Overview of Monitoring Systems Used During Construction and Permanent Structural Monitoring

By:

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Bachelor of Science in Civil and Environmental Engineering
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Abstract

The construction industry is constantly looking for ways to expedite construction time and minimize cost. Both of these goals are becoming more difficult to achieve due to the increasing number of construction jobs in highly populated, urbanized areas. Monitoring systems have become common in the construction field, from helping in construction phasing to maintaining design parameters, instrumentation seems to have earned a permanent place in the construction process.

Just as monitoring is essential in the field of construction it may also become an integrated part of structures over long periods of time. Load cells are used for years to make sure tension members keep their pre-tension characteristics, and strain gauges have been successfully used for over six years in One Financial Center to aid in the assessment of the building's behavioral reactions to the extensive construction work from the Central Artery Project.

New technologies that can make permanent and continuous monitoring possible are being researched and are the topic of many articles, speeches and studies. It seems inevitable that technology will soon enable us to observe the behavior of structures at any point in time and from any location. But with this wealth of information comes a constant stream of responsibility.
This paper investigates the monitoring technology available for use during construction and the technology being researched for use in a permanent basis, as well as the different aspects inherent to continuous information such as liability and data management.

Even though it is clear that within the next few years the technology will be available to continuously monitor a structure, this analysis raises the question of whether we will be able to change our way of practicing to accommodate technology.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering.

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The people in the monitoring industry that took the time to explain the different aspects of technology that were not mentioned in books, in particular: Dr. W. Allen Marr and Mr. David Druss.

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Chapter 1

Monitoring Systems Used During Construction

Different types of monitoring systems are used in every type of project in the construction industry. As urbanization grows and the demand for construction within compact spaces increases, the need to use monitoring devices in innovative ways to ensure the successful completion of a project without any adverse impacts to surrounding existing structures is becoming a natural requirement of everyday construction. In this chapter I will explore the reasons and resources available for monitoring structures or soils in the construction industry.

1.1 Why Monitor During Construction

There are several reasons why the use of monitoring devices during construction is becoming more popular in industry. They are all aimed at either reducing costs, improving safety, maintaining quality and most importantly minimizing liability.

1.1.1 Reducing Costs

Maintaining a project close to its expected budget is a very challenging task in itself. To this challenge one must add the high cost of possible litigations as well as contingency plans.

Monitoring systems can aid in maintaining the budget within limits by providing early alert signals of possible failure; thus avoiding the need for executing a contingency plan. They can also pinpoint the cause of concern making it easier to work directly on the source of the problem, and implementing a correction.

Monitoring devices can also aid in:

1. Determining the best time to perform a task, as in excavating procedures or when staging fill layers on embankments;
2. Determine when to stop a task, such as driving piles once they have reached their required end bearing capacity;

3. Help in scheduling, as when controlling the sequence for compaction grouting.[15]

The data collected from these instruments can be used to improve the performance of the construction team, thereby helping reduce the overall cost of construction.

1.1.2 Improving Safety

The construction industry is full of dangerous situations. A good monitoring system would effectively assist in keeping those situations in control and provide a fair warning of possible failure.

Sensors can be connected to an alarm system that is triggered whenever a certain dangerous reading point is reached, giving workers enough time to remediate the situation or evacuate the site if necessary.

Deep excavations are one of the most common places to find these types of sensor networks, because the risk to human life is so great in these situations.

1.1.3 Maintaining Quality

Although civil engineers use well-known techniques and incorporate factors of safety in their designs in order to keep it as conservative as it is economically possible, there are several assumptions that must be made in the design process that are worth checking in the field.

Critical assumptions made in the design process and unforeseen site conditions can be checked and made evident during construction through the use of sensors and other monitoring devices. The data collected does not only ensure the quality of the structure, or reveal if some design changes are in order, but it also helps any disputes regarding differing site conditions get resolved in a timely and effective manner.

Monitoring systems can also keep the design engineers informed about the quality of the contractor's work and his consistency with any pre-specified requirements. This is especially important during the construction of sensitive or critical structural elements or during excavation.

Monitoring systems can also provide detailed, physical proof of the quality of work of a company. They have the potential of not only improving the company's reputation but also increasing the number of its potential customers. "Like other business processes, improvement can only be assessed by measurement...this is especially the case for projects that use performance-based specifications.

Future contracts may reward contractors and engineers for good performance of the completed facility. A good instrumentation system will be a central part of determining the quality of work."[15]

1.1.4 Minimizing Liability

Abutters can be the main cause of litigation, followed by differing site conditions claims by contractors. Litigation costs can be quite significant especially for large urban projects. Therefore, a strategically placed set of sensors can provide invaluable information when it is time to determine who is responsible for what.

Abutters can be rest assured that the vibrations caused by a nearby construction site will not affect their building, simply by presenting to them a set of instrumentation data that shows the safety of the constructions procedures that are taking place (i.e. data that shows the work done falls within the factors of safety required). "Humans typically sense the presence of vibrations at a level less than 10% of the level that begins to cause minor architectural damage to the building. Building owners may become concerned for the safety of their building when they sense the relatively low level vibrations."[15]

If litigation takes place, instrumentation data can help in the accurate assessment of damages induced by a particular construction activity; thus reducing the probability of an inflated claim.

Instrumentation also aids in the assessment of responsibility between engineers and contractors and helps determine if a certain construction method should not be used by providing both parties a better understanding of the actual site conditions.

1.2 Monitoring Instruments Available

Due to the many uncertainties regarding soil and overall underground conditions, Geotechnical engineers have been the pioneers at instrumentation. They must design using field observations and instrumentation data, as well as empirical equations based on previous observations. As a matter of fact, most of the instruments available in the market for the assessment of structural behavior were used first by Geotechnical engineers.

The information to follow describes some of the different and most popular instruments used in the construction industry today. More detailed information regarding each of the instruments presented in this section can be obtained from "Geotechnical Instrumentation For Monitoring Field Performance" by John Dunnicliff, 1988.

1.2.1 Water Pressure Monitoring Devices

Under equilibrium conditions, that is when there is no flow of groundwater, the groundwater pressure increases linearly with depth, and if a monitoring pipe with perforations only at its bottom were inserted at any level, the groundwater pressure at that point would make the water level in the pipe rise to the groundwater level regardless of the number of soil layers, types of soil or length of the pipe (Figure 1.1).

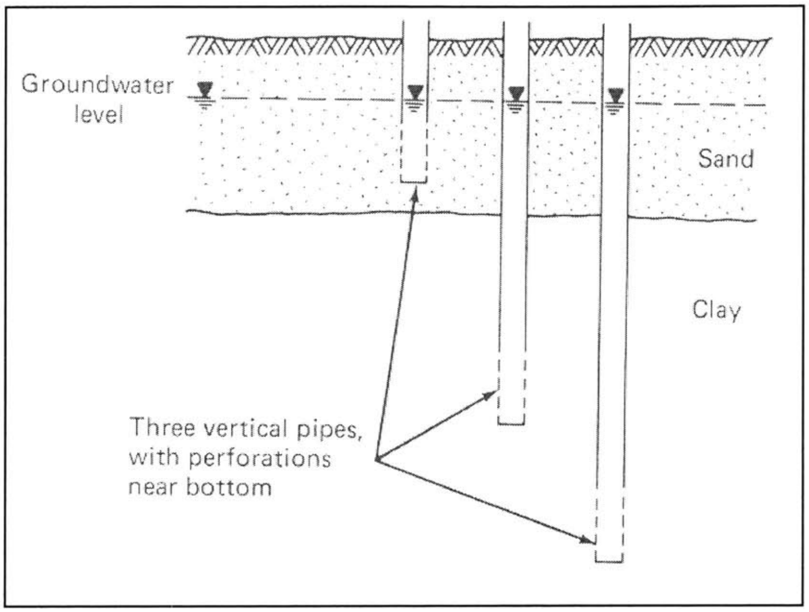


Figure 1.1 Groundwater level under static conditions
Dunnicliff, 1988

When there is flow of water, such as when there is an increase in load or pressure on the soil, the groundwater level from each of the monitoring pipes will not be indicative of the general condition of the groundwater, but instead will indicate the water pressure at a particular location within the soil (Figure 1.2), this specific water pressure is called the pore water pressure. Pore water pressure exists in saturated soils only, and the rate at which the pore water pressure dissipates varies greatly according to the type of soil. Granular soils such as sand are highly permeable, thus allowing the excess pore water pressure caused by a change in loading or overall soil pressure conditions to dissipate almost instantly. Therefore, the pore water pressure in sand would indicate the groundwater level.

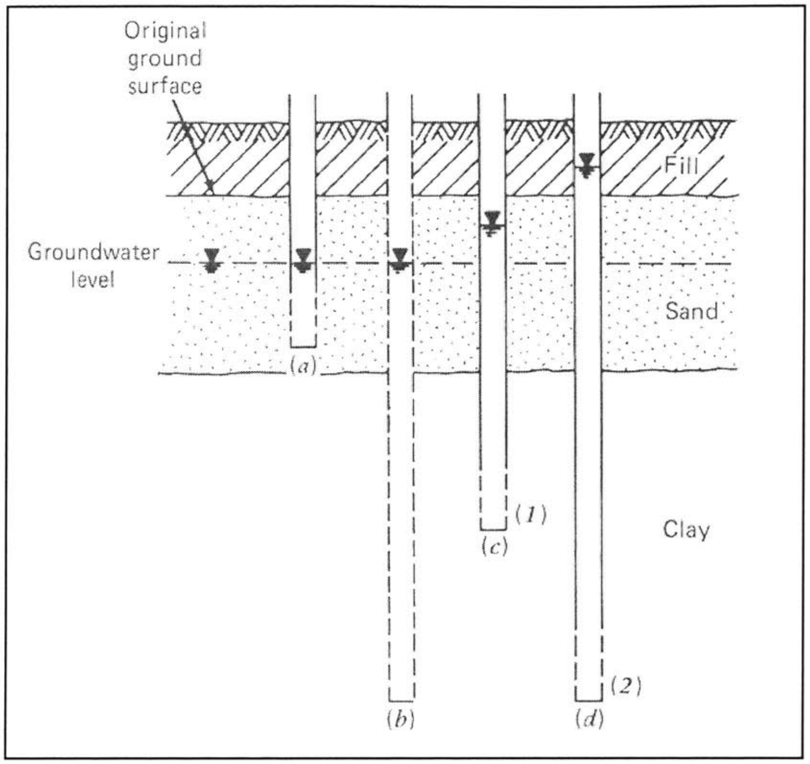


Figure 1.2 Groundwater level and pore water pressure under groundwater flowing conditions. [5]

Clays are impermeable soils. Excess pore water pressures in clay take a long time to dissipate. Pore pressures taken in a clay layer would indicate a higher groundwater level, until the clay layer is completely consolidated.

Figure 1.2 shows the pore water pressures at each soil layer. Pipe C has a lower water level than pipe D even though they are both located in the clay layer, because the water at this level in the clay has to travel less to reach the sand layer in which it is free to flow, making the pore water pressure at this point in the layer lower than the pore water pressure at the bottom of pipe D, where the water must travel a longer trajectory.

All the pipes in Figure 1.2 have perforations only on their lower sections, except for pipe B, which is perforated throughout. Pipe B is then considered an **observation well** while the other pipes are called **piezometers.**

"As a general rule, piezometers are sealed within the soil so that they respond only to changes of pore water pressure at a local zone, whereas observation wells are not sealed within the soil, so that they respond to changes of groundwater pressure throughout their length"[5]

1.2.1.1 Observation Wells

As can be observed in Figure 1.2, observation wells provide a vertical connection between the different soil strata. The water pressure in the saturated clay layer shown in Figure 1.2 would create a flow of water from the clay to the sand. This would be particularly dangerous if contamination existed in the clay, for the contaminants would be spread throughout the soil layers.

Observation wells should only be used in permeable soils where the underground water is under equilibrium conditions (Figure 1.1). Seldom can an engineer assume uniform soil conditions, though.

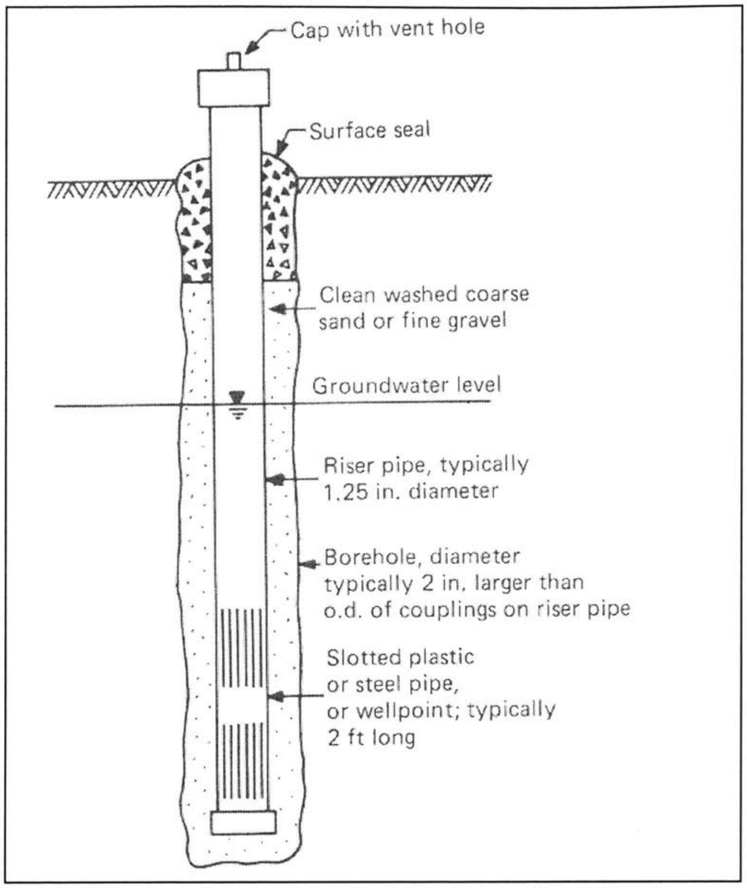


Figure 1.3 Observation well. [5]

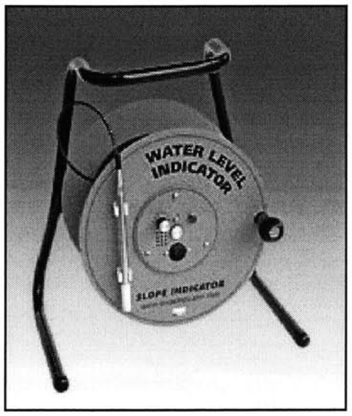


Figure 1.4 Water level indicator [23]

Observation wells are easy to install and requires no technical involvement, making it very cost efficient.

