Geotechnical Instrumentation

A BEGINNER'S GUIDE

Compiled by Gerald Davie M.Sc.
GeoZone GeoServices.
www.geozone.co.za   info@geozone.co.za

Why do we need to monitor field performance?

In geotechnical engineering the Engineer works with a wide range of naturally occurring, heterogeneous material, but exact numerical values of their engineering properties cannot be assigned.

Laboratory and field testing can only provide a range of possible values, but are not definitive.

Geotechnical engineering relies on judgement when selecting the most probable values of the in situ materials.

Instrumentation allows for monitoring of performance during construction, and if required, the geotechnical model can be updated and the engineering design revised to take into account the behaviour of the structure.

What can we measure with Instrumentation?

- Total stress in soil and stress change in rock
- Groundwater pressure
- Load and strain in structural members
- Deformation
- Temperature

The Future

Technology is advancing at a breath-taking pace. We all have apps on our phones that monitor a host of things – heart rate, driving style, exercise to mention a few. Google monitors our movements, our searches, our buying habits and suggests possible purchases based on our profile. So monitoring is becoming increasingly commonplace. We already monitor the passage of time, the amount of fuel in our tank, the speed at which we drive and the temperature of our houses and offices. There is no reason why monitoring should not become increasingly important in other aspects of our lives, including that of monitoring the behaviour of our structures.

The future is already here.

Planning a Monitoring System

"every instrument installed on a project should be selected and placed to assist in answering a specific question. Following this simple rule is the key to successful field instrumentation."

Ralph Peck

Steps to Planning a Monitoring Programme

1) Define the Project Conditions
2) Predict Mechanisms that Control Behaviour
3) Define the Geotechnical Questions that need to be answered
4) Define the Purpose of the Instrumentation
5) Select the Parameters that need to be answered
6) Predict Magnitudes of Change
7) Devise Remedial Action
8) Assess Tasks for Design, Construction and Operation Phases
9) Select Instruments
10) Select Instrument Locations
11) Plan Recording of Factors that may Influence Measured Data
12) Establish Procedures for Ensuring Reading Correctness
13) List the Specific Purpose of Each Instrument
14) Prepare Budget
15) Write Instrument Procurement Specifications
16) Plan Installation
17) Plan Regular Calibration and Maintenance
18) Plan Data Collection, Processing, Presentation, Interpretation, Reporting and Implementation
19) Write Contractual Arrangements for Field Instrumentation Services
20) Update Budget.

Whew. That is a long list of stuff to think about.

In summary, the instrumentation system should be designed to answer specific questions based on an existing geotechnical model. This model should be able to make predictions as to the behaviour of the rock mass, soil fabric or the interface between the structure and the encompassing natural materials. The instrumentation system should then be based around this geotechnical model.

It is often wise to involve the instrumentation specialists at the outset when designing a system, as they will be able to provide valuable input into what instruments are most suitable for the job.

We are often asked to quote or tender for the instrumentation portion of a project. Generally the specifications are so loose that it is impossible to price correctly based on the available data. The contractor may only send through the instrumentation specification without the rest of the contract document.

The questions that we usually struggle to get answers on include:

- How do they want to read the instruments? Do they want a hand held data logger or a fully automated logging system?
- Do they want to be able to access the logger remotely.
- What magnitude of pressure/displacement/strain is required for the instruments
- What are the cable distances from the instruments to the multiplexers/switchboxes/data loggers?
- How many multicore cables are required?

Tendering is always a stressful business and not having good information just adds to the stresses,

So it is important that the entire contract document is submitted to the instrumentation company so that they can measure the cable lengths and design the system architecture.

But there is a better way……………….

Get us involved at the outset so that we can design the system. Once the design is finalised it is easy to specify cable lengths, the number of junction boxes, multiplexers, data loggers and the myriad of things that go into a successful monitoring system.

It will indeed be a beautiful thing.

So let us get down to the nuts and bolts.

Firstly let us look at get to grip with some of the more esoteric aspects of instrumentation including:

- Vibrating Wire
- 4-20 mA
- Wheatstone Bridges
- Digital signals
- Multiplexer

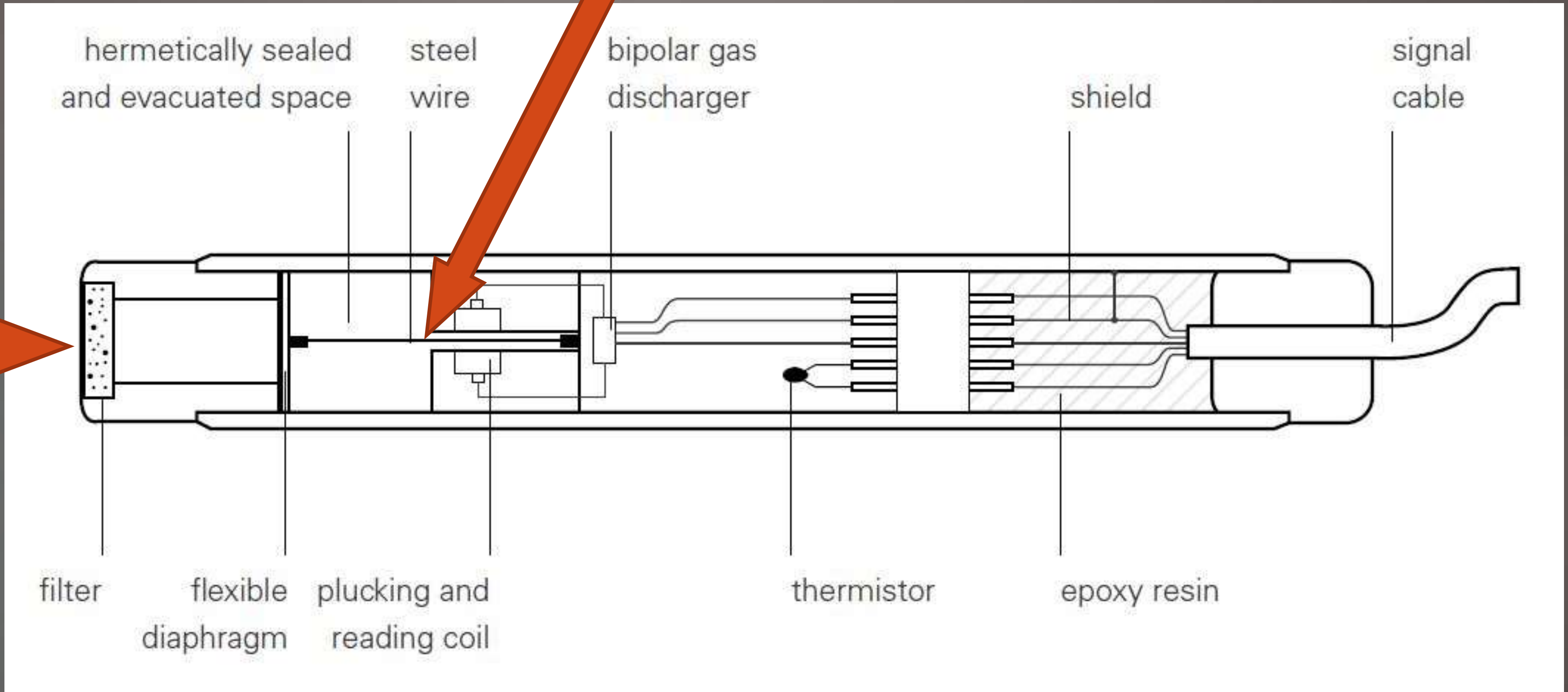
Vibrating Wire

Imagine a guitar spring. When the tension is increased, the frequency of the vibration increases and a higher note is emitted, and vice versa. Vibrating wire technology works the same. Water pressure variations for instance will change the tension on wire, tensioned within an evacuated chamber with one end of the wire attached to the moving part of the sensor. A coil plucks the wire which vibrates at a frequency governed by the pressure on the transducer. A secondary coil measures the frequency of the vibration, which is transmitted back to the read-out unit and read directly in Hertz or converted to engineering units. And that is essentially how vibrating wire technology works. Well understood, robust and versatile.

