

NOTE: This application guide is intended only to give an overview of the several types of inclinometers 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 - INCLINOMETERS

1.0 General description

An inclinometer measures **TILT** (the measurand) which is used in several calculations (computations) to quantify displacement and deflections of slopes, embankments, and structures.

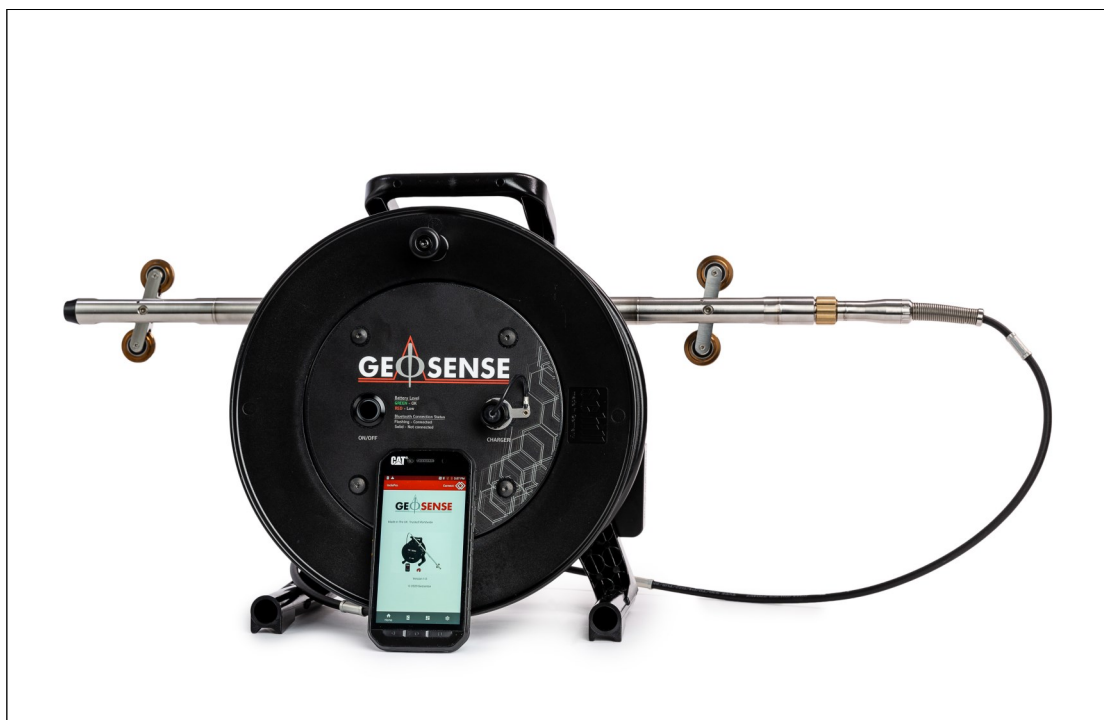
There are two types of inclinometer:-

- **Portable**
- **In-place**

1.1 Portable inclinometer

The portable system comprises of several components as follows:-

- 1.) Wheeled probe
- 2.) Reel
- 3.) Cable
- 4.) Readout (Android Smart Device)
- 5.) Accessories including cable gates, battery chargers, spare batteries



2.0 Principle of operation

MEMS inclinometers employ 'State of the Art' MEMS sensor technology. MEMS (Micro -Electro - Mechanical Systems) are an integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate through micro fabrication technology.

The mechanical structure of a typical MEMS sensor is shown in Figures 1 & 2 below

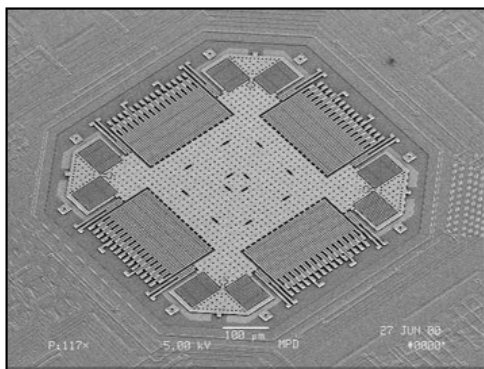


Figure 1

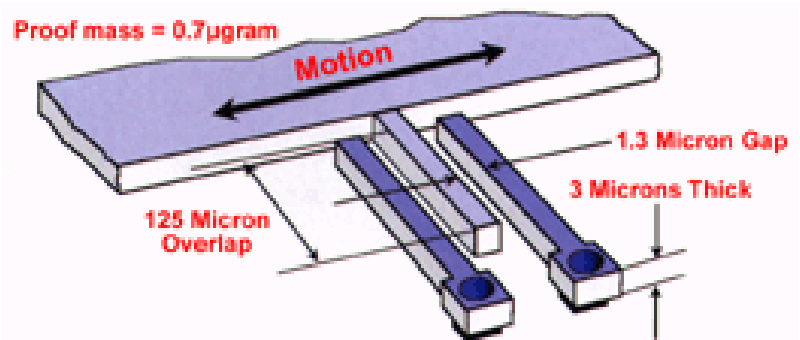


Figure 2

Polysilicon springs suspend the MEMS structure above the substrate such that the body of the sensor (also known as the 'proof mass') can move in the X and Y axes.

Acceleration causes deflection of the proof mass from its centre position. Around the four sides of the square proof mass are 32 sets of radial fingers. These fingers are positioned between plates that are fixed to the substrate. Each finger and pair of fixed plates make up a differential capacitor, and the deflection of the proof mass is determined by measuring the differential capacitance.

This sensing method has the ability of sensing both dynamic acceleration (i.e. shock or vibration) and static acceleration (i.e. inclination or rotation). Signal conditioning is carried out within inclinometers so that a simple output signal is obtained. This output can be used in conjunction with a calibration sheet to easily calculate the amount of tilt that has occurred.

The MEMS sensors within inclinometers are configured to measure inclination from vertical. As movement occurs, the inclinometer will move with its mounting, thus changing the inclination of the internal sensors.

Portable inclinometers

Within portable inclinometers there are two MEMS sensors mounted 90° to each other (biaxial) which have the following operating ranges:-

- Portable vertical ± 30° from vertical
- Portable inclined ± 30° from 35° from horizontal
- Portable horizontal ± 30° from horizontal

