NOTE: This application guide is intended only to give an overview of the several types of tilt sensors 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.

GEOSENSE

APPLICATION GUIDE - MEMS TILT SENSORS

1.0 General description

Tilt Meters measure **TILT** (the measurand) and is used in several calculations (computations) to quantify rotation and settlement of buildings and structures.

They are available in the following types:

- In-place Tilt Meter
- Portable Tilt Meter
- Submersible Tilt Meter
- Tilt Beam

1.1 In-place Tilt Meter

Comprises of a small enclosure which houses a printed circuit board (PCB) onto which is mounted a uniaxial or bi-axial MEMS accelerometer.

The PCB is also fitted with a complex signal conditioning system to ensure that the signal outputs are stable and repeatable.

Designed to measure tilt they are attached by attaching to a mounting plate which is bolted to the structure.

A cable connects the sensor output to a manual readout or data logger.

1.2 Portable Tilt Meter

Comprises of a small enclosure (which houses a printed circuit board onto which is mounted two (bi-axial) MEMS accelerometers), interconnecting cable, stainless steel tilt plates, and the readout instrument.

The PCB is also fitted with a complex signal conditioning system to ensure that the signal outputs are stable and repeatable.

Designed to measure tilt by placing in-situ tilt plates which are bolted or bonded to the structure. The measuring sensor is then accurately, and repeatedly, located into the tilt plates during the reading.

A cable connects the sensor output to a manual readout or data logger.

1.0 General description contd...

1.3 Submersible Tilt Meter
Comprises of a watertight enclosure (IP68) which houses a printed circuit board (PCB) onto which is mounted one (uniaxial) or two (bi-axial) MEMS accelerometers.

The PCB is also fitted with a complex signal conditioning system to ensure that the signal outputs are stable and repeatable.

Designed to measure tilt on submerged structures either on a vertical, inclined or horizontal surface. They can be attached to a submerged structure by bolting, bonding or welding.

A cable connects the sensor output to a manual readout or data logger.

1.4 In-place Tilt Beam
Comprises of a GRP or stainless steel beam onto which is mounted a uniaxial or bi-axial MEMS Tilt sensor PCB housed in a waterproof housing.

The beam can vary in length e.g. 1,2,3M and can be coupled together to form a continuous string and the signal cables BUSSED together.

The PCB is also fitted with a complex signal conditioning system to ensure that the signal outputs are stable and repeatable.

Designed to measure tilt and provide a settlement profiles they are attached by bolting to the structure. They can be mounted horizontally or vertically.

A cable connects the sensor output to a manual readout or data logger.

2.0 Principle of operation

MEMS Tilt Meters 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.

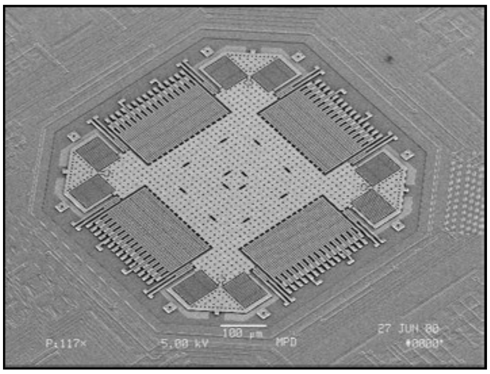


Figure 1

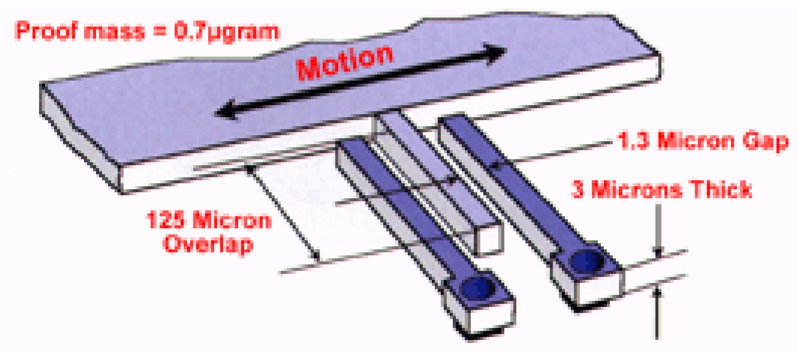


Figure 2

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 Tilt Meters 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 Tilt Meters are configured to measure inclination from vertical. As movement occurs, the Tilt Meter will move with its mounting, thus changing the inclination of the internal sensors.

The MEMS sensors within Tilt Meters measure tilt over a range of +/- 15º. In the bi-axial model, a second MEMS sensor is mounted at 90º to the other sensor and measures tilt in the orthogonal direction, on the horizontal plane. Once mounted on a structure they are normally adjusted to read close to zero, their mid-point. An **'initial reading'** is then recorded and any changes in the inclination of the structure are identified by comparing the current readings with the initial readings.

