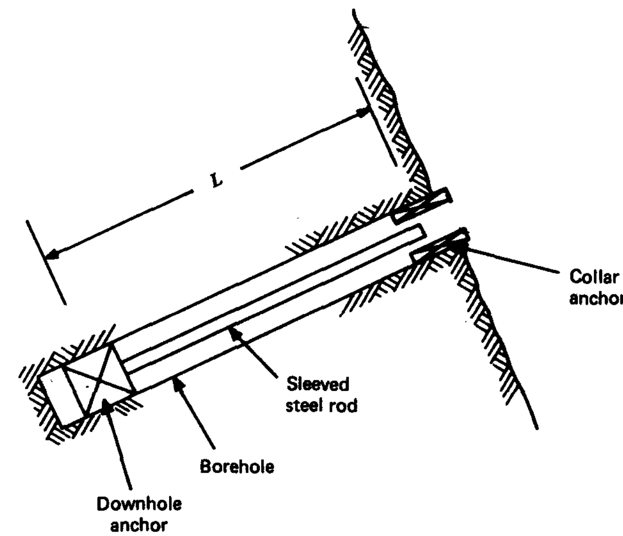


Figure 12.50. Operating principle of fixed borehole extensometer.

ever, larger coils can readily be manufactured to allow measurement over larger distances. Lord and Koerner (1977) describe a modified soil strain gage that uses a commercially available metal detector.

The primary advantage is the lack of any mechanical linkage between the coils; therefore, placement is simplified and conformance with strain of the soil is excellent. These devices are applicable for measuring both static and dynamic strains and are not affected by soil composition, moisture content, or temperature changes in the soil between the coils. Long-term precision is approximately $\pm 0.05\%$ strain, but dynamic values as small as $\pm 0.001\%$ strain can be detected. The primary disadvantage is sensitivity to the presence of metal objects, and movement of metal objects can cause a change in the electromagnetic field. This can create significant measurement errors unless adequate electrical shielding is installed. Stationary metal objects, however, generally do not cause a problem. The gages are also sensitive to changes in relative orientation of the coils.

12.7. FIXED BOREHOLE EXTENSOMETERS*

Fixed borehole extensometers are defined in this book as devices installed in boreholes in soil or rock for monitoring the changing distance between two or more points along the axis of a borehole, without use of a movable probe. When the location of one measurement point is determined with respect to a fixed reference datum, the devices also provide absolute deformation data.

Typical applications are monitoring deformations around underground excavation in rock and behind the faces of excavated slopes. Fixed borehole extensometers are also used for monitoring consolidation settlements in soil, bottom heave in open cut excavations, and strain in concrete structures.

The operating principle is shown in Figure 12.50. The distance from the face of the collar anchor to the end of the rod is measured using either a mechanical or an electrical transducer. The device shown is a single-point borehole extensometer (SPBX), but several downhole anchors can be located in a single borehole, each with an attached rod from the downhole anchor to the collar anchor, to create a multipoint borehole extensometer (MPBX). MPBXs are used to monitor the deformation or strain pattern along the axis of an appropriately oriented borehole, for example, so that potential failure zones can be located and dangerous deep

*Written with the assistance of J. Barrie Sellers, President, Geokon, Inc., Lebanon, NH, and Howard B. Dutro, Vice President, Slope Indicator Company, Seattle, WA.

seated movements separated from surface spalling. Several SPBXs of different lengths, installed near each other, can serve the same purpose as an MPBX. Tensioned wires can be used instead of rods.

Many types of fixed borehole extensometer are available, the primary variables being choice of rods or wires, anchor type, SPBX or MPBX, transducer type, and extensometer head. These variables are discussed in the following sections. Alternative instrument types and installation, reading, data calculation, and processing procedures are described in ISRM (1981b). O'Rourke and Ranson (1979) provide comprehensive data on instrument performance.

12.7.1. Choice of Rods or Wires

In general, rod extensometers are of a simpler design than wire types and are more easily installed, especially if only one anchor is installed per borehole. They are generally preferred for extensometers up to about 300 ft (90 m) long, but the advantages of rods over wires are reduced as the length of the extensometer increases.

Wires

Wires are typically single-strand stainless steel, 0.02–0.05 in. (0.5–1.3 mm) in diameter. When wires are used, wires **must** be straightened by use of a wire straightener before extensometer assembly and, if this is not done, precision will be greatly reduced.

When the tension in the wire may vary, for example, when coil springs or cantilevers are used, wire stretch must be taken into account. Wire tension may vary as movement occurs along the extensometer, and wire stretch factors are usually supplied by the extensometer manufacturer. These factors can sometimes be verified after the extensometer is installed, by moving the extensometer head a known amount to and fro in line with the borehole axis and measuring the corresponding reading change. Some extensometer designs attempt to overcome wire stretch corrections by using constant-tension devices. Negator springs designed to exert a constant force are appropriate when very long range is required, but they should not be used when requiring high accuracy over a small range, because accuracy can be limited by hysteresis. Despite the cumbersome aspects of pulleys and suspended weights, similar to the system shown in Figure 12.45, they provide good tension control and are a good choice for permanently tensioned wire extensometers in applications where the head arrangements are acceptable.

Rods

Rods are typically 0.2–0.5 in. (5–13 mm) in diameter and are available in mild steel, stainless steel, aluminum alloy, fiberglass, and invar. A carbon fiber/vinyl ester composite material has been developed (Beloff, 1986) for use in high-temperature applications, such as studies relating to disposal of high-level nuclear waste, and can be manufactured to create a near-zero longitudinal thermal coefficient.

Rods are shipped either in coils or in straight lengths typically 10 ft (3 m) long. The straight lengths are generally connected with threaded flush couplings. Coiled steel and aluminum alloy rods may need to be straightened before installation, using a tool supplied by the manufacturer, but this is not necessary for coiled fiberglass rods. Rods should be encased in individual plastic sleeves to minimize frictional effects, and sleeves can be filled with oil if the borehole is inclined downward.

Rods are sometimes allowed to remain slack within their sleeves but sometimes are tensioned by coil springs, and there is no unanimity of opinion on the advantages of tensioning the rods. Proponents of tensioning argue that tensioning minimizes slack in the system. For some types of extensometer head, tensioning also allows the head to be moved outward a known distance to examine frictional effects. Opponents of tensioning argue that, because no borehole is perfectly straight, tensioning will increase normal stresses between a rod and its sleeve, thus increasing frictional effects and reducing precision. Opponents also argue that use of untensioned rods allows frictional effects to be examined at any time, by incorporating a bayonet disconnect fitting (Figure 12.53a) between the rod and downhole anchor. The rod can then be turned at the collar anchor to disconnect it from the downhole anchor and moved within its sleeve. The author has had good success with this arrangement and generally favors untensioned rods, but there is a need for comparative evaluations.

When using the bayonet disconnect fitting, thread sealing compound must be used on all threaded rod connections, and the rods must protrude beyond the face of the collar anchor so that they can be gripped and turned. The arrangement also simplifies installation, because rods can generally be inserted within sleeves as a separate step, after anchors and sleeves have been installed. When using the bayonet fitting in upward installations, a stop should be provided near the upper end of each rod so that rods cannot fall out of sleeves and cause injury to reading personnel, and rods must be installed concurrently with sleeves.

12.7.2. Choice of Downhole Anchor

ISRM (1981b) recommends a criterion for anchor adequacy, based on an applied load of 220 lb (100 kg) or five times the rod or wire tension, whichever is greater. ISRM recommends that, when subjected to this load, the anchor should not move in either direction by an amount greater than the sensitivity of the instrument. Hawkes (1978) describes many of the available downhole anchors; these and others in common use are discussed in the following subsections.

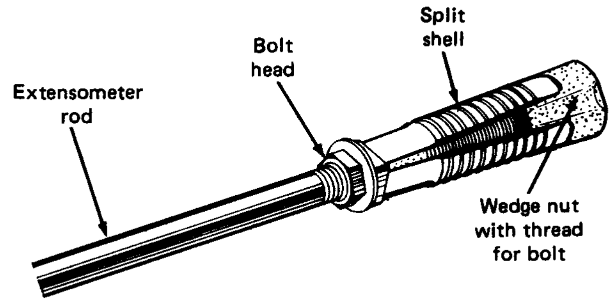
Applications for each anchor are suggested, but the generalizations will not apply to all cases. Several manufacturers of geotechnical instruments have wide experience in performance of their anchors under a variety of conditions, and their advice should be sought before selecting anchors. Factors that affect selection include soil or rock type and quality, borehole depth, borehole diameter, inclination and wall roughness, number of downhole anchors, use of rods or wires, and type of extensometer head.

Expanding Wedge Anchors

Two *expanding wedge anchors* are shown in Figure 12.51.

The *rockbolt expansion shell anchor* consists of a one-piece cylindrical split shell and a wedge nut. Rotation of the extensometer rod causes the wedge nut to move axially relative to the shell, expanding it into close contact with the walls of the borehole. To prevent the shell from rotating, it must initially be in rubbing contact with the borehole wall. Similar anchors are available with a split shell and wedge nut at each end. A steel block can be welded to each part of the split shell to allow gripping in a large-diameter borehole. The large setting force of the rockbolt expansion shell anchor enables it to be used at locations affected by blasting.

The *flat wedge spring anchor* consists of a flat



(a)

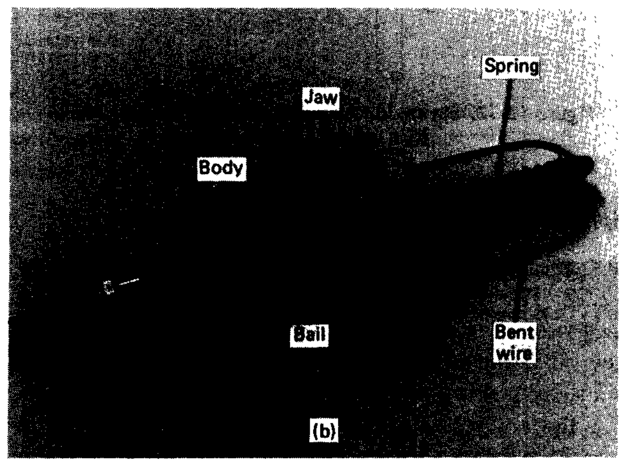


Figure 12.51. Expanding wedge anchors: (a) rockbolt expansion shell anchor (courtesy of Irad Gage, a Division of Klein Associates, Inc., Salem, NH) and (b) flat wedge spring anchor (courtesy of Slope Indicator Company, Seattle, WA).

wedge-shaped body with two expansion jaws, connected by a bent wire and spring loaded against the body as shown. The extensometer wire is attached to the body. When the anchor is pushed down the borehole on the end of a setting rod, the jaws rub against the sides of the borehole under the action of the spring. The anchor body is then pulled back by the extensometer wire to lock it into place. The anchor is designed for multipoint installations and the wires from deeper anchors are threaded through the bail prior to setting.

The rockbolt expansion shell anchor is generally the preferred anchor for single- and double-point rod extensometers installed in rock. The flat wedge spring anchor is useful in upward boreholes in rock, where multiple anchors are required. Both anchors can be installed rapidly, have wide expansion capabilities, and thus are suitable for boreholes with rough uneven walls.

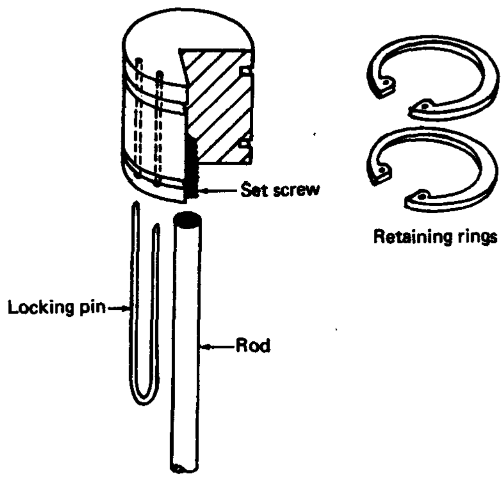


Figure 12.52. Spring-loaded anchor (after Hawkes, 1978).

Spring-Loaded Anchors

A typical *spring-loaded anchor* is shown in Figure 12.52. The anchor is also referred to as a *C-anchor* and *snap-ring anchor*. It is installed by pushing into the borehole to the required depth and tripping the rings by pulling out a U-shaped locking pin, allowing the rings to spring out against the wall of the borehole. These anchors are useful in hard or competent rock where smooth uniform boreholes can be drilled. Under these conditions, they offer the ultimate in installation speed and simplicity, where several anchors are installed in the same borehole. Dutta (1982) reports on pull tests within 3 in. (76 mm) diameter steel pipe, indicating a resistance to pullout in excess of 200 lb (90 kg). Other tests by Dutta indicate that the anchors are not likely to be disturbed by nearby blasting.

Groutable Anchors

Groutable anchors (Figure 12.53) are simple to install and are usually the preferred anchors for boreholes in rock that are inclined downward. Nominally horizontal boreholes can often be inclined slightly downward to allow their use. They are suitable for use at locations affected by blasting but not for use in soil, as the grout may inhibit conformance. The measurement rods or wires are sleeved within plastic pipes or tubes to isolate them from the grout.

Extensometers incorporating groutable anchors are preassembled at the surface and pushed into the borehole, with tubes for grout outlets and air vents as discussed in Chapter 17. Boreholes directed upward require a stage grouting procedure, and an alternative anchor is usually preferable.

Hydraulic Anchors

Two types of *hydraulic anchor*, which can be used with rods or wires, are shown in Figure 12.54.

The *expanding tube type* is suitable for use in soil or rock. A soft metal tube is flattened, its ends sealed, and wrapped around the body of the anchor. The tube is pressurized by hydraulic oil to expand it beyond the yield point of the metal and in contact with the walls of the borehole. When hydraulic pressure is released, the tube maintains its deformed shape.

The *prong type* is used primarily in soft ground, where the anchor must be forced outward into the soil to spread the anchorage forces and prevent slippage. Hydraulic oil pumped to the anchor forces the prongs outward into the walls of the borehole. Single- and double-acting versions are available.

12.7.3. Choice of Single-Point or Multipoint Extensometer

In general, the more anchors installed in one borehole, the greater are installation difficulties and duration, with possible consequent delay to construction schedules. MPBXs typically have between four and eight anchors and generally require more skilled installation personnel than SPBXs.

Several SPBXs installed side by side in boreholes of different lengths can simulate an MPBX and may result in overall economy and reduced construction delay. However, the applicability of this option is affected by many site-specific conditions, including borehole length, type and number of anchors, and type of extensometer head. When a cluster of SPBXs is used and core recovery is required for planning the installation and interpreting data, only the deepest SPBX hole need be cored, and the shallower holes can be percussion drilled if that is more economical. If the collar anchors can be set in the same block of intact rock, anchor movement data are calculated as for an MPBX. However, if collar anchors may move with respect to each other and if downhole relative deformation data are required, their relative movement must be measured. If the SPBX heads are installed in a vertical line, the mechanical tiltmeter described in Section 12.4.1 can sometimes be used for this purpose.

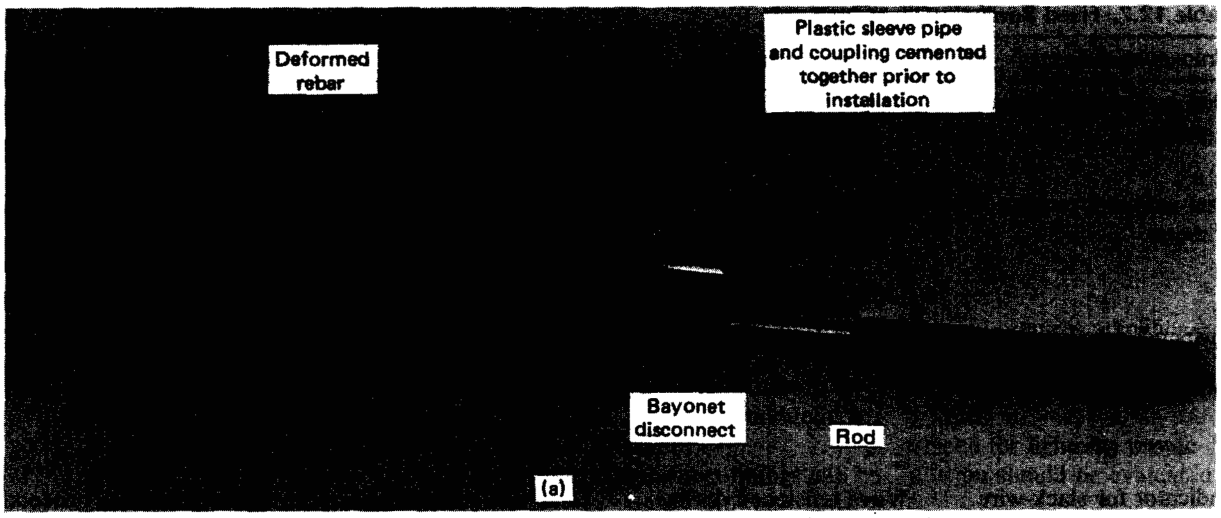


Figure 12.53a. Groutable anchor for rod extensometer (courtesy of Geskon, Inc., Lebanon, NH).

Figure 12.53b. Groutable anchor for multipoint wire extensometer (courtesy of Slope Indicator Company, Seattle, WA).

12.7.4. Choice of Transducer and Extensometer Head

Mechanical and electrical transducers are available for reading fixed borehole extensometers. Mechanical transducers are less expensive and are generally more reliable and more resistant to damage. When access to the collar anchor is available, mechanical transducers should be the first choice unless automatic or remote monitoring is required. In other cases, electrical transducers must be used, but arrangements should be made within the measuring head for backup mechanical reading without disturbing the electrical transducers, so that a periodic check can be made on the electrical system by creating temporary access.

Mechanical and electrical transducers are described and compared in Chapter 8. The following subsections provide additional information relevant

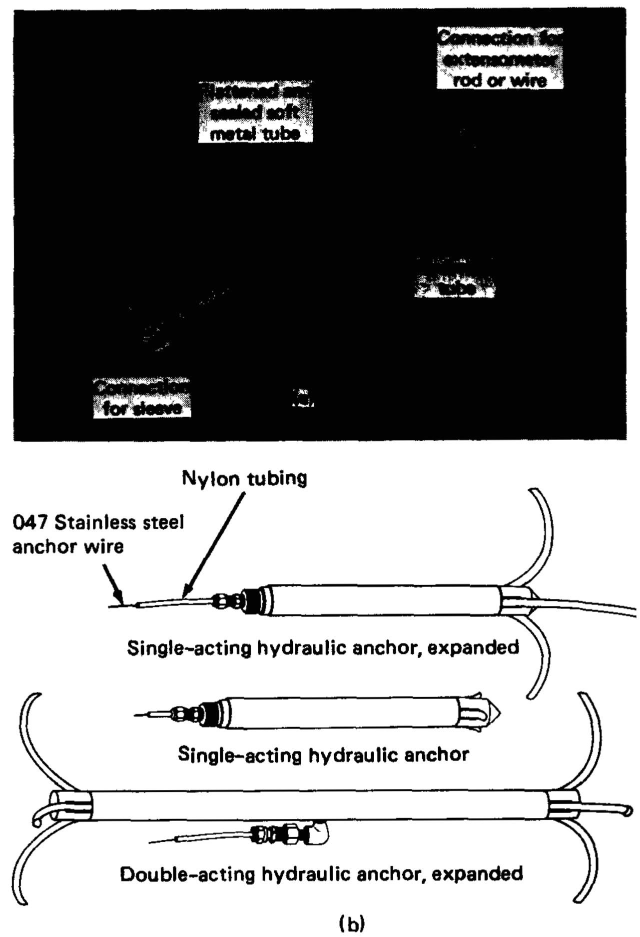


Figure 12.54. Hydraulic anchors: (a) expanding tube type and (b) prong type (courtesy of Slope Indicator Company, Seattle, WA).

Table 12.7. Fixed Borehole Extensometers[a]

Transducer	Rods or Wires	Advantages	Limitations
Dial indicator or micrometer	Rods	Large range Disconnect fittings can be used[b]	Requires access to extensometer head
Dial indicator or micrometer	Variable-tension wires with coil springs	Downhole wire friction can be examined[c]	Requires more skill to install than rod system Requires access to extensometer head
Suspended weights (similar to Figure 12.45)	Constant-tension wires	Excellent tension control Reliable for deep boreholes Dual tension reading provides check	Bulky head Requires access to extensometer head
Indicator for slack-wire extensometer (e.g., Figure 12.55)	Wires tensioned during reading	Dual tension reading provides check	Tedious reading procedure Requires access to extensometer head
Electrical resistance strain gage (e.g., Figure 12.56)	Variable-tension wires	Downhole wire friction can be examined[c] Can be read with dial indicator or micrometer to check electrical reading	Limited range Low electrical output Lead wire effects Errors owing to moisture, temperature, and electrical connections are possible Need for lightning protection should be evaluated
LVDT, DCDT, or linear potentiometer (e.g., Figures 12.57, 12.58, 12.59)	Rods, or variable-tension wires with coil springs	Versions available with transducers mounted in series between anchors for improved physical protection Versions available for use as heave gages in open cut excavations Disconnect fittings can be used[b] or downhole wire friction can be examined[c]	LVDTs have unwanted lead wire effects Linear potentiometers require perfect water seal at rod entry Need for lightning protection should be evaluated
Rotary potentiometer or rotary transformer	Constant-tension wires with constant-force springs	Long range Can be read with dial indicator or micrometer to check electrical reading Can be read initially with dial indicator or micrometer and later converted to electrical transducer	Precision likely to be reduced by hysteresis in springs Need for lightning protection should be evaluated
Vibrating wire	Rods, or variable-tension wires with coil springs	Lead wire effects minimal Disconnect fittings can be used[b] or downhole wire friction can be examined[c]	Special manufacturing techniques required to minimize zero drift Need for lightning protection should be evaluated

Table 12.7. ***(Continued)***

Transducer	Rods or Wires	Advantages	Limitations
Induction coil (e.g., Figures 12.60, 12.61)	Rod	No need for strong mechanical connection between transducers and rock Lead wire effects minimal Radio telemetered SPBX available	Need for lightning protection should be evaluated
Magnetostrictive (sonic probe) (e.g., Figure 12.62)	Rods	MPBX requires only one transducer MPBX requires only a single six-conductor cable Disconnect fittings can be used[b] Can be read with dial indicator or micrometer to check electrical readings Can be read initially with dial indicator or micrometer and later converted to electrical transducer	Signal requires amplification if lead wires are longer than about 600 ft (200 m) Need for lightning protection should be evaluated

[a]For additional comparative data between use of rods or wires, downhole anchor types, and SPBX or MPBX configurations, see Sections 12.7.1.–12.7.3. Mechanical transducers should be used in preference to electrical transducers wherever access is available. Assuming that the deepest anchor or the head can serve as an immovable reference point, precision of all extensometers is generally ±0.001–0.005 in. (±0.03–0.13 mm).

[b]If untensioned rods are used, or if rods are temporarily detensioned, downhole friction can be examined by using bayonet disconnect fittings between rods and downhole anchors. See Section 12.7.1.

[c]This can sometimes be done by moving the head outward a known distance. See Section 12.7.1.

to their use as transducers for fixed borehole extensometers. In general, each transducer can be used with any of the anchor types, and with a single-point or multipoint system. Table 12.7 provides comparative data on various combinations of transducers, rods, and wires. Selection of a particular arrangement depends on site-specific conditions and needs, instrument availability, and experience of installation personnel.

Dial Indicator or Micrometer

Depth micrometers are more rugged than dial indicators and thus are preferred; micrometers with digital counters capable of reading movements to 0.001 in. (0.03 mm) are preferable. A minimum of two should be available in case one is damaged. Dial indicators and micrometers should be checked regularly against a standard to verify that there has been no change in the zero reading, and most geotechnical instrumentation manufacturers will supply a pipe with one end closed for this purpose.

Suspended Weights

The *suspended weight* arrangement shown in Figure 12.45 can be used for reading fixed borehole extensometers. Excellent tension control is provided, and the arrangement is well suited for multipoint wire extensometers where access is available and where the bulky head arrangement can be tolerated. Whittaker and Woodrow (1977) describe the design and performance of an extensometer with suspended weights.

Hedley (1969) describes a useful technique to examine downhole friction characteristics and to verify precision, whereby readings are always taken at two different but standard wire tensions. The difference in reading at these two tensions should be the same every time a set of readings is taken. A small

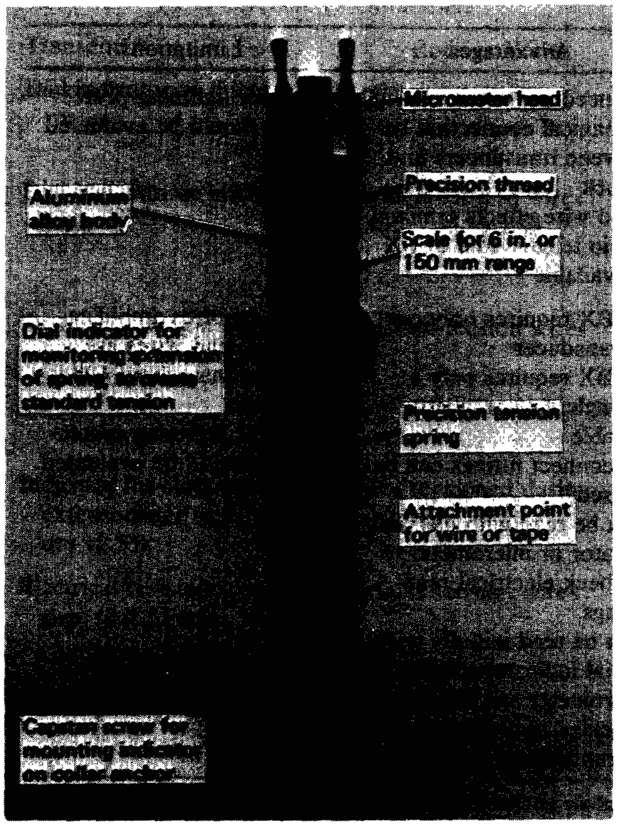


Figure 12.55. Indicator for slack-wire extensometer: Mark 2 model (courtesy of Terrascience Systems Ltd., Vancouver, Canada).

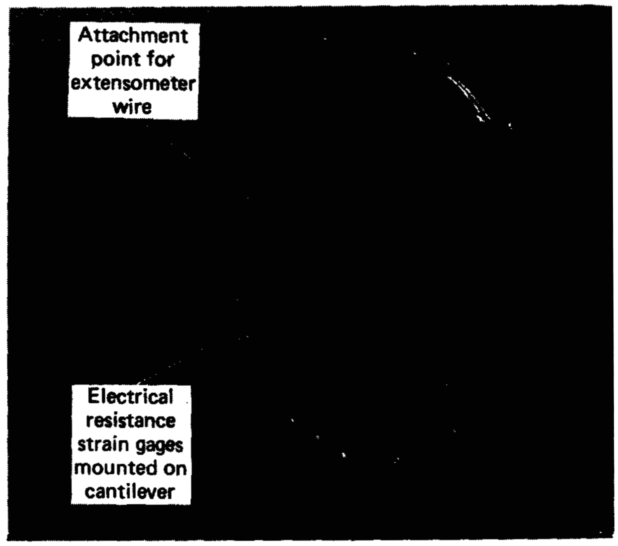


Figure 12.56. Extensometer head with electrical resistance strain gage transducers (courtesy of Slope Indicator Company, Seattle, WA).

change could mean that friction in the borehole has altered, while a major change indicates that the wire is obstructed or the borehole has sheared and clamped the wires. The readings at two tensions provide a means of determining the location of any obstruction.

Indicator for Slack-Wire Extensometer

The *slack-wire* extensometer indicator (Potts, 1957) allows application of standard tension to a wire and includes a micrometer for reading deformation. As shown in Figure 12.55, the capstan screw of the Mark 2 version is threaded on to the collar anchor, the extensometer wire is connected temporarily to the attachment point, tension is applied to the wire by rotating the micrometer head until the dial indicator reads a standard value, and the micrometer is read. When used with a multipoint system, the micrometer head is retracted, the first wire removed from the attachment point and replaced with a second wire, and the procedure repeated. The indicator can be used with wires up to 600 ft (180 m) long and has a reading range of 6 in. (150 mm.)

The lighter Mark 1 version is limited to extensometer wire lengths up to about 100 ft (30 m), and tension is applied directly by turning the micrometer. The thread within the micrometer must therefore sustain the full tension; there is a risk of stripping the thread, and the author does not favor this version.

