Geotechnical and Structural Instrumentation for Road Tunnels

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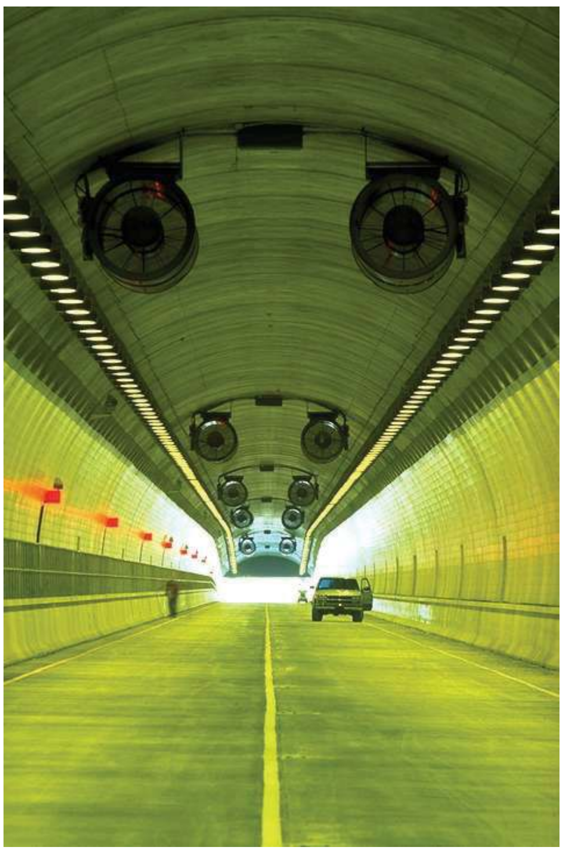
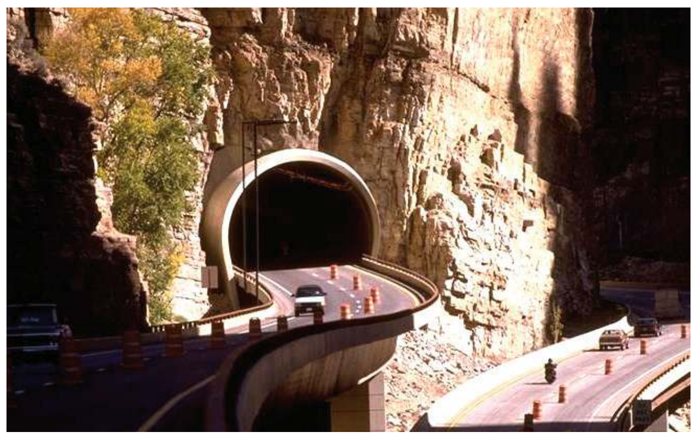
Technical Manual for Design and Construction of Road Tunnels — Civil Elements





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16. Abstract

The increased use of underground space for transportation systems and the increasing complexity and constraints of constructing and maintaining above ground transportation infrastructure have prompted the need to develop this technical manual. This FHWA manual is intended to be a single-source technical manual providing guidelines for planning, design, construction and rehabilitation of road tunnels, and encompasses various types of road tunnels including mined, bored, cut-and-cover, immersed, and jacked box tunnels. The scope of the manual is primarily limited to the civil elements of road tunnels.

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Road tunnel, highway tunnel, geotechnical investigation, geotechnical baseline report, cut-and-cover tunnel, drill-and-blast, mined tunnel, bored tunnel, rock tunneling, soft ground tunneling, sequential excavation method (SEM), immersed tunnel, jacked box tunnel, seismic consideration, instrumentation, risk management, rehabilitation.	No restrictions.

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CONVERSION FACTORS

Approximate Conversions to SI Units			Approximate Conversions from SI Units		
When you know	Multiply by	To find	When you know	Multiply by	To find
		(a) Length			
inch	25.4	millimeter	millimeter	0.039	inch
foot	0.305	meter	meter	3.28	foot
yard	0.914	meter	meter	1.09	yard
mile	1.61	kilometer	kilometer	0.621	mile
		(b) Area			
square inches	645.2	square millimeters	square millimeters	0.0016	square inches
square feet	0.093	square meters	square meters	10.764	square feet
acres	0.405	hectares	hectares	2.47	acres
square miles	2.59	square kilometers	square kilometers	0.386	square miles
		(c) Volume			
fluid ounces	29.57	milliliters	milliliters	0.034	fluid ounces
gallons	3.785	liters	liters	0.264	gallons
cubic feet	0.028	cubic meters	cubic meters	35.32	cubic feet
cubic yards	0.765	cubic meters	cubic meters	1.308	cubic yards
		(d) Mass			
ounces	28.35	grams	grams	0.035	ounces
pounds	0.454	kilograms	kilograms	2.205	pounds
short tons (2000 lb)	0.907	megagrams (tonne)	megagrams (tonne)	1.102	short tons (2000 lb)
		(e) Force			
pound	4.448	Newton	Newton	0.2248	pound
		(f) Pressure, Stress, Modulus of Elasticity			
pounds per square foot	47.88	Pascals	Pascals	0.021	pounds per square foot
pounds per square inch	6.895	kiloPascals	kiloPascals	0.145	pounds per square inch
		(g) Density			
pounds per cubic foot	16.019	kilograms per cubic meter	kilograms per cubic meter	0.0624	pounds per cubic feet
		(h) Temperature			
Fahrenheit temperature(°F)	5/9(°F- 32)	Celsius temperature(°C)	Celsius temperature(°C)	9/5(°C)+ 32	Fahrenheit temperature(°F)

Notes: 1) The primary metric (SI) units used in civil engineering are meter (m), kilogram (kg), second(s), newton (N) and pascal (Pa=N/m^2).
2) In a "soft" conversion, an English measurement is mathematically converted to its exact metric equivalent.
3) In a "hard" conversion, a new rounded metric number is created that is convenient to work with and remember.

FOREWORD

The FHWA Technical Manual for Design and Construction of Road Tunnels – Civil Elements has been published to provide guidelines and recommendations for planning, design, construction and structural rehabilitation and repair of the civil elements of road tunnels, including cut-and-cover tunnels, mined and bored tunnels, immersed tunnels and jacked box tunnels. The latest edition of the AASHTO LRFD Bridge Design and Construction Specifications are used to the greatest extent applicable in the design examples. This manual focuses primarily on the civil elements of design and construction of road tunnels. It is the intent of FHWA to collaborate with AASHTO to further develop manuals for the design and construction of other key tunnel elements, such as, ventilation, lighting, fire life safety, mechanical, electrical and control systems.

FHWA intends to work with road tunnel owners in developing a manual on the maintenance, operation and inspection of road tunnels. This manual is expected to expand on the two currently available FHWA publications: (1) Highway and Rail Transit Tunnel Inspection Manual and (2) Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual.

M. Myint Lwin, Director
Office of Bridge Technology

CHAPTER 15
GEOTECHNICAL AND STRUCTURAL INSTRUMENTATION

15.1 INTRODUCTION

In the context of this manual, the primary purpose of geotechnical and structural instrumentation is to monitor the performance of the underground construction process in order to avoid or mitigate problems. If such monitoring also serves a scientific function, or leads to advancement in design procedures, that is a bonus rather than a primary reason for its implementation. A few decades ago monitoring was not a particularly easy task because the tools were few and some not so well developed. Monitoring was generally performed manually, and the refining of data to a state of usability from the raw readings often required long hours of "number crunching" with relatively crude calculators and more long hours of plotting charts and graphs by hand.

The world of the early 21st century is very different for those who pursue the art of determining what ongoing construction is doing to its surroundings, or even to itself. Advanced and refined types of instrumentation abound, and electronics coupled with computers has made remote monitoring, even from half a world away, practically an everyday affair. It is common for even medium sized projects to run a computerized database that reduces raw readings to usable data and can report on any combination of instruments and data plots within minutes. It can also inform interested parties any time of the day or night if movements or stresses have reached pre-set trigger levels that demand some kind of mitigative action. The possibilities have not gone unnoticed by project Owners, and comprehensive instrumentation and monitoring programs are becoming the norm rather than the exception. This is perhaps especially true in the world of tunneling where even small mis-steps can result in damage that may lead to lawsuits or the shutting down of operations.

Readers should be aware that much of the instrumentation described herein may not lend itself particularly well to rural highway tunnels, especially those located in hilly or mountainous terrain that may limit the need for instrumentation if great tunnel depth minimizes ground settlement at the surface, and if lack of surface development minimizes the number of third-party abutters who could be affected by construction. Also, even if a tunnel does require monitoring for whatever reason, great depth may minimize possibilities for damage to surface installations and push designers and constructors toward more in-tunnel installations.

The amazingly large number of instrument types available to tunnelers means that this chapter can do little more than "broad brush" the subject. The most common and/or most promising types of instrument will be covered, but readers will have to turn to the references to see what else is available. A few types will be covered to some degree in other chapters; for example, earth pressure cells that are commonly used by those who specialize in Sequential Excavation Method (SEM) tunneling (Chapter 9), but are not so much used by those who work in other types of underground construction. Although vibration monitoring will be covered herein, the monitoring of noise will not be covered because it is normally considered an environmental rather than a structural or geotechnical concern. Some instruments, such as those used to determine in-situ ground stresses prior to tunneling, will not be covered because they more rightly belong in the category of site investigation instrumentation. And finally, there will not be space to delve deeply into the theory of operation of the various instruments discussed, so readers will again have to turn to the referenced publications for more details.

The first few sections of this chapter will discuss the types of measurements typically made:

- Ground Movement away from the tunnel
- Building Movement for structures within the zone of influence
- Tunnel movement of the tunnel being constructed or adjacent tubes
- Dynamic Ground Movement from Drill & Blast
- Groundwater Movement and Pressure due to changes in the water percolation pattern

The first three items comprise quasi-static changes in position, and the last is also concerned with long-term effects. In contrast, Dynamic Ground Movement covers response due to vibration caused by the shock waves generated by explosive charges used to excavate rock.

All of the monitoring needs to be coordinated to fit with the tunnel construction schedule, and to establish the actions that must be taken in response to the instrumentation findings. These topics are discussed in the final section of this chapter.

15.2 GROUND MOVEMENTS – VERTICAL & LATERAL DEFORMATIONS

15.2.1 Purpose of Monitoring

The primary purpose for monitoring ground movements is to detect them while they are still small and to modify construction procedures before the movements grow large enough to constitute a real problem by affecting either the advancing excavation or some contiguous existing facility. For the advancing excavation, ground support has to be based on conditions encountered; monitoring either confirms the adequacy of the support or indicates whether more or different support may be required. Existing facilities may be at the ground surface – roads, railroads, buildings and the like – or they may be below ground in the form of utilities or other transportation tunnels such as subways. The first line of defense against potentially damaging movements is to detect them at depth in the ground immediately surrounding the advancing tunnel and take mitigative action before those movements can "percolate" upward toward the surface. This kind of monitoring can provide an indication of whether ground treatment such as grouting is effectively limiting movements that might otherwise result in troublesome settlements. Ground can, of course, move upward as well as downward, in the form of heave from unloading that can destabilize the invert of the tunnel under construction, and as a side effect lead to lateral, possibly damaging deformations as the ground moves toward the excavation to take up the slack. In addition to helping control the ground, the data developed can be used (and this may be said of all monitoring discussed in succeeding paragraphs) to verify design assumptions and to evaluate claims by construction contractors and third-party abutters.

15.2.2 Equipment, Applications, Limitations

Several types of instrumentation are used to monitor ground movement:

- Deep Benchmarks
- Survey Points
- Borros Points
- Probe Extensometers
- Fixed Borehole Extensometers, either measured from the surface or during advance of the tunnel
- Telltales or Roof Monitors
- Heave Gages

- Conventional Inclinometers
- In-place Inclinometers
- Convergence Gages

15.2.2.1 Deep Benchmarks

Deep Benchmarks (Figure 15-1) are steel pipes/casings drilled into stable strata – preferably sound bedrock – outside the advancing tunnel's zone of influence. They are used when existing benchmarks, such as those installed by the USGS, are not available and it is important to know actual elevation changes of other instruments meant to detect movements. If installed close to the construction, deep benchmarks need to be carried below invert. They must be absolutely stable in spite of any ground movements that are occurring because it is the surface level collars of these devices that become the unmoving points from which locations and elevations of other instruments can be determined by surveying. A major complication in the installation of benchmarks can be the difficulty of installing them in a location and/or to a depth that absolutely guarantees no movement as tunneling proceeds. In this regard the lowering of groundwater in a soft ground environment can contribute to ground settlements well outside the immediate projected footprint of the advancing tunnel, so the instrument has to be well placed to guard against this eventuality. In cases of very large projects or overlapping projects that cause the water table to be drawn down across a large area, benchmarks have been known to settle even when founded in bedrock because some rock types can be dependent to a degree on pore water pressure for their ability to carry load.

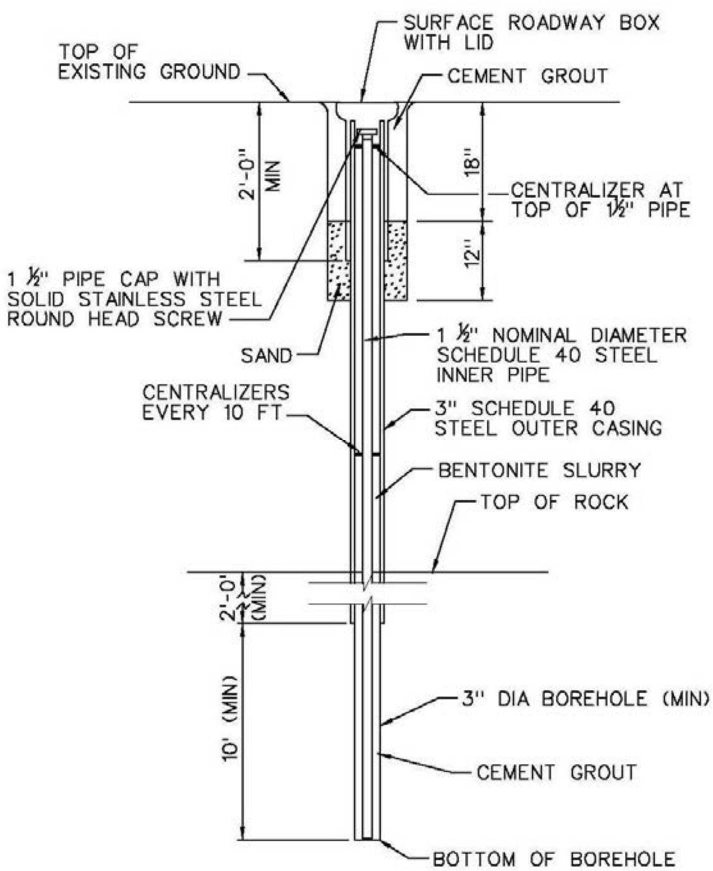

Figure 15-1 Deep Benchmark

15.2.2.2 Survey Points

Survey Points are used to detect ground movements at the surface or a few feet below the surface. They may be as simple as wooden stakes driven into the ground and their elevations surveyed through backsighting to a deep benchmark (Figure 15-2). Penetration needs to be at least a foot or so to guard against dislodgment, and the tops should not extend high enough to interfere with mowing machines if they are in a grassy area that requires routine maintenance. A survey point may also be somewhat more sophisticated and take the form of a steel rod with a rounded reference head driven several feet into the ground for better avoidance of possible dislodgment and surface effects such as frost heave (See Figure 15-3). This type of point needs to be protected at the surface by a small utility type roadbox with a secured cover so there is no disturbance to the rounded head. A rounded head is considered best because a surveyor can then always find the high point that has been surveyed in the past for good continuity in the readings. Because there is no hard connection between the rod and the roadbox – the one sort of "floats" inside the other – the survey point is also protected from being pushed down in case of the passage of a heavy vehicle. The major concerns with any type of survey point is the need to keep it out of the way of other users of the area and also protected against damage that may require replacement and lead to loss of continuity between the latest reading and the string of readings taken in the past.