A probe, also called water level indicator, and a graduated cable are used to measure the elevation of the groundwater. The probe sends a signal to the operator, which usually consists of a lighted lamp and a buzzer, and the operator then reads the depth-to-water measurements from the graduated cable.

1.2.1.2 Piezometers

There are several types of piezometers. The three most popular piezometers used in the construction industry are:

- **Open Standpipe Piezometer:**

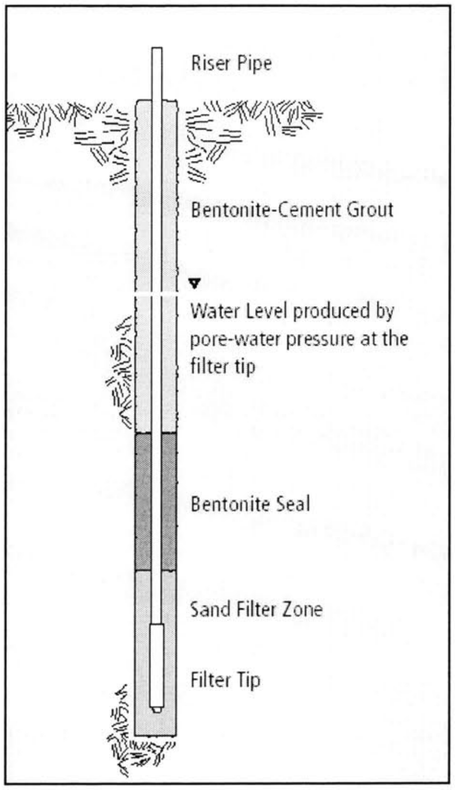


Figure 1.5 Open standpipe piezometer. [23]

The open standpipe piezometer measures the pore water pressure of only one area. It is very similar to the observations wells because they also use a pipe and probe to measure the pore water pressure. The way this piezometer measures only the water pressure at a particular level is by means of a filter element at the bottom tip of the pipe, thus collecting water of only that area.

After the pipe with its filtering tip is installed, they are covered with sand and sealed with bentonite to allow readings of that particular zone. If the pipe were installed by means of a borehole, the hole would then be backfilled with grout, such as bentonite-cement grout.

- **Pneumatic Piezometer**

This type of piezometer is installed in the same manner as the open standpipe piezometer , that is, installed in a borehole, dropped into place, sealed and backfilled.

The following is the description of the operating principles behind pneumatic piezometers as described in Slope Indicator's product catalog[23]:

“The piezometer (pneumatic) contains a flexible diaphragm. Water acts on one side of the diaphragm while gas pressure acts on the other.When a reading is required, a pneumatic indicator is connected to the terminal or directly to the tubing. Compressed nitrogen gas from the indicator flows down the input tube to increase gas pressure on the diaphragm. When the gas pressure exceeds the water pressure, the diaphragm is forced away from the vent tube, allowing excess gas to escape via the vent tube. When the return flow of gas is detected at the surface, the gas supply is shut off. Gas pressure in the piezometer decreases until water pressure forces the diaphragm to its original position, preventing further escape of the gas through the vent tube.

At this point gas pressure equals water pressure, and a reading can be obtained from the pressure gauge on the indicator."[23]

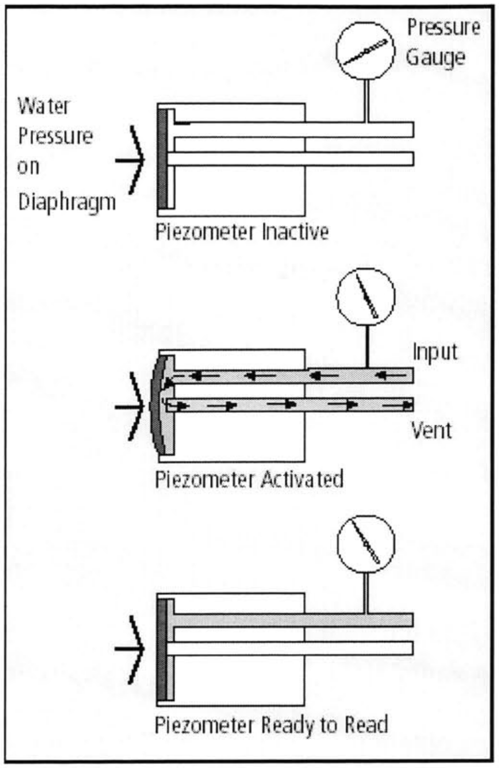


Figure 1.6 Pneumatic piezometer working principle. [23]

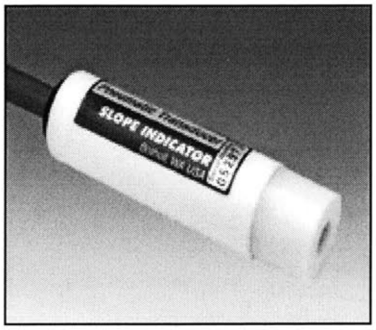


Figure 1.7 Pneumatic transducer. [23]

- **Vibrating Wire Piezometer**

As the pneumatic piezometer, the vibrating wire piezometer uses a diaphragm to sense water pressure, but the diaphragm in this case converts water pressure into a frequency signal.

A tensioned wire is attached to the midpoint of the diaphragm, thus a change in deflection of the diaphragm causes a change in tension in the wire. When an electromagnetic coil that is located close to the steel wire excites it, the wire vibrates at its natural frequency sending a signal that is transmitted to a readout device. The tension in the wire is then compared to its original recorded tensioned to determine an increase or decrease in water pressure.

Table 1.1 Advantages and disadvantages of Different Types of Piezometers. [5]

Instrument Type	Advantages	Limitations[a]
Observation well (Figure 9.1)	Can be installed by drillers without participation of geotechnical personnel	Provides undesirable vertical connection between strata and is therefore often misleading; should rarely be used
Open standpipe piezometer (Figure 9.2)	Reliable Long successful performance record Self-de-airing if inside diameter of standpipe is adequate Integrity of seal can be checked after installation Can be converted to diaphragm piezometer Can be used for sampling groundwater Can be used to measure permeability	Long time lag Subject to damage by construction equipment and by vertical compression of soil around standpipe Extension of standpipe through embankment fill interrupts construction and causes inferior compaction Porous filter can plug owing to repeated water inflow and outflow Push-in versions subject to several potential errors: see Section 9.16
Twin-tube hydraulic piezometer (Figure 9.9)	Inaccessible components have no moving parts Reliable Long successful performance record When installed in fill, integrity can be checked after installation Piezometer cavity can be flushed Can be used to measure permeability	Application generally limited to long-term monitoring of pore water pressure in embankment dams Elaborate terminal arrangements needed Tubing must not be significantly above minimum piezometric elevation Periodic flushing may be required Attention to many details is necessary: see Appendix E
Pneumatic piezometer (Figure 9.14)	Short time lag Calibrated part of system accessible Minimum interference to construction: level of tubes and readout independent of level of tip No freezing problems	Attention must be paid to many details when making selection: see Section 8.3 Push-in version subject to several potential errors: see Section 9.16
Vibrating wire piezometer (Figure 9.16)	Easy to read Short time lag Minimum interference to construction: level of lead wires and readout independent of level of tip Lead wire effects minimal Can be used to read negative pore water pressures No freezing problems	Special manufacturing techniques required to minimize zero drift Need for lightning protection should be evaluated Push-in version subject to several potential errors: see Section 9.16
Unbonded electrical resistance piezometer (Figure 9.19)	Easy to read Short time lag Minimum interference to construction: level of lead wires and readout independent of level of tip Can be used to read negative pore water pressures No freezing problems Provides temperature measurement Some types suitable for dynamic measurements	Low electrical output Lead wire effects Errors caused by moisture and electrical connections are possible Need for lightning protection should be evaluated

Table 1.1 Advantages and disadvantages of Different Types of Piezometers (Cont). [5]

Instrument Type	Advantages	Limitations[a]
Bonded electrical resistance piezometer (Figure 9.21)	Easy to read Short time lag Minimum interference to construction: level of lead wires and readout independent of level of tip Suitable for dynamic measurements Can be used to read negative pore water pressures No freezing problems	Low electrical output Lead wire effects Errors caused by moisture, temperature, and electrical connections are possible. Long-term stability uncertain Need for lightning protection should be evaluated Push-in version subject to several potential errors: see Section 9.16
Multipoint piezometer, with packers (e.g., Figures 9.36 and 9.37)	Provides detailed pressure–depth measurements Can be installed in horizontal or upward boreholes Other advantages depend on type of piezometer: see above in table	Limited number of measurement points Other limitations depend on type of piezometer: see above in table
Multipoint piezometer, surrounded with grout	Provides detailed pressure–depth measurements Simple installation procedure Other advantages depend on type of piezometer: see above in table	Limited number of measurement points Applicable only in uniform clay of known properties Difficult to ensure in-place grout of known properties Other limitations depend on type of piezometer: see above in table
Multipoint push-in piezometer	Provides detailed pressure–depth measurements Simple installation procedure Other advantages depend on type of piezometer: see above in table	Limited number of measurement points Subject to several potential errors: see Section 9.16 Other limitations depend on type of piezometer: see above in table
Multipoint piezometer, with movable probe (e.g., Figures 9.38 and 9.39)	Provides detailed pressure–depth measurements Unlimited number of measurement points Allows determination of permeability Calibrated part of system accessible Great depth capability Westbay Instruments system can be used for sampling groundwater and can be combined with inclinometer casing	Complex installation procedure Periodic manual readings only

1.2.2 Strain Monitoring Devices

As their name indicates, strain gauges measure the strain in members caused by the members' elongation (due to tension) or shortening (due to compression). There are several types of strain gauges, some are mechanical and others use different kinds of transducers to measure strain. The most widely used transducers in strain gauges are the vibrating wire and the electrical resistance transducers.

Strain gauges can be separated into three groups: mechanical, embedment and surface-mounted.

1.2.2.1 Electrical Resistance Transducers

The principle behind electrical resistance strain transducers is that a change in resistance in a strain wire or foil is proportional to its change in length, and thus, changes in strain can be calculated with the following formula:

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} \times GF$$

Where ΔR is the change in resistance, R is the original resistance, ΔL is the change in length, L is the initial length, and GF is the gauge factor, which is close to 2 for bonded foil and bonded wire gauges and between 50 and 200 for semiconductor strain gauges (refer to Dunnicliff, 1988 for details on the different types of electrical resistance strain gauges).

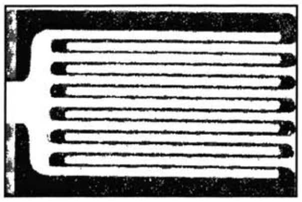


Figure 1.8 Foil transducer. [26]

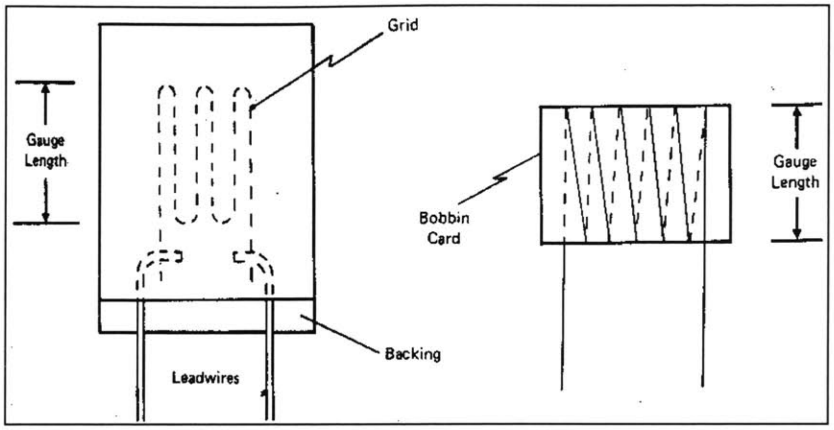


Figure 1.9 Electrical wire transducers.[26].

1.2.2.2 Vibrating Wire Transducers

These are the most widely used transducers in the world of monitoring. They are used in strain, load, pressure, settlement and deformation gauges, as well as in the pressure sensors used in piezometers.

The principle behind vibrating wire transducers is that the change in frequency obtained from a tensioned wire can be related to the change in strain. The way in which this is achieved is by fixing the ends of a tensioned wire and comparing its original natural frequency with its natural frequency once it has been strained. An electromagnetic coil is used to excite the wire in order to read its natural frequency. [20,26]

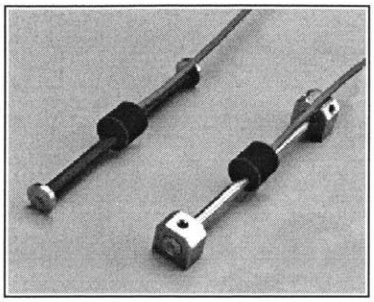


Figure 1.10 Vibrating wire surface strain gauges. [20]

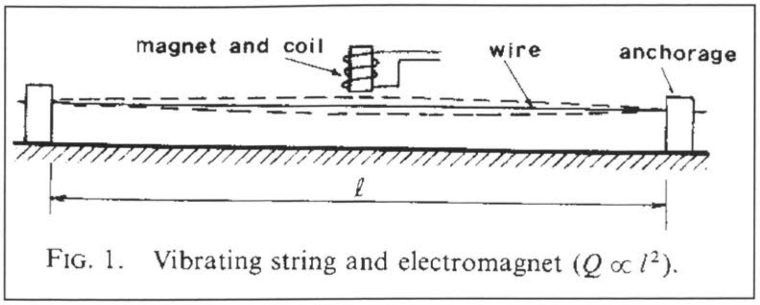


Figure 1.11 Vibrating string and electromagnetic coil. [26]

The relationship between frequency and stress as follows:

$$f = \frac{1}{2L}\sqrt{\frac{\sigma g}{\rho}}$$

where:

f = natural frequency
L = length of vibrating wire (in)
σ = stress in the wire (lb/in^2)
ρ = density of the wire material (lb/in^3)
g = acceleration due to gravity (in/sec^2)

And knowing the relationship between stress and strain to be:

$$E = \frac{\sigma}{\varepsilon}$$

where:

E = modulus of elasticity of the wire (lb/in^3)

ε = strain in the wire

Leads to the relationship between strain and frequency as:

$$f = \frac{1}{2L}\sqrt{\frac{Eg\varepsilon}{\rho}}$$

Thus, the resultant strain can be easily obtained by the equation:

$$\varepsilon = \frac{4L^2 f^2 \rho}{Eg}$$

1.2.2.3 Mechanical Strain Gauges

These are the most common and economical strain gauges used in the field. As their name indicates, they mechanically determine the change in strain by directly measuring the change in length. There are several types of mechanical strain gauges, one of the most popular is the portable strain gauge with dial indicator. Crackmeters can also be used to determine change in length.

