

**NOTE: This application guide is intended only to give an overview of the several types of piezometers including where and why they are used, how they are typically installed and how data is obtained from them. Please note it is not a definitive guide.**

## APPLICATION GUIDE - PIEZOMETERS

### 1.0 General description

Piezometers measure **PRESSURE** (the measurand) and are used to confirm pore water pressure and/or ground water levels which are used in several calculations (computations) to quantify other parameters which influence the performance of soil and rock.

They are available in several different types including Casagrande, vibrating wire, strain gauge, hydraulic and pneumatic.

Standpipe piezometers are made up of low air entry porous plastic or ceramic elements which are connected to standpipe tubing and lowered into a predrilled borehole. (Alternative types may be driven or pushed into soft soil).

The porous element is surrounded by filter sand, known as the “response zone” and a Bentonite seal is placed above the sand.

Water level measurements are normally made using a water level meter (dipmeter) or in the case of artesian pressure a Bourdon pressure gauge can be attached to the top of the standpipe.



Casagrande piezometer tips



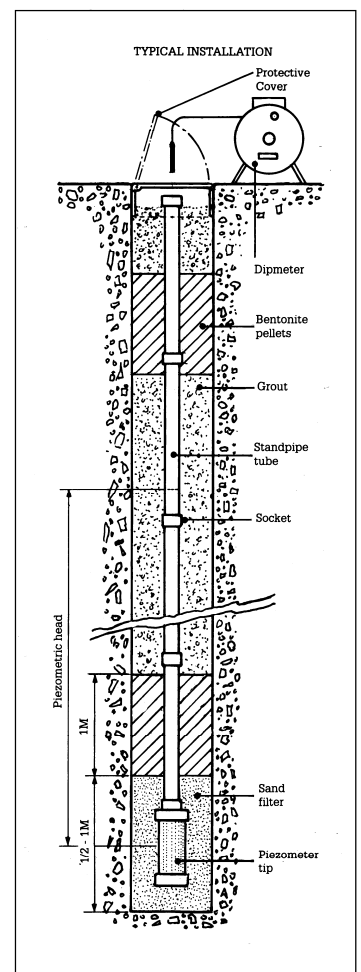
Water level meter



Bentonite pellets



Piezometer access tubing



Typical installation

#### Advantages

- Simple
- Long term reliability
- Low cost

#### Limitations

- Long lag time, in clays
- Negative pressure cannot be measured
- Automation can be expensive
- Open to damaged by construction activity

## 1.0 General description contd...

### 2.) Vibrating wire piezometers

A range of VW piezometers consisting of the following components:-

- Outer body
- Internal vibrating wire sensor
- Internal pressure diaphragm
- Filter tip (high or low air entry)
- Cable



#### Types of filter

The filter separates the pore fluid from the structure of the soil in which the piezometer is installed and are classified into two categories high air entry & low air entry.

A filter with a **high resistance to air entry** value is a fine filter (1μ alumo silicate ceramic - 3 bar, 2μ alumo silicate ceramic -1 bar) with a low permeability ( $\sim 3 \times 10^{-8}$  m/s) and are normally installed in unsaturated soil

A filter with a **low resistance to air entry** value is a coarse filter (50μ 316 sintered stainless steel) with a relatively high permeability of ( $\sim 3 \times 10^{-4}$  m/s) and are normally installed in saturated soils or open water.

VW piezometers measure **PRESSURE** are available in several pressure ratings from 70 to 6895 kPa.

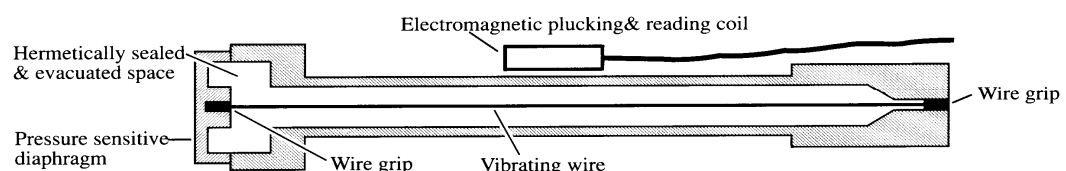
#### Operating principle & output signal

The Vibrating Wire Piezometer consists of a tensioned steel wire, anchored at one end to a flexible diaphragm ( the sensing element ) and at the other end to the inner body, all sealed into a stainless steel body. The internal parts of all Geosense piezometers are identical, only the thickness of the diaphragm and the geometry of the body changes.

Two opposing coils are located within the inner body close to the axis of the wire. When a brief voltage excitation, or swept frequency excitation is applied to the coils, a magnetic field is induced causing the wire to oscillate at its' resonant frequency. The wire continues to oscillate for a short period through the 'field' of the permanent magnet, thus generating an alternating current (sinusoidal) output. The frequency of this current **output** is detected and processed by a vibrating wire readout unit, or by a data logger equipped with a vibrating wire interface, where it is converted into 'Engineering' units of pressure.

As fluid pressure is applied to the exposed side of the flexible diaphragm, the diaphragm deflects, causing a change in the tension of the wire behind it. The change in tension of the wire results in a change in resonant frequency of oscillation of the wire, with the square of frequency of oscillation being directly proportional to the applied pressure.