Readings are usually taken at two different but standard wire tensions as described previously for the suspended weight system, and the difference in the two micrometer readings should always be the same.

Electrical Resistance Strain Gage Transducer

Figure 12.56 shows an eight-point extensometer head with electrical resistance strain gage transducers, using cantilevers to exert wire tension. Strain gages are connected in half bridge networks, but full bridge networks are available as an option. Relative deformation between the collar anchor and a downhole anchor causes bending of the corresponding cantilever and change in strain gage reading. Backup mechanical readings can be made by inserting a dial indicator through holes in the cover plate, to bear against each cantilever near its tip. Wire tension varies as movement occurs, and wire

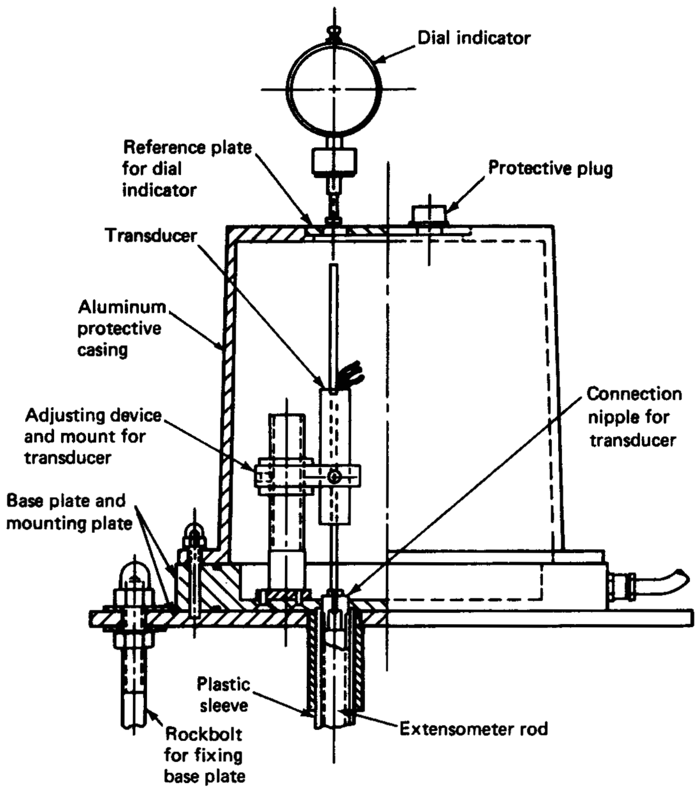


Figure 12.57. Head for fixed borehole extensometer (courtesy of Interfels GmbH, Bentheim, West Germany).

stretch factors must be accounted for by calibration or computation. This type of head is not currently used extensively.

LVDT, DCDT, and Linear Potentiometer

LVDTs, DCDTs, and linear potentiometers are all used as transducers for single-point and multipoint borehole extensometers. Comparisons among the three types are given in Chapter 8.

A single-point version is shown in Figure 12.57, and a similar arrangement is in use for multipoint versions. The arrangement allows for remote readings and also for backup mechanical readings.

Normally, all transducers are housed in an extensometer head as shown in Figure 12.57, but an alternative multipoint configuration is available with the transducers in series. In the series configuration, a transducer is mounted between each anchor, using appropriate lengths of extensometer rod. An example is shown in Figure 12.58 and is installed by inserting each anchor/transducer/rod module in turn and setting the mechanical anchor with an installation tool. Each module is spring loaded so that the downhole end of each rod can contact the adjacent anchor at any point on its surface. The system is retrievable. The series configuration gives a more direct measurement of relative deformation between adjacent anchors and increases reliability where the extensometer head is subject to mechanical damage. However, the transducers are less readily accessible for any necessary checking and maintenance, and this is generally a disadvantage. In very deep holes the series configuration may be the system of choice, because it overcomes the need for very long rods.

Rotary transducers can be used when a long range is required. When downhole wires are used, each wire passes over a pulley in the head and is attached to a constant-force spring. A single-turn or multiturn rotary potentiometer or rotary transformer is mounted on the axle of the pulley, so that relative movement between the collar anchor and

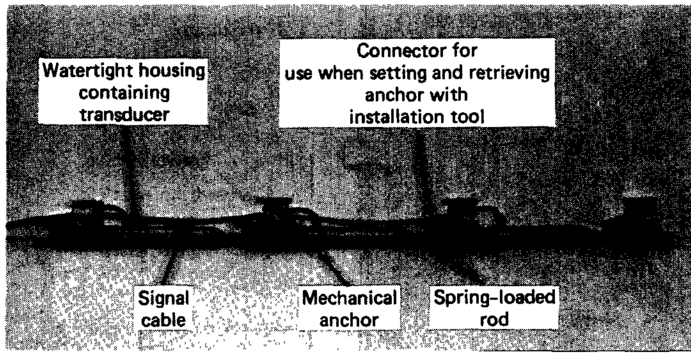


Figure 12.58. Fixed borehole extensometer, with LVDTs, DCDTs, or linear potentiometers mounted in series: Roctest Model BOF-EX (courtesy of Roctest Ltd., Montreal, Canada).

the downhole anchor causes an output change. When downhole rods are used, a flexible wire is attached to the end of each rod and passes over a pulley. Shuri and Green (1987) describe an extensometer head of this type.

Versions of fixed borehole extensometers with LVDT, DCDT, and linear potentiometer transducers are available for monitoring bottom heave at the base of open cut excavations. The arrangement is shown in Figure 12.59, requiring that a borehole is drilled to below the anticipated seat of heave, and setting a deep anchor. A sleeved rod spans between the anchor and an electrical linear displacement transducer set below the eventual bottom of the excavation, such that any change in distance between the transducer and deep anchor causes an identical movement within the transducer itself. An electrical cable passes up the borehole to the ground surface, and arrangements are made for damage protection and cable retrieval as described in Section 12.5.7 for the probe extensometer with a magnet/reed switch transducer. The upper connector on the coiled electrical cable is attached to the expanding plug, so that a gage reading can be made whenever the plug is retrieved. Several transducers can be set in the same borehole, each with a rod attached to the deep anchor, to provide a pattern of heave measurement with depth. If the transducers are functioning on completion of excavation, a multiconductor cable can be spliced to the separate coiled cables and routed to a suitable remote location for subsequent monitoring of recompression settlements.

Vibrating Wire Transducer

Conventional vibrating wire transducers have insufficient range for direct use in fixed borehole extensometers, but if a coil spring is added in series with the extensometer wire and vibrating wire, adequate range is created.

Induction Coil Transducer

A transducer with a frequency-displacement induction coil, described in Chapter 8, is used by Telemac in their *Distofor* fixed borehole extensometer (Bellier and Debreuille, 1977; Bordes and Debreuille, 1983). As shown in Figure 12.60, steel rings are mounted within telescoping PVC pipe couplings, and the system is grouted within a borehole. A single central rod is inserted through all rings, with a primary coil mounted on the rod alongside each ring. Changes in frequency output are con-

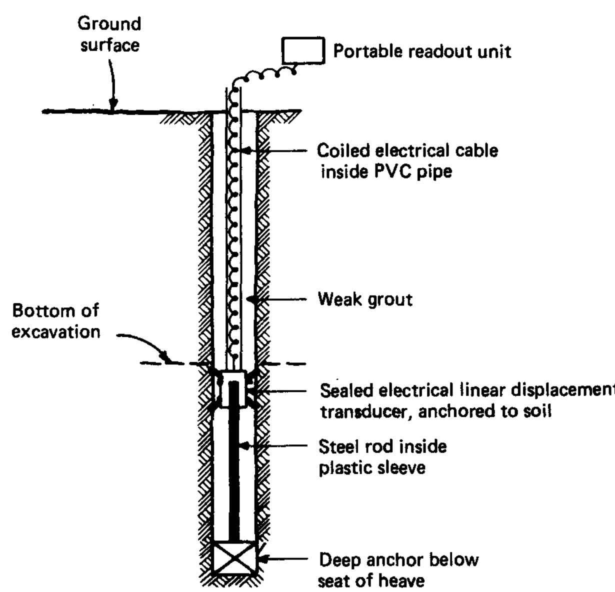


Figure 12.59. Schematic of fixed borehole extensometer arranged for monitoring heave at the bottom of open cut excavations.

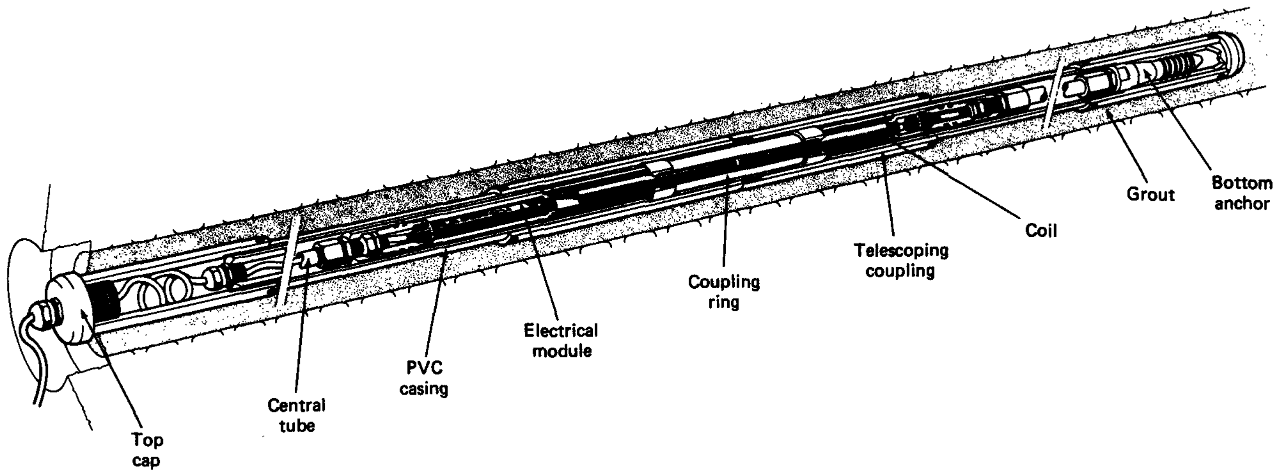


Figure 12.60. ***Distofor*** **fixed borehole extensometer (courtesy of Telemac, Asnières, France).**

verted to deformation, using conversion tables, with a measurement precision of about ±0.001 in. (±0.03 mm) and a range of ±2.5 in. (±60 mm). Londe (1982) indicates that the fundamental advantage of this instrument over conventional fixed borehole extensometers using rods or wires is the absence of any strong mechanical connection between the transducers and the rock.

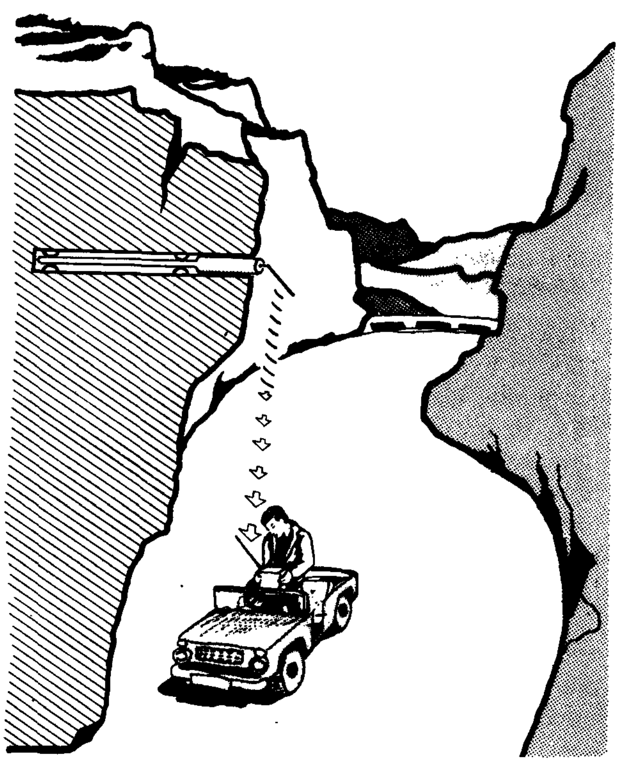


Figure 12.61. ***Radiofor*** **single-point fixed borehole extensometer (courtesy of Telemac, Asnières, France).**

The single-point version shown in Figure 12.61, the *Radiofor,* can be read remotely with a portable battery-operated indicator. The frequency output is transmitted as a radio signal, thus overcoming the need for lead wires. Operating range for the signal in tunnels is reported as 60 ft (20 m), elsewhere 1000 ft (300 m). The device was originally developed for monitoring tunnel convergence during driving but is also suitable for monitoring deformations of rock slopes. The transmitter and sensor are recoverable.

Magnetostrictive Transducer

The *magnetostrictive transducer (sonic probe),* described in Chapter 8, can be either left in place at the extensometer head or used as a portable "wand." The head arrangement is shown in Figure 12.62. A bar magnet is mounted on each rod, near the collar anchor, and the distance is measured between each magnet and a reference magnet mounted in the head.

12.7.5. Installation of Fixed Borehole Extensometers

When planning installation procedures, one should follow the Chapter 17 guidelines. Particular attention should be given to whether groundwater must be prevented from passing along the borehole. If an open borehole is unacceptable, it should be filled with grout, and downhole components must be se-

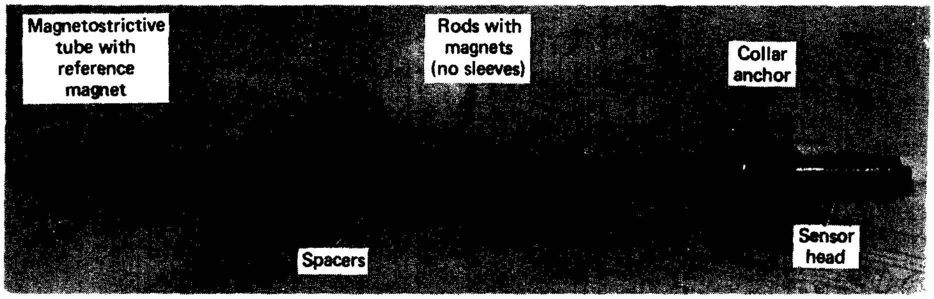


Figure 12.62. Head arrangements for fixed borehole extensometer with magnetostrictive transducer (*sonic probe*) (courtesy of Irad Gage, a Division of Klein Associates, Inc., Salem, NH).

lected accordingly. Additional points are given in the following subsections.

Borehole Requirements

Most fixed borehole extensometers have minimum and maximum allowable borehole diameters, and selection of the instrument should be influenced by available methods for drilling the borehole. Sometimes the allowable diameter variation is very small, and *go* and *no-go* gages may be required to check whether the borehole falls within the allowable tolerance.

If possible, boreholes for multipoint extensometers should be arranged such that either the collar anchor or deepest downhole anchor can be used as an immovable reference point. This assessment should be based on the geology, the geometry of the excavation or structure, and on other site-specific features. If fixity is in doubt, provision should be made to monitor absolute deformation of the collar anchor on a regular basis, using surveying methods or a convergence gage. Anchor locations should also be based on geology and geometry, and clearly cored holes are helpful. If not determined from rock cores, discontinuities can sometimes be located by borehole television or borescope surveys.

Where excavation will occur close beneath the deepest anchor, for example, a tunnel, a "telltale" consisting of a colored plastic tube may be attached to the anchor to protrude into the path of the future excavation. Subsequent exposure of the telltale indicates the borehole location.

Installation of Downhole Components

When multipoint borehole extensometers are assembled, the various rods or wires must not become entangled. Correct relative positions must be ma tained at all times. Color coding is often helpf with corresponding colored marks around t mouth of the borehole.

When using groutable anchors, the guidelin given in Section 17.5.6 should be followed. A thi cement grout is normally used, and no sand shou be included in the mix. When used in rock whe predicted deformations are compressive, gro strength should be weakened by use of additiv Buoyancy forces must be overcome, and gro pressure must be controlled to avoid collapse of t sleeves protecting extensometer rods or wires. flexible plastic tubing is used for the sleeves, risk collapse can be avoided by filling the tubes with and pressurizing the oil with a hand pump un grout sets. More details of these procedures a given in Chapter 17.

12.7.6. Subsurface Settlement Points

Subsurface settlement points are categorized in th book as fixed borehole extensometers but are us for monitoring absolute deformation rather than r ative deformation between a collar anchor and downhole anchor. Typical applications are for mo itoring settlement below embankments and su charges, above soft ground tunnels or adjacent braced excavations, and for monitoring uplift du ing grouting operations.

The device consists essentially of a riser pi anchored at the bottom of a vertical borehole and outer casing to isolate the riser pipe from downdr forces caused by settlement of soil above the a chor. Settlement of the anchor is determined b measuring the elevation of the top of the riser pip using surveying methods. Three arrangements a

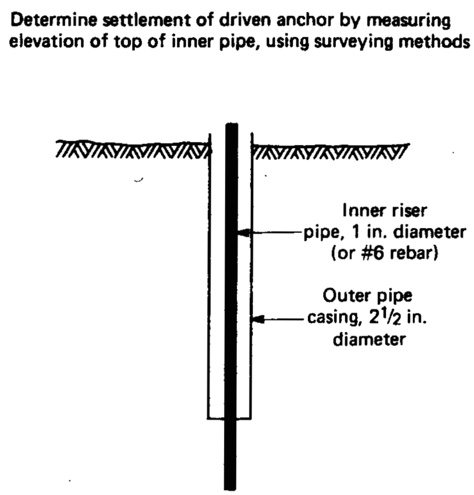


Figure 12.63. Schematic of subsurface settlement point with driven anchor.

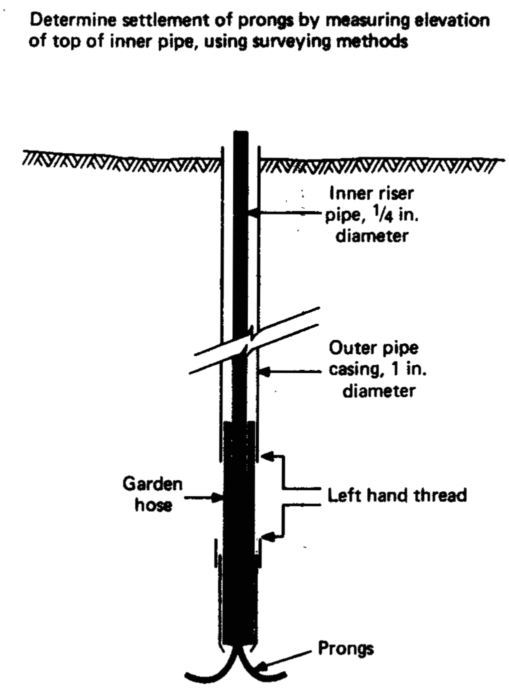


Figure 12.64. Schematic of Borros anchor.

in common use and are described in the following subsections.

Driven or Grouted Anchor

A typical arrangement, sometimes referred to as a *deep settlement point*, is shown in Figure 12.63. Outer pipe casing is driven to the required depth and cleaned out. If the casing is set in a predrilled hole, the annular space between the casing and borehole should be backfilled with sand, pea gravel, or grout, and any grout should be allowed to set before the riser pipe is installed. The riser pipe is then inserted and driven 1–3 ft (300 mm to 1 m) below the bottom of the casing. A rounded reference surface is often attached to the top of the riser pipe and the arrangement protected by a surface cover. Details are given by Cording et al. (1975).

When a more secure anchor is required, a measured quantity of grout can be tremied to the bottom of the borehole before inserting the riser pipe, the riser pipe driven through the grout, and the outer casing bumped back so that its bottom remains about 1 ft (300 mm) above the top of the grout.

Borros Anchor

The *Borros anchor,* or *Geonor settlement probe,* is shown in Figure 12.64. The anchor consists of three steel prongs housed within a short length of 1 in. (25 mm) steel pipe, with points emerging from slots in a conical drive point. The upper end of the 1 in. (25 mm) pipe has a left-hand thread, and 0.25 in. (6 mm) steel pipe is welded to the tops of the prongs.

A borehole is advanced to a few feet above the planned anchor depth and the anchor inserted by attaching extension lengths of riser and outer pipe. All threads are wrench-tight, except the left-hand thread, which is greased and hand-tight. When the point reaches the bottom of the borehole, it is driven 1–3 ft (300 mm to 1 m) by driving on the top of the outer pipe. The prongs are then ejected by driving on the riser, the left-hand thread opened by turning the outer pipe clockwise, and the outer pipe bumped back a distance larger than the anticipated vertical compression of the soil above the anchor. Any drill casing used to advance the borehole is then withdrawn.

The Borros anchor provides a more positive anchorage than the driven anchor. However, although a frequently used and simple device, a problem can arise owing to binding of the riser where it exits from the bottom of the outer pipe, such that downdrag forces cause settlement of the prongs. The problem can be minimized by installing an O-ring bushing or a length of greased garden hose in the annular space at the bottom of the pipes. Settlement of the prongs in soft clays can also be caused by the weight of the riser, particularly during the

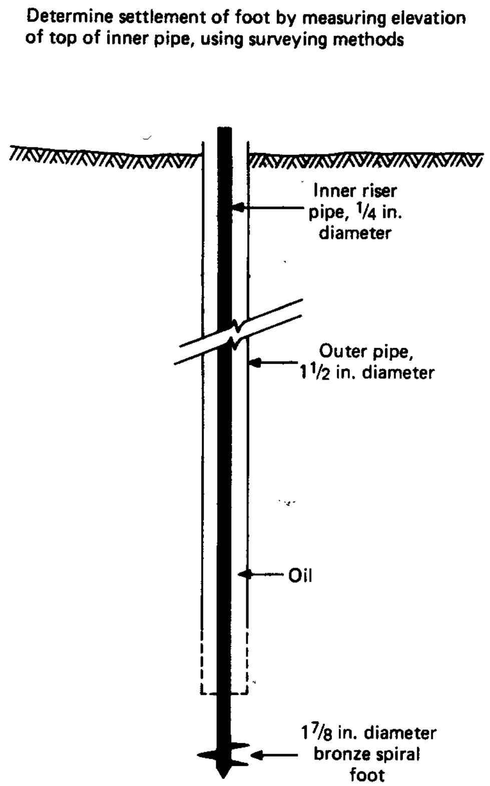


Figure 12.65. Schematic of spiral-foot subsurface settlement point.

period soon after installation, when soil strength is reduced by high pore water pressures that are created as prongs are ejected. The top of the riser should be supported to avoid settlement of the prongs during this period. Longer-term settlement of the prongs with respect to surrounding soft clay can be avoided by counterweighting the riser pipe at the top with a rope, pulley, and weight.

Spiral-foot Anchor

The *spiral-foot anchor,* shown in Figure 12.65, overcomes some of the problems described above for the Borros anchor.

The anchor consists of one or more turns of a bronze helical auger (Bozozuk, 1968) and is connected to a 0.25 in. (6 mm) steel riser pipe. A borehole is advanced to a few inches above the planned anchor depth and the spiral-foot, riser pipe, and outer casing inserted. The spiral-foot is screwed down to the required elevation, and the outer casing is raised and the drill casing withdrawn as for the Borros anchor. Oil is pumped down the riser pipe, out through holes provided just above the foot, and up into the outer casing, providing protection from corrosion and against damage from freezing. Increased anchorage can be obtained by using additional auger turns or a larger diameter auger, but the arrangement appears to suffer from the same potential problem of pipe binding, discussed previously for the Borros anchor. Again, use of garden hose or an O-ring bushing should overcome this problem, provided that the holes for oil outlet are drilled sufficiently high up the riser pipe.

Assuming that the riser pipe is properly anchored and sleeved, measurement accuracy of all three arrangements depends on accuracy of surveying methods, and ±0.1 in. (±3 mm) is typical.

When the riser pipe is carried upward through fill, compaction around the pipe cannot be made with large compaction equipment; thus, compaction tends to be inferior. Interruption to normal filling is costly, and damage by construction equipment is possible. Other limitations are the potential for cumulative errors owing to the addition of pipe lengths and the requirement for a survey crew when taking readings. Liquid level gages (Section 12.10) sometimes provide an alternative measurement method.

12.7.7. Rod Settlement Gage

A single-point fixed borehole extensometer can be used for precise monitoring of ground surface settlement or heave, by using a deep benchmark arrangement similar to the one shown in Figure 12.7 and attaching a dial indicator to the top sleeve. The dial indicator stem bears on the top of the riser pipe to provide data for direct determination of absolute settlement without the need for a survey crew. The system is referred to in this book as a *rod settlement gage* but is also called a *precision settlement gage.* Accuracy is generally ±0.002–0.005 in. (±0.05–0.13 mm). The gage can also be used as a benchmark for surveying methods.

12.8. INCLINOMETERS*

Inclinometers fall within the category of *transverse deformation gages* (Section 12.9) but, because they are used so much more widely than alternative transverse deformation gages, they merit a separate section in this book.

*Written with the assistance of P. Erik Mikkelsen, Vice President, Slope Indicator Company, Seattle, WA.

Inclinometers are defined as devices for monitoring deformation normal to the axis of a pipe by means of a probe passing along the pipe. The probe contains a gravity-sensing transducer designed to measure inclination with respect to the vertical. The pipe may be installed either in a borehole or in fill, and in most applications is installed in a near-vertical alignment, so that the inclinometer provides data for defining subsurface horizontal deformation. Inclinometers are also referred to as *slope inclinometers, probe inclinometers,* and *slope indicators.*

Typical applications include the following:

1. Determining the zone of landslide movement.
2. Monitoring the extent and rate of horizontal movement of embankment dams, embankments on soft ground, and alongside open cut excavations or tunnels.
3. Monitoring the deflection of bulkheads, piles, or retaining walls.

Some probes can be operated within a horizontal pipe, for monitoring settlement of embankments, oil tanks, and other structures on soft ground, and in this application are an alternative to full-profile liquid level gages (Section 12.10). Measurements within an inclined pipe are also possible, for example, when monitoring deformation of the upstream face of concrete face rockfill dams. In addition to their use for deformation monitoring, inclinometers can be used for absolute determination of position, for example, in borehole directional surveys, and for determining the alignment of piles and slurry trenches. Inclinometers have also been used to estimate bending moments: this application is discussed in Section 12.8.11.

Most inclinometer systems have four major components:

1. A permanently installed guide casing, made of plastic, aluminum alloy, fiberglass, or steel. When horizontal deformation measurements are required, the casing is installed in a near-vertical alignment. The guide casing usually has tracking grooves for controlling orientation of the probe.
2. A portable probe containing a gravity-sensing transducer.
3. A portable readout unit for power supply and indication of probe inclination.

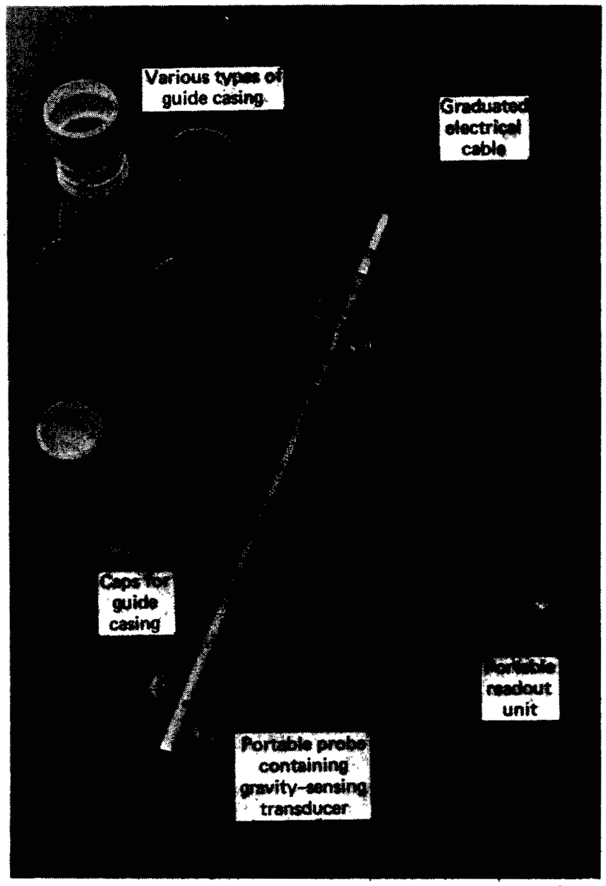


Figure 12.66. Inclinometer system: Slope Indicator Company Digitilt® system (courtesy of Slope Indicator Company, Seattle, WA).

4. A graduated electrical cable linking the probe to the readout unit.

Examples of these components are shown in Figure 12.66.