Tilt Meters are available with an Analogue (4-20mA) or Digital (RS-485) outputs.

Tilt Beams have a digital or digital BUS (RS485) output.

3.0 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.

APPLICATIONS	ELEMENT	CONFIGURATION	MEASURAND	COMPUTATION
Structures	Retaining walls	Point	Tilt	Rotation
		Linked	Tilt	Bending Displacement Settlement
	Bridges	Point	Tilt	Rotation
		Linked	Tilt	Bending Displacement Settlement
	Buildings	Point	Tilt	Rotation Differential settlement
		Linked	Tilt	Bending Displacement Settlement
	Towers & columns	Point	Tilt	Rotation
		Linked	Tilt	Bending Displacement
Excavation	Retaining walls	Point	Tilt	Rotation
		Linked	Tilt	Bending Displacement
	Nearby buildings	Point	Tilt	Rotation Differential settlement
		Linked	Tilt	Bending Displacement Settlement
Tunnelling	Lining	Point	Tilt	Convergence Rotation
		Linked	Tilt	Convergence Rotation Settlement Displacement
De-watering	Nearby buildings	Point	Tilt	Rotation Differential settlement
		Linked	Tilt	Bending Displacement Settlement
Slope stability	Soil/rock mass	Point	Tilt	Rotation
		Linked	Tilt	Rotation Settlement Displacement
Dams	Concrete face	Point	Tilt	Rotation
		Linked	Tilt	Rotation Settlement Displacement
	Mass concrete	Point	Tilt	Rotation
	Intake tower	Point	Tilt	Rotation

3.0 Typical applications contd...

APPLICATIONS	ELEMENT	CONFIGURATION	MEASURAND	COMPUTATION
Compensation grouting	Buildings	Point	Tilt	Rotation Differential settlement
		Linked	Tilt	Bending Displacement Settlement
Rail	Track	Point	Tilt	Rotation
		Linked	Tilt	Rotation Settlement Displacement
	Bridges	Point	Tilt	Rotation
		Linked	Tilt	Bending Displacement Settlement
	Tunnel lining	Point	Tilt	Convergence Rotation
		Linked	Tilt	Convergence Rotation Settlement Displacement
	Slope	Point	Tilt	Rotation
	Embankment	Point	Tilt	Rotation
		Linked	Tilt	Rotation Settlement Displacement
Road	Bridges	Point	Tilt	Rotation
		Linked	Tilt	Bending Displacement Settlement
	Tunnel lining	Point	Tilt	Convergence Rotation
		Linked	Tilt	Convergence Rotation Settlement Displacement
	Slope	Point	Tilt	Rotation
	Embankment	Point	Tilt	Rotation
		Linked	Tilt	Rotation Settlement Displacement

3.0 Typical applications contd...

Overview

Tilt meters and Tilt beams can be used to monitor changes of tilt of structures and infrastructures. These changes can be as a result of construction activities such as tunnelling, excavation, dewatering and loading. In addition tilt changes can occur due to natural phenomena such as landslides, wind loading and flooding.

The choice of Tilt sensor will depend on the individual application but the key issues to be considered for each type are outlined below.

3.1 In-place Tilt Meter (including submersible)

- Measures Tilt at a point which is referred to as rotation
- Can detect differential movement (multiple units) but not absolute displacement
- Can be mounted with bracket on vertical, inclined or horizontal surfaces
- Bracket can be mounted can be on wide range of surfaces e.g. concrete, steel
- Mounting of bracket can be done by bolting, bonding or welding
- Standard brackets are available but special brackets can be made to suit specific applications
- Digital sensors can have a BUS connection where only one cable is required to connect all sensors together
- Can be connected to a wireless node as part of a wireless sensor system
- Can be read with a manual readout or linked into an automatic data acquisition system

3.2 Portable Tilt Meter

- Measures Tilt at a point which is referred to as rotation
- Detect differential movement but not absolute displacement
- Tilt plates can be mounted on vertical, inclined or horizontal surfaces
- Tilt plates can be mounted on wide range of surfaces e.g. concrete, steel
- Access to the tilt plate locations is required to carry out reading operations
- Protection of the tilt plates is recommended
- Is read with the portable tilt meter unit

Key notes:

Whilst temperature has little or no effect on the tilt sensor itself, the effect of temperature changes on its mountings and the structure to which it is fixed may be significant. Consequently temperature data should be recorded as part of routine tilt monitoring.

Careful consideration should be given to the positioning of tilt sensors so that the effects of temperature changes are minimised.