#### Transducer Schematic



#### Advantages

- Easy to read
- Short lag time
- Can be automated
- Can read negative pore water pressure
- Long cable lengths > 2000m can be used

#### Limitations

- Needs lightning protection
- Push-in versions subject to errors

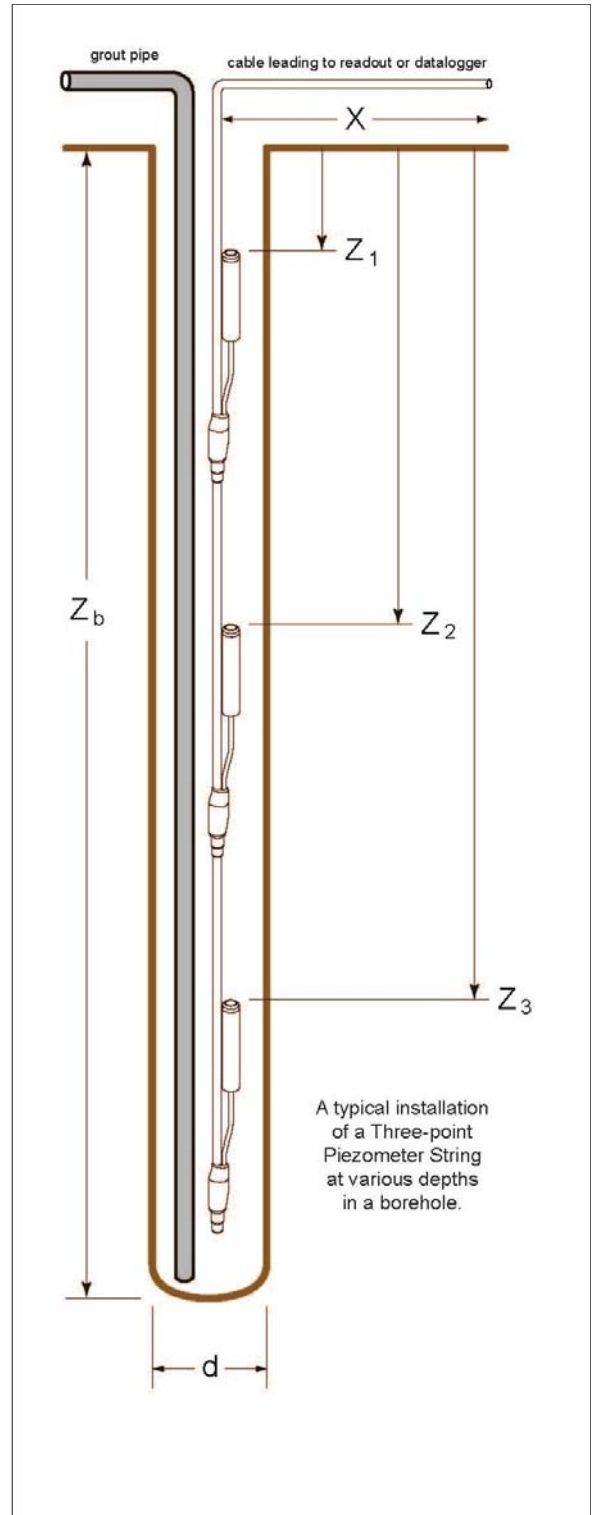
## 1.0 General description contd...

### 3.) Vibrating wire multi-point piezometer string



Multi-point piezometers comprise of several piezometers connected together on a common cable which allows multiple piezometers to be simply and reliably installed in a single borehole.

The piezometer string and grout pipe are placed in the borehole and cement-Bentonite grout is pumped until the borehole is filled. This is known as the “fully grouted method” and is gaining popularity for VW piezometer installation.



## 1.0 General description contd...

### 4.) Strain gauge piezometers

A range of strain gauge piezometers consisting of the following components:-

- Outer body
- Internal strain gauge sensor
- Internal pressure diaphragm
- Filter tip (high or low air entry)
- Cable
- Strain gauge readout



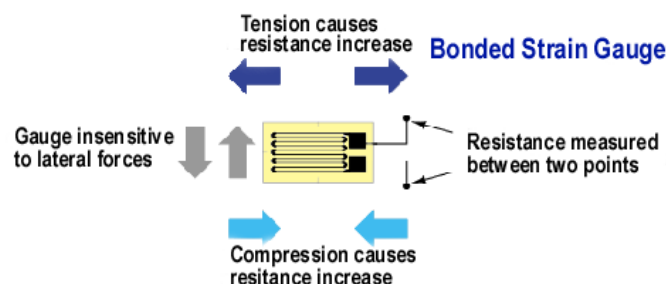
#### Types of filter

(see previous page under Vibrating Wire Piezometers)

Strain gauge piezometers measure **PRESSURE** and are available in several pressure ratings from 345 to 6895 kPa.

#### Operating principle & output signal

The Strain Gauge Piezometer consists of internal strain gages which convert mechanical motion into an electronic signal. Resistance is proportional to the strain experienced by the sensor. If a wire is held under tension, it gets slightly longer and its cross-sectional area is reduced. This changes its resistance (R) in proportion to the strain sensitivity (S) of the wire's resistance.



When a strain is introduced, the strain sensitivity, which is also called the gage factor (GF), is given by:

$$GF = \frac{(\Delta R/R)}{(\Delta L/L)} = \frac{(\Delta R/R)}{\text{Strain}}$$

As fluid pressure is applied to the exposed side of the flexible diaphragm, the diaphragm deflects, causing a change in the resistance of the strain gauge. The resultant resistance **output** can be measured in 4-20mA or 0-10mV and converted into Engineering Units using a strain gauge readout.

