

Wireless Optical Displacement Sensor for convergence and divergence monitoring

Markus Rennen¹

¹*Senceive Ltd, London, UK*

E-mail: mrennen@senceive.com

ABSTRACT: The construction and modification of tunnels brings a requirement for precise measurement of convergence and divergence to safeguard the structure, maintain safety and provide the assurance needed to maintain efficient progress.

Established methods include manual measurement using tape extensometers and automated methods using photogrammetry and automated total stations. Drawbacks include the need for frequent access, power supply, cabling, and cost.

The paper describes how the development of reliable optical displacement sensors (ODS) has changed the landscape. ODS sensors are connected to a long-range wireless mesh communications network via a solar-powered gateway outside the tunnel, with data instantly transmitted to the internet. A sensor and its reflector target can be installed in 20 minutes and is almost maintenance free for a decade. Tunnel movement is measured to sub-millimetre precision with repeatability of $\pm 0.15\text{mm}$. Integration of a triaxial tilt sensor allows slope distance to be converted to horizontal and vertical changes and allows rotational movement to be determined.

Applications include new-build and long-term structural health monitoring. Case studies will be given, including the refurbishment of rail tunnels in Spain where the ODS measured movement during track lowering in a situation where no other automated system was considered viable.

KEYWORDS: Tunnelling, Underground space, Convergence, Monitoring, Instrumentation,

1 INTRODUCTION

Automation of monitoring in general appears undeniably tempting right up to the moment at which prices are discussed. That's when suddenly manual surveys seems not so outdated anymore.

Obviously this perspective is rather short-sighted if automation is applied where it can exploit its' advantages, i.e.

- in areas where access is limited, difficult or dangerous,
- in projects where frequent recording rates (e.g. shorter than one day) are required,
- where long-term observations (e.g. longer than one year) are desired or
- where it takes care of repetitive procedures to release human resources for decision-making tasks
- any combination of the above.

The nature of tunnelling more or less represents all of the above. Monitoring works are not only repetitive, but can potentially disrupt and delay tunnel construction or operation because of the constrained access conditions. Such delay can give rise to significant cost and schedule issues.

A common parameter in tunnel monitoring is convergence as observation of changes of the tunnel profile perpendicular to the alignment. This can be conducted as life cycle monitoring of ageing masonry tunnels as well as temporary observation of deformation induced by adjacent construction measures or even advance and construction of the tunnel itself.

In all of the above cases wireless condition monitoring (WCM) seems to be an intelligent solution with regards to costs, ease of installation and efficiency. The optical displacement sensor (ODS) is a typical component of a modern WCM-system representing unrivalled simplicity in convergence monitoring.

2 CONVERGENCE

2.1 Tunnel Deformation

Excavation of a tunnel or close to an existing tunnel will cause volume loss and thus a disturbance of the surrounding medium. In order to re-establish the initially lost equilibrium, depending on the material, the ambient environment starts to settle - with the tendency to fill the void represented by the tunnel or cavity.

The design of tunnel profile and lining type are intended to deflect external loads in order to maintain stability and establish a new final

equilibrium with the surrounding ground. Only if this precondition is reached can operation of the tunnel be safe and provide support of the overburden, e.g. bearing urban infrastructure.

Therefore it is essential to observe tunnel deformation as a component of a project's holistic monitoring concept.

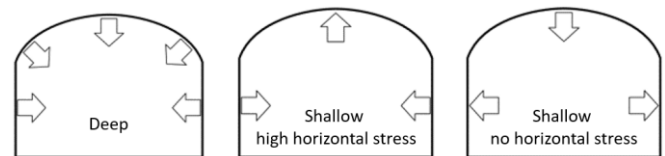


Figure 1: Scenarios of Convergence [Erlandsson, O. 2020]

Depending on the tunnel profile, surrounding regime, overburden etc. the tunnel can experience various types of deformation (see Figure 1). As convergence we consider the displacement of a point towards or away from the interior, i.e. the centre point of the profile area. For a circular profile this would be the perpendicular direction to the outside tangent.

For efficient convergence observation it is crucial to estimate the pattern of deformation in advance to distribute sensors appropriately and yield representative results. Segmental lined tunnels will deform at the joints as the segments can be considered rigid, while masonry lined tunnels might deform inhomogeneously and require more thorough consideration of placement of the sensors.