The repeatability of readings for a portable tilt meter system is operator and environment dependent.

3.0 Typical applications contd...

3.3 Tilt Beam

- Single beam - measures Tilt over its length which is referred to as rotation
- Linked beams can be used to calculate a profile of movement
- Available in a range of gauge lengths e.g. 1,2,3m
- With one or both ends fixed a measurement of absolute displacement can be calculated
- Can be mounted with bracket on vertical, inclined or horizontal surfaces
- Can be mounted on a wide range of surfaces e.g. concrete, steel
- Mounting can be done by bolting, bonding or welding
- Digital sensors can have a BUS connection where only one cable is required to connect all sensors together
- Can be connected to a wireless node as part of a wireless sensor system
- Can be read with a manual readout or linked into an automatic data acquisition system

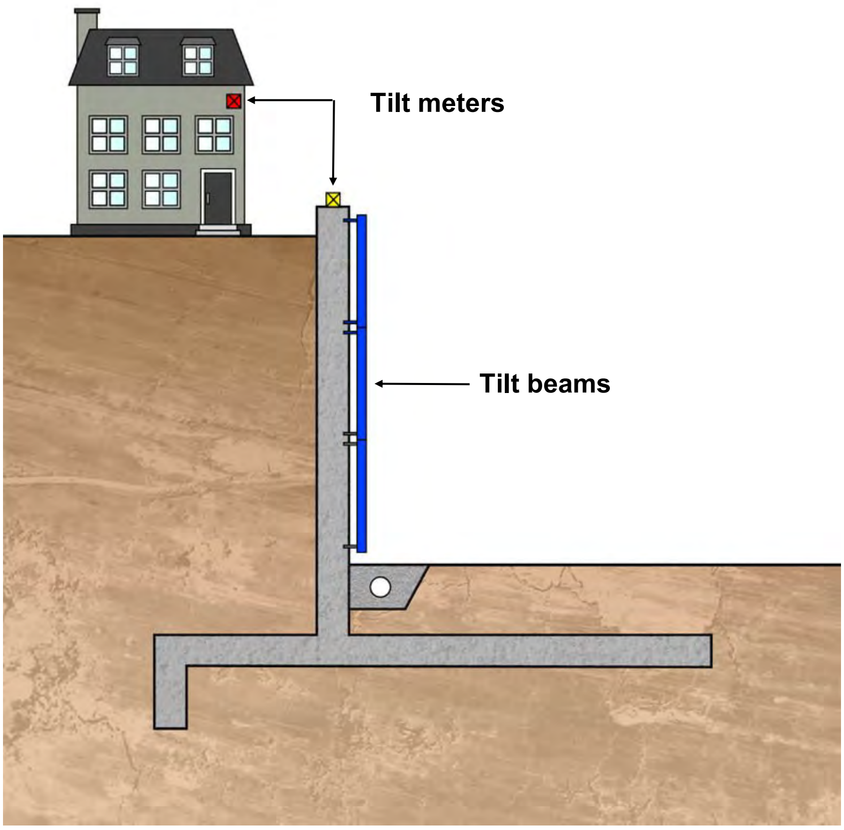
3.4 Track monitoring system

- Linked bi-axial tilt sensors mounted longitudinally measures the rotation of each beam between fixing points in the A axis.
- Rotations are combined to generate a settlement profile along the track.
- Twist in the B axis at each fixing is also monitored and therefore the change in cant at these points can be calculated.
- Available with a range of gauge lengths e.g. 1,2,3m
- With one or both ends fixed a measurement of absolute displacement can be calculated
- Can be mounted with bracket on vertical, inclined or horizontal surfaces
- Can be mounted on a wide range of surfaces e.g. concrete, steel
- Mounting can be done by bolting, bonding or welding
- Digital sensors can have a BUS connection where only one cable is required to connect all sensors together
- Can be connected to a wireless node as part of a wireless sensor system
- Can be read with a manual readout or linked into an automatic data acquisition system

3.0 Typical applications contd...

Retaining walls

Tilt Meters and Tilt beams can be used to measure movements and stability before, during and after construction of a retaining wall, and to measure the movements occurring on any nearby structures.