Figure 12.67 shows the normal principle of inclinometer operation for near-vertical guide casings. After installation of the casing, the probe is lowered to the bottom and an inclination reading is made. Additional readings are made as the probe is raised incrementally to the top of the casing, providing data for determination of initial casing alignment. The differences between these initial readings and a subsequent set define any change in alignment. Provided that one end of the casing is fixed from translation or that translation is measured by separate means, these differences allow calculation of absolute horizontal deformation at any point along the casing.

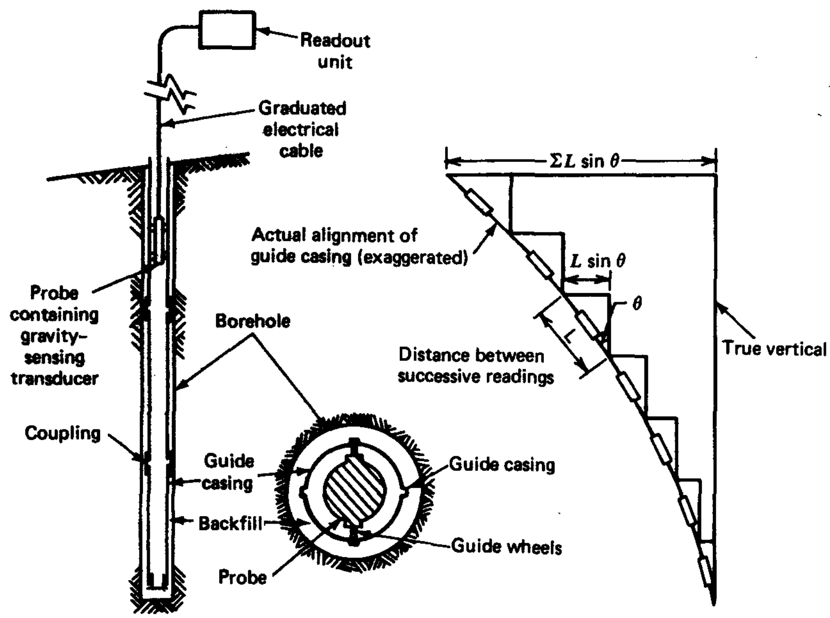


Figure 12.67. Principle of inclinometer operation.

Inclinometers are described in many publications, including Gould and Dunnicliff (1971), Green and Mikkelsen (1986), ISRM (1981a), and Wilson and Mikkelsen (1978).

12.8.1. Types of Inclinometer

Inclinometer types in common use are described in the following subsections, and comparative information is given in Table 12.8. Most inclinometers provide casing inclination data in two mutually perpendicular near-vertical planes. Thus, horizontal components of movement, both transverse and parallel to any chosen direction, can be computed from the measurements.

Inclinometer with Force Balance Accelerometer Transducer

A force balance accelerometer is mounted in the probe such that voltage output is proportional to inclination. The biaxial version includes two transducers, one mounted below the other, with sensing planes 90 degrees apart. The force required to balance the mass, and thus the output voltage, is directly proportional to sin θ (Figure 12.67); therefore, the digital readout is used directly in calculations. The inclinometer with force balance accelerometer transducer has become the most widely used type.

Manual and automatic readout units are available. Manual units are the simplest and least expensive and consist of a power supply, controls, and one or two digital displays. An example is shown in Figure 12.66. The readings are recorded on field data sheets, for later calculation by hand or electronic calculator or for input to a computer program.

Automatic readout units contain a power supply, controls, one or two digital displays, and either magnetic cassette tape or solid-state recording capability. Weeks and Starzewski (1986) describe an automatic readout unit developed in England by Geotechnical Instruments (U.K.) Ltd. and shown in Figure 12.68. Mikkelsen and Wilson (1983) describe a *Recorder–Processor–Printer (RPP)*, developed in the United States by Slope Indicator Company and shown in Figure 12.69, that has field checking, editing, data reduction, and plotting capability. Thomas (1985) presents time and cost comparisons for manual and automatic readout units manufactured by Slope Indicator Company and concludes that when the volume of inclinometer reading work exceeds 600 ft (180 m) of casing per month, the *RPP* is

Table 12.8. Inclinometers

Type of Inclinometer	Advantages	Limitations	Typical Range	Approximate Precision[a]
Force balance accelerometer transducer (e.g., Figure 12.66)	Long successful experience record Most widely used type Version available with automatic readout, recording, data reduction, and plotting provisions Versions available for use in 1.5 in. (38 mm) inside diameter grooved casing Versions available for use in horizontal casing for monitoring settlement		±30°, optional to ±90°	±0.05–0.5 in. in 100 ft (±1–13 mm in 30 m)
Slope Indicator Series 200B (Figure 12.70)	Long successful experience record	Standard version is uniaxial No provision for automatic readout No longer manufactured	±12°, optional to ±25°	±0.3–1.0 in. in 100 ft (±8–25 mm in 30 m)
Bonded resistance strain gage transducer	Version available for use in smooth 1.5 in. (38 mm) inside diameter pipe	Errors owing to moisture, temperature, and electrical connections are possible Abandoned by most manufacturers	±20°	±0.02–1.0 in. in 100 ft (±0.5–25 mm in 30 m)
Vibrating wire transducer	Long successful experience record	Special manufacturing techniques required to minimize zero drift Bulky transducer results in large probe Abandoned by most manufacturers	±20°	±0.1–0.5 in. in 100 ft (±3–13 mm in 30 m)
Electrolytic level transducer		Size of transducer limits its use to near-horizontal holes Short experience record	±40°	±2 in. in 100 ft (±50 mm in 30 m)
Shear probe (*poor man's inclinometer*) (e.g., Figure 12.78)	Simple Inexpensive	Poor precision Does not measure inclination Cannot determine curvature below point of smallest curvature	±30°	Very crude

[a] Defined as repeatability with which the instrument can determine the horizontal position of one end of a near-vertical casing with respect to the other (±1 in. in 100 ft corresponds to about ±25 mm in 30 m, $\pm 8 \times 10^{-4}$ radian, or ±170 arc-seconds). Repeatability in near-horizontal casings is similar. Repeatability is decreased in inclined casing: see Section 12.8.2.

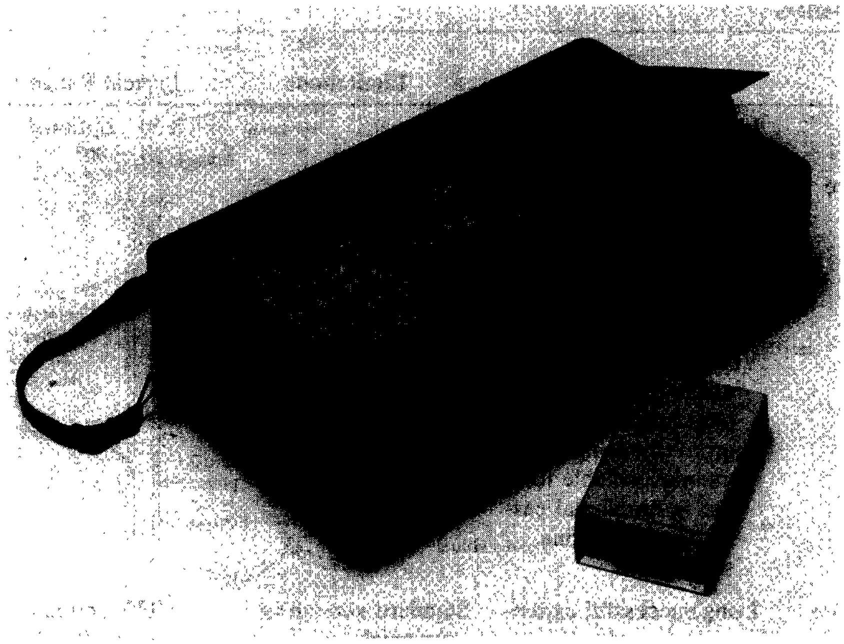


Figure 12.68. Solid-state data logger for inclinometer (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England).

more economical than alternative readout units available from the same manufacturer.

Slope Indicator Series 200B

The Slope Indicator Series 200B uniaxial inclinometer (Figure 12.70), manufactured until recently by Slope Indicator Company, has a potentiometric transducer for measuring inclination. Major components of the transducer are a free-swinging pendulum and an arc-shaped resistance coil, mounted so that the center of the arc corresponds with the pivot of the pendulum. The tip of the pendulum acts as a wiper on the resistance coil, subdividing the coil into two resistances that form one-half of a balance bridge circuit. Resistance output depends on the position of the tip on the resistance coil and thus on the inclination of the probe. The other half of the bridge, including switches, batteries, and potentiometer indicator, is enclosed in the readout unit. Cornforth (1974) and Green (1974) give performance details.

Inclinometer with Bonded Resistance Strain Gage Transducer

Bonded resistance strain gages are mounted around a pendulum that is not free to pivot at its upper end. Tilt causes bending strains in the pendulum and a change in strain gage output. A Wheatstone bridge circuit is used for monitoring.

Green (1974) compares the performance of a bonded resistance strain gage inclinometer with the Slope Indicator Series 200B. Kallstenius and Ber-

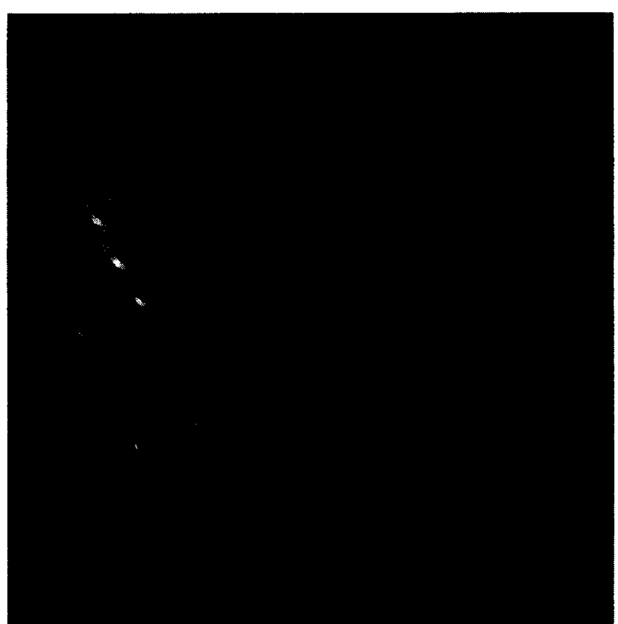


Figure 12.69. Recorder–Processor–Printer (RPP) for Digitilt® inclinometer (courtesy of Slope Indicator Company, Seattle, WA).

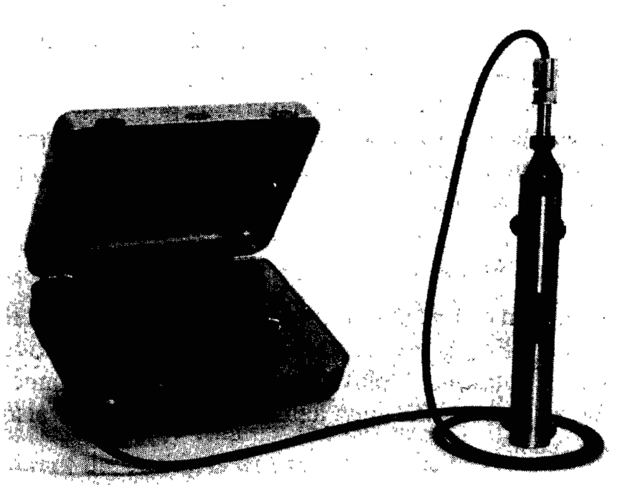


Figure 12.70. Slope Indicator Series 200B inclinometer (courtesy of Slope Indicator Company, Seattle, WA).

gau (1961) describe a bonded resistance strain gage inclinometer, developed by the Swedish Geotechnical Institute, that operates within a standard 1.5 in. (38 mm) inside diameter PVC pipe. The inclinometer is attached to orientation rods, and precision is reported as ±0.4 in. in 100 ft (±10 mm in 30 m).

Inclinometer with Vibrating Wire Transducer

Vibrating wire transducers are mounted on a stiff pendulum in a similar configuration to the inclinometer with a bonded resistance strain gage transducer. Two transducers are required for uniaxial tilt monitoring, four for biaxial monitoring. The readout unit houses power supply, controls, and a frequency counter.

Inclinometer with Electrolytic Level Transducer

An inclinometer with electrolytic level transducer is described by Gravina and Carson (1983) for operation within 1.4 in. (36 mm) inside diameter drill rods in near-horizontal holes. The instrument has been designed for borehole directional surveying in coal mines as drilling of gas drainage holes progresses. A self-orienting mechanism, including a DC motor, slip rings, and mercury switch, is provided to orient the electrolytic level transducer into a vertical plane prior to each reading. A piston is mounted on the front of the probe to allow the probe to be driven along the drill rods under water pressure, while the instrument cable passes through a stuffing box mounted on the outer end of the drill rods.

Cooke and Price (1974) report on the use of inclinometers with electrolytic level transducers, but with their version it was not possible to locate the instrument in exactly the same positions for each set of readings. An in-place version (Section 12.9.3), with a train of transducers, was found to be more satisfactory.

Shear Probe

Although it does not measure inclination, the simple *shear probe* described in Section 12.9.1 is also referred to as a *poor man's inclinometer*.

12.8.2. Factors Affecting Precision of Inclinometer Data

Factors affecting precision of inclinometer data are discussed in the following subsections. However, the overriding factor within control of the user is the skill and care of personnel responsible for all phases of the measurement program.

Precision of Gravity-Sensing Transducer

Manufacturers normally specify the precision of the gravity-sensing transducer, and a systematic check should be made on a regular basis to ensure that the transducer is functioning satisfactorily (Section 12.8.6).

Errors can be grouped into three categories: *scaling, zero offset,* and *azimuth rotation.* The scaling of a transducer is the relationship between input and output and defines the slope of the calibration plot. The zero offset (also called *bias*) of an inclinometer is the reading when the probe is in a true-vertical alignment. Azimuth rotation error results from the difference in orientation between the axis of the transducer and the wheel assembly on the probe, and this cannot be set during manufacture to closer than about ±0.5 degree. All three sources of error can be created by rough handling, wear of the wheel carriage, electronic aging, and temperature change.

Design and Condition of Wheel Assembly

Wilson and Mikkelsen (1977) indicate that the probe should have a well-designed wheel carriage with little or no side-play in the wheels, axle, and swing-arm assemblies. Preferably, wheels should have sealed double ball bearings, and the wheel profile should be compatible with the geometry of the grooves in the casing. During extensive use, these parts wear out more than other parts and should be easy to replace when worn excessively.

Casing Alignment

Table 12.8 includes approximate values for precision with which various inclinometers can be used to determine the horizontal position of one end of a near-vertical casing with respect to the other end. When an inclinometer probe is to be used for vertical deformation measurements in near-horizontal casing, the gravity-sensing transducer is mounted with its axis perpendicular to the long axis of the probe. Precision in near-horizontal casings is similar to near-vertical casings and may on occasion be better because greater control of groove orientation is usually possible when casing is installed horizontally in a trench. Precision degrades as the alignment of near-vertical casings deviates from vertical, and as the alignment of near-horizontal casings deviates from horizontal.

When an inclinometer probe is to be used in inclined casing, two approaches are possible. The first approach uses a conventional "vertical" probe in casings inclined within 45 degrees of vertical and a conventional "horizontal" probe in casings inclined within 45 degrees of horizontal. With this approach the transducer will not be working in the most sensitive part of its range, but this is a small price to pay for the ability to use the *check-sum* procedure, described in Section 12.8.9. The second approach uses the conventional probes in casings inclined within approximately 25 degrees of vertical and horizontal and a special probe for the remaining inclinations. In this special probe the transducer is mounted so that its axis is approximately vertical when the probe is within the inclined casing. Although the transducer is now working in the most sensitive part of its range, the *check-sum* procedure cannot be used, and the second approach is not recommended.

When measurements are made in inclined casings, changes in azimuth can cause substantial errors. For example, when the casing is 5 degrees off vertical, an error of 2 in. per 100 ft (50 mm per 30 m) is caused if the azimuth changes by 1 degree (Wilson and Mikkelsen, 1978). A detailed discussion of errors in inclined casings is given by Mikkelsen and Wilson (1983).

Penman and Hussain (1984) describe an ingenious method for making deformation measurements on the upstream face of an embankment da with an upstream asphaltic membrane. Rather th running an inclinometer within inclined casing, t inclinometer remains near-vertical and is track down the upstream face on a trolley device, therel overcoming difficulties associated with inclin measurements.

Casing Diameter

Precision can be maximized by using large-diamet casing. For a given wheel thickness and groo width, rotational "play" decreases as casing diam ter increases, and thus azimuth rotation error al decreases.

Borehole Backfilling Procedure

Poor-quality backfilling around the casing m cause scatter in readings shortly after installatio but usually the backfill will stabilize with time. maximum precision is required, the boring proc dure should be planned to minimize disturbance surrounding ground, and backfill should fill the a nular space completely. Grout backfill is general more effective than a compacted granular backfi Installation procedures are described in Secti 12.8.4.

Spiraling of Casing

When casing is installed in boreholes, the orient tion of the casing grooves at depth is not necessari the same as at the surface. Extrusion of aluminu casing may cause a spiral as large as 1 degree per ft (3 m) length, and similar deviations have be noted in extruded and machine-grooved plastic ca ing. Green (1974) measured a spiral of 18 degrees an 80 ft (24 m) length of coupled extruded plast casing, and others have reported similar measur ments. Exposure to hot sunlight prior to installati will often cause spiraling of initially true plastic ca ing, and lengths should always be stored in t shade and supported adequately to avoid bendin

The spiral of each length can be measured befo installation. For example, lengths of casing can set on V-blocks on a bench and a plumb line nylon filament hung alongside each end. Spiral c be estimated to about 1 degree by setting one e parallel to the plumb line, making sure the casing not twisted by placement in the blocks, and obser ing by eye at the other end. Alternative methods f measuring the spiral of individual lengths are ava able from casing manufacturers: for example, Slope Indicator Company has a method that uses a standard biaxial inclinometer within casing held in a near-horizontal alignment.

If possible, lengths of casing should be selected so that successive spirals cancel out each other.

Spiraling can also be created by using poor installation techniques. When lengths of casing are assembled, alternate couplings should be twisted left and right before fixing, because manufacturing tolerances usually allow for some rotational movement. If grooves turn out of the planned orientation during installation, they should never be forced back merely by rotating the casing top. If the bottom of the casing is free to rotate, the top should be raised and lowered repeatedly as the orientation is gradually corrected. Drill casing and hollow-stem augers should be withdrawn without rotation.

When casing is installed in fill, groove orientation is easier to control, and spiraling usually does not degrade precision in near-vertical and near-horizontal installations. However, as discussed above, errors in inclined casings can be large.

A survey of spiral after casing installation is recommended when difficulties have occurred during installation and for casings deeper than about 200 ft (60 m), particularly if it is necessary to know the exact direction of ground movements at depth. A survey can be made in one of two ways. First, most manufacturers supply a spiral survey instrument (e.g., the *spiral checking sensor* shown in Figure 12.71), typically consisting of a 5 ft (1.5 m) long rod between upper and lower guide wheels, with a rotary transducer mounted at one end. Second, a system can be assembled from a dummy inclinometer probe or appropriately sized rectangular plate, connected via a universal joint to orientation rods, fitted with high-precision tongue-and-groove connections (Figure 12.71). The assembly is lowered within the casing, and orientation of the rods with respect to the top of the casing is recorded as more rods are added and the probe or plate passes down the grooves within the entire casing. Orientation can be measured with a circular protractor mounted on the top of the casing.

For a particular installation, groove spiraling does not change with time, and thus a single set of spiral survey data can be used with biaxial inclinometer data to determine true direction of deformation, or deformation in any predetermined plane. Adjustment of data to correct for groove spiral entails graphic or computerized data reduction.

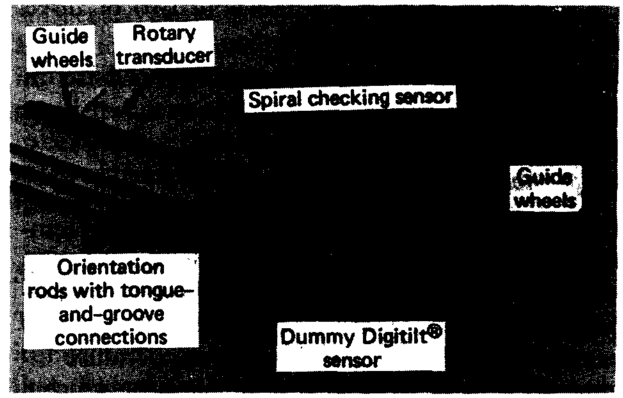


Figure 12.71. Instruments for measuring spiral in inclinometer casing after installation (courtesy of Slope Indicator Company, Seattle, WA).

Repeatability of Reading Position

Any lack of care in repeating depth measurements to the inclinometer probe with each set of readings will markedly reduce precision. The cable should not be subject to stretch or slip between the components of the cable and should be marked permanently and accurately. This source of error increases with increasing length of casing and is aggravated if the depth of casing grooves is irregular or if installed casing is not straight, and its significance increases with increase in precision of the gravity-sensing transducer. Methods of reading in casing equipped with telescoping couplings are discussed in Section 12.8.8.

Depth Interval Between Reading Positions

Maximum precision is achieved by using a reading interval equal to the spacing between wheels on the inclinometer probe. If the interval is greater than the wheelbase of the probe and deformations of the casing are not composed of smooth curves or straight lines between measuring points, significant errors may arise. Reading with a 2 ft (610 mm) probe at depth intervals as great as 5 ft (1.5 m) could miss shear zones of vital interest entirely. However, in cases where localized movement (e.g., at a shear zone) is known to be absent, for example, as is often the case when monitoring the bending of piles during a lateral load test, reading effort can be minimized by the following method:

1. Taking readings initially at the wheelbase interval.

2. Taking subsequent readings at two or three times the wheelbase interval.
3. Taking periodic readings at the wheelbase interval as a check.

Temperature Effects

If the gravity-sensing transducer is sensitive to temperature, a change in reading may be noted as the probe enters water within the casing. Potentiometer, vibrating wire, and force balance accelerometer transducers do not exhibit major temperature effects, but bonded resistance strain gage transducers may show a greater variation in reading with change in temperature. However, in all cases a waiting period of at least 10 minutes should be allowed for temperature stabilization after the probe has been lowered to the first reading position, before readings are taken. Most readout units also show some reading variation with temperature, and for maximum precision the readout unit should not be used in extreme temperatures. Errors caused by temperature variation of the readout unit increase with increasing departure of the probe from vertical.

Handling of Probe

Shock to the probe can cause a zero shift of the transducer. Errors can be minimized by careful handling and by operating the probe only when connected to the readout unit with power switched on. The bottom of the probe should be provided with a rubber cushion, and during operation the probe should never be allowed to contact the bottom of the casing suddenly.

12.8.3. Types of Inclinometer Casing

Plastic, aluminum alloy, and fiberglass casings are available, with either rigid or telescoping couplings. Examples are shown in Figures 12.72 and 12.73. Steel casing is also available but is used less frequently.

Plastic Casing

ABS (acrylonitrile/butadiene/styrene) is the most commonly used plastic casing and is suitable for most applications. Alternative plastics, such as PVC (polyvinylchloride), tend to be more brittle, especially at low temperatures. Most plastic casing is manufactured by broaching the grooves in extruded pipe, but in some cases the pipe is grooved

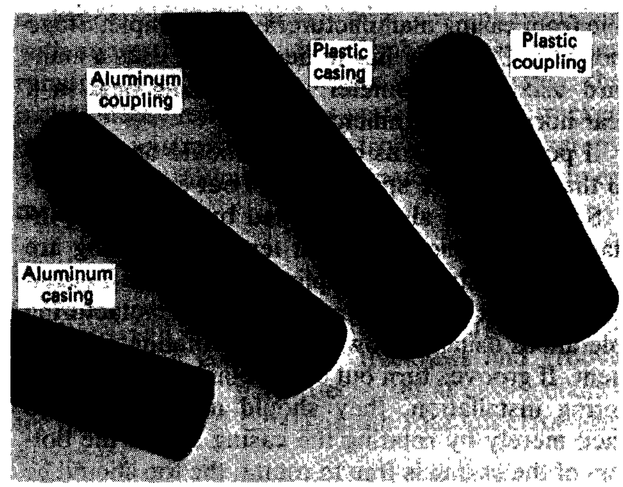


Figure 12.72. Inclinometer casing (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England).

during extrusion. Outside diameters range from 1.9 to 3.5 in. (48–89 mm).

Rigid couplings are available with self-aligning grooves or keys and are preferable to couplings requiring use of a special aligning tool. A self-aligning coupling developed by Westbay Instruments Ltd. has O-rings for sealing, and nylon shear wires to lock the coupling and casing together. These couplings are very convenient since they minimize installation time and necessary skill and allow for easy disassembly if difficulties are encountered during installation or when casing is used for borehole directional surveys, but they have a larger outside

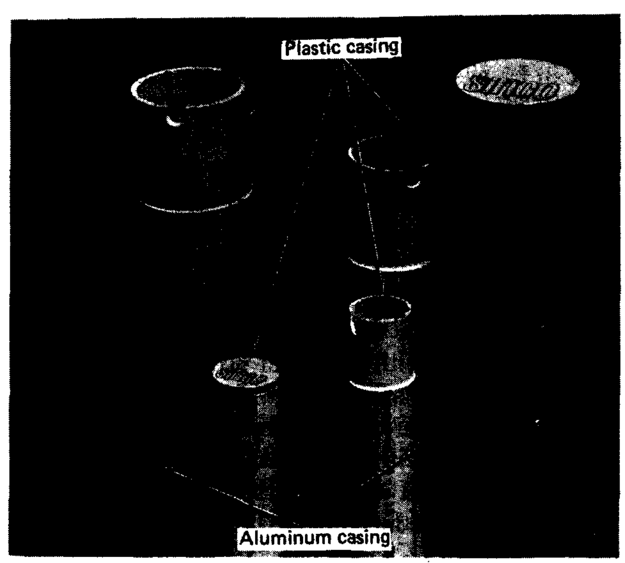


Figure 12.73. Inclinometer casing (courtesy of Slope Indicator Company, Seattle, WA).

diameter than conventional couplings. The Westbay coupling is also available with a spring-loaded port for use as a multipoint piezometer (Section 9.9) and can be installed on inclinometer casing to allow measurements of both transverse deformation and groundwater pressure.

Telescoping plastic couplings also have self-aligning grooves or keys, and standard versions typically have a telescoping range of up to 6 in. (150 mm), allowing for 9% compression when used with 5 ft (1.5 m) casing lengths. Long-range telescoping ABS couplings have recently been developed by Slope Indicator Company for use in very soft clays subjected to large vertical compression and allow for up to 30% compression (Handfelt et al., 1987).

Aluminum Casing

Aluminum alloy casing is grooved during extrusion, the groove also appearing on the outside profile as a protrusion. Outside diameters, measured across opposite protrusions, range from 2.4 to 3.4 in. (61–86 mm), and slightly larger-diameter extrusions of the same shape are used for rigid and telescoping couplings. The maximum range of telescoping couplings is typically 6 in. (150 mm).

Aluminum casing is subject to corrosion, either by groundwater or by free lime in cement grout used during installation, and several cases of total corrosion within a period of a few months have been reported. In most applications casing should therefore be treated both on the inside and outside with a suitable coating (e.g., baked-on epoxy paint), but corrosion potential remains at any cut ends or rivet holes.

Steel Casing

Seamless welded square steel tubing, available from suppliers of steel pipe, can sometimes be used as inclinometer casing, and most inclinometer probes allow the wheels to ride in the tubing corners. Possible applications include measurements on driven steel piles, applications where cost must be minimized and where lower accuracy is acceptable, and special applications when other instruments (e.g., strain gages in piles) are attached to the outside of the casing.

A 2 in. (50 mm) outside, 1.75 in. (44 mm) inside size tubing is typically used, but a larger size should be used when significant transverse deformations are expected. Alternatively, the inclinometer probe can be arranged such that wheels ride on the flat surfaces, requiring a larger size of tubing (e.g., DiBiagio and Myrvoll, 1985). Extruded steel tubing usually has excessive twist and is not recommended, but seamless welded tubing is not twisted excessively. Couplings are made from suitably sized seamless welded square steel tubing and often have a very loose fit.