#### Advantages

- ♦ Fast response
- ♦ Suitable for dynamic measurements
- ♦ High accuracy
- ♦ Easy to read
- ♦ Can be easily automated
- ♦ Various outputs

#### Limitations

- Needs lightning protection
- Cannot use long cable lengths
- Changes in cable length cause calibration offsets
- Errors caused by moisture & electrical connections

## 1.0 General description contd...

### 5.) Hydraulic Piezometers

Hydraulic piezometers consist of the following components:-

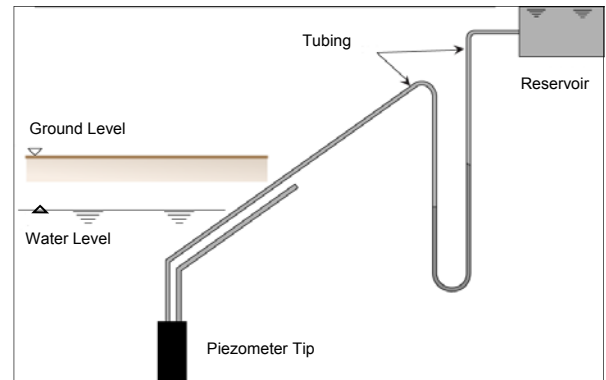
- Piezometer tip (high or low air entry)
- Twin-tubing filled with de-aired water
- Terminal Panel fitted with pressure gauges or transducer
- Hydraulic readout

#### Types of filter

The filter separates the pore fluid from the structure of the soil in which the piezometer is installed and are classified into two categories high air entry & low air entry.

A filter with a **high resistance to air entry** value is a fine filter (1 $\mu$  alumo silicate ceramic - 3 bar, 2 $\mu$  alumo silicate ceramic -1 bar) with a low permeability ( $\sim 3 \times 10^{-8}$  m/s) and are normally installed in unsaturated soil

A filter with a **low resistance to air entry** value is a coarse filter (50 $\mu$  316 sintered stainless steel) with a relatively high permeability of ( $\sim 3 \times 10^{-4}$  m/s) and are normally installed in saturated soils or open water.



### Operating principle & output signal

These types of piezometers consist of a tip and twin tubing that are filled with a de-aired liquid, which reacts to changes in pressure. These changes in pressure **output** can then be read by the use of manometers, pressure gauges and pressure transducers.

Due to the dual pipe make-up of this type of piezometer it has the ability to replace the de-aired liquid, which also allows soil permeability to be measured.

The fluid in the tubing must be de-aired as air bubbles in the system cause slower response times and errors. A symptom of this is when the reading from one tube does not match the other.

#### Advantages

- Simple, reliable mechanism
- Inaccessible components have no moving parts
- Piezometer tip can be flushed
- Can be used to measure permeability
- Can read negative pore pressures

#### Limitations

- Needs periodic de-airing with special equipment
- Prone to damage by freezing
- Large enclosure needed for readout & de-airing equipment
- Limited to 5 metre elevation above piezo-metric head

## 1.0 General description contd...

### 6.) Pneumatic Piezometers

Pneumatic piezometers consist of the following components:-

- Piezometer tip (high & low air entry)
- Twin-tubing filled with de-aired water
- Water reservoir
- Pneumatic readout

#### Types of filter

A filter with a **high air entry** value is a fine filter (1 $\mu$  ceramic - 1 bar)

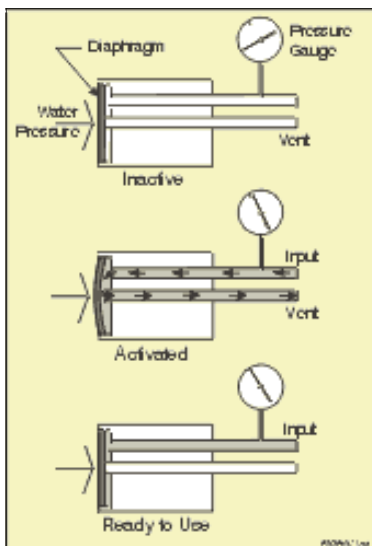
A filter with a **low air entry** value is a coarse filter (70 $\mu$  316 sintered stainless steel)

Pneumatic piezometers measure **WATER PRESSURE**.



### Operating Principle & output signal

The piezometer contains a flexible diaphragm. Water pressure acts on one side of the diaphragm and 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 gas pressure exceeds 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 gas through the vent tube. At this point, gas pressure equals water pressure, and the pneumatic indicator shows the reading on its pressure gauge.

#### Advantages

- Short lag time
- No drift issues
- No freezing problems
- Calibrated part accessible

#### Disadvantages

- Time consuming when taking readings from deep boreholes
- Difficult to automate
- Needs a supply of nitrogen or carbon dioxide.

## 2.0 Typical applications

The following table lists the typical applications, the elements that are monitored, the measurand the sensor is measuring and the result that can be computed from the sensor information.