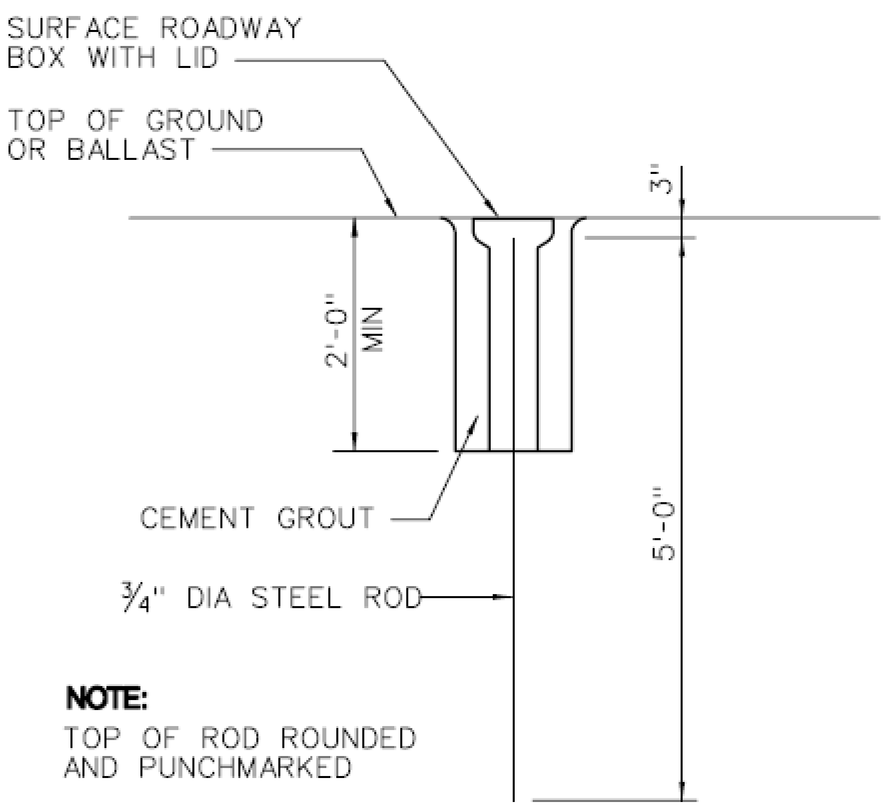

Figure 15-2 Survey Point

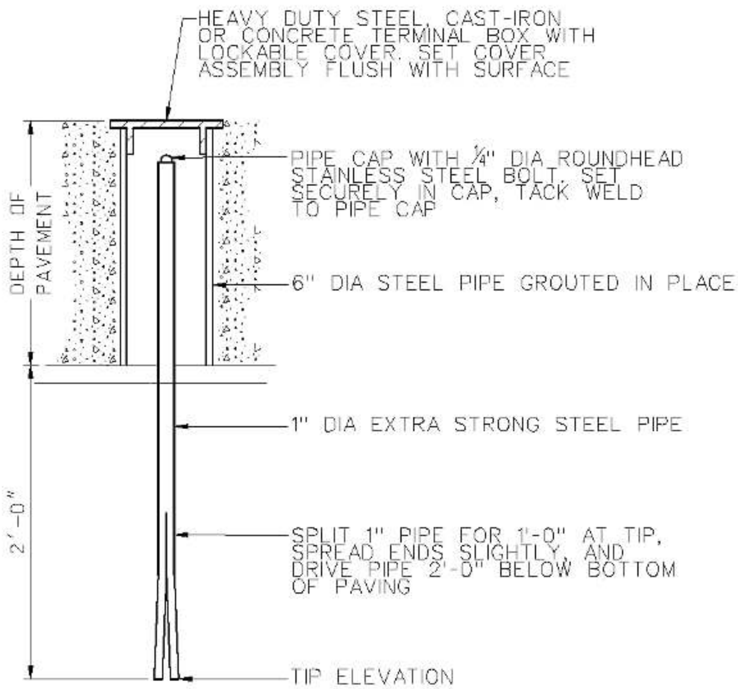

Figure 15-3 Survey Point in Rigid Pavement Surface

15.2.2.3 Borros Points

A Borros Point is basically an anchor at the lower end of a driven pipe (See Figure 15-4). The anchor consists of three steel prongs housed within a short length of steel pipe with points emerging from slots in a conical drive point. Installation is achieved by advancing a borehole in soft ground to a few feet above the planned anchor depth and the anchor inserted by attaching extension lengths of riser pipe and outer pipe. When the point reaches the bottom of the hole, it is driven deeper by driving on the top of the outer pipe. The prongs are then ejected by driving on the riser while the prongs are released and the outer pipe bumped back a short distance to achieve a positive anchorage. Such installations are useful for determining the amount of settlement at one precise depth with more certainty than the simple driven steel rod described above, and they are relatively simple and economical. The amount of anchor movement is determined by surveying or otherwise measuring the movement of the inner riser pipe at the ground surface. One disadvantage with such movement detection (and this can be said of most instruments whose data depends on movements measured in a surface mounted reference head) is that, if settlement is great enough to have affected the surface at reading time, then the whole instrument may be moving downward by a certain amount while the anchor is moving downward by a greater amount. Absolute anchor movement may then be difficult to judge unless ground elevation surveys are undertaken at that time and the changes added to the apparent anchor movement.

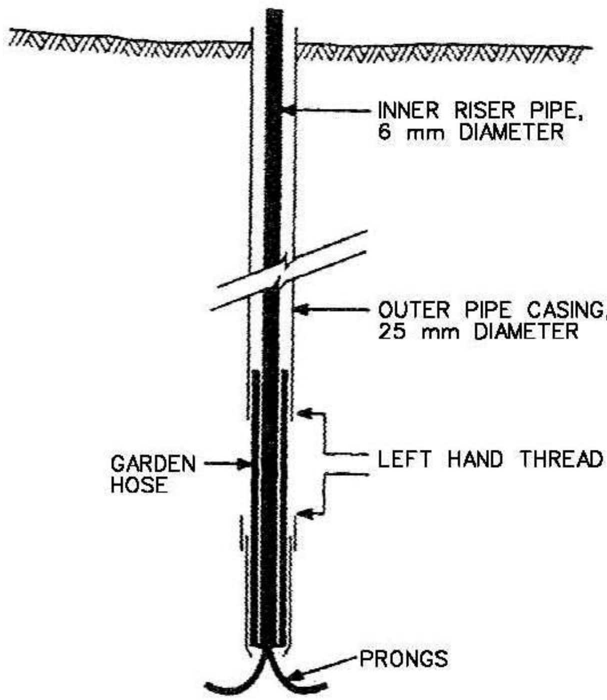

Figure 15-4 Schematic of Borros Point (After Dunnicliff, 1988, 1993)

15.2.2.4 Probe Extensometers

Probe Extensometers are used to measure the change in distance between two or more points within a drilled hole in soft ground, through use of a portable probe containing an electrical transducer. As shown in Figure 15-5, the probe, which contains a reed switch, is inserted into a casing in the drill hole in which the reference points, each of which contains an array of bar magnets, have been fixed in a way to surround the casing on the outside. In the most common type of installation, the reference points are held in place by spring loaded anchors – leaf springs – that ”bite” into the ground. The points are free to move with the ground because the outer support casing will have been removed and replaced by grout. The probe detects the depth of the reference points for an indication of whether the soil at those depths is settling due to disturbance from construction. A probe extensometer can thus measure the settlements at a much larger number of depths than can a Borros Point. Probe extensometers are generally drilled to a depth below any potential zone of influence near a cut-and-cover or mined tunnel. The bottom reference point then becomes the unmoving reference from which the movements of the shallower points are judged. In a typical situation near a mined tunnel, it is likely that the lowest moving point will exhibit the most settlement, and that settlements will prove to be less as the probe moves up the casing to where the settlement trough is widening. One problem with probe extensometers is that collection of data can be operator sensitive as the instrument reader strains to detect the exact location of the probe at each reference point depth by listening for the electronic “beep” to ensure readings at precisely the same spot time after time. Another concern may be the time required for monitoring, especially if a large number of reference points have been installed, because the probe does have to be lowered to the bottom of the casing and then readings collected as it is slowly winched back to the surface.

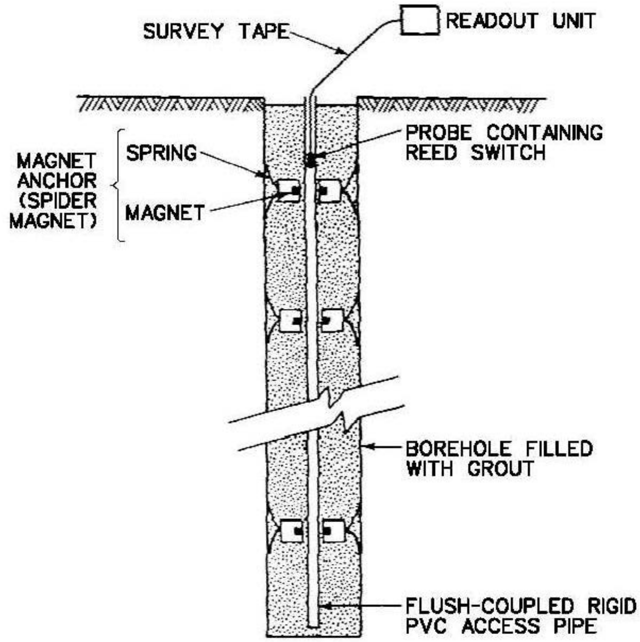

Figure 15-5 Schematic of Probe Extensometer with Magnet/Reed Switch Tansducer, Installed in a Borehole (After Dunnicliff, 1988, 1993)

15.2.2.5 Fixed Borehole Extensometers Installed from Ground Surface

Fixed Borehole Extensometers installed from ground surface may be used in soft ground or rock and may be Single Position (SPBX) for settlement measurements at one specific elevation or Multiple Position (MPBX) for measurements at several elevations. Figure 15-6 illustrates a schematic of an MPBX. The anchors of a borehole extensometer are grouted into the ground, commonly at various distances above the crown of an advancing tunnel, and connected to surface mounted reference heads by small diameter rods of steel or fiberglass. By detecting movement of the tops of the rods at the surface, one can tell how much each anchor – and hence its increment of soil or rock – is moving in response to excavation and so take steps to mitigate developing problems. Manual readings can be taken in a matter of minutes, assuming there is no problem with access to the instrument collar. However, automatic readings with an electrical transducer and datalogger – which can be salvaged/moved for use on other instruments – are relatively inexpensive and can provide real time data that feeds directly and quickly into a computer for fast analysis and databasing. Although extensometers oriented vertically over mined tunnel crowns are the most common installations, two others may prove useful in particular situations: (a) instruments angled in toward tunnel crowns or haunches from sidewalks where vertical installations are precluded by heavily travelled roads; and (b) instruments installed along the sidewalls of mined tunnels or cut-and-cover excavations where a knowledge of the vertical component of overall ground movement may be advantageous. A common problem with manually read instruments is the one of operator sensitivity, and if more than one reader is employed, they need to practice together to make certain they can monitor with good consistency. Remote monitoring leads to the concern that data collectors and analyzers may, without themselves personally having an eye on the construction operation, be unaware of the type and scheduling of activities that are affecting the data. Hence it may be necessary to make arrangements for construction progress reports to be delivered on a tighter schedule than otherwise might be necessary.

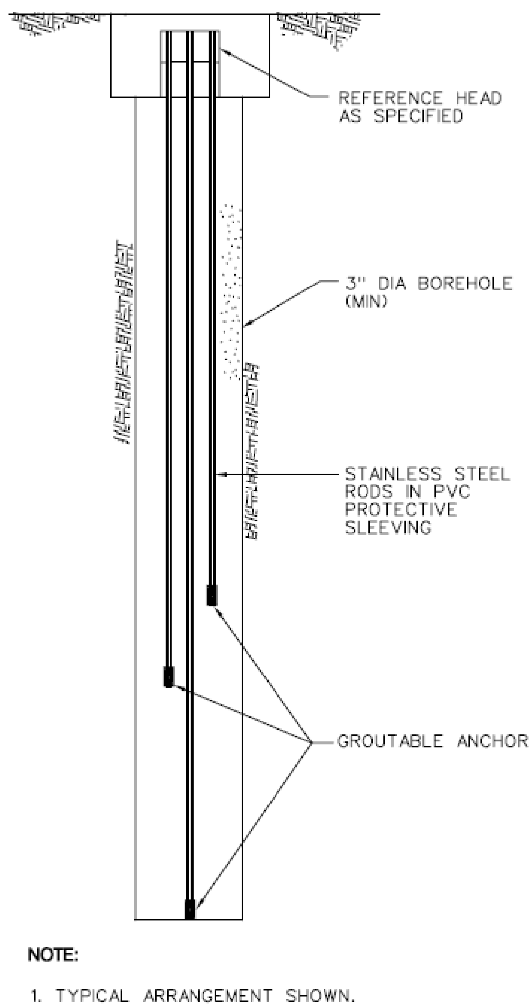

Figure 15-6 Multiple Position Borehole Extensometer Installed from Ground Surface

15.2.2.6 Fixed Borehole Extensometers Installed from Advancing Excavations

Fixed Borehole Extensometers installed from advancing excavations are a fairly obvious need if sidewall movements are required for a cut-and-cover excavation. Such horizontal installations are common and the drilling/installing operation has to mesh with the construction so that the larger operation is not overly impacted by what may appear to be a peripheral activity. (Note: "Horizontal" installations are seldom truly horizontal because angling downward by 10 or 15 degrees makes it much easier to manage the grouting of the anchors.) The installation of extensometers oriented from the vertical to the horizontal – including all angles in between – from inside advancing mined rock tunnels may be mandated by the lack of access from the ground surface (Figure 15-7). If possible, they are normally installed just behind a tunnel working face or the tail shield of a TBM. In this position they can provide data on incipient fallouts or more subtle rock movements toward the opening. If installed where a small tunnel is to be enlarged to greater size at a later time, the instrument heads can be recessed beyond the initial excavation outline and saved for use in monitoring the larger excavation. In this way they provide an almost complete history of rock movements from the earliest to the latest point in time. Another way to use these instruments is to install them from a first driven tunnel toward the location of a following twin tunnel. Readings then indicate whether the pillar between the two tunnels is loosening so that steps can be taken to mitigate the problem.

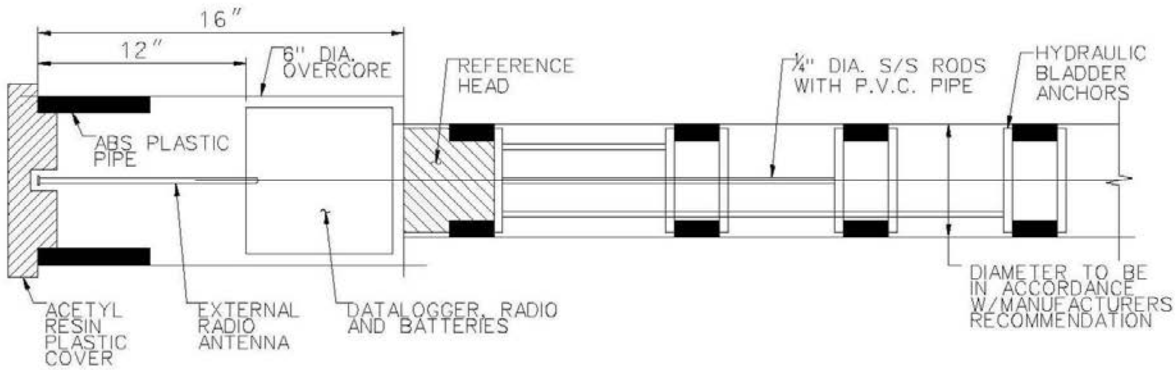

Figure 15-7 Horizontal Borehole Extensometer Installed from Advancing Excavation

Complications for these in-tunnel instruments are more numerous than for those installed from somewhere outside the excavation. As noted, the installation has to be meshed with the construction operation, a particularly tricky proposition in the confines of a small mined tunnel, where constructor complaints of interference are extremely common. Even the collection of data, if it is performed manually, may be obtrusive, especially if cessation of tunneling, use of ladders, or help from constructor personnel are involved. Remote monitoring is also possible, but then there is electrical wiring to be run and the need to find a place for the datalogger(s) to be out of the way. By whatever method the in-tunnel instruments are monitored, the reference heads need to be protected, often by countersinking them in the tunnel wall and perhaps through installation of protective covers. This is especially true where there is going to be more blasting in the vicinity, but also true even where blasting is not involved. Miners tend to have little reverence for objects whose importance is not obvious to them, so vandalism and theft of instrument accoutrements has to be guarded against. Finally, there is the fact that an in-tunnel instrument is almost always installed after the tunneled ground has started to relax, so the initial readings are seldom true zero points from which to compute follow-on movements. The instrumentation specialist's only recourse is to continually press the constructor for access to install instruments at the earliest possible opportunity.

15.2.2.7 Telltales or Roof Monitors

Telltales or Roof Monitors (Figure 15-8) are other devices that can be installed from inside an advancing rock tunnel. They are designed to be installed with anchors in stable rock beyond the tips of rock bolts in tunnel roofs to provide fast feedback on stability. The immediate safety of the miners/tunnelers is the primary reason for the instrument's use. The devices were pioneered in French coal mines in the 1970s and further refined by the British and others in succeeding years. The first ones were steel rods with a single anchor and visual movement indicators in the tunnel roof that could be seen by miners as they worked. Simple and installable by rock bolting crews, they proved vulnerable to shearing due to movement of rock blocks and were eventually replaced by more flexible steel wires that are less prone to failure. Modern versions have as many as three anchors and can be wired for remote reading by a trained person watching the data on a laptop computer. Roof monitors are widely used around much of the world and are gaining acceptance in the U.S., where they deserve to join the ranks of commonly used instruments. They are now used in civil as well as mine construction and also in rock other than flat lying sedimentaries commonly associated with coal seams. As of this writing, the primary factor in considering use of roof monitors in the U.S. may be the need to educate tunnel designers and constructors in their efficacy and ease of use.

