Sensing and monitoring in tunnels testing and monitoring methods for the assessment of tunnels

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Abstract
The paper presents a review of testing methods and a classification of strategies and tools in terms of technologies and techniques applied to the monitoring of tunnels. In particular, the topic is contextualized through a brief introduction in Chapter 1, followed by defect taxonomy and degradation mechanisms in Chapters 2 and 3, respectively. Chapters 4 and 5 are related to monitoring strategies and technologies. The former consists of purpose-based categorization of monitoring policies, while the latter consists of classification of monitoring methods including nondestructive and semidestructive techniques as well as of classification of various types of sensors also based on the physical or chemical quantity measured. General rules of implementation and operation of tunnel monitoring systems are presented taking into account international expert knowledge as well as contemporary practical experience in Austria. Considered issues are related to the fib Model Code 2020 (MC2020) focused on evaluation of structural performance assisted by monitoring and testing. Chapter 6 presents challenges related to the monitoring implementation and operation. Chapter 7 discusses about monitoring characteristics in new tunnel, including...
1 | INTRODUCTION

1.1 | General considerations

Monitoring of tunnel infrastructure is a very complex task, involving vital asset of the community, thus being of great responsibility, as also discussed in Bien (2019) regarding bridges. In fact, tunnel and bridges share being both complex physical systems consisting of many heterogeneous components, that might undergo various degradation processes. In order to properly manage operation and maintenance of tunnels, the whole monitoring must be efficient. Here it is intended for monitoring system the planning of all activities finalized to collect data on the structure defects to assess the tunnel condition as a background tool for the competent management.

Furthermore, it is an interdisciplinary activity that requires experts in integrated and various disciplines, including, but not limited to: structure inspection, non-destructive testing, structural and electronic engineering, numerical modeling and simulation techniques, data processing, communication and archiving techniques, software design and implementation methods, and operations coordination. A team of experts, which cooperates and efficiently communicates on the topic, is often times necessary in order to develop a unified analysis and planning of monitoring activities. The topic is in great demand and subject of research in many countries and in many international research projects, such as:

- Eurostars E!12,267 OpOrTunIty (Operation Oriented Tunnel Inspection System), Fraunhofer-Institute For Physical Measurement Techniques, Press ReleasE, January 8, 2019,
- TRITon—Trentino Research and Innovation for Tunnel mONitoring,
- Value-based tunnel repair strategy for London Underground (CSIC with Industry Partner London Underground),
- Collaborative Research Center SFB 837, Interaction Modeling in Mechanized Tunneling.

One main target is, in the long run, to enhance the asset management of aging structures through improved monitoring strategies. This can be achieved by studying new approaches that help better quantifying and assessing the performance of tunnel systems, as well as assuring expected performance level via new quality specifications. Many of the topics introduced in this paper are directly related to the part “Evaluation of structural performance. Evaluations assisted by monitoring and testing” of the fib Model Code 2020 (MC2020). As defined already by Bien (2019), in this current document a few definitions are repeatedly used. In particular, “tunnel defect” is defined as a phenomenon that could impair the technical and/or functional condition of the structure as a result of a degradation process. The term “tunnel technical condition” refers to a measure of differences between the real and the designed value for specific technical parameters, for example, geometry, material characteristics, and so forth. Finally, “tunnel functional condition” refers instead to a measure of conformity between actual operational conditions and user required conditions, for example, load capacity, clearance, maximum speed, and so forth.

Another aspect in the long-term impact and behavior of the rock/gravel mass is that, currently, there is not any comprehensive or unified design standard related to tunnel structures. The design standards or guidelines implemented for each project are therefore selected and applied by the tunnel owner or by the related authority. However, the project-specific rock or soil conditions, the several possible types of tunnel by use, and the excavation and support methods not necessarily do, thus increasing the variation in the life cycle management of the structural lining.