2.0 Principle of operation contd...

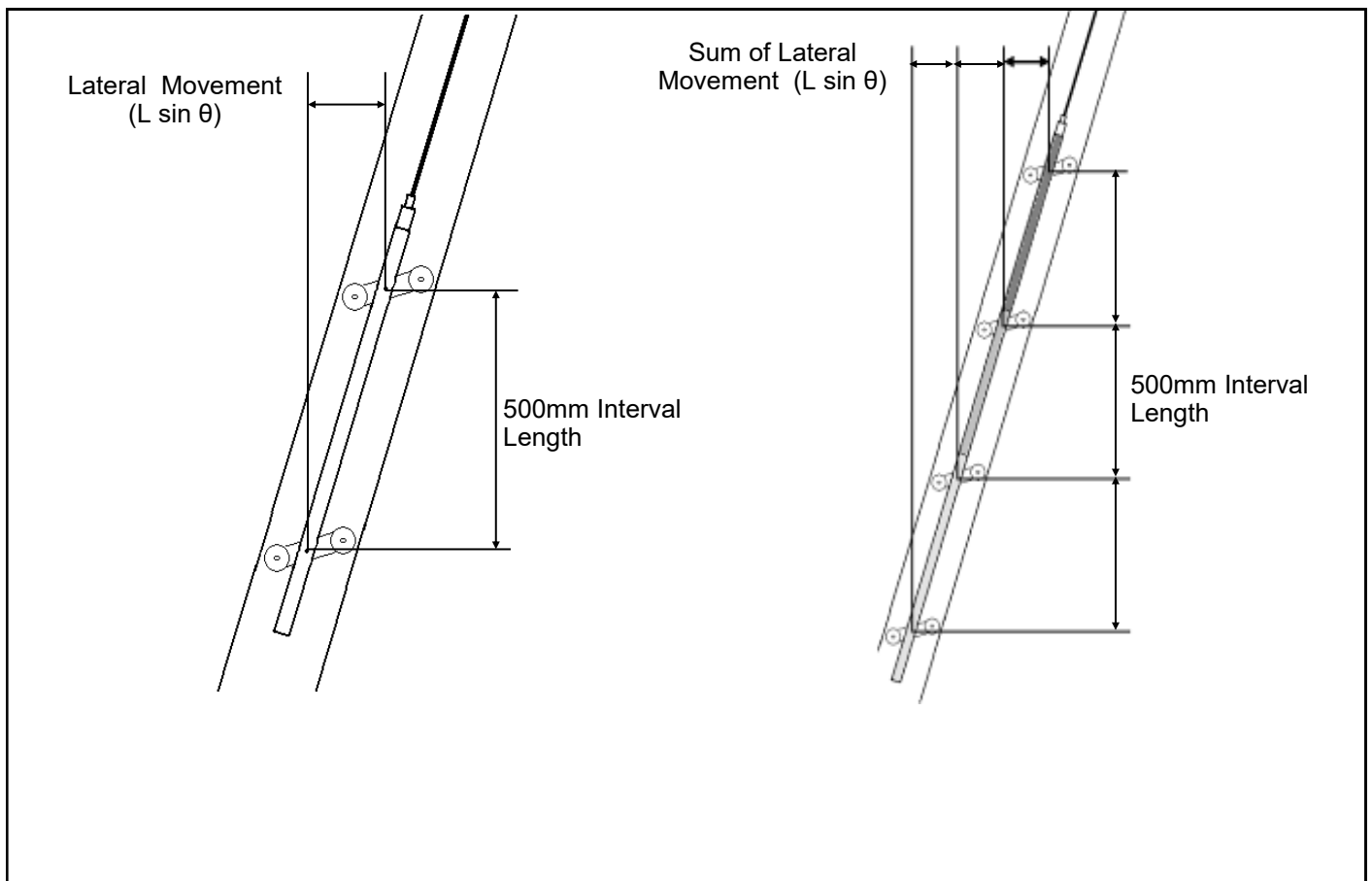
An inclinometer sensor actually measures tilt, rather than lateral movement and therefore the basic principle requires calculations using the sine function, an angle, and the hypotenuse of a right angled triangle. This produces a value for the 'Deviation from Vertical'.

The software in the readout often carries out the conversion of the 'tilt' to an 'offset' over the length of the probe, a value in mm will indicate that the top of the probe is offset from the bottom by this value; the Deviation from Vertical. The wheel centres are the 'gauge length' of the probe, over which the measurements are made.

A portable inclinometer probe has its two sets of wheels at a distance of 500mm apart. In order to obtain a complete survey of the ground along the inclinometer casing it requires a series of measurements to be taken.

The probe is placed at the base of the casing and a reading taken. The probe is then raised at 500mm intervals and readings taken until the probe reaches the top of the casing. This set of readings is known as the A+ readings.

The probe is then rotated 180°, replaced into the casing to the base and a second set of readings taken as described previously. This second set is known as A- readings. As inclinometers have two accelerometers with their axes at 90° the A axis is in line with the wheels and the B axis orthogonal to it.



2.0 Principle of operation

Deformation is measured using a special inclinometer casing which is placed into a borehole, cast into concrete or included in a structure or embankment.

The casing has four orthogonal grooves designed to fit the wheels of the probe. The probe is passed along the casing to measure its inclination, with respect to vertical, or 45° or horizontal, at 500mm intervals.

The probe contains two MEMS accelerometers whose structure is flexed when acted on by gravity. This changes their capacitance and their output voltage. The output voltage is proportional to the sine of the angle of inclination and therefore also proportional to the horizontal deviation of a vertical borehole or the vertical deviation of a horizontal borehole.

In order to avoid confusion there is an industry standard which defines the orientation of the probe and casing as follows:-

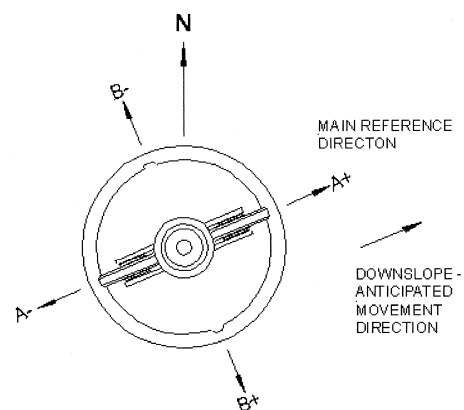
A axis = the direction of the anticipated movement

A+ = the orientation of the casing groove into which the leading wheel of the inclinometer probe is located on the first run of a set of readings. This is also the orientation of the primary sensor

A- = the orientation of the casing groove into which the leading wheel of the inclinometer probe is located on the second run of a set of readings. This is also the orientation of the primary sensor

B+ = the orientation of the secondary sensor during the first run of a set of readings

B- = the orientation of the secondary sensor during the second run of a set of readings

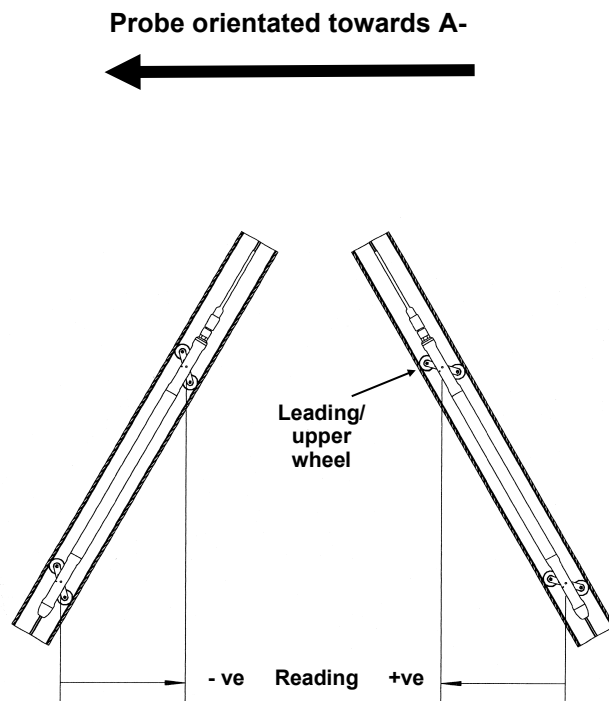
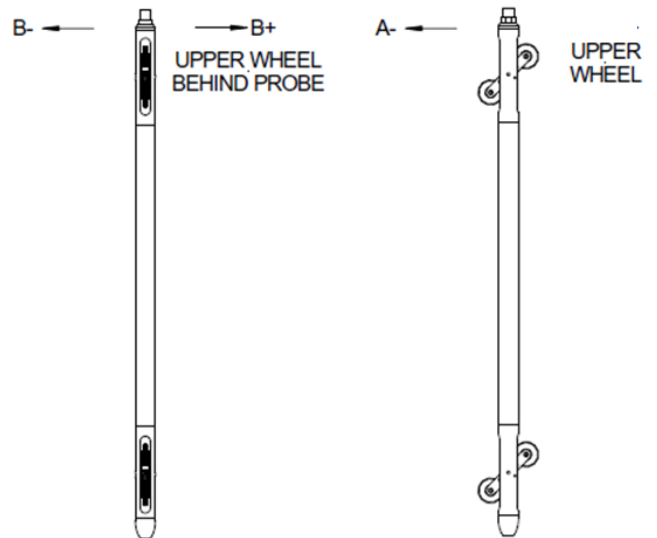
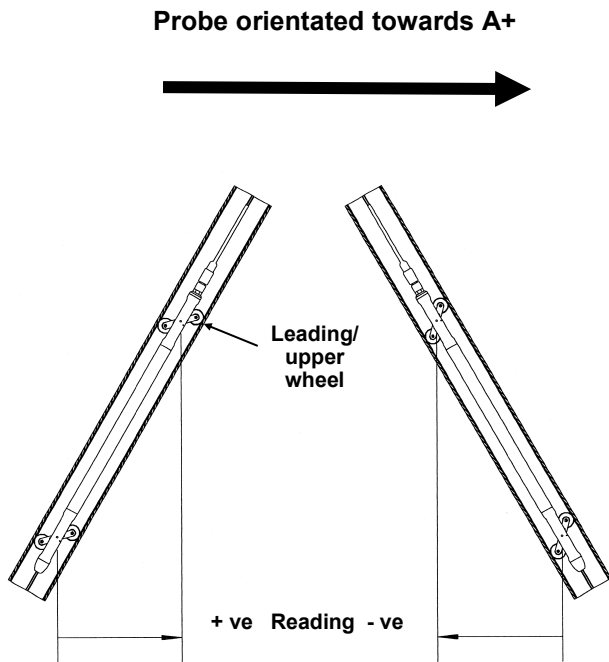