Vibrating Wire

Tensioned VW wire

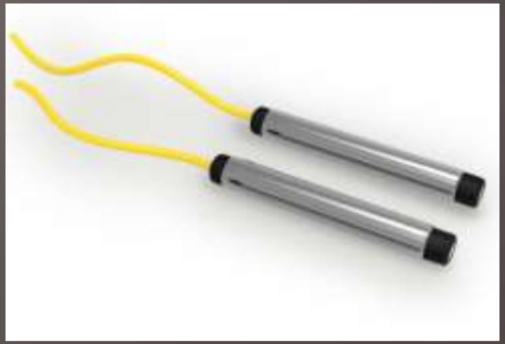
H_2O Pressure



Typical VW set up – in this case for a VW Piezometer

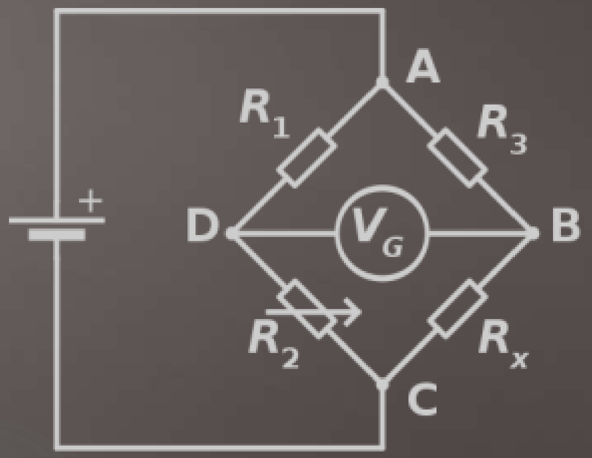
4-20 MilliAmp

A point-to-point or multi-drop circuit mainly used in the process automation field to transmit signals from instruments and sensors in the field to a controller. It sends an analog signal from 4 to 20 mA that represents 0 to 100% of some process variable. As a current loop signal, 4-20 mA also powers the sensor transmitter on the same wire pair, and 4-20mA provides more resistance to interference than a voltage-based line. PCMag.com



Wheatstone Bridge

A **Wheatstone bridge** is an electrical circuit used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component. The primary benefit of a Wheatstone bridge is its ability to provide extremely accurate measurements (in contrast with something like a simple voltage divider). Its operation is similar to the original potentiometer. (Wikipedia)



Digital Signals

A digital signal is used to represent data as a sequence of discrete values; at any given time it can only take on one of a finite number of values. This contrasts with an analog signal, which represents continuous values; at any given time it represents a real number within a continuous range of values.

Simple digital signals represent information in discrete bands of analog levels. In most digital circuits, the signal can have two possible values; this is called a binary signal. They are represented by two voltage bands: one near a reference value (typically termed as ground or zero volts), and the other a value near the supply voltage. These correspond to the two values "zero" and "one" (or "false" and "true") of the Boolean domain, so at any given time a binary signal represents one binary digit (bit). Because of this discretization, relatively small changes to the analog signal levels do not leave the discrete envelope, and as a result are ignored by signal state sensing circuitry. As a result, digital signals have noise immunity;

In a digital signal, the physical quantity representing the information may be a variable electric current or voltage, the intensity, phase or polarization of an optical or other electromagnetic field, acoustic pressure, the magnetization of a magnetic storage media, etcetera. Digital signals are used in all digital electronics, notably computing equipment and data transmission.(Wikipedia)

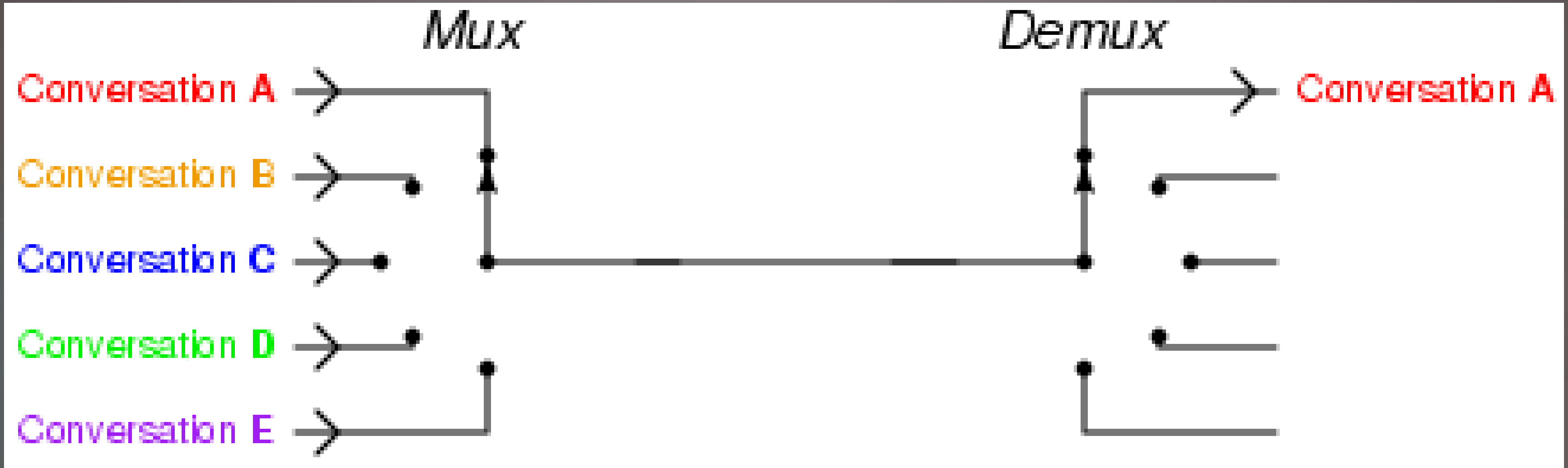
Multiplexers

A **Multiplexer** (or Mux) is a device that selects one of several analog or digital input signals and forwards the selected input into a single line. A multiplexer of 2^n inputs has n select lines, which are used to select which input line to send to the output. Multiplexers are mainly used to increase the amount of data that can be sent over the network within a certain amount of time and bandwidth. A multiplexer is also called a data selector.

An electronic multiplexer makes it possible for several signals to share one device or resource, for example, one A/D converter or one communication line, instead of having one device per input signal.

An electronic multiplexer can be considered as a multiple-input, single-output switch.

