Tunnel Monitoring
(Measuring different quantities in tunneling projects)
by Resensys Wireless SenSpot™ Sensors

Underground structures such as tunnels are very important in transportation. Tunnels can be used for carrying freights and passengers (commuter tunnels), water (hydro-electric and hydraulic applications), sewage, etc. Tunnels are more cost-effective than open cuts beyond certain depths. Tunnels avoid disturbing or interfering with surface life and traffic during construction. A tunnel boring machine (TBM) is a machine that is used to excavate tunnels and it can bore through different kind of ground conditions, hard rock, sand, etc.

One of the critical aspects in tunnel design and construction is the monitoring of tunnels, surrounding environment and building structures within the affected/predicted region of tunneling construction. This monitoring occurs during the construction, commissioning and also during the lifecycle/ maintenance phases of the tunnel. So, monitoring and measuring different structural quantities in tunneling must be part of tunnel design, planning and execution and can have significant impact on the costs/ profitability of the tunneling venture and also on the safety and risk of property damage during the venture. Different tools are used to support with these measurement observations, and indicate the need for adjustments to the tunneling plan or the need for preventative repairs. Instrumentation and monitoring is a necessary component of site investigation, design confirmation and safety of the tunnel structures.

Resensys Wireless SenSpot™ sensors can be implemented during each of the three phases of construction of tunnels and subways; before operation, during operation and after operation for examination.

The applicable, measurable and monitorable quantities in monitoring of tunnels, surrounding environment and building structures within the affected/predicted region of tunneling construction are strain, tilt/inclination, displacement, vibration, underground water level and ambient temperature.

Strain (Tunnel Lining)

Pre-cast Tunnel Liners (Tunnel Lining) are prepared to match the requirements of a tunnel. They are planned and designed to resist the earth pressure and groundwater head. Also, they deliver the basis for the tunnel's ultimate use. Multiple liner segments are combined to make a ring.

Wireless Strain Gauge SenSpot™ can be used for monitoring strains in Commuter Tunnel Linings and concrete pre-cast segments. They can also be applied, to measure and investigate tension in rock bolts and anchors used in tunneling projects, by monitoring strain variations and monitoring loads on struts.

The significant goal of stress/strain measurements during construction in mountain tunnels is to ensure that ground pressures are sufficiently measured and controlled, i.e., there exists an sufficient margin of safety against collapse, including roof collapse, bottom lift, failure of the excavation face, yielding of the support system, etc. Strain/Stress measurements devices are typically mounted in the roof of tunnels and

at certain points along walls of the tunnels to measure and monitor stress/strain components in tunnel projects. [1]

Tilt/Inclination (Tunnel Lining and Surrounding Structures)

Resensys Health Monitoring System can be used for Tunnel Concrete Segments and can be installed in tight spaces and hard-to-access places around the TBM without the need for additional wiring. The system includes a series of Wireless Tilt/Inclination SenSpot™, fixed to the tunnel wall on each of the pre-cast concrete segments created in place as tunnel lining by a Tunnel Boring Machine (TBM). It is supposed that each concrete segment is a rigid body and the complete ring deforms by rotation of the single segments that relates to another one. The rotation points are the connection sides between adjacent segments. This hypothesis is very often considered as acceptable by tunnel designers and authorities. While this is close to reality, points should be investigated using traditional convergence measurements or surveying methods to confirm its rationality for each separate tunneling circumstance.

The Tunnel Health/Profile Monitoring System contains of a series of Wireless Tilt/Inclination SenSpot™ that are deployed on each of the concrete segments of a segment ring, including the main segment. Each Wireless Tilt/Inclination SenSpot™ is attached on a base plate and it helps to set the vertical axis of the SenSpot™. Thus, it will be oriented appropriately when attached on the concrete segment. Spatial displacement of the concrete segments causes changes to tilt data. The Gateway SeniMax™collects the data routinely and automatically, and transmits it to a PC/Laptop for further analysis using the SenScope™ software. The computer then analyzes the data, and calculates the displacement profile for presentation, thereby providing real time tilt and deformation data as well as graphs to assist with the visual interpretation of the corresponding data. The system is available in either open or closed loop configurations

Wireless Tilt/Inclination SenSpot™ sensors can also be installed on the structures or buildings that could be affected in the vicinity of the tunnel operations. Resensys Wireless Tilt/Inclination SenSpot™sensors can record changes in vertical & horizontal tilt (roll & pitch). These sensors can be mounted at exterior wall/surface of building structures that are in the affected area, providing valuable indications of potential impact to these surrounding structures, or conversely confirming that all is proceeding according to the tunneling plan.