Key Notes:

- Inclinometer casing traditionally has four grooves. This is a result of the fact that early inclinometers included only one sensor. Therefore in order to obtain a full survey the casing had to be surveyed in four directions.
- As there appears to be no definitive industry explanation as to why four grooves are still used it is understood that they have been retained to provide an element of flexibility/redundancy during installation where if necessary the B axis grooves could be used.

3.0 Industry convention

In order to avoid confusion as to the direction of tilt of the probe, a positive value indicates that the top of the probe is tilting in the direction of the “leading wheel” (upper wheel) as illustrated below.



4.0 Typical reasons to install inclinometers

Site Investigation – Inclinometers are used to ascertain the soil stability of a site, by monitoring movements and by also locate the shear plane.

Design verification and adjustments – Inclinometers can also be used to verify movements in, terms of magnitude, direction and that rate of movement of a structure. The readings obtained then can be compared to the allowable movements that are specified in the designs parameters. If the readings in the design specification are surpassed then remediation measures can be taken.

Long term performance – Changes in the ground conditions can be highlighted by the installation of inclinometers. Long term measurements can be made with inclinometers placed behind the retaining walls. If movements are detected from behind the wall, before they are visible, this would allow remediation measurers to be under taken.

Corrective measures - as they are used to monitor the magnitude, direction and rate of movement this information helps Engineers determine the need for corrective measures such as placing temporary ?????at the base of an unstable slope prior to full remedial works being carried out.

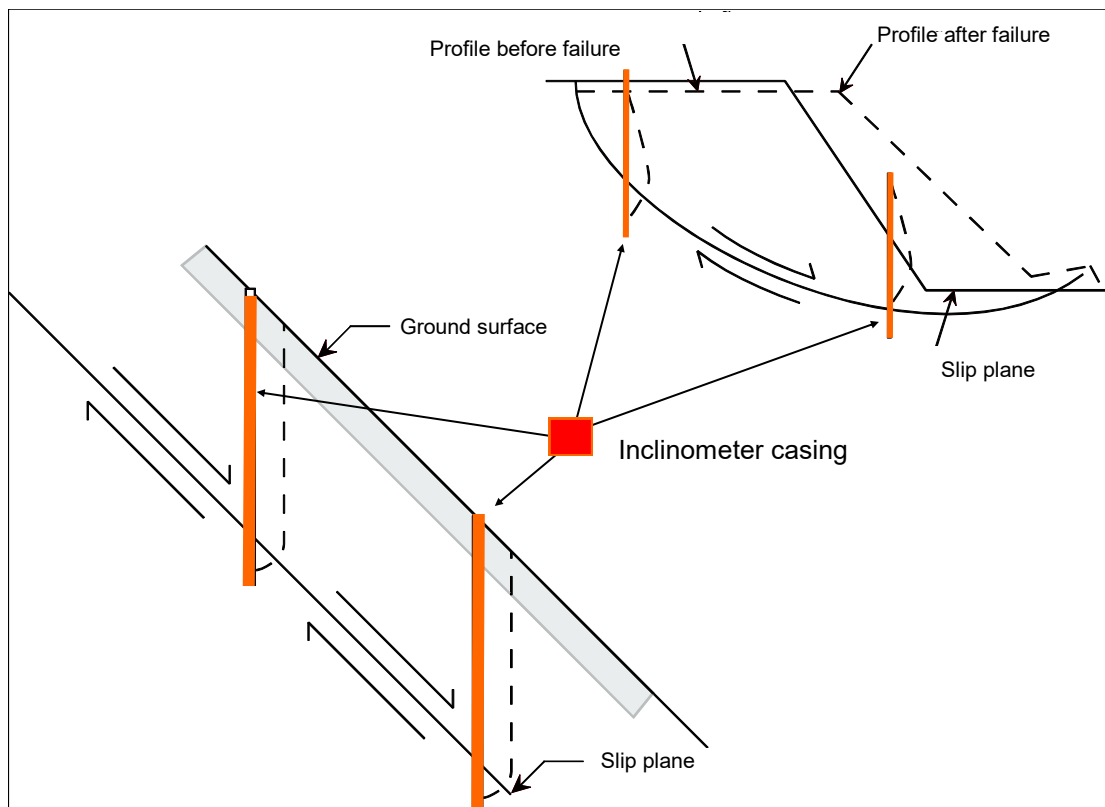
Safety - inclinometers are widely used for monitoring slopes adjacent to infrastructure such as roads and rail where failure can lead to serious damage or loss of life. In addition monitoring of deep excavations with diaphragm walls especially adjacent to existing buildings gives advance warning if any movements are occurring and the ability to alter excavation techniques or increase the wall support.