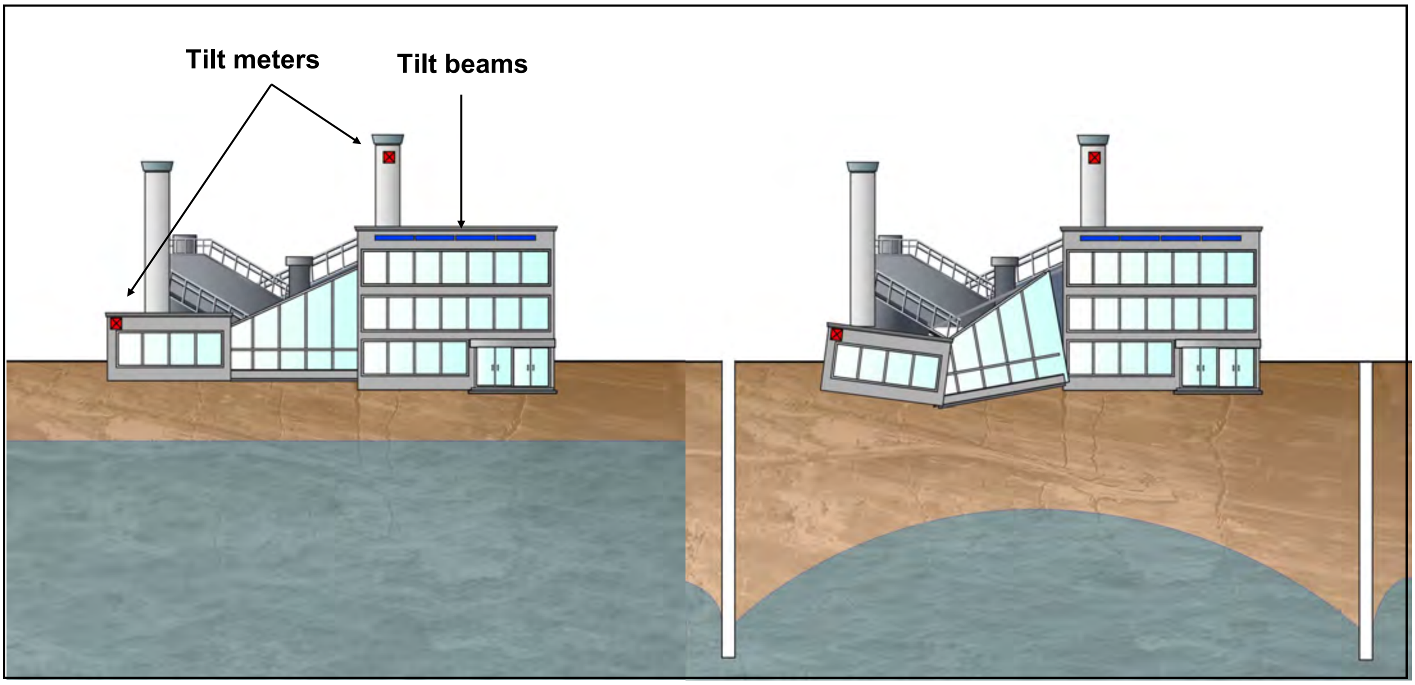


Where and what we monitor	Why we monitor
Retaining wall face (blue) Tilt profile	To detect (calculate and monitor) bending in order to confirm the integrity (stability) of the wall
Top of retaining wall (yellow) Tilt	To detect (calculate and monitor) rotational movement of the wall
Nearby structure (red) Tilt	To detect (calculate and monitor) rotational movement of nearby structures

3.0 Typical applications contd...

Dewatering Systems

Evaluation of differential settlement on structures due to dewatering operations.



Where and what we monitor

Nearby structures

Tilt profile (tilt beams)

Tilt (rotation)

Why we monitor

To monitor the effects of groundwater lowering and the effects of subsequent differential settlement

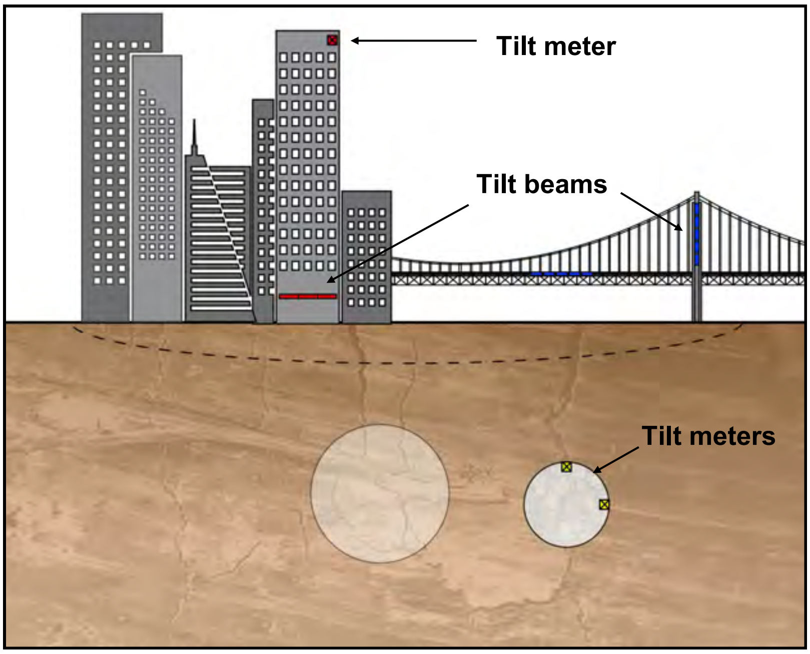
3.0 Typical applications contd...