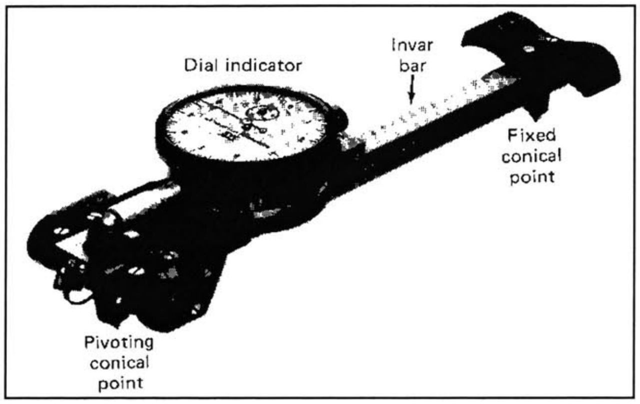


Figure 1.12 Portable mechanical gauge with dial indicator. [5]

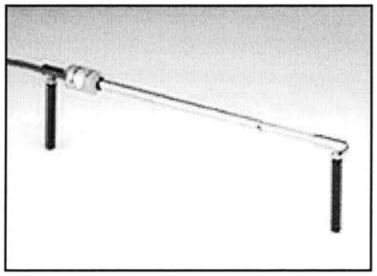


Figure 1.13 Crackmeter. [9]

1.2.2.4 Embedment Strain Gauges

These types of strain gauges are installed inside the structural members. They can be welded or tied to the reinforcing bars of a reinforced concrete member or pre-stressed concrete. They can also be installed in mass concrete structures right after or right before pouring the concrete.

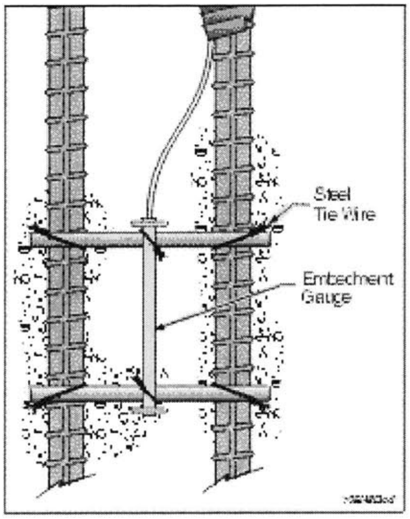


Figure 1.14 Tied Strain Gauge. [23]

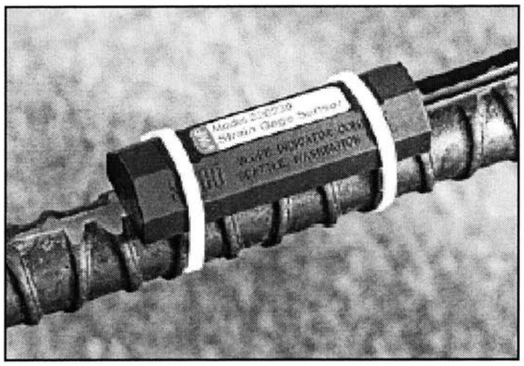


Figure 1.15 Spot-welded strain gauge on reinforcing bar. [23]

The most commonly used embedment strain gauges use either the vibrating wire or the electrical resistance transducers.

1.2.2.5 Surface-Mounted Strain Gauges

This type of strain gauges can also use electrical resistance or vibrating wire transducers or be mechanical in nature. They are welded or bolted to the structural member's surface. The most commonly used non-mechanical surface-mounted strain gauges are the vibrating wire arc weldable strain gauges that can be welded to the surface of a steel structure or, just by changing their mounting blocks, bolted to any structural surface.

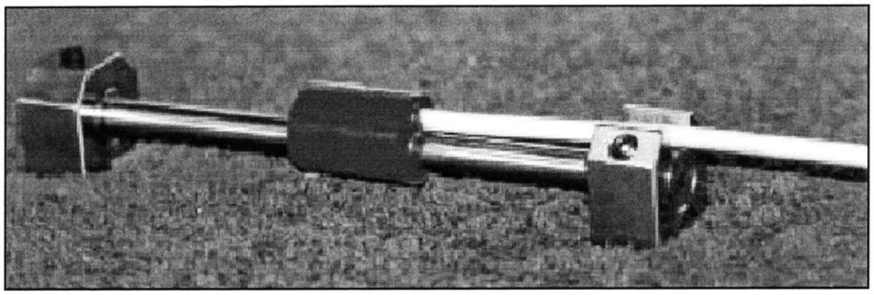


Figure 1.16 Arc-weldable strain gauge. [10]

As with any instrument, the choice of strain gauge needed for a particular situation must be based on the requirements set for that job, environmental conditions, expected accuracy, ultimate goals, type of expertise available, etc.

Dunnicliff summarized the limitations, benefits and other characteristics of a variety of strain gauges as follows:

Table 1.2 Comparison between different types of embedment strain gauges. [5]

Gage Type	Advantages	Limitations	Typical Gage Length	Typical Range (microstrain)	Sensitivity (microstrain)	Approximate Accuracy (microstrain)
Multiple telltales	Simple Inexpensive	Requires access to telltales (but can be converted to remote reading device)	Unlimited	Unlimited	Depends on application	±25–400
Vibrating wire; type similar to arc welded surface-mounted gage (e.g., Figure 13.28)	Lead wire effects minimal No conformance problem Remote readout Readout can be automated Factory waterproofing	Cannot be used to measure high-frequency dynamic strains Special manufacturing techniques required to minimize zero drift Need for lightning protection should be evaluated	5–10 in. (130–250 mm)	3000	0.2–2	±5–50
Vibrating wire; *sister bar* type (Figure 13.29)	Robust Easy to install Lead wire effects minimal Remote readout Readout can be automated Factory waterproofing	Cannot be used to measure high-frequency dynamic strains Special manufacturing techniques required to minimize zero drift Special design features required to minimize inclusion effects Sister bar must be small relative to size of structural member Need for lightning protection should be evaluated	Debonded length, plus 100× bar diameter	3000	0.2–2	±5–50
Bonded foil or weldable resistance gage; *sister bar* type (similar to Figure 13.29)	Robust Easy to install Suitable for monitoring dynamic strains Remote readout Readout can be automated Factory waterproofing	Special design features required to minimize inclusion effects Low electrical output Lead wire effects Errors owing to moisture, temperature, and electrical connections are possible Need for lightning protection should be evaluated	Debonded length, plus 100× bar diameter	20,000	1–4	±1–100

Table 1.2 Comparison between different types of embedment strain gauges(cont'd). [5]

Gage Type	Advantages	Limitations	Typical Gage Length	Typical Range (microstrain)	Sensitivity (microstrain)	Approximate Accuracy (microstrain)
Unbonded resistance (e.g., Figure 13.30)	Long good performance record No conformance problem Provides temperature measurement Remote readout Readout can be automated Factory waterproofing Suitable for monitoring dynamic strains but only up to about 25 Hz	Low electrical output Lead wire effects Errors owing to moisture, temperature, and electrical connections are possible Need for lightning protection should be evaluated	4–20 in. (100–500 mm)	3000	1.5–6	±20–75 (±2% full scale)
Mustran cell (Figure 13.31)	Robust Modulus matched Remote readout Readout can be automated	Large size Not available commercially Low electrical output Lead wire effects Errors owing to moisture, temperature, and electrical connections are possible Need for lightning protection should be evaluated	6–10 in. (150–250 mm)	1000	1–4	±10–50
Plastic encased gage (e.g., Figure 13.32)	Low cost Robust Easy to install No conformance problem Remote readout Readout can be automated Suitable for monitoring dynamic strains	Unstable in long term Low electrical output Lead wire effects Errors owing to moisture, temperature, and electrical connections are possible Need for lightning protection should be evaluated	0.5–10 in. (13–250 mm)	20,000	1–4	±10–50
Eaton Corporation gage (Figure 13.33)	No conformance problem Remote readout Readout can be automated Factory waterproofing Suitable for monitoring dynamic strains	Must be cast in a briquette before installation Low electrical output Lead wire effects Errors owing to moisture, temperature, and electrical connections are possible Need for lightning protection should be evaluated	2–6 in. (50–150 mm)	20,000	1–4	±10–50

Table 1.3 Comparison between different types of surface strain gauges. [5]

Gage Type	Advantages	Limitations	Typical Gage Length	Typical Range (microstrain)	Sensitivity (microstrain)	Approximate Accuracy (microstrain)
Portable dial indicator (e.g., Figure 13.16)	Simple Inexpensive Waterproofing not required Calibration can be checked at any time No delicate parts attached to structure	Requires access to structure Requires extreme care to read	2–80 in. (50–2000 mm)	Up to 50,000	3–50	± 5–200
Scratch (e.g., Figure 13.18)	Inexpensive Self-recording Waterproofing not required	Requires access to structure Requires skill to read Strains must be dynamic and large	3–48 in. (75–1200 mm)	Up to 6000	30–300	±25–200
Multiple telltales	Simple Inexpensive	Requires access to telltales (but can be converted to remote reading device)	Unlimited	Unlimited	Depends on application	±25–400
Vibrating wire (e.g., Figure 13.20)	Remote readout Lead wire effects minimal Readout can be automated Factory waterproofing Arc welded or bolted version is reusable	Limited range Cannot be used to measure high-frequency dynamic strains Special manufacturing techniques required to minimize zero drift Need for lightning protection should be evaluated	2–14 in. (50–350 mm)	3000	0.2–2	±5–50
Electrical resistance (weldable and bonded foil) (e.g., Figures 13.22, 13.23, 13.24)	Remote readout Readout can be automated Suitable for monitoring dynamic strains	Low electrical output Lead wire effects Errors owing to moisture, temperature, and electrical connections are possible Installation of bonded gages requires great skill and experience Need for lightning protection should be evaluated	0.01–6 in. (0.25–150 mm)	20,000	1–4	±1–100

1.2.3 Pressure Cells

There are different types of pressure cells, the type used most frequently is called the total pressure cell.

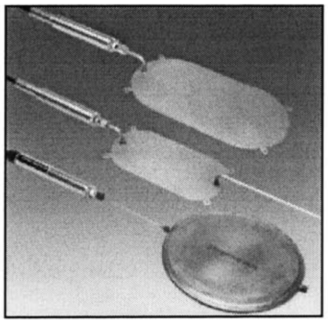


Figure 1.17 Pressure Cells. [23]

"The total pressure cell measures the combined pressure of effective stress and pore water pressure. The total pressure cell consists of circular plates of stainless steel. The edges of the plates are welded together to form a sealed cavity, which is filled with fluid. Then a pressure transducer is attached to the cell.

The cell is installed with its sensitive surface in direct contact with the soil. The total pressure acting on that surface is transmitted to the fluid inside the cell and measured by the pressure transducer.

Total pressure cells are embedded in fill or mounted on structures. In fill, cells are often installed in arrays. Each cell is placed on a different orientation and covered with hand-compacted fill. On structures, the cell is typically placed into a recess so that its sensitive side is flush with the surface of the structure." [23]

1.2.4 Load Cells

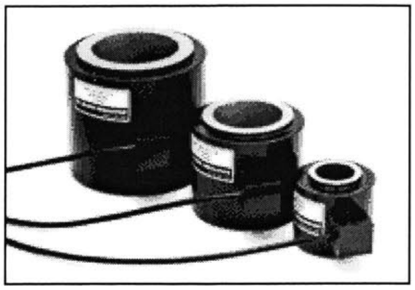


Figure 1.18 Load cells. [23]

"Load cells are designed to measure loads in tiebacks, rock bolts, and cables.

At least four strain gauge rosettes are bonded to the spool. Each rosette consists of two strain gauges, one oriented to measure axial strain and the other oriented to measure tangential strain. The rosettes are spaced evenly around the periphery of the spool and are wired together to provide a single output.

For best results, the load cell is centered on the bar and bearing plates are placed above and below the cell. Bearing plates must be able to distribute the load without bending or yielding." [23]

There are several kinds of load cells, they vary according to the types of transducers they use. There are also mechanical load cells. Some of the load cells available are:

1.2.4.1 Mechanical Load Cells

“Mechanical load cells usually contain either a torsion lever system or an elastic cup spring that is deformed during load application. Deformation is sensed by a dial indicator and calibrated to load.” [5]

1.2.4.2 Hydraulic Load Cells

“Hydraulic load cells consist of a flat liquid-filled chamber connected to a pressure transducer. A central hole can permit use with tiebacks or rock-bolts. The pressure transducer can be a bourdon tube pressure gauge, requiring visual access to the cell for reading, or an electrical or pneumatic pressure transducer can be used to allow remote reading.” [5]

1.2.4.3 Electrical Resistance Load Cells

This type of load cells use the electrical resistance strain gauges discussed in section1.2.2.1. The principle behind it is the same as described above regarding load cells in general.

1.2.4.4 Vibrating Wire Load Cells

This type of load cell uses vibrating wire strain gauges previously described in section 1.2.2.2

Table 1.4 Comparison between different types of load cells. [5]

Type of Load Cell	Advantages	Limitations	Approximate Accuracy
Mechanical (e.g., Figure 13.1)	Robust and reliable	Requires access to cell	±2–10%[a]
Telltale (Figure 13.19)	Simple Inexpensive Calibrated in place	Requires access to telltale (but can be converted to remote reading device)	±2–10%
Hydraulic (Figure 13.2)	Low profile Remote readout is possible	Requires large-area rigid bearing plates	±2–10%[a]
Electrical resistance (Figure 13.4)	Remote readout Readout can be automated	Low electrical output Lead wire effects Errors owing to moisture and electrical connections are possible Need for lightning protection should be evaluated	±2–5%[a]
Vibrating wire (e.g., Figure 13.6)	Remote readout Lead wire effects minimal Readout can be automated Single-gage versions available for in-line use in tension	Special manufacturing techniques required to minimize zero drift Need for lightning protection should be evaluated	Single-gage versions for in-line use in tension, better than ±2% Multigage versions for general use, ±2–5%[a]
Photoelastic (Figure 13.8)	Robust and reliable	Requires access to cell Limited capacity Requires skill to read Most users prefer more direct numerical reading	±2–5%
Calibrated hydraulic jack (e.g., Figure 13.10)	Readily available	Low accuracy Error usually on unsafe side for load testing Should not be used alone for load measurement	±10–25%
Cable tension meter (e.g., Figures 13.12, 13.13, 13.14)	Removable versions available for use without need to unload cable; one meter can be used on many cables	Removable versions require calibration for each cable type and size	±2–5%

1.2.5 Inclinometers

There are many kinds of inclinometers, one of the newest models is the "EI Vertical In-Place Inclinometer" by Slope Indicator.