Another important aspect worth of being mentioned is failure mechanisms and associated risks. In fact, failures of tunnel support systems during construction may mobilize a large part of the underground space, thus causing a series of chain events, such as influx of large ground volumes or flooding of the excavated tunnel,
excessive settlements or collapses of assets in vicinity and on the surface, and significant delays in delivery. During operation, it is often considered that the tunnel and ground interaction is a relatively stable and thus reliable load bearing system. However, consequences of failure are still of great significance as noted above. Moreover, any difficulties of maintenance activities in the tunnel need to be carried out in a live condition or with minimal interruption of the tunnel with particularly tight schedule, and typically with high-risk activities and with work in confined spaces. As a consequence, advanced life cycle performance assessment techniques become of great importance. In particular, associated areas with typical monitoring tasks in tunneling are shown in Figure 1.

1.2 | Taxonomy of tunnels

Tunnel management is highly related to tunnel classifications.

**Depending on the use**, it is possible to classify tunnels in:

- transportation tunnels,
- energy supply and cable tunnels,
- sewage and water treatment tunnels,
- pressurized flow tunnels,
- auxiliary structures.

Transportation tunnels comprise probably the largest tunnel number and they can be additionally classified in railway, road and pedestrian tunnels. Railway tunnels can also be divided into heavy, rural, and freight rail tunnels, or in urban, light rail or metros. Road tunnels can be divided into highway and motorway tunnels. Auxiliary tunnels may include: vertical access and escalator shafts, ventilation tunnels, or cross passages. Tunnel structures are also used for access and withdrawal of material in mines and in the oil and gas industry, thus playing an important role, depending on the duration of life cycle management project. Additionally, in some cases, complex combined systems are devised, as for example, combined railway and highway tunnels, or transportation and flood relief tunnels.

It can be stated that in most types of tunnel structures, the load development in the long term is essentially stable. Pressurized tunnels are typically parts of hydropower plants during construction (diversion tunnels) or operation (headrace/penstock tunnels), and they are fundamentally distinct from other types of tunnels, since the inner applied load may exceed the ground loads, and it can become a significant cyclic action. Rock swelling over time may also exceed tunnel’s stability.

**Depending on the load bearing system**, tunnels are differently classified. Typically, tunnels are constructed with a primary support in order to create a safe and suitable underground space, which accommodates the installation of a final lining of the tunnel and the required infrastructure. In some cases, the primary support also partly or even entirely acts as the final and long-term support of the tunnel.

Regarding the support system, one can distinguish between unlined tunnels in very healthy rock environments, such as rock or soil anchoring pattern, tunnels with a lining constructed with bricks (often perennial structures), cast-in place or sprayed concrete, as well as concrete, cast-iron, or steel prefabricated segments. Regarding tunnels with a concrete final lining, it should be noted that in many cases unreinforced or fiber reinforced material is used, instead of reinforced rebar. These aspects can strongly influence the failure or degradation modes, in

![Monitoring of Tunnels](image-url)
correlation with the environmental and loading conditions. The various types of linings are correlated to various possible tunnel shapes. For example, segmentally lined tunnels are of circular shapes, while brick and sprayed lined tunnels mostly implement arch shapes. The shape in relation to the stress field around the tunnel may additionally influence the susceptibility of the tunnel to degradation processes (e.g., concrete lining under mild compression can prove to remain unaffected of material degradation phenomena such as cracking or creep).

The load bearing system is also strongly associated to the selected construction method. In relation to this matter, one can distinguish between tunnels excavated with: drill and blast method (hard rock), road-header (soft and hard rock) method, and conventional or mechanized like Tunnel Boring Machine (TBM) excavation methods (rocks and soft soil). Cut and cover tunnels are usually constructed at shallow depths, which are then related to soft rock or soil. Manual excavation has been implemented to a great extent only for historical and older tunnels, as well as for minor excavations in very confined underground areas. Based on the investigations of, it is evident that more than 83% of tunnels are lined with un- or reinforced concrete. Brick, iron or steel segments have generally been used in the lining of manually constructed tunnels. Drill and blast, road-header, and conventional excavation are associated with anchoring systems and sprayed concrete support systems. TBM excavation is associated with concrete segments (rarely with unlined or sprayed concrete linings in rock). Therefore, a maintenance strategy may be indirectly influenced by the tunnel construction method classification.