New tunnel construction

Tunnelling activities especially in urban areas can lead to significant settlement of the ground surface which can affect the integrity of nearby structures.

In order to minimise the effects of settlement on these structures, compensation grouting is often utilised. Tilt sensors are used to monitoring for settlement and/or heave during tunnelling and grouting.

Tilt meters provide a point rotation and are generally used to identify structural rotation. Tilt beams which can be joined together in a chain provide a profile of settlement which can be used to control compensation grouting.

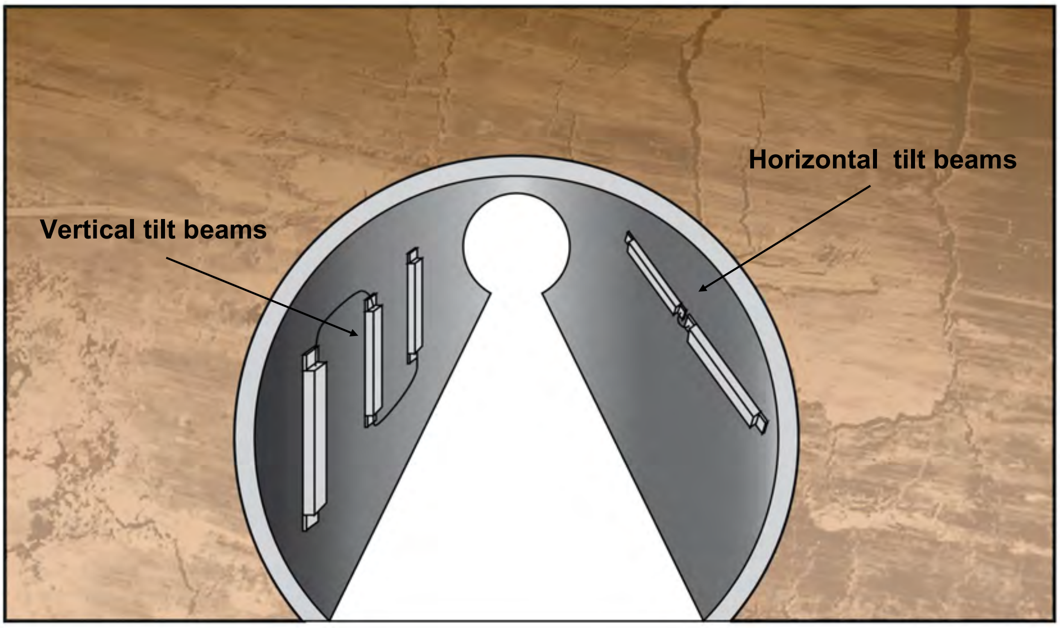


Where and what we monitor	Why we monitor
Adjacent buildings Tilt (Rotation)	Point measurement to provide an early warning of structural movement Profile monitoring to calculate, monitor and control settlement
Subsurface infrastructure (rail, sewer, power, water tunnels) Tilt (Rotation)	Profile monitoring to calculate, monitor and control settlement/heave Point measurements to detect rotation and convergence
Surface transport network (rail and road) Tilt (Rotation)	Point measurement to provide an early warning of structural movement. Profile monitoring to calculate, monitor and control settlement/heave

3.0 Typical applications contd...

Existing tunnel monitoring

The construction of new tunnels particularly in urban areas are often adjacent to existing tunnels and therefore the effect of tunnelling needs to be monitored.



Where and what we monitor

Tunnel wall - vertical tilt beam

Tilt (Rotation)

Tunnel wall - horizontal tilt beam
Tilt (Rotation)