Multiplexers

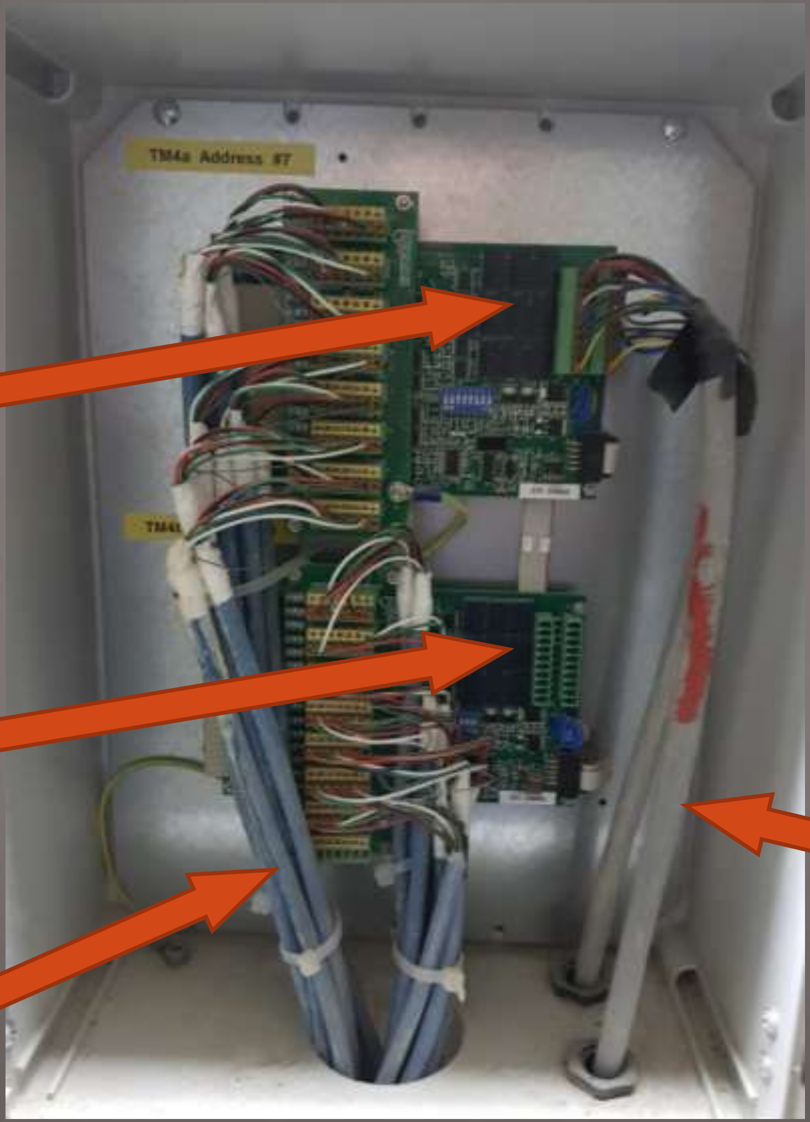


Multiplexer: Conversation A is followed by Conversation B, etc

Multiplexers

24 Channel Multiplexer

24 Channel Multiplexer



Outgoing RS485 Network Cables

Incoming Signal Cables

Types of Instruments

There is a wide range of instruments available, all of which are designed to answer specific questions. The instruments discussed below are by no means an exhaustive list, but covers the main categories and applications.

Piezometers

These generally comprise two types, **Vibrating Wire** and **Casagrande**. There are also electrical piezometers which are more accurate than vibrating wire versions, and able to cope with rapid fluctuations in hydraulic head.

Vibrating wire piezometers are installed in dams, tailings dams, land fill sites and landslides to measure the piezometric head within the soil or rock mass. They are cheap, readily available and easy to monitor. Where the conditions are aggressive, titanium steel versions can be installed to withstand acidic or corrosive environments.

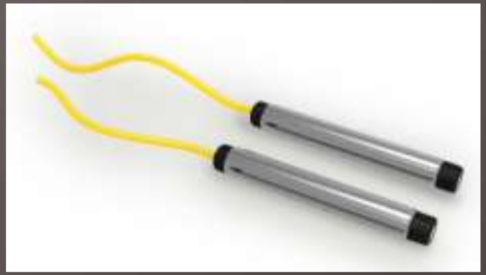
VW piezometers can be read with hand-held loggers or wired into a central data logging unit.

Piezo-resistive Piezometers

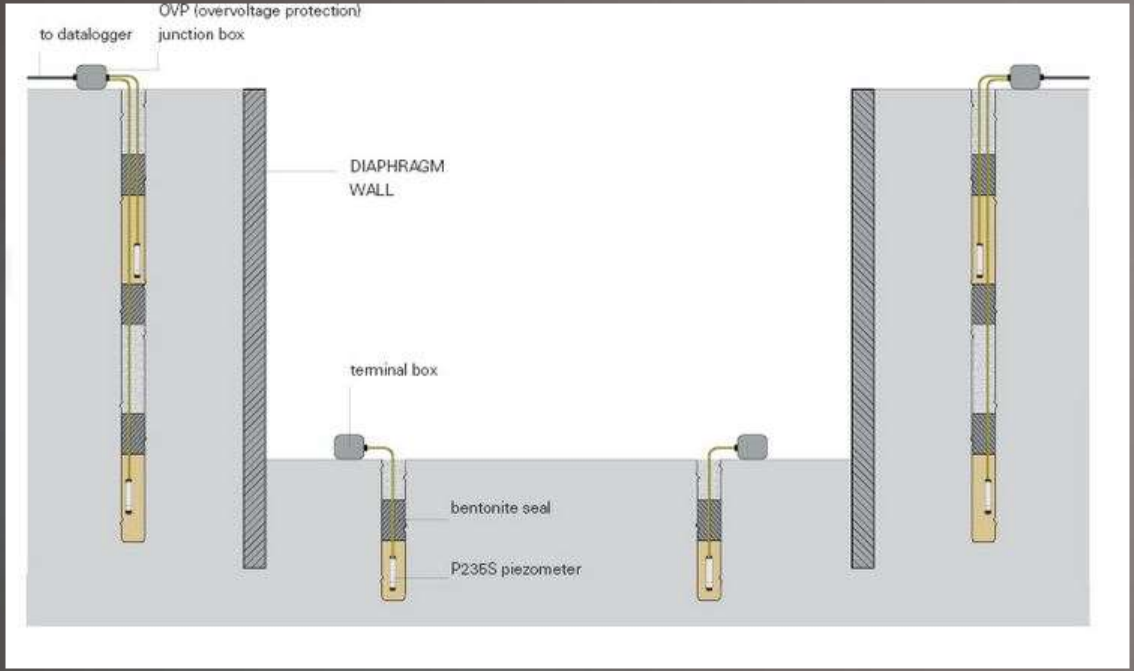
Piezo-resistive piezometers, also called semiconductor piezometers or strain gauge piezometers, are very accurate pressure transducers suitable for high frequency readings and short term applications.