Displacement (Surrounding Structures)

Wireless Displacement/Crack Meter SenSpot™ sensors can also be used to measure movement and opening of existing cracks in nearby building structures in the tunneling projects area. This can be important when tunnels are being constructed in historic or previously developed areas, or where ongoing tunnel operations could be considered to have a potential effect on vulnerable buildings.

[1] Maghsoudi, A., & Kalantari, B. (2014). Monitoring instrumentation in underground structures. Open Journal of Civil Engineering, 2014.

Vibration (Surrounding Structures)

Vibration monitoring can be important during the tunnel construction and operation stages (in applications such as commuter tunnels) to monitor vibrations associated with the tunneling activity. It can also be important to understand whether subsequent vibration effects due to separate construction actions conducted on the surface are causing vibrations that might have a harmful effect on existing tunnel or subways within proximity of the new project location. In each of these cases (new tunnel excavation and separate but concurrent construction activities), ground vibration occurs. These vibrations can damage buildings structures and roads within the tunneling zone and cause delays and excessive costs to the projects.

Resensys monitoring system are able to measure vibration levels using Wireless Vibration/Acceleration SenSpot™ sensors. Measured data is viewable very quickly by Resensys software; SenScope™ and depending on the projects, alarm systems or triggers can be set using pre-determined thresholds. Thus, stakeholders are able to take informed actions in a timely manner. Resensys monitoring systems can thus warnwarn the project authorities by emails to pre-determined decision-makers and the alerts can be seen through details on SenScope™ and authorities' PC/Laptop.

Water Level

To monitor underground water level within the affected/predicted region of tunneling construction, Wireless Ultrasonic Level Meter SenSpot™ can be used. This device provides an easy way to install a scalable solution for measuring water level or any kind of distance (e.g. height, object detection and dimensions).

General Characteristics of Resensys Systems

Resensys Wireless SenSpot™ sensors are well-suited for tunneling applications because of their accurate data collection and high rates of data transmission. They are wireless, and low-power, meaning that they are easy and cost effective to install and maintain. They have adjustable triggering threshold and sampling intervals and provide accurate, reliable and repeatable results, without need for calibration in the field.

SenSpot™ data helps the stakeholders and engineers make informed decisions about how quickly construction can progress. In addition, Resensys products can provide early warning of imminent failure and catastrophe by their Alarm feature by alerting when pre-set data thresholds have been exceeded. Resensys real time monitoring system can thus pre-warn of potential effects on adjacent structures and utilities.

Resensys sensors' ultra-low power usage allows for both short and long term use. A key benefit of this power-efficiency is that short-term uses can be easily repeated multiple times without the need for battery replacement or intra-test charging if users wish to use the products for their own experimental tests. After tests, the same sensors can also be left on the tunnel or structures for long-term use (tunnel/structure health monitoring). After installation, SenSpot™ does not need battery replacement or any other maintenance during its entire service life.

Resensys' wireless design is quick and easy to install because there is no additional wiring required. This reduces installation cost and time, making Resensys solutions a cost-effective way for owners to get the quality data they need for Tunnel Monitoring and decision-making.

Resensys Wireless SenSpot™ sensors are able to monitor structural quantities such as tilt, displacement, strain, vibration and ambient temperature in concrete, steel and composite materials under wet, humid and extreme weather conditions (-40°C to +65°C or -40°F to +150°F). The products are corrosion resistant and can withstand salty environments. They are small in size and lightweight.

A Resensys monitoring of tunnels, surrounding environment and building structures within the affected/predicted region of tunneling construction solution comprises the following components:

- SenSpot™ sensors (for strain, tilt, displacement, vibration and water level): which are attached to a tunnel/building structure and its corresponding members. The required number of sensors per tunnel/ building structure depends on construction or design requirements).
- SeniMax™: gateway/ data logger, which collects SenSpot™ data at the site and sends it to a remote server (one unit can cover as many as 100 SenSpot™ sensors).
- Repeater: may be used to extend the range of the SenSpot™ sensors.
- SenScope™: software for data analysis and visualization.