Why we monitor

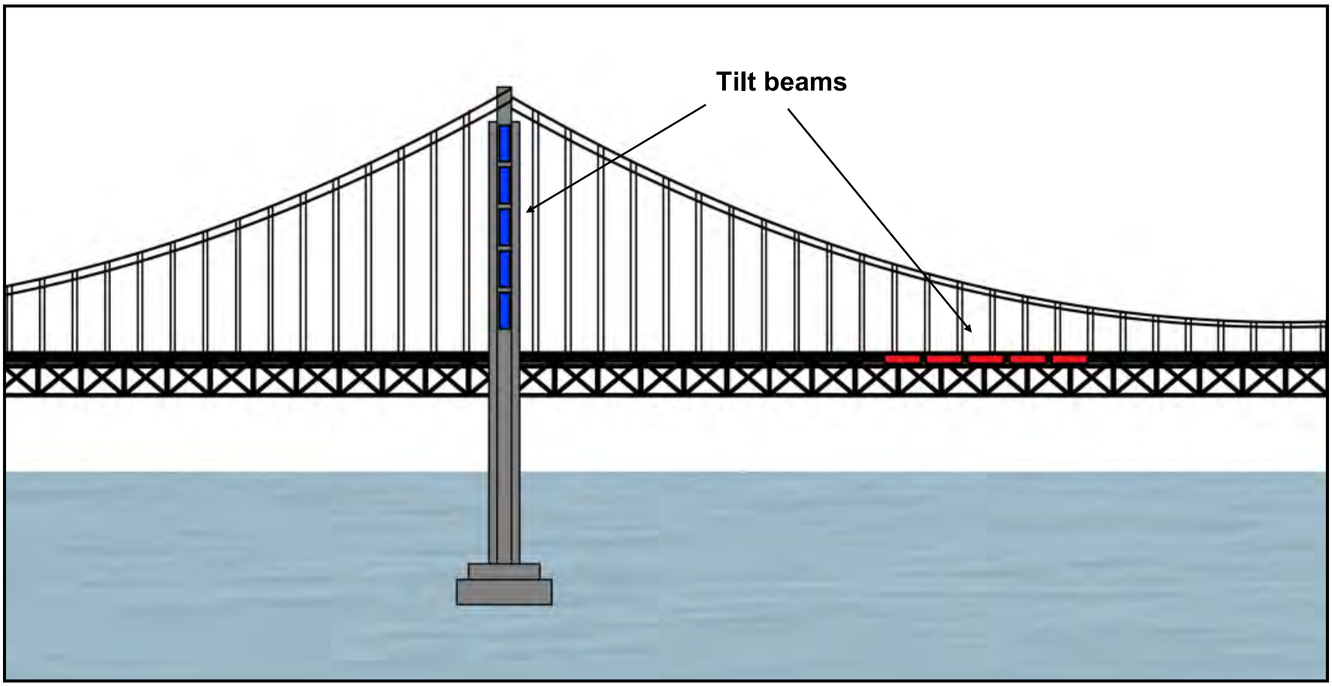
Tilt profile to calculate convergence

Tilt profile to calculate settlement or heave

3.0 Typical applications contd...

Bending/Deflections

Tilt beams can be used to monitor bending (deflection) as a result of load on structures such as bridges, pylons, wind turbines, towers, silos and masts.