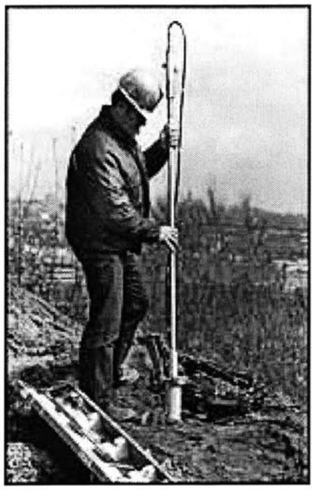


Figure 1.19 Inclinometer installation. [23]

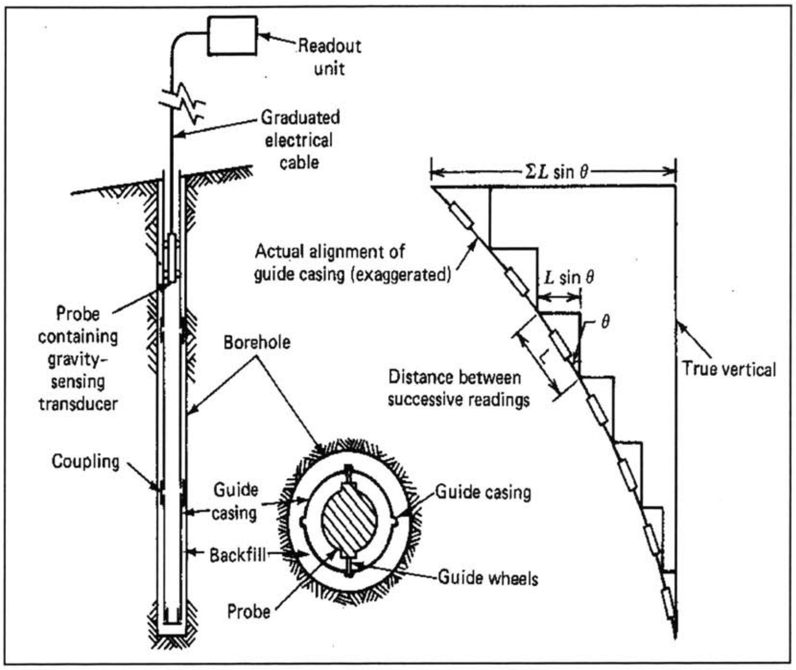


Figure 1.20 Inclinometer working principle. [5]

The inclinometer system consists of a casing and a string of electrolytic inclinometer sensors. The casing is installed in a vertical borehole. The sensors, each connected to the other by a pivot point are placed inside the casing. Ground movement provokes a displacement in the casing which in turn tilts the sensors inside of it. Lateral movement is obtained by multiplying the sine of the tilt angle obtained from the sensors with the gauge length of the sensors. The total displacement can be calculated by subtracting the initial readings from the displaced values.

1.2.6 Crackmeters

Crackmeters use the same principle as the strain gauges in that they determine the change in length in a member. Crackmeters can be mechanical or use the same vibrating wire or electrical resistance transducers from sections1.2.2.1 and 1.2.2.2.

The arm of the crackmeter must extend over the crack and be secured at both ends to the structural member.

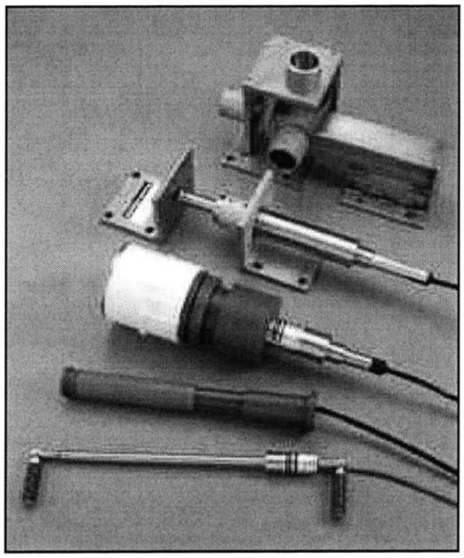


Figure 1.21 Crakmeters and jointmeters. [23]

1.3 Price List

Prices (not including cost of installation) for a few of the instruments mentioned in this chapter are as follows:

Inclinometers:	Reading data logger $9,000-$10,000 Case 62/10ft
Piezometers:	$350 each ${}^{C/}$62 cents/ ft of cable $1200 handheld readout
Total pressure cells:	$680
Strain gauges:	$40 each $70 per pick up sensor $1200 handheld readout
Tiltmeters:	$400-$800
Data loggers (with phone, radio, satellite connections):	1 channel-$500 16 inputs-$8000

*Prices provided by Rudy Saavedra, sales representative from Slope Indicator. [22]

1.4 Case Studies of Monitoring Implementation

The implementations of full scale monitoring systems for two substantial projects are studied. One is the monitoring system used to quantify the movement of the Mansion House in London due to tunneling in 1989, the other is the multifaceted and extensive instrumentation systems used in Boston's own Big Dig, the biggest and most complex civil engineering project in U.S. history.

1.4.1 The Big Dig

The "Big Dig", the most ambitious civil engineering project in American history is also the project that has used the largest number and variety of monitoring instruments. The information to follow comes from Dr. Allen Marr, president of Geotest and Geocomp, one of the companies awarded the monitoring contract at the Big Dig, and Lewis Edgers, et al, who are also engineers involved in the project.

"The $10.8 billion project consists of 161 lane miles of urban highway – about half underground in a 7.5-mile corridor – through the heart of one of America's oldest and most historic cities. The heart of the project is replacement of Boston's aging, elevated Central Artery (I-93) with a modern eight-to-ten lane underground expressway. The project will also extend the Massachusetts Turnpike (I-90) to Logan Airport, build a dramatic 10-lane cable-stayed bridge across the Charles River, create a state-of-the-art incident response and traffic management system, construct five major highway interchanges and have the largest vehicular tunnel ventilation system in the world. The CA/T is unprecedented since all construction is taking place in the middle of downtown Boston which must remain open and accessible for business, residents, and tourists." [16]

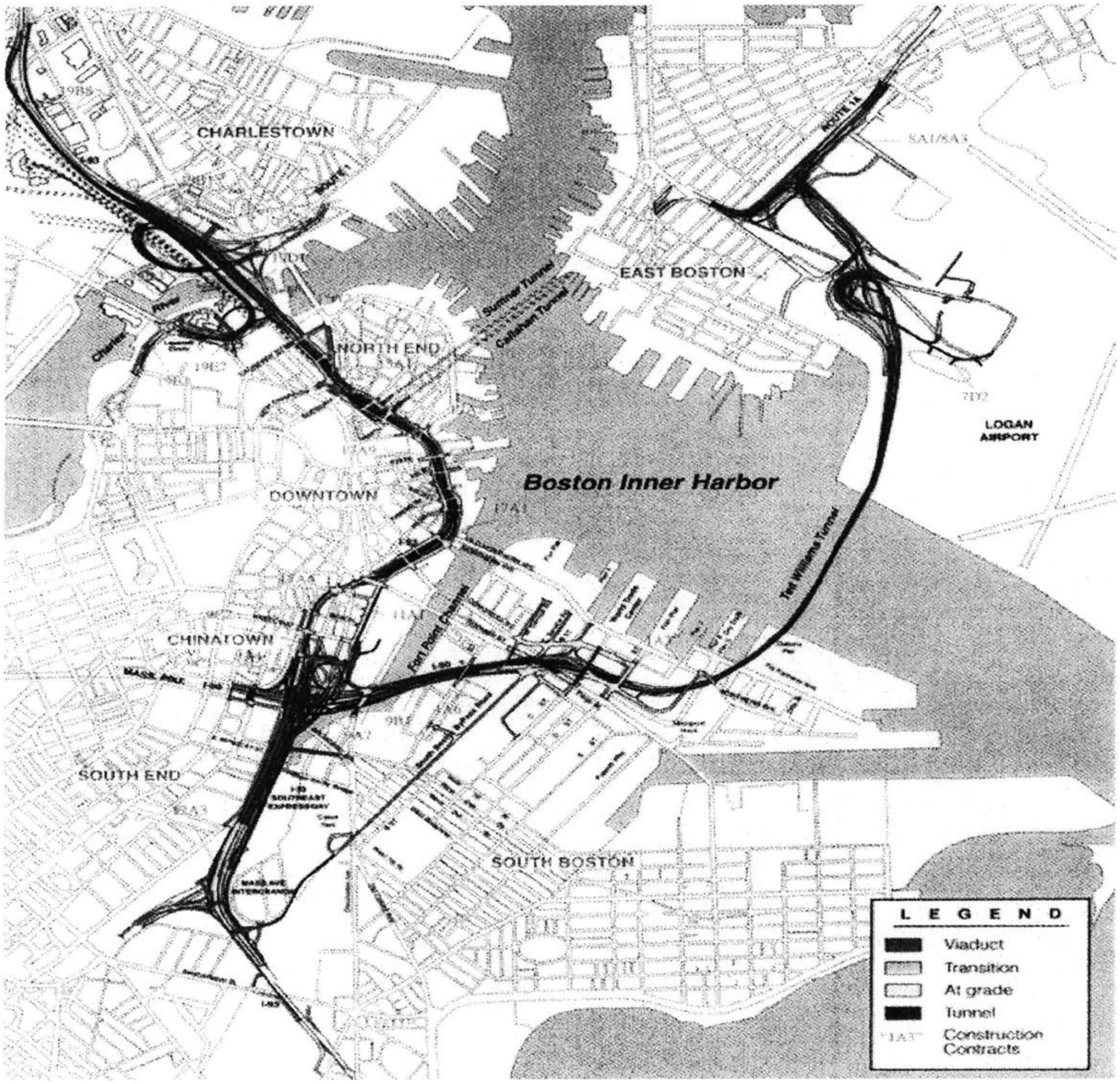


Figure 1.22 Central Artery Project Layout. [16]

This complex construction requires a complex and extensive monitoring system. There are limits on deflection and vibration movements for the buildings around the area that require constant supervision. The role of the instrumentation is to not only help maintain construction within these limits, thus minimizing liability, but also to keep track of the contractor's means and methods, thus helping establish the party who is liable.

"The purposes of the instrumentation program (Bechtel/Parsons Brinkerhoff, 1991) are to provide data to help the project team to:

- Prevent or minimize damage to structures by providing data to determine the source of ground deformations
- Develop protective and preventive measures to structures
- Select appropriate remedial measures where required
- Evaluate critical design assumptions where significant uncertainty exists
- Determine the adequacy of the contractor's methods, procedures and equipment
- Monitor the effectiveness of protective, remedial, and mitigative measures
- Provide feedback to the contractor on his performance

- Assess the contractor's performance, assess contractor-initiated design changes, change orders, changed conditions, and disputes
- Provide documentation for assessing damages sustained to adjacent structures allegedly resulting from ground deformations and other construction related activities
- Advance the state-of-the-art by providing performance data to improve future designs" [16]

1.4.1.1 Instrumentation Threshold Values

"The project involves more than 140 separate design and construction contracts. To obtain consistency in instrumentation and data across the entire project, the Management Consultant (MG) defined a set of objectives for all instrumentation, developed a project wide instrumentation specification, and defined a method to collect and process data from the instrumentation.

Bechtel Parsons Brinkerhoff establish the idea of using threshold and limiting response values for each instrument. Readings below the threshold value indicate no potential for damage to adjacent structures. Readings that exceed it indicate uncertainty exists regarding potential damage. The contractor is alerted and all parties involved increase their level of vigilance for execution of the work.” [16]

Table 1.5 CA/T Allowed Instrumentation Thresholds. [16]

Instrument Type	Threshold Value	Limiting Value
Piezometers outside excavation in fill	1 ft decrease below HL during utility excavation	2 ft decrease below HL during utility excavation
Piezometers outside excavation in clay	20 ft within 100 ft of building 6 ft more than 100 ft from building	Not specified
Piezometers inside excavation in bedrock	Not specified	5 ft below that required to maintain FS for uplift > 1.1
Piezometers outside excavation in till and rock	20 ft decrease	40 ft decrease
Inclinometers in slurry wall and soil	0.001*D for north and south walls 0.0015*D for east and west walls	0.002*D for north and south walls 0.0025*D for east and west walls
Probe extensometers	1 inch settlement of any point	2.5 inches settlement of any point
Deformation monitoring points-Type 1	1 inch of settlement	2.5 inches of settlement
Deformation monitoring points-Type 2	Angular distortion of 1/1,200	Angular distortion of 1/1,000
Deformation points on manholes	Vertical: 1/4 inch	Vertical: 3/4 inch
Strain gages on struts	100 percent of allowable stress	125 percent of allowable stress
Seismographs	For historic structures: PPV□0.2 ips For non-historic structures:PPV□0.3 ips	For historic structures: PPV□0.3 ips For non-historic structures:PPV□0.5 ips
D=depth of excavation; HL= historic low water level; PPV=maximum peak particle velocity; ips=inches per sec; 1 ft=0.3 m; 1 inch=25.4 mm		

1.4.1.2 The Contract

“The Management Consultant (MC) established an internal geotechnical instrumentation group (GIG) to develop the reading schedule for each instrument and to examine the data coming from the instrumentation. Each contractor would be provided with the data associated with its contract and be responsible for interpreting that data to control his work.

This approach would allow all parties to have immediate access to consistent, checked performance data and reduce the potential for arguments caused by conflicting and incomplete data sets. The contractors were given the right to collect their own readings from instruments on their contracts anytime. They could also install any additional instrumentation they required for specific needs.” [16]

“The MC and the owner decided to award a single contract to monitor all geotechnical instrumentation, excluding those read by survey, for a six year period.