Resensys **Wireless Strain SenSpot™ sensor** for Tunnel Monitoring Application

Resensys **Wireless Tilt SenSpot™ sensor** for Tunnel Monitoring Application

Resensys **Wireless Vibration/Acceleration SenSpot™ sensor** for Tunnel Monitoring Application

Resensys **Wireless Displacement SenSpot™ sensor** for Tunnel Monitoring Application

Wireless Water Level Meter SenSpot™ (Ultrasonic Level Meter SenSpot™) for Tunnel Monitoring Application (Monitoring Underground Water Level)

Resensys Wireless SenSpot™ sensors are easily placed/ installed on elements and members as determined by authority's/client's suggestion/ needs. The sensors are mounted with adhesive or flange mounted depending on the application. A SeniMax™ data acquisition unit is conveniently mounted nearby (within 1.0Km (0.62miles) free space of the SenSpot™ sensors) and a SenScope™ module is installed on the client's/authority's laptop or PC.

A complete Resensys SHM system includes software and hardware components for (1) the reliable collection of SenSpot™ data, (2) aggregation of the data, (3) the addition of timestamps, (4) communication of encrypted data to a remote server, and finally, (5) an interface for data visualization and detection of structural issues. Figure below shows a picture of a practical Resensys health monitoring system, which can be used for tunnel monitoring.

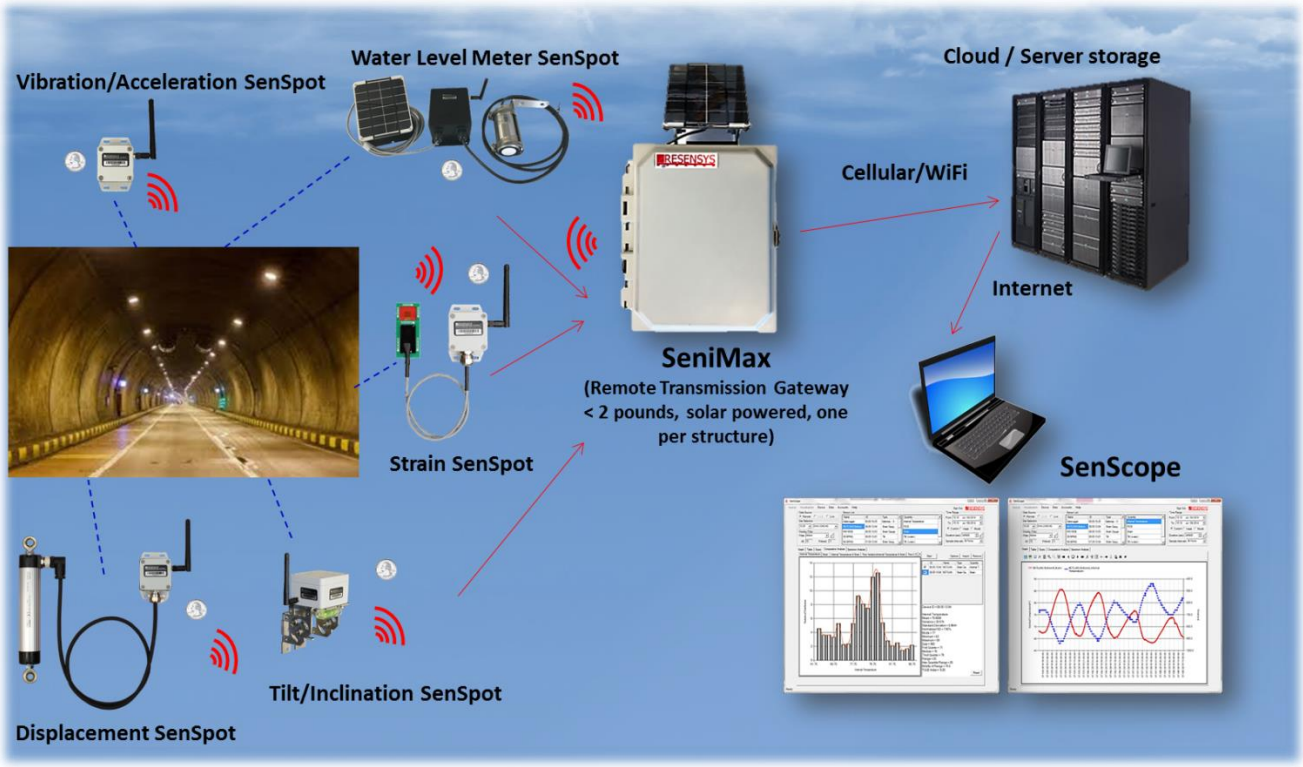

Illustration of Resensys health monitoring system based on Wireless SenSpot™ sensors for Tunnel Monitoring