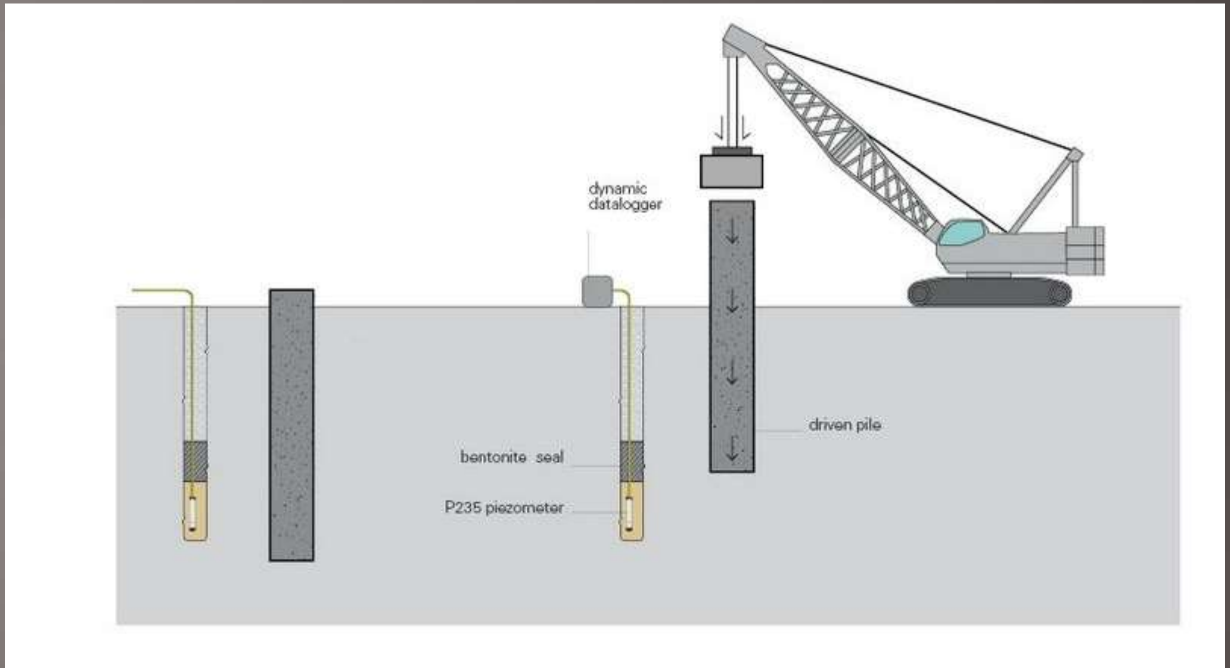
Their robust 4-20mA output signals are easy to read and automate with automatic data loggers and suitable for long-distance transmissions.

They can be connected to seismic dataloggers for monitoring rapid changes in pore-water pressure such as those produced by earthquakes.



Piezo-resistive Piezometers





Applications of Piezo resistive Piezometers

Casagrande and Stand Pipe Piezometers

Casagrande filter units are used to measure water pressures in permeable soil. The filter unit is made with high density polyethylene. They are available in different models to suite the required applications. Filter units have a threaded cap joint with two 0.5" twin tubes or a 1.5" single tube. Casagrande piezometers can be read manually with water level meter (dip meter) or automatically with a pressure transducer connected to an automatic datalogger.

Standpipe piezometers are used to monitor ground water levels. The standpipe filter unit consists of a slotted tube covered by geotechnical fabric for allow for the entry of water. Standpipe piezometers are usually manually read with a dip meter, but can also be monitored with vented pressure transducers or vibrating wire piezometers connected to a datalogger.

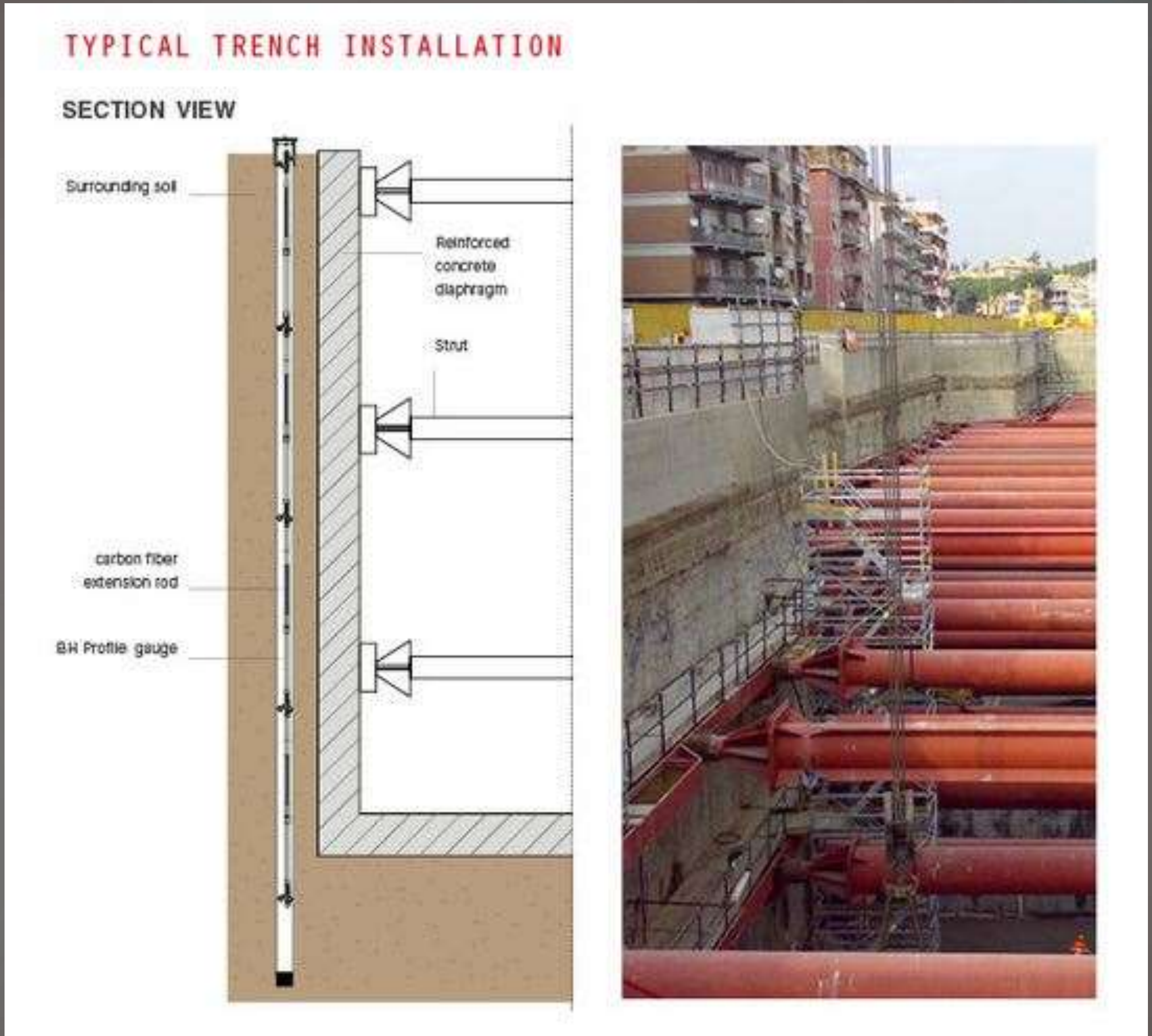
Borehole Inclinometers

Inclinometers are used in conjunction with borehole casings to measure the displacement of the surrounding soil or rock mass over time. Traditionally they comprise a single probe which is lowered down the inclinometer casing to measure deflections. Grooves in the casings ensure that the guide wheels of the probe always run on the same trajectory in relation to the casing. The initial run will provide the baseline data against which all subsequent readings will be measured. Accelerometers within the probe then measure changes in the deflection of the casing over time.