5.0 Typical applications

| APPLICATION | ELEMENT | MEASURAND | COMPUTATIONS |
|------------------------------------|---|-----------|--|
| | | | |
| Dams & Embankments | Dam toe | Tilt | Rotation (slip planes) |
| | Body | Tilt | Rotation (Lateral movement) |
| | Foundation | Tilt | Rotation (Lateral movement) |
| | Structures | Tilt | Rotation (bending) |
| | | | |
| Retaining Walls & deep excavations | Wall (diaphragm, sheet, contiguous piles etc) | Tilt | Rotation |
| | Wall to foundation | Tilt | Rotation (Lateral movement) |
| | Supported material | Tilt | Rotation (Lateral movement) |
| | | | |
| Slopes & embankments | Body | Tilt | Rotation (slip planes) |
| | | | |
| Load Testing | Piles (horizontal loading) | Tilt | Rotation (bending) |
| | | | |
| Tunnels & shafts | Adjacent soils | Tilt | Settlement & rotation (lateral movement) |
| | | | |
| Bridges | Piers Abutments | Tilt | Rotation |
| | | Tilt | Rotation (slip planes) |
| | | | |
| Ground improvement | Body | Tilt | Rotation (Lateral movement) |

5.0 Typical applications contd...

Slope /Landslides –

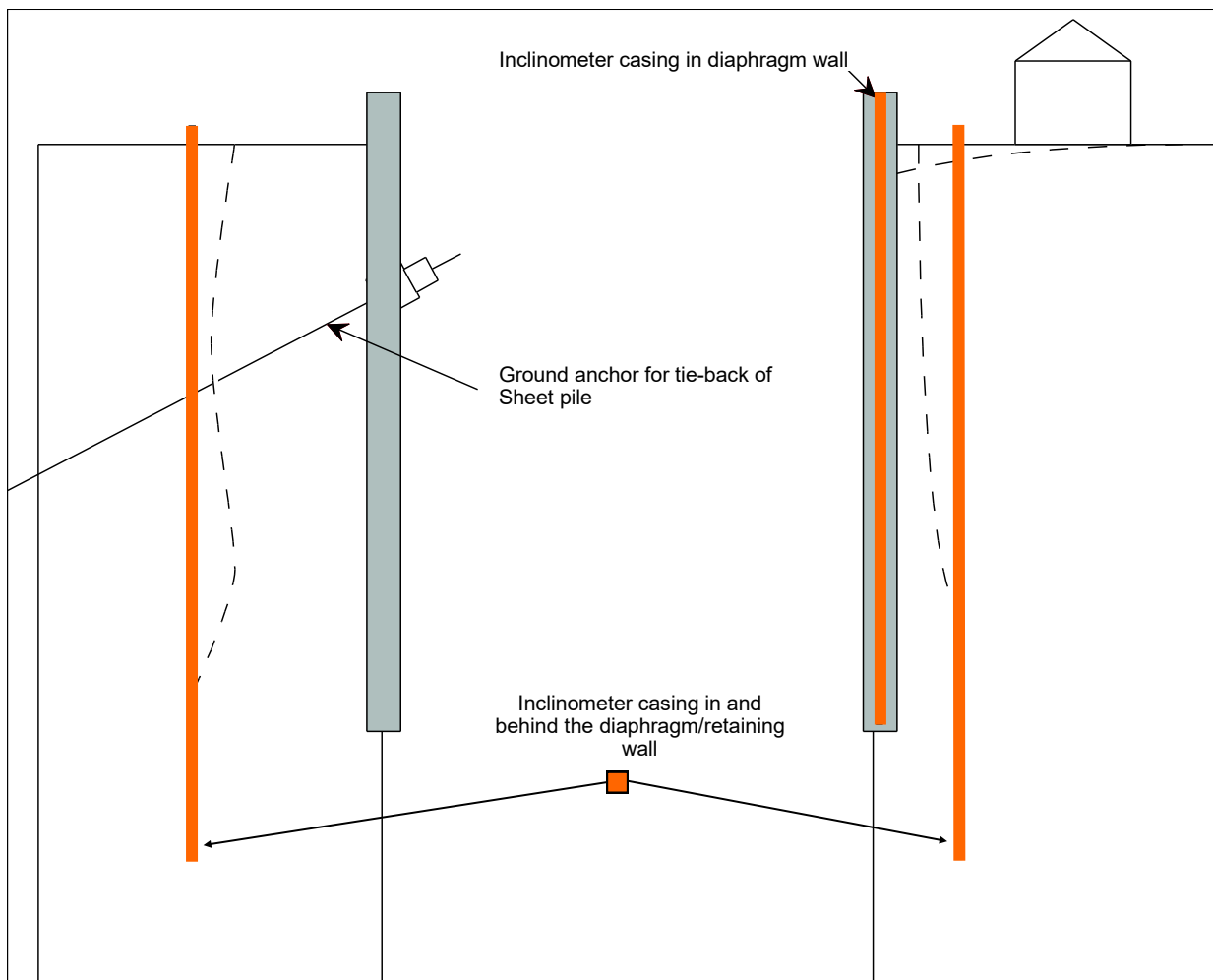


Inclinometers can be located in slopes and in areas that are sensitive to landslides and can help to identify the following:-

- **Locate Shear zones**
- **Identify if shearing is occurring in plan or circular form**
- **Measurement of movement**
- **Determine if movements are continues**
- **Determine the speed of movement**

5.0 Typical applications contd...

Sheet Piles and Diaphragm Walls

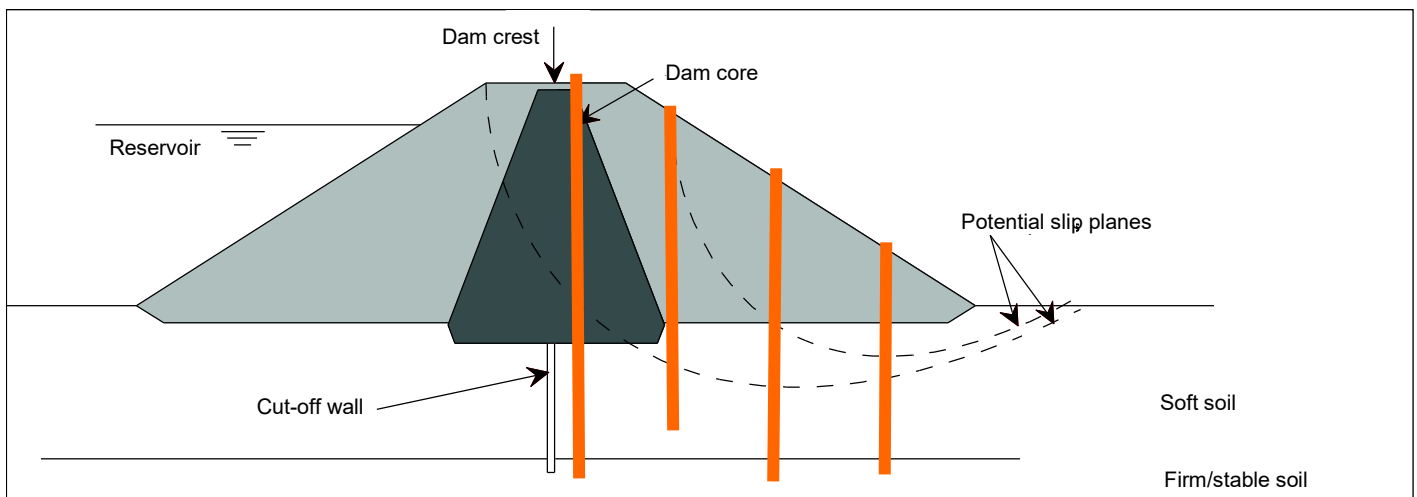


Inclinometers can be located in diaphragm/retaining walls to confirm the following:-

- **Stability of the retaining wall**
- **Deflection of the walls**
- **Any movements that occur in the walls are within the design limitations**
- **Ground movements that will affect other buildings near by**
- **The performance of struts, rock bolts or anchors**

5.0 Typical applications contd...

Earth/rockfill dams



Inclinometers help to identify the following parameters:-

- **Movement in downstream section of dam (during and after construction).**
- **Identification of shear zones in dam foundations.**
- **Identification of movement in upstream section of dam (during and after construction).**
- **Identification of :**