2.2 Common Observation Techniques

The strategy of continuous observation depends on a variety of criteria, not least those already mentioned in the introduction above. Generally speaking, monitoring is the observation of change and thus the comparison of an in-situ current state with an initial state some time in the past, represented by a zero- or baseline-measurement. In addition the parameters observed need to be identical and comparable in both epochs which might require some information about the environmental conditions. In the case of geometric observations like convergence, the location of the observed spot must be identical or at least be restored with sufficient precision. The latter becomes increasingly significant if the tunnel undergoes renovation or the initial survey is carried out when only the preliminary lining is installed.

The first and foremost consideration would be the observation frequency. If annual observation repetition is required and access is not an obstacle automation is hardly economical. Manual observations can be conducted using Geodetic Total Stations, tape extensometers (see Figure 2) or in modern days even terrestrial laser scanning.



Figure 2: Manual Tape Extensometer [Soil Instruments]

- a) For total station observations the tunnel profile is equipped with reflectors, ideally prisms, that are observed from the total station's location by horizontal and vertical angle and slope distance (Figure 3), which are converted into local coordinates at millimetre accuracy. The linear distance between these coordinates represents the observation parameter. Depending on the spacing between the profiles and the visibility along the line of sight, a number of profiles can be observed from one standpoint before moving onwards.
- b) In order to observe convergence using a tape extensometer, eye bolts will be installed at the opposing ends of the intended chord and the extensometer temporarily hooked into them. The reading can then be taken from the micrometer. Tape extensometers are easy to use and provide high accuracy up to $\pm 0.2\text{mm}$. The measurement will require some effort and support such as hydraulic access platforms. In any case, the measurement tape or wire has to be removed after measurement as it would impede tunnel works or hamper operation.
- c) Laser scanning covers the tunnel surface with an enormous density of measurements and can provide valuable information, particularly in the case of inhomogeneous deformation or irregular surfaces. However, identification of discrete points might be difficult and the extraordinary volume of data requires some effort in data processing and most probably some manual intervention.

All the above methods require qualified personnel operating the survey equipment, working "through the tunnel" by observing section after section. This sequential strategy limits the observation frequency significantly and makes short observation intervals $< 1\text{day}$ unrealistic or at least highly inefficient.

2.3 Automation of Observation

Automation is a valid strategy to overcome the observation obstacles encountered by manual surveys and initially mentioned in the introduction. In order to achieve automation the survey equipment needs to be permanently installed. Hence, tape extensometers are already disqualified as they would interfere with tunnel and construction operations.



Figure 3: Convergence observation utilising total stations

Theoretically, laser scanners could be installed, but the hardware cost would usually prohibit the permanent installation of multiple

instruments. Thus, Robotic Total Stations (RTS) remain a widely used means of deformation observation.

Here, by far the biggest share of hardware investment lies in the total station itself. In order to minimize these costs multiple convergence sections would be observed from one location.

This seems efficient, but has drawbacks. The quality of observation will decrease with increasing distance as dust, fuel emissions and other sources of haze cause the line of sight to be blurred and physical obstructions such as traffic or machinery block it entirely. Measurement at distance is further complicated by increasing distance making targets appear closer to each and therefore harder to discriminate (Figure 2). To make things worse, the RTS itself will most likely be located in the unfavourable position on a bracket mounted to one side of the tunnel. Hence, alternatives might be required.

In recent years miniaturisation led to the development of devices referred to as "Nodes", that combine sensor, data transmission and power supply in a single compact housing. The key term here is *Wireless Condition Monitoring (WCM)* and their ease of use makes them attractive alternatives in many of the scenarios described above

2.4 Wireless Observation Constellation

Wireless Condition Monitoring systems essentially consist of three components: i) the sensor-node, ii) the gateway and iii) the data management platform.

Compact design and low power consumption of the node allow easy installation of the field equipment even by non-experts with only minimal maintenance required for up to 15 years depending on the sensor. The nodes establish communication between an implemented sensor, such as a MEMS tilt sensor and/or a laser based optical distance sensor ODS (Figure 4), or a connected external sensor (such as a potentiometric crack meter, vibrating-wire strain gauge, or PT100 temperature sensor). The data is transmitted either via 868/915MHz LoRaWAN based signal or meshed 2.4GHz Wi-Fi-frequency to a gateway. It is temporarily stored at the gateway and transferred either via cellular network or ethernet landline to a remote central server.