Selection of Inclinometer Casing

The type of casing and coupling, together with the installation procedure, should be selected to ensure that the casing conforms with soil or rock movements. Selection among the inclinometer casing and coupling options depends on the answers to the following questions:

1. Will the casing be subject to axial compression or extension? If axial compression or extension in excess of about 1% is expected, telescoping couplings should be used to prevent damage to the casing and to ensure conformance. If a probe extensometer will be used within the inclinometer casing to monitor axial movements, the guidelines given for combined probe extensometers and inclinometer casings in Section 12.5.10 should be followed.
2. What is the predicted transverse deformation? Users sometimes express concern that inclinometer casing may be too stiff to follow transverse ground movements in soft soils. This concern implies that the soil might flow around the casing, but available evidence suggests that casing movement conforms with soil movement. However, when installed in soft soil, deformations at a distinct shear zone are likely to cause local nonconformance, such that shear measurements are more gradual than actual deformation. Deformation at a distinct shear zone will cause bending of the casing, and excessive localized bending will prevent passage of the probe. If substantial deformation is predicted at distinct shear zones, a large-diameter casing and small-diameter probe should be used. In extreme cases the casing can be installed in a large-diameter borehole and surrounded by a soft grout, as described in Section 12.8.4. Manufacturers will provide bending limits for their various probe casing combinations.

3. Is maximum precision required? As indicated in Section 12.8.2, precision can be maximized by using large-diameter casing.
4. What will be the alignment of the installed casing? When the gravity-sensing transducer is mounted with its axis at an angle to the long axis of the inclinometer probe, for example, for measurement of settlement in near-horizontal casing, the diameter of the probe will generally be larger than standard probes, and larger-diameter casing will be required.
5. What will be the climatic conditions during installation? When plastic casing is exposed to hot sunlight, groove spiraling may increase and lengths may become warped. Use of plastic casing in hot temperatures entails shaded storage. Solvent cement for plastic casing cannot be used in very cold conditions: options are therefore plastic casing with Westbay Instruments Ltd. self-aligning couplings or aluminum, fiberglass or steel casing.
6. Are there limitations on acceptable casing diameter? For example, drilling costs usually increase with borehole diameter. Where casing is installed in concrete, structural considerations may limit diameter. Where casing is installed within pipes attached to H-piles, allowable pipe diameter may be the controlling factor. If the diameter is limited, couplings that do not protrude beyond the outside diameter of the casing will usually be preferred.
7. Will installation personnel be skilled and careful? If not, Westbay Instruments Ltd. self-aligning couplings may be preferred.
8. Is longevity required? Major factors are groundwater alkalinity or free lime in cement grout used during installation and the existence of stray ground currents, which may be present in urban environments. If pH is greater than about 10 or if stray ground currents are suspected, plastic casing should be used. When aluminum casing is used in alkaline conditions, both the inside and outside should be treated with a suitable coating to prevent corrosion.
9. What is the depth of the installation? Users sometimes favor aluminum casing in very deep installations, fearing that plastic casing may be damaged by external grout pressure or axial stresses during installation. These concerns can be overcome by use of appropriate installation procedures, sometimes including stage grouting, and should not be a reason for rejecting plastic casing.
10. What backfill will be used? Plastic couplings are easier to seal against intrusion of backfill than aluminum, fiberglass or steel couplings. If grout backfill is used, a good seal is imperative. If a granular backfill is used in a borehole installation, the outside profile at couplings should be flush, otherwise backfill may bridge above the couplings.
11. What are the costs of alternative types of casing?

12.8.4. Installation of Inclinometer Casing

When planning installation procedures, one should follow the guidelines given in Chapter 17. Additional guidelines for installation of inclinometer casing are given in the following subsections.

Installation procedures vary widely, according to the type of casing and couplings and to site-specific conditions. Procedures are described by AASHTO (1978), ISRM (1981a), Wilson and Mikkelsen (1977,1978), and in the instruction manuals of various manufacturers of inclinometers.

When installing inclinometer casing for use in combination with a probe extensometer, one should follow the guidelines given in Section 12.5.10.

Coupling Requirements

Care must always be taken to seal inclinometer couplings and bottom caps against intrusion of backfill. Couplings with O-rings do not require additional sealing, but others usually require sealing mastic and tape. Where pop-rivets are intended to shear to allow telescoping movement, sealing mastic and tape should be used over the rivet heads. Even with rigid riveted couplings, the stem of the rivet occasionally pulls out during installation, and rivet heads should be filed smooth and sealed. Solvent cement is used on most rigid plastic couplings for sealing and tensile strength, and usually one or more pop-rivets are installed on each side of the coupling to provide strength while the cement sets. When maximum tensile strength is required across cemented couplings in ABS or PVC casing, a primer should be used before the solvent cement is applied. The primer etches the surfaces and allows proper adhesion. Rivets should not be installed in casing grooves or any other location that would interfere with tracking of the probe.

When assembling couplings, one must be careful to avoid creating spiraled casing. Alternate couplings should be twisted left and right before fixing.

Installation in Fill

Inclinometer casing is installed in fill by using the methods described in Chapter 17. When a mechanical probe is used within inclinometer casing to monitor compression of the fill, settlement collars must be attached to the casing (Section 12.5.3).

Borehole Requirements

Inclinometer casing can occasionally be installed in an unsupported borehole. However, where there is risk of borehole collapse during installation, the borehole should be supported by drilling mud, drill casing, or hollow-stem augers. Drill casing or hollow-stem augers should be used if any doubt exists about the ability of drilling mud to support the borehole. If maximum precision is required, the boring procedure should be planned to minimize disturbance of the surrounding ground, and boreholes for vertical installations should be as near as possible to true vertical.

In general, the bottom of the inclinometer casing should be fixed from translation so that absolute deformation data can be calculated by assuming base fixity, and thus the borehole should be advanced to stable ground. This assessment should be based on the geology, the geometry of the excavation or structure, and other site-specific factors. A depth of 10–20 ft (3–6 m) below the expected active deformation zone is suggested for most installations. Additional borehole length should be allowed for any added weight required at the casing bottom to overcome buoyancy during installation. As described in Section 12.8.6, it is often convenient to continue one borehole to a greater depth than required for deformation data and to use the bottom length of inclinometer casing for checking the instrument.

Samples are normally taken to define stratigraphy, as input to the decision on borehole depth and to assist with interpretation of data.

Inclined boreholes are not recommended for inclinometer casings, because groove orientation is

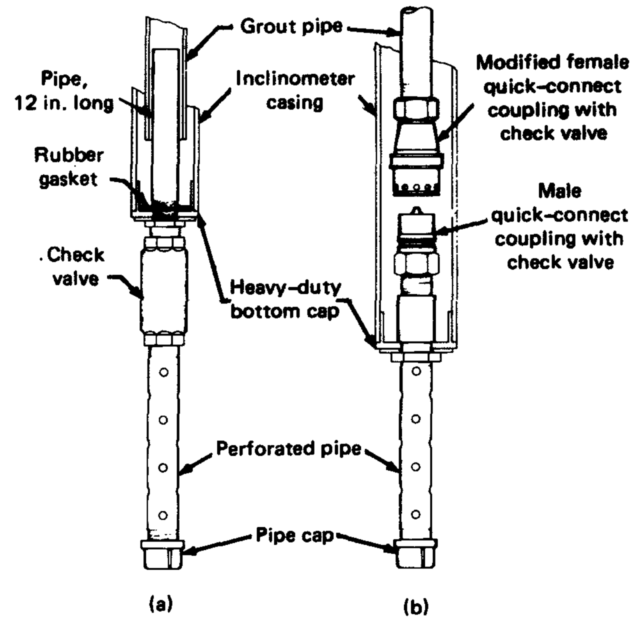


Figure 12.74. Arrangements for grouting through a pipe within inclinometer casing: (a) single shutoff arrangement with gasket seal and (b) double shutoff arrangement with quick-connect (courtesy of Slope Indicator Company, Seattle, WA).

difficult to control and will typically have a spiral on the order of 3–10 degrees per 100 ft (30 m) (Mikkelsen and Wilson, 1983).

Installation in Boreholes

The annular space between the borehole wall and inclinometer casing should be backfilled with grout, sand, or pea gravel. Grout backfill is more likely than granular backfill to fill the annular space completely but cannot be used if grout would be lost into the surrounding ground.

When a grout backfill is used, grout can be tremied via a pipe inserted outside the inclinometer casing, but the arrangements shown in Figure 12.74 allow installation in a smaller-diameter borehole.

When the arrangement in Figure 12.74a is used, steel pipe or drill rod is lowered over the 12 in. (300 mm) long pipe to seal against the rubber gasket and is used for grouting. After the annular space between the borehole wall and inclinometer casing is filled with grout, a measured volume of water is pumped to displace grout from most of the grout pipe, the grout pipe is raised a short distance, and the check valve closes. The remaining grout in the grout pipe is removed by flushing thoroughly with water, under low flow to avoid reopening the check valve. Two methods are available for overcoming buoyancy until grout sets and for ensuring that the casing remains as straight as possible in the borehole. First, an adequate bottom weight can be attached to the bottom cap. Second, the weight of the grout pipe can be used, temporarily weighting the top of the inclinometer casing while the grout pipe is raised to flush with water. The second method is preferable for deep holes, for which the magnitude of the bottom weight would become excessive. The first method must be used if the inclinometer casing has telescoping couplings.

When the arrangement in Figure 12.74b is used, both check valves are opened when the two fittings mate under the weight of the grout pipe and close after grouting when the grout pipe is raised, thereby preventing spillage of grout into the inclinometer casing. It is important to fill the grout pipe with water prior to mating the two fittings, otherwise particles from the bottom of the borehole are likely to be washed into the check valves and prevent later closure. A conservative installation will include a check valve below the bottom cap, of the type shown in Figure 12.74a, and a spare female quick-connect should always be on hand for use if grout is allowed to set in the fitting attached to the grout pipe. Although the arrangement in Figure 12.74b prevents spillage of grout when the grout pipe is raised, the weight of the grout pipe cannot readily be used to overcome buoyancy; thus, a bottom weight must be used.

When an outside tremie pipe is used for grouting, buoyancy can be overcome by use of a bottom weight, the weight of a temporary internal pipe, or a first stage of grout can be allowed to set around the bottom 10 ft (3m) of the casing so that no buoyancy forces remain.

For all methods of overcoming buoyancy, the attachment between the bottom cap and casing must be adequately strong. The manufacturer should be consulted for information on the capacity of the standard attachment and for methods of reinforcement.

Drill casing and hollow-stem augers must be withdrawn without rotation.

An example of a procedure for installing inclinometer casing in a borehole, including a required materials and equipment list, is given in Appendix G. This example procedure should not be used as a "cookbook" procedure: each installation has its own criteria, dependent on site-specific conditions and needs, available materials and equipment, and the skill of installation personnel.

Installation when Large Movements Are Expected o Thin Shear Zones

As indicated in Section 12.8.3, deformation at a dis tinct shear zone will cause bending of the casing and excessive localized bending will prevent pas sage of the probe. If substantial deformation is pre dicted at distinct shear zones, a large-diameter cas ing and small-diameter probe should be used. It i also helpful to use a large borehole and soft backfil so that the casing causes the backfill to shea thereby prolonging the life of the installation. In thi case the localized large shear movements will b redistributed over a larger casing length, but this i preferable to shearing the casing or blocking prob access.

Careful monitoring, by using the *shear prob* technique described in Section 12.9.1, can provide forewarning of blocking probe access and can indi cate the timeliness of converting the system to *slope extensometer* (Section 12.9.1). A single an chor can be installed below the shear zone, usuall at the bottom of the casing, and subsequent defor mation monitored. If the single wire is left slac between slope extensometer readings, inclinomete readings can usually be obtained until blockage oc curs.

Installation on Piles

When installing casing on solder piles or drive steel piles, two methods are possible. First, squar steel tubing can be welded directly to the piles an used as inclinometer casing. Second, a steel pip can be welded to the pile and inclinometer casin installed within the pipe, using a grout backfill an one of the arrangements shown in Figure 12.74 This second method allows drilling through the stee pipe after pile installation, to create base fixity b setting the inclinometer casing below the tip of th pile, and is usually preferable.

12.8.5. General Guidelines on Use of Inclinometers

General guidelines on instrument calibration an maintenance and on data collection, processing presentation, interpretation, and reporting are give in Chapters 16 and 18. Additional guidelines for inclinometer use are given in manufacturers' instruction manuals, by Green and Mikkelsen (1986), ISRM (1981a), and Wilson and Mikkelsen (1978), and are summarized in the following sections.

12.8.6. Calibration

An inclinometer can be returned to the manufacturer for regular calibration checks, but it is usually inconvenient to do this on a frequent schedule. There are three available methods for making field checks of an inclinometer for use in near-vertical casings and additional methods for near-horizontal and inclined casings. These are described in turn.

All the field checks described in the following subsections can only be used to examine variations in field readings with time, and these values cannot be evaluated by referencing to similar data obtained during factory calibration. For comparison with the original factory calibration, the probe must be returned to the manufacturer. An inclinometer should be subjected to one of the field checks regularly and repaired by the manufacturer when appropriate. If this is done, there should be no need to send it to the manufacturer on a regular schedule for routine checking.

Near-Vertical Test Casing

A short length of test casing can be installed in suitably stable ground at a location where the temperature remains as constant as possible. The unheated basement of a building founded on bedrock is an ideal location. If drilling is inconvenient, the casing can be embedded in a concrete block formed by a 55 gallon (208 liter) oil drum founded on bedrock. The casing should be a 4 ft (1.2 m) length of standard inclinometer casing, installed so that one pair of grooves is in a vertical plane and the other pair 10–15 degrees inclined from the vertical.

Readings are taken, after waiting for temperature stabilization, with the wheels oriented in the four grooves at 90 degrees apart, with the biaxial probe hanging on the cable at a standard position within the test casing. These eight readings (i.e., transducers *A* and *B* for each wheel orientation) provide a check on *azimuth rotation, scaling,* and *zero offset (bias)* errors and provide data for systematic error corrections if necessary. More details on the procedure are available from some manufacturers of inclinometers.

Test in Bottom of Near-Vertical Field Casing

One inclinometer casing can be installed in the field to a greater depth than required for deformation data and the bottom length used as a stable reference for checking purposes. The bottom 20 or 30 ft (6 or 9 m) should be installed in rock or firm soil that, without doubt, will not move throughout the instrument use period. Prior to taking field readings on any day, check measurements should be made within this zone, following the same procedure described previously for a test casing. However, because the casing will not have significant inclination, this method does not provide as good a check on scaling as the previous method.

Figure 12.75. Inclinometer test stand, master type (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England).

Test Stand

A test stand is provided by some manufacturers for checking the health of the instrument, as described previously for a test casing. A highly accurate *master test stand* (Ohdedar and Dawes, 1983; Figure 12.75) can be used or, alternatively, a less accurate *field test stand* (Figure 12.76). When this method is

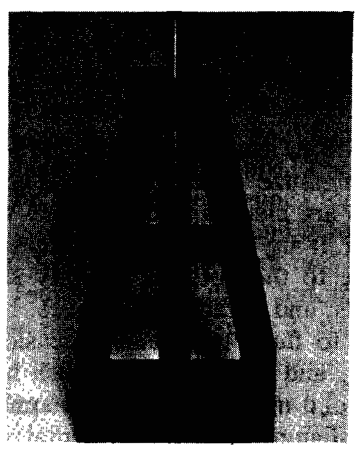


Figure 12.76. Inclinometer test stand, field type (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England).

employed, it is essential that the test stand remains absolutely stable, both as the set of readings is taken and between sets of readings.

Checks on Inclinometer for Use in Near-Horizontal Casings

When an inclinometer probe is to be used for vertical deformation measurements in near-horizontal casing, it can be checked in a similar way to a conventional inclinometer. The procedure requires two test casings, the first near-horizontal with the grooves oriented 10 degrees off vertical and the second inclined 10 degrees off horizontal but with the grooves oriented vertically.

Checks on Inclinometer for Use in Inclined Casings

When an inclinometer probe is to be used for measurements in inclined casing, the method of checking depends on the configuration of the transducers, as described in Section 12.8.2. If a conventional "vertical" or "horizontal" probe is used, the instrument can be checked as described above. If a special probe is used, with its transducer mounted so that its axis is approximately vertical when the probe is within the inclined casing, the instrument can be checked by taking readings in a test casing installed at the average inclination of casings in the field. However, the probe cannot be rotated 180 degrees or turned end-for-end, so that the check is less reliable than for a conventional probe.

12.8.7. Maintenance

The inclinometer probe should be checked frequently and wheel fixtures and bearings tightened and replaced as necessary. After each casing has been read, guide wheels should be cleaned and oiled.

For long-term installations it is particularly important to minimize wear of the casing grooves. Primary needs are clean and oiled guide wheels and clean casing. If any solid material enters the casing, it will settle to the bottom, possibly stick to the guide wheels, and abrade the grooves. It is usually worthwhile to flush the casing occasionally with clean water, and a large bottle brush helps to remove any solid material. The need applies to casings at all alignments, and horizontal casings are particularly prone to deposition of material in the lowest groove.

12.8.8. Data Collection

Data collection generally requires two trained tec nicians.

Although they may fit other manufacturers' ca ing, instruments supplied by different manufactu ers should not be used interchangeably. In the inte est of accuracy, even the interchangeable use probes supplied by the same manufacturer shou be avoided (Wilson and Mikkelsen, 1978). Use the same technicians, instrument, and cable for measurements on a particular project is highly d sirable, and mandatory if high precision is require

Field Check on Inclinometer

Prior to collecting data on any day, a field che should be made to ensure that the inclinometer sy tem is functioning correctly, preferably by usi one of the methods described in Section 12.8.6.

If experienced users consider this recoı mendation to be unnecessarily conservative th should, as a minimum, use the following procedur

1. Lower the probe to a point within the casin preferably about 20 ft (6 m) below the wat level.
2. Wait for temperature stability (usually at lea 10 minutes).
3. Take repeated readings.
4. Remove the probe, rotate it 180 degree lower it to the same point.
5. Wait for temperature stability and take r peated readings.
6. Examine the stability of *check-sums* (Sectio 12.8.9).

By using this procedure, any tendency for drift the check-sums can be detected before data are co lected. Good stability of check-sums during ea data set is essential for good accuracy.

Measurement Method

The probe should be inserted to the bottom of vertical or inclined casing or the "far" end of horizontal casing. A measurement traverse is ma by holding the probe stationary at each depth inte val throughout the casing and recording depth a inclination data. Maximum precision is achieved use of a reading interval equal to the inclinomet wheelbase.

When reading in near-vertical casings, readings in one vertical plane are normally taken with the probe at one orientation and then repeated with the probe turned through 180 degrees. Measuring locations must be identical to those in the first traverse. If a uniaxial probe is used and deformation data in both vertical planes are required, two further traverses are made, with the probe guide wheels in the second pair of grooves, 90 degrees from the first. By reducing data based on the differences between readings, 180 degrees apart, systematic instrument errors and errors caused by casing irregularities are minimized. An excellent check on the reliability of each measurement is provided by calculating the algebraic sum of readings 180 degrees apart, and this should be done **in the field** while collecting the data. These are referred to as *check-sums* and are discussed further in the following section on data processing.

When reading in near-horizontal casings, the same check-sum procedure is used by turning the inclinometer probe end-for-end, and a cable connection is provided at each end for this purpose.

When reading in inclined casings, the check-sum procedure is possible if the axis of the transducer is mounted parallel or perpendicular to the long axis of the inclinometer probe, but this is not possible with the inclined mounting arrangement described in Section 12.8.2.

Initial Readings

Measurements of the initial profile, to which all subsequent data will be related, should follow the guidelines for initial readings given in Chapter 18. When taking initial readings, a fixed orientation reference for the probe should be established and recorded and consistently used for all subsequent reading sets. For a biaxial inclinometer, generally accepted practice is to orient the *A* transducer so that it will register deformation in the principal plane of interest as a positive change.

At the time of initial readings, survey measurements should, if practicable, be made on the top of the casing to establish its lateral position to within the accuracy required of inclinometer measurements. If base fixity is in doubt, provision should be made to monitor absolute transverse deformation of the top of the casing on a regular basis, using surveying methods. Even with confidence in base fixity, it is good practice to check calculated data occasionally by survey measurements on the top of the casing.

Readings Within Telescoping Casing

If the inclinometer casing incorporates telescoping couplings, the depth below ground surface of each element in the stratigraphic profile and of the corresponding casing section will not remain constant. In this situation, two methods of data collection and processing are possible.

First, inclinometer readings are made at constant locations with respect to the stratigraphic profile. Telescoping coupling locations are recognized by feeling a "bump" as inclinometer guide wheels pass into or out of a coupling, and inclination readings are taken at constant distances from the nearest coupling. Length changes across couplings are determined by using a mechanical probe extensometer within the inclinometer casing, and these data are used during data processing.

Second, readings are taken at uniform depth intervals, settlement data are obtained either by using a probe extensometer or by alternative method, and a computer program is used to interpolate the inclination of the casing at the same elevations as the initial set of data.

The first method is the more accurate, because in the second method the guide wheels may rest on a corner at the end of a section of casing, causing poor repeatability. However, the second method requires less overall effort and is suitable if the reduced accuracy is acceptable.

Automatic Recording

Although it increases data collection speed, an automatic readout unit may be subject to a significant limitation.

With manual data recording, data collection personnel can scan the data in the field for variations in the check-sums and make corrections or repeat readings immediately. Automatic readout units with field checking and editing capability also allow these checks to be made. However, some automatic units do not allow the check-sums to be examined in the field, and data must be scanned for errors after being printed out in the office and before computer processing. Additional field work may be needed if errors are found, and use of an automatic readout unit may not necessarily increase overall efficiency.

12.8.9. Data Processing

The first step in data processing should be a review of the check-sums, and **this should be done while**

collecting the data. The check-sum is usually equal to twice the zero offset (bias) of the transducer.

Check-sums are used to examine data for errors, and ideally the check-sums should remain constant for all depth intervals in a given data set. In reality, the check-sums vary according to casing conditions, instrument performance, and operator technique. If opposite walls of the casing are not parallel, if wheels are influenced by the uneven inside profile of telescoping couplings, or if depth control is not precise, the check-sum may vary randomly about a mean value. Small variations do not usually indicate a problem.

Some inclinometer manufacturers will indicate the magnitude of normal variations in check-sums. For example, for its Digitilt® inclinometer, Slope Indicator Company (1987) states that the check-sum should remain within ± 10 or 20 units of the mean of all check-sums for that data set. Typical standard deviations for the *A* axis are 1–10 and are usually double for the *B* axis. In general, a standard deviation greater than 10–20 units indicates problems with casing irregularities, the instrument, or operator technique.

After reviewing check-sums, data processing consists of four steps: 180 degree differences, "change" at each reading depth by subtracting each 180 degree difference from the initial value, "cumulative change" by cumulating change data from the bottom of the traverse upward, and conversion of cumulative change to deformation units via a calibration constant.

Manual reduction of inclinometer data is tedious and time consuming and, as a minimum, a small programmable calculator should be used. Because the calculations are based on a cumulative process, it only requires one error to produce completely misleading results. Consequently, manual reduction of inclinometer data is practicable only where a small number of casings are involved and when they are read at infrequent intervals. Powerful IBM-PC compatible software is available for reduction and plotting of inclinometer data and for error detection and correction, and the author strongly recommends its use. For example, the PC-SLIN data reduction program, available from Slope Indicator Company, has error detection routines that make a statistical evaluation of variations in check-sums from the mean value and provide an expedient method for detecting mistakes and evaluating errors in the data. Green and Mikkelsen (1986) present good summary of data processing procedures an sources of error.

If an automatic readout unit has been used, dat can be entered into a computer, via a telephor modem if required, after the scan for errors. Use a *Recorder–Processor–Printer* allows data redu tion in the field.

When preparing to plot data, special attentic should be paid to the orientation sign conventio Some manufacturers provide guidelines in their i struction manual.

The two plots shown in Figure 12.77 are in con mon use. The "change" plot is useful to dramati the location of deformation zones. The "cumulativ change" plot gives a more graphic representation the actual deformation pattern and is more readil understood by personnel unfamiliar with the dat reduction procedures. A third plot, of deformatio at a particular depth versus time, is particularly us ful in studying deformation trends and making pr dictions. For example, such plots might be prepare for the Figure 12.77 data at depths of 16 and 46 fee

If a groove spiral survey has been made, spir data can be used with biaxial inclinometer data determine true direction of deformation or deform tion in any predetermined plane.

12.8.10. Data Interpretation

The normal purpose of inclinometer measuremen is to define the location of any deforming zone an to allow an evaluation of that zone as time pr gresses, rather than to survey an exact profile of th casing. Often the deforming zone is only a few fe thick, and the sum of the changes over a few adj cent reading depths will often be representative the magnitude and rate of the entire movemen Thus, the most useful plots are generally plots deformation at a few selected depths versus tim and the Figure 12.77 plots are merely steps in visu alizing what is occurring and in developing the d formation–time plots. The cumulative change pl may in fact be misleading because, although the i strument may be operating within its range of prec sion, over a period of time it may suggest tiltin back and forth. If a small kink begins to develo somewhere in the plot, primary concern should l with the developing kink and not with the overa tilt.

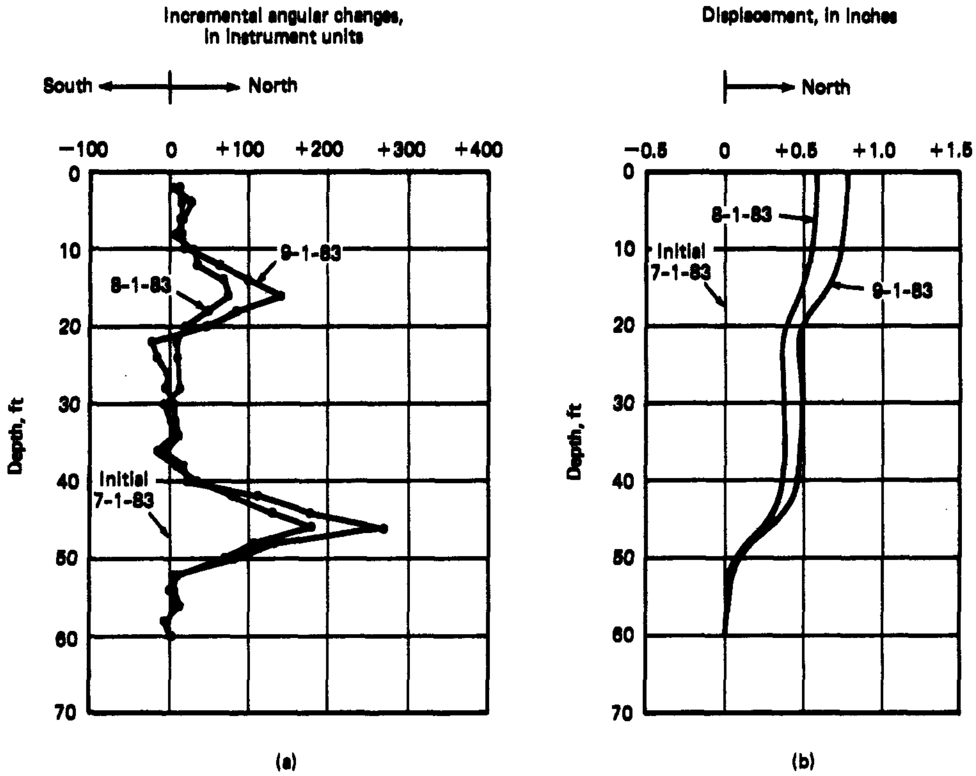


Figure 12.77. Typical plots of inclinometer data: (a) "change" plot and (b) "cumulative change" plot (courtesy of Slope Indicator Company, Seattle, WA).

12.8.11. Use of Inclinometer Data to Estimate Bending Moments*

Moments and corresponding stresses in structures can sometimes be back-calculated from inclinometer measurements. The moment diagram can be obtained from

$$M_x = \frac{d\theta_x}{dx} \cdot EI_x,$$

where: θ_x = angle measured by inclinometer at section x,
M_x = moment at section x,
E = elastic modulus,
I_x = moment of inertia of section x.

If inclinometer readings are taken at 2 ft (610 mm) depth intervals, the above equation can be rewritten as

$$M_x = \left(\frac{\theta_x - \theta_{x-1}}{24}\right) EI_x = \frac{\Delta\theta_x}{24} \cdot EI_x.$$

As indicated in Table 12.8, the best possible precision for inclinometer data, when using a force balance accelerometer transducer, is ±0.05 in. in 100 ft (±1 mm in 30 m, $\pm 4 \times 10^{-5}$ radian, ±9 arc-seconds). This high precision is possible only when maximizing the quality of all factors discussed in Section 12.8.2 and by taking at least three sets of readings for each data set, so that repeatability can be examined.