Depending on the typical failure type, the failure types in a tunnel can be principally differentiated between failures in the construction and in the operational phase. During operation, structural failures can be related to failure of the lining / support system itself, or failure of the installed secondary structures. In both cases, failures can result from loss of load-bearing capacity due to excessive loading situations (internal or external pressures), degradation of materials, and accidents or defects. Fire accidents have been under particular focus, as a consequence of historical catastrophic events in high-importance tunnel structures. Nonetheless, vital parts for the tunnel operation are typically the tunnel infrastructure (e.g., equipment and secondary structures), since (a) they are directly affecting the tunnel user and (b) in most cases the tunnel load bearing structure is—if at all—slowly affected throughout the operational phase, beyond handover of construction. Structures that can be emphasized in a life cycle management strategy, can also be accordingly grouped and prioritized in suspended structures, wall elements, invert structures and tunnel permanent support/lining.

A further type of failure often observed in tunnels is groundwater ingress in form of leakage. This is associated, from a structural viewpoint, with durability of the lining and of the reinforcement. This can also be further associated with the diffusion of aggressive substances from the surrounding substrate as it is discussed in typical exposure classes of concrete structures.

2 | DEFECT CLASSIFICATION

A consistent and comprehensive taxonomy of the most recurrent structural defects can lead to a more effective monitoring of the structural conditions, as also explained in Bien (2019), in full analogy with bridges. The classification of tunnel defects presented in Table 1 stems from a proposals described in Cigna et al. and was developed in the form of a three-level hierarchical system:

- level 1: basic classes of defects,
- level 2: types of defects defined for each basic class,
- level 3: categories of defects proposed for each type of defects.

The basic classes of defects (level 1) can be defined as follows:

- deformation caused by rock deformation
- deformation: incorrect geometry of constructed element as well as changes of structure geometry during operation, with changes of mutual distances between structure points—incompatible with the design,
- destruction of material: deterioration of physical and/or chemical as well as structural features of material in relation to the designed values,
- loss of material: decrease of designed amount of structural material,
- discontinuity: break of continuity of a structural material—inconsistent with the design (crack or fracture),
- contamination—appearance of any type of dirtiness or not designed vegetation on the structure,
- displacement: change of the position of the structure or its part—incompatible with the design, but without changes of mutual distances between structure points (without deformation); or restrictions in the designed displacement capabilities of the structure.

Proposed classification of defects of tunnels with concrete final lining with bar or fiber reinforcement is presented in Table 1.

This classification can be of great support in identifying and in describing the most recurrent defects specific for tunnel structures. The classification can be further
developed and level-diversified, in accordance with multi-level taxonomy. The main scope in classifying defects would be to reach comparable results among independent inspectors performing similar tasks. It also invests great importance in the formulation of tunnel quality specifications and in the examination of the

| Class of defect          | Type of defect                | Category of defect                                      |
|-------------------------|-------------------------------|--------------------------------------------------------|
| Deformation             | Incorrect geometry of constructed element | Incorrect shape of concrete segments                    |
|                         |                               | Uneven lining midline                                   |
|                         |                               | Invalid arrangement of reinforcement                    |
|                         |                               | Inconsistent tolerances                                 |
| Change of the geometry of cross section | Excessive elastic deformation | Distortion                                              |
|                         |                               | Permanent deformation                                   |
| Destruction of material | Change of the chemical characteristics | Change of concrete characteristics                      |
|                         |                               | Change of reinforcing steel characteristics             |
|                         | Change of the physical characteristics | Change of rock bolts/anchors characteristics          |
|                         |                               | Change of protective layers characteristics            |
|                         |                               | Change of concrete characteristics                     |
|                         |                               | Change of reinforcing steel characteristics             |
|                         |                               | Change of rock bolts/anchors characteristics           |
|                         |                               | Change of protective layers characteristics            |
| Loss of material        | Loss of structural material   | Loss of concrete                                        |
|                         |                               | Loss of reinforcing steel                               |
|                         | Loss of material of protective layer | Loss of bolts/anchors material                        |
|                         |                               | Loss of material of concrete protection                 |
|                         |                               | Loss of protection of reinforcing steel                |
|                         |                               | Loss of waterproofing (incl. joints, gaskets)         |
| Discontinuity           | Crack                         | Crack of concrete                                       |
|                         |                               | Crack of reinforcing steel                             |
|                         |                               | Crack of waterproofing                                 |
|                         |                               | Crack of protective layer                              |
|                         | Fracture                      | Fracture of concrete                                    |
|                         |                               | Fracture of reinforcing steel                          |
|                         |                               | Fracture of protective layer                           |
|                         |                               | Fracture of rock bolts/anchors                         |
| Contamination           | Inorganic                     | Aggressive                                             |
|                         |                               | Neutral                                                |
|                         |                               | Groundwater ingress                                    |
|                         | Organic                       | Aggressive                                             |
|                         |                               | Neutral                                                |
| Displacement            | Incorrect linear displacement | Excessive movement                                      |
|                         |                               | Restricted movement                                    |
|                         | Incorrect rotation            | Excessive movement                                      |
|                         |                               | Restricted movement                                    |
structure performance indicators during the complete process of condition monitoring.