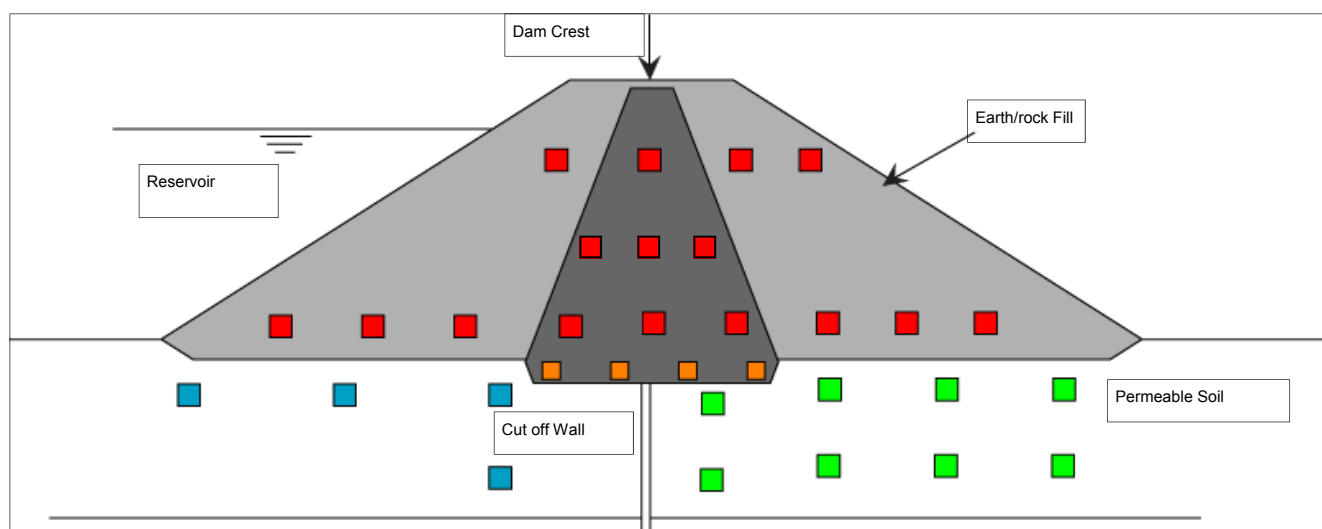
APPLICATION	ELEMENT	MEASURAND	COMPUTATION
<b>Dam</b>	Foundation	Pressure	Uplift pressure Shear strength Seepage
	Embankment	Pressure	Pore pressure Shear strength Permeability
	Abutments	Pressure	Pore pressure Shear strength Groundwater level
	Reservoir	Pressure	Water level
<b>Deep excavation</b>	Base of excavation	Pressure	Uplift pressure
	Behind the retaining wall	Pressure	Pore pressure Groundwater level Active pressure
<b>Slopes</b>	Cuttings	Pressure	Pore pressure Shear strength Load
	Embankments	Pressure	Pore pressure Shear strength Load
<b>Ground Improvement/Stabilisation</b>	Drains	Pressure	Pore pressure
	Surcharging	Pressure	Pore pressure Shear strength
<b>Dewatering</b>	Groundwater	Pressure	Groundwater level
<b>Hydrogeology</b>	Groundwater	Pressure	Groundwater level
<b>Underground structures</b>	Foundation	Pressure	Pore pressure Uplift pressure
	Surrounding strata	Pressure	Pore pressure Load
<b>Tunnel</b>	Groundwater	Pressure	Groundwater level
	Surrounding strata	Pressure	Pore pressure Load



### 3.0 Typical applications contd...

#### Earth/rock fill dams

Used mainly to control fill placement, monitor pore water pressures, up lift pressures and to indicate seepage rates.



#### Where and what we monitor

#### Why we monitor

- **Dam body**  
Monitor pore pressures during and after construction

Control fill placement in core

Excess pore pressure generated whilst placing fill can cause instability within the embankment. Measurements can be used to control the filling operations so as to avoid potential failure.

For long term safety monitoring of pore pressures within the embankment.

- **Upstream foundation**  
Monitor up-lift pressures

To determine changes in the effective stress within the foundation which affects stability, during and after construction.

- **Downstream foundation**  
Monitor up-lift pressures  
Monitor pore pressure

To determine changes in the effective stress within the foundation which affects stability, during and after construction.

Changes in pore pressure within the foundation can indicate a failure of the cut-off wall.

- **Contact zone**  
Monitor contact pore pressures

Excess pore pressure at the contact zone can cause both leakage and instability.

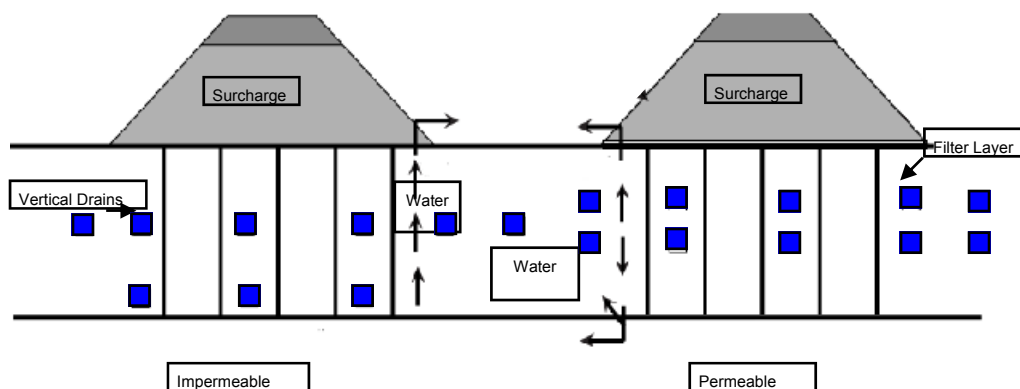


### 3.0 Typical applications contd...

#### Embankment constructed for consolidation (surcharge)

Embankments may be created to consolidate the ground below them. The aim of this method is to induce settlement by increasing the load on the pore water so that it dissipates faster than would normally occur. Piezometers are used to monitor and identify when pore water pressures have dissipated to the required level.

Where permeability is particularly low, band drains can be installed to allow a preferential drainage route thereby increasing the rate of consolidation.