Technical Specifications:

	Wireless Strain SenSpot™ sensor	Wireless Tilt SenSpot™ sensor	Wireless Displacement SenSpot™ sensor
Size (Dimension)	76.2mm (3") x 33.4mm (1.3") x10mm (0.4")	-Transmitter Dimension: 79.6mm(3.13")x74.6mm(2.94″) x 52mm(2.05") - AssemblyDimension:120.8mm (4.76") x 96.6mm (3.8")x149.9mm (5.9")	Model 2": 176mm [6.9"], Model 3": 201mm[7.9"], Model 4": 227mm[8.9"], Model 6": 277mm[10.9"]
Weight	147g (5.2 oz.)	180 g (6.3 oz.)	245 g (8.6 oz.)
Mounting	- Self-adhesive, no drilling is required (e.g. steel) -Flange-mount, drilling is required (e.g. concrete)	Flange-mount or adhesive tape	self-adhesive or flange-mount
Accuracy (Resolution)	2μStrain	-Narrow Range HRT: ≤0.0003º(5.2μrad) -Regular tilt : 0.1º	0.1mm (4mil)
Measurement Range	-	-Operating range: • Narrow Range High Resolution Tilt : ± 0.5º(with respect to vertical position) • Regular tilt: all directions -Linear range: • Narrow Range HRT: ±1º • Mid-Range HRT: ±10º -Repeatability: • Narrow Range HRT: ≤0.001º (17.5μrad) • Regular Tilt:1º -Time constant: ≤1sec(High resolution tilt)	25mm (1"), 50mm (2"), 75mm (3"), 100mm (4"), 150mm (6"), 300mm (12")
Operating temperature	-40°Cto +65°C (-40 °F to +150°F)	-40°C to +65°C(-40°Fto +150°F)	-40°C to+65°C(-40°F to +150°F)
Lifetime	minimum expected life without battery replacement is 3 years (Ultra-low-power)	battery life of 10 years (Ultra-low-power)	battery life of 10 years (Ultra-low-power)
Installation Time	1-2 minutes	1-2 minutes	1-2 minutes
Complementary sensing	temperature, battery voltage, etc.	temperature, battery voltage, etc.	temperature, battery voltage, etc.
Communication range	1.0km(0.62mile)free space	1.0km(0.62mile)free space	1.0km(0.62mile)free space
Power source	Replaceable lithium-ion battery	Replaceable lithium ion battery	Replaceable lithium-ion battery
Wireless communication	no wiring needed for deploying the system- IEEE 802.15.4	no wiring is required for data collection- IEEE 802.15.4	no wiring needed for deploying the system- IEEE 802.15.4

Technical Specifications:

	Wireless Vibration/Acceleration SenSpot™ sensor	SenSpot™Wireless Level/Height Meter
Size (Dimension)	50mm (1.96") x 50mm (1.96") x 34mm (1.34")	-Ultrasonic Probe Dimension: Height 11cm (4.33") Radius : 2.5cm (1") Mounting: 15cm(5.90") *10cm (3.94") corner brace
Weight	About 120grams (4.2 oz.)	-Wireless transceiver: 450g (1 lb) -Ultrasonic distance meter: 0.8kg (1.8lb) -Solar panel: 100 g (3.5oz)
Mounting	- Self-adhesive, no drilling is required (e.g. steel) -Flange-mount, drilling is required (e.g. concrete)	Flange-mount or adhesive tape
Accuracy (Resolution)	4 ug ("g" is the acceleration of gravity)	3cm (0.1ft)
Measurement Range	±2g ("g" is the acceleration of gravity)	-Optimal Range: 6.1m (20ft.) -Max Range: 9.1m (30ft.)
Operating temperature	-40°C to +65°C (-40 °F to +150°F)	-40°C to +65°C(-40°Fto +150°F)
Lifetime	battery life of 10 years (Ultra-low-power)	Battery life of 10 years (Ultra-low-power)
Installation Time	1-2 minutes	1-2 minutes
Complementary sensing	temperature, battery voltage, etc.	Temperature, battery voltage, etc.
Communication range	1.0km(0.62mile)free space	1.0km(0.62mile)free space
Power source	Replaceable lithium ion battery	Replaceable lithium ion battery
Wireless communication	no wiring needed for deploying the system- IEEE 802.15.4	No wiring is required for data collection- IEEE 802.15.4