Technology now allows for a string of in-place extensometers to be placed in a borehole to measure deflections of the casing on an ongoing basis. Critical areas such as slip planes can be targeted to provide crucial data on the behaviour of a slope or retaining wall.

Borehole Inclinometers

Guide wheels



Application of Borehole In Place Inclinometers (IPI’s)

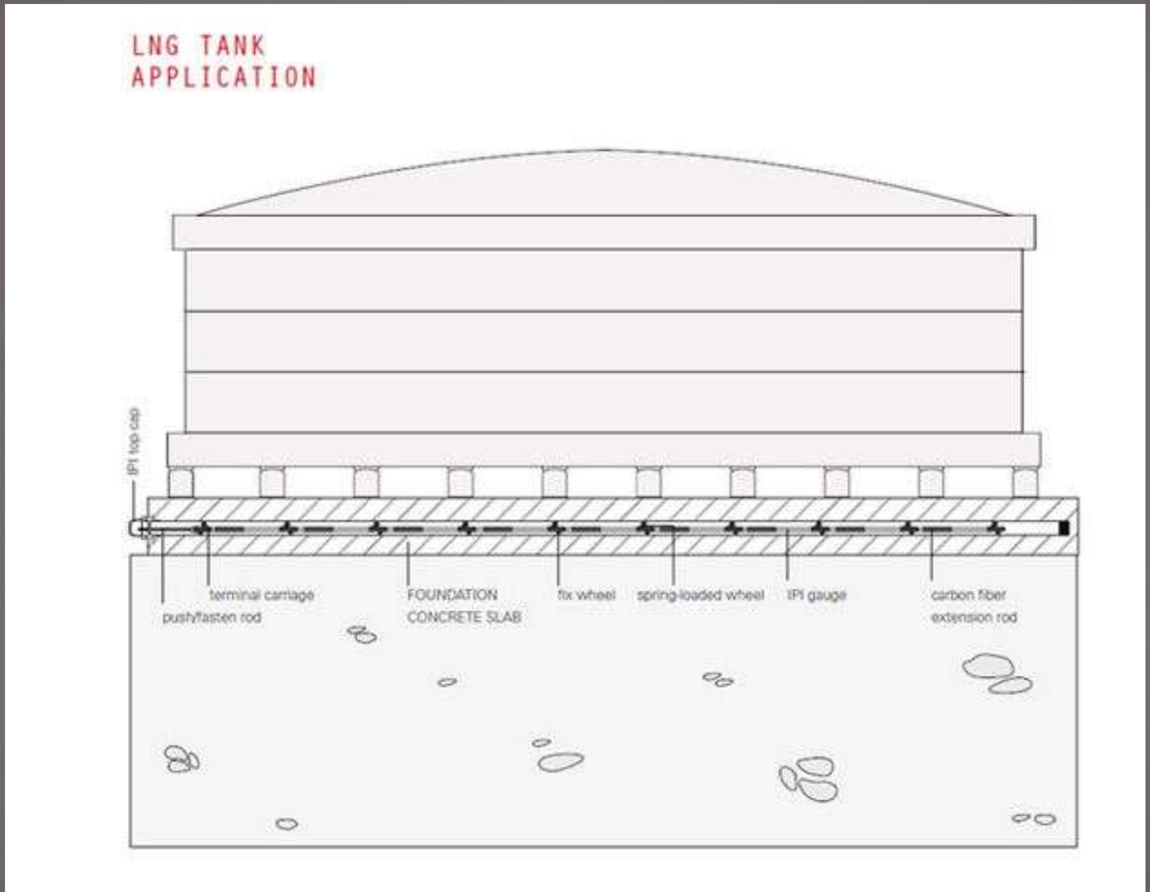
Horizontal In Place Inclinometers

Horizontal In Place Inclinometers consists of a stainless steel and thermoplastic resin assembly with one fixed wheel (close to the joint) and one spring loaded wheel. The string is composed of a chain of IPI gauges with carbon fibre extension rods and a terminal wheels assembly. A string of horizontal IPIs is usually installed inside inclinometer casing buried within trenches, foundations or horizontal drill hole for automatic monitoring of settlement or heave.

Main features are:

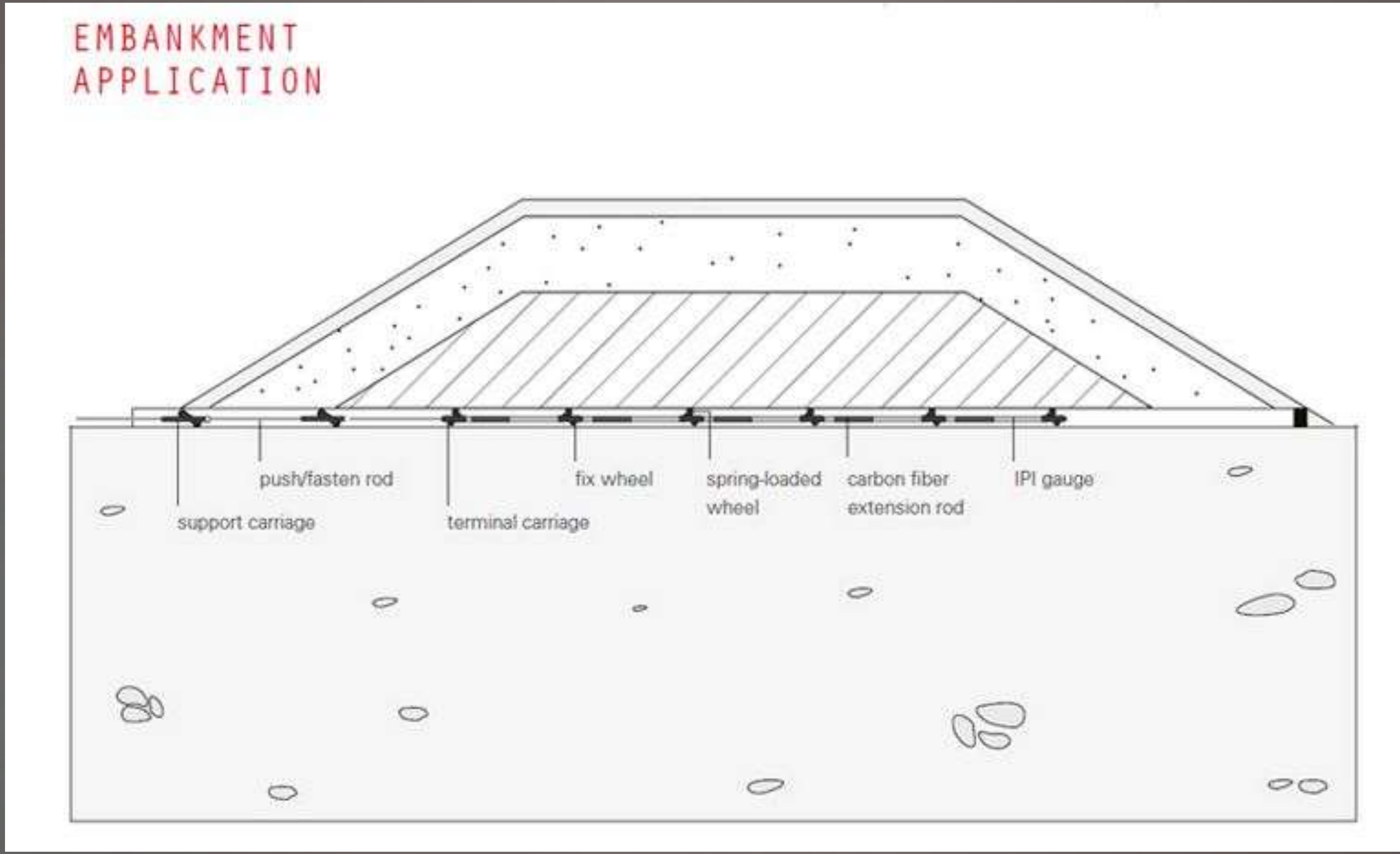
- Removable and modular system for multiple installation
- High resolution and accuracy
- Available in both digital model (RS485 - Modbus protocol) and analogue version (4-20 mA output)
- Automatic monitoring with a datalogger