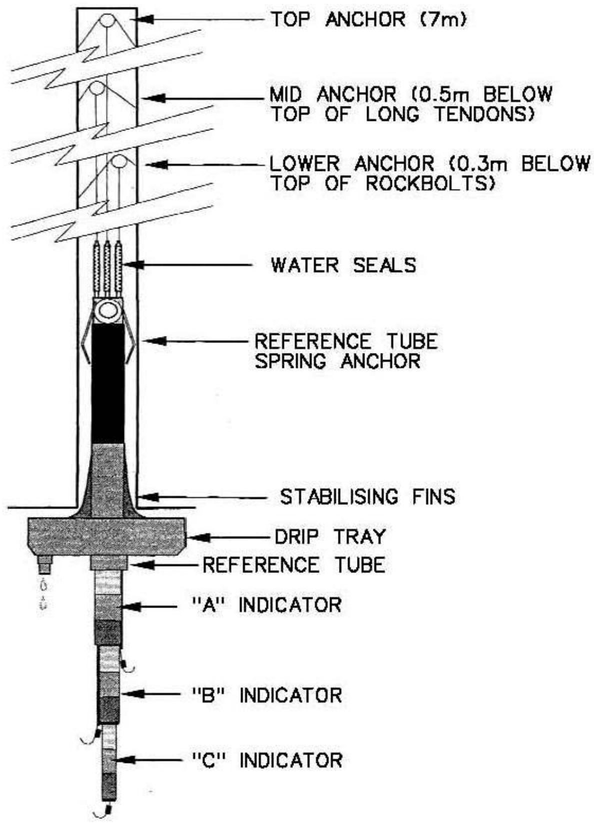

Figure 15-8 Triple Height Telltale or Roof Monitor

15.2.2.8 Heave Gages

Heave Gages are most commonly used when excavating for open cut or cut-and-cover in soft clay where there is potential for the bottom to fail by heaving as overburden load is removed. There are several instruments with which heave can be detected and measured, but almost all either suffer from lack of accuracy or are prone to damage or malfunction. Interestingly, the magnet/reed switch gage packaged as for a probe extensometer is probably the best alternative (Figure 15-9). In this type of installation the user measures increasing rather than decreasing distances between spider magnets and a fixed bottom anchor. With care taken to make certain the bottom anchor is well below any expected zone of movement, the installation is made inside the cofferdam prior to start of excavation. After initial readings are taken the access pipe is sealed 5 to 10 feet below the ground surface through use of an expanding plug set with an insertion tool, and the pipe is cut with an internal cutting tool just above the plug. A good fix is made on the plan location of the instrument and, just before the excavation reaches the plug, the pipe is located, a reading made, and the pipe again sealed and cut. The procedure is repeated until excavation is complete. The concern with such installations – a concern not overcome with alternative installation types – is that any large excavation is made by means of heavy equipment, and operators are not prone to watching and caring for things as small as a heave gage pipe. It is common for the gages to be damaged beyond use, and their protection can be assured only through some forceful construction management and sometimes the levying of penalties for instruments damaged as a result of contractor carelessness.

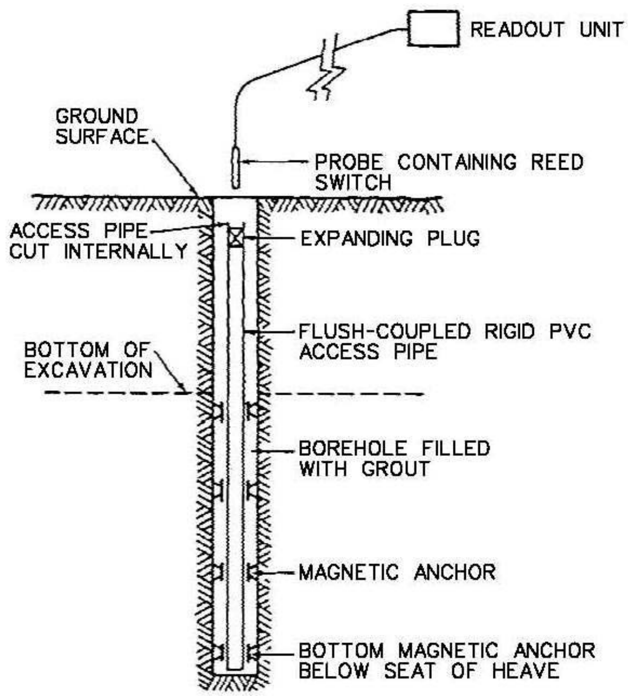

Figure 15-9 Heave Cage

15.2.2.9 Conventional Inclinometers

As shown in Figure 15-10, conventional Inclinometers are aluminum or plastic casings drilled vertically to below the level of construction into a stable stratum and used to determine whether the surrounding ground, either rock or unconsolidated material, is moving laterally toward the excavation. Each casing has tracking grooves to guide the sensing probe for orientation both parallel to and at right angles to the axis of the excavation. The probe, which contains tilt sensors, is lowered on a graduated cable to the bottom of the hole and winched upward, with stops at 2-foot intervals for collection of inclination data by means of a readout unit at the ground surface. An iterative process of tilt calculations from the unmoving bottom of the casing permits plotting of a profile that fixes each measured increment of casing in space in relation to the excavation. An initial set of inclination readings is taken before excavation begins and each set of readings thereafter during construction provides data on how the ground is moving when the user plots the newer movement curves against the initial pre-construction curves. The inclinometers are normally situated a few feet from the excavation periphery of open cut or cut-and-cover excavations, but may also be installed just outside a mined tunnel where lateral movement data may be combined with vertical movement data from the extensometers discussed above. The term “conventional inclinometer” is used herein to distinguish the manually read instrument from the “in-place” instruments described below. The major concern with a conventional inclinometer is the time consumed in the monitoring process. Readings are performed twice in each monitoring visit, once with the probe inserted in the “A” direction tracking grooves, then again with the probe in the “B” direction. A “check sum” procedure is carried out by examining the sum of the two readings at the same depth, 180 degrees apart, in order to remove any long term drift of the transducers from the calculations. It commonly requires 45 or so minutes for a reader to collect data from a 100-foot deep instrument, and that is assuming no indication of excessive movements, which, if discovered, may require another set of readings for confirmation that the movements are real and not due to a reading error or instrument malfunction.

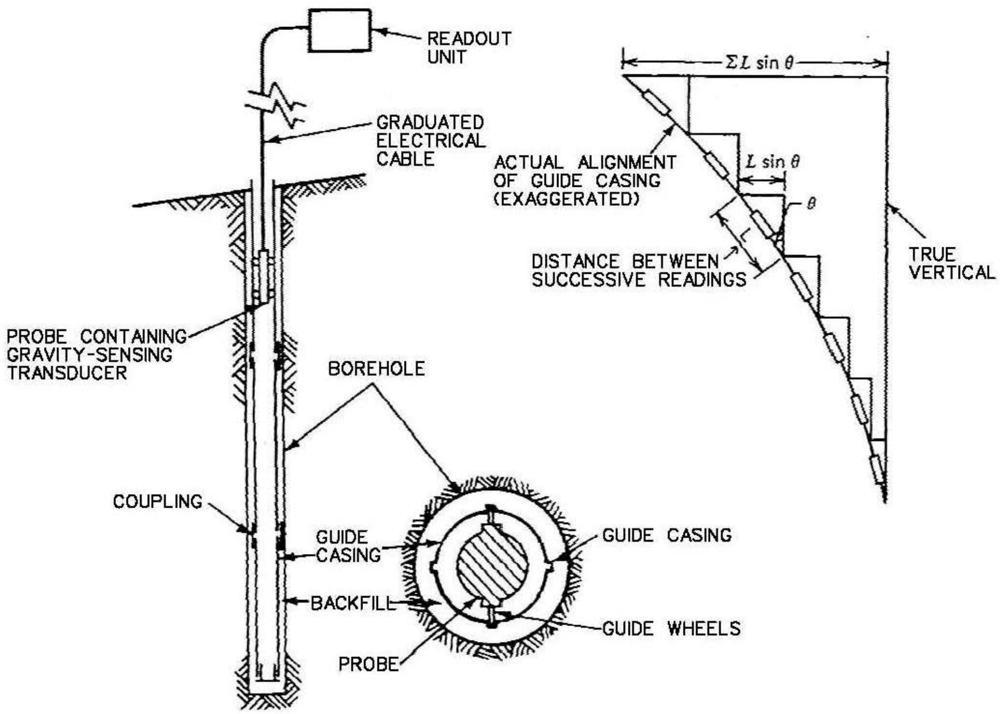

Figure 15-10 Principal of Conventional Inclinometer Operation (After Dunnicliff, 1988, 1993)

15.2.2.10 In-Place Inclinometers

In-Place Inclinometers are typically used for monitoring subsurface deformations around excavations when rapid monitoring is required or when instrumented locations are difficult to access for continued manual readings. The sensors are computer driven, gravity-sensing transducers joined in a string by articulated rods, and they can be installed equidistantly in the casing or concentrated in zones of expected movement (Figure 15-11). With the in-place instrument, as many as ten or twelve sensors are mounted in the casing and left semi-permanently in place. A larger number of sensors would be difficult to install in a standard size drill hole because each sensor has its own set of signal wires that take up space, and a very large number of sensors could result in the need for an uneconomically large diameter drill hole. Signals are fed to a datalogger at the surface and can be collected as often as required, or even fed by telephone line to the database computer for something close to real time monitoring. Compared with conventional instruments, the in-place inclinometer hardware is expensive and complex. This can sometimes be compensated to a degree by removing sensors from a bypassed instrument and installing them in a new location as the excavation progresses. A not-so-easily-overcome disadvantage of the in-place instrument lies in the fact that, if there is any long term drift in any of the sensors, it cannot be overcome through the check sums procedure described above. It is also true that the somewhat limited number of sensors in a standard in-place installation leads to a less smooth plot of movements compared with what can be achieved with the conventional inclinometer.

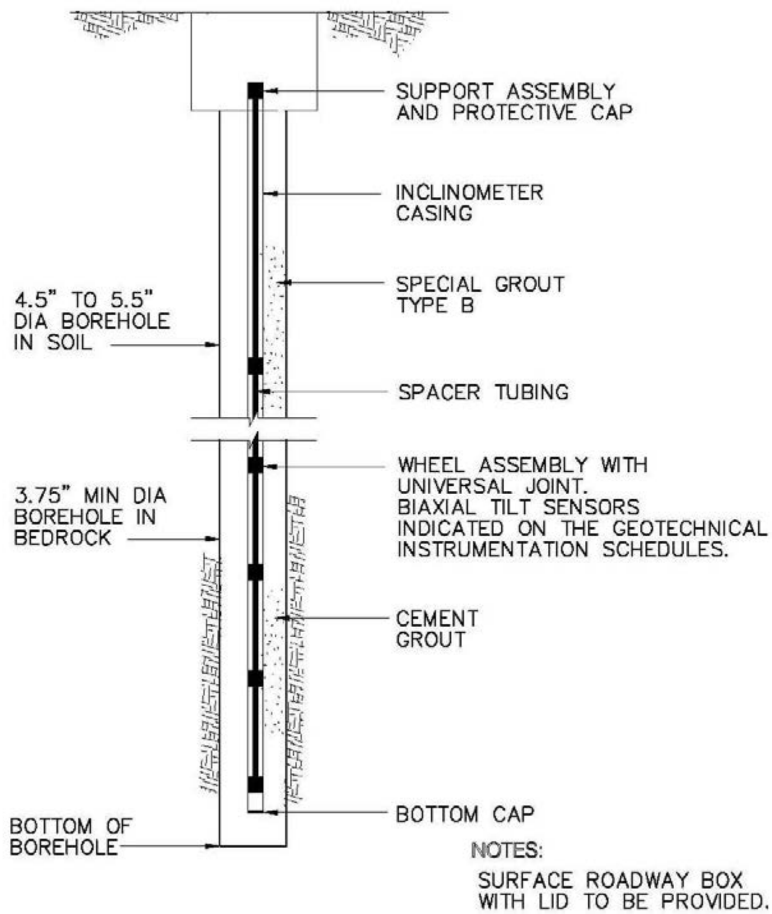

Figure 15-11 In-Place Inclinometer

15.2.2.11 Convergence Gages

Convergence Gages may be used for monitoring closure of the ground across either open excavations or mined tunnels. In the first instance they perform a function similar to an inclinometer, although with many fewer data points to give a full picture of movements. In the second function, they detect the load redistribution during and after excavation and the extent to which resulting structure/ground interaction affects the tunnel shape and the lining. Until now the typical gage has been a Tape Extensometer, which includes a steel tape with holes punched at 50 mm intervals (see Figure 15-12). Anchors that define monitoring points consist of eyelets on the ends of grouted rebar sections that extend into the ground for a foot or so (Figure 15-13). The tension in the tape is controlled by a compression spring, and standardization of tension is achieved by rotating the collar until scribed lines are in alignment. After attachment of the extensometer to the anchors and standardization of the tension, readings of distances are made by adding the dial indicator reading to the tape reading. In a typical mined tunnel the pattern of anchors includes one in each sidewall at springline level and one as close as possible to the center of tunnel crown. Three readings are taken in a tent shaped pattern and the results indicate whether the tunnel support is behaving in a predictable way. For very large tunnels, the patterns may be more like trapezoids or overlapping triangles, which requires the installation of additional anchors. Such readings are only relative readings, and if absolute elevation changes are needed, this is usually accomplished by surveying the anchor that is in the crown. (Installation directly in the high point of the crown is seldom possible because of the presence of the ventilation and other lines.)

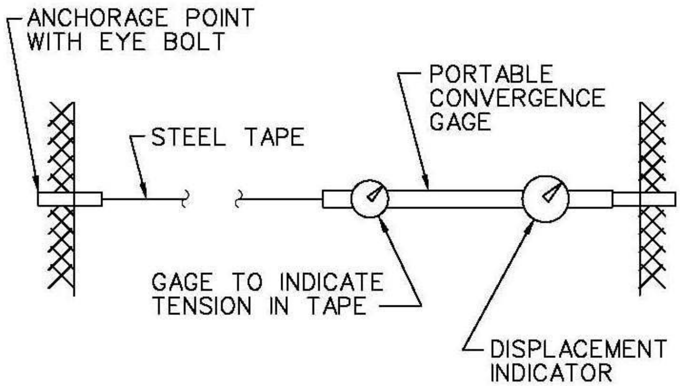

Figure 15-12 Tape Extensometer Typical Detail

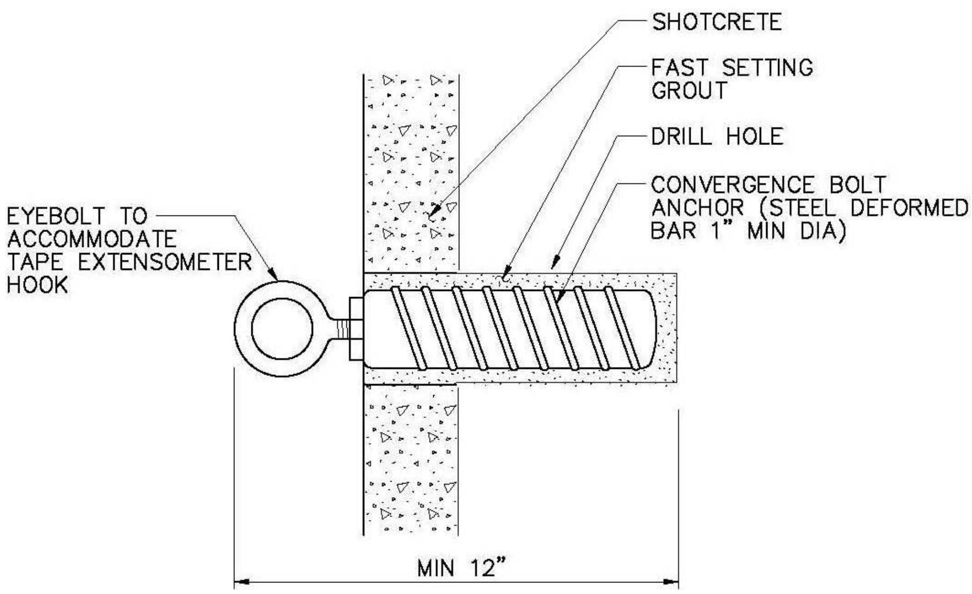

Figure 15-13 Typical Convergence Bolt Installation Arrangement

Whether the tunnel is conventionally mined or excavated by TBM, it is important to install anchors and begin readings at the earliest practicable time before the ground has begun to "work." Unfortunately, this cannot always be accomplished, especially in a TBM tunnel because, even if the anchors can be installed in a timely manner, there are scores or even hundreds of feet of trailing gear that make the stretching of a tape extensometer essentially impossible. This means that measurements may not begin until the machine is a long way past the monitoring point and knowledge of total from-the-beginning movements cannot be obtained. For this reason it seems likely that an alternative to the tape extensometer is going to be the best choice for future monitoring of tunnel convergence, and it will be in the form of a distometer. The device is small, hand held, and can be used to very accurately determine distances to a target by emitting a laser or infrared beam that is reflected from the target and detected by the same device. By installing brackets or bolts that also include targets at the places where tape extensometer eyelets would normally be placed, monitoring personnel can detect the changing shape of a tunnel without having to stretch a physical connection between points. There remains the problem that a physical object – such as TBM trailing gear – between targets will interfere with the distometer lines of sight and still not permit measurements in the standard tent shape. By judicious placement of additional brackets and targets at monitoring sections, it should be possible to gather data by working around the trailing gear in a TBM tunnel with patterns of measurements more like the afore mentioned trapezoids or overlapping triangles.