3 | DEGRADATION MECHANISMS

Tunnel structures are affected by multiple degradation mechanisms that can possibly lead to first defect generation, then failures and finally even collapses (Bien 2019). When two or more mechanisms act simultaneously, degradation processes at a final stage either on the tunnel structures as a whole or on selected elements take place.

Degradation mechanisms can be generally divided into three groups:

- chemical mechanisms—causing structure deterioration as a result of chemical processes: carbonation, corrosion, reactions between aggressive material components, and so forth,
- physical mechanisms—when deterioration is a consequence of physical phenomena: erosion, overloading, fatigue, crystallization, extreme temperatures, freeze–thaw action, rheological effects, and so forth,
- biological mechanisms—in the case of deterioration aroused by biological organisms: microbes, plants, animals, and so forth.

Relationships between the degradation mechanisms typical for tunnels with concrete lining and basic classes of defects are presented in Table 2.

4 | MONITORING STRATEGIES

As defined in17 and in accordance with Bien (2019) monitoring can be generally defined as a coordinated act of acquiring, processing, communicating and archiving information about the actions on a structure and/or the action effects on a structure over a given period of time. As shown in Figure 2 policies for transportation structures monitoring, including tunnels and bridges, can be divided into two main categories, namely load-independent and load-dependent.

In analogy with Bien (2019) for bridges, load independent monitoring of tunnels consists of both regular and special inspections. In both cases visual examination, nondestructive testing (NDT) and/or semidestructive testing (SDT) can be performed, regardless of the structure loads.5,18–28 Regular inspections are typically performed on a basic level (every year) and on an advanced level (every 4–5 years) and this can be usually applied to all existing structures. Detailed procedures and requirements are generally defined in national regulations.

The load-dependent category, also called technical monitoring, is based on the observation of a structure response to operation loads and environment by means of installed technical measuring equipment.29–39 It is characterized by the installation of a technical monitoring system finalized to the data acquisition and processing, that continuously and autonomously provides real-time information about a structure or its component. The result of this analysis is conveying information regarding the exact estimation of tunnel conditions inherent to aspects that can generally not be fully described by means of inspections only.

In this category static and dynamic controlled proof load tests can be listed, including short- and long-term technical monitoring under normal loading as well as under natural environmental conditions. Predefined proof load tests are usually applied before opening a new structure to traffic or after completing major rehabilitation works. For short-term monitoring it is intended a process which usually last from 24 hr to a few days by means of temporarily installed sensors, while for the long-term monitoring a process which involves a permanently mounted system is intended. In both cases, transducers for sensing physical or chemical quantities with the use of programmable electronic equipment that acquire, process and communicate data are employed. Tailored algorithms are developed for the data acquisition, processing and communication.

The overall objective of technical monitoring is to support inspections at improving the knowledge on structures and their behavior, including recognition and evaluation of areas that are out of reach. The information obtained by monitoring can be used for the following different purposes of structural performance evaluation:

- identification/verification of tunnel actual technical parameters,
- identification of tunnel loads and environmental actions,
- monitoring of tunnel reaction to loads and other influences,
- recognition of tunnel degradation processes,
- detection of structure defects,
- documentation of tunnel history and prediction of its remaining life-time.

Table 3 lists the types of technical monitoring systems in analogy with Bien (2019) for bridges. In particular, depending on analysis goals, the following basic types of technical monitoring systems can be distinguished:

- Action monitoring—allowing measurement of the magnitude as well as the spatial and time-based distribution
of specific external influences acting on a structure or its component, including loads and environmental actions.