Horizontal IPI Applications



Measurement of settlement below tank

Horizontal IPI Applications



Measurement of settlement below an embankment

Tiltmeters

In some instances it is important to monitor the changing angle of tilt of a structure – for example a retaining wall or the Leaning Tower of Pisa.

This may best be accomplished by placing an array of tilt meters at selected locations on the structure to measure the tilt. On board accelerometers will record the rate and angle of tilt over time.

Tiltmeters

Wall mounted Tiltmeter

Crackmeters and Jointmeters

Sometimes you need to know the magnitude and rate of displacement across a discontinuity. This can be a joint in a dam, a crack in a building or a failure plane in a rock mass. So how does one measure these displacements? With a crackmeter of course.

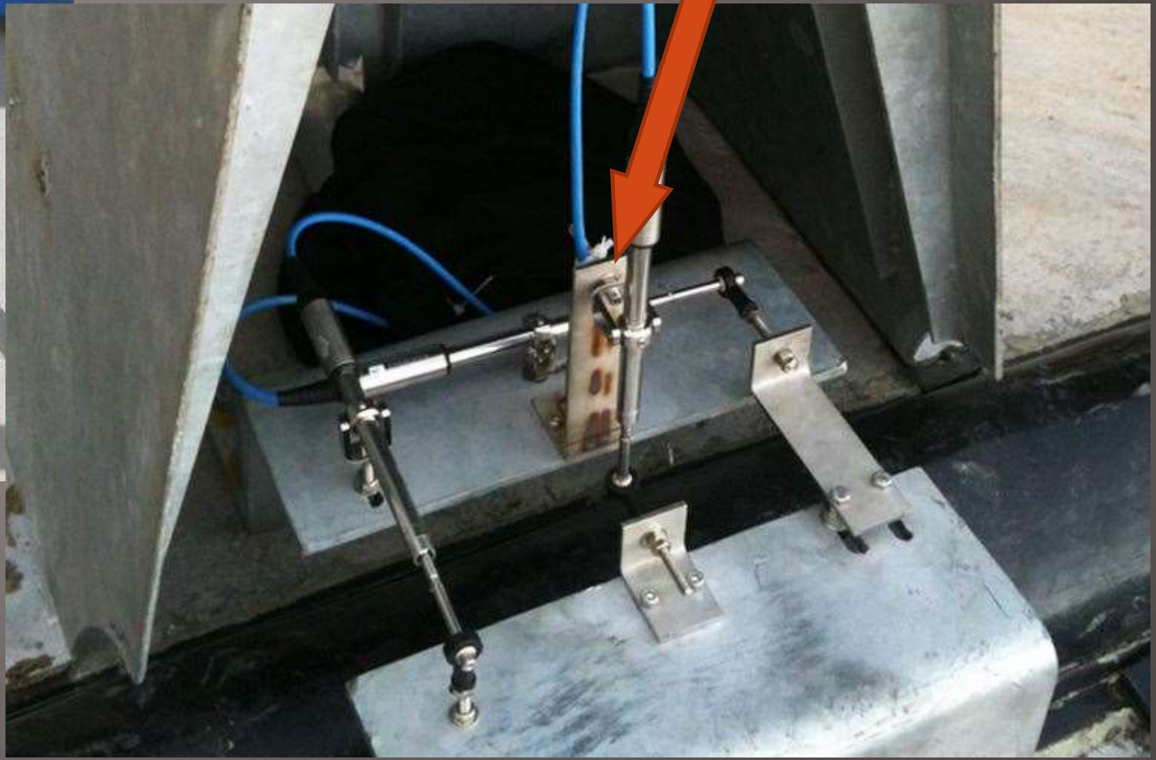
The instrument assembly includes a sensor housing and target, with each end equipped with screw anchors. Typically the anchors are fixed on the opposite sides of the joint (crack).

A displacement transducer housed in the sensor body is positioned across the joint/crack enabling measurement of the displacement between the anchors. 3D systems can be installed to measure X, Y and Z components of movement.

Crackmeters and Jointmeters

Measurement of displacement across a joint

A 3D arrangement of Joint Meters



Strain Gauges

Vibrating wire strain gages are used to monitor strain in steel or in reinforced concrete and massive concrete structures.

Arc-weldable VW strain-gauges are designed for arc welding to steel structure such as tunnel linings, piles and bridges.

Embedment VW strain-gauges are directly embedded in concrete for strain measurements of piles, foundations, dams, tunnel, etc.

Due to their long life and high reliability, vibrating wire strain gauges are the most robust solution for monitoring strain in concrete and metal structures.