During the planning and design phases of the project, the MC developed a database system to receive, store, retrieve and plot data from all geotechnical instruments using the project's Oracle based Geographic Information System (GIS). The geotechnical instrumentation contractor (GIC) and the surveying contractor would place data into this system. Then the project staff could retrieve the specific data they needed in graphical and tabular form on their computer screen or as a printout. The GIS system included provisions to plot groups of instruments over time and produce contours of data in plan and cross section. The goal was to provide the ability to view all instrumentation data at any location on the project immediately." [16]

Table 1.6 Responsibilities for Instrumentation Activities. [16]

Management Consultant - (MC)
- -manage GIC contract
- -coordinate requests for readings
- -provide weekly and daily reading requests to GIC
- -maintain GIS database of instrumentation data and locations
- -receive and distribute GIC reports
- -evaluate and interpret data from instrumentation
- -respond to complaints about performance

Geotechnical Instrumentation Contractor - (GIC)
- -maintain and calibrate readout equipment
- -read instrumentation as requested
- -check and validate data
- -place data into GIS database
- -produce daily printed and electronic reports for previous 24 hrs of readings
- -produce weekly summary reports
- -notify specified party when instrument exceeds Response Value
- -maintain Ready Action Team to respond to emergency requests

Construction Contractors - (CC)
- -procure and install instrumentation
- -procure readout equipment
- -maintain instrumentation and replace if necessary
- -evaluate readings taken by GIC to control safety of work
- -take additional readings if required for safety of work

Section Designers -(SD)
- -specify locations for instrumentation
- -specify Threshold and Limiting Response Values
- -evaluate instrumentation data when Response Values are exceeded

“Procurement and installation of the geotechnical instrumentation were made a part of the construction contracts. The contractor on each section must install and maintain the instrumentation in working order. Contractors also Procure the Readout equipment required for reading the instrumentation. He must collect three sets of initial readings that show stable, reproducible data. At that point the readout equipment and responsibility for taking readings are transferred to the GIC. Any in place instrument that becomes damaged or inoperable must be repaired or replaced by the contractor. The readout equipment is maintained and repaired by the GIC.” [16]

“The instrumentation contract was developed as a unit price contract, i.e., the contractor would be paid a set price for each successful reading on each type of instrument. The use of unit prices is attractive to the owner because it provides a way to control costs compared with the traditional time and materials contract.

The contract requires all data collected in a given day to be processed, checked, and entered into the GIS system by 8:00 a.m. of the following day. Three printed copies of a summary report are also required by the same time. These copies were intended for the MC, the resident engineer, and the contractor. The printed reports contain a summary and time history plots of all instruments that exceeded the thresholds established. The contract contains penalty clauses for submitting incorrect data and for late reports. It also provides for a ready action team to be on call always. This team must be capable of reading and reporting data for any instrument on the project within two hours of receiving notice.

Soon after the start of work, complaints began to flow about vibrations from building residents and owners. Work procedures were modified to allow pick up and report of data from all seismographs by 1:00 p.m. of the same day, to respond to any complaint about vibrations.

In April 1997, the joint venture of Geocomp and TLB Associates, referred to as GCB, was awarded the geotechnical instrumentation contract" [16]

1.4.1.3 Instrumentation Readings

"A networked PC system was placed in the GCB's project office. A database system was built to handle the checking and transferring of data. It was expanded to process reading requests, prepare work orders, download information into the portable data readouts (PDR), and upload data from the PDRs into a temporary database.

The PDR is connected to the readout device and the reading is placed into the PDR electronically. Data can also be keyed in by use of the PDRs keypad.

To determine data validity, the reading history of each instrument was used to establish a reading range of valid data. These are the guidelines used to establish this data range:

- Plus/minus two standard deviations from the mean value, using the most recent eight readings to compute mean and standard deviation
- Maximum and minimum values of the most recent eight readings
- Predetermined anticipated value plus-minus an acceptable error. This is used for instruments with very small reading fluctuations, such as crack gauges and tape extensometers
- A range determined by the specific conditions for the instrument

If the readings fall outside of the accepted range, the PDR instructs the technician to check the readout equipment and take the reading again. If the second reading also falls outside the range, the PDR instructs the technician on what action to take, such as contacting the MC, etc." [16]

Table 1.7 Predicted instrumentation readings. [16]

Instrument	Expected Total Number
Observation Wells	787
Piezometers	1,181
Crack Gauges	145
Convergence Gages	65
Mechanical Strain Gauges	102
Vibrating Wire Strain Gauges by Data Logger	5,865
Inclinometers	501
In-place Slope Inclinometers	31
Multiple Point Heave Gauges	129
Single Point Extensometer	59
Multiple Point Extensometers	21
Probe Extensometers	405
In-Place Tiltmeters	343
Dial Gauges	2
Shear Displacement Gauges	10
Load Cells	170
TOTAL	9,816

Table 1.8 Instrumentation readings as of 2000. [16]

Instrument Type	Number Presently Read	Readings to Date	Projected Total Readings for Contract
Seismographs	32	19,000,000	41,000,000
Inclinometers	842	6,000,000	13,000,000
Facade Monitoring Points	122	480,000	950,000
Vibrating Wire Strain Gauges	130	220,000	650,000
Vibrating Wire Piezometers	990	146,000	200,000
Probe Extensometers	226	75,000	166,000
Crack Gauges	1,043	71,000	157,000
Observation Wells	320	20,000	45,000
Convergence Gauges	215	20,000	44,000
Vibrating Wire Load Cells	55	11,000	24,000
Tiltmeters	48	8,500	19,000
Shear Displacement Gages	17	2,000	5,000
Multiple Point Probe Ext.	6	2,700	6,000
Single Point Probe Ext.	17	2,100	5,000
Dial Gauges	4	1,600	3,500
TOTALS	4,067	26,059,900	56,274,500

1.4.1.4 Abutters

There was major concern regarding the possible effects of the deep excavations to the adjacent buildings. An overview of the interaction between the project team and the representatives of two such buildings (the Federal Reserve Bank (FRB) and One Financial Center (OFC)) is presented in this section.

" The management of the FRB and OFC complexes assembled their own teams of consultants to work with the CA/T project management consultant to develop measures to minimize the effects of the excavations under their buildings. The CA/T project management consultant has submitted key information to the FRB and OFC for review, documents such as:

- Draft contract plans and specifications as the bid documents were developed over a number of years
- CA/T project contract addenda
- Contractor submittals such as support of excavation design and value engineering proposals, and
- All relevant instrumentation data

Regular meetings were established between the FRB and OFC consultants and the CA/T project management team, as well as contractor representatives when appropriate. Meetings are schedule every two months or more often if needed. At various times, project representation has included design, instrumentation, construction, and management personnel." [6]

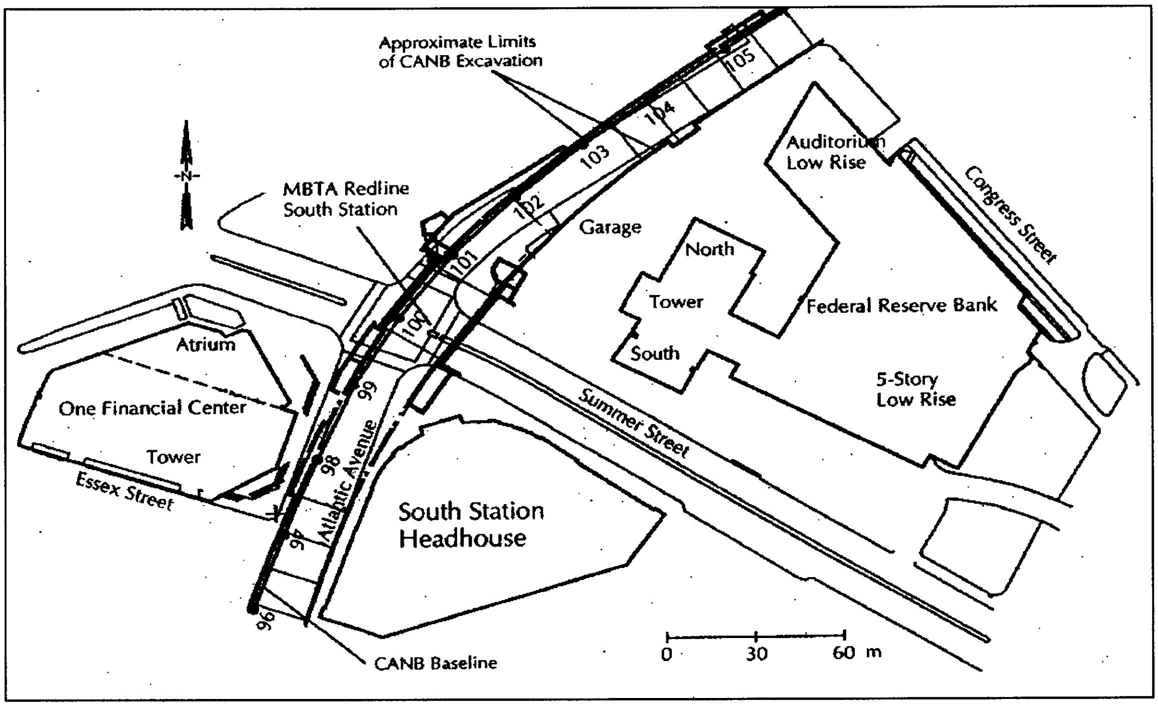


Figure 1.23 Location of One Financial Center and the Federal Reserve Bank. [6]

"These meetings have led to a number of measures including:

- Additional ground movement and structural analyses of the FRB and OFC
- Additions to the CA/T project instrumentation program
- Special contract provisions such as strict limits on the longitudinal extent and time duration of unsupported excavation between bracing levels and

tieback support that maybe implemented if instrument response values are reached

Instruments were installed on the buildings to assess their responses to the excavation. Some of these instruments are:

In the Federal Reserve Bank:

- Deformation monitoring points (DMPs)
- 33 convergence gauge anchorage points (CGAPs) to measure relative horizontal movements
- 3 inclinometers
- 4 seismographs to measure vibrations
- 280 vibrating wire strain gauges (VWSG)

In One Financial Center:

- 7 DMPs
- 6 CGAPs
- 6 shear displacement gauges to measure the relative horizontal movement between the foundation mat and the atrium slab on grade
- 5 single position borehole extensometers to measure settlement of the foundation mat
- 1 dial gauge to measure the relative movement between the beam and column at a critical location in the lower garage
- 21 tiltmeters to measure tilt of the foundation mat
- 72 VWSGs

The dewatering of the area required for excavation lowered the groundwater level causing the buildings to settle but it also reduced the impact of vibrations on the buildings because it made the soil stiffer. [6]

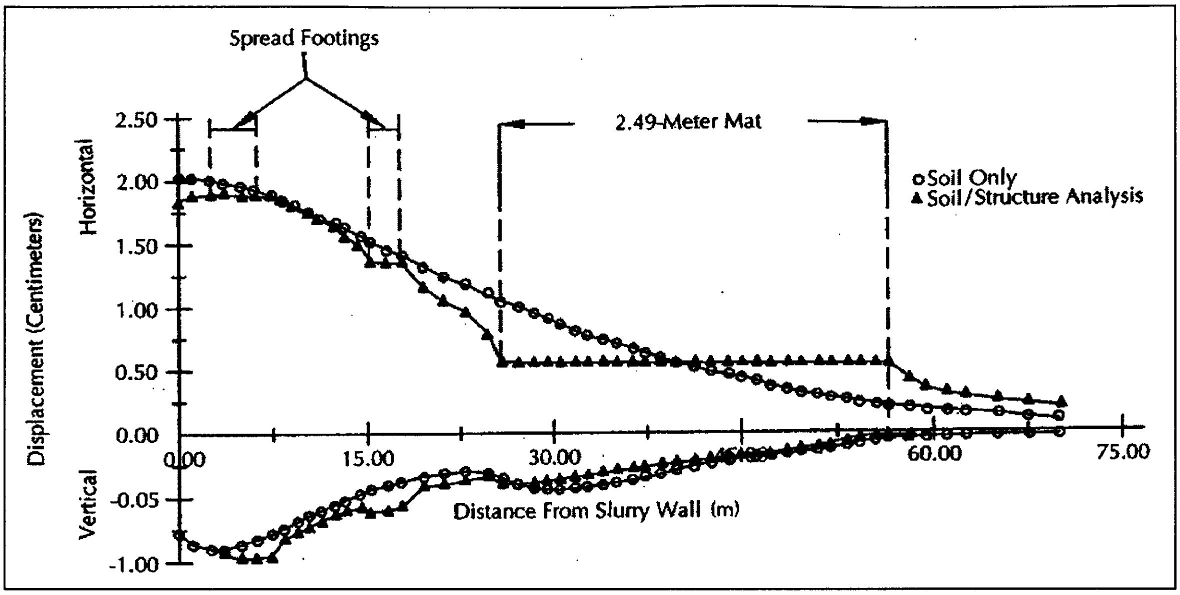


Figure 1.24 Vertical and horizontal displacements of the Federal Reserve Bank. [6]

"In a project of this complexity, size and duration, clear communication between interested parties is essential. Regular working group meetings have been particularly important for establishing procedures for transmitting information, for abutter review of design and construction, and for maintaining continuity of effort. It requires that the abutter and project have appropriate technical expertise, and that they cooperate and communicate early." [6]

1.4.2 The Mansion House Project

The information gathered regarding instrumentation for this project was collected from the articles written by J. Forbes, et al [7] and G. Price, et al [21].

The tunneling work needed for the City extension of the Docklands Light Railway was to take place close to the old Mansion House. Most of the tunneling work for the railway project was located in London Clay, except the portions located through Thames Gravels. After a pedestrian bridge was excavated underneath the Mansion House causing settlements seemingly surpassing the long-term limits, construction was halted and continued only after an extensive monitoring system was installed to aid in determining the stages of construction. The results from the instrumentation system determined the need to relocate the Central Line link passage and controlled the phased construction. [7]

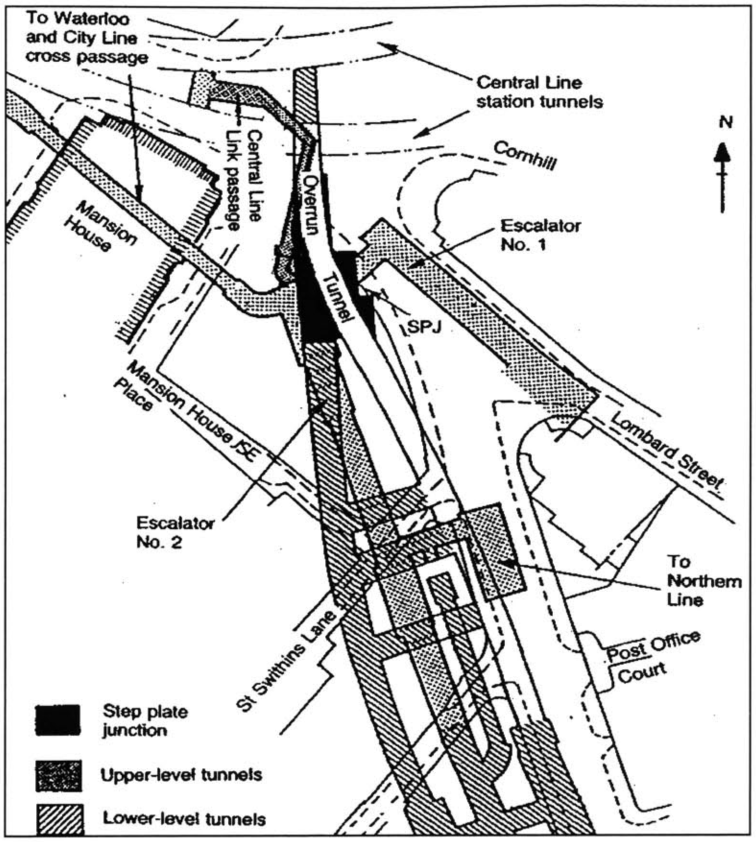


Figure 1.25 Tunneling within the Mansion House area. [7]

A series of monitoring systems were used to measure different areas of concern during tunneling construction, this were:

- **Monitoring of Vertical Movement of Foundations**

Two different systems were adopted simultaneously to monitor differential settlement in the foundations by recording the angle of distortion between each load-bearing unit. One was an electro-level beam system and the other a water-leveling system.