Type of movement

Depth of movement

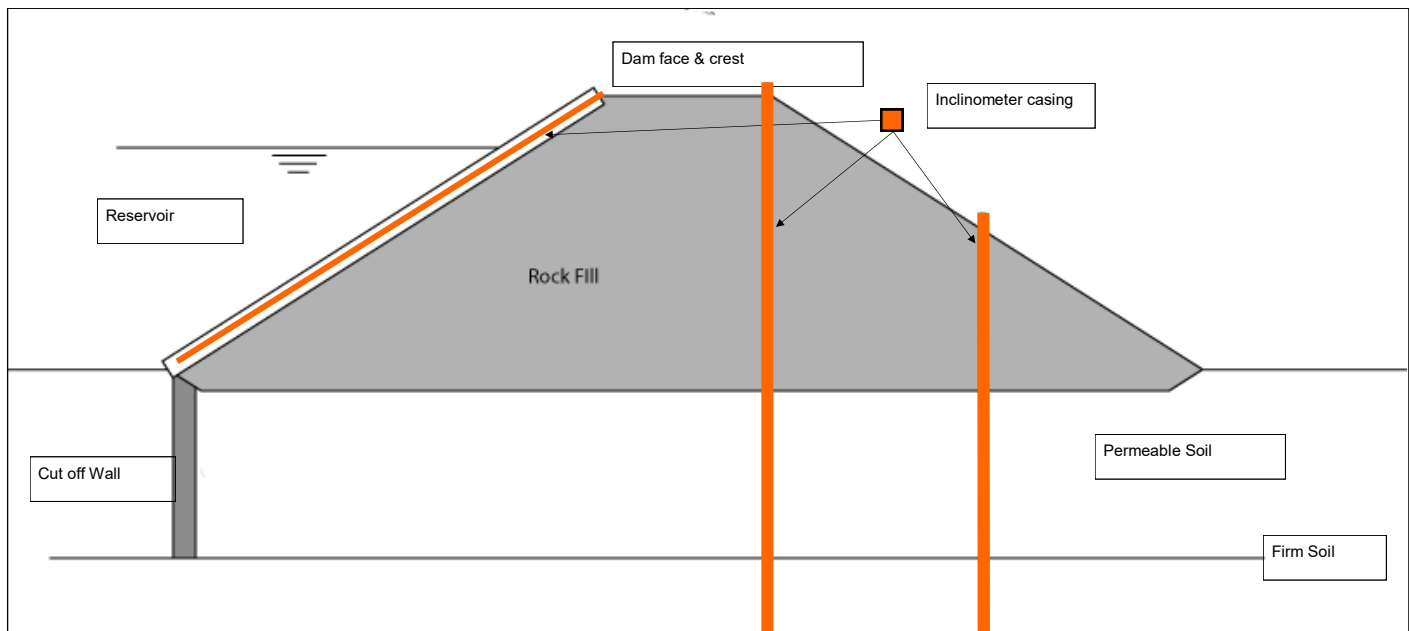
Direction of movement

Magnitude of movement

Rate of movement

5.0 Typical applications contd...

Concrete faced dam

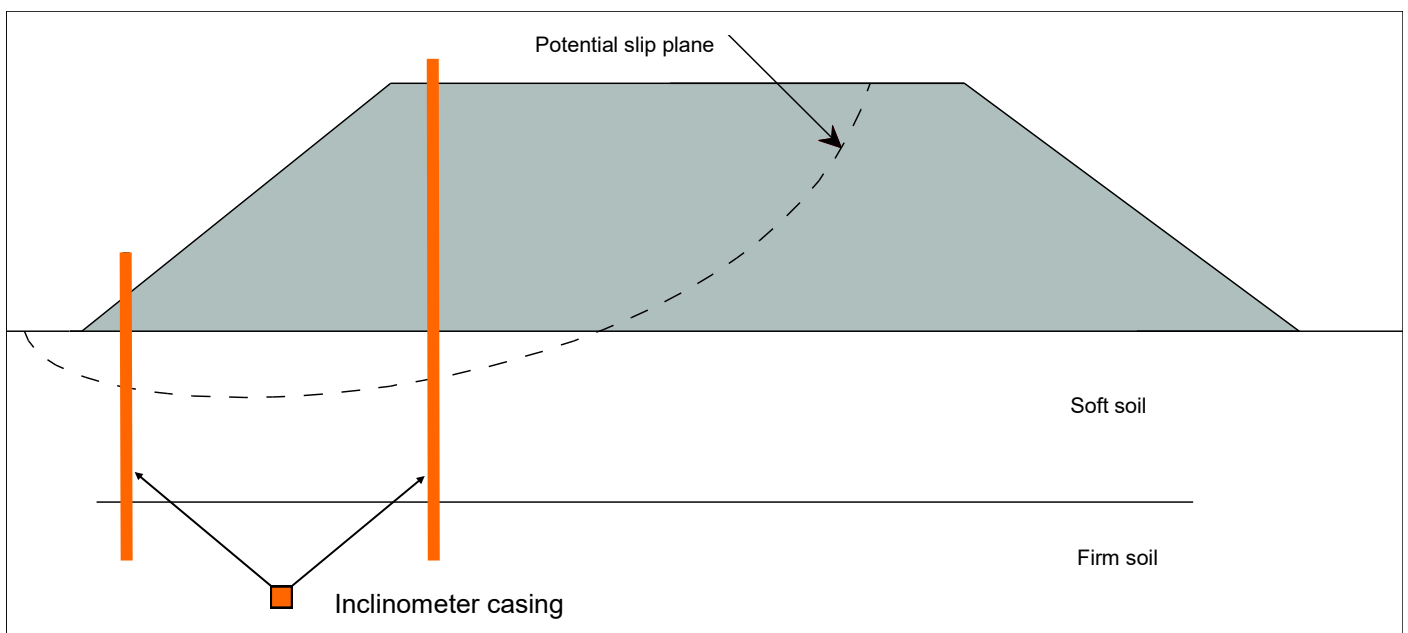


Inclinometers help to monitor and/or establish the following :-

- Deformation of the concrete face slab which can lead to propagation of cracks and result in seepage through the dam
- The stability of upstream slopes during and after filling (impounding) as failure could result in dam over-topping.
- Movement in the downstream side of the dam especially during filling (impounding)
- Whether any shear zones develop in the foundation
- The type, depth, direction, magnitude and rate of movement