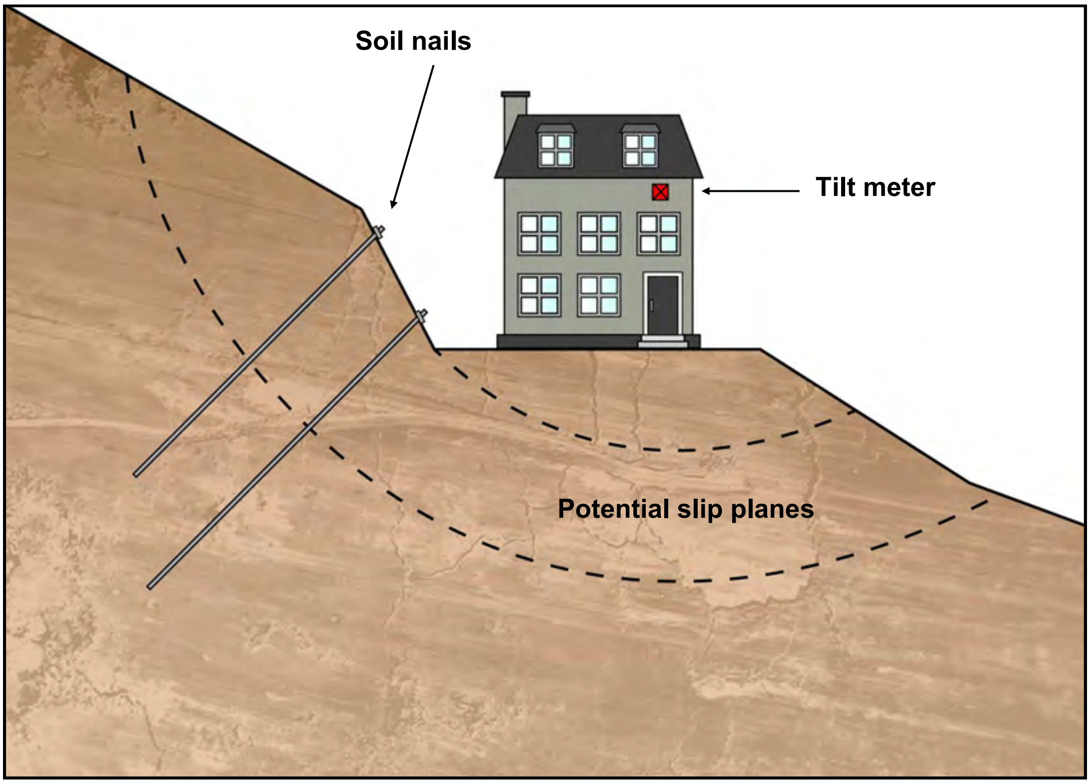


Where & what we monitor	Why we monitor
Bridge deck Tilt	To calculate bending (deflection) of the bridge deck
Bridge tower, wind turbine, towers, silos & masts Tilt	Monitor the structural integrity and stability under loading

3.0 Typical applications contd...

Cuttings

Tilt beams can be used to monitor tilt on structures in areas where slope stability problems may be anticipated or monitor the effects of stabilisation measures such as soil nails.



Where & what we monitor

Adjacent structure

Tilt

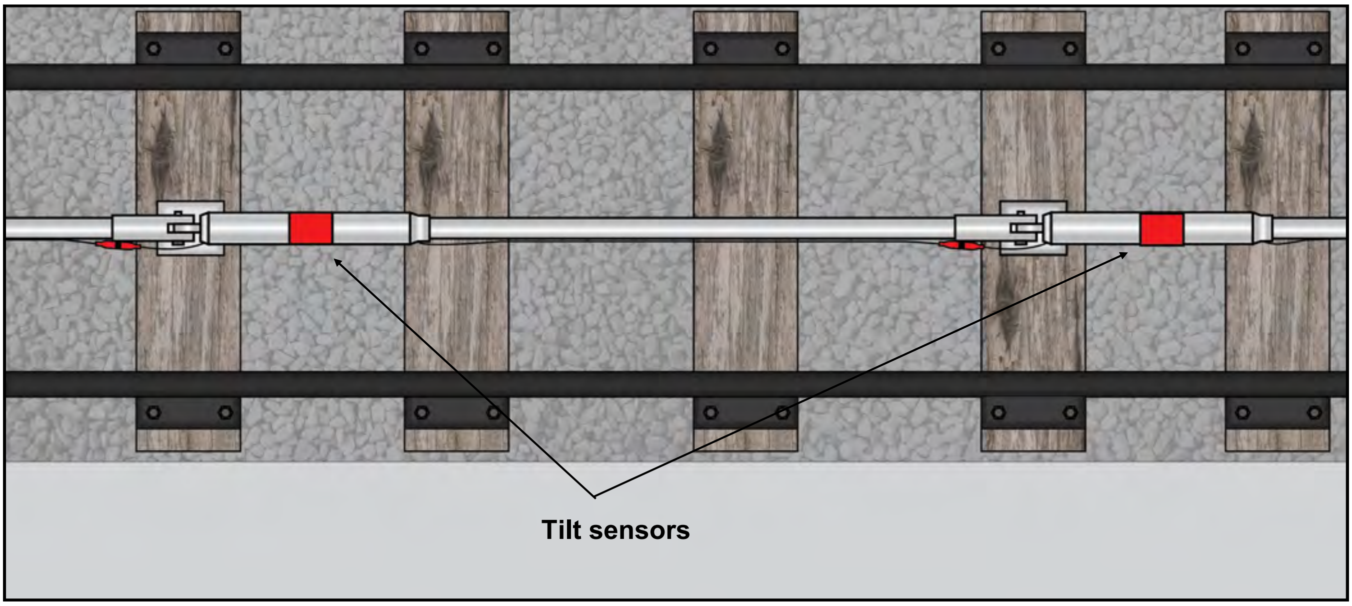
Why we monitor

To detect (calculate and monitor) rotational movement of nearby structures to provide warning of slope instability

3.0 Typical applications contd...

Track monitoring

Biaxial tilt sensors can be linked together with rods and fixings which are free to move relative to each other so that a settlement profile can be calculated.



Where we monitor

Rail track

Tilt

Why we monitor

The integrity and geometry of rail tracks is paramount to operating a safe railway.

Monitoring Cant is one of the main ways that the geometry is checked.

Cant can be calculated from tilt profile measurements.

By calculating changes in cant the structural integrity and stability of the track can be monitored

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4.0 Reading Tilt Sensors

4.1 Signal output

The readings generated by Analogue Tilt Sensors are in current

- *Current* : 4mA to 20mA for -15 degrees to +15 degrees

  The tilt meter is powered with a 8 - 15 volt current loop (two wires) from which it draws the current to power itself. As it is tilted the output changes from 4 mA at 15 degrees in negative direction of its axis, to 20 mA at 15 degrees in the positive direction. The current is then converted into an angle by a simple **linear** calculation using the supplied calibration details.