15.3 MONITORING OF EXISTING STRUCTURES

15.3.1 Purpose of Monitoring

If the different parts of a structure should move uniformly by even large amounts, damage could be minimal, maybe non-existent, except perhaps for penetrating utilities such as water pipes that might not be able to accommodate themselves to such movements. However, most structures affected by construction react by exhibiting more movement of the parts closest to the excavation than of the parts that are further away. This differential movement is the principal cause of construction related damages because the affected structure may be subjected to forces it was not designed for. A building, for example, whose footings are settling on one side while the other side settles less or not at all will suffer tilting of some walls, and the racking that ensues may cause cracking or spalling of some architectural features, freezing of doors and windows, or, in the worst case, failure of one or more of the structural members. A bridge whose footings are subjected to differential movements may undergo extensions that literally tear it apart. In general, the detection of settlements is the first line of defense in the protection of existing facilities, whether they be surface (roadways, buildings, bridges) or subsurface (utilities, transit tunnels, other highway tunnels). The detection of tilting can also be useful and has become more common as the development of monitoring devices has proceeded in the direction of increased automation. The simplest kind of monitoring involves the detection and the tracking of joint separations and crack propagation in structural concrete or architectural finishes. The ideal is to detect and mitigate some or all of these movements before they have become severe enough to cause serious damage or perhaps constitute a hazard.

15.3.2 Equipment, Applications, Limitations

As with ground movement instrumentation, there are a number of choices of instrumentation:

- Deformation Monitoring Points
- Structural Monitoring Points
- Robotic Total Stations
- Tiltmeters
- Utility Monitoring Points
- Horizontal Inclinometers
- Liquid Level Gages
- Tilt Sensors on Beams
- Crack Gages

15.3.2.1 Deformation Monitoring Points

Deformation monitoring points on roads, streets or sidewalks can be as simple as paint marks that get surveyed on a routine basis. However, paint has the disadvantage that it can be visually obtrusive, may wear off with time, and may not display a single spot that surveyors can return to time after time for good data continuity. A better alternative is a small bolt-like devise set in an expansion sleeve that can be installed in a small hole drilled in concrete or asphalt as shown in Figure 5-14. The point should have a *slightly* protruding rounded head with a consistent high point that is always findable by a surveyor as he or she searches for the same unchanging spot on which to set the stadia rod. It is important that the point not protrude too much because it might then become a tripping hazard or be vulnerable to damage from equipment such as snow plows. Although they are inexpensive to purchase and install, the ultimate cost of deformation monitoring points can grow to become relatively high if data collection becomes intensive because it depends upon the mobilization of survey crews. Also, such monitoring is not always foolproof because surveyors are not necessarily attuned to the need for that high degree of accuracy that is sought by instrumentation specialists. It is very common for data thus generated to exhibit a fair amount of "flutter," i.e., apparent up-down movements that are not real, but are only the result of inconsistencies in the survey process. Such inconsistencies may result from the too-often changing of personnel in survey crews, changes that happen commonly due to the nature of the business. Luckily, extreme accuracy is not required in much of this paved surface monitoring, so if the surveyors can reliably detect changes of one-quarter inch or so, that is often good enough.

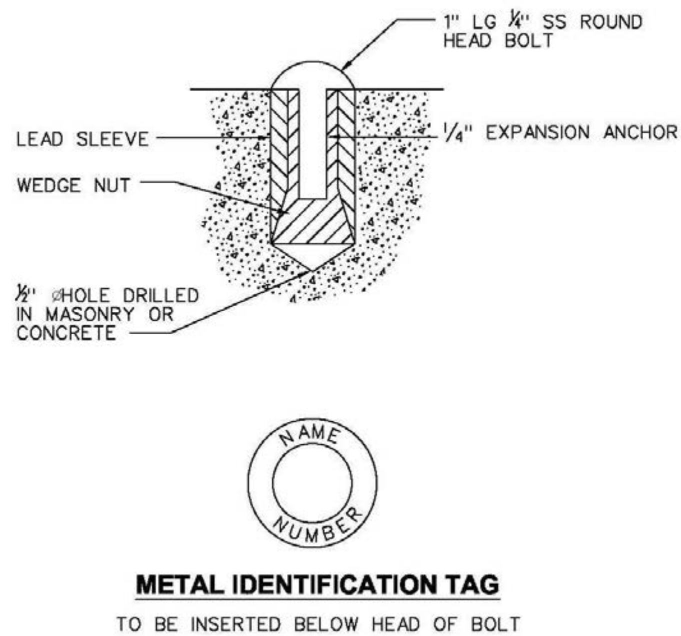

Figure 15-14 Deformation Monitoring Point in Masonry or Concrete Slab

15.3.2.2 Structural Monitoring Points

Structural Monitoring Points are survey points that are placed directly on the structures of concern, most often being installed on a vertical wall of a building or a structural element of a bridge (See Figure 15-15). Except for buildings, most structures can accommodate the monitoring point likely to do the best job and the "points" may take several forms. The simplest is a tiny scratch mark that can be easily found on each monitoring visit by a survey crew. A similar point is a stick-on decal target, which is a bit more obtrusive, but easily removable once it is no longer needed. A problem with such surface treatments is that, for buildings particularly, the monitoring point may be only on a facade that moves independently of the underlying structural elements whose movements it is important to detect. This may be overcome by the installation of a bolt-like device that penetrates to the underlying structure for a truer indication of the movements taking place. The choice of monitoring points will often depend on the wishes of owners or managers of buildings who may object to the visual obtrusiveness or potential for damage from whatever may be installed. Possible damage can extend to the post-construction period when the monitoring point may have to be removed and patched, something that is often insisted on by the party who permitted its installation. Thus, it may be necessary to repair the scars left by the removal, which may entail the use of solvents, infilling, spackling, polishing, painting or replacement for satisfactory restoration.

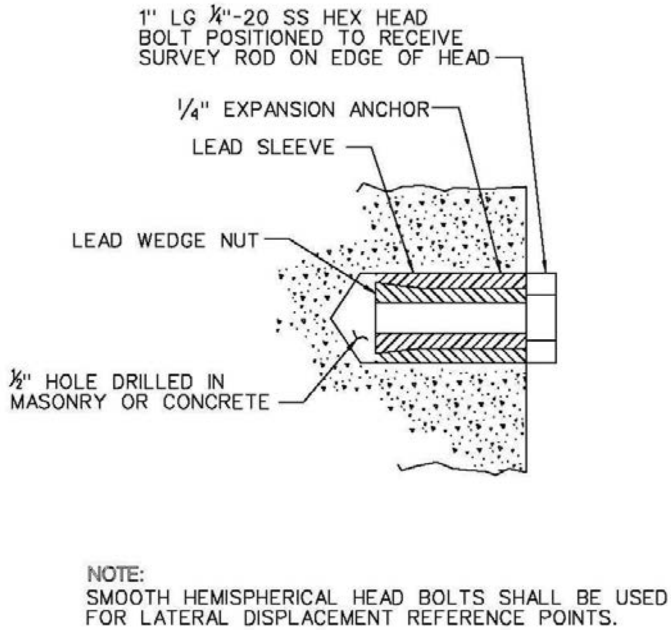

Figure 15-15 Structure Monitoring Point in Vertical Masonry or Concrete Surface

A large consideration in the use of structural monitoring points is the need to depend upon surveyors for the collection of data. Compared with roads and sidewalks, most structures have tight specifications on permissible movements (a lower mitigation-triggering level of 1/4 inch being not unusual), so surveying generally needs to be of a somewhat higher order, not necessarily as stringent as Class I, but at least done with additional care. One way to achieve this is to hold briefings in which the importance of great accuracy is instilled in the surveyors who will do the work. Another (if it is possible in the economic climate of the day) is to write and enforce the survey contract so that each group of structures is always monitored by the same crew using exactly the same equipment. In this way, the “flutter” may be reduced so as to minimize the need for instrumentation interpreters to average the peaks and valleys in determining if settlements are real or only apparent.

15.3.2.3 Robotic Total Stations

Robotic Total Stations are used for obtaining almost real time data on movements in three dimensions when it is not feasible to continually mobilize survey crews to collect data. The operation of a Total Station instrument (theodolite) is based on an electronic distance meter (EDM), which uses electromagnetic energy to determine distances and angles with a small computer built directly into the instrument. Accuracy is generally much greater than that achievable with the use of classical optical surveying. Moreover, the equipment based on EDMs is capable of detecting target movements along all three possible plotting axes, the x, the y and the z. Total stations used in geotechnical and structural monitoring are electro-optical and use either lasers or infrared light as the signal generator.

Robotic (also called automated motorized) total stations are configured to sit atop small electric motors and to rotate about their axes. As shown in Figure 15-16, they are mounted semi-permanently and, at pre-determined intervals, automatically "wake up" to aim themselves at arrays of special glass target prisms (Figure 15-17) that can provide good return signals from a variety of angles. The target prisms, which are 2 to 3 inches in diameter, are installed on structures of concern and the total station instruments installed on other structures as much as 300 feet away. It is best to have the total stations installed outside the expected zone of influence for absolute certainty of measuring target movements with accuracy. However, it is standard practice to install some of the prisms definitely outside the influence zone so that they become reference points from which the total station can determine its own position and calculate the positions of the other prisms that may be subject to movement. Clear lines of sight from total station to target prisms are a requirement so that careful planning is required for proper placement. Data is recorded by means of the total station's own computer and may be fed to a centralized database computer by means of telephone lines or radio signal.

A major aspect of robotic total station use is the front end expense incurred. Depending upon the number purchased, the cost of top quality target prisms can range from $80 to $200 each in 2009 dollars. The total stations can cost from 30 to $40 thousand each, and they generally require the services of a specialist for the installation and maintenance. Nevertheless, for many projects where almost real time data on structural movements is necessary, this may be the only monitoring system capable of meeting all requirements.

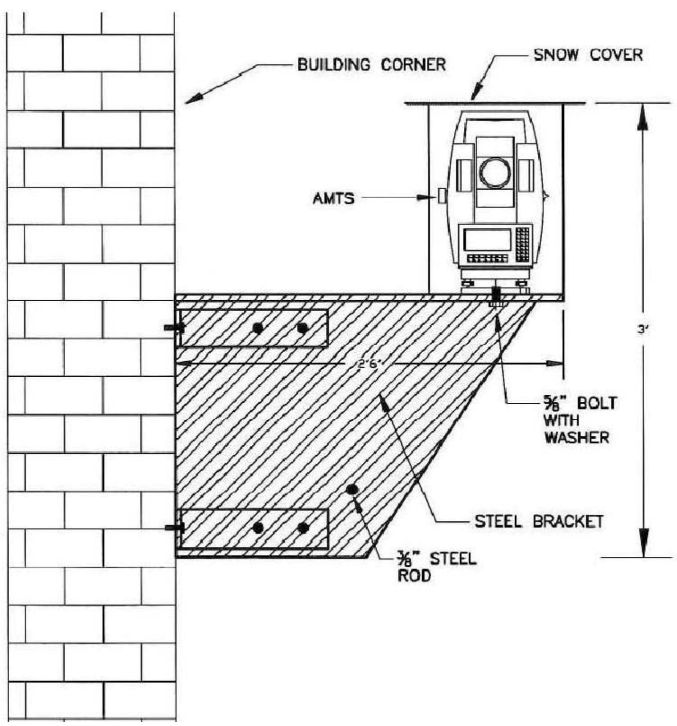

Figure 15-16 Robotic Total Station Instrument

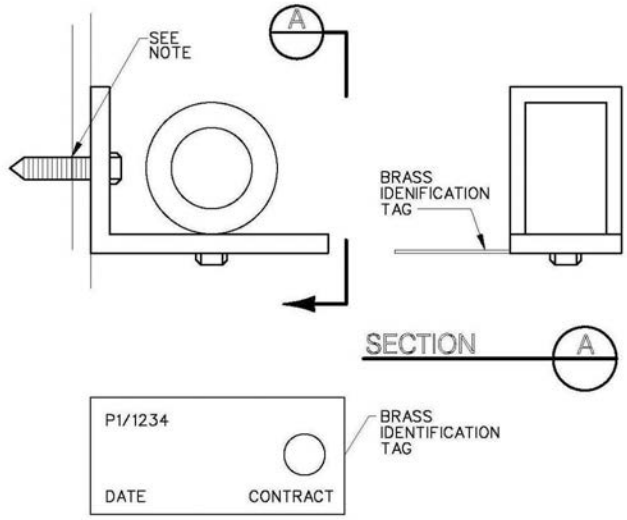

Figure 15-17 Target Prism for Robotic Total Station

15.3.2.4 Tiltmeters

Tiltmeters are used to measure the change in inclination of structural members such as floors, walls, support columns, abutments, and the like, which may tilt when the ground beneath is being lost into an advancing excavation. Manual tiltmeters generally consist of reference points on plates attached to the surface of interest and monitored by means of a portable readout unit, the functioning of which is based on an accelerometer transducer. Because such an arrangement can be operator sensitive and reading is somewhat labor intensive, especially where continued access is not easy, it is becoming more common to collect data remotely by means of electrically powered tiltmeters whose sensing elements may consist of accelerometer or electrolytic level transducers placed in housings that can be attached to the element to be monitored. If only one direction of movement is expected, the chosen instrument may be uni-axial, but if there is a possibility of combinations of movement, the bi-axial instrument would need to be used. Figure 15-18 illustrates a biaxial tiltmeter. Because tiltmeters can inform users only about rotational components of movement, data must be combined with that from other instruments to determine levels of settlement that may be affecting the structure. The most difficult tiltmeter installations are those required for structural elements somewhere inside a building that is occupied. Even the manually read instrument, with a flat 6 to 8-inch diameter plate being the part attached, is somewhat visually obtrusive and may be objected to by a building manager. Remotely read tiltmeters are even more obtrusive because they need to be wired for electric power and connected to a powered datalogger that will probably need to have telephone connections if true real time data is needed. There is some controversy within the monitoring community about the best installation height for these instruments, with some opting for lower floors and some for higher floors where absolute wall movement – though perhaps not *tilt* per se – will be greater. The argument is often laid to rest by a building manager who will permit such installations only in basement levels to better keep them out of the way.

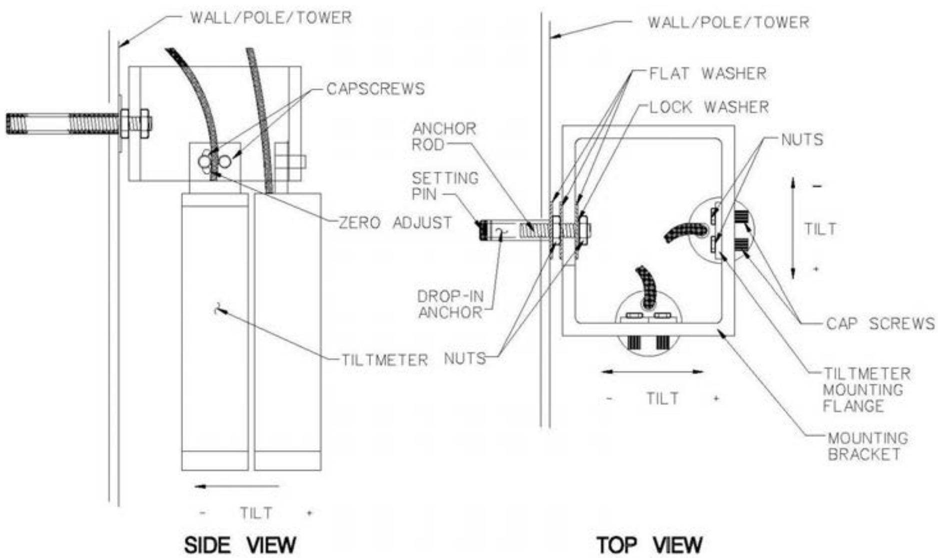

Figure 15-18 Biaxial Tiltmeter

15.3.2.5 Utility Monitoring Points

Utility Monitoring Points are very simple instruments used to determine whether an existing utility such as a water line is settling in response to an excavation proceeding nearby or underneath. The device consists of a small pipe with a rounded survey point or arrangement for use of a feeler gage at the upper end. This pipe is situated inside a larger piece of casing attached to a road box for surface protection. The lower end of the small pipe is attached to the top of the utility to be monitored and data collected by determining whether the top seems to be moving downward.