5.0 Typical applications contd...

Embankments

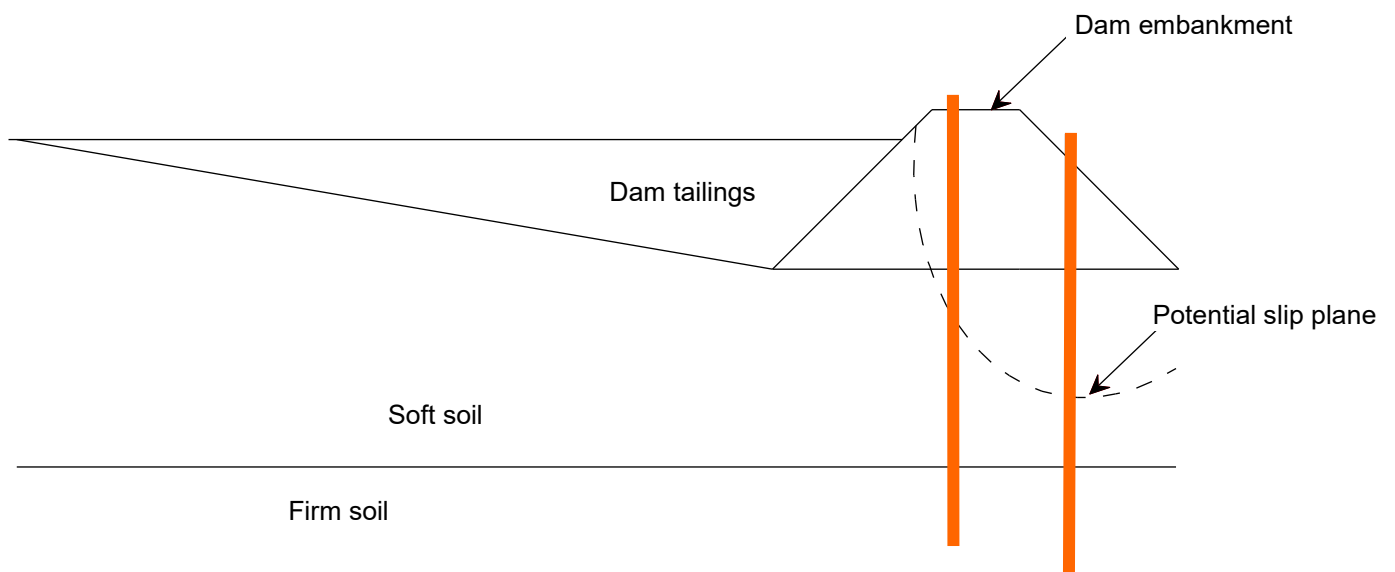


Inclinometers help to monitor and/or measure the following :-

- The location of any shear zones and what type e.g. circular or planar
- The movement at the shear zone and determine whether the movement is constant, increasing or decreasing
- Lateral movement of soft foundation material

5.0 Typical applications contd...

Tailings dam

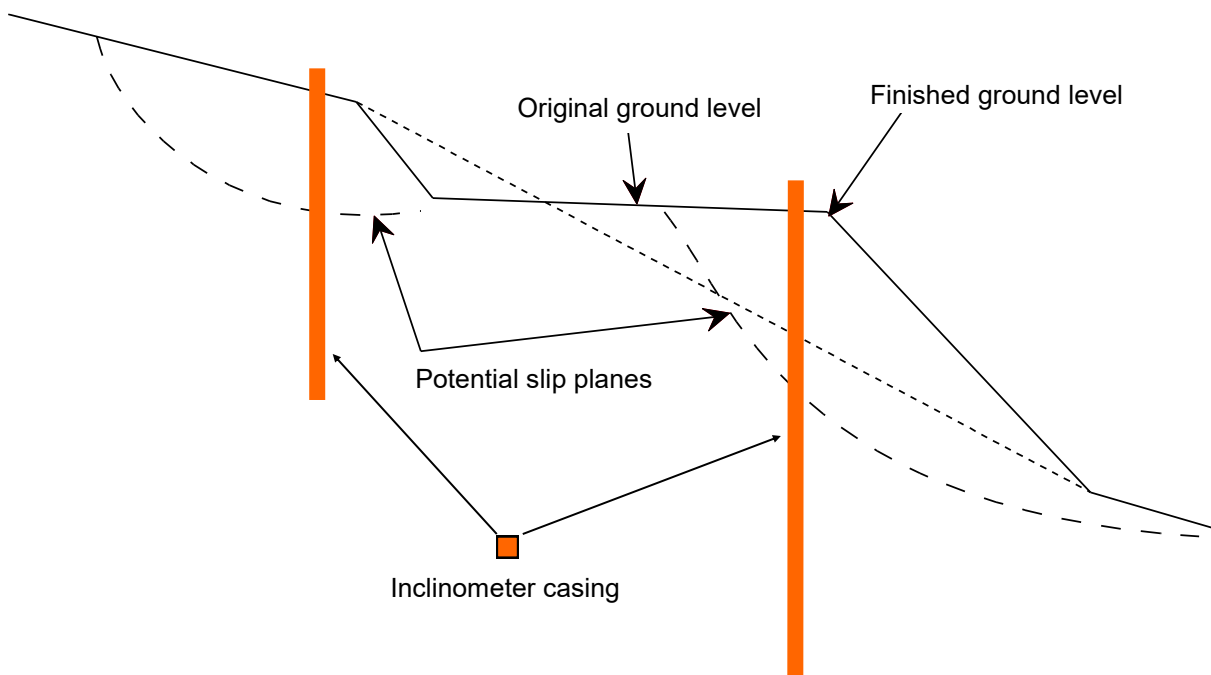


Inclinometers help to monitor and/or measure the following :-

- The location of any shear zones and what type e.g. circular or planar
- The movement at the shear zone and determine whether the movement is constant, increasing or decreasing
- Lateral movement of soft foundation material