Electro-Level Beam System (EL)

“The principle of the EL beam system is that relative vertical movements of two reference points supporting the beams can be determined from the beam length and the change in angle monitored by the EL.” [21]

“The primary system consisted of 55 EL units arranged in four strings along the basement walls. The ELs, mounted on beams, monitored slope changes between adjacent reference pins” [7]. “The advantage of a continuous beam system is that it detects local shear movements that might be missed using tilt monitoring at discrete points.” [21]

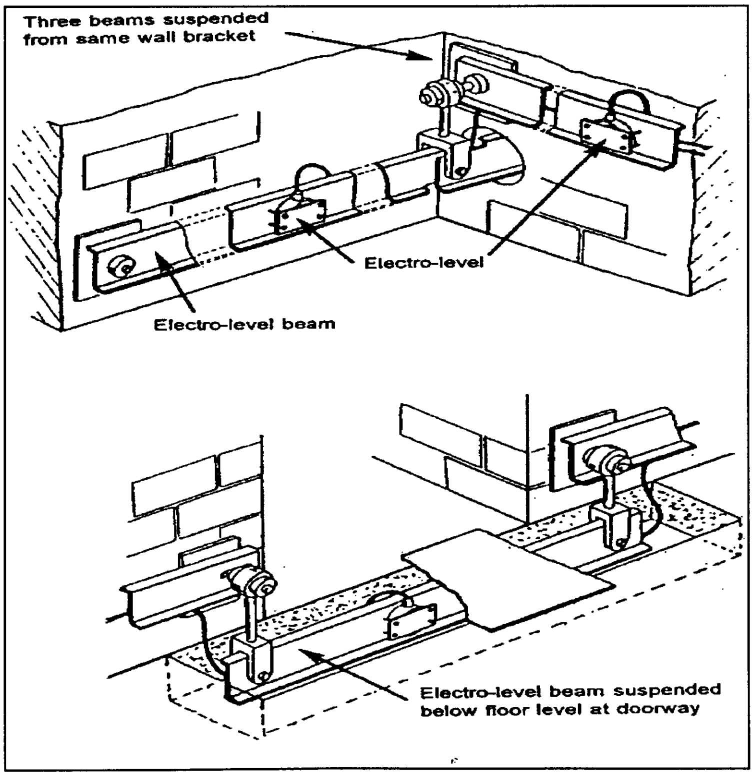


Figure 1.26 Typical electro-level beam configurations in Mansion House basement. [21]

"Data were to be assessed on a daily basis and immediate action was to be taken if agreed angular distortion values of 1 in 2000 (alert level) and 1 in 1000 (action level) were exceeded. All ELs were connected to a computer logging system, which was set to read at one-hour intervals. The tilt angle was derived through calibration constants and recorded together with date, time and ambient temperature data. This allowed immediate inspection of readings followed by notification of all groups concerned, should any critical situation develop." [7]

Water-Leveling System

"The water-leveling system comprised an array of 13 precision water-level gauges (WLGs). WG1 was a datum gauge located in the southwest corner, this part being expected to be least affected by the construction of the Docklands Light Railway overrun tunnel. Vertical movements at the location of each gauge caused a change in gauge water levels relative to that in the datum gauge." [21]

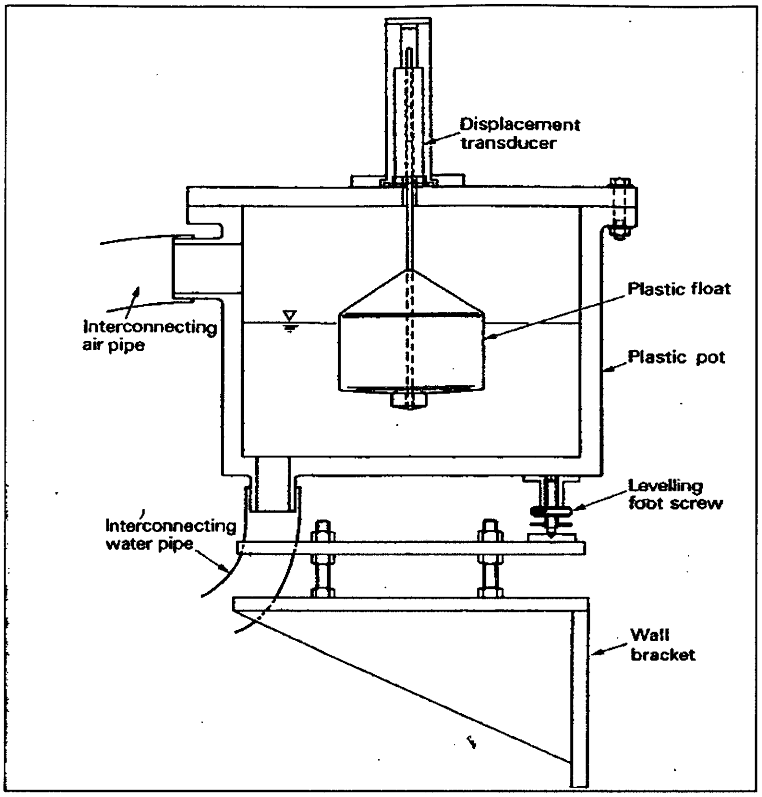


Figure 1.27 Water leveling system installed in the Mansion House. [21]

"To obtain differential building movements, the zero reading of each sensor was subtracted from later readings to give the change of water-level which was compared with the change in water level in the datum gauge." [21]

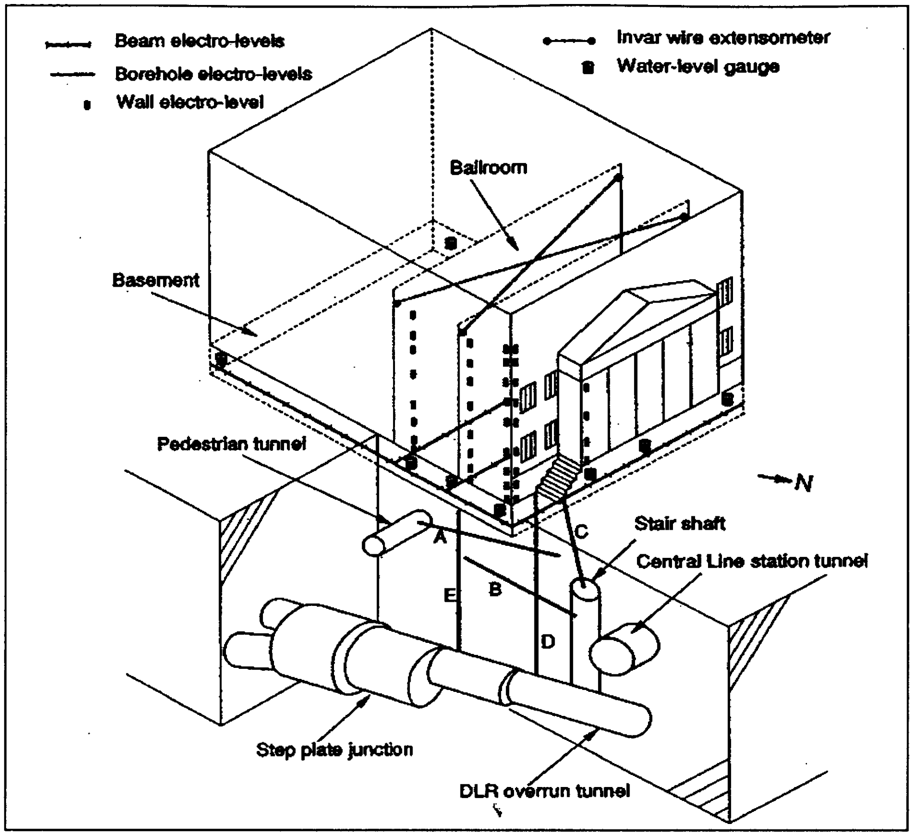


Figure 1.28 Instrumentation systems used at the Mansion House. [21]

Comparison Between the Two Different Instrumentation Systems Used to Determine Settlement

“Both the EL beam and WLG systems required expert installation for optimum performance, with hole having to be cut through walls and channels in floors. Greater maintenance was, however, required on the water level gauge system, with three monthly inspections being needed to check for water loss, condensation in air pipes and mould growth in float chambers.” [21]

"The WLG system provided a direct measurement of vertical movement of any monitoring gauge relative to the datum gauge, while the EL beam system gave an incremental series of vertical movements along a run (or train) of beams." [21]

"The two systems were used to check independently the settlement of the building at locations where the two systems had coincident monitoring points. The accuracy and reliability of the two systems were comparable." [21]

- **Crack Width Monitoring**

Performed first manually, monitoring cracks was undertaken with the aid of linear variable differential transformer transducers. The data was read with data loggers, which were calibrated for temperature, and humidity, which were monitored through integrated circuit temperature sensors and capacitive humidity probes respectively.

- **Subsurface Movement Monitoring**

"Three horizontal lines of Els were installed in the ground as to provide correlation with the vertical displacements recorded by the global precise leveling. Two inclinometer lines were also installed to determine the lateral ground displacement with depth. Each vertical and horizontal string was hand-read three time per week during construction and once a week thereafter." [7]

- **Monitoring of Aboveground Structure**

"Three types of instruments were installed to monitor the behavior of the Mansion House superstructure during construction of the railway tunnel: tilt gauges mounted on the external walls to monitor out-of-plane wall movements; invar wire gauges to monitor shaking of the ballroom; and load cells to monitor changes of load in the pre-tensioned tie bars." [21]

- **Data Acquisition Systems**

Two data acquisition systems were used in this project: a computer based system and a Data-logger-based system.

Computer Based Modular Data Acquisition System

"The El beam system, discrete wall Els, vibrating wire load cells and vertical borehole Els and temperature sensors were all connected to a specially designed modular data acquisition system. This system allows any number of any types of commonly used monitoring instruments to be logged by a controller unit. Its functions were to check the time continuously and at predetermined times to log the data and store to disk (normally once an hour) and to send the new data consultant's office once a day. When it was time to read a set of data, the control program ran a series of programs to log the different sets of instruments. Four logging programs were used, one for the Els beams, one for the Els on the walls, one for the vibrating wire gauges and one for the vertical borehole Els." [21]

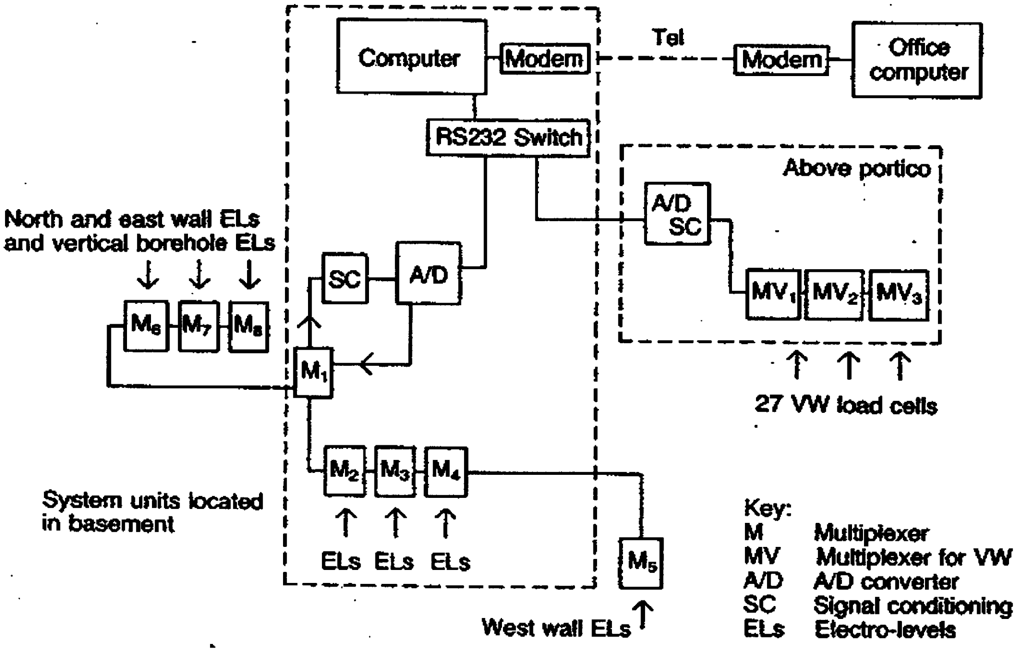


Figure 1.29 Layout of computer-based modular data acquisition system. [21]

Data-Logger-Based Acquisition System

This computerized data logger system was installed primarily to run the water-leveling system, but it was also used to retrieve data from the invar wire gauges and some temperature-sensing thermocouples. The data logger system processed the information retrieved from the instruments, calibrated the information and compared it to the initial data recorded by the instruments in order to calculate building movements.

It is important to mention that although the Electro-Level Beam system was installed to monitor the structural behavior of the Mansion House during tunnel construction, it was kept after construction to assess the movements of the building during renovation and was later modified to serve as a long-term monitoring system to keep track of foundation movements.

1.4 Cost Efficiency of Monitoring

Probable risks must be given a dollar value in order to compare them to the cost of monitoring as a possible preventive measure.

Dr. Allen Marr established a quick and simple approximate way of assessing risk and assigning it a cost value that can be used to determine if the cost of instrumentation is justified. He presents three tables to demonstrate this simple technique with a geotechnical example regarding a new highway embankment to be constructed on soft soil and next to a high-speed railway.