#### Where and what we monitor

#### Why we monitor

##### ■ Embankment sub-soil

Pore-water pressure

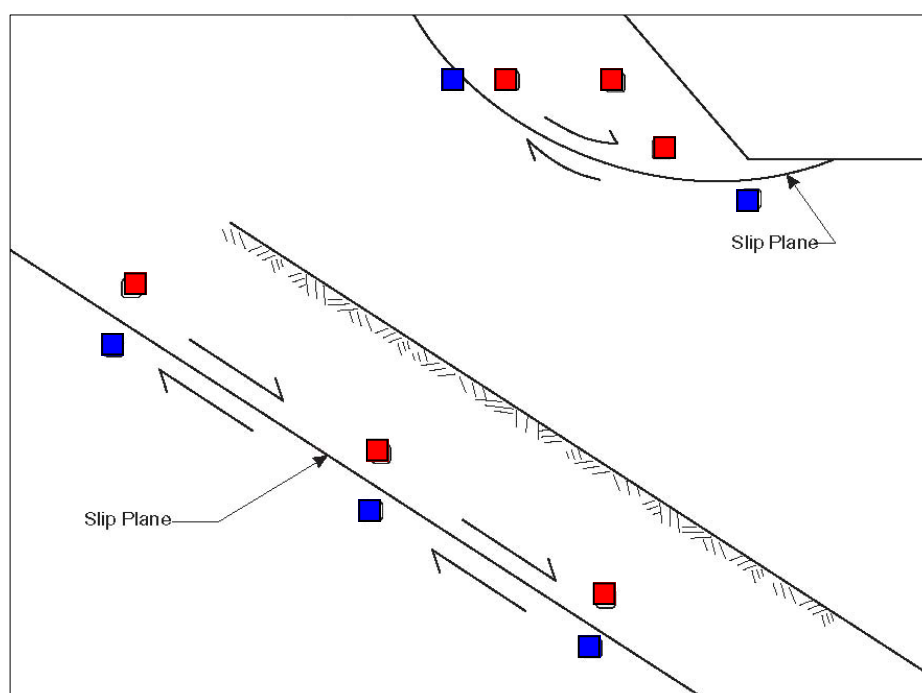
Excess pore pressure generated whilst placing fill can cause instability within the embankment sub-strata.

Measurements can be used to control the filling operations so as to avoid potential failure of the sub-strata and to monitor the effectiveness of the drainage system.

### 3.0 Typical applications contd...

#### Slope stability

One of the main mechanisms of failure of slopes and embankments is increased pore pressure reducing in reduced shear strength. Monitoring the pore pressure at strategic positions within critical slopes can provide indications of changes in slope instability.



#### Where and what we monitor

#### Why we monitor

To allow calculation of shear strength

Increase in pore-water pressure decreases the shear strength of the soil. A reduction in shear strength can lead to failure of a slope.

■ **Below potential shear zone**  
Monitor pore-water pressure

■ **Above potential shear zone**  
Monitor groundwater level

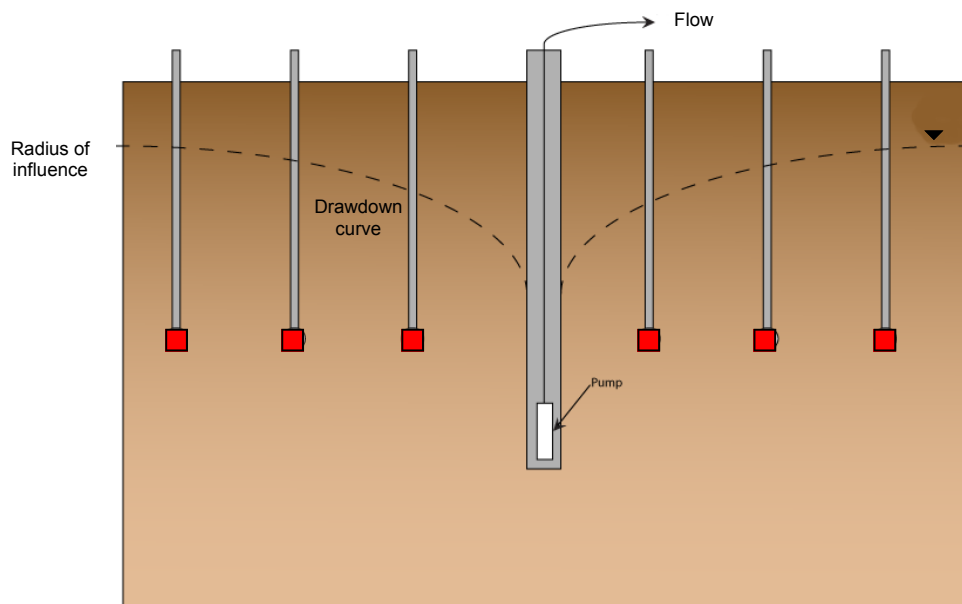
Groundwater levels add to the mass of the soil and if this becomes too high it can overcome the shear strength of the soil and lead to failure of the slope.

### 3.0 Typical applications contd...

#### Pumping tests

Pumping tests are carried out to determine the rate of pumping which is required to dewater the soil. The test includes measuring the flow and drawdown to identify the radius of influence which is used to design a dewatering system. Dewatering is required where excavation is to be carried out below the water table in non-cohesive soils to ensure stability of the excavation.

In addition pumping tests can be used to determine in-situ permeability.



#### ■ Where and what we monitor

Monitor groundwater levels below in an array around the pumping well

#### Why we monitor

If the volume of water pumped out of the well is higher than the recharge value of the soil then the soil will become dewatered.