5.0 Typical applications contd...

Cuttings

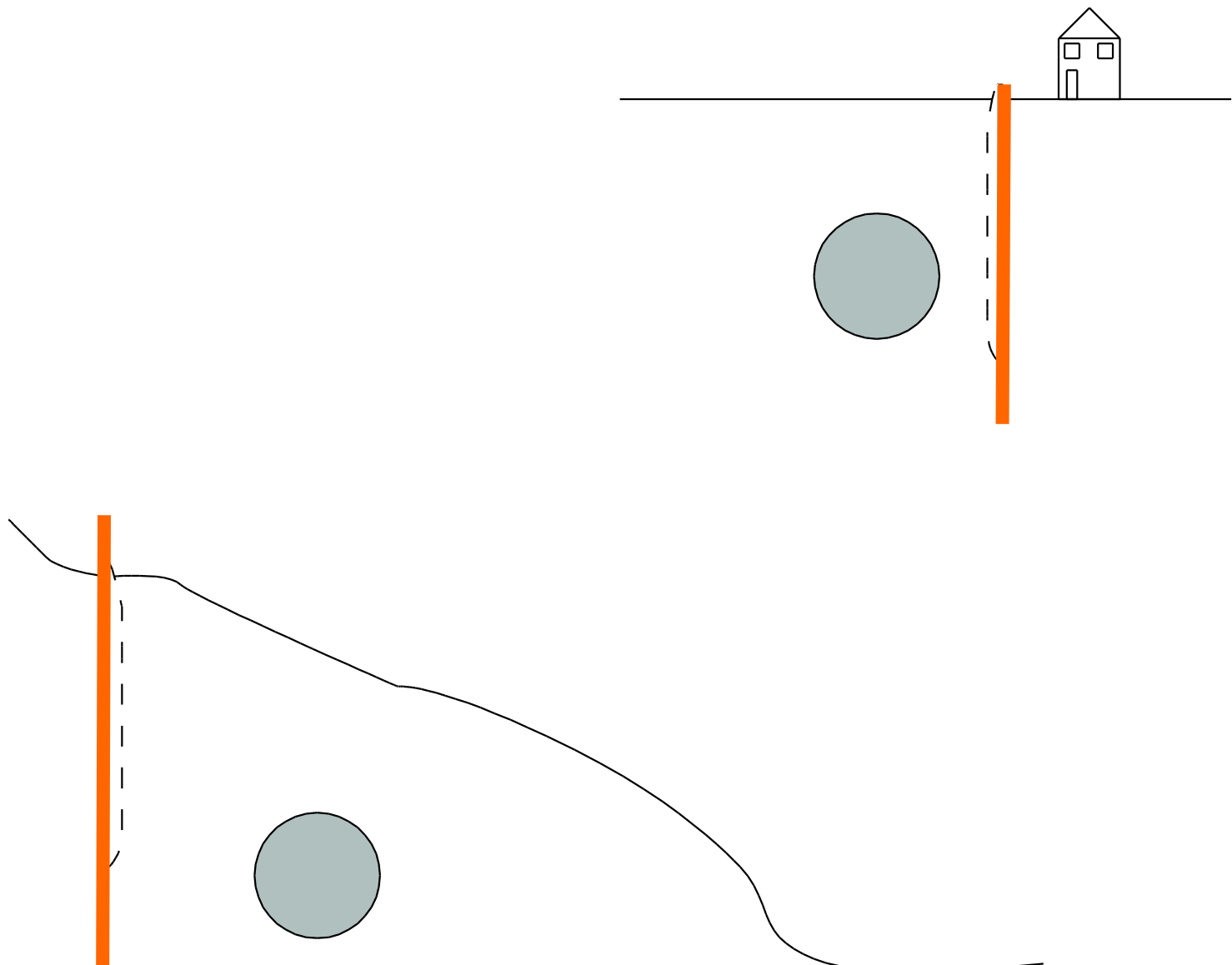


Inclinometers help to monitor and/or measure the following :-

- Locate shear zones
- Identify if shearing is occurring in plan or circular form.
- The movement at the shear zone and determine whether the movement is constant, increasing or decreasing

5.0 Typical applications contd...

Tunnels

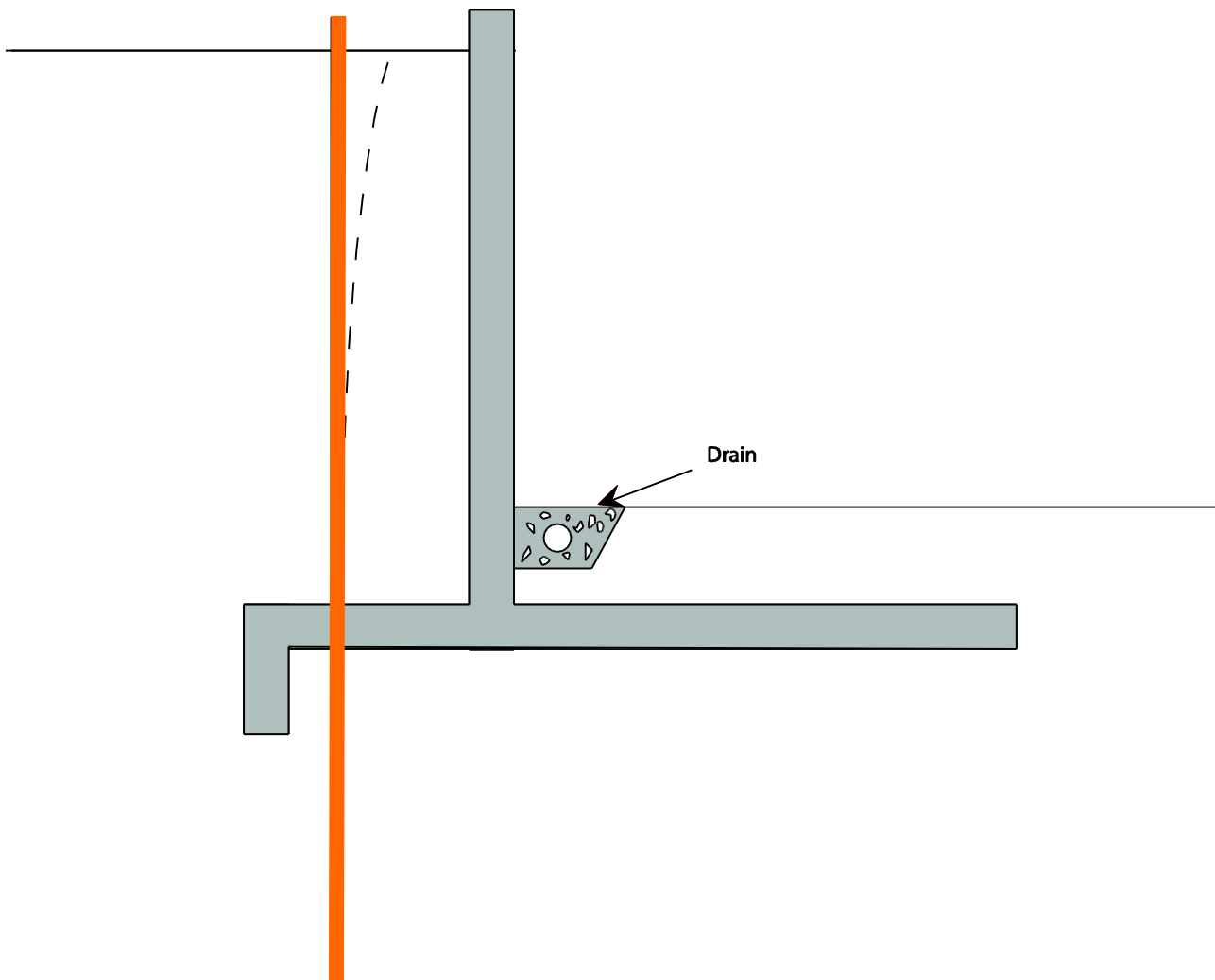


Inclinometers help to:-

- Monitor movements in the soil due to construction of tunnels that may harm near by services/ underground structures and buildings on the surface
- Check design assumptions and modify model as required

5.0 Typical applications contd...

Retaining wall

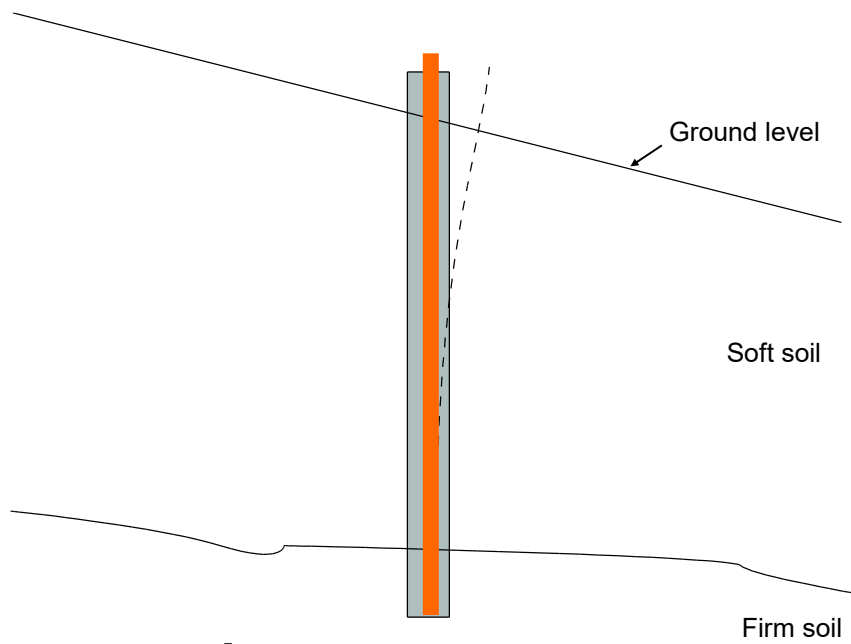


Inclinometers measure and/or monitor:-

- **Rotation of the wall**
- **Bending of the wall**

5.0 Typical applications contd...

Laterally loaded pile



Inclinometers measure and/or monitor:-

- **Bending of the pile**
- **Limits of movement to provide information for remedial action**

6.0 Purpose of inclinometer measurements

Locate and measure lateral movement

Lateral movement or “displacement” is the change of position of the inclinometer casing. Displacement of the inclinometer is taken away from the original reading by the most recent reading taken from the inclinometer. Once a number of readings have been attained then the movement of the structure can be shown incrementally. Cumulative displacement is the addition of all the incremental data.