- Reaction monitoring—allowing measurement of the state of displacement, stress/strain level and their distribution in a structure as well as identification of vibration parameters: frequency, velocity, amplification, damping caused by traffic loads and other influences.
- Performance monitoring—allowing to evaluate whether a structure or its component meets the performance requirements under specific or any actions, defined by the performance indicators.
- Health monitoring—allowing the real-time assessment and prediction of health condition of a structure or its component by means of their safety and functional characteristics.

As valid for bridges in Bien (2019), it is important to individually design each monitoring system, taking into account the specific problematics of the case. In most of the practical applications, it can be said that each specific implementation results from a mixture of the categories listed in Table 3.

However, advanced monitoring systems are not technically needed for all analyzed tunnel structures, besides not being also economically feasible. In fact, its application is typically limited to the following situations (Bien, 2019):

- tunnels with innovative structural and/or material solutions,
- very important tunnel structures that are strategic components of transportation system,

| Degradation mechanisms | Class of defects |
|------------------------|-----------------|
|                        | Deformation     | Destruction    | Loss of material | Discontinuity | Contamination | Displacement |
| Physical               |                |                |                  |              |              |              |
| Accumulation of inorganic dirtiness | | | | | | |
| Cyclic freeze-throw action | | | | | | |
| Erosion                | | | | | | |
| Crystallization        | | | | | | |
| Extreme temperatures   | | | | | | |
| Creep                  | | | | | | |
| Relaxation             | | | | | | |
| Shrinkage              | | | | | | |
| Overloading            | | | | | | |
| Fatigue                | | | | | | |
| Geotechnical condition changes | | | | | | |
| Chemical               |                |                |                  |              |              |              |
| Carbonation            | | | | | | |
| Corrosion              | | | | | | |
| Aggressive compounds action | | | | | | |
| Chemical dissolving/leaching | | | | | | |
| Reactions between material components | | | | | | |
| Biological             |                |                |                  |              |              |              |
| Accumulation of organic dirtiness | | | | | | |
| Activity of microbes   | | | | | | |
| Activity of plants     | | | | | | |
| Activity of animals    | | | | | | |

Note: ■, basic degradation mechanism; □, additional degradation mechanism.
damaged structures awaiting rehabilitation or replacement,
selected reference tunnel structures, representative for the national tunnel asset, monitored for creation and verification of degradation models.

Only components which are critical for the safety, durability and resistance of the whole structure are object of the technical monitoring process. Selection of the most efficient strategy and technology of the tunnel monitoring should be based on analysis of fundamental aspects like (Bien, 2019): measurement frequency, type of controlled quantities, nature of monitored processes, technologies of data transmission, and so forth—as presented Figure 3.

5 | MONITORING TECHNOLOGIES

Depending upon the purposes of the monitoring procedures, specific technologies, which can substantially differ from each other, are applicable. Classification of the technologies can be based on the:

- frequency of inspections/measurements, thus including:
  - continuous observation with defined frequency of measurements,
  - periodical observations with predefined schedule and program,
  - irregular observations/measurements dependent on specified conditions;
- type of monitored occurrences, namely:
  - physical parameters,
  - chemical processes,
  - biological phenomena.

In the case of inspections for the load-independent monitoring a wide range of nondestructive testing methods (NDT) and semidestructive testing methods (SDT) can be used, as also discussed for bridges by (Bien, 2019). In the former case, the techniques fully preserve the integrity of the tested structures.

In the case of the semidestructive testing methods, the techniques involve material samples to be taken apart.