Wireless communication minimises installation effort and reduces the risk of accidental damage or vandalism causing loss of data that cabled systems can experience. The long battery life reduces the need for maintenance to almost zero and allows re-deployment on multiple short-term projects if not required for long-term life cycle monitoring. Intelligent systems enable remote system modification according to the stage of works, related expectations of the development of changes or requirements of contingency measures.



Figure 2: Wireless 3-axes tilt nodes, left with integrated optical displacement sensor (ODS)

Last but not least, WCM allows easy modification and expansion of the system by gradually adding more and even different sensors, all communicating within the same platform without the need for additional cables. It is relatively simple to relocate or replace elements of the system, for example to focus resources close to the tunnelling face as construction progresses. Even the subsequent

extension by additional sensor types is reduced to the mere hardware installation.

The data management platform provides access for multiple users with adequately defined user roles. The data is stored and further processed if required. In the event of pre-defined threshold values being breached, automated alarms can be sent to approved stakeholders.

3 PROJECT EXAMPLES

3.1 Costa Blanca - Martorell Tunnels – Spain

As part of the Mediterranean Rail Corridor project, the Spanish Rail Infrastructure Operator ADIF needed to upgrade three old tunnels in the Catalonia region for use by bigger, faster trains. Located on the line between the towns of Martorell and Castellsbal, each tunnel was several hundred metres in length. Main contractor Dragados was tasked with strengthening the linings, lowering the track and installing overhead electrification.

By lowering the invert the overall tunnel geometry was altered and there was a need to closely observe whether the redistribution of loads would jeopardise structural integrity. Continuous monitoring was instructed in order to compare predicted and actual movement. This was viewed as essential to protect the workforce and provide timely warning of any significant deformation that would require a response from the construction team.

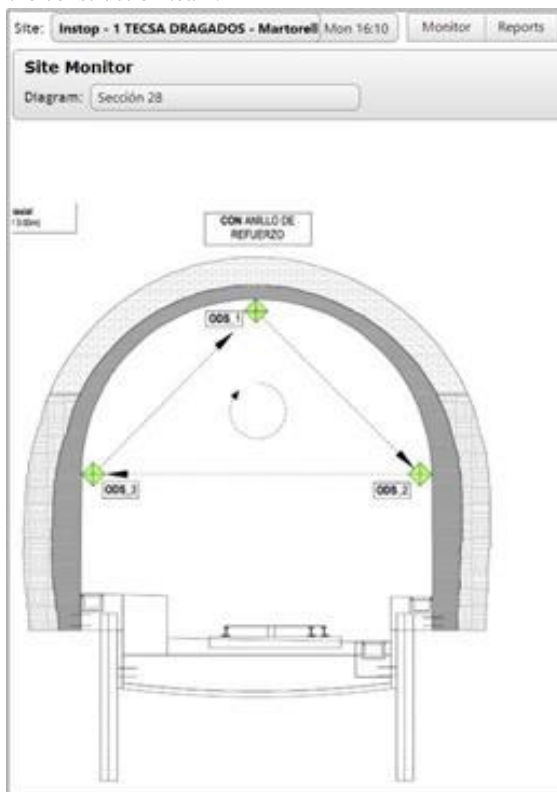


Figure 5: Section diagram screenshot from the data management platform

The requirement for near real-time monitoring throughout the works made automated monitoring the obvious, and probably only, choice. Conditions for long distance optical observations were expected to be very dusty, with sight lines blocked by construction machinery and materials. The use of total stations was therefore rejected.

Dragados and its assigned monitoring consultant INSTOP opted for a Senceive™ WCM system utilising laser distance sensors (ODS) in a triangular arrangement, i.e. a node at each spring line and one at the crown (Figure 5). Although also relying on optical observations, the distances observed in this configuration are much shorter and therefore more reliable than in any applicable total station arrangement.

The ODS nodes include a 3-axes MEMS tilt sensor enabling observation of rotational movement at each location regardless of the node orientation, as well as measuring the distance to a reflective target (see Figure 7). Arrays of ODS nodes were installed at 25 m intervals such that Costa Blanca tunnel featured 30 ODS profiles, Martorell tunnel 27 profiles and Castellsbal tunnel 35 profiles.

Achieving the nominal submillimetre accuracy not only depends on the environmental conditions, i.e. the medium the laser beam has to travel through, but also the quality and orientation of the target. Aiming at rough and/or oblique surfaces decreases accuracy as the incidence point might shift inadequately. Therefore specific targets were installed to provide a reflective, smooth surface at 90° incidence angle (Figure 7). In addition to the distance measurements the ODS's 3-axes-MEMS tilt sensor allows the observation of rotational movements without the node being restricted to horizontal orientated installation (Figure 6).