Unfortunately, such an instrument works well only if the monitored utility is exposed in a trench, and the inner pipe of the instrument attached before the utility is re-covered with backfill. When such an installation is attempted with a utility that is not exposed, one of two things may happen: (a) because the location of utilities is seldom known with absolute certainty, there is danger that the installing drillers may penetrate the utility, leading to a larger problem than the new tunnel under construction would have created; and (b) in the confines of a small drill hole it is extremely difficult to actually attach the monitoring pipe to the top of the utility, so it is possible for the utility to settle without there being an indication from the instrument of the movement’s true severity.

In a case such as this, the best fallback position is to install a Borros Point (Figure 15-4) or an SPBX beside and to invert depth of the utility. If ground movement is observed at that location, it may be an indication that excavation procedures need to be modified to contain a problem. Depending upon its size and stiffness, a utility may be able to bridge over a zone of disturbance and so be in no immediate danger, but ground settlement of a certain magnitude can be an indication that the movement needs to be arrested before it does become serious.

15.3.2.6 Horizontal Inclinometers

Horizontal Inclinometers are simply inclinometers turned on their sides and the transducers in the probe (conventional instrument) or sensors (in-place instrument) mounted such that the sensitive axes are perpendicular to the length of the pipe (Figure 15-19). In this way, an inclinometer is measuring the vertical rather than the lateral movements of the instrumented structure. One use for a horizontal inclinometer is in the determination of settlement of a utility along a reach that requires continuous data not producible by the utility monitoring points or extensometers described above. Due to difficulty of continuous access for monitoring, such an inclinometer installation is more likely to entail an in-place instrument that can be remotely read, but even here access may pose at least a minor challenge. If the utility is large and the flow of contained liquids can be controlled, then inclinometer casing may be strung and attached to the roof inside the instrumented structure. If the utility is too small for entry or the liquids cannot be controlled, then it would need to be exposed in a trench for instrument attachment to the outside and then backfilled. In either case, arrangements would be made for wiring to be run to a datalogger for essentially real time monitoring. Difficulty of access for installation is an obvious drawback, but when the need for monitoring is over, it should always be possible to salvage the expensive sensors for re-use.

If entry into the utility were possible for installation, then it should also be possible for recovery efforts. If the instrument were installed and then covered over by backfill, a small manhole will have been provided for access to the reference head and the wiring, and it is from here that the sensors and their attached wires can be removed.

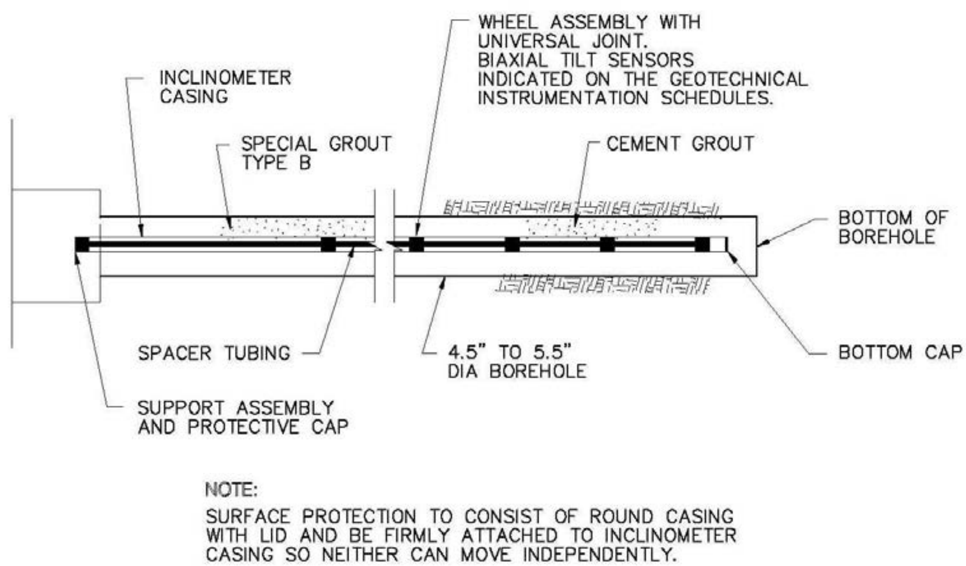

Figure 15-19 Horizontal In-Place Inclinometer

15.3.2.7 Liquid Level Gages

Liquid Level Gages are systems of sensors installed in an array that measures the height of a column of water within each gage as shown in Figure 15-20. Sensor gages are connected by small 1/4 to 1-inch diameter tubes or pipes to a reference gage outside the zone of influence. The reference gage is actually a reservoir, with its contained liquid generally kept under pressure to avoid the undesirable effects of barometric changes. The liquid completely fills all of the tubes throughout the array of components, none of the liquid is exposed to outside atmosphere, and so it is referred to as a closed pressurized system. With the liquid always at the same elevation, settlements of the instrumented locations are indicated as the heights of the columns of water within the gages change in relation to the gage housings, which are moving. Signal outputs are most commonly driven by LVDTs (see description under electrical crack gages below) or vibrating wire (see surface mounted strain gages under 15.4.2) force transducers. The closed systems are small and flexible and can be configured to fit into the convoluted layouts of many instrumented structures. Readings are collected remotely through wiring of the system to a datalogger. Such systems are commonly installed in or on a structure where continuous settlement measurement to an accuracy of several millimeters is needed and where continued access for maintenance is not a large problem.

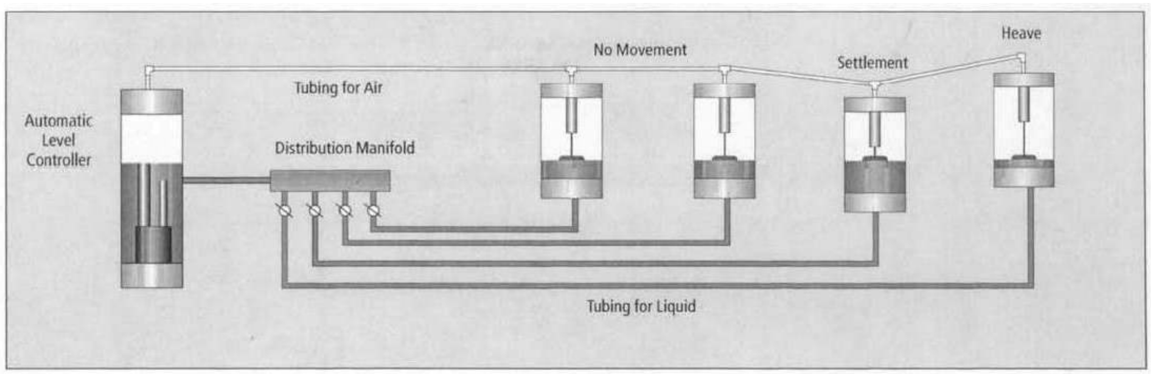

Figure 15-20 Multipoint Closed Liquid Level System

Maintenance visits are a must with these systems, and so the issue of access has to be taken seriously. During installation, which must be performed with great care, the system has to be charged with de-aired water and then purged to make certain no air bubbles have intruded to remain within it. This is one reason most installations utilize some kind of semi transparent plastic tubing; it permits visual detection of bubbles and makes purging them easier. This is critical because air bubbles will migrate to high points in the tubing or to the sensors themselves and can cause readings to be very inaccurate or can even shut down the system altogether. Then, during operation, it is very common for bubbles to appear in spite of careful installation. This may occur due to leakage from the outside, tiny amounts of air coming out of solution and accumulating, etc. Interestingly, the pressurization of the system can inhibit the emergence of bubbles, but never stop it entirely. No closed system is immune to this problem and maintenance visits may be required for purging and de-airing as often as every 6 to 8 weeks. This is why continued access can be so important to the closed pressurized system's functionality.

The maintenance problem can be largely overcome through the use of an open channel system which consists of sensors connected by pipes that are only half filled with water as shown in Figure 15-21. Open to the atmosphere, neither the liquid nor the sensors are affected by the problem of air bubbles. They can be installed to lengths of several thousand feet, operate for many months with hardly any maintenance, and still detect movements to sub-millimeter accuracy. However, such systems are large, heavy (due to the piping), sometimes difficult to install in structures with complicated layouts, and are much higher in front end costs than the smaller closed systems. At present, only a few open channel systems have been installed in the U.S. and only one or two corporate entities have expertise in their manufacture and installation. It seems likely that they will have a much larger presence in the future if downsizing of the components can lower purchase prices and make installations faster and easier.

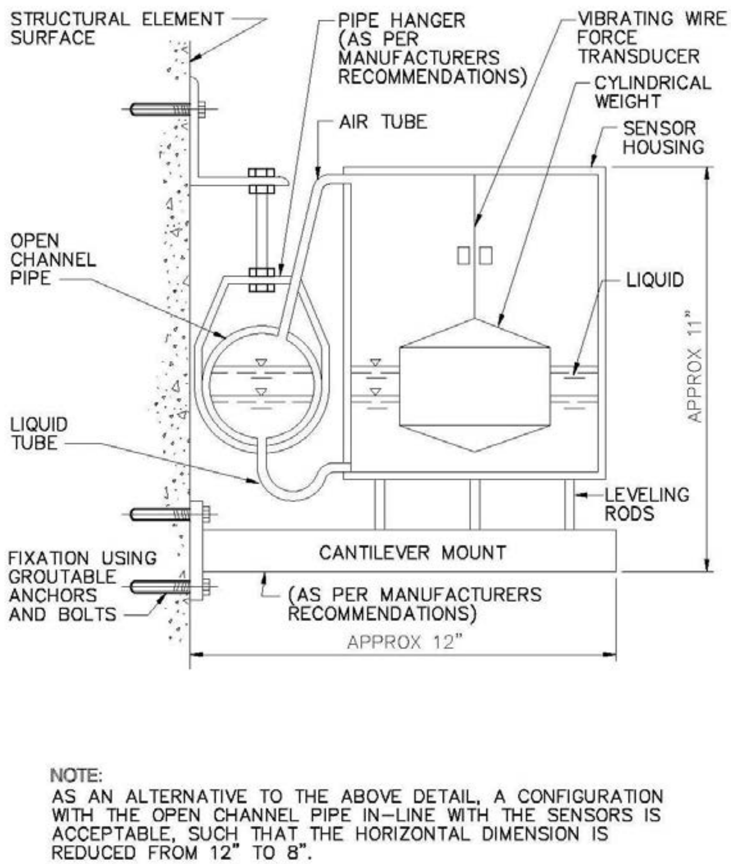

Figure 15-21 Open Channel Liquid Level System

15.3.2.8 Tilt Sensors on Beams

Tilt Sensors on Beams, when packaged to monitor elevation changes rather than tilt per se, consist of sensors attached to metallic rods or beams, with the beams linked together with pivots (Figure 15-22). By monitoring changing tilt of each sensor and knowing the length of each +/- 5-foot long beam, users can calculate elevation changes of each pivot with respect to the datum. The relative tilt of each sensor and beam is set in the field and elevation change data determined by making an initial scan of readings, called the reference set, and mathematically subtracting readings in that scan from each subsequent scan. All elevation change data is referenced to one end of the system defined as the datum. Ideally, the datum is in a stable area not likely to move, and its absolute elevation is generally determined by an initial optical survey. Integrating the data is an iterative process as settlements are computed from sensor to sensor. Readings are collected by having the system connected with a datalogger for almost real time monitoring.

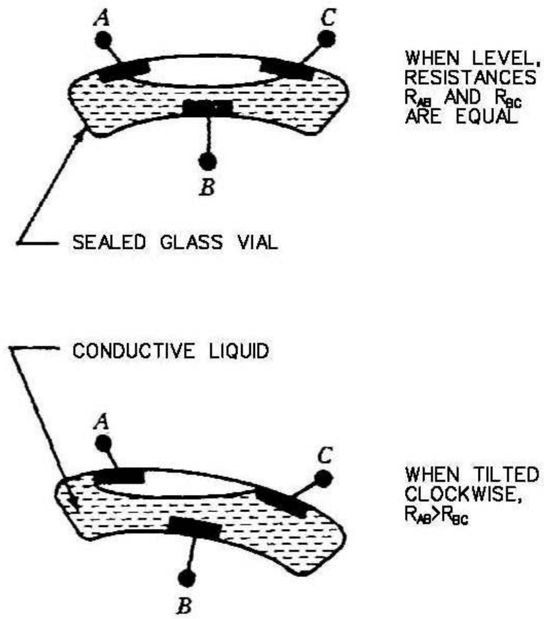

Figure 15-22 Schematic of Electrolytic Level Tilt Sensor (After Dunnicliff, 1988, 1993)

Such installations can work on bridges, the balustrades of buildings, the walls or safety walks of existing tunnels, or even railroad tracks. However, they do depend upon sensing of the mechanical movements of a string of components, and the components need to be as free from interference as possible. If installed where workers or moving equipment may be present, they have to be protected by installation of metallic housings or half rounds of heavy plastic casing. Another potential problem stems from changing temperatures, especially in the outdoors where there may be exposure to severe or very changeable weather. Although the sensors may fare as well as they would in any other type of installation, such as in a tiltmeter housing, the beams and the pivots are metal and subject to thermal effects with the potential to skew the data in unexpected ways. Users need to be aware that, if even one sensor or sensor/beam combination fails for any reason and requires replacement, the whole string of sensors and beams will need to be reinitialized.

15.3.2.9 Crack Gages

Crack Gages (also sometimes called Jointmeters) as installed on structures are typically used for monitoring cracks in concrete or plaster, or for determining whether movement across joints is exceeding a structure's design limits. The first appearance of cracks can be an indication of structural distress, and their growth, either in width or length, can be an indication that stress is increasing, as can the continued widening of an expansion joint. There are several ways of measuring these movements; only the two most common can be covered herein.

As shown in Figure 15-23, a Grid Crack Gage consists of two overlapping transparent plastic plates, one installed on each side of the discontinuity and held in place with epoxy or mounting screws. 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. Data is kept in notebooks and has to be keypunched into a computer if needed for an electronic database. Such gages are inexpensive to purchase and install, but readings may vary with changes in monitoring personnel and this has to be guarded against. There are three circumstances in which such simple devices may prove inadequate: (a) where cracks are too narrow or are widening too slowly for the human eye to detect their growth; (b) where continued physical access is very difficult and remote monitoring is required; and (c) where something close to real time monitoring is required. Such difficulties may be overcome through the selection and installation of Electrical Crack Gages as shown in Figure 15-24.

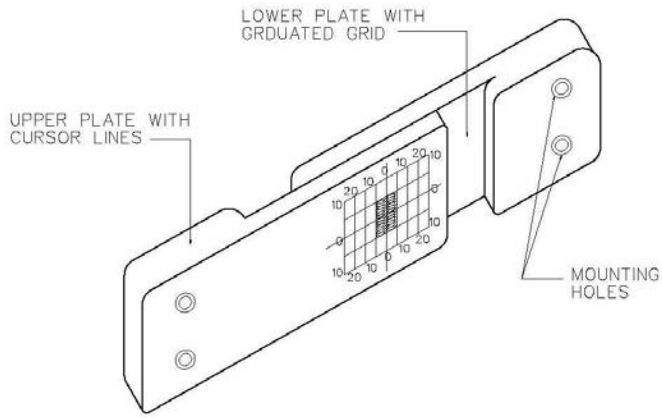

Figure 15-23 Grid Crack Gauge

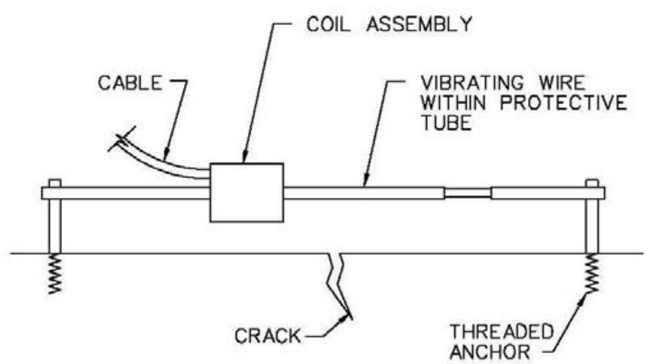

Figure 15-24 Electrical Crack Gauge

There are a number of electrical gage types, but most are based on an arrangement of pins attached on opposite sides of a joint or crack, with the pins connected by sliding extension rods whose differential movements are detected by a built-in transducer. The most common transducer is the linear variable displacement transformer (LVDT) that consists of a movable magnetic core passing through one primary and two secondary coils. Data readouts depend upon detection and measurement of differences between voltages generated in the secondary coils, magnitudes of which depend on the proximity of the moving magnetic core to the secondary coils. Users may prefer to pick up the gage signals by using a small low power radio transmitter installed at the instrument location to avoid the transmission of alternating currents through long lead wires that can introduce output-degrading cable effects.