Strain Gauges

Weldable Strain Gauge

A Rosette of Embedment Strain Gauges

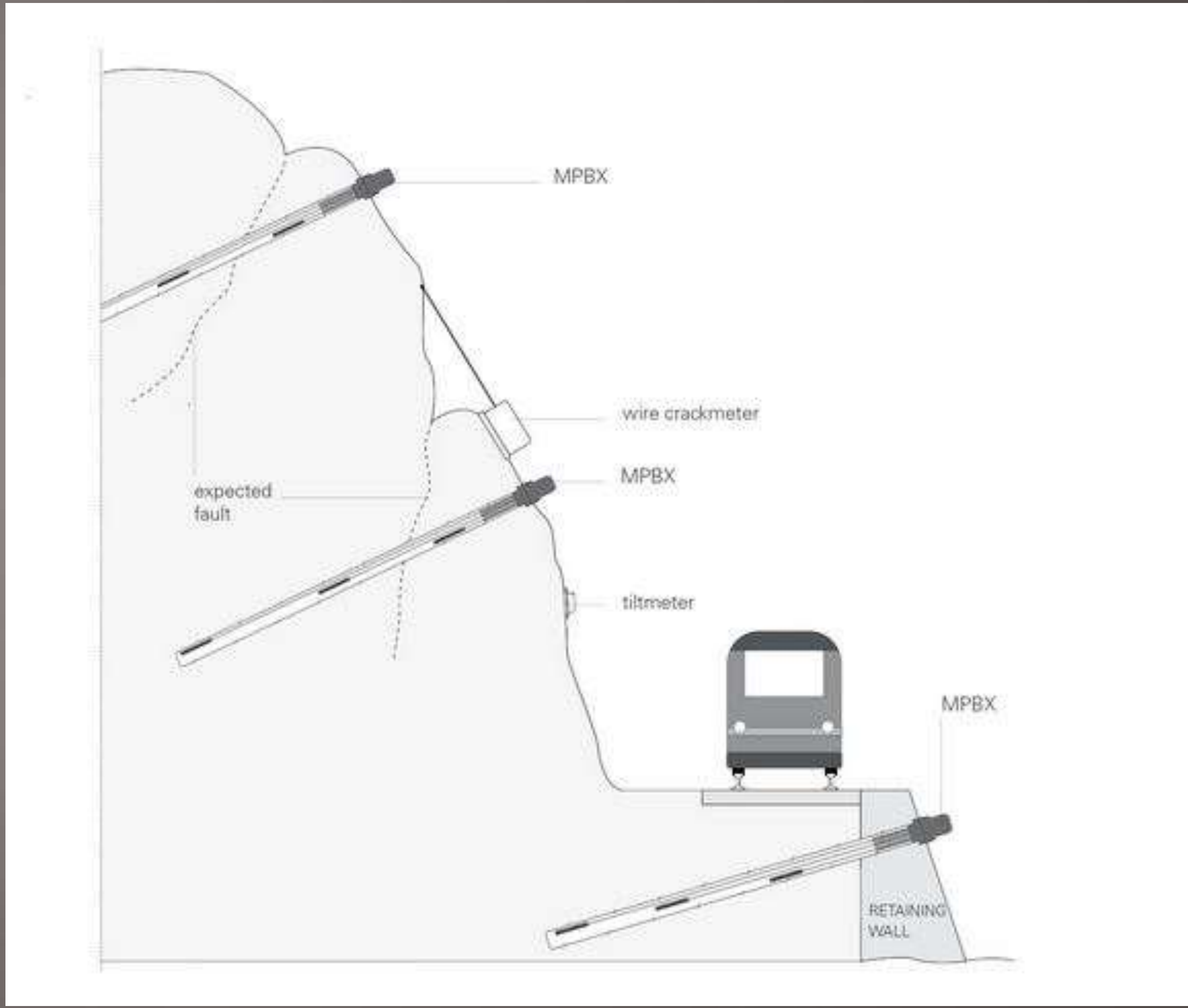
Multipoint Borehole Extensometers

Multi-point rod extensometers are installed in boreholes to monitor displacements at depths of your choosing, depending on the lengths of rods specified. A factory set lengths of measuring rods are enclosed in a nylon tube which separates the rod from the encompassing grout. The end of the rod is fixed to a steel groutable anchor.

Preassembled fibre glass rods are coiled at factory and shipped ready for installation. The complete assembly is inserted into the borehole and then grouted, fixing the anchors into the rock or soil mass but allowing free movement of each rod within its sleeve.

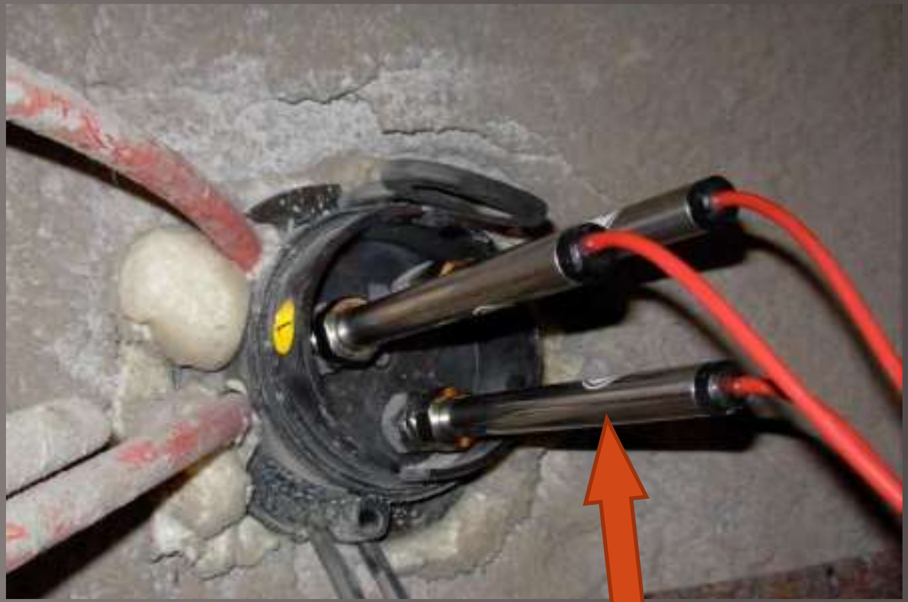
Relative movements between the anchors and the reference head are measured manually with a calliper or linear transducers, assembled on the reference head for remote monitoring.

Multipoint Borehole Extensometers



Typical Application for Extensometers

Multipoint Borehole Extensometers



The business end of the
Multipoint Extensometer

Hydraulic Anchor Load Cells

Hydraulic anchor load cells are used to monitor loads in tiebacks, rock bolts and retaining walls.

They consist of two ring-shaped stainless steel plates welded together around their circumference. The annular space between the plates is filled under vacuum by deaired oil. The load is directly measured by a Bourdon manometer connected to the cell body.

The manometer is calibrated in the laboratory to allow direct readings in kilonewtons. Electrical models equipped with pressure transducers are also available for remote readings. A very stiff distribution plate is supplied to ensure that the load is applied equally over the loading surface of the cell.

Hydraulic Anchor Load Cells

Solid Resistive Load Cells for Pile Testing

These are specially designed for pile testing, consisting of a cylinder body made of heat-treated steel instrumented with 4 strain-gauges. They are tested for long-term stability under heavy operating conditions. Electric cable can connect load cells to a suitable remote datalogging system for real-time monitoring.

Solid Resistive Load Cells for Pile Testing

Electro-hydraulic Load Cells

Electro-hydraulic load cells consist of a stainless steel pad with a pressure transducer. The piston pad is made by welding two plates together on their outer edge. The internal cavity is saturated under high vacuum with de-aired oil to form a rigid cell which is able to transmit load to a pressure transducer.

They are specially designed for steel lining and strut monitoring. Special distribution plates are available for application between non parallel surfaces.

Electro-hydraulic Load Cells

Load Cell

Reading a load cell prior to installation

Data Loggers and Read Out Units

The choice of loggers depends on the application and the number of instruments installed. For example, a dam may contain literally dozens of instruments which would be difficult to monitor efficiently if read by hand, so normally a fully automated system is installed to interrogate the system at set intervals. This provides meaningful data over time which can be used to analyse the dams performance. However a tailings dam with 4 vibrating piezometers installed can easily be read using a hand-held read-out unit or automated with a minilogger.

Portable data loggers can be configured and used to interrogate the instruments, storing the data until such time as it can be downloaded back at the office.