Inclinometer data can give good results when used with flexible steel structures such as sheet or steel piles (e.g., Boissier et al., 1978), where deflections are large and the section modulus is known. However, they are of limited use for stiff composite structures such as drilled shafts, reinforced slurry walls, and reinforced concrete retaining walls, both because angular changes are likely to be very small and because the moment of inertia is not known accurately (Wolosick and Feldman, 1987). Because

*Written with the assistance of Alex I. Feldman, Senior Engineer, Shannon & Wilson, Inc., Seattle, WA.

the behavior of concrete is inelastic, these zones also vary with time. For such structures, inclinometer data should be used for estimating bending moments only if other measurements can be used for checking, such as measurement of internal stresses or external load. Examples of measurements in a sheet pile wall, slurry wall, and cylinder pile wall are given by Gould and Dunnicliff (1971). Saxena (1974) and Soares (1983) describe measurements in slurry walls.

12.9. TRANSVERSE DEFORMATION GAGES

Transverse deformation gages are defined in this book as devices installed within a borehole or pipe for monitoring deformation normal to the axis of the borehole or pipe. Inclinometers fall within this category but are described separately in Section 12.8.

Typical applications are determination of depth and extent of sliding zones in natural and excavated slopes and earth fills, and measurement of the pattern of horizontal deformation within embankment dams and around braced excavations. Transverse deformation gages include shear plane indicators, plumb lines, inverted pendulums, in-place inclinometers, and deflectometers.

Borehole directional survey instruments are also discussed in this section.

12.9.1. Shear Plane Indicators

Shear plane indicators range from crude and inexpensive rupture stakes to more precise and expensive slope extensometers.

Rupture Stakes

In soft clays simple wooden stakes can be pushed or driven into the ground to a depth beyond the anticipated shear plane. Shearing will break the stakes, and the depth to the shear plane can be determined by pulling out the upper part of each stake. Stakes can be 2 × 1 in. (50 × 25 mm) softwood, or hardwood beading, without knots. Eide and Holmberg (1972) made saw cuts halfway through each stake at 2 in. (50 mm) intervals to ensure breakage. Stakes are usually installed by first pushing or driving a steel pipe with a loose end cap, inserting the stake within the pipe, raising the pipe while pushing on the stake to dislodge the end cap, and withdrawing the pipe. This is an economical procedure if installations can be made by hand, but if a drill rig is required, the shear probe described in the following subsection may be the preferred approach. Because there is a significant risk of breakage when removing stakes, a large number should be used so that false data can be discarded.

Shear Probe

The *shear probe*, also referred to as a *poor man's inclinometer, slip indicator*, and *poor boy*, consists of plastic tubing or thin-wall polyvinylchloride (PVC) pipe, installed in a nominally vertical borehole. The depth to the top of the shear zone is determined by lowering a rigid rod within the tubing or pipe and measuring the depth at which the rod stops at a bend. The depth to the bottom of the shear zone can be measured by leaving a rod with an attached graduated nylon line at the bottom of the tubing or pipe and pulling on the line until the rod stops. Curvature can be determined by inserting a series of rigid rods of different lengths and noting the depth at which each rod will not pass further down the tubing or pipe. Curvature is given by:

$$R = \frac{L^2}{8\,(D_1 - D_2)},$$

where: R = radius of curvature of tubing or pipe,
D_1 = inside diameter of tubing or pipe,
D_2 = outside diameter of rod,
L = length of rod.

Components of the system typically used in England are shown in Figure 12.78. The PVC pipe is used as temporary sleeving around the plastic tubing, while the borehole is backfilled with sand, and is withdrawn as backfilling proceeds. In the United States, thin-wall PVC pipe is normally used instead of tubing, and therefore the temporary sleeving is unnecessary. Typically, the pipe is 2 in. (50 mm) SDR 21 PVC with belled ends, and a typical set of four reading rods consists of 1 in. (25 mm) pipe, 6, 15, 30, and 40 in. (150, 380, 760, and 1020 mm) long, each arranged for separate attachment to a 100 ft (30 m) long graduated 0.125 in. (3 mm) diameter steel cable. The shortest rod will stop at a bend of 6 in. (150 mm) radius, the longest at a bend of 20 ft (6 m) radius.

In soft clays the pipe can usually be installed by attaching a strong bottom plug and pushing inside

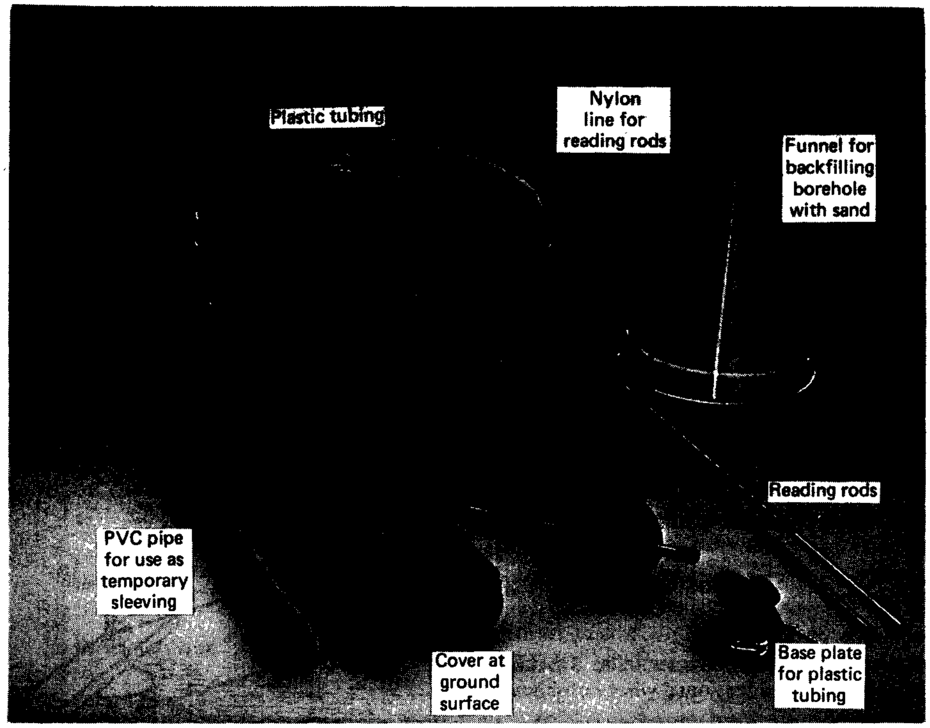


Figure 12.78. Slip indicator components (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England).

with drill rods. In stiffer soils it may be necessary to drive casing, clean out, insert the belled-end pipe, and withdraw the casing. Clearly, the pipe should be installed as straight as possible.

McGuffey (1971) describes use of the shear probe in observation well pipes, allowing monitoring of both groundwater level and horizontal deformation. A similar arrangement would be possible in open standpipe piezometers.

Shear Strip

The *shear strip* consists of a parallel electrical circuit made up of resistors that are mounted on a brittle backing strip and waterproofed. As shown in Figure 12.79, the locations of up to two breaks in the strip are determined by measuring resistances at the top and bottom of the strip. Resistors can be spaced at any interval, but 3 ft (1 m) is typical, and the maximum number of resistors per strip is about 100.

The device is generally installed in soil by drilling a 3 in. (76 mm) diameter borehole, inserting 2 in. (50 mm) PVC or polyethylene pipe, inserting the shear strip with a polyethylene grout tube, grouting with cement grout, and withdrawing the grout tube. Installation in rock is similar, but the protective pipe is usually unnecessary. The shear strip can be connected to an automatic recording system and also arranged to sound an alarm if the strip breaks.

Slope Extensometer

The *slope extensometer* (Kirschke, 1977; Müller et al., 1977) is a multipoint fixed borehole extensometer with tensioned wires, arranged for monitoring

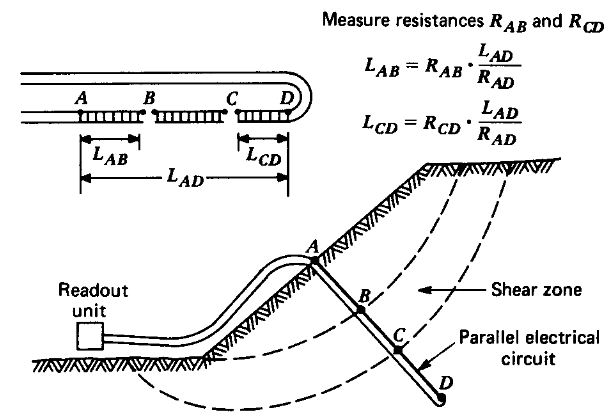


Figure 12.79. Schematic of shear strip.

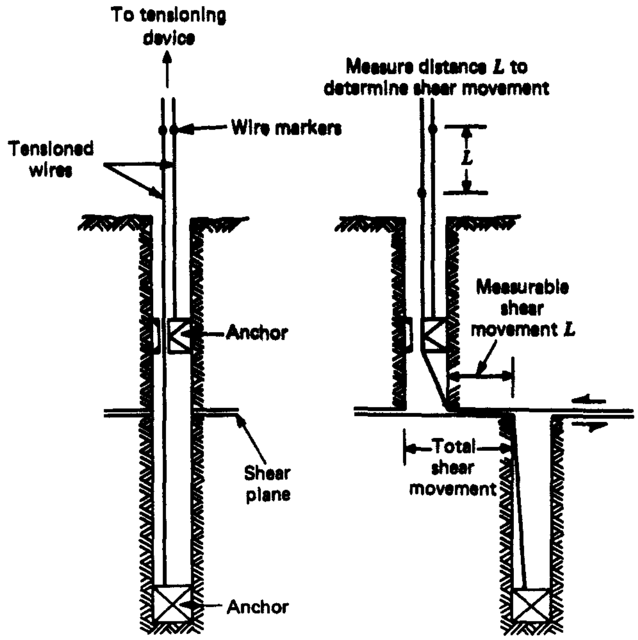


Figure 12.80. Schematic of slope extensometer (after Kirschke, 1977). Note: Additional anchors and tensioned wires not shown.

deformations normal to the axis of the borehole (Figure 12.80). Up to about 10 anchors and wires can be installed in a borehole.

Initial shear deformation will not cause an equivalent reading change, owing to lateral movement of the wires within the borehole, but after the borehole has been separated completely, the reading change will equal the shear deformation. Wires are tensioned either by coil springs or by pulleys and suspended weights, and deformations between wire markers are read with a ruler. Measurement precision can be increased by using alternative mechanical or electrical transducers.

When compared with more conventional inclinometer measurements, advantages of the slope extensometer include a simple and rapid reading procedure, the option to provide an alarm by inclusion of limit switches, and the ability to monitor much larger shear deformations. However, Kirschke (1977) comments that the device is suitable only for monitoring distinct shear planes or thin shear zones.

12.9.2. Plumb Line and Inverted Pendulum

Plumb lines, or *hanging pendulums*, can be used for monitoring horizontal displacements of concrete dams, dam abutments, shafts, and tall buildings. A typical arrangement is shown in Figure 12.81.

Inverted pendulums are used for the same purposes as plumb lines and are applicable where access is not available to the bottom of the system. They can also be used for accurate measurements of absolute ground surface deformation and as horizontal control stations for surveying methods (Marsland, 1974b). A typical arrangement is shown in Figure 12.82. The float, which is free to move in a water tank, tensions the wire and keeps it vertical.

Clearly, both systems require a near-vertical duct when installed as construction progresses or a near-vertical borehole when installed after completion of construction or in original ground. The instruments can be read to an accuracy of ±0.02 in.

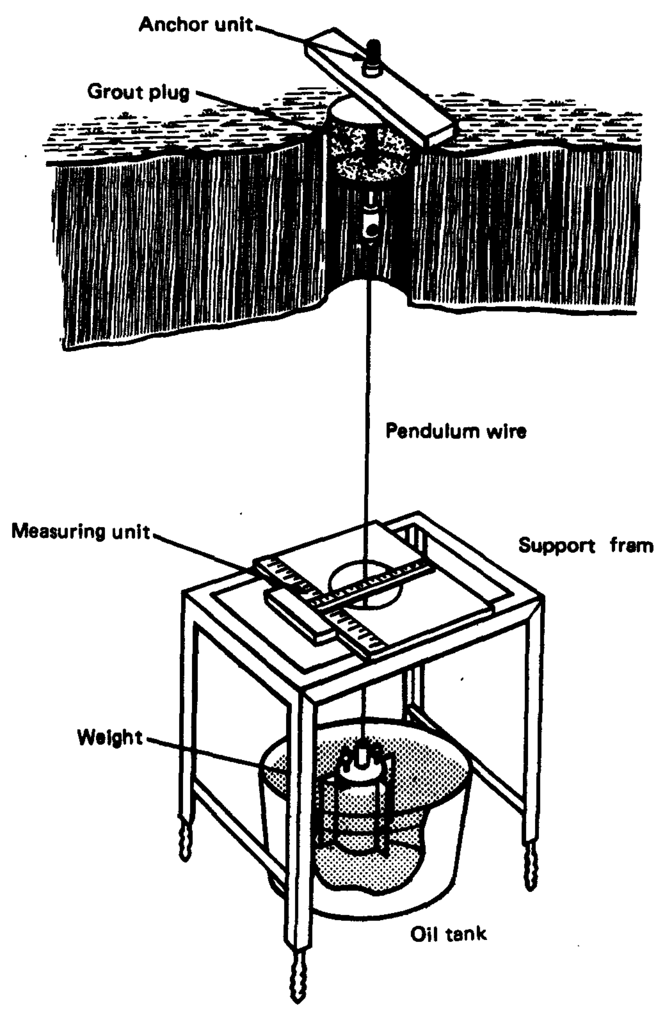


Figure 12.81. Plumb line (courtesy of Soil Instruments Ltd., Uckfield, England).

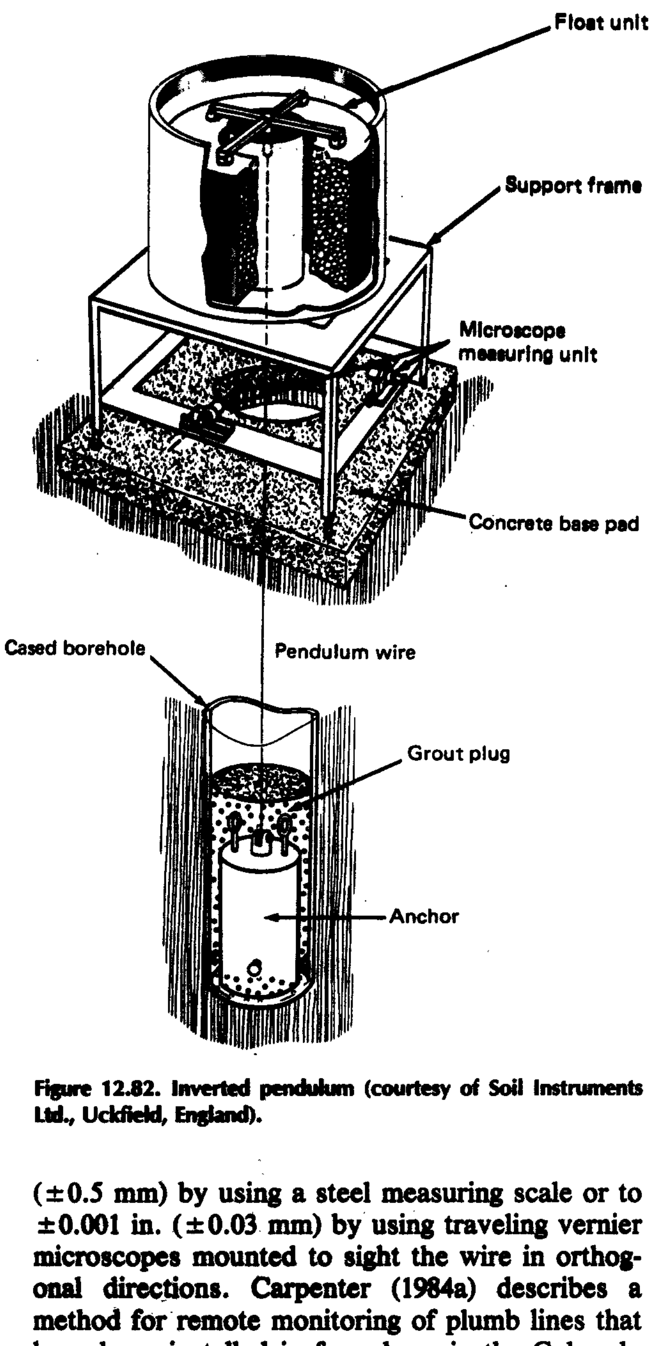


Figure 12.82. Inverted pendulum (courtesy of Soil Instruments Ltd., Uckfield, England).

(±0.5 mm) by using a steel measuring scale or to ±0.001 in. (±0.03 mm) by using traveling vernier microscopes mounted to sight the wire in orthogonal directions. Carpenter (1984a) describes a method for remote monitoring of plumb lines that have been installed in four dams in the Colorado River Storage Project. The system was designed around an optical vision system used for control of industrial robots. Rays from light-emitting diodes are used to sense the shadow of the pendulum wire, and signals are projected on to a linear photodiode array that is scanned by a microprocessor. The commercial supplier of the system is given in Appendix D.

Advantages of plumb lines and inverted pendulums include their simplicity and longevity. Their main disadvantage is the difficulty in creating a straight vertical duct or borehole, and borehole installations may require specialized and expensive drilling. Debreuil and Hamelin (1974) describe a technique for drilling 3 in. (76 mm) diameter holes using standard equipment, directional drilling techniques, and an inverted pendulum for monitoring verticality as drilling proceeds.

12.9.3. In-Place Inclinometers and Multiple Deflectometers*

In-place inclinometers and *multiple deflectometers* are typically used for monitoring subsurface deformations around excavations or within slopes, when rapid or automatic monitoring is required.

In-Place Inclinometers

An *in-place inclinometer* is generally designed to operate in a near-vertical borehole and provides essentially the same data as a conventional inclinometer (Section 12.8). The device, shown schematically in Figure 12.83, consists of a series of gravity-sensing transducers joined by articulated rods. Uniaxial or biaxial transducers can be used. The transducers are positioned at intervals along the borehole axis and can be concentrated in zones of expected movement. Movement data are calculated using the same methods as for conventional inclinometers.

Figure 12.84 shows an in-place inclinometer with force balance accelerometers as gravity-sensing transducers. Londe (1982) describes a system with a pendulum blade and induction transducers, and Cooke and Price (1974) report on development of a system with electrolytic level transducers.

The device generally uses standard inclinometer casing as guide pipe and can be removed for repairs. However, data continuity will be interrupted when the device is removed and replaced. When compared with conventional inclinometers, advantages include more rapid reading, an option for continuous automatic reading, and an option for connection to a console for transmission of data to remote locations or for triggering an alarm if deformation exceeds a predetermined amount. Disadvantages include greater complexity and expense of the

*Written with the assistance of Howard B. Dutro and P. Erik Mikkelsen, Vice Presidents, Slope Indicator Company, Seattle, WA.

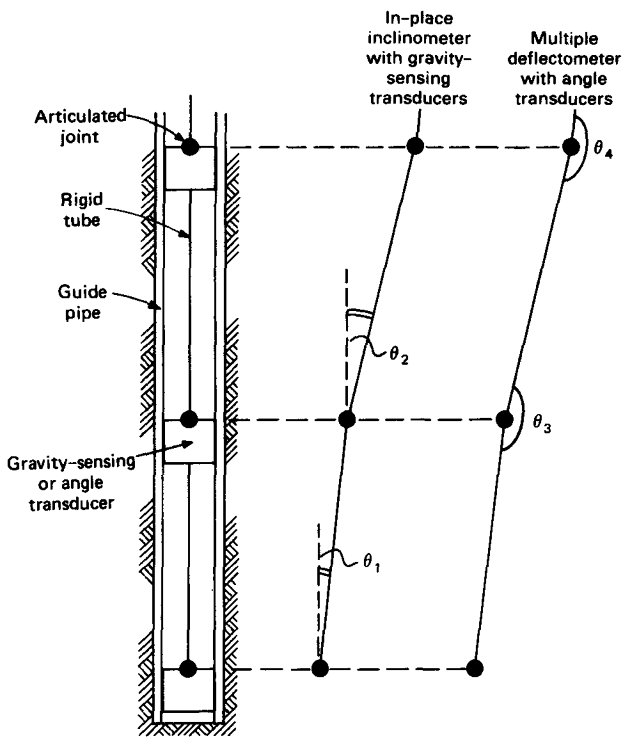


Figure 12.83. Schematic of in-place inclinometer and multiple deflectometer.

hardware. When conventional inclinometers are read, any long-term drift of the gravity-sensing transducers is removed from calculations by taking a second set of readings with the inclinometer rotated 180 degrees (the *check-sum* procedure), but this is not possible with the in-place version. Although the transducers are generally stable, there is always the possibility of a "rogue transducer," and this possibility should be recognized if one is planning to use an in-place inclinometer for long-term applications where high precision is required.

In-place inclinometers can be used effectively in combination with a conventional inclinometer. An in-place version can first be installed to define the location of any transverse deformation, with minimal labor costs for reading. If deformation occurs, the in-place system can be removed and the moving zone monitored with a conventional inclinometer. Alternatively, a conventional inclinometer can be used first to indicate any deformation and an in-place version later installed across a critical deforming zone to minimize subsequent effort and perhaps to provide an alarm trigger.

Typical field precision is ±0.02–0.04 in. over a 10 ft gage length (approximately ±0.5–1.0 mm in 3 m, ±34–69 arc-seconds), and it is believed th greater precision can be obtained by careful use oi conventional inclinometer with a force balance a celerometer transducer.

The in-place inclinometer, together with install tion, calculation, data processing, and reportii procedures, is described by ISRM (1981a).

Multiple Deflectometers

Multiple deflectometers, also referred to as *cha deflectometers,* operate on a similar principle to i place inclinometers, but rotation is measured by a gle transducers instead of tilt transducers (Figur 12.83 and 12.85).

Two versions are commercially available: a ticulated rods with full bridge bonded resistan strain gage transducers attached to cantilevers ar a tensioned wire passing over knife edges with i duction transducers.

Multiple deflectometers are usually install within inclinometer casing. The system can usual

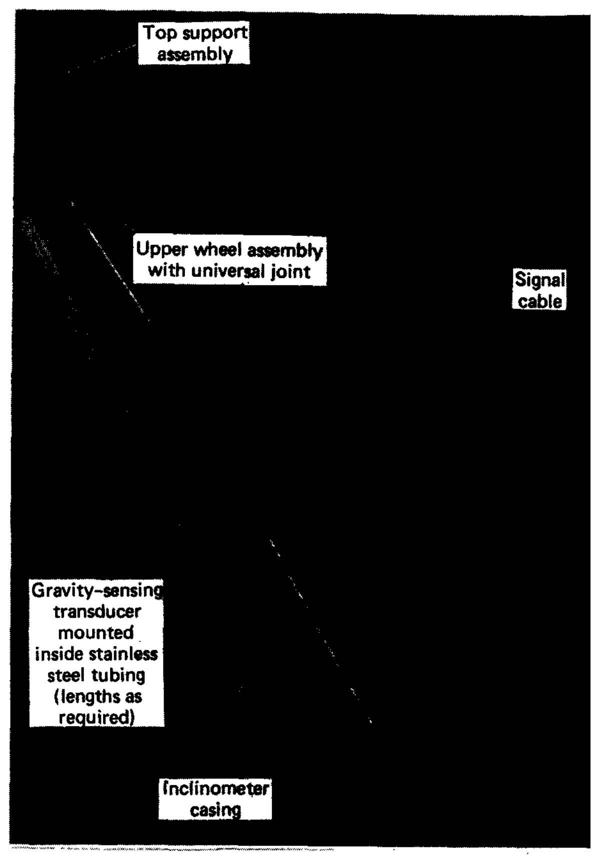


Figure 12.84. In-place inclinometer (courtesy of Slope Indicat Company, Seattle, WA).

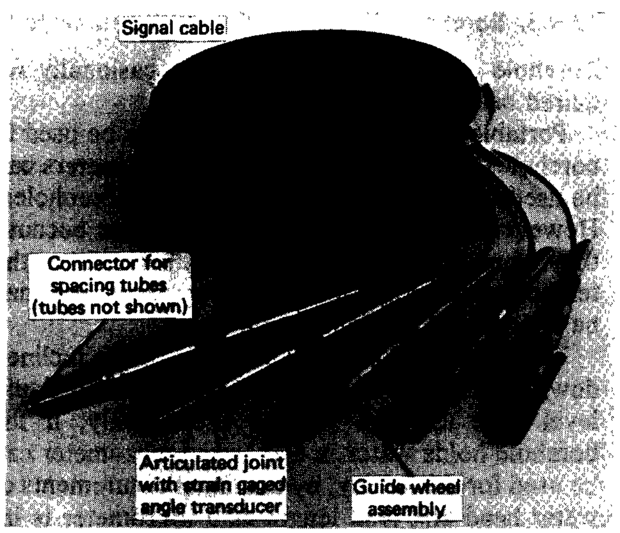


Figure 12.85. Downhole components of multiple deflectometer (courtesy of Slope Indicator Company, Seattle, WA).

be removed from the borehole at any time for maintenance and calibration, but data continuity will be interrupted when the device is removed and replaced.

Although advantages and limitations are generally the same as for in-place inclinometers, there are three important differences between the two systems. The first favors multiple deflectometers, while the second and third favor in-place inclinometers. First, multiple deflectometers are not limited by borehole inclination, because their transducers are not referenced to gravity. They can therefore be used to sense horizontal deformation in a horizontal borehole. Second, because deflectometer data are calculated by determining the position of one arm of the instrument relative to another, and **not** with respect to gravity, the device has no means of sensing rotation of the system as a whole. Third, deflectometer errors accumulate exponentially, whereas inclinometer errors accumulate arithmetically.

Multiple deflectometers have not been used widely and performance experience is sparse. Müller and Müller (1970) describe a tensioned wire version with induction transducers and quote a precision of ±0.0015 in. over a 15 ft gage length (approximately ±0.04 mm in 4.6 m). This appears to be a case of unusually high precision, perhaps when not operating through mechanical zero (Dutro, 1985). The author believes that, under field conditions, users should assume a typical precision similar to that suggested previously for in-place inclinometers.

12.9.4. Portable Borehole Deflectometers

The deflectometer is also available in a portable version, allowing similar use as a conventional inclinometer but without the limitation of borehole inclination. It can therefore be used to provide horizontal deformation data in a horizontal hole as well as for borehole directional surveys.

A typical instrument consists of two beams of equal length connected by an articulated joint, with an angle transducer arranged to sense angular rotation between the two beams. Some systems operate within grooved inclinometer casing, and others require use of insertion rods for orientation control. Data reduction procedures are similar to procedures used in conventional surveying by open traverse lines and are described by Dutro (1977).

The most accurate instrument known to the author was developed by the Federal Institute of Technology, Zürich, (Kovari et al., 1979), and is available from Solexperts AG. It uses the same sphere/cone-shaped measuring points as the sliding micrometer (Figure 12.31), spaced 1.5 m (4.9 ft) apart, has linear displacement transducers, and is attached to insertion rods. For a borehole 30 m (100 ft) long, the repeatability of transverse deformation measurement is reported as ±2–3 mm (±0.08–0.12 in.) (Thut, 1987). Figure 12.86 shows the basic arrangement, including transducers for measuring

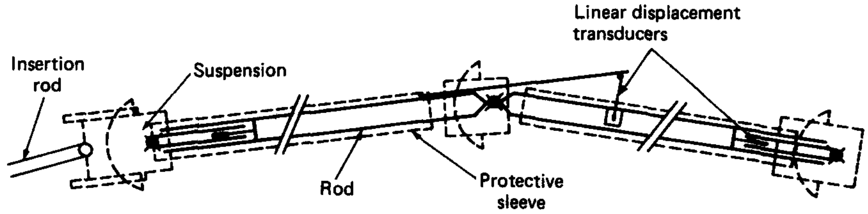


Figure 12.86. *Extenso-Deflectometer* (after Kovari et al., 1979). Reprinted from ASCE 4th RETC, Atlanta, June 1979, "New Developments in the Instrumentation of Underground Openings."

axial deformation, so that the instrument functions as a combined portable borehole deflectometer and probe extensometer. The portable borehole deflectometer is commercially available, but the combined instrument shown in Figure 12.86 has not been developed.