The readings generated by Digital Tilt Sensors are in 'Sine of the Angle'.

- *Digital*: -0.2588 sin-1 to +0.2588 sin-1

  The tilt meter is supplied with 8 - 15 volts to power the internal processor and sensors via the RS485 'bus' cable. Each sensor has a unique identification or 'address'. The interrogating logger or readout 'requests' a reading from a particular 'address'. The value returned from the processor is a value in $\sin^{-1}$ (the sine of the angle with respect to vertical) which can then be easily converted into a reading in degrees or other engineering units.

4.2 Signal conversion

Analogue

Each Tilt Meter or Beam has a unique calibration sheet and the simple calculation converts the sensor output to engineering units, commonly *degrees* or *mm/metre*. The output from the sensor must be compared with its

Calibration factors - below are typical calibration factors found on an **Analogue** tilt meter calibration sheet.

Calibration Factors	**0.03234**	mA to Sin θ
	1.87418	mA to Degrees θ
	33.4937	mA to mm/m

Digital

Each Tilt Meter or Beam is individually calibrated but is embedded within the sensor so that the output is already converted into Sine of the angle.

4.0 Reading tilt sensors contd...

4.2 Signal conversion contd...

- **Milliamps Reading into Degrees**

The conversion of a milliamp output into an angle in degrees is based on the linear **Y** = **(M * X)** +**C** relationship, where ….

Y = Value of the angle of tilt from vertical
M = Calibration Factor (for the angle from the calibration sheet)
X = Milliamp reading
C = Zero reading (from the calibration sheet)

If for example:

M = 1.8750 per mA.
X **= 14.974 mA**
C = 12.000 mA at Zero degrees
Y = (14.974 - 12.000) * 1.8750
Y **= + 5.57625 degrees**

- **Milliamps Reading into mm/m**

The conversion of a milliamp output into a mm / m value is, again, based on the linear **Y** = **(M * X)** +**C** relationship, where ….

Y = Theoretical offset from vertical over a distance of 1m, with respect to vertical.
M = Calibration Factor (for mm/m, from the calibration sheet)
X = Milliamp reading
C = Zero reading (from the calibration sheet)

If for example:

M = 32.3524 mm per mA.
X **= 14.974 mA**
C = 12.000 mA at Zero degrees
Y = (14.974 - 12.000) * 32.3524
Y **= +96.22 mm/m**

4.0 Reading tilt sensors contd...

4.3 Signal conversion - Digital

The readings from digital tilt sensors are already converted to engineering units within the board and are provided in the form of Sine of the angle of tilt. Consequently no additional calibration factors need be applied.

To convert from one engineering unit to another (degrees or mm/m) only a simple calculation is required as shown below:-

- **The Sine of the angle into the angle**

  To convert from the Sine of an angle to an angle it is necessary to use the ArcSin or Sin^{-1} mathematical function:-

  Y = Value from tilt meter (Sine of the angle) - for example 0.08716

  Angle in degrees = **Y** (0.08716) Sin^{-1}

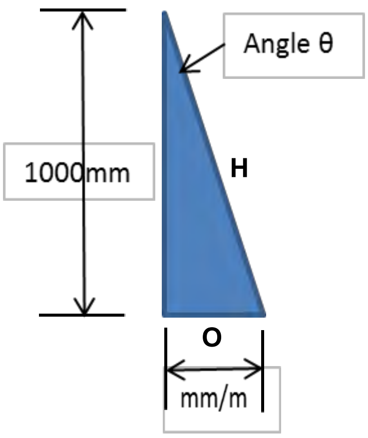
  Angle in degrees = 5.000º

- **Sine of angle to mm/m**

  Y = Value from tilt meter (Sine of the angle) - for example 0.08716

  mm/m = **Y** (0.08716) x 1000

  = 87.16mm/m



$\text{Sine } \theta = \frac{O}{H}$

4.0 Reading tilt sensors contd...

4.4 Hand held readouts

There are several types of handheld readouts available most of which, are able to read MEMS tilt sensors 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.

4.5 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

- **Digital to analogue interface**
  An interface is required for digital tilt sensors which convert the RS485 signal into a RS 232 signal 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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Geosense Ltd

Nova House . Rougham Industrial Estate . Rougham . Bury St Edmunds . Suffolk . IP30 9ND . England .

Tel: +44 (0) 1359 270457 . Fax: +44 (0) 1359 272860 . email: info@geosense.co.uk . www.geosense.co.uk

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