15.4 TUNNEL DEFORMATION

15.4.1 Purpose of Monitoring

When the temporary or permanent structural support for a tunnel is being designed, calculations are performed to predict the kinds of movements and stresses the support can safely be subjected to before there is danger of failure. It is the job of instrumentation specialists to track those movements and stresses and provide guidance on whether the support or the construction process needs to be modified to ensure short term safety and long term stability of the completed tunnel. For braced excavations it is standard practice to measure the loads on some of the support members, and often to combine these with measurements of the support member deflections if the measurement of ground movements outside the support system are not sufficient to present a complete picture of support performance. It is possible to thus monitor the significant performance related behavior of soldier piles, slurry walls, struts, tiebacks and other elements of open cut or cut-and-cover excavations. In mined tunnels it is generally more common to use deflection measurements as a first line of defense against adverse developments because the eccentricities in the movements of many support members, such as steel ribs, make stress and load measurements much more complicated and prone to varying interpretation than they are for braced excavations.

15.4.2 Equipment, Applications, Limitations

Monitoring of the tunnel itself is similar to ground movement monitoring, using the following instrumentation:

- Deformation Monitoring Points
- Inclinometers in Slurry Walls
- Surface Mounted Strain Gages
- Load Cells
- Convergence Gages
- Robotic Total Stations

15.4.2.1 Deformation Monitoring Points

Deformation Monitoring Points (DMP) on support elements take several forms, but all have one thing in common: they are semi-permanent points to which a surveyor can return again and again and be certain of monitoring exactly the same point. A DMP may consist of a short bolt inside an expandable sleeve if mounted in a small drilled hole in concrete, such as a slurry wall (Figure 15-25), or may be the head of a bolt that is tack welded to a steel surface such as the top of a soldier pile. A DMP can be surveyed for both lateral and vertical movements to help determine whether the upper reaches of support may be “kicking in” or perhaps settling downward as the ground moves. If mounted in or on a vertical surface, the bolt head must have enough stick-out to permit a stadia rod to be rested on it. If mounted in or on a horizontal surface, the bolt head must be rounded, especially if it is to be used for determining vertical movements, for the same reason that a round head DMP is important in the monitoring of roads and streets. If the DMP were simply a flat plate, it would be too easy for the rod person to set up on a slightly different spot with each survey, especially if the monitored support element were bending inward, and this could result in cumulative errors in the elevation data plots. For support elements it is desirable that elevation surveys be carried out to an accuracy of as little as 1/4 or even 1/16 inch, and every effort should be expended to make this as easy for the surveyors as possible. The largest problem for this type of monitoring is the same as was previously discussed in ensuring survey accuracy, except that the difficulties may be greater in this instance because the surveyors are more likely to be working in the middle of heavy construction activity, hence more rushed and/or more distracted.

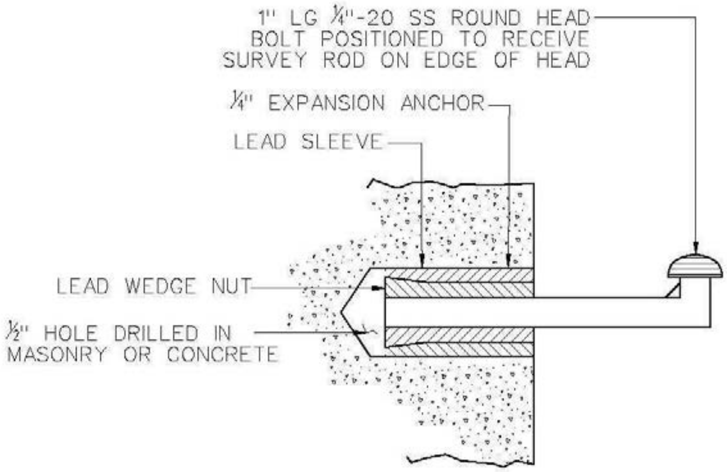

Figure 15-25 Deformation Monitoring Point in Vertical Masonry or Concrete Surface

15.4.2.2 Inclinometers in Slurry Walls

Inclinometers in slurry walls are very similar to those previously described for ground installations, except that drilling is not generally required (Figure 15-26). Installation is accomplished by fastening the instrument casing inside the wall panel's rebar cage as that element is being fabricated. As the cage is lowered into the slurry trench, the inclinometer casing goes with it and remains in place as the slurry is displaced during the introduction of concrete. Because the slurry wall will have been designed to penetrate below any zone of expected movement, the bottom of the inclinometer casing is the presumed unmoving reference from which tilting of shallower points along the casing are calculated. Monitoring is accomplished by the instrumentation specialist lowering a probe to the bottom of the casing and collecting readings as it is winched back to the surface. The biggest problem with an inclinometer in such an installation is the essential impossibility of repair if anything has gone seriously wrong. Also, one cannot replace the instrument by simply drilling a new casing into reinforced concrete a foot or two away. If the instrument is considered absolutely essential, it might be feasible to drill a new one into the ground just in back of the wall, but long drill holes tend to wander away from the vertical – perhaps in a direction away from the slurry wall – and chances are not good that the replacement instrument would truly indicate what the slurry wall itself is doing. This possibility of damage is one argument against the installation of in-place inclinometers in this type of support. Depending on the seriousness and the depth of any damage to the casing, some or most of the expensive sensors could be stuck and impossible to recover.

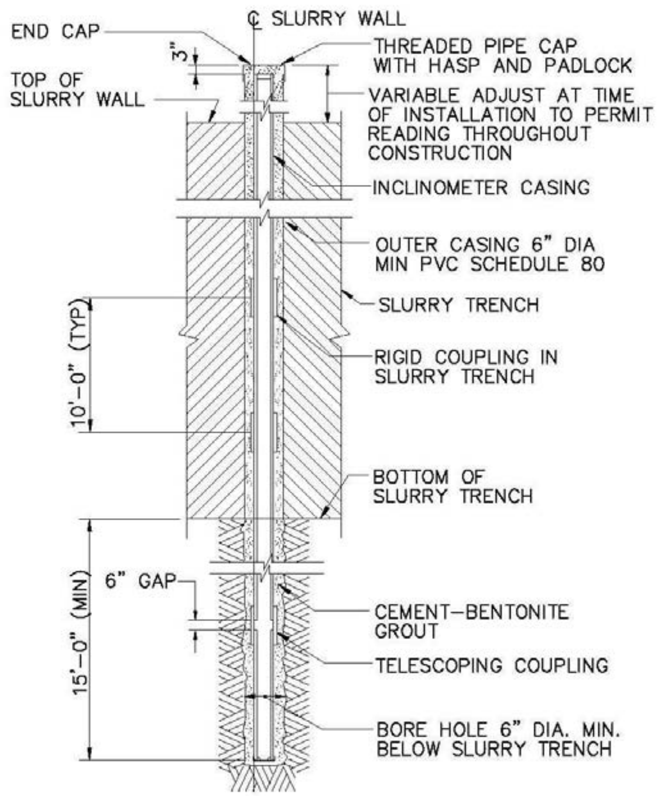

Figure 15-26 Inclinometer Casing in Slurry Wall

15.4.2.3 Surface Mounted Strain Gages

Surface Mounted Strain Gages are most commonly used to determine stresses and loads in struts across braced excavations. Although many kinds are available, the vibrating wire type finds the widest application because of a stable output that is in the form of signal frequency rather than magnitude. Figure 15-27 shows a schematic of the vibrating wire type strain gage. In this instrument’s packaging, a length of steel wire is clamped at its ends inside a small housing and tensioned so that it is free to vibrate at its natural frequency. The frequency varies with the tension, which depends upon the amount of compression or extension of the instrumented strut to which the gage has been attached by spot welding or bolting. The wire is magnetically plucked by a readout device, and the frequency changes measured and translated into strain, which can in turn be translated into stresses and loads on the instrumented member from a knowledge of the material’s modulus. The point of the measurements is that designers will have calculated the permissible loads in the struts and the instrumentation specialist is collecting data to determine if the struts may be approaching their design limits. Gages are typically mounted 2 to 3 strut widths/diameters from the ends in order to avoid the “end effects” that degrade accuracy. Because a strut will bend downward from forces of gravity even when not under load, creating compression at the top and extension at the bottom, it is necessary to install several gages arranged in patterns around the neutral axis and average the readings for the closest possible approximation of maximum stress.

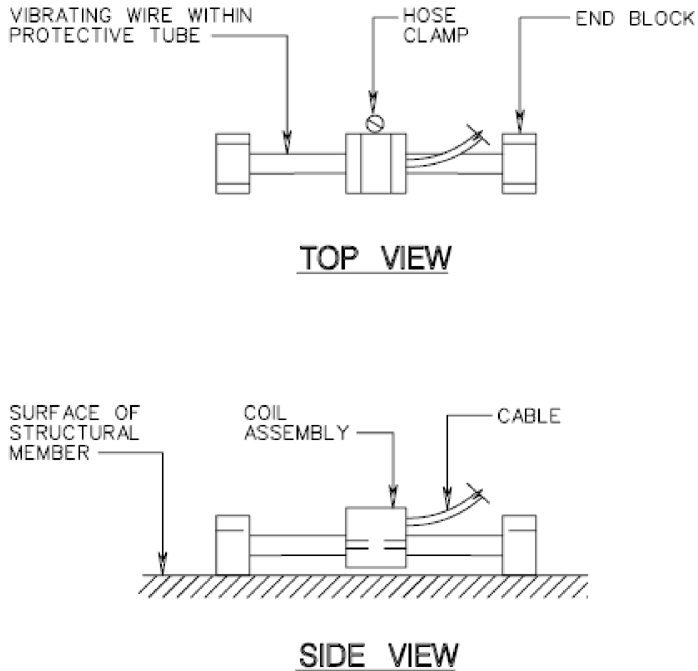

Figure 15-27 Surface Mounted Vibrating Wire Strain Gauge

Many things can go wrong with such installations, and they need to be undertaken with the greatest of care by experts with good experience. However, as noted in the introduction, the greatest problem with these types of measurements can reside in the agendas of the various parties who may need to understand the data and perhaps take action to mitigate apparent problems. Measurements of ground and structure *movements* are in general understood by most people associated with tunneling. However, stresses and strains require a certain amount of sophistication to comprehend, and even among those with the sophistication, interpretations of what the data mean can vary wildly. It is very common for constructors and their consultants to believe instruments are faulty, that data has not been properly collected, or data has not been properly reduced to good engineering values if taking mitigative action is going to interfere with the field operations. Also as previously noted, this is why use of strain gages can be fraught with complications if used on the steel ribs in mined tunnels. Compared with struts in braced excavations, ribs under load can bend and twist in many unanticipated ways, and placing strain gages in the best configurations just where they need to be placed can be difficult.

15.4.2.4 Load Cells

Load Cells are, in general, arrays of strain gages embedded in housings which are placed in instrumented tunnels under construction in such a way that loading forces pass through the cells. For the reasons stated in the strain gage description above, very stable vibrating wire transducers are the data collecting elements on which most load cell configurations are based. As shown in Figure 15-28, the load cell is a "donut" of steel or aluminum with several transducers mounted inside in a way to be read separately and averaged in the readout device. Transducers are oriented so that half of them measure tangential strains and half of them measure axial strains. Integration of the individual strain outputs helps reduce errors that might result from load misalignment or off center loading. Although load cells may be installed on tensioned rockbolts in mined tunnels, their more common use is in non-braced open excavations. Here the cell is installed on a tieback near the rock face and locked down with thick bearing plates, washers and a large steel nut. In most cases the instrument will be wired for electrical remote reading because it will be left in place for a considerable amount of time, and direct access for data collection will often not be available once the excavation has passed below the tieback's level. If a load cell seems to be producing questionable data, the most likely cause is misalignment of the instrument on the shaft of the tieback. For the most part, tiebacks are angled downward rather than being installed horizontally, and careful placement of bearing plates and washers of the correct thickness is essential.

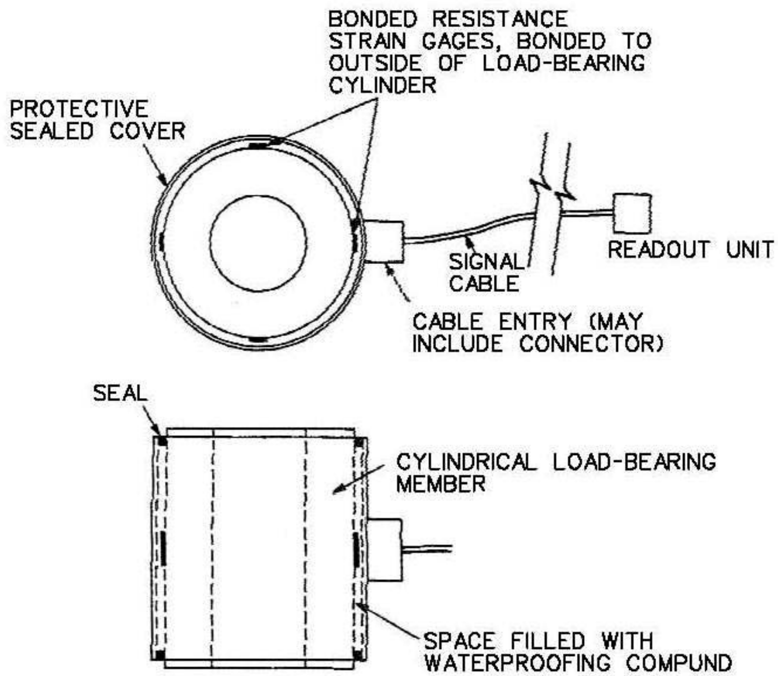

Figure 15-28 Schematic of Electrical Resistance Load Cell (After Dunnicliff, 1988, 1993)

15.4.2.5 Convergence Gages

Convergence Gages may be used on tunnel supports just as they are in monitoring of tunneled ground as described in 15.2.2. above. For the most part it is best to monitor the ground itself because that gives the best from-the-beginning measurements that constitute good initial movement readings. However, if it is necessary for whatever reason, similar anchors, eyelets, cradles and survey targets can also be installed on steel supports, shotcrete linings, and final concrete linings. As in the earlier discussion, it appears that distometers should be the chosen replacement for the older tape extensometers when measuring the distortions.

In modern mining there are situations which do not lend themselves to easy measurement of ground movements from the tunnel itself because of the chosen method of ground support. The most common of these situations results from the use of a TBM where pre-cast concrete segments are erected after each push to form another 4 or 5 feet of completed tunnel ring directly behind the shield. These theoretically perfect circles can distort as ground loads or other pressures – as from a contiguous tunnel also under construction – begin to exert themselves. The tunnel lining may "oval" with long axis vertical from high side pressures, or oval with long axis horizontal from high vertical pressures or low side pressures (the contiguous tunnel again.) Most instrumentation specifications call for deformation measurements to begin as soon as possible and for them to be taken as often as once or twice per day at first, with monitoring schedules tapering off as the TBM recedes from individual measurement sections. As with monitoring of ground movements, the most common problem with these measurements of lining distortion is the difficulty of getting good lines of sight directly behind the machine in order to achieve a true zero movement initial reading.

15.4.2.6 Robotic Total Stations

Robotic Total Stations as described for existing structures in 15.3.2. above can also be used to monitor the opening that is under construction. However, there are possibly more limitations on underground installations than on installations associated with inhabited buildings above. A total station instrument sitting atop its motorized support platform has a footprint of at least one square foot, its height is a bit greater, and the platform may protrude from the tunnel wall as much as 18 inches. The package would hardly fit well into a small tunnel, and would be constantly on the move as the tunnel advanced. Hence, the most logical place for such monitoring of active construction would be within a large mined chamber or perhaps a large open excavation. Even here, however, the uses might be more restricted than is at first obvious. The average construction site is a hostile environment, and the decision to install such an expensive piece of equipment cannot be taken lightly. The dust alone on some construction sites might be enough to force heavy maintenance procedures on the part of users. Even in the outdoors, target prisms have to undergo regular maintenance because signals can be so degraded by the accumulating dust from the atmosphere. The interior of a construction site is much worse; maintenance of the expensive instrument itself would be more onerous than usual, and many target prisms would likely be at a height that requires use of a manlift for access. It seems probable that the best use for robotic total stations would be found in an advanced stage of large construction where most of the final concreting has been accomplished and the structure needs to be monitored in something close to real time as the finish stage of construction proceeds.