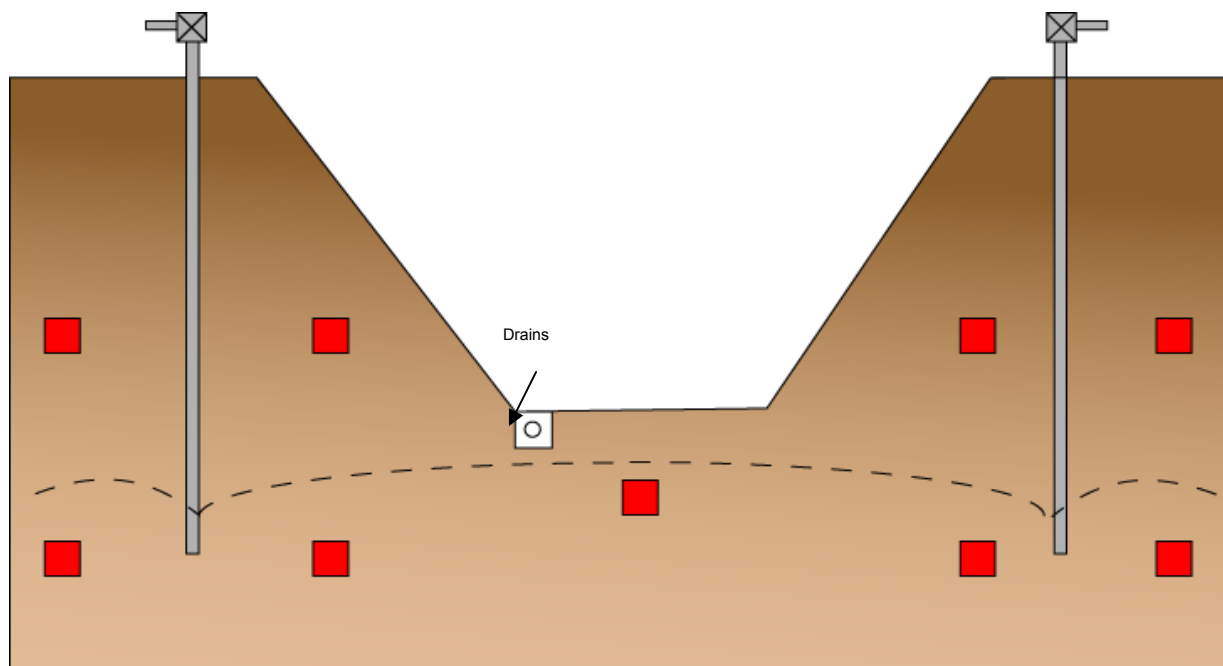
The point at which no drawdown occurs is known as the radius of Influence. Knowing this radius of Influence and the shape of the drawdown curve enables a dewatering scheme to be accurately designed.

Data can also be used to determine the in-situ permeability.

### 3.0 Typical applications contd...

#### Dewatering Systems

Piezometers are used to measure groundwater levels and thus the effectiveness of the dewatering system. They can also be automated with alarms to provide an early warning system in case of pump failure.



#### Where and what we monitor

#### Why we monitor

- Monitor groundwater levels below, in and around the excavation and the wells

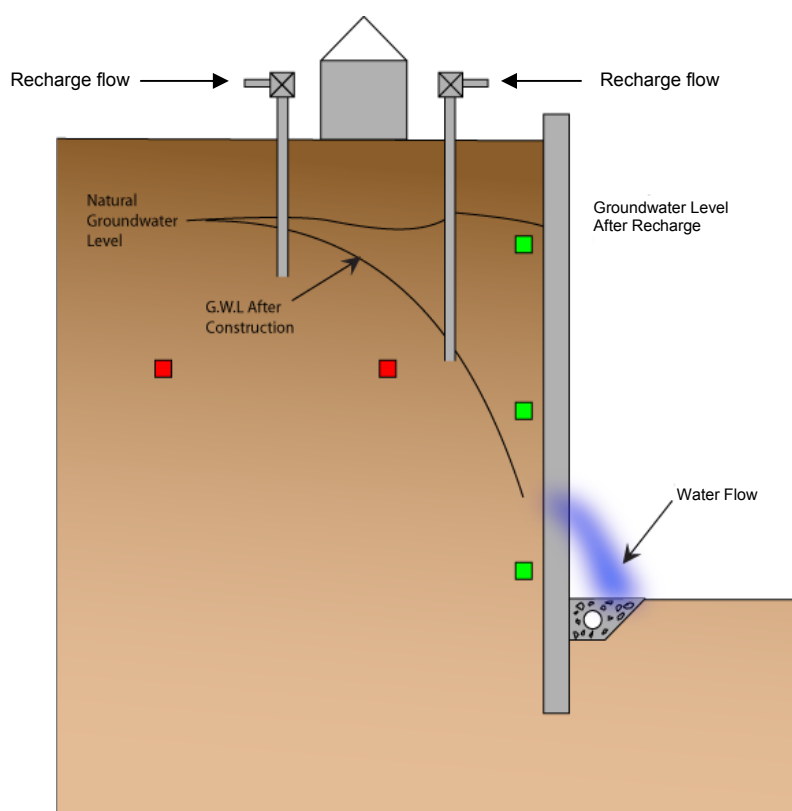
In order to carry out excavation in saturated non-cohesive soils the groundwater level must be reduced to a level that is below the intended excavation level .

### 3.0 Typical applications contd...

#### Groundwater recharge

Where dewatering is carried out adjacent to structures the subsequent consolidation of the soil as the water is removed can cause damage. To minimise settlement, water from the dewatering wells is pumped back into the soil (recharge).

Piezometers are used to monitor groundwater levels and determine the effectiveness of recharge. They can also be used to monitor the passive loads being applied to the wall.



#### Where and what we monitor

#### Why we monitor



Monitor groundwater levels around the excavation.

If the recharge rate is too high the groundwater level will not be low enough to allow stable excavation. If too low, settlement may occur.