First a table relating common adjectives to probability values is created:

Table 1.9 Risk probability values. [15]

Likelihood	Probability of Occurrence	Risk Probability
Zero, none, impossible	<0.0001	0.01%
Virtually impossible	0.00011 to 0.01	1%
Very unlikely, improbable, barely possible	0.011 to 0.1	10%
Moderate, considerable, somewhat unlikely	0.11 to 0.5	50%
Likely, probable	0.51 to 0.9	90%
Highly likely, very probable	>0.9	100%

Next, the total costs of possible adverse outcomes is determined:

Table 1.10 Example of total outcome cost. [15]

Undesirable Outcome	Likelihood	Consequence
Foundation Failure	Unlikely	$2,000,000 to fix and 6 month delay
Excessive settlement of highway	Moderate	$300,000 to fix
Excessive movement of railway	Very Likely	Trains shut down if movement is unexpected

Finally, a weighted cost table of the probable undesirable outcomes is put together:

Table 1.11 Example of potential risk cost. [15]

Outcome	Consequence	Probability	Risk Cost
Foundation failure	$2,000,000 fix plus $5,000,000 delay	0.1	$700,000
Excessive settlement of highway	$300,000 to fix	0.5	$150,000
Excessive movement of railway	$300,000 labor	0.9	$2,700,000

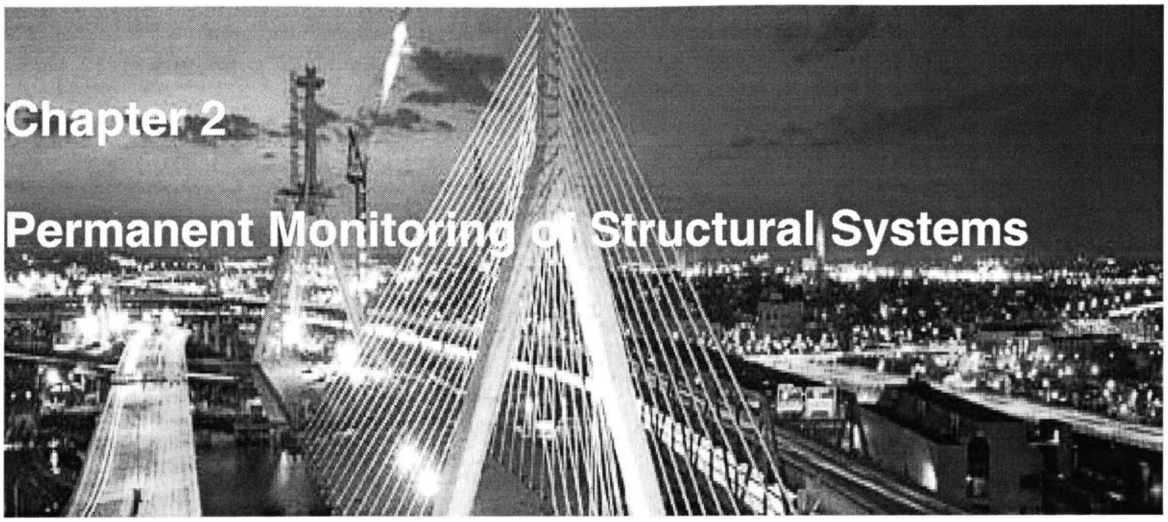
In Dr Marr's example it is easy to see that the railway poses the biggest threat, and thus it seems justifiable that the embankment should be monitored to avoid the need of a standby crew on the railway. The instruments would warn of any potential soil movements, giving enough time to schedule night or weekend maintenance of the railway, therefore avoiding the need of shutting down the trains.

This approach to cost/benefit analysis can be easily adapted to any civil engineering application and more sophisticated techniques can be implemented to or performed instead of this simple decision making tool. Whenever the weighted cost of the risk exceeds the total cost of instrumentation, monitoring should be considered.

1.5 Conclusions

Structural and geotechnical monitoring is already a permanent element of large urban construction. Instrumentation technology has been improved over the years making monitoring devices not only more reliable but also more cost effective. The presence of electronic data loggers has revolutionized the monitoring industry, allowing several sensors to connect to it and providing remote data transmition. Monitoring has also helped improve the critical relationship amongst project members (design engineers and contractors) and between project teams and abutters. Instrumentation has proven to facilitate construction, help in construction phasing, assist in contingency planning, assess structural health and behavior, check on construction methods, and help maintain construction parameters.

Even though monitoring systems add yet another cost to already large construction budget, they should be seriously considered if the risk costs are larger than the cost of instrumentation, especially considering the savings there could be by avoiding possible litigation procedures.



Chapter 2

Permanent Monitoring of Structural Systems

2.1 Why Monitor Structural Systems on a Permanent Basis

Up to date, there are several ways in which to examine the health of structures, either periodically or when something is obviously, that is, plain to see with the naked eye, wrong. So far, there is no standard practice to help engineers and inspectors monitor the health of a structure on a permanent basis or give them an inside view of the true condition of a building or bridge. Permanent monitoring can also help verify design assumptions regarding long-term structural behavior and determine if there is a need for renovation.

Recent advances in technology may just aid the professionals in the civil engineering field make more informed decisions and assessments of the health of new and existing structures.

2.2 Continuous Monitoring

One possible way of monitoring a structure on a permanent basis is to continuously gather data and update the system's database on a regular basis. Continuous data gathering means a compilation of complete and comprehensive information gathered regarding the structure at any and all points in time. It also means an enormous amount of information collected that must be sorted through. A decision-making system must be implemented in order to determine where to send the data after it is sorted, whether it must be stored or disregarded. It also means increased cost and a greater possibility of false alarms.

2.3 Periodic Monitoring

Once a permanent system is installed, it can be kept in sleep mode only to be woken by a central or a portable data collection unit during inspection time. Although this mode of data collection would not provide constant structural information, it would significantly aid in the health diagnosis of the structure whenever it undergoes inspection. It would provide a better understanding on the internal conditions of the members without having to process the exorbitant amount data common to continuous monitoring. And because the sensors in the system do not need to work constantly, the need for power will be minimal and the sensors' batteries will last longer.

2.4 Available Technology and Technology Under Research

There are several features that can be effectively incorporated into new or existing structures to measure the forces acting on them or the strains and stresses they endure. Most of these technologies are expensive and require expert installation. An evaluation of the costs versus the benefits for using or not using a certain technology must by performed in order to decide whether the use of these technological advances is cost effective for a particular project.

2.4.1 Smart Pins

Also known as load pins, smart pins use strain gauge technology located inside them to measure the change in strain in structural connections and use this information to calculate the load the connections are bearing.

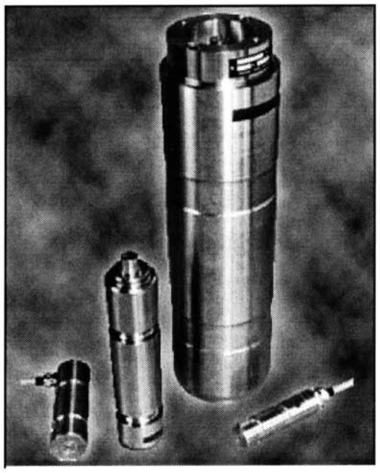


Figure 2.1 Smart Pins. [14]

2.4.2 Load Cells

Load cells are commonly used during the installation of tiebacks, but they are strong instruments designed to last for several years and can be used for long-term performance monitoring. As the smart pins, load cells also determine the magnitude of the load applied on a member with the aid of strain sensors located around the load cell's center hole. These strain sensors measure axial and transverse strain.

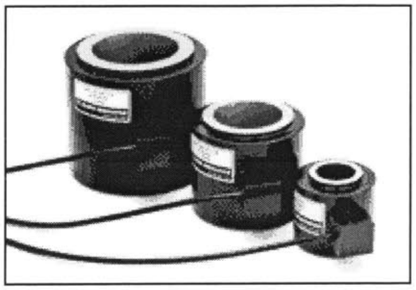


Figure 2.2 Load cells. [23]

2.4.3 Smart bearings

Smart bearings being researched are for use mainly in bridges; they can sense the distribution of loads through strain gauges that are embedded into a panel located between the bearing pads, they operate under the principle that a change in structural stiffness changes the overall distribution of loads. The multi-axial strain gauges enables the bearing to sense vertical as well as shear strains. The reactions at the supports can then be calculated and compared to the design reactions. The structure can then be tested under controlled loading conditions. If a support were carrying a greater percentage of the load than it is supposed to, then it would be evident that the structure is not sound anymore and that further investigation is necessary. [3]

2.4.4 Acoustic Emission Sensors

Though they have not been used as long-term structural health monitoring devices, yet; the FHWA's Nondestructive Evaluation Validation Center is testing a prototype that could be installed in bridges to monitor internal cracks in concrete members. Acoustic emission sensors evaluate the slow growth of cracks by detecting the ultrasonic stress waves produced by the release in energy following a crack. The prototype uses a battery pack, making it possible to work in remote locations; it has an eight-channel instrument to reduce noise, and can transmit information via modem or radio. It is yet to be seeing if this experimental prototype will overcome the noise and sensitivity problems of its predecesors. [3]

2.4.5 Laser Technology

Mostly used in bridges, laser technology enables us to determine the exact coordinates of a single point in the structure at a particular time. This is helpful because total deflections can be measured by loading the structure with a pre-determined load and measuring how much it moves. This technology can measure several points in a short amount of time but it requires a clear line of sight, which is not always available in an urban area.

2.4.6 Data Acquisition

A combination of the same instruments used during construction and discussed in Chapter 1 and the instruments mentioned in section 2.4 can be used to permanently assess the health of a structure. These instruments can work as the sensors to detect the variations in strain, load, stress, inclination, deflection, etc, and send this information to an integrated processing unit to which they are wired and which has the capability of processing the information and send it to a remote location in a wireless fashion.

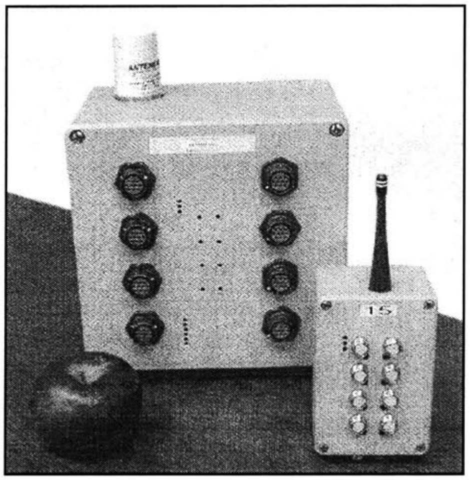


Figure 2.3 Remote data loggers. [8]

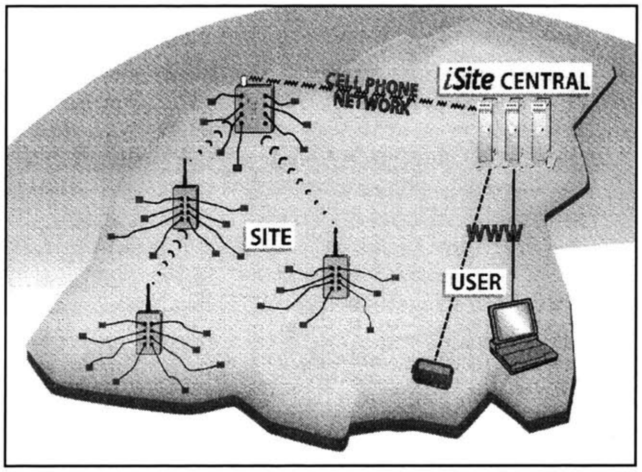


Figure 2.4 *i*Site wireless we-based instrumentation monitoring system. [8]

This type of technology is already in use in the industry. The data loggers are integrated with temperature sensors to calibrate the data as they receive it from the structural sensors and use a radio transceiver to transmit the data received to a central computer. This computer can be connected to the worldwide web, thus making the data retrieved available for downloading at any given moment, allowing the parties involved to stay informed. The system can also trigger an alarm at certain pre-programmed thresholds to warn of an impending problem. If continuous data does not be received, the data loggers can easily be programmed to keep only the highest reading of the day for each instrument.

Lightening is a major concern for outside instruments. Most data loggers are also protected from lightening by the use of lightening conductors attached to their cases. Radio signal duration is also a concern because an FCC broadcast license must be obtained in order to send a continuous signal; this can be avoided by transmitting an intermittent signal to the central data processor.

Geocomp offers a web-based instrumentation monitoring system called *i*Site. It provides all the services stated above. As described in their catalog, the system consists of nodes that receive data from a number of sensors and that transmit the information to a central processing unit via cell phone. The central processing unit in turn transmits the data to the interested parties through the web, a modem, cell phone, an RS232 connection, or a landline. These nodes can send their radio signals up to 200 meters in line-of-site applications. Where their distance exceeds this limit, the nodes outside the appropriate range can be implemented with long range radio transceivers or be hardwired to other nodes that fall within the range. Up to eight sensors of up to four volts each can be connected to each data logger.

The *i*Site alarm system triggers the web server to send a pre-programmed message to a cell phone, e-mail address or pager, indicating the I.D. of the node that triggered the alarm as well as the data collected from that node.

The data loggers run on batteries that need recharging every two weeks, which is not only inconvenient but can also prove costly and requires access to the instruments; they can also be powered by an AC connection or by solar cells.