Besides the challenging environment, one more reason for choosing WCM was the tight schedule, which provided a very short window for installation. Because the system is configured before installation, and because of its modular characteristics a wireless system is easy to install, even by non-specialists. At four sections per hour an entire tunnel installation was completed within a single working day.



Figure 6: ODS pointing towards a target located at the tunnel crown; 3-axes tilt sensors allow installation in arbitrary orientation; simultaneous operation of tilt beams for observation of longitudinal settlement/upheaval



Figure 7: Laser visible on reflective target

At Costa Blanca and Martorell tunnels the system included instruments to automatically observe longitudinal settlement. The system consisted of fixed length beams daisy-chained in cardanic wall mounts (Figure 6 and 11) with wireless tilt nodes fixed to the beams. Via trigonometric functions any longitudinal tilt could be converted into vertical displacement by the known length of the beam. The accumulation of the incremental vertical displacements along the chain yielded longitudinal settlement or upheaval.

As the components of the system were located relatively far apart, the long-range LoRaWAN system was the chosen communication platform. Each tunnel was equipped with its own gateway serving a system with the furthest node 1.2 km away. Gateways also received signals from the nodes located in the other tunnels – at distance of up to 8 km. However, to maintain redundancy the multi-gateway constellation was retained.

Specific diligence was required on the Martorell tunnel as the city of Martorell and its high rise buildings was located directly above. A number of rod extensometers were therefore installed to observe vertical ground movement at three levels (3m/6m/9m), each communicating its readings to the solar-powered gateway via multi-channel vibrating wire nodes (Figure 8).



Figure 4: 3x Rod extensometer connected to a LoRaWAN 4-Channel Vibrating Wire Node

All of the systems were delivered pre-configured and with all sensors functioning. It was therefore possible to check system performance within minutes of installation – avoiding the need for potentially disruptive repeat visits to site.

The renovation of the three tunnels, including their intermediate galleries, was completed within three months (see Figure 9) with a monitoring system of more than 400 nodes in place for about four months. After demobilisation, the components were re-deployed on other INSTOP projects.

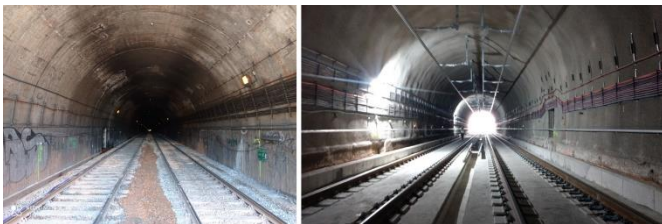


Figure 9: Martorell Tunnel before (left) and after (right) renovation

3.2 Chipping Sodbury Tunnel - UK

A comparable situation to the previous case was encountered in Chipping Sodbury Tunnel near Bristol, UK. The 1902 completed and thus more than 100 years old structure is 4000 m in length and features a brick-lined arch-profile of 8.4×6.4 m (w \times h). In order to comply with modern requirements there was a need to lower the track

by 150 mm in places to achieve the required clearances for a new alignment design including electrification.

Again, a tight schedule and challenging site conditions, plus the need to keep trains running, necessitated a solution using automated monitoring methods.

The monitoring consultant AECOM had gained experience in similar renovation projects and could therefore utilise the proven technology of WCM. Again, tunnel

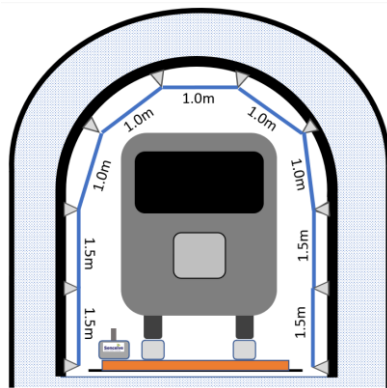


Figure 7: Schematic View of convergence observation by tilt beam chains; lower left: track monitoring by high-G tilt node mounted to sleeper

geometry, obstructions by traffic and construction activity, as well as dusty, humid atmospheric conditions prohibited total station observations.

Unlike in the Spanish tunnels described above it was possible to access cellular signal reception throughout the entire length of Chipping Sodbury Tunnel. Therefore Senceive's proprietary communication platform Flatmesh™ could be employed. Due to the greater bandwidth of the 2.4GHz signal, the platform provided optimised synchronisation and extremely short message pulses for high frequency observations. The wireless mesh platform provided significant redundancy and therefore a high level of system reliability.