Monitor groundwater level on the outside of the wall

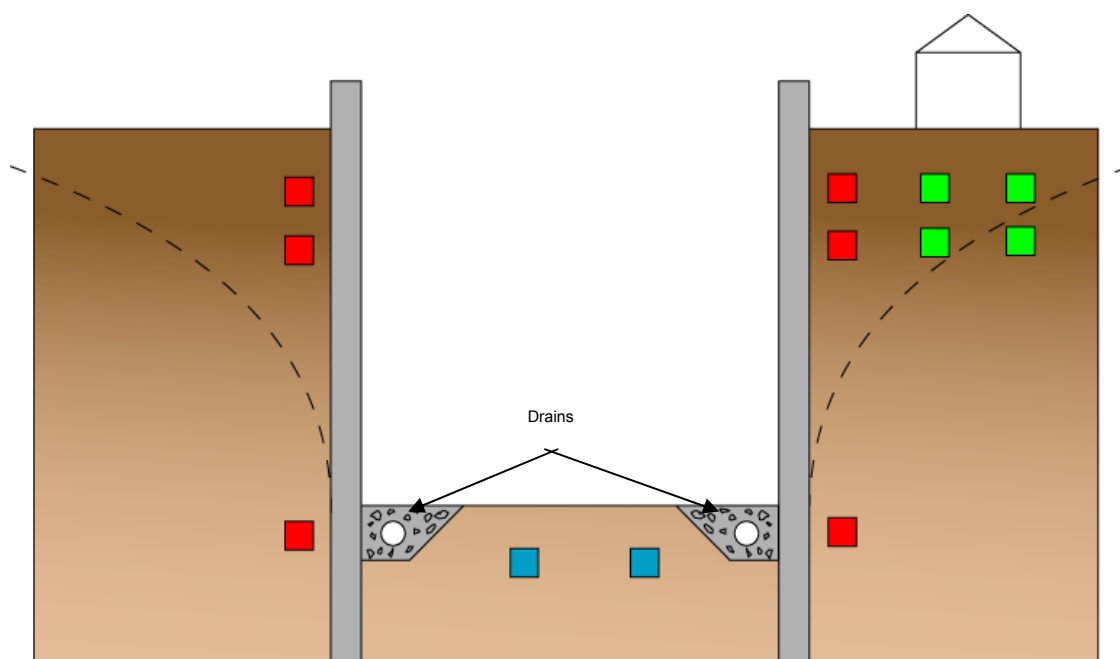
If the groundwater level is too high then the loading on the retaining structure may increase to an unsafe level.

### 3.0 Typical applications contd...

#### Deep excavation


Retaining walls are designed to support soil masses which cannot support themselves. The pressure exerted by the soil mass on the outside of the wall (active pressure) and the soil on the inside of the structure (passive pressure) is important for the stability of the excavation.

Pore-water pressure under the invert of the excavation can cause heave if not controlled.




#### Where and what we monitor


#### Why we monitor

 Monitor pore-water pressure and/or groundwater level under the base of the excavation

If the pore-water pressure is too high in the base of the excavation heave can occur causing instability of the excavation

 Monitor pore-water pressure and/or groundwater level behind the wall

Pore-water pressure is used to calculate active pressure behind the wall and then the subsequent load in order to ensure its stability as excavation progresses

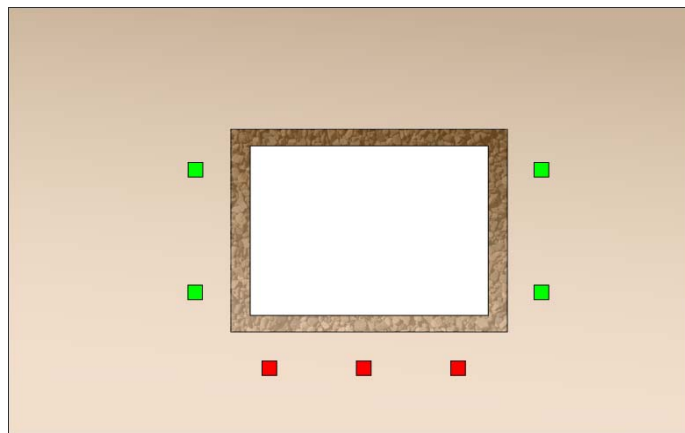
 Monitor groundwater level on the outside of the wall & underneath adjacent buildings

Groundwater level is used to confirm the effectiveness of the dewatering system (where applicable) and the predict settlement underneath adjacent structures

### 3.0 Typical applications contd...


#### Underground Structures

Piezometers are also used to determine pore water and uplift pressures on underground structures; they can also be used to see what effect water pressures and levels are having on joints in the underground structure.




#### Where and what we monitor

#### Why we monitor

 **Beneath the structure**  
Groundwater pressure

To determine uplift pressures to ensure the stability of the buried structure

 **Around the structure**  
Groundwater pressure

To determine pressures acting on the buried structure to determine any joint movement and structural integrity



## 4.0 Installation

### 4.1 Introduction

Whilst piezometers are generally robust devices, they are precision measuring instruments. They and their associated equipment should always be handled with care during transportation, storage and installation.

Installations will always be site specific and the following are points to be considered when planning an installation:-

- Ensure correct filter type is suitable for the soil type
- Ensure the correct type of piezometer is selected for the application e.g. Filter pocket, fully grouted, Drive-in
- Do not allow saturated piezometers to freeze
- All equipment should be stored in an environment that is protected from direct sunlight
- Label tubing and cables clearly. Colour coded tapes are commonly used for instrument identification and to mark installation depth
- Borehole depth should be checked prior to installation
- Cable routing should be selected carefully so as to minimise the risk of breakages

### 4.2 Filter preparation

Piezometers are fitted with a filter. Transducer type piezometers are fitted with removable filters which should be saturated prior to installation.