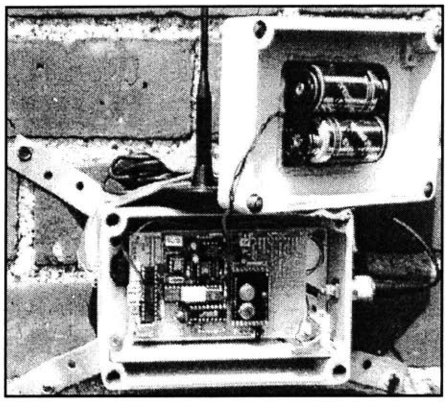


Figure 2.5 Tilt meter data logger. [8]

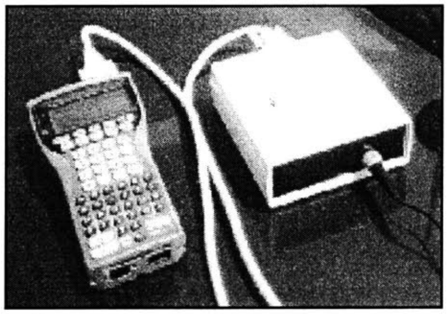


Figure 2.6 Handheld readout unit. [8]

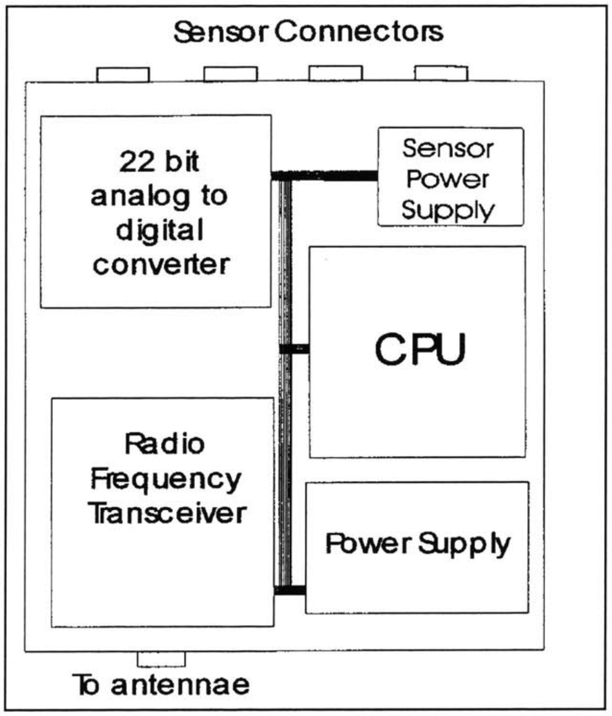


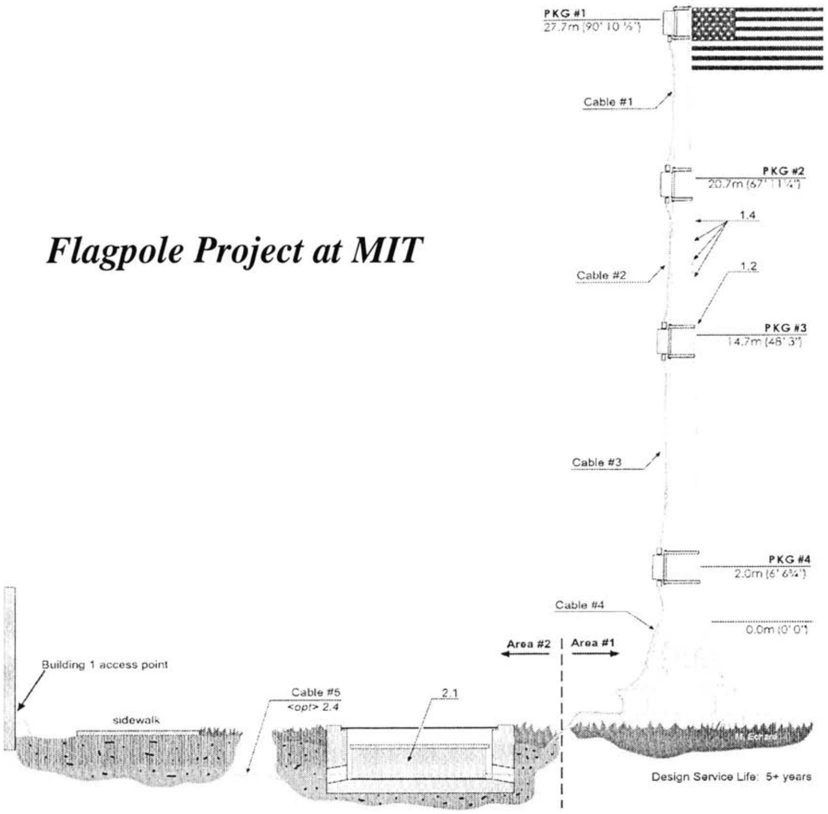
Figure 2.7 Comprehensive tilt meter-data logger layout. [8]

One of the projects in which Geocomp was involved, for which a remote monitoring system was used, consisted of the installation of a tilt meter system, complete with central processor unit, analog to digital converter and radio frequency transceiver, to monitor settlement. This system, unlike the remote system described above, has all its computer and radio components located right inside the data logger, which keeps the data obtained in its memory until it is retrieved by a handheld readout unit. The readout unit sends a request to read a particular cell ID. The sensor cell receives the request, wakes up and powers the sensor, takes the reading and broadcasts it. This non-continuous kind of information gathering saves on energy and is practical for most non-critical applications.

As described in the previous chapter, a vast variety of instruments were and are still used in the Central Artery Project. Due to the long duration and the location of the project, the sensitivity, reliability and longevity of the products offered by the monitoring industry were put to the test. Tiltmeters that proved inefficient when used to monitor One Financial Center, have now been improved; strain gauges have been proved to last six years and counting, inclinometers have been found to be extremely reliable even with passing time.

2.5 Case Study

Flagpole Project at MIT



The case study in consideration is the continuous monitoring of the flagpole in DuPont Court at MIT.

The purpose of this project is to obtain a continuous record of the acceleration experienced at the top of the flagpole and transmit it in real time to a central computer located in Building 1. This research is motivated by the idea of an I-city. As R. Sudarshan explains in his thesis on the flagpole project, the I-city is a place where sensing, signal processing, simulation and control come together to create smarter and safer physical infrastructure. "Data from buildings and its surroundings is collected by sensors, and transmitted in real-time to a centralized cluster of servers using wireless transmission. The signals are then processed to remove noise and test for inconsistencies and fed to a fast simulation model. The results from the simulation are then processed to determine if corrective action needs to be taken. If so, actuators on the building are triggered to control its displacement, or, in the case of emergencies, the appropriate emergency personnel are immediately notified." [24]

If data could be obtained, filtered and processed, and a reaction could be triggered almost immediately, the concept of active control could be effectively implemented. This seems to be more applicable to structural active control due to wind than it would be to control the structure during an earthquake, especially if the peak of the earthquake happens promptly after the earthquake begins, such as El Centro. Passive control seems more appropriate for sudden El Centro-type earthquakes. But even for this type of destructive earthquakes, an active monitoring system could detect imminent structural failure and trigger an emergency evacuation system within the building.

The flagpole project team assembled themselves the parts needed for the real-time data acquisition system. The accelerometers located in the flagpole are wired to a filtering system in Building 1 and the data is stored in a central computer and sent to the web via modem. There are products available in the market that will do all of the data retrieving, processing and will send it to the web or another computer as well as send a message when needed via, modem, phone or satellite. To reduce the amount of small levels of noise that may linger after the signal is filtered, the lowest bits of readings maybe ignored. The main concern is to get a complete system that will process all the information and filter it in almost no time at all. The iSite web-based vibration monitoring system by Geocomp is a three-channel velocity or acceleration recorder with a 16-bit resolution and 2400 Hz sampling rate, this model maybe too slow for the flagpole application, but with the great number of large instrumentation companies available, there is probably a model that would fit anyone's need.

Infokom GmbH in collaboration with Jenasensoric and Bauhus-University, have developed a structure monitoring system (SMS 2001) that monitors structures on a continuous and permanent basis. Some of the projects they are working at the moment are the long-term monitoring of the bridge over the river Ilm in Darnstedt to determine its remaining service life after a loading test, and they are also using monitoring to determine the structural reactions on a road bridge over the Elbe-Seiten-Kanal near Bad Bevensen. [13]

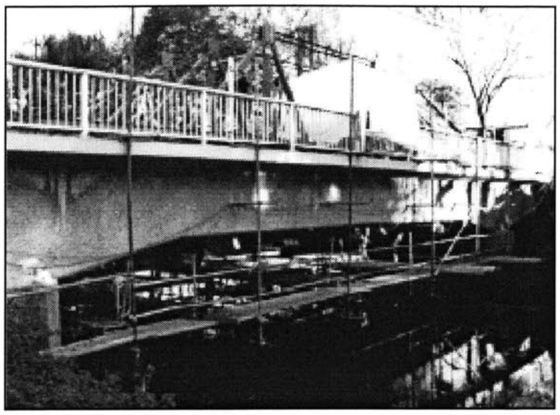


Figure 2.8 Bridge being monitored over the river Ilm in Darnstedt. [13]

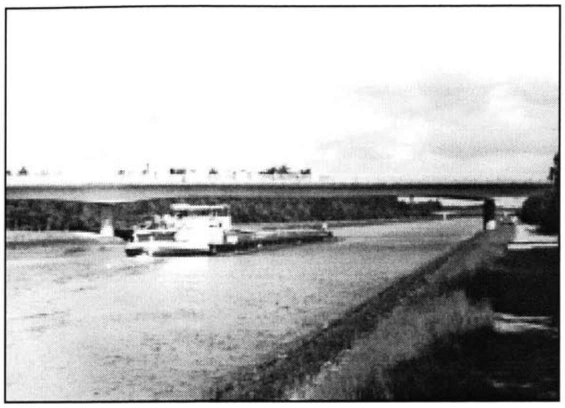


Figure 2.9 Bridge being monitored over the Elbe-Seiten-Kanal near Bad Bevensen. [13]

The company is based in Germany. I tried unsuccessfully to contact the three company members for whom e-mail addresses are given in their website, but this company seems to have expertise already in the area of permanent monitoring; they may have valuable information to offer that may aid in getting closer to the I-city ideal.

2.6 Issues of Concern

Some important aspects of permanent monitoring that must be considered before adopting a permanent system are:

2.6.1 False Alarms

False alarms are one of the main aspects to consider when deciding whether or not a permanent monitoring system should be installed and what type of monitoring system it should be (continuous or periodic).

Natural Structural Fluctuations

Structural materials naturally respond to changes in temperature, humidity, wind, etc. causing fluctuations that maybe large enough to trigger off alarm monitoring systems. In order to avoid false alarms due to natural structural fluctuations, the behavior of the structure in question should be monitored before an extraneous activity such as construction takes place. Thus, providing enough information to discern whether a particular behavior is caused by a certain activity or is simply the structure's natural behavior to its environment.

It is not always clear what degree of the structure's behavior is caused by what factor, and exactly how much of the readings fluctuations can be associated to noise.

Instrument Malfunction

This is a source of major concern in permanent monitoring. If lives are at stake and one of the sensors does not work properly sending an erroneous warning signal, should the building or bridge be immediately evacuated? How many times should this false alarm cause unnecessary evacuations before it begins to be completely ignored? Again, when deciding on the necessity of a permanent monitoring system, the likelihood of instrument malfunction must be taken into consideration.

2.6.2 Data Management

This can prove particularly crucial for continuous monitoring. The amount of data obtained is at best overwhelming, and each bit of information must be processed and stored. Special attention must be paid to the exact requirements of the job to determine exactly what type of data is needed; data discrimination should be exercised as much as possible. Not only does it take time to process the information but it also requires a great amount of memory space, more problems are bound to happen which means more maintenance calls, which in turn means a greater amount of capital invested in the project. There products that will only keep the highest reading of the day or any number of readings as specified, according to the specifications of the project, this maybe a solution to the problem of too much information.

2.6.3 Reading Frequency

Another big decision to make when monitoring for long periods of time is how often to collect and send data. Again, this decision must be made on a case-by-case basis according to main goals establish for the instrumentation. At a moment of crisis or when the monitoring system is part of an active control mechanism continuous readings maybe the best solution while periodic readings maybe more suitable at other times.

2.6.4 Instrument Location

Instrumentation would not be effective if it were not located properly. If a strainmeter were located on a section of the member that experiences minimal stress, it would certainly not be indicative of the behavior of such member. Sensors must be placed in locations of maximum stress or maximum displacement, as appropriate for the type of instrument, in order to reflect the worst conditions the member is experiencing.

2.6.5 Liability

This is probably the main reason why continuous structural health monitoring may not become a routine element of every structure. For structures that require stable conditions at all times such as nuclear plants, microchips laboratories, etc, the installation of continuous monitoring systems on a permanent basis may become an inherent part of the building itself, and it maybe stipulated in the design and construction contracts of the building before it is built; but for the rest of the structures that do not fall into this category, the need for permanent monitoring may not seem so obvious from the designer's and contractor's point of view because it may indicate design or construction flaws that would make them liable for repayment. It may not seem obvious from the owner's point of view either since they must pay the bill. Only if they (the owners) can appreciate the benefits of permanent monitoring, through the savings they would see in the future by avoiding big structural repairs through preventive measures adopted whenever the sensors indicate the possibility of a problem, would they be willing to adopt this kind of systems. This would mainly occur in big and complex projects, though, and at the end the lawyers, once again, would be the most benefited from the process, since the amount of disclaimers would dramatically increase in every building contract.

2.6.6 Power

This is one of the main concerns for structures in remote locations. Thus far we have yet to see a completely wireless sensor. The sensors available today run on AC or battery power. As one can appreciate in section 2.4, Geocomp's data loggers' batteries must be recharged every two weeks, which can prove not only tiresome but also costly.

The closest we are to wireless sensor technology is through the use of batteries recharged by solar power. This is still not an application that would be fitted for every situation, though.

2.6.7 Cost

Unless safety is seriously threatened making the use of monitoring systems unavoidable, cost should always be considered to determine if and how much monitoring is needed. Refer to Chapter 1, Section1.4 for details on how to quickly decide if monitoring is a cost effective alternative through the use of a simple cost/benefit analysis.

2.7 Monitoring Checklist

To ensure successful monitoring, every project must be evaluated individually and in the following manner:

- Determine the project's individual needs.
- Determine the overall project and site conditions.
- Define the critical members that need to be monitored
- Define the purpose of the instrumentation
- Pick the instrumentation that would best suit the needs
- Run a cost/benefit analysis to see if the instrumentation benefits justify the costs
- Predict the structure's behavior
- Establish the best places to install the sensors

- Pick the type of monitoring needed (temporary, continuous-permanent, periodic-permanent)
- Establish the natural behavior of the structure due to environmental conditions (when it applies)
- Determine data collection intervals
- Establish alarm thresholds
- Establish the methods of communication (web, phone, written, etc) and the parties that must be contacted
- Schedule and plan for maintenance and calibration
- Establish a contingency plan

2.8 Conclusions

As with any other business decision, the need for permanent monitoring must be assessed considering safety, probability of occurrence, and cost, but we also must consider the potential liability that a constant flow of information may bring.

False alarms are bound to happen on a regular basis, owners must determine if they are willing to compromise their businesses by subjecting the people that work and live in their buildings to frequent evacuation exercises, or even worse, if they are willing to ignore a “false alarm” only to find out that it may be a real threat this time; they must also consider an additional expense by contracting an instrumentation professional to review the instrumentation data that surpasses the pre-determined safety thresholds on a regular basis in order to minimize unnecessary evacuation procedures. Engineers and contractors must also evaluate how much responsibility and for how long they are willing to offer a “warranty” on their structures.

Permanent monitoring may work best in most cases when it serves to thoroughly check structural health at certain pre-determined long time intervals with the possibility of turning the monitoring system “on” for continuous monitoring when there is an element of concern.

Technology is making the idea of an I-city and continuous permanent monitoring ever more graspable, the question is are we ready to assume the responsibility of continuous information?.

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