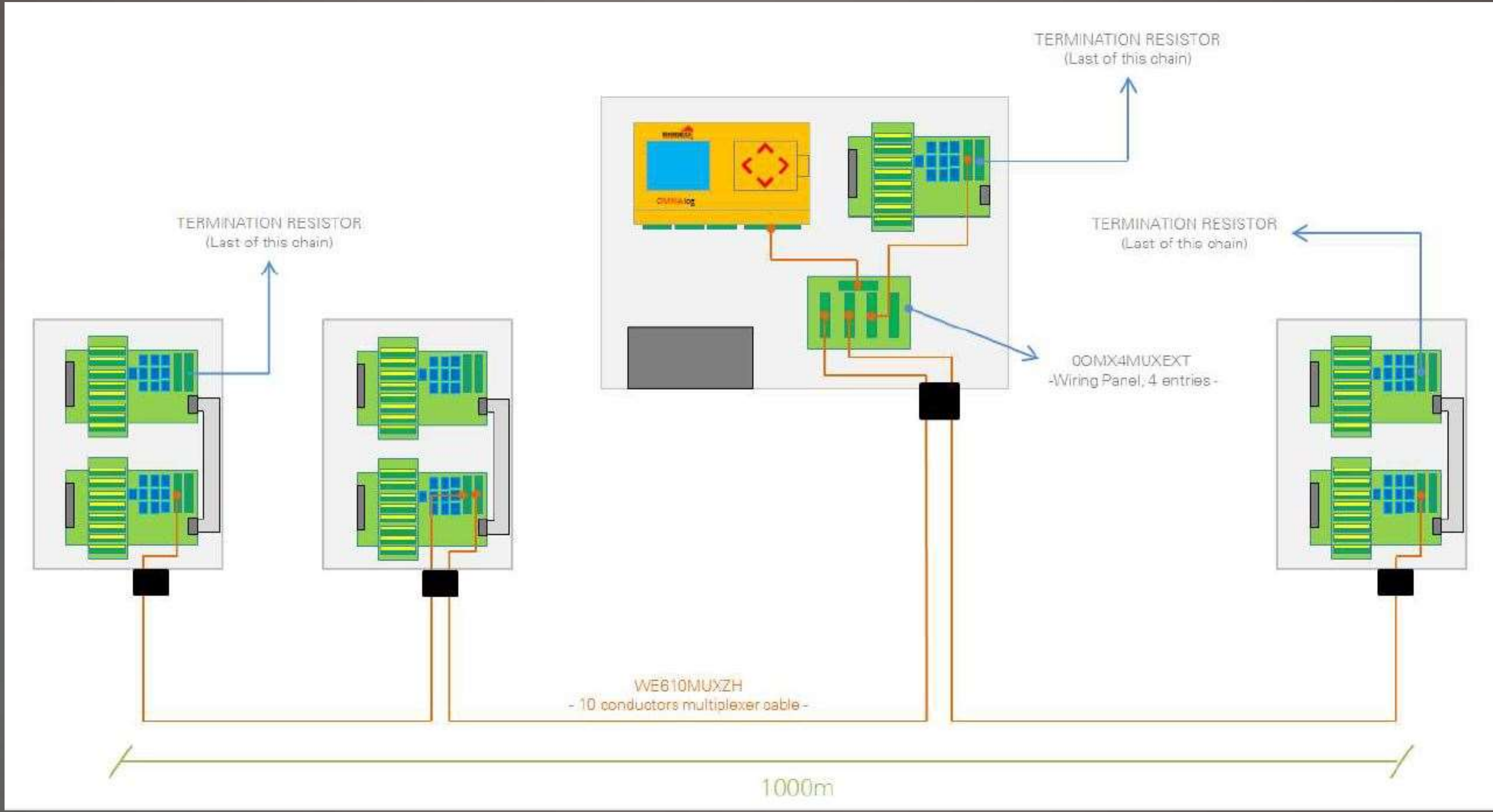
Hand held read out units are just that – they provide a reading on a display screen which then needs to be physically written down onto a record sheet for later capture. Great if you only have a few instruments.

Data Loggers and Read Out Units

Which brings us finally to a fully automated system. Signal cables from the instruments are joined into multicore cables which run through to the multiplexers and then through to the data logger. Alternatively signal cables are connected directly into multiplexers located throughout the dam or mine in what is known as a distributed architecture. RS485 cables link the multiplexers in a daisy chain arrangement to the Data Logger. This arrangement can save hundreds of metres of multicore cable.

But this is about data loggers. Some instrument manufacturers are moving to on-board servers with their own IP address, which can be configured through any web browser. An integrated modem then allows for remote access from literally anywhere in the world if set up correctly. This can be a game changer when it comes to maintaining, interrogating and updating a system.

System Architecture



A distributed system architecture with external multiplexers

Data Loggers and Read Out Units

Logger

Modem

Incoming network cables

Cables

Careful thought needs to be given to cabling in terms of their carrying capacity and length. Any VW wire instrument for example will occupy 2 channels in a multicore cable due to the VW sensor and the thermistor. In total a 16 pair (32 wires) multicore cable can carry 8 VW instruments. As soon as that capacity is exceeded a new multicore cable is required, which may comprise an 8 pair channel cable, as a cheaper option, or alternatively a single signal cable that extends from the instrument all the way to the Mux wherever that is located. Channel requirements vary according to the type of instrument installed.

The point is that **knowing the length of cable runs is not enough** – the number of channels that need to be monitored needs to be precisely understood to arrive at the exact length of cable required for a project. In addition it is important to account for the need to lay these cables in a sinusoidal manner in trenches, wastage, unforeseen requirements, etc and it is always prudent to add an additional 20 percent to the final calculated cable figure.

Be warned therefore that specifying cable lengths can be fraught with problems and needs to be calculated in a holistic way to ensure that there are no shortfalls in the system.

Peripherals

In addition to the instruments, data loggers and multiplexers, a host of other issues need to be considered and addressed when designing a system. These include but are not limited to the following:

- Junction boxes
- Cable jointing kits
- Installation rods
- Saturation devices
- Types of cable – expensive low smoke zero halogen or lower spec?
- Length of cable runs and extra over for sinusoidal laying down of cables in cable trenches
- Power supplies
- Cell phone access
- Security
- Lightning protection and earthing
- Supply of bentonite pellets, concrete, filter sand, cement etc
- Drilling requirements

In Summary

I hope to have provided you with some insights into this whole instrumentation industry. It can be a dark art and at times it has a bad reputation, not so much due to poor quality instruments but because of the numerous snares that can trap the unaware. If the check lists at the beginning of this guide are followed then the project should meet with success. But then again, it is difficult to have in depth knowledge of what is a vast subject, and even more to stay abreast of all the new developments in the industry.

In many instances the failure of a system is not due to short circuits in the electronics, but rather short circuits in the human system on which the system relies. People resign, retire or otherwise move on and often continuity is disrupted and the system is allowed to fall into disrepair. Processing and interpreting data is also an ongoing commitment, but technology is working to address this aspect of monitoring and we can assist in this regard.

The End

Reverting back to my opening remarks, it is much better if we can be involved at the outset when designing a system. This will ensure that all the boxes are ticked and the correct specifications provided for those bidding on the project and prevent the stressful scramble on the part of all parties concerned trying to get a price in before the closing date.

Please do not hesitate to email us on **info@geozone.co.za** or call +27 33 343 3915 or +27 82 9260626. Visit **www.geozone.co.za/instrumentation** for more information. We will also gladly send you a product catalogue with the full range of instruments available for monitoring your project.

GeoZone GeoServices

www.geozone.co.za **info@geozone.co.za**