The displacement can be seen of an inclinometer in relation to a fixed point near to the bottom of the inclinometer casing. However if the bottom of the casing is moving then the reference point of how much the inclinometer has moved can be taken from the top of the casing, that will have to be surveyed before.

Locate Shear zones

Inclinometers are ideal for the investigation and location of shear zones, within slopes and retaining walls for example. The accurate location, depth and type of shearing that is occurring in the affected ground that is identified by inclinometers provides information that can be used to calculate the likelihood of lateral earth movement occurring. This information provided by the inclinometer also provides information that is used to produce factors of safety for the slope.

Identify if shearing is occurring in plane or circular form.

The inclinometer probe also can identify what kind of shearing is occurring in a slope that can not be seen to the naked eye. The identification of the kind of shearing that is occurring e.g. plan or circular failure, will influence the calculations that need to be carried out in order to make the slope safe.

Determine if movements are continuous

The inclinometer probes can also identify if a slope or retaining wall is continuous. In many cases the slopes can become dormant to movement, until some environmental conditions suddenly change, due to freak weather events or the removal of vegetation and drainage. If movement starts to occur then the inclinometer probe can identify that movement is occurring and then remedial actions can then take place.

Thus the inclinometer probes can be used as a warning device that is permanently in-place around sensitive areas, such as areas of high population.

Determine the speed of movement.

The determination of the speed of movement is key to any slope or retaining wall, this is because of the calculation of the slope stability analysis and how long it will take to reach an area of sensitivity. If needed from the speed of movement a decision can be made in the response of the speed of movement, for example if the speed of movement is too fast that a temporary sheet pile wall will need to be put in place or other remedial activities may need to be carried out, so that the speed of movement is reduced or stopped and this can only be done with measurements taken from an inclinometer probe.

7.0 Portable inclinometer measurements & plots

At any position within the inclinometer casing, three readings are recorded.

- Depth
- Inclination (tilt) of the sensors in the “A” direction
- Inclination (tilt) of the sensors in the “B” direction

To minimise possible system errors, readings using portable inclinometers are each recorded twice. The probe (in which the sensors are housed) is first read in the primary direction, “A+” then rotated through 180 degrees “A-” and the whole survey re-read.

During data reduction, because there are two readings, the A- reading is subtracted from the A+ and the resultant is divided by 2. This maintains the direction of the movement , indicated by a positive or negative sign.

Prior to any monitoring of a manually read inclinometer installation, a series of sets of inclinometer surveys are recorded (usually 3sets) in a particular casing. These are called the Base Readings and usually one set is selected as the reference for all future calculations for this installation.

Deviation

An inclinometer sensor actually measures tilt, rather than lateral movement and therefore the basic principle requires calculations using the sine function, an angle, and the hypotenuse of a right angled triangle. This produces a value for the ‘Deviation from Vertical’.

The software in the readout often carries out the conversion of the ‘tilt’ to an ‘offset’ over the length of the probe, a value in mm will indicate that the top of the probe is offset from the bottom by this value; the Deviation from Vertical. The wheel centres are the ‘gauge length’ of the probe, over which the measurements are made.

Displacements

Displacements are calculated by comparing the current readings to the ‘Base’ or previous readings. Changes in deviation are called displacements as any change indicates that the casing has moved from its original position. When displacements are summed and plotted, the result is a high resolution representation of movement.

Checksum or Face Difference

A checksum or face difference is a function of the sum of an A+ reading and an A- reading at the same depth. In some cases it is divided by 2 and in other not. It serves as a ‘check’ on the quality of the data and the integrity of the inclinometer tubes.

Inclinometer plots

Common graphical display of inclinometer measurements include:

1. **Cumulative displacement** - a plot of cumulative displacement at depth against time. Starting, normally, at the base of the installation, the displacements at each elevation are added together to create an accumulative plot of displacements at each elevation from the base upwards. Sequential data sets generate a new plot line.
2. **Incremental displacement** - a plot of incremental displacement at depth at each depth. Sequential data sets generate a new plot line.
4. **Cumulative deviation** – a plot showing the profile of the casing relative to vertical (cumulative deviation against depth). Since inclination of the casing can contribute to error, the cumulative deviation plot is useful for diagnosing and correcting “rotational” errors.
5. **Incremental deviation** - a plot of the readings converted to lateral offset at each reading interval (incremental deviation against depth).

7.0 Inclinometer measurements & plots contd...

6. **Checksum** - shows checksums for each data set and can be used to evaluate the quality of the datasets. Spikes in the plot may indicate bad readings or a characteristic of the casing.

7. **Polar cumulative displacement** – shows the cumulative displacement of the casing movement assuming the top or bottom of the casing as reference and as origin of the movements. This is the change in position of the tube looking along its length.

8. **Polar cumulative deviation** - shows the cumulative deviation of the casing assuming the top or bottom of the casing as reference and as origin of the measurements. This is the actual 'shape' of the installed tube looking along its length.

Inclinometer bias - the difference between a probe's non-zero value at true verticality is known as the probe's bias. Every inclinometer probe has a very small bias, which can change through the life of the probe.

Bias shifts are not normally a matter for concern because the value of the bias is effectively eliminated by the standard two-pass survey and data reduction procedure.

Inclinometer Bias-Shift Error - A bias-shift error occurs when the data reduction procedure is unable to eliminate the

8.0 Operation

8.1 Good practice

When conducting inclinometer surveys there are a number of good working measures that includes:-

- The use of the same probe and cable - this provides the most accurate survey.
- When conducting an inclinometer survey it is important to mark the direction or groove of the first readings that are to be taken.
- When taking the first readings after installation, it is good practice to take at least 3 initial readings first, so that reliable data can be obtained from the inclinometer casing.
- Use the same reference point, either the bottom or top of the casing.
- Using a cable gate at the top provides a more repeatable point and helps protect the cable from damage.
- Ensure the probe is adequately protected for storage and transportation.

8.2 Instrument preparation and handling

- Ensure that probe wheels and carriages are moving smoothly. If necessary spray with suitable lubricant
- Inspect O-rings and connectors for wear and damage.
NEVER USE AN OIL BASED LUBRICANT ON THE CABLE TO PROBE CONNECTOR AS THIS WILL DAMAGE IT
- Ensure the cable reel and readout have fully charged batteries.
- Attach probe to cable, ensuring the connection is hand tight (do not over tighten)
- Connect the ASD (Android Smart Device) to probe and cable reel via Bluetooth.

8.3 An inclinometer survey

- Identify the A+ groove in the casing. Insert the probe so that the lowermost wheel is in the opposite groove (A-) and the uppermost wheel is in the A+ groove.
- Lower probe to base of casing and where necessary allow the probe temperature to stabilise.
- Using the cable gate to support the cable, raise the probe through 500mm intervals, allowing the readings to stabilise at each interval and then record them on the readout.
- Once the probe reaches the top of the casing, remove it, rotate it 180° and reinsert into the casing so that the lowest wheel is in the A+ groove. Lower to base of casing and complete survey.
- If a point or measurement is missed lower the inclinometer probe to one point below the missed recording point and pull up to the missed point again and record the reading.

8.4 Taking readings - please refer to Operators Manual

8.5 Data handling - data can either be manipulated manually or by specialist software packages such as SiteMaster - for full details please refer to the Data Handling section or the manual



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