Instruments manufactured in the United States by Slope Indicator Company have strain gaged cantilevers to sense angular rotation between the two beams and operate either within grooved inclinometer casing or smooth-walled pipes. O'Rourke and Kumbhojkar (1984) provide guidelines on the measurement procedure and sources of error when using these instruments. The major sources of error are mechanical interference in the articulation and positioning uncertainties in successive legs of a traverse, and both can be minimized by carefully following established reading procedures and by repeated traverses. Dutro (1984) indicates that, when following these procedures within a 100 ft (30 m) long smooth-walled clean pipe, the instrument enables the true position of one end of the pipe with respect to the other end to be determined to within ±6 in. (±150 mm). Robinson et al. (1985) report on laboratory and field test measurements, indicating that the vertical profile for a 15.2 m (50 ft) near-horizontal grooved casing could be measured to an accuracy of ±12 mm (±0.5 in.), while the horizontal profile could be measured to an accuracy of ±4 mm (±0.15 in.). The particular instrument used tended to change its zero value between readings, and this resulted in measurement errors of ±50 mm (±2 in.) over the length of the casing. The use of a developed data correction constant was found to produce accurate measurements to within ±8 mm (±0.3 in.). It is believed that the above accuracies were limited by mechanical shortcomings in the design of the instrument then available from Slope Indicator Company. Design of an improved version is in progress.

The accuracies reported above should not be converted to a proportion of the length of pipe or casing and used to estimate accuracy for pipes and casings of different lengths, because the error accumulates with the number of measurements according to the power function given by Dutro (1977).

12.9.5. Fiber-Optic Sensor

The *fiber-optic microbending sensor* has a potential use as a transverse deformation gage and is described in Section 12.11.4.

12.9.6. Borehole Directional Survey Instruments

Borehole directional surveys are occasionally required before installing instruments.

Portable borehole deflectometers can be used in boreholes at any inclination, and inclinometers can be used to survey the vertical profile of boreholes. However, both methods are cumbersome because they usually require either orientation rods or the temporary insertion of inclinometer casing and may be unnecessarily precise.

The vertical profile of a borehole that is inclined downward can be surveyed with a full-profile liquid level gage (Section 12.10). Alternatively, if the borehole holds water, a diaphragm piezometer can be used for the survey, by making measurements of water head and lead length as a piezometer is inserted into the borehole. If the borehole will not hold water, a closed-ended PVC pipe can be inserted temporarily and filled with water.

A comprehensive description of borehole directional surveying methods, ranging from the simple acid etch technique to more complex photographic and gyroscopic methods, is given by Cumming (1956). Two methods described by Cumming are used occasionally for directional surveys of boreholes prior to installing geotechnical instruments and are outlined in the following subsections. Commercial sources are included in Table D.7 of Appendix D.

Photographic Method

Inclination is measured by photographically recording the position of the tip of a free-swinging pendulum, and orientation is indicated by a magnetic compass. *Single-shot* and *multiple-shot* versions are available, a timing mechanism controlling the photographic exposures (Figure 12.87). Inclination angles can be read to the nearest 0.25 degree and compass bearings to the nearest 0.5 degree. Survey services are provided by several companies specializing in oil field operations.

Pajari Method

The device used in the Pajari method contains a pendulum, magnetic compass, and timing mechanism (Figure 12.88). A single reading is taken for each insertion, by setting the timing mechanism, inserting the instrument to the required measurement point, waiting for the timing mechanism to lock the pendulum and compass, and retrieving and reading the instrument.

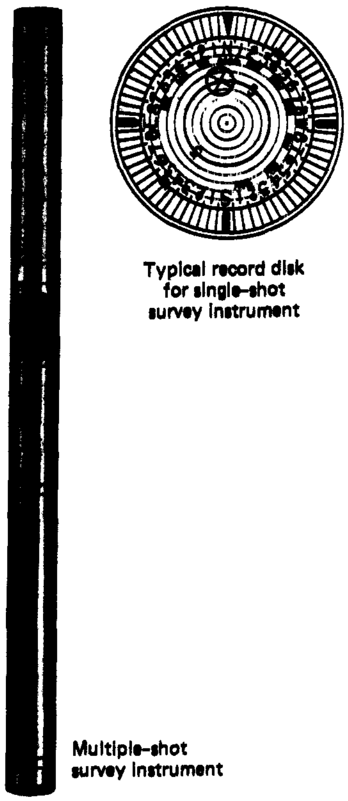


Figure 12.87. Borehole directional survey instrument, photographic type (courtesy of Eastman Christensen Company, Houston, TX).

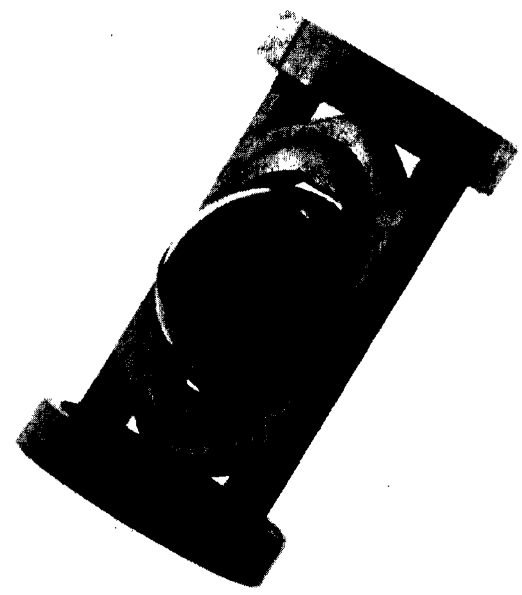


Figure 12.88. Pajari borehole directional survey instrument (courtesy of Pajari Instruments Ltd., Orillia, Ontario, Canada).

12.10. LIQUID LEVEL GAGES

Liquid level gages are defined in this book as instruments that incorporate a liquid-filled tube or pipe for determination of relative vertical deformation. Relative elevation is determined either from the equivalence of liquid level in a manometer or from the pressure transmitted by the liquid.

The primary application for liquid level gages is monitoring settlements within embankments or embankment foundations. In general, they are alternatives to vertical probe extensometers, settlement platforms, and subsurface settlement points, allowing installation to be made without frequent interruption to normal fill placement and compaction and minimizing the potential for instrument damage. Most liquid level gages also allow measurements to be taken at a central reading location. Certain types of liquid level gage can also be used where more precise measurements are required, such as when monitoring the settlement of structures.

The gages only provide a means of measuring **relative** elevations between two or more points. If **absolute** settlement or heave is required, as is usually the case, data must be referenced to a benchmark. If one end of the gage cannot be mounted directly on a benchmark, a surveying method will normally be used, and accuracy may be dependent on accuracy of the surveying method.

In general, liquid level gages are sensitive to liquid density changes caused by temperature variation, to surface tension effects, and to any discontinuity of liquid in the liquid-filled tube. These three sources of error are discussed in detail in Section 8.2.3, which also provides guidelines on selection of tubing material and diameter, tubing fittings, liquid, and routing of liquid-filled tubes. The greatest potential source of error is discontinuity of liquid caused by the presence of gas, and great care must always be taken to ensure absence of gas. Precision claimed for these instruments is sometimes unrealistic, and users are encouraged to study this section and Section 8.2.3 before selecting liquid level gages.

A general caution about the use of mercury in these systems is appropriate. In the United States mercury is considered to be a hazardous material, and environmental restrictions prevent its use in many applications. In addition, if mercury remains in plastic tubing in the long term, there is evidence that it can leach gas from the tubing and create discontinuities in the mercury. Also, oxidation can cause contamination and blockage of the tubing. When mercury is used, it should be triple distilled.

Single-point, multipoint, and full-profile liquid level gages are available. Single-point gages can be grouped into three categories, depending on the relative elevations of the two ends of the system: both ends at the same elevation, readout unit higher than the cell, and readout unit lower than the cell. Gages are described in turn, and comparative information is given in Table 12.9.

All tubing diameters referred to in this discussion of liquid level gages are **inside** diameters, because the **inside** diameter impacts on the behavior of fluid within the tubing. The reader is cautioned about a possible confusion: industry standards use the **outside** diameter when referring to tubing sizes.

12.10.1. Single-Point Gages with Both Ends at Same Elevation

Hose Levels

A simple liquid level manometer was used in ancient times for establishing relative levels during construction of canals in Mesopotamia, between the Tigris and Euphrates rivers in what is now Iraq. Modern versions are usually called *hose levels* and are used primarily for precise long-term measurement of differential settlement within buildings, where operating conditions can be well controlled.

The hose level, also called the *Terzaghi water level meter,* consists of two burettes connected by a length of transparent water-filled tube, normally of 0.38 in. (10 mm) **inside** diameter. The burettes are hung on a pair of wall-mounted observation pins, and micrometer spindles are advanced to touch the water surfaces simultaneously. Relative elevations of pins are determined from micrometer readings, and absolute elevations are determined by mounting one of the pins over a benchmark. The version manufactured earlier by Soiltest, Inc. is shown in Figure 12.89, but this product has been discontinued, and the author is not aware of a current commercial source.

The arrangement is described by the Corps of Engineers (1980) and Terzaghi (1938), and revisions to Terzaghi's design are detailed by Casagrande et al. (1967). Other versions—together with methods of minimizing errors resulting from discontinuity of the liquid, temperature differences along the hose, and differences in atmospheric pressure between

Table 12.9. Liquid Level Gages

Gage	Advantages	Limitations[a]	Approximate Precision[b]
Hose level (e.g., Figure 12.89)	Very precise	Great care needed to minimize errors Both ends must be at same elevation and barometric pressure Accuracy reduced significantly if forced air ventilation systems cause different air pressures at ends	±0.001–0.5 in. (±0.03–13 mm)
Multistation hose level (Figure 12.90)	Simple	Both ends must be at same elevation and barometric pressure	±0.1–0.5 in. (±3–13 mm)
Single-point overflow gage with both ends at same elevation (Figure 12.91)	Cell can be attached to a subsurface settlement point to allow readout above measuring point	Unless cell is attached to a subsurface settlement point, both ends must be at same elevation Both ends must be at same barometric pressure Only single point is monitored	±0.02–0.8 in. (±0.5–20 mm)

Table 12.9. (*Continued*)

Gage	Advantages	Limitations[a]	Approximate Precision[b]
Single-point gage with pressure transducer in cell, with readout unit higher than cell (Figure 12.93)	Cell can be installed in a borehole Backpressured version available so that liquid-filled tube can readily be checked for continuity of liquid	Design and operation of transducer requires close attention to many details to ensure precision; see Section 12.10.2 Version with vibrating wire transducer may be subject to damage by overranging the transducer if initial filling with liquid is completed before shipment; see Section 12.10.6. If transducer cavity is vented, potential for corrosion and reading errors. If transducer cavity is not vented, gage sensitive to changes in barometric pressure Regular de-airing of liquid required (but backpressured version greatly reduces frequency) Only single point is monitored Requires accurate knowledge of liquid density Readout unit must be above cell Use of mercury creates possible environmental hazard[c]	With pneumatic transducer and aqueous solution: ±0.5–1.5 in. (±13–38 mm) With vibrating wire transducer and mercury: ±0.1–1.0 in. (±3–25 mm)
Single-point gage with pressure transducer in readout unit, with readout unit higher or lower than cell (Figure 12.96)	Liquid-filled tube can readily be checked for continuity of liquid by increasing backpressure No buried transducer Readout can be above or below cell Cell can be installed in a borehole	Only single point is monitored Requires accurate knowledge of liquid density	With electrical pressure transducer and aqueous solution: ±0.25–1.0 in. (±6–25 mm)
Single-point overflow gage with readout unit higher or lower than cell (Figure 12.98)	Readout can be above or below cell Cell can be installed in a borehole	Regular de-airing of liquid required when readout is higher than cell Both ends must be at same barometric pressure Only single point is monitored Requires accurate knowledge of liquid density	±0.4–0.8 in. (±10–20 mm)
Multipoint gage with interconnected chambers (e.g., Figure 12.99)	Precise Automatic recording	All chambers must be at same elevation and barometric pressure	±0.004–0.1 in. (±0.1–3 mm)

Table 12.9. (*Continued*)

Gage	Advantages	Limitations[a]	Approximate Precision[b]
Full-profile overflow gage (similar to Figure 12.91)	No limit to number of measuring points No delicate or expensive parts buried Can be used with probe extensometer to measure both horizontal and vertical deformations Can be used for elevation surveys along a near-horizontal or inclined borehole, pipeline, or culvert	Both ends must be at same elevation and barometric pressure Buried pipe must slope upward from access point Longitudinal position of measuring point must be controlled very carefully	±0.1–0.8 in. (±3–20 mn
Full-profile gage with pressure transducer in probe and attached liquid-filled tube (similar to Figure 12.93; also Figure 12.100)	No limit to number of measuring points No delicate or expensive parts buried Can be used with probe extensometer to measure both horizontal and vertical deformations Can be used for elevation surveys along a near-horizontal or inclined borehole, pipeline, or culvert	Cumbersome Design and operation of transducer requires close attention to many details to ensure precision; see Section 12.10.2 Versions with vibrating wire or electrical resistance transducer are subject to overranging while handling. If transducer cavity is vented, potential for corrosion and reading errors. If transducer cavity is not vented, gage sensitive to changes in barometric pressure Version with bladder has limited range, and great operator care is required Prone to temperature errors if external air temperature is very different from temperature in pipe Regular de-airing of liquid required Liquid-filled tube must be transparent Requires accurate knowledge of liquid density Readout unit must be above probe Use of mercury creates possible environmental hazard[c] Longitudinal position of measuring point must be controlled very carefully	With pneumatic transducer and aqueous solı tion: ±0.5–1.5 in. (±13–38 mm) With vibrating wire or electrical resistance transducer and mercury: ±0.1–1.0 in. (±3–25 mm) With bladder: ±0.3–1.5 in. (±8–38 mm)
Full profile gage with pressure transducer in readout unit and attached liquid-filled tube (similar to Figure 12.96)	Liquid-filled tube can be checked for continuity of liquid by increasing backpressure	Cumbersome Prone to temperature errors if external air temperature is very different from temperature in pipe	With electrical pressure transducer and aqueous solution: ±0.25–1.0 in. (±6–25 mm)

Table 12.9. (*Continued*)

Gage	Advantages	Limitations[a]	Approximate Precision[b]
	No limit to number of measuring points No delicate or expensive parts buried Can be used with probe extensometer to measure both horizontal and vertical deformations Can be used for elevation surveys along a near-horizontal or inclined borehole, pipeline, or culvert	Requires accurate knowledge of liquid density Longitudinal position of measuring point must be controlled very carefully	
Full-profile gage with pressure transducer in probe but without attached liquid-filled tube (Figure 12.103)	Can be used for elevation surveys along downward inclined boreholes No limit to number of measuring points No delicate or expensive parts buried	Great care needed to ensure pipe is completely filled with liquid Buried pipe must not leak Sensitive to barometric pressure if pressure transducer is not vented Requires accurate knowledge of liquid density Readout unit must be above probe Longitudinal position of measuring point must be controlled very carefully	±0.05–20 in. (±1.3–510 mm)
Double fluid full-profile gage (DFSD) (Figure 12.104)	Very long profiles can be monitored No open pipe required Automatic data acquisition system available No limit to number of measuring points No delicate or expensive parts buried	Complex control system Excessive pressure can burst tube Tube cannot be more than 20 ft (6 m) below readout unit Requires accurate knowledge of liquid densities Readout unit must be above tubing Use of mercury creates possible environmental hazard[c] Longitudinal position of measuring point must be controlled very carefully	±0.1–1.5 in. (±3–38 mm)

[a] All gages are sensitive to liquid density changes caused by temperature variation, to surface tension effects, and to any discontinuity of liquid in the liquid-filled tube. See this section and Section 8.2.3 for details and recommendations. They are also subject to freezing problems.

[b] Precision refers to *relative* elevations betwen two or more parts of the gage and is highly dependent on factors discussed in Section 8.2.3. If *absolute* settlement or heave is required, data must be referenced to a benchmark, and accuracy will usually be dependent on the referencing method.

[c] If left in tubing long term, mercury can leach gas from tubing and create discontinuities in liquid. Also, oxidation can cause contamination and blocking of tubing.

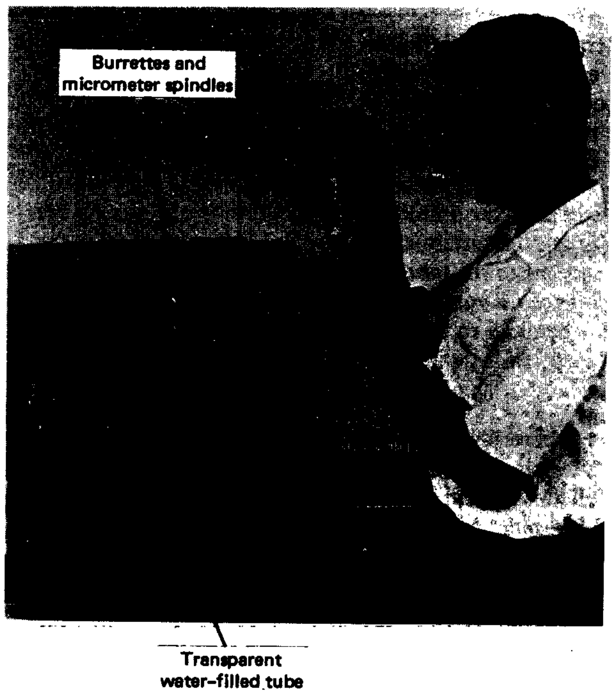


Figure 12.89. Terzaghi water level meter (courtesy of Soiltest, Inc., Evanston, IL).

the two water surfaces—are described by Gould and Dunnicliff (1971).

A multistation hose level, Figure 12.90 (Warner, 1978), is used for monitoring compaction grouting and slab jacking of highway pavements or buildings. The reservoirs are fixed at locations where monitoring is required, and the tubes are routed to a terminal panel and scale alongside the grout pump for direct observation by the pump operator. A single hose can also be used for contouring a structure prior to compaction grouting or slab jacking, by setting the reservoir at a fixed location and placing the other end at successive points on the structure.

Overflow Gages

The most frequently used instruments with both ends at the same elevation are called *overflow gages*, or alternatively *hydraulic leveling devices*, *water overflow pots*, or *overflow weirs*. They are commonly used for settlement measurements in embankment dams and as alternatives to settlement platforms during construction of embankments on soft ground, overcoming the need to extend a riser pipe through the embankment.

The instrument is described by Penman et al.

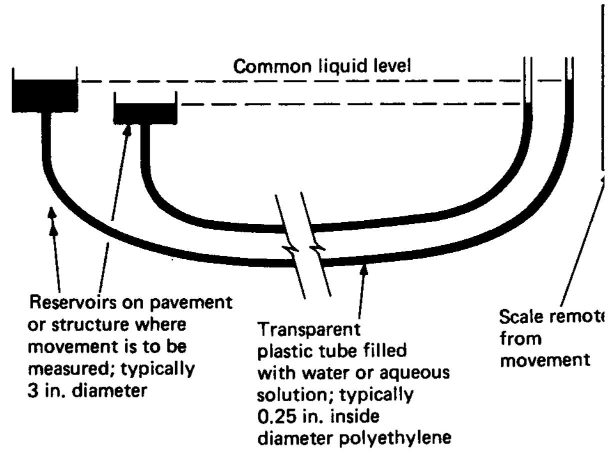


Figure 12.90. Schematic of multistation hose level.

(1975) and shown schematically in Figure 12.91 The gage is normally read by adding liquid to th liquid-filled tube at the readout station, causin overflow in the cell such that the visible level at th readout station stabilizes at the same elevation a the overflow point. The vent tube is essential t maintain equal pressure on both surfaces of liquic and the drain tube is needed to allow overflowe liquid to drain out of the cell. A four-tube versior with duplicate liquid-filled tubes, provides a verif cation of reading correctness and is the preferre instrument. Penman et al. (1975) indicate that it i necessary to flush the liquid-filled tube with at leas its own volume of de-aired liquid before repro ducible readings can be obtained. Forsyth an McCauley (1973) and the New York Department c Transportation (1979) indicate that liquid is not noı mally added for highway applications, because lic uid overflows as settlement occurs. However, thi procedure optimistically assumes no discontinuit of liquid and no loss of liquid by evaporation, an

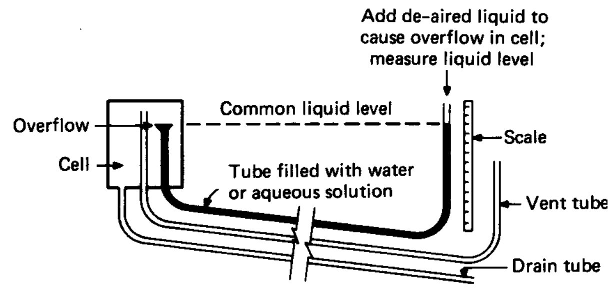


Figure 12.91. Schematic of overflow gage with both ends at sam elevation.

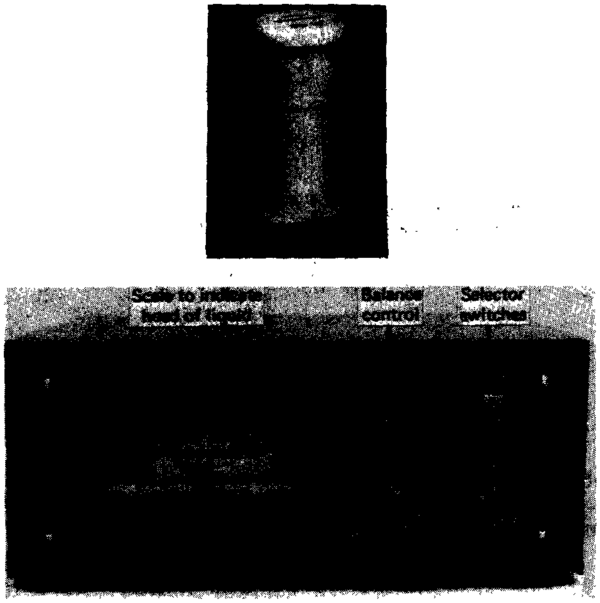


Figure 12.92. Overflow liquid level gage: (top) cell and (bottom) readout unit (courtesy of Glötzl GmbH, Karlsruhe, West Germany and Geo Group, Inc., Wheaton, MD).

good practice involves establishing a regular flushing schedule, reading before and after, and revising the schedule in accordance with changes caused by flushing.

Figure 12.92 shows the cell and readout unit manufactured by Glötzl. The liquid-filled tubes from a maximum of five cells are connected to the readout unit, and selector switches allow connection to each tube in turn. An electrical pressure transducer in the readout unit is used to indicate the head of liquid.

Forsyth and McCauley (1973) describe a gage without a drain tube, in which overflowing liquid drains directly into the embankment. Assumptions when using this gage are first that the embankment is sufficiently pervious to allow free draining, second that barometric pressure has free connection to the buried gage, and third that there is no chance of a free water surface rising above the level of the overflow at any time during the active life of the gage. This version of the overflow gage is not recommended.

As indicated in Section 8.2.3, the optimum inside diameter of the liquid-filled tube is 0.25 in. (6 mm).

The diameter of the vent tube should be large enough to create air pressure equilibrium along the tube but small enough so that any water that enters the tube can be blown out. Penman et al. (197 indicate that when 0.6 in. (15 mm) inside diamet vent tubes were used to satisfy the first criterio and they become flooded, it was extremely difficu to remove all the water. Water traps formed an destroyed the accuracy of the gages. An inside d ameter of 0.25 in. (6 mm) appears to be a maximu for ensuring that water can be blown out, and eve with this diameter a steady continuous flow of d gas is needed to remove the film of water remaini in the tube. If the film is not removed after blowi out water, it will collect at a low point and aga form a water trap. With the compromise of 0.25 i (6 mm) inside diameter vent tubes, air pressu equilibrium can be achieved with an error of le than 0.005 in. (0.1 mm) head of water in 5 minut over 600 ft (180 m). The inside diameter of the dra tube is usually the same as the vent tube.

The optimum inside diameter of all three (or fou tubes is therefore 0.25 in. (6 mm). However, avai able commercial versions have liquid-filled and ve tubes ranging from 0.2 to 0.4 in. (5–10 mm) insid diameter. The volume within the cell, between th overflow point and the drain tube connectio should be significantly larger than the volume of th liquid-filled tube, so that the overflow point do not become submerged during flushing. Backup liquid in the drain tube can cause false readings an can be overcome by applying air pressure to th vent tube until liquid ceases to flow from the dra tube. It is advisable to install the drain tube on continuous slope toward the readout unit.

The overflow gage can be used for monitori vertical deformation below the elevation of th readout unit by attaching the cell to the top of subsurface settlement point (Section 12.7.6). If th arrangement is used beneath an embankment, protective cover must be provided around and ov the cell, with sufficient internal height to allow se tlement of the cover without contacting the ce (New York Department of Transporation, 1979 Special precautions must also be made to prote the tubes near the cell from damage as settleme proceeds.

12.10.2. Single-Point Gages with Readout Unit Higher than Cell

Gages that allow the readout unit to be higher tha the cell include either a pressure transducer or method of applying a suction or backpressure to th overflow gage described in the previous section.

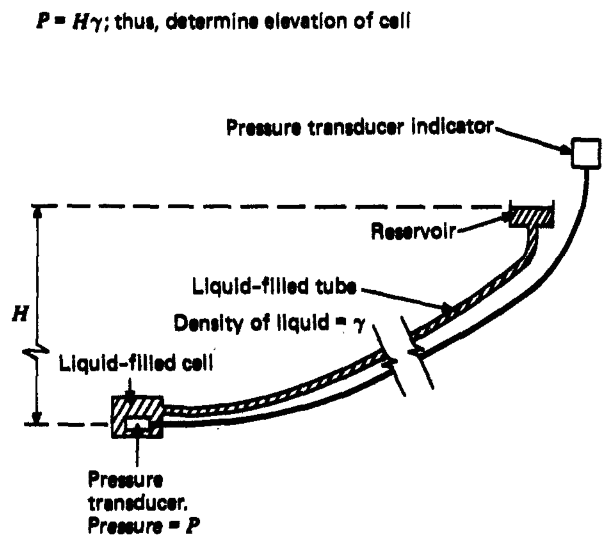


Figure 12.93. Schematic of liquid level gage with pressure transducer in cell, with readout unit higher than cell.

Gages with Pressure Transducer in Cell

The arrangement is shown schematically in Figure 12.93. The pressure transducer can be either a pneumatic (e.g., Figures 12.94 and 12.95) or vibrating wire type. The upper surface of the liquid column is at a known elevation at the readout location; therefore, relative elevation of the transducer and reservoir can be determined from the pressure measurement and liquid density.

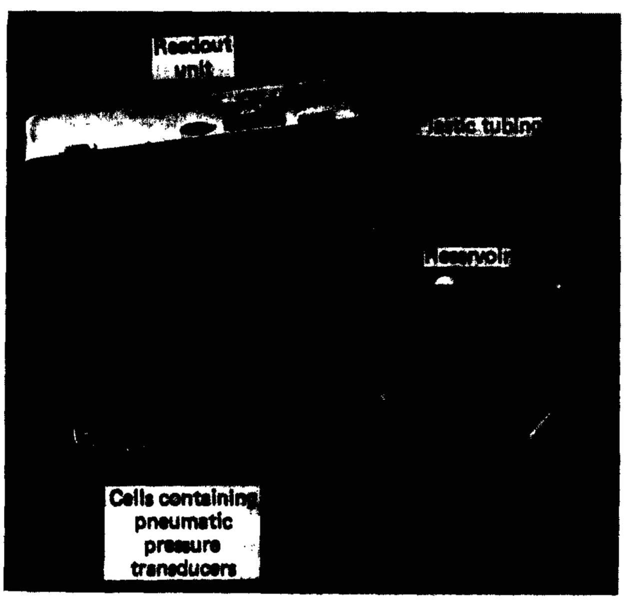


Figure 12.94. Liquid level gage with pneumatic pressure transducer in cell, with readout unit higher than cell (courtesy of Slope Indicator Company, Seattle, WA).

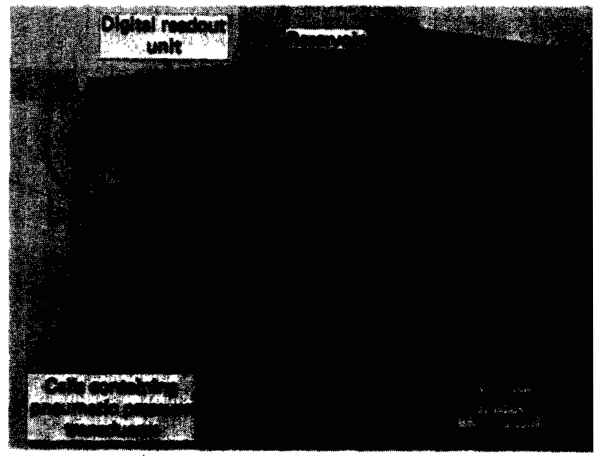


Figure 12.95. Liquid level gage with pneumatic pressure tra ducer in cell, with readout unit higher than cell (courtesy of S Instruments Ltd., Uckfield, England).