15.5 DYNAMIC GROUND MOVEMENT – VIBRATIONS

15.5.1 Purpose of Monitoring

As opposed to the measurements discussed earlier, which concerned long-term effects of the construction of a tunnel on the gross movement of either the ground or buildings adjacent to the tunnel, these measurements are taken to establish the potential impact of drill and blast excavation on structures. Use of explosives often causes concern on the part of stakeholders in the neighborhood of a tunnel excavation. Aside from the images generated by blasting, there is real concern due to the sudden (and sometimes perceptible) motion generated by the explosive energy that is not used in fragmenting rock, but that propagates away from the blast site.

The usual method of monitoring these motions is based upon research studies that correlate the potential for damage from blast vibrations with the motion of the ground

15.5.2 Equipment, Applications, Limitations

There are two general types of equipment used for monitoring the Dynamic Ground Movement induced by blasting:

- Blast Seismographs

- Dynamic Strain Gages

Blast seismographs are used to monitor ground motion at structures within the zone of influence. Dynamic strain gages are used to monitor the actual strain (or relative displacement) of structural elements of such structures. Both of these instruments monitor data during the actual blast event, though for convenience they may be set to monitor before the actual blasting.

15.5.2.1 Blast Seismographs

The standard blast monitoring equipment has been blast seismographs. These instruments measure the vibration waves generated by blasting then propagate through ground, soil, and structures. This is the dynamic measurement of a wave that is extended in time and space; therefore, there is no single value that totally describes a blast wave. Through many years of research, it has been determined that the single most descriptive value that can be associated with the potential for structural damage is "Peak Particle Velocity," or PPV. As a blast vibration wave travels, it is analogous to waves on water. If one imagines a bobber on the water, the velocity of the bobber moving as the wave passes is the particle velocity. The peak particle velocity is the highest value of velocity during that wave passage. This value is expressed (in the US) in inches per second.

Blast seismographs measure three components of ground motion: vertical, longitudinal (horizontal along the direction from the blast) and transverse (perpendicular to that direction). The highest of these three values is used as a vibration criterion. There is typically a fourth channel used for above-ground blasting that monitors air overpressure or airblast, but this channel is generally not used when blasting in tunnels, since there is no direct exposure to surface structures.

As mentioned, criteria for blasting have been developed based upon occurrences of damage. Most of the studies done have concentrated on typical residential wood frame structures. Because structures respond in many ways to vibrations that are imposed at the base of the structure, in most cases the vibration is monitored on the ground outside of the structures. The potential for damage is then inferred from the association of the PPV with the potential for damage of a particular structure type. Sometimes the frequency of the vibration is also incorporated in the criteria, but this is not always the case. Criteria are usually adjusted upwards when the structure type is more substantial or engineered, relative to the criteria used for residential structures.

15.5.2.2 Dynamic Strain Gages

Because there is so little accumulated damage data for some structures, an alternative method for monitoring, using dynamic strain gages, has been adopted recently. For engineered structures and infrastructure elements, actual failure criteria can be developed that are independent of the mode of excitation. In this case, a level of strain, which is a dimensionless measure of relative motion, is used as a criterion for avoidance of damage. Strain ε is defined as $\varepsilon = \Delta l / l$, where Δl is the change in length of an element, and this is divided by the length of the element. Measurement on a small length of a structural element may then represent the deformation of the entire element when the total structural configuration is known.

Dynamic strain gages are traditionally thin foil resistance gages, which are connected to other gages in what is called a Wheatstone bridge. The gages change resistance when they are deformed. This arrangement of gages will then produce a voltage output that is monitored during the blasting process. The foil gages have been in use for over a half a century, initially in static strain environments, such as those described in 15.4.2.3 above. Though it is a mature technology, there are sometimes problems when the gages are in electrically noisy environments, or where there are temperature fluctuations. Although they have only been used recently, piezoelectric and fiber optic strain gages are not susceptible to as many problems as are the foil gages.

Dynamic strain gages, since they measure strain on a particular element that is of concern, must be carefully located to obtain the values that can be associated with potential failure of the element. Strain gage mounting must be carefully chosen on a representative location, and a measurement on the ground surface (as is done with blast seismographs) is NOT appropriate.

There is not as much background documentation in associating damage with strain from blasting; however the fundamentals of strain-based failure criteria have been used for many years. The use of strain gages is limited to where there is a sound understanding of the actual limiting strain values that can be accepted as safe, based upon engineering documentation.

15.6 GROUNDWATER BEHAVIOR

15.6.1 Purpose of Monitoring

In a landmark 1984 study titled *Geotechnical Site Investigations for Underground Projects*, the National Academy of Sciences catalogued problems associated with the construction of 84 mined tunnels in the U.S. and Canada, and stated bluntly in its conclusion, "The presence of water accounts, either directly or indirectly, for the majority of construction problems." Thus, even if groundwater does not flow into an advancing excavation in huge quantities to become a primary problem, it may still alter the ground in a way to make its behavior worse than it would otherwise be, and so become a serious secondary problem. For example, seemingly solid rock may be destabilized by the presence of water if the liquid carries binding particles out of otherwise closed joints or lubricates the joint faces to decrease frictional forces that hold rock blocks in place. Soft ground fares even worse in the presence of water as seepage forces may carry materials into the excavation, thus exacerbating the loss of ground, or perhaps causing subsidence above simply due to the pumping of water if the overlying soils are compressible. Most tunneling experts know that somewhat controllable "running ground" may become much-harder-to-control "flowing ground" if water is present and its effects are not checked. It is a given that, in most soft ground mined or cut-and-cover excavations where the water table is high, some kind of dewatering will need to be carried out to keep the headings safe. It is also a given that, even if formal pre-construction dewatering is not carried out, the excavation will probably cause a decrease in the level of the groundwater as intruding water is pumped out to create dry, workable conditions. Interestingly, even the drying up of the ground to make tunneling easier can have its own unwanted side effects if there are abutting facilities that depend upon the water table staying close to its original elevation for them to maintain their functionality.

15.6.2 Equipment, Applications, Limitations

Three standard types of instrumentation are used to determine the effect of tunnel construction on groundwater movements and pressures:

- Observation Wells
- Open Standpipe Piezometers
- Diaphragm Piezometers

15.6.2.1 Observation Wells

Observation Wells are the simplest and least expensive instruments in the list of devices used to determine groundwater pressures. A well consists of a perforated section of pipe attached to a riser pipe installed in a borehole filled with filter material, generally sand or pea gravel (Figure 15-29). The filter prevents fines from migrating in with the water and clogging the well. The filter may extend to only a few feet above the perforated section or may go almost to the ground surface, but the well must have a mortar seal near the top of the riser pipe to prevent surface runoff from entering the hole. Also, a vent is required in the top cap so that water is free to rise and fall in the pipe. The height of the groundwater table is generally measured by lowering an electrical probe at the end of a graduated cable until it touches the top of the water. A circuit is then completed and so indicated by the flicker of an indicator light or sound of a buzzer at the upper end of the cable. Such wells are installed in tunneled ground where it is assumed that the ground is continuously permeable and groundwater pressures will increase uniformly with depth. Tunnel designers try to gain an understanding of the groundwater regime as design proceeds and often will specify the level to which the water must be pulled down by a dewatering program before construction is permitted to proceed too far. It is common to require dewatering to a level a few feet below final invert for either a soft ground mined tunnel or braced excavation. An observation well would then be installed to two or three feet below that drawdown level to be certain of detecting the new during-construction top of water table. The most common problem with observation wells is that they may not be the instrument appropriate for the situation because the complexity of geologic stratification is actually greater than anticipated. If readings seem inexplicable, it may be because the water level corresponds to the head in the most permeable zone rather than to a straight line correlation with depth from the ground surface. It is possible that the wells may need to be supplemented with other instruments such as piezometers.

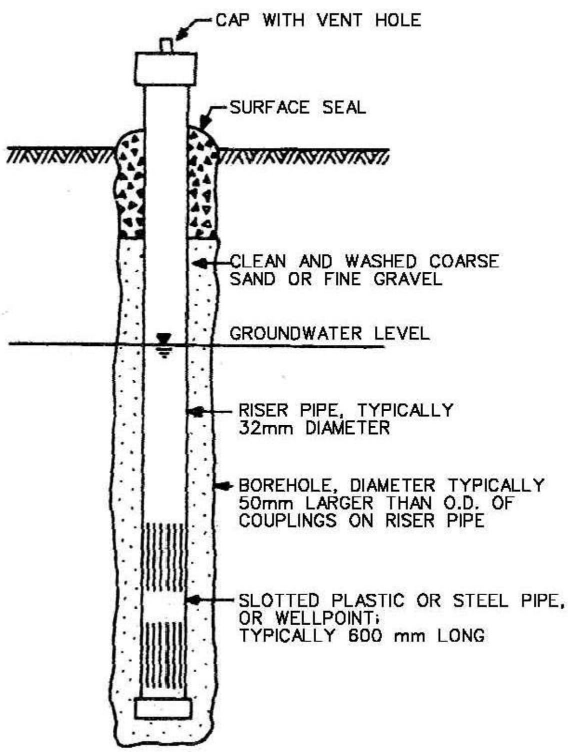

Figure 15-29 Schematic of Observation Well (After Dunnicliff, 1988, 1993)

15.6.2.2 Open Standpipe Piezometers

Open Standpipe Piezometers are very similar in construction to observation wells, with one major difference: as defined by Dunnicliff, the porous filter element is sealed with bentonitic grout into a particular permeable stratum so the instrument responds to groundwater pressure only at that level and not to pressures at other elevations (Figure 15-30). Such a piezometer may be installed in soil strata or in bedrock and will function as long as the porus intake and filter are sealed in a zone that permits water to flow. In soil the instrument will be measuring pore water pressure; in rock, it will generally be measuring joint water pressure. The instrument creates little or no vertical hydraulic connection between strata and, in contrast to simple observation wells, readings will be more accurate. If stratification is somewhat complex, several piezometers installed at different depths in the same small area would probably reveal more than one level of pressures, as in the case of a perched water table above a clay stratum exhibiting pressures different from those in a permeable stratum below the layer of clay. In construction monitoring it is usual to install the porus intakes at the critical levels only, as in just below the inverts to where the water table needs to be lowered. Another common depth for the intakes would be at the boundary between an upper layer of sand and a lower layer of impervious clay in which the excavation bottoms out. In the latter situation, the dewatering subcontractor would probably be able to pull the water table down only to a few feet above the clay, and that is the elevation that would need to be monitored. Lack of expected response from an open standpipe piezometer is sometimes caused by clogging of the filter due to repeated water inflow and outflow. This may be remedied by high pressure flushing, something readily accomplished if the drill rig used during installation is still in the area. A more serious problem would result from the porous intake having been installed in a relatively impermeable silt or clay stratum because the borehole was not properly logged prior to installation. The only solution would probably be to install another instrument – perhaps another type of instrument – at the same plan location, with more attention being paid to good geologic logging and placement of the porous intake.

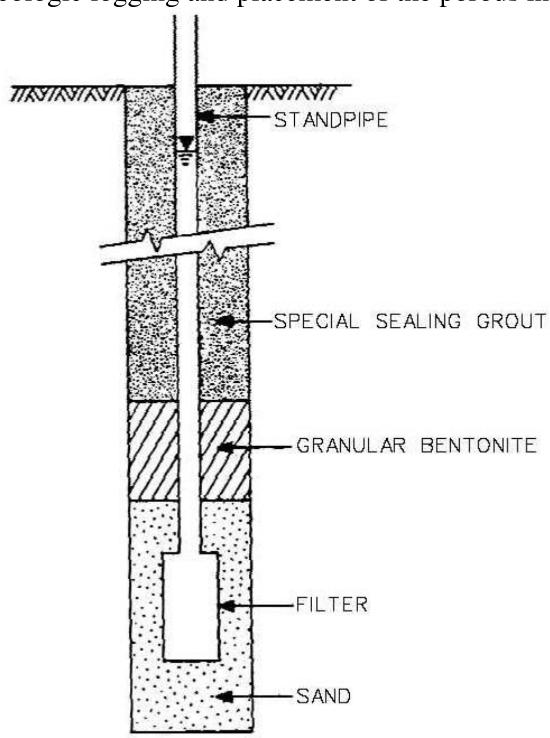

Figure 15-30 Schematic of Open Standpipe Piezometer Installed in Borehole (After Dunnicliff, 1988, 1993)

15.6.2.3 Diaphragm Piezometers – Fully Grouted Type

As noted earlier, a *piezometer* is a device that is sealed within the ground so that it responds only to groundwater pressure around itself and not to groundwater pressures at other elevations. There are several situations that point to the need for a device that is more sophisticated than the simple open standpipe instrument:

1. Need to measure pore water or joint water pressure in a stratum of very low permeability. The hydrodynamic time lag for an open standpipe instrument is large, meaning that it responds slowly to changes in piezometric head because a significant volume of water must flow to register a change. This cannot happen in materials of low permeability such as clay or massive bedrock with few joints.
2. Some situations make it undesirable to have a rigid standpipe connecting with the surface, especially in the midst of heavy construction.
3. Repeated water flow reversals can cause the sand or pea gravel filter to clog.
4. In very cold climates there is a chance of freeze-up and resultant loss of opportunity to collect data.
5. A large number of readings and/or something close to real time monitoring may be required, but the open standpipe instrument does not lend itself readily to this type of data collection.

Thus there are times when monitoring personnel are forced to choose a type of piezometer consisting of a unit that is pre-manufactured to interpose a diaphragm between the transducer and the pressure source. Pneumatic, electrical resistance and vibrating wire are the three most common type of such instrument. The vibrating wire type us usually chosen because it operates with a short time lag, offers little interference to construction, and the lead wires can easily be connected to a surface readout unit or to a datalogger for real time monitoring.

Even these instruments, however, have always suffered from a major shortcoming: the assumed need to place filters around the sensing units and granular bentonite/cement grout seals and backfilling in the boreholes around and above the monitored elevation. Bridging and material stickiness can make proper emplacement difficult and may lead to degradation of data accuracy or outright instrument malfunction. This emplacement difficulty particularly complicates the installation of multiple piezometers in one borehole, so if readings from various elevations are required, it may mandate the drilling of a separate hole for each elevation that requires measurement.

An obvious way around these difficulties would seemingly have been to forgo the filters and encase diaphragm piezometers and their accoutrements in a cement-bentonite mix seal all the way to the surface in *fully-grouted* installations. However, prevailing opinion for many years was that the grout around the sensing unit might have extremes of permeability that would prevent an instrument from responding accurately to changes in pressures. But from work that began in 1990, it has now been shown that this does not have to be the case. A diaphragm piezometer generally requires only a small flow to respond to water pressure changes, and the grout is able to transmit this small volume over the short distance that separates the sensing unit from the ground in a standard size borehole. The response can be enhanced if the installer minimizes this distance, which can be accomplished through the use of an expandable assembly that lessens the distance between sensor and borehole wall, thus reducing the thickness of the grout between sensor and ground. Studies have shown that accuracy of pressure measurements will be good not only when the permeability of the grout is lower than that of the surrounding ground (which had been assumed all along), but also when the permeability of the mix is up to three orders of magnitude greater than that of the surrounding ground. Obviously, every situation requires that some work be done to formulate a grout mix of an appropriate permeability to be effective at the site being monitored.

Fully-grouted piezometers can be emplaced by loose attachment then detachment from a sacrificial plastic pipe that is withdrawn (along with any support casing) as the grout is tremied in from the bottom up. It is relatively easy to install more than one instrument in the same hole for water pressure measurements at several elevations. As many as ten in holes penetrating to 500 ft depths have been successfully installed.

Good experience in a greater than 15-year time frame prior to 2009 has shown that most diaphragm piezometers need to be installed as fully-grouted types for the sake of increased simplicity and the collection of much more data at lower cost than had been the case with older methods.