#### **Saturating LAE (Low resistance to air entry) for medium or high permeable soils:-**

- Place piezometer probe in water for 15 minutes
- Gently tap the probe to remove any bubbles from the probe head

#### **Saturating HAE (High resistance to air entry) for low permeable soils:-**

Geosense HAE filters are always saturated in the factory and covered with an impermeable membrane in order to keep them saturated.

#### **Preparation by Immersion:**

- Prepare de-aired water (this is boiled water and allowed to cool down)
- Plug the ends of the probe so that water is only allowed to react with the outside of the probe
- Allow air to escape from the top plug (as seen in the diagram below)
- Allow the probe to stand in de-aired water for 24 hours

### 4.3 Piezometer installation

The requirements for piezometer installations are wide and varied and therefore for details of full installation of each individual type of piezometer please refer to the installation manual.

#### **Key Note:**

De-aired water is either by boiled water that is allowed to cool under vacuum or produced by special water de-aerators

## 5.0 Reading piezometers

The information in the following section only refers to that of vibrating wire piezometers. For details on other types of piezometer please refer to the individual installation and operation manuals.

### VW piezometers

Interrogation of vibrating wire piezometers can be carried out using hand held readouts and/or automatic data acquisition systems (data loggers).

#### 5.1 Signal output

The signal generated by a vibrating wire piezometer is a frequency. A specialist vibrating wire readout or data logger is used to excite and measure the response of the sensor. The measurement of the response is displayed by the readout in the following formats:-

- **Frequency** - the unit of which is Hertz (Hz)
- **Linear Digits (B unit)**  
The frequency output from VW sensors is not proportional to the applied change in length of the wire. In order to overcome the problem of a linear conversion described the frequency value can be squared, thereby rendering it linear, but quite large. To reduce its size, it is often divided by 1000 (or multiplied by  $10^{-3}$ ). The expression  $\text{Hz}^2/1000$  (or  $\text{Hz}^2 \times 10^{-3}$ ) is the most commonly adopted as a 'linear' digital output often referred to as B Units.
- **Period Units ( P )** Some readout devices utilise the 'counter' function available in many common integrated circuits.

Period Units represent the time taken for the wire to vibrate over one full oscillation, expressed in seconds. Due to the very small size of the number generated most equipment manufacturers display the unit multiplied by either 1000 (  $10^3$  ) or 10000000 (  $10^7$  ).

The relationship between Period units and Frequency units is expressed as

$$P = \frac{1}{\text{Frequency}}$$

#### 5.2 Signal conversion

To enable conversion from the raw data ( in the units described above ) into engineering units such as pressure an instrument requires a Calibration Factor . The value of the calibration factor will vary depending upon the engineering units into which the raw data is to be converted.

The engineering units typically associated with vibrating wire piezometers are:

- Metres of water
- kPa
- psi

## 5.0 Reading piezometers contd...

### 5.2 Signal conversion contd...

#### Linear Calculation

This is the most straightforward calculation to convert 'raw' data to engineering units. It can be easily carried out using a simple calculator. It assumes that the reading is in Linear Digits ( Hz<sup>2</sup>/1000 ).

Where this is not the case, the reading should be converted to these units prior to application of the calibration factors. For most applications this equation is perfectly adequate and is carried out as follows:

Pressure ( kPa ) = Linear Factor for kPa (k) x ( Current Reading - Zero Reading )

An example of the calculation from Linear Digits ( Hz<sup>2</sup>/1000) to kPa using a

Polynomial equation is given below:-

Calibration Factors for kPa A = - 6.3014 -7

B = - 0.1685013

C = 1664.594

Current Reading in Linear Digits = 9244.3

#### Equation

Pressure in kPa = [ A x ( Reading )<sup>2</sup> ] + [ B x Reading ] + C

= [ - 6.3014 -7 x (9244.3)<sup>2</sup> ] + [ - 0.1685013 x 9244.3 ] + 1664.594

= - 53.85 - 1557.67 + 1664.59

= 53.07 kPa

## 5.0 Reading piezometers contd...

### 5.3 Hand held readouts

There are several types of handheld readouts available most of which, are able to read any type of vibrating wire instrument and options include:-

- Direct display - readings need to be manually recorded
- Data storage - readings can be stored for later downloading
- Facility to convert to engineering units - calibration factors and zero values are entered and stored on the unit allowing the conversion to be performed.

### 5.4 Automatic data acquisition systems

A system designed to regularly record data from instruments independent of operator input, often used in remote environments. A data logger controls and logs the sensor readings and can respond to pre-set alarm trigger levels through on-board software.

Typical components could include:-

- **Central processing unit (CPU)** – to which all the components are linked
- **Vibrating wire interface**  
A vibrating wire interface is used to excite VW sensors and on measuring the response performs a Fourier transform which converts the signal frequency into a digital signal e.g. RS 232 which can be transferred to a CPU
- **Multiplexers:** A relay mechanism controlled by the CPU to switch between multiple sensors so that they can be monitored by a single CPU
- **Power Supplies:** A power supply provides regulated power to the logger and sensors. Power is drawn from a battery that is charged either from an AC supply or a solar panel
- **Communication:** Remote or local connection to the CPU to program or download data including GSM, GPRS, radio and cable
- **Software:** Which allows the user to configure code to control the CPU, interrogate and download stored readings either as raw data or engineering units.



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