Figure 12.93 shows only one liquid-filled tub but in practice it is preferable to have two tubes that flushing is possible and independent measur ments can be made on each tube as a check.

Precision of these gages is dependent on two m jor factors. First, the pressure transducer must re the liquid head correctly and second, the liqu must transmit static head correctly from the fr surface at the reservoir to the diaphragm of tl pressure transducer. The discussion of the first m jor factor will consider pneumatic and vibrati wire transducers separately.

When using pneumatic pressure transducers, o must pay close attention to the factors discussed Section 8.3. When using the transducer for mor toring settlement, precision requirements are mu greater and much more difficult to achieve th when the transducer is used for monitoring po water pressure or total stress. If the transducer read under a condition of no gas flow (Figure 8.6 very careful control of gas pressure is essential. the transducer is read as gas is flowing (Figure 8 or 8.8), the rate of gas flow should be as low a constant as possible, and a flow meter should pre erably be included in the system. The flow contro ler should be insensitive to variations in temper ture, and the accuracy of the flow meter should b within 0.5 cm^3/min. The types of flow controlle and flow meters that are adequate when monitori pore water pressure and total stress may not b adequately precise when monitoring settlemen Also, it is very important to use a pneumatic tran ducer with a very low volumetric displacement the diaphragm (Section 8.3), because large vo umetric displacement may cause a pressure surge in the liquid-filled tube and errors in the liquid part of the system.

When using vibrating wire pressure transducers, one must pay close attention to the factors discussed in Section 8.4.9. If the cavity behind the diaphragm is hermetically sealed, the gage is sensitive to changes in barometric pressure. On the other hand, if the cavity is vented to atmosphere to avoid this limitation, the transducer is subject to corrosion, and if any water enters the vent tube significant reading errors may be caused by the air/water interfaces (Penman, 1978). These are significant disadvantages. In addition, if initial filling of the liquid-filled tubes is completed before the gage is installed, care must be taken while handling the system to avoid overranging the vibrating wire transducer. Bearing in mind these various limitations, the author prefers pneumatic transducers when using this type of liquid level gage.

The second major factor that affects precision is the liquid part of the system. The system must transmit static head correctly from the free surface at the reservoir to the diaphragm of the pressure transducer, and close attention must be given to the factors discussed in Section 8.2.3. The selection of tubing diameter is critical. An upper limit is necessary to ensure that any gas in the tube can readily be displaced, and a lower limit is necessary to ensure that equilibrium is achieved in an acceptably small time. When aqueous solutions are used, the inside diameter of the liquid-filled tube should be between 0.17 and 0.25 in. (4.3–6 mm). If a larger diameter is used, gas cannot readily be displaced during initial filling and subsequent flushing. If a smaller diameter is used, the equilibrium time is likely to be too long, and any gas/liquid interfaces may create significant errors (Penman, 1978). An inside diameter of 0.25 in. (6 mm) is strongly recommended if a pressure surge is caused by movement of the liquid column at the time of reading, for example, by using a pneumatic transducer with significant volumetric displacement. When mercury is used, the inside diameter of the tubing normally ranges from 0.07 to 0.2 in. (2–5 mm).

The instrument shown in Figure 12.95 is available with a system for backpressuring both the reservoir and pneumatic transducer with air pressure. The magnitude of the air pressure is not used in calculations, because it is applied to both ends of the system. This version allows a check to be made for continuity of liquid, by taking readings as the air pressure is increased. In fact, if an initially de-aired system does become discontinuous, provided the amount of free gas in the liquid is not excessive, it can often be driven into solution under the backpressure.

The author believes that the precision of gages with pneumatic transducers and aqueous solutions is generally limited to ±0.5 in. (±13 mm). This precision is possible provided that the above guidelines for the diameter of the liquid-filled tube are followed and that temperature variations in the liquid-filled tube are not great (Section 8.2.3). Gages with vibrating wire transducers and mercury can be used to obtain higher precision but are subject to the limitations given in Table 12.9. Until a sufficient bank of data has been obtained to demonstrate precision, the author recommends that users conduct full-scale calibrations prior to field installation.

Gages with Pressure Transducer in Readout Unit

The arrangement is shown in Figures 12.96 and 12.97.

Figure 12.96 shows only two tubes, but in practice it is preferable to have two liquid-filled tubes and two tubes for gas, so that flushing is possible and independent measurements can be made on each liquid-filled tube as a check. The rubber bladder is made slightly larger than the rigid case of the cell and is therefore never in tension. Initially, the liquid-filled tubes are connected to a reservoir to ensure that the rubber bladder is expanded to fill the rigid case. Sufficient gas pressure is then applied to overcome the liquid head H, thereby compressing the liquid slightly, ensuring that all liquid is at a pressure greater than atmospheric pressure and that gas and liquid pressures across the bladder are equal. The magnitude of the gas pressure is not used in calculations, because it is applied to both ends of the system. The change in pressure transducer reading, divided by the specific gravity of the liquid, gives vertical deformation directly.

The gage shown in Figure 12.96 has two major advantages when compared with the gage shown in Figure 12.93. First, a check can readily be made for continuity of liquid, by taking readings as the gas pressure is increased. If two liquid-filled tubes are provided, separate readings provide an additional check. In fact, if an initially de-aired system does become discontinuous, provided the amount of free gas in the liquid is not excessive, it can often be driven into solution under the backpressure. Second, the transducer is accessible for checking and recalibration if necessary. Additionally, there is no

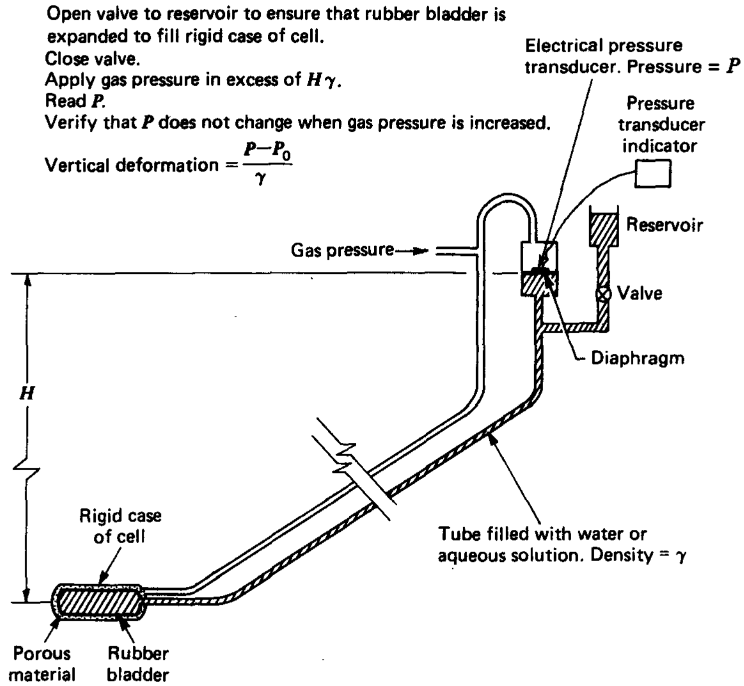


Figure 12.96. Schematic of liquid level gage with pressure transducer in readout unit, with readout unit higher than cell.

error caused by the pressure surge associated with using a pneumatic transducer in the system shown in Figure 12.93.

Precision of these gages is dependent on the same two major factors discussed for the gage shown in Figure 12.93: the pressure transducer must read the liquid head correctly and the liquid must transmit static head correctly. These conditions are easier to achieve when the system is backpressured and when the transducer is accessible, and therefore the gage shown in Figure 12.96 is preferred. A liquid-filled tubing inside diameter of between 0.17 and 0.25 in. (4.3–6 mm) is a good choice when aqueous solutions are used. A precision of ±0.25 in. (±6 mm) appears to be possible, provided that the above guidelines for the diameter of the liquid-filled tube are followed and that temperature variations in the liquid-filled tube are not great (Section 8.2.3).

Overflow Gages

The *overflow gage* shown in Figure 12.91 can be converted for use with the readout unit higher than the cell, by applying either a measured suction to the readout end of the liquid-filled tube or a m sured backpressure to the vent tube.

The former version is shown in Figure 12.98 described by Penman (1982) and Penman et (1975). The 1982 paper describes a revised met of reading, and this should be used in preferenc the 1975 method. This gage is limited to an eleva difference between the cell and readout unit about 15 ft (4.6 m): at a greater distance the liq tends to become discontinuous. Precision is t cally ±0.4 in. (±10 mm).

The latter version is described by Dunni (1968) and has duplicate air tubes both to allow culation of air and to give two independent mean measuring air pressure. This system allows m surements to be made at up to 100 ft (30 m) ele tion difference between the cell and readout u and precision is ±0.8 in. (±20 mm).

12.10.3. Single-Point Gages with Readout Unit Lower than Cell

The backpressured gage shown in Figures 12.96 12.97 can be used with the readout unit lower t the cell. As an alternative, the *overflow gage* sho

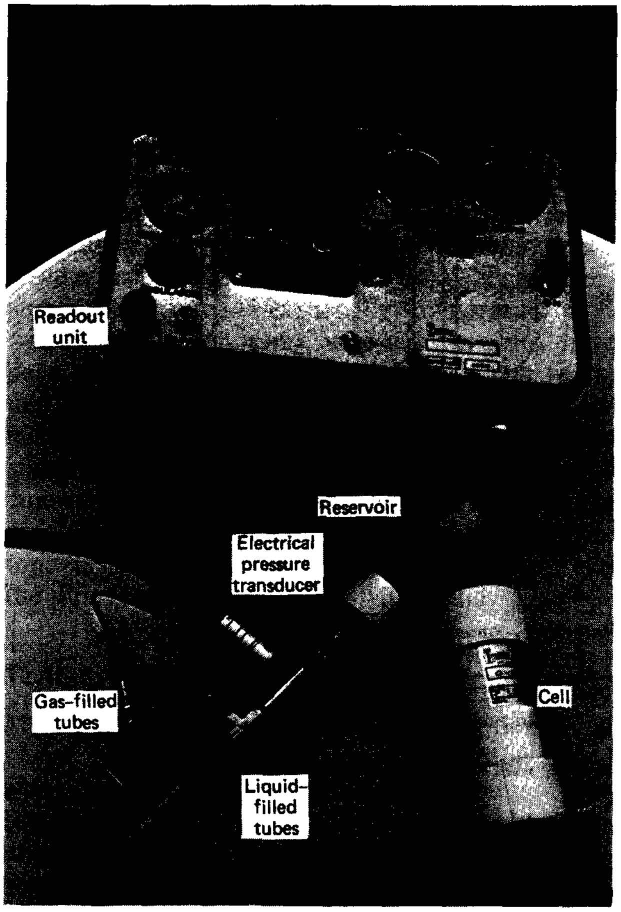


Figure 12.97. Liquid level gage with electrical pressure transducer in readout unit (courtesy of Thor International, Inc., Seattle, WA).

in Figure 12.98 can be used with the readout unit lower than the cell by applying a measured pressure to the readout end of the liquid-filled tube (Penman, 1982).

12.10.4. Multipoint Gages

Various *multipoint gages* have been developed, but most users prefer to install several single-point gages, usually because failure of a single gage in a multipoint system may result in loss of the entire system. However, a multipoint gage that consists of a series of interconnected liquid-filled chambers, placed at a similar elevation, is available and useful and is described in the following paragraphs.

Figure 12.99 shows a version manufactured by Geokon, Inc., recently developed for monitoring vertical deformation along a bench on the slope of an open pit mine. The DCDTs are connected to a console and can be arranged to sound an alarm in the event that a predetermined settlement is exceeded at any chamber. There are 11 chambers and interconnecting pipework, all covered by about 3 ft (1 m) of fill to minimize inaccuracy caused by temperature variations. The liquid is a 3:2 ethylene glycol/water mix, and precision over a 1000 ft (300 m) long system is about ± 0.02 in. (± 0.5 mm). The version is based on an original design by the Building Research Establishment in England (Ward et al., 1968), which achieved a precision of ± 0.004 in. (± 0.1 mm) during a loading test on chalk, by using a magnifying lever on each float. Precision of all versions is affected by temperature variations, which were greater at the open pit mine than the loading test on chalk.

Readers may question why this system used such a large-diameter liquid-filled pipe (nominal diameter 3 in., 76 mm), whereas for single-point systems 0.25 in. (6 mm) **inside** diameter tubes are recommended so that continuity of liquid is ensured. The problem of filling a near-horizontal large-diameter pipe with liquid was demonstrated during recent tests in Colorado. A 1.5 in. (38 mm) nominal diameter PVC pipe was laid on reasonably level ground around a building, with the two ends terminating in vertical risers alongside each other. Pouring water in one riser, supposedly to fill the pipe, resulted in unrepeatable relative water levels in the two risers, and levels were up to 1.5 in. (38 mm) different, indicating errors resulting from breaks in continuity of liquid. If a pipe or tube with an **inside** diameter larger than 0.25 in. (6 mm) is used, trapped air must be excluded in one of two ways. First, outlets for air bleeding must be provided on the top of the pipe at any point where a crest may form, and in any event no further apart than about 100 ft (30 m). Second, the pipe should be installed with a pronounced slope toward each end (i.e., in a vertical U or V shape). The first approach is more reliable and is used in the arrangement shown in Figure 12.99, the connectors to the floats acting as air bleeds. The author believes that the arrangment shown in Figure 12.99 would be satisfactory during the short-term if a 0.25 in. (6 mm) **inside** diameter liquid-filled tube had been used instead of the larger-diameter pipe, but that occasional flushing with de-aired liquid would be needed to maintain continuity of liquid in the long-term. In summary, if air bleeds or pronounced slopes can be provided (with confidence that their effectiveness will not be reduced by shape

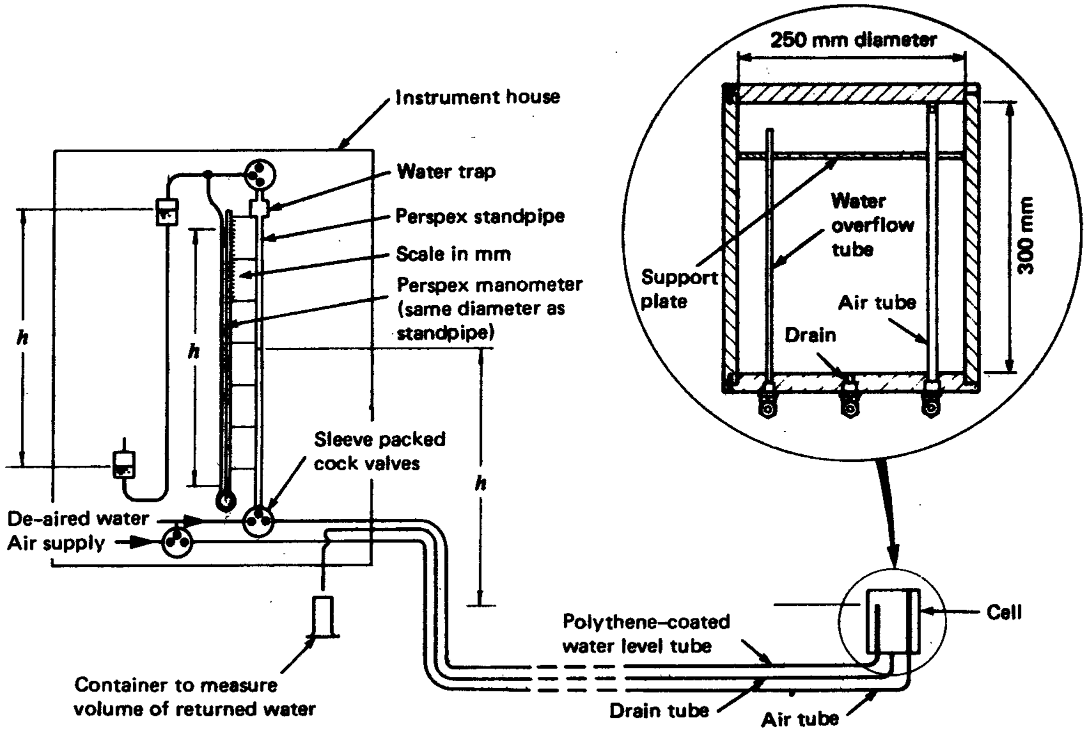


Figure 12.98. Schematic of liquid level gage, overflow type, with readout unit higher than cell (after Penman, 1982).

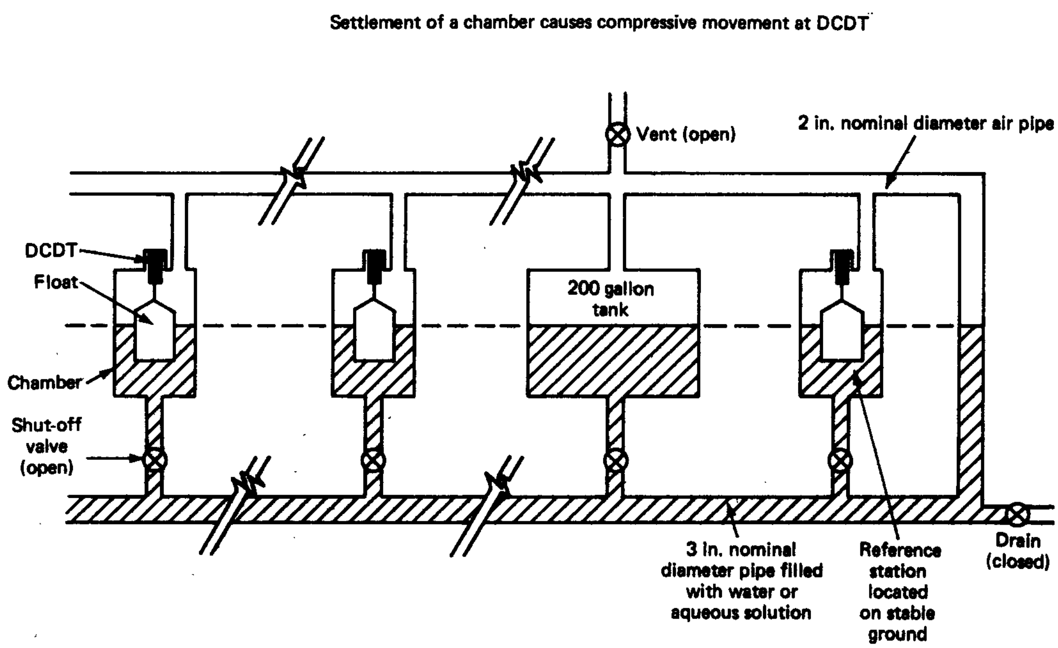


Figure 12.99. Schematic of multipoint gage (courtesy of Geokon, Inc., Lebanon, NH).

changes as vertical deformation occurs), a large-diameter pipe can be used. If not, a 0.25 in. (6 mm) inside diameter tube should be used, with occasional flushing.

Müller et al. (1977) describe a system similar to the arrangement shown in Figure 12.99, incorporating a capacitance transducer. The instrument is manufactured by Interfels. Geonor manufactures a system that uses a vibrating wire transducer to measure the buoyancy of a partially submerged float.

Two similar vibrating wire/float systems have been used satisfactorily in Russia for many years: first, the arrangement with separate air- and liquid-filled pipes as shown in Figure 12.99 and second, a single pipe of about 12 in. (305 mm) diameter, with connections to float chambers at intervals along the pipe. The connection for air enters the pipe at the top, the connection for liquid at the bottom, and the pipe remains partly filled with liquid.

12.10.5. Full-Profile Gages

Most *full-profile gages* consist of a near-horizontal plastic pipe and an instrument that can be pulled along the pipe. Readings are made at points within the pipe, and the entire vertical profile can be determined. Differences in vertical profile with time provide data for determination of vertical deformation.

These gages are particularly appropriate where vertical deformation is likely to be nonuniform, such that many single-point gages would otherwise be required. They provide the same data as an inclinometer used within horizontal inclinometer casing, and in fact an inclinometer may often be the instrument of choice if high accuracy is required. Most gages can also be used for surveying elevations along a near-horizontal or inclined borehole, or along the invert of a pipeline or culvert. Survival records are generally excellent, since no delicate parts are buried, and the instruments can be checked on a day-to-day basis and any malfunctions corrected in the laboratory. The expensive and calibrated part of the system is portable and can be used at several locations on one project or on several projects.

The distance of the instrument from one end of the pipe is established from graduations on a traction line and must be controlled carefully. For example, if part of the pipe is inclined at an angle of 10 degrees to the horizontal when using an aqueous solution in the system, a longitudinal positioning error of 1 in. (25 mm) will cause a measurement error of about 0.17 in. (4.3 mm). If maximum precision is required, the pipe should be as horizontal as possible. If the pipe is also arranged as a probe extensometer, both vertical and horizontal deformations can be monitored, and probe extensometer data can be used to control longitudinal positioning of the full-profile gage.

Various types of full-profile gage are described in the following subsections.

Overflow Gage

The cell of the overflow gage shown in Figure 12.91 is shaped as a probe (Penman, 1982; Penman and Charles, 1982). The pipe, typically 2.5 in. (63 mm) Sch. 40 PVC, is inclined slightly upward away from the readout and is free-draining.

Gages with Pressure Transducer in Probe and Attached Liquid-Filled Tube

Most of the single-point gages based on the arrangement shown in Figure 12.93 can be manufactured as full-profile gages using pneumatic, electrical resistance strain gage, or vibrating wire pressure transducers, with aqueous liquids or mercury. Typical pipe diameter is 1.5 in. (38 mm) nominal; requirements for tubing, transducer, and readout unit are as discussed previously for single-point gages, and precision is similar. When used as a full-profile gage, the liquid-filled tube should be transparent, so that regular inspections can be made for continuity of liquid. If any gas is observed in the liquid, the gage should be flushed with fresh de-aired liquid. Reading correctness should be verified on each day prior to any field readings, by using the gage to measure a known elevation difference.

Bergdahl and Broms (1967) describe a full-profile gage, shown schematically in Figure 12.100. With the readout unit higher than the probe, air pressure is slowly applied to the inside of the bladder until a small quantity of liquid returns to the readout unit, indicating an air/liquid pressure balance across the bladder. In the original version the air tube was contained coaxially within the liquid-filled tube, thus creating a large wetted surface for the liquid. This feature created a long time lag between application of air pressure and stabilization of the free liquid surface, and precision was poor when tubes were longer than about 100 ft (30 m). An improved version, manufactured by Water Nold Company, Inc. under the trade name *Aquaducer*™ (Figure 12.101), uses separate tubes and a 0.25 in. (6 mm)

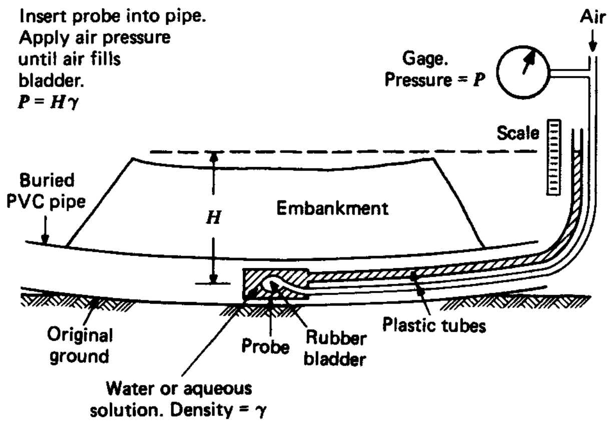


Figure 12.100. Schematic of full-profile gage, with air/liquid pressure balance across a bladder.

inside diameter liquid-filled tube. Standard tubing length is 500 ft (150 m), allowing profiles of up to 1000 ft (300 m) to be surveyed if access is available to both ends of the pipe. The elevation difference between the probe and readout is limited by the strength of the bladder to about 10 ft (3 m).

Gages with Pressure Transducer in Readout Unit and Attached Liquid-Filled Tube

The single-point gage shown in Figure 12.96, with the pressure transducer in the readout unit, can be manufactured as a full-profile gage, as illustrated in Figure 12.102. Because the liquid is backpressured, this version is preferable to the version with a pressure transducer in the probe.

Gages with Pressure Transducer in Probe and without Attached Liquid-Filled Tube

The types of full-profile gages described previously have attached liquid-filled tubes and therefore tend to be cumbersome. Also, the liquid in the liquid-filled tube may be subject to large temperature changes during insertion and withdrawal from the pipe, with consequent thermal errors. In an effort to overcome these limitations, several gages have been developed whereby a pressure transducer is pulled along a liquid-filled pipe or tube. The arrangement is shown in Figure 12.103.

A version described by Bozozuk (1969) used an unbonded resistance strain gage pressure transducer within a 1 in. (25 mm) nominal diameter pipe. The instrument is subject to significant errors (Tao, 1979), including error caused by temperature sen-

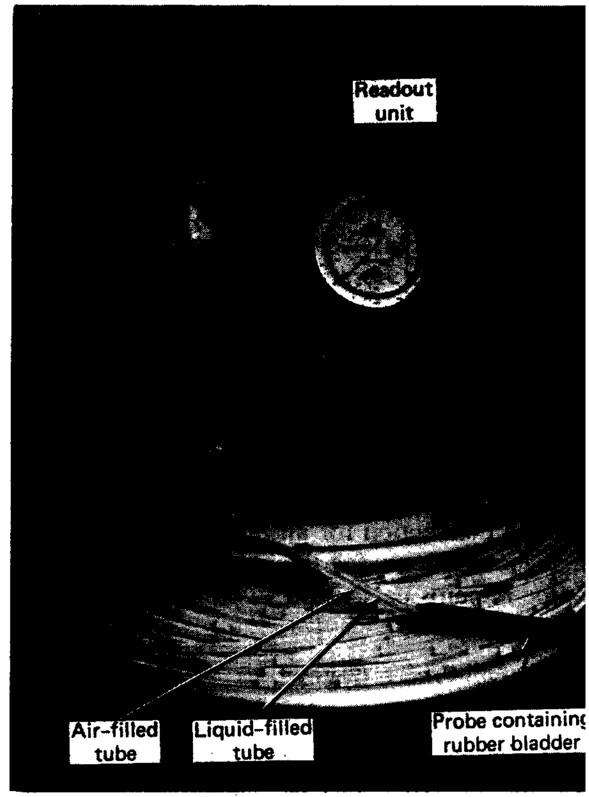


Figure 12.101. *Aquaducer*™ full-profile liquid level gage (courtesy of Water Nold Company, Inc., Natick, MA).

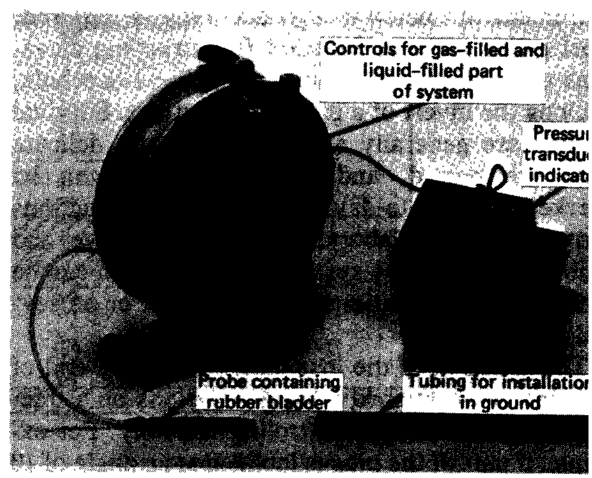


Figure 12.102. Full-profile gage, with pressure transducer readout unit, and attached liquid-filled tube (*hydrostatic profile gauge*) (courtesy of Soil Instruments Ltd., Uckfield, England).