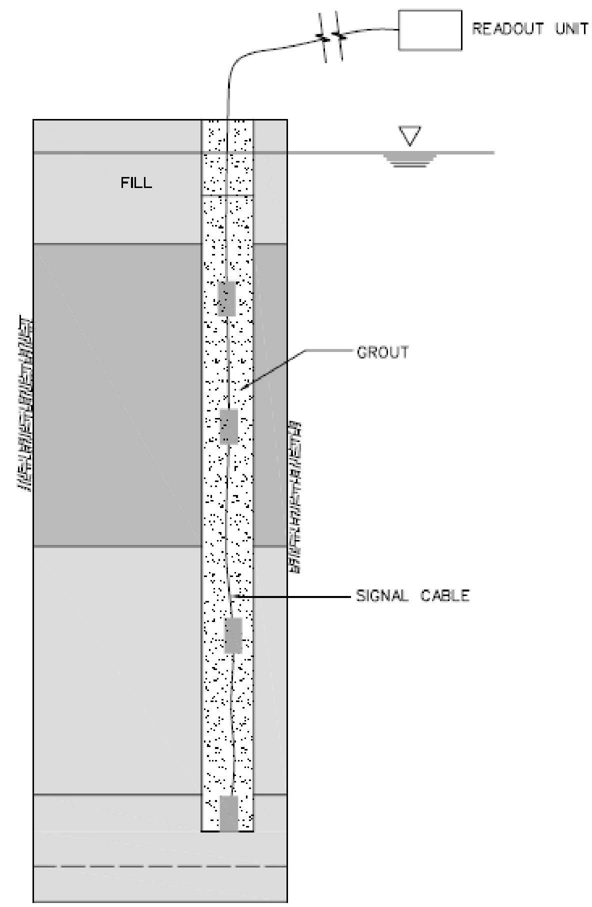

Figure 15-31 Schematic of Multiple Fully-Grouted Diaphragm Piezometer

A continuing use for piezometers and observation wells depends upon their being left in place after construction is complete because of the effects the permanent structure may have on the groundwater regime. For example, if the water table remains depressed due to leakage into the new tunnels, a continuation in monitoring may indicate whether attention needs to be paid to protection of wood support piles that remain exposed to air, or perhaps to wells or ponds that have been wholly or partially dried up. An opposite problem may stem from the mounding up of groundwater because it's normal gradient is interrupted by the presence of the new tunnel, which may result in situations such as once dry basements that are now prone to flooding. Although leaving the instruments in place may result in increased maintenance costs, they can prove to be valuable sources of data when certain long term problems are being investigated.

15.7 INSTRUMENTATION MANAGEMENT

15.7.1 Objectives

As noted in the introduction to this chapter, the primary function of most instrumentation programs is to monitor performance of the construction process in order to avoid or mitigate problems. There are, of course, other related purposes, and proper management of the program will include decisions on which of the following deserve primary consideration and which may be considered of lesser importance:

1. To prevent or minimize damage to existing structures and the structure under construction by providing data to determine the source and magnitude of ground movements.
2. To assess the safety of all works by comparing the observed response of ground and structures with the predicted response and allowable deformations of disturbance levels.
3. To develop protective and preventive measures for existing and new structures.
4. To select appropriate remedial measures where required.
5. To evaluate critical design assumptions where significant uncertainty exists.
6. To determine adequacy of the Contractor's methods, procedures and equipment.
7. To monitor the effectiveness of protective, remedial and mitigative measures.
8. To assess the Contractor's performance, Contractor-initiated design changes, change orders, changed conditions and disputes.
9. To provide feedback to the Contractor on its performance.
10. To provide documentation for assessing damages sustained to adjacent structures allegedly resulting from ground deformations and other construction related activities.
11. To advance the state of the art by providing performance data to help improve future designs.

An overriding factor in considering what is important about instrumentation may spring from new demands being made by insurance and bonding companies. In many parts of Europe they already have the power to require that every tunneling project, prior to construction, undergo a process of *Risk Analysis* or *Risk Assessment*. Then, during construction, periodic audits are conducted to determine whether a project is successfully practicing *Risk Management*. A low score on this point could result in the cancellation of insurance and the possible termination of the project. Although not yet to such an advanced stage, the tunneling industry in the U.S. is becoming very attuned to the necessity of Risk Analysis and Management, and a good instrumentation program can help to reduce the possibility of major problems. It can be shown to the satisfaction of most observers that a good monitoring program has the potential to pay for itself many times over through the monies saved from incidents that were prevented from happening. In other words, Risk Management backed up by good instrumentation and monitoring can be very cost effective.

15.7.2 Planning of the Program

Much of the following material is predicated on the assumption that any particular project will follow the standard U.S. Design-Bid-Build method of services procurement. Where an alternative method such as Design-Build may be a possibility, we will try to point out how this could affect the instrumentation program under consideration.

As noted by Dunnicliff (1988, 1993), the steps in planning an instrumentation program should proceed in the following order:

1. Predict mechanisms that control behavior of the tunneling medium
2. Define the geotechnical questions that need to be answered

3. Define the purpose of the instrumentation
4. Select the parameters to be monitored
5. Predict magnitudes of change
6. Devise remedial action
7. Assign tasks for design, construction, and operation phases
8. Select Instruments
9. Select instrument locations
10. Plan recording of factors that may influence measured data
11. Establish procedures for ensuring reading correctness
12. List the specific purpose of each instrument
13. Prepare a budget
14. Write instrument procurement specifications
15. Plan installation
16. Plan regular calibration and maintenance
17. Plan data collection, processing, presentation, interpretation, reporting, and implementation
18. Write contractual arrangements for field instrumentation services
19. Update budget

Many of these points will be covered in more detail in the following pages, but no. 2 deserves special emphasis here; Dunnicliff stated it in the following terms:

> ***Every instrument on a project should be selected and placed to assist in answering a specific question: if there is no question, there should be no instrumentation.***

The basic point can also be stated as, "Do not do something just because it is possible or because it might result in something that would be nice to know." Movement in that direction can result in wasted monies and the proliferation of excess – perhaps even conflicting – data that leads to confusion.

Serious work on planning an instrumentation program will probably not begin until some time after the 30-percent design level has been completed because only then will such aspects of the project as geology, tunnel alignment, structural design and probable methods of construction be coming into good focus. Program design should be carried out by geotechnical engineers and geologists who have a good knowledge of instrumentation, assisted as necessary by the structural engineers with the most knowledge of how the new and existing structures are likely to react to the changing forces to which they will be subjected.

15.7.3 Guidelines for Selection of Instrument Types, Numbers, Locations

Due to the large number of permutations and combinations of highway tunnel types, sizes, depths and geographic/geologic locales, it would be very difficult to list truly useful guidelines in the space allotted herein. A few of the authors' thoughts on the subject can be found in preceding sections 15.3 through 15.6, but even those 20 or so pages can only begin to suggest what can or should be done. But in addition to space limitations, there is also a danger in the listing of specific guidelines in a manual such as this because it can lead to a user's thinking of the materials as a "cookbook" in which the solutions to most problems are contained and for which no further thought needs to be given. Instrumentation and monitoring is too large a subject for this kind of treatment, and readers are urged to absorb the contents of as many of the listed references as possible in order to knowledgably compile their own project-specific guidelines for the undertaking at hand. That suggested task is summarized in nos. 8 and 9 in section 15.7.2. above.

15.7.4 Remote (Automated) versus Manual Monitoring

As noted in the introduction, the automation of many, perhaps most, types of instrumentation is now possible and in some cases even relatively easy. This does not mean that it should always be done because increasing sophistication may also mean an increase in front end costs, maintenance costs, and in the number of things that can go wrong. Some of these considerations were covered briefly in preceding paragraphs, but without any large generalizations or guidelines having been promulgated.

It is easy to lose sight of one of the advantages of hands-on, manual monitoring, namely that it puts the data collecting technician or engineer on the job site where he or she can observe the construction operations that are influencing the readings. This can be a huge advantage because the interpretation of instrumentation data requires the comparison of one instrument type with another for mutual confirmation of correctness, and then seeing if the data plots match up with known construction activities, such as the removal of a strut or the increased depth of an excavation. Without such information being provided by the geotech field personnel, the instrumentation interpreter has to spend time digging out construction inspectors' reports or talking with various other people who may have knowledge of daily occurrences at the site. Valuable time can thus be lost, a serious consideration if adverse circumstances are developing fast. However, if data interpreters are depending upon their field personnel to provide feedback, those personnel need to have at least some minimal training in construction terminology and methods. For example, it is not helpful if monitoring personnel do not have the vocabulary to note whether they are observing the installation of a strut or a whaler.

Following are some of the most important reasons for choosing automation over manual monitoring of instruments:

1. When there is a requirement for data to be available in real time or something close to real time.
2. When easy and/or continued access to a monitored location is not assured.
3. When there is uncertainty about the continued availability of monitoring personnel.
4. When manual readings are subject to "operator sensitivity" and the same person or crew cannot always be available to monitor an instrument time after time.
5. When manual monitoring would unduly interfere with construction operations.
6. When manual monitoring would be too time consuming; e.g., the several-times-per-day reading of conventional inclinometers.
7. When data needs to be turned around quickly and distributed to multiple parties located in different offices.

15.7.5 Establishment of Warning/Action Levels

At one time it was common for instrumentation program designers to write specifications on equipment types and installation procedures, but then leave up to construction contractors and field instrumentation specialists the decisions on whether allowable movements (or other parameters) were about to be exceeded. This can lead to endless arguments on whether mitigative action needs to be taken and whether the Contractor deserves extra payment for directed actions he may not have forseen when submitting a bid price. Such problems can be alleviated to a degree by specifying the instrument reading levels which call for some action to be taken. Depending on a project Owner's preferred wording, the action triggering levels may be called instrument *Response Levels*, comprised of *Review* and *Alert Levels*, or *Response Values*, comprised of *Threshold* and *Limiting Values*.

The actions are generally specified in the following manner:

A. If a Review Level/Threshold Value is reached, the Contractor is to meet with the Construction Manager to discuss response actions. If the CM so decides, the Contractor is to submit a plan of action and follow up within a given time frame so that the Alert Level/Limiting Value is not reached. The CM may also call for the installation of additional instruments.

B. If, in spite of all efforts, the Alert Level/Limiting Value is reached, the Contractor is to stop work and again meet with the CM. If the CM so decides, the Contractor is to submit another plan of action and follow up within a given time frame so that the Alert Level/Limiting Value is not exceeded. Again, the CM may also call for the installation of additional instruments.

Such wordsmithing is easy compared with the effort involved in actually deciding what kind of levels/values to specify, because it may entail much time spent in structural and geotechnical analysis. It is not uncommon for specifications to stipulate only the actions required when settlements of any existing structure have reached a certain magnitude, or when the vibrations from blasting have exceeded a certain peak particle velocity. However, there are many other parameters that may deserve attention. Following is a partial list of what may be appropriate to consider for inclusion in specifications:

- Depth to which groundwater level must be lowered or depth to which it may be permitted to rise.
- Allowable vertical movements of anchors or sensors located at various depths in the ground.
- Allowable lateral deflections from the vertical as stated in relation to the depth of any sensing point in an inclinometer.
- Allowable deformations of ground or linings in the tunnel under construction.
- Allowable settlements for individual existing structures (as opposed to one set of figures applying to all structures equally).
- Allowable tilting of the walls in individual existing structures.
- Allowable differential settlements and angular distortions for existing structures.
- Allowable increases in widths of structural cracks or expansion joints.
- Allowable load increases in braced excavation struts or tiebacks in non-braced excavations.
- Rate of change of any of the above, in addition to the absolute magnitude.

In the interest of good risk management, it is recommended that designers of instrumentation and monitoring programs include what they consider the most important of the parameters in the specified action-triggering levels.

As these levels are being set, designers should guard against one pitfall: the assignment of readings that are beyond the sensing capabilities of the instrument. For instance, if a lower action-triggering level of ¼ inch has been specified for a settlement point, one must be assured that the survey procedures used to collect data can reliably detect settlements down to 1/16 inch, for otherwise construction managers may be constantly responding to apparent emergencies that are not real but are only a result of survey "flutter." Likewise, the higher action-triggering levels must be set a realistic distance above the lower ones to avoid similar problems. In the noted example, a lower level of ¼ inch perhaps should not be matched with an upper level of 3/8 inch because that is an increase of only 1/16 inch, still pushing the level of probable surveying accuracy. Again one might end up responding to apparent emergencies that are not real.

15.7.5.1 Criteria

It is not within the scope of this document to establish criteria for tunneling projects; however, any monitoring program that is developed to protect adjacent properties must be consistent with both the types of measurements as well as the actual limiting values that are consistent with standard industry practice.

Criteria may be set either by regulations (Federal, State, and/or Local), or by specifications.

Measurement Category	**Instrumentation**	**Type of Reading**	**Units**
Ground Movement	Survey Point	Displacement	Inches
Dynamic Ground Movement	Blast Seismograph	Peak Particle Velocity	Inches/second
Dynamic Ground Movement	Strain Gage	Strain	Microstrain

15.7.6 Division of Responsibility

15.7.6.1 Tasks or Actions

Tasks or Actions required for an instrumentation and monitoring program can be summarized as follows:

1. Lay out, design, specify.
2. Procure/furnish.
3. Interface with abutters for permission to install.
4. Install.
5. Maintain.
6. Monitor.
7. Reduce data.
8. Maintain database.
9. Distribute reduced data.
10. Interpret/analyze data.
11. Take mitigative action as required.
12. Remove instruments when need for them is ended.

<u>Potential Performing Entities</u> include the following four, any of whom may be assisted by a specialist consultant or subcontractor:

- The Owner
- The Design Engineer (not a separate entity in cases where the state – the Owner – is also the designer)
- The Construction Manager
- The Construction Contractor

In the case of Design-Build contracting, it is essentially a given that the Construction Contractor will be responsible for all of the listed tasks. This entity will probably be assisted by a consulting engineering firm to carry out the general design, and by an instrumentation specialist to attend to the matters related to instrument procurement, installation and monitoring, but it is the Contractor who takes the overall responsibility for the project.

In the more general (for the U.S.) case of Design-Bid-Build contracting, decisions have to be made by the Owner on how to assign the various responsibilities. Ideally, the Owner or the Owner's designer or

Construction Manager should be responsible for all of the 12 listed tasks except for nos. 3 and 11. Since the Contractor is not even aboard at the time of instrumentation program development, the tasks related to no.1 have to be undertaken by the designers of the project. The Contractor could perform no. 3 and must be the one to perform no. 11. (More will be said shortly about task no. 10.)

In the real world, it is a fact that most owners prefer to relegate to contractors the responsibility for furnishing, installing, maintaining and removing instrumentation, often because it, as a result of being included in a competitive low bid process, seems to provide equipment and services at the lowest possible cost. However, monies that seem to be saved by this decision may be less than they at first appear because low-bidding contractors will seldom opt for the highest quality instruments and will probably be constantly pushing for alternative instrument types for their own convenience rather than for the good of the project. Such contractor responsibilities can be considered acceptable only if the following rules are adhered to: (a) specifications must require the services of properly qualified instrumentation specialists; (b) specifications must be very detailed in the requirements for instrumentation hardware and installation methods, especially if the project is broken up into multiple contracts, where consistency from contract to contract has to be assured; and (c) the CM's staff must make every effort to diligently review contractor submittals and to inspect the field work as installations proceed.

If these rules are followed, it may be acceptable to turn over tasks 2, 4, 5 and 12 to a construction contractor, but one thing must be borne in mind: the Contractor's primary job is to *construct*. Instrumentation related activities are peripheral to that job; they will probably be viewed by the Contractor as a nuisance at best, and possibly as deleterious to progress. The CM needs to be cognizent of this attitude and thus to exercise the oversight necessary to ensure that unacceptable shortcuts are not taken.

One other aspect of low bid construction work can make relegation of these tasks to the constructor at least acceptable if not exactly desirable. When instrument installation is carried out by forces directly responsible to the Owner, there are many instances where the Contractor will have to provide assistance, perhaps even going so far as to shut down operations for a time. This can lead to endless friction with the CM and very likely to many claims for extras as the Contractor perceives too much interference in the construction process. Some of this conflict can be avoided if the actions of the instrument installation personnel are more under the control of the party responsible for progressing the primary job of excavation and support, i.e., the Contractor.

It can never be good policy, however, to turn the instrumentation monitoring, databasing, and data distribution over to the party whose actions are being "policed" through use of that data. Data collection and related tasks must be the responsibility of someone answering directly to the Owner, and that would normally be the Construction Manager. However, along with the responsibility for monitoring must go the responsibility, not just for distributing the reduced data, but also distributing it within a useful time frame. This normally means the morning after the day on which the data is collected, but in the modern world it may be much faster. With many instruments being monitored electronically in real time, and the data fed directly to the Project's main computer, much data can be delivered around the clock and alerts can be issued to users of cellphones and laptops when there is indication that action trigger levels have been reached or exceeded.

Regarding the interpretation of instrumentation data (task no. 10 above) the CM's forces will have to do it as a matter of course to ensure that construction operations are proceeding according to specification. However, it is not incumbent on the CM to immediately deliver interpretations to the Contractor along with the data. The Contractor is still the party with primary responsibility for safety of the job, and therefore, he must also have responsibility for performing an independent interpretation of what the monitoring data means and stand ready to pursue whatever mitigating actions seem indicated. Otherwise, the Owner will have bought into a part of the responsibility for safety that by right belongs elsewhere.

15.7.7 Instrumentation and Monitoring for SEM Tunneling

As discussed in Chapter 9, instrumentation and monitoring is an integral part of the SEM tunneling for the verification of design assumptions made regarding the interaction between the ground and initial support as a response to the excavation process by means of in-situ monitoring. It aims at a detailed and systematic measurement of deflection and stress of the initial lining. Monitoring data are collected thoroughly and systematically.

Readers are referred to Chapter 9 "SEM Tunneling" for discussions about monitoring management for SEM application.