Hence, establishing communication proved to be relatively straightforward by simply installing gateways at regular intervals to gather the data from adjacent nodes.



Figure 5: Vertical tilt-beams supplementing horizontal beams chains, NanoPlus nodes provide compact design

As stated before, 3-axes tilt sensors can be installed in any orientation without the necessity of prior levelling. Therefore the initial approach was to install daisy chained tilt-beams within the tunnel section representing deformation arrays (example see Figure 10). AECOM chose miniaturised Senceive NanoPlus MEMS tilt nodes (Figure 4, centre) for compactness and their confidence in the IP68 performance under the expected wet and dusty ambient conditions. The use of shape arrays had been considered but rejected because each chain would have needed its own gateway, whereas data from numerous tilt sensors could be gathered at a single gateway – saving time and money.

As the work progressed it was found to be impractical to install beam chains at some locations where tunnel curvature meant they would have projected into the tunnel and caused an obstruction. Hence, individual tilt beams were installed only at crucial locations (Figure 11), still employing more than 200 nodes throughout the tunnel. Where convergence observation was required, tilt nodes were substituted by ODS nodes positioned to measure the distance to the opposite wall.

Permanent online access to the data management platform allowed remote temporary deactivation of the inherent alarming during blockage of the line of sight by construction works in order to avoid false alarms.



Figure 6: Convergence observation by ODS mounted to tilt beam

The tracks were lowered one after the other; the behaviour of the remaining track was observed using rail-specific vibration resistant tilt nodes (see e.g. Figure 10). A total of 843 of these High-G tilt nodes were installed, at 3 m centres within and adjacent to the immediate area of impact. In addition, it was considered crucial to ensure proper operation of the tunnel drainage, realised by a subsurface culvert located in the centre of the tunnel. It was expected that any significant impact on this structure would result in measurable deflection of the

invert and thus the track, so additional tilt nodes were installed on sleepers to observe movement related to the invert.

4 CONCLUSION

The monitoring programmes described here found that neither of the presented projects encountered significant deformation. However, because the works were conducted under the umbrella of risk mitigation by meticulous observation of structural changes and deformation they could be progressed with confidence and efficiency. The use of the optical displacement sensor in particular enabled analysis of convergence in situations that would not have been possible with other methods. The use of automated wireless systems in general demonstrated that their capability encompasses the entire workflow from data acquisition via transfer and processing towards multi-user data visualisation and thus, provision of the observed parameters to all involved disciplines without delay.

Looking forward, the obtained information can be fed into the “observational method”, i.e. the feedback loop suggested by Peck [Peck R. 1969], confirming or refuting the design assumption in a “learn-as-you-go” procedure. This allows timely modification of processes in order to optimise construction progress and reduce the hazard risks.

An additional advantage of the presented solutions is that the initial installation (“ab initio” system) can be expanded to multi-sensor, multi-purpose systems by successively adding sensors in response to changing conditions and requirements (“best-way-out” method).

The ease of use of the system promotes the common and efficient utilisation of automated methods in physical and commercial risk mitigation, even at early stages by making “deformation monitoring an integral part of decision making in the design-construction-supervision-maintenance system” [Kavvasdas M.J., 2005].

4. REFERENCES

British Tunnelling Society (2011), “Monitoring Underground Construction – A best practice guide”, British Tunnelling Society and Institution of Civil Engineering, Reprint 2014), ISBN 978-0-7277-4118-9.

Erlendsson, Olof (2020) “Comparison of Tunnel Convergence Measurement Methods”; Degree Project in the Built Environment, KTH Royal Institute of Technology, School of Architecture and the Built Environment, Stockholm, Sweden

INSTOP (2021) <https://www.youtube.com/watch?v=hSOjfC8eGho>

Kavvasdas, M.J. (2005) "Monitoring Ground Deformation in Tunnelling: Current practice in Transportation Tunnels". Engineering Geology Volume 79, Issues 1–2, 2005, pp 93-113, ISSN 0013-7952

Peck, R.B. (1969) “Advantages and Limitations of the Observational Method in Applied Soil Mechanics” 1969, Géotechnique, pp 171-187, V 19, N 2, 10.1680/geot.1969.19.2.171

Soil Instruments (2021)

<https://www.soilinstruments.com/products/extensometers/digital-tape-extensometer/>