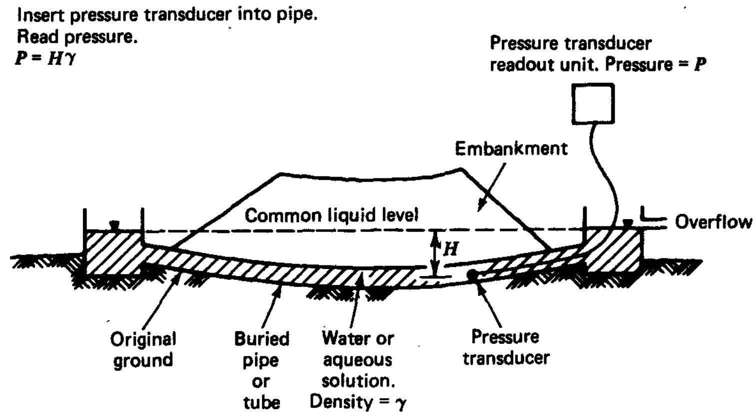


Figure 12.103. Schematic of full-profile gage, without attached liquid-filled tube.

sitivity of the pressure transducer, and it has not been widely used. However, with the advent of small stable bonded and unbonded resistance strain gage, vibrating wire, and pneumatic pressure transducers, this arrangement should be applicable in cases where access is available to both ends of the pipe or tube, where temperature variations are not great, where the barometric pressure at each end of the system is substantially the same (i.e., where air currents are not great), and where complete liquid-filling can be maintained. As discussed earlier, the last condition requires outlets for air bleeding, pronounced upward slopes toward the ends of the pipe, or a 0.25 in. (6 mm) **inside** diameter tube.

The author is not aware of commercially available versions with stable transducers, but Audibert (1985) reports on the successful development and use, by the Houston, TX, office of The Earth Technology Corporation, of a system using a miniature piezoresistive pressure transducer within 0.25 in. (6 mm) **inside** diameter thick wall tubing. The pressure transducer was Model No. 8507-2, manufactured by Endevco Corporation, San Juan Capistrano, CA, with an outside diameter of 0.092 in. (2.3 mm), a range of 0–2 lb/in.^{2} (0–14 kPa), a burst pressure of ± 40 lb/in.^{2} (275 kPa), and a rated temperature sensitivity of 0.003 lb/in.^{2}/°F (0.037 kPa/°C). The system was used to make settlement measurements within a block of soil during a large-scale model test, conducted in a non-air-conditioned warehouse, and achieved a precision of ± 0.05 in. (± 1.3 mm). This high precision indicates that the transducer was in a very uniform temperature environment: the rated temperature sensitivity corresponds to an error of 0.83 in. per 10°F (38 mm per 10°C) and illustrates the difficulty of achieving high precision in a field environment. However, future improvements in pressure transducers may make this system more applicable for general field use.

It is interesting to note that the **inside** diameter (0.25 in., 6 mm) chosen by Audibert for the tubing is the same as the inside diameter recommended by the author in Section 8.2.3 and that therefore Audibert had no difficulties caused by discontinuity of liquid.

The author recommends that, whenever the type of gage shown in Figure 12.103 is used, instrument data should be compared with elevation data determined by surveying methods before backfilling over the pipe or tube and that repeatability tests should be made before accepting data. In most cases it may be more prudent to use the type of gage with an attached liquid-filled tube.

The gage without an attached liquid-filled tube is particularly suitable for surveying elevations along downward inclined boreholes. If the borehole is watertight, the survey merely involves lowering the pressure transducer through the water on a graduated cable and recording and plotting pressure and cable graduation at intervals to the bottom of the borehole. If the borehole is not watertight, a plastic pipe with a bottom cap can be inserted temporarily and filled with water.

Double Fluid Settlement Gages

A *double fluid settlement gage* has been developed by the Road Research Laboratory in England (Irwin, 1964). A buried reservoir containing mercury is pressurized by air during reading and the mercury driven along a 0.11 in. (2.8 mm) **inside** diameter nylon tube. The position of the mercury is detected by

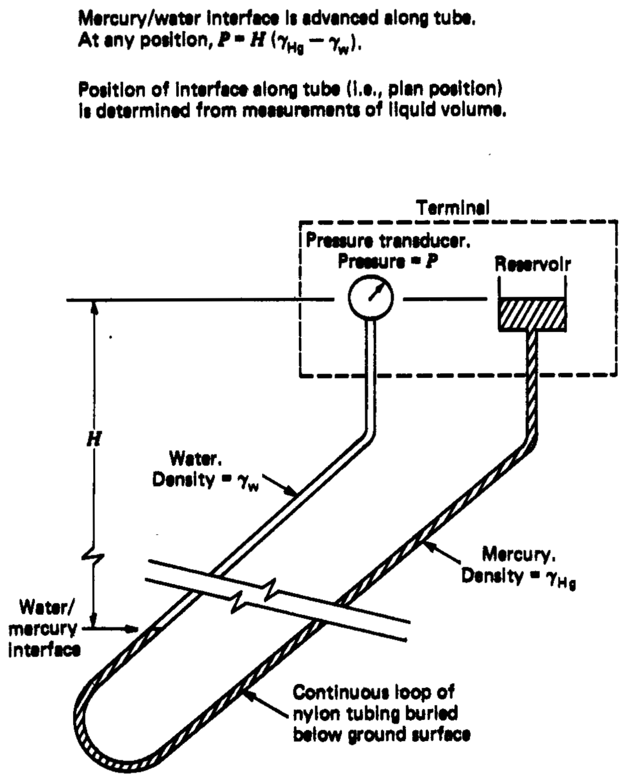


Figure 12.104. Schematic of double fluid settlement gage.

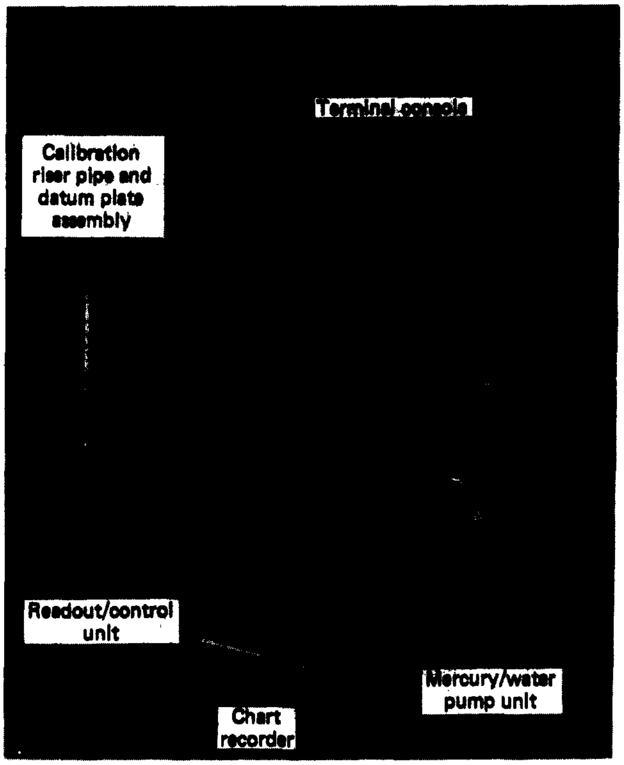
electrical contacts in the tube and settlement is determined by measuring the air pressure. Later, the design was modified to create a multipoint system with intermediate measuring points (Irwin, 1967). Estimated errors were less than ±0.1 in. (±2.5 mm) over distances up to 200 ft (60 m) between the reading station and the mercury reservoir.

Subsequently, a double fluid settlement gage was developed by the project engineers during construction of Tarbela Dam in Pakistan and subsequently named the *TAMS double fluid settlement device (DFSD)*. The gage is described by Clements (1978) and Clements and Durney (1982), and some measurement results are given by Szalay and Marino (1981). The operating principle is shown in Figure 12.104.

A continuous loop of 0.11 in. (2.8 mm) inside diameter polyethylene-sheathed nylon tubing is installed in a near-horizontal trench, and the ends of the loop are terminated at a common accessible point. Prior to measurement the tubing is filled with de-aired water. During the measuring phase a water/mercury interface is formed, and mercury is allowed to bleed into the tubing to advance the interface. By maintaining the free surface of the merc at a constant level and monitoring the pressure the top of the water column as shown in Fig 12.104, a continuous record of the elevation of interface is obtained. The position of the interfac determined by measuring the volume of wa forced out of the tubing, and a confirmation of interface position can be obtained by creating sn discrete risers at several points in the tubing du installation and using these as indicators. On co pletion of the measuring sequence, the mercury removed from the installed tubing and replaced water.

At Tarbela Dam the length of individual tu exceeded 4000 ft (1220 m), and clearly no other g could have provided a continuous settlement pro for this application. Since its original developme the system has been improved and used succe fully in several embankment dams, notably for termining the settlement profile across zones of ferent compressibilities, for example, between core and downstream filter. Clements and Dur (1982) and Clements (1984) describe three versi of the DFSD:

1. A manually operated system similar to original development, designed to ope over tubing lengths up to approximately 4 ft (1220 m) and to accommodate elevation ferences up to 20 ft (6 m). The terminal can be higher than 20 ft (6 m) above the low part of the tube, otherwise pressures bec excessive. Precision is dependent on th factors. First, the elevation differences in system: the smaller the differences, greater the precision. Second, the length tubing: the longer the tubing, the less is precision, owing to inertia and wall fricti Third, the expertise and patience of operator: under average conditions a pr sion of ±0.4–1.5 in. (±10–38 mm) is typi
2. A portable manual system, designed to op ate over tubing lengths of up to 650 ft (200 and to accommodate elevation differen less than 4 ft (1.2 m). A precision of appr mately ±0.1 in. (±3 mm) is achievable.
3. An automatic system (Figure 12.105), signed to accommodate tubing lengths up 3300 ft (1000 m) and elevation differences excess of 10 ft (3 m). A precision of ±0.4 (±10 mm) is achievable.



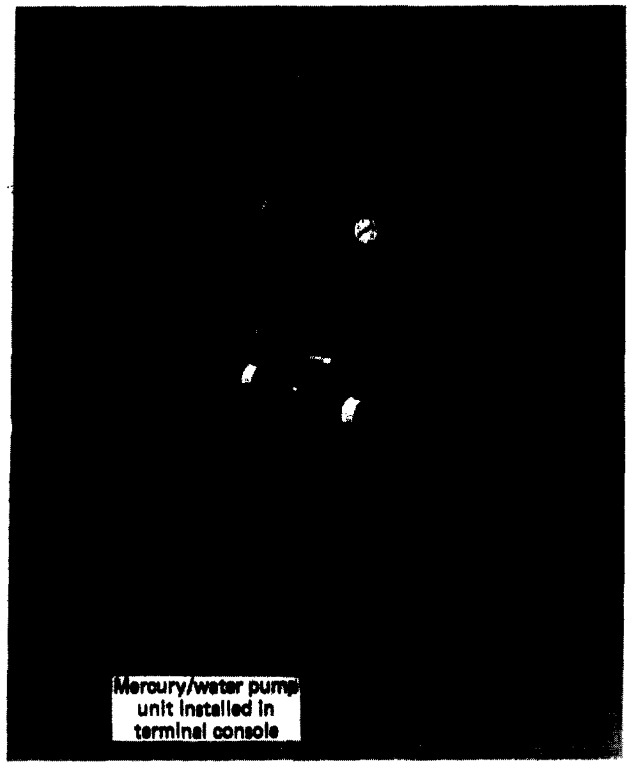


Figure 12.105. Automatic plotter system for double fluid settlement gage (courtesy of Soil Instruments Ltd., Uckfield, England).

Clements (1984) recommends that the slope of the tubing should normally not exceed 1 in 10, to prevent the possibility of interface breakup during the stop/start transitions when the instrument is read manually. However, interface breakup is normally encountered only when the operator allows an excessive rate of mercury feed. This concern does not exist with the continuously feeding automatic system, and it has been demonstrated that no breakup occurs even when the interface is forced to "loop the loop" in a vertically coiled tube.

When installing tubing for the DFSD, a duplicate length should be installed alongside the primary tube for use in the event of damage by application of excessive pressure.

12.10.6. Filling and Flushing Liquid-Filled Tubes

Two accessible liquid-filled tubes, with appropriate fittings and valves, are strongly recommended for all systems that are left in place, so that they can be flushed if discontinuity of liquid is suspected. Recommendations for tubing material, fittings, and liquid are given in Section 8.2.3.

In general, initial filling of liquid-filled tubes is best done by applying a vacuum at one end and allowing liquid to enter from the other end. This procedure reduces the amount of air in the tube, therefore reducing the chance of breaking continuity of the liquid, and minimizes the time required. During subsequent flushing, it is usually best to blow all liquid out of the tube under air pressure and introduce fresh liquid as described above.

In the United States many manufacturers complete the initial filling of liquid-filled tubes before shipment to the user. This practice runs the risk of the liquid becoming discontinuous during shipment and may require that special measures be taken to prevent damage to pressure transducers or other components subjected to the pressure of the liquid. In Europe it is more common practice to complete the initial filling in the field. This practice requires appropriately competent field personnel and may require filling and subsequent emptying at the factory so that factory calibrations can be made. Clearly, there are points in favor of both approaches, but in general the author recommends the European practice.

Nylon tubes are likely to require more flushing than polyethylene tubes during their initial use. Nylon tends to absorb water and leach gas until it becomes fully saturated with water, and therefore one or two additional flushes are often needed before the system can be fully commissioned.

12.10.7. Recommendations for Choice of Liquid Level Gage

It is not possible to make definitive recommendations for choice of a liquid level gage, and any one of the types described above may on occasion be the instrument of choice. The selection depends on the application, site-specific conditions and needs, the number of measuring points required, the relative elevations of measuring points and readout unit, availability of and familiarity with hardware, required precision, and the general factors given in Section 4.9 and the more specific factors given in this section and in Table 12.9.

12.10.8. Installation of Liquid Level Gages

Installation of liquid level gages in boreholes and in fill should follow the guidelines given in Chapter 17. When installed in boreholes, tubing can be prespiraled, as described in Section 17.5.1, to avoid damage caused by large vertical compression of the surrounding soil.

12.11. MISCELLANEOUS DEFORMATION GAGES

Various deformation gages do not fit readily into previously described categories: telltales, convergence gages for slurry trenches, time domain reflectometry, fiber-optic sensors, and acoustic emission monitoring.

12.11.1. Telltales

When a sleeved rod or wire is attached to an inaccessible point, routed to an accessible point, and used with a transducer for monitoring the changing distance between the two points, the device is referred to as a *telltale*. When a telltale is inst in the ground, it is the same as a single-point borehole extensometer, described in Section Telltales can also be installed in or on structur monitoring relative deformation, for example, tieback anchor for determining movement of th chor with respect to the anchor head or on a d pile or drilled shaft for determining tip settle during a load test.

As described in Chapter 13, *multiple telltale* be used for determination of strain and lo structural members. Figure 12.106 shows one telltales used for this purpose during a recent d shaft load test with which the author was invo

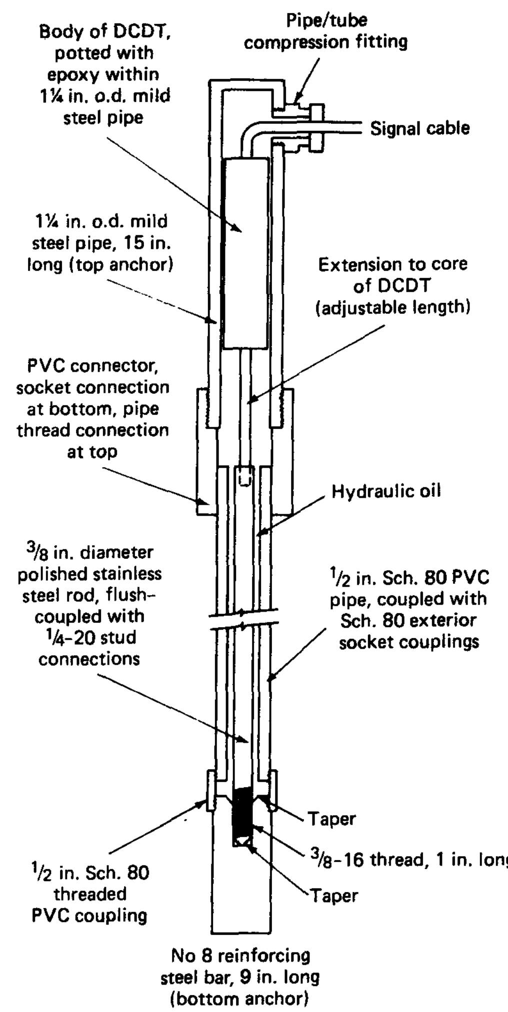


Figure 12.106. Schematic of one telltale that forms par remotely-read multiple telltale system for a drilled shaft loa

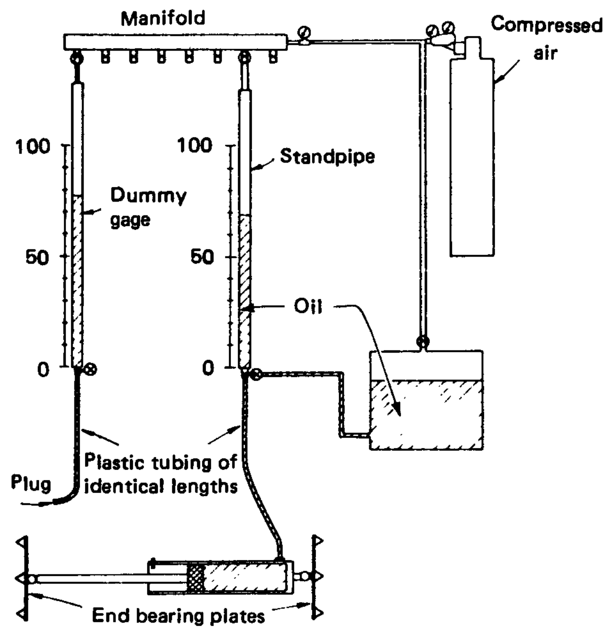


Figure 12.107. Schematic of hydraulic gage used to measure convergence of slurry trench (after DiBiagio and Myrvoll, 1972).

The top of the top anchor was installed about 12 in. (305 mm) below the shaft butt.

12.11.2. Convergence Gages for Slurry Trenches

Methods of monitoring stability in relation to time, while conducting full-scale tests of slurry trench excavations, are outlined in Chapter 19. The methods include monitoring closure of the trench. Two types of gage are available: the first gage is applicable if reinforcing steel is installed in the excavation, the second gage if reinforcing steel is not installed.

A *hydraulic gage* is described by DiBiagio and Myrvoll (1972) and shown in Figure 12.107. It consists of a piston within an oil-filled piston chamber, set horizontally across the trench. End bearing plates contact opposite walls of the trench, one attached to the end of the piston rod, the other to the opposite end of the assembly. A standpipe rises vertically from the piston chamber. A reduction in the width of the trench causes movement of the piston and an upward flow of oil into the standpipe; thus, the level of oil in the standpipe can be related to the width of the trench. The gage is attached to the reinforcing cage prior to installation in the trench.

An alternative instrument was used successfully in a recent full-scale test with which the author was involved and is shown in Figure 12.108. The instrument incorporated a *soil strain gage*, as described in Section 12.6.5. Coils 15 in. (380 mm) in diameter were embedded in opposite sides of the trench using a double-acting hydraulic jack, supported on orientation rods. Prior to installation five plastic tent pegs were attached to the back of each coil, the jack retracted, the coils supported on opposite ends of the jack, the jack and coils attached to the orientation rods and lowered into the trench, the jack actuated to drive the tent pegs into the soil until the coils were at the surface of the trench wall, and the jack retracted and withdrawn. Measurements were taken while the trench was filled with slurry, after concrete pouring, and after concrete set, with a pre-

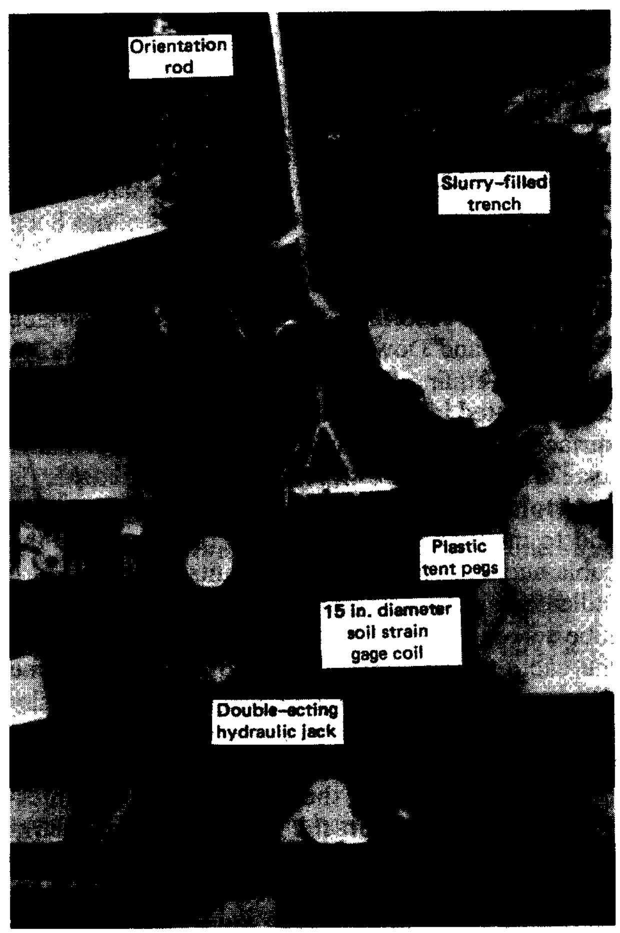


Figure 12.108. Gage used to measure convergence of slurry trench, based on *soil strain gage* transducer.

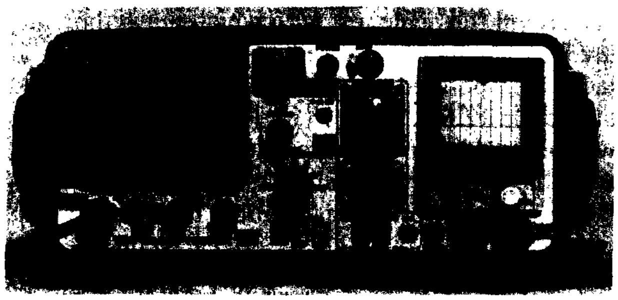


Figure 12.109. Time domain reflectometry (TDR) cable tester: Tektronix Model 1503 (courtesy of Tektronix, Inc., Beaverton, OR).

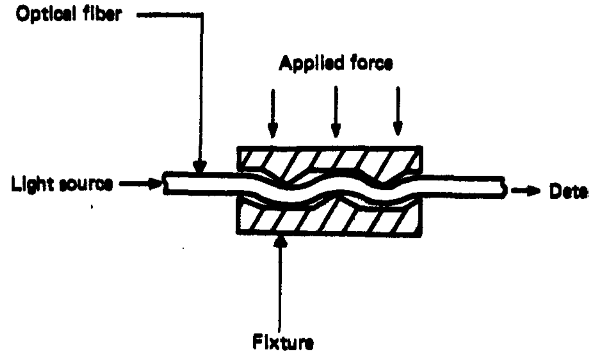


Figure 12.110. Fiber-optic microbending sensor (after Kro 1983). Reprinted by permission. Copyright © 1983, Instrum Society of America.

cision of approximately ±0.1 in. (±3 mm). Data were not influenced by the presence of slurry or concrete. This alternative would not be possible in a trench with reinforcing steel, because the steel would influence the output of the induction coil transducers.

12.11.3. Time Domain Reflectometry

Time domain reflectometry (TDR), originally developed to locate breaks in power line cables, has been used to monitor the successive collapse of roof strata after underground mining and the propagation of the resulting cave toward the surface (O'Connor and Dowding, 1984; Wade and Conroy, 1980). The equipment consists of a coaxial electrical cable grouted in a vertical borehole from the ground surface to the mine and a standard TDR cable tester* (e.g., Figure 12.109). The cable tester is used to transmit an electrical pulse along the cable and to monitor the return signal, and faults in the cable such as crimps, short circuits, or breaks are indicated as characteristic signals on a cathode ray tube screen and on a paper record. The distance to the cable fault is proportional to the elapsed time between transmission and arrival of a reflected signal. Accuracy is about 2% of the distance between the tester and the cable break. This can be improved by precrimping the cable at 10 ft (3 m) intervals: the crimps distort the signal and act as markers on the arrival waveform, to which any further distortions or breaks may be related.

*Commercial sources are given in Appendix D.

12.11.4. Fiber-Optic Sensors*

Fiber-optic sensors (Davis, 1985; Davis et al., 198 Kersten and Kist, 1984; Krohn, 1983) depend on t ability of the fibers to carry light from a source tc photosensitive detector. Fiber-optic sensors can used to sense the relative position between an o ject and the end of a fiber or the distance betwe two points along a fiber; they can also indica bending. They are unaffected by temperature humidity extremes and are immune to electric noise. Small size and ability to transmit light alo curved paths can provide access to normally ina cessible areas, and reliability is high because mc sensors are passive.

The author is not aware that fiber-optic sensc have been used in geotechnical applications, b they appear to have good potential for monitori deformation both along and transverse to the fibe When optical fibers bend, small amounts of light a lost through the walls. By using the microbendi sensor shown in Figure 12.110, changes in the inte sity of received light can be related to the magnitu of transverse deformation. By using a pulsed sy tem, axial deformation and bending can be moı tored at all points along a fiber. Fiber-optic senso therefore have the potential for providing the san information as a combination of an inclinometer t gether with a probe or fixed borehole extensomete although precision has not yet been proved. A rea time *continuous fiber-optic strain monitoring sy*

*Written with the assistance of Richard W. Griffiths, G2 Consu tants, Pacific Palisades, CA.

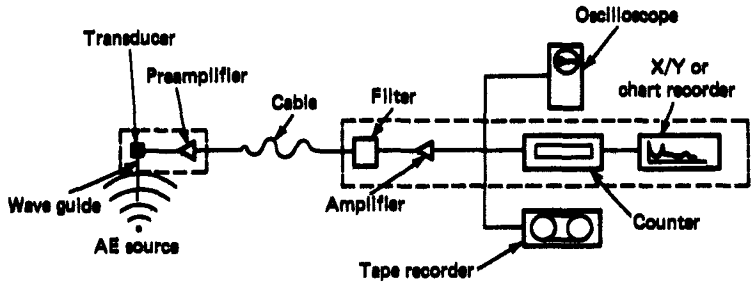


Figure 12.111. Schematic of basic single-channel acoustic emission monitoring system for recording total counts or count rate (after Koerner et al., 1981). Reprinted with permission from ASTM STP 750. Copyright ASTM, 1916 Race Street, Philadelphia, PA 19103.

tem is currently being developed (McKeehan and Griffiths, 1986; McKeehan et al., 1986; *Oil & Gas Journal*, 1985), and has been patented. Once the system is developed, geotechnical applications are likely to follow.

12.11.5. Acoustic Emission Monitoring*

Acoustic emissions are sounds generated within a soil or rock material that has been stressed and subsequently deforms. Sometimes these sounds are audible, for example, wood cracking, ice expanding, or soil and rock particles abrading against one another, but more often they are not, owing to their low amplitude or high frequency or both.

A piezoelectric transducer is generally used as a "pickup" to detect the acoustic emissions and produces an electrical signal proportional to the amplitude of sound or vibration being detected. The signal is then amplified, filtered, and counted or recorded in some quantifiable manner. Unwanted machine and environmental noise are electronically filtered from the signal or separately quantified and subtracted from the measurements. The counts or recordings of the emissions are then correlated with the basic material behavior to determine empirically the relative stability of the given material. Usually, if no acoustic emissions are present, the material is in equilibrium and therefore stable. If emissions are observed, the material is not in equilibrium and may be in a condition that eventually leads to failure. The technique was originated by the U.S. Bureau of Mines in the 1930s to detect mine pillar, wall, and roof instability. The method is sometimes referred to as *microseismic detection* and *subaudible rock noise monitoring*, but the term *acoustic emission*, or simply *AE*, is becoming the accepted term.

*Written with the assistance of Robert M. Koerner, Professor, Drexel University, Philadelphia, PA.

As shown in Figure 12.111, the components of an acoustic emission monitoring system consist of a waveguide to bring the signals from within the ground to a convenient monitoring point, a transducer (geophone, accelerometer, or hydrophone) to convert the mechanical wave to an electrical signal, a preamplifier to amplify the signal if long cable is being used, filters to eliminate undesirable portions of the signal, an amplifier to amplify the signal further, and a quantification system. The dashed lines in Figure 12.111 indicate components that are grouped in self-contained boxes.

Field monitoring efforts in AE have been directed to the following topics:

- Stability assessment of earth embankments
- Standup time of excavations in soil and rock
- Stability of bracing and anchors in ground support systems
- Providing an early warning of subsidence
- Determination of preconsolidation and prestress values in soil
- Detection of seepage, grout penetration, and hydrofracturing

AE is most effective when the amplitude of the signals is high and thus is more effective for rock and cohesionless soil than for cohesive soil. Guidelines for practical use of AE are given by Drnevich and Gray (1981), Hardy and Leighton (1975, 1978, 1981), and Koerner et al. (1976, 1977, 1978).