### TABLE 3 Types of technical monitoring systems and expected effects based on the work of Bien (2019)

| Type of monitoring system | Monitoring effects |
|---------------------------|-------------------|
| Action monitoring         | Characteristics of all loads acting on a tunnel structure |
|                           | Geometry and speed of vehicles |
|                           | Environmental influences (temperature, wind, humidity, earthquakes, etc.) |
|                           | Monitoring of accidents on the structure and in the neighborhood |
| Reaction monitoring       | Technical parameters of structural elements |
|                           | Displacements, strains, stresses, vibration frequency, velocity and amplifications, etc. of structural elements |
|                           | Verification of theoretical analyses |
|                           | Modal parameters of the structure |
|                           | Dynamic amplification factors |
|                           | Material effort level |
| Performance monitoring    | Identification of critical values of measured quantities |
|                           | Detection and identification of tunnel defects based on measured quantities |
|                           | Monitoring of parameters of defects (location, extent, intensity) |
|                           | Assessment of tunnel technical and/or functional condition |
| Health monitoring         | Changes of technical and/or functional condition |
|                           | History of loads and environmental influences (temperature, wind, humidity, earthquakes, etc.) |
|                           | Observation of degradation processes progress (e.g., depth of concrete carbonation, corrosion advancement, etc.) |
|                           | Determination of input values for degradation models |
|                           | Remaining life-time prediction based on degradation model |
as well as minor breach of the structural integrity. Table 4 presents a classification of the most popular SDT methods and techniques, where physical, chemical, and biological methods applied during field and laboratory tests are distinguished.

In monitoring of tunnel structures by means of installed equipment, a wide range of measuring techniques and sensors can be engaged, for example, References 28, 30, 36, 37, 39. Typical tools applied for monitoring of forces/effects acting on a structure are here presented in Table 5.

As far as reactions to loads, other actions or performance and health monitoring are concerned, the following physical and chemical quantities can be considered, for example:28–39:

- linear and angular displacements,
- strain and stress level,
- vibration characteristics,
- crack opening changes,
- surface movements and influence to adjacent structures,
- quantities specifically related to degradation processes.

The most widely applied measuring techniques and types of sensors for tunnel monitoring are presented in Table 6. Additional techniques allowing the monitoring and processing of deformations as well as surface alterations relay on optical sensing and photogrammetric methods, which are discussed in detail further below.

6 | Monitoring Implementation and Operation

In analogy with Bien (2019), the general scheme for the implementation procedure of long-term monitoring systems based on sensors is presented in Figure 4. Initially, type and goals of the monitoring system are chosen, thus defining the system architecture design. A detailed design of aforementioned system follows, which is then installed on the structure. This poses the basis for the testing itself. Experimental values should be compared to the theoretical model of the structure.31 Testing process should also confirm that tunnel performance indicators can be observed using the applied monitoring system.

In case of positive results of testing procedures, acceptance for operation follows. During long-term working of the system some maintenance activities are often necessary, also including modifications of the system elements and improvements of the structural theoretical model engaged in analysis of measurement results.

Contemporary tunnel monitoring systems are more and more equipped with knowledge-based expert tools that support not only the processing and the analysis of experimental data, but also decisions to be taken during the management of the tunnel operation and maintenance, for example, References 17, 41–44. Another key point to be mentioned is that Information Technology (IT) rapidly develops, thus preluding to the fact that tunnel health-monitoring systems will be soon part of the
Unified Building Information Management (BIM) process. Operation scheme of an advanced monitoring system is presented in Figure 5. The basic components of the systems are:

- measuring system with an equipment transmitting data to acquisition module,
- data processing module using theoretical model of the structure for analysis and interpretation of measurement results,
- module responsible for presentation of output data, often equipped with visualization tools,
- expert system supporting decisions in management of tunnel operation and maintenance by means of information collected in data and knowledge base.17,42,44

| TABLE 4 | Classification of SDT methods and techniques based on the work of Bien (2019) |
| --- | --- |
| **Testing methods** | **Measuring techniques** |
| Field tests |  |
| Physical methods | Pull-out/pull-off tests |
|  | Penetration tests |
|  | Water resistance test |
|  | Probe drilling and ground sampling (inside/outside of tunnel) |
|  | Pressure techniques (flat-jack test, water penetration test, etc.) |
| Chemical methods | Rainbow/pH tests |
|  | Chloride test |
|  | Alkaline test |
|  | Electroanalytical tests |

| TABLE 5 | Monitoring of loads and environmental impacts based on the work of Bien (2019) |
| --- | --- |
| **Physical quantity** | **Measuring techniques and sensors** |
| Temperature | Thermocouples |
|  | Thermistors |
|  | Electrical resistance thermometers |
| Humidity | Hygrometers |
|  | MEMS sensors |
| Lighting | TV/video cameras |
|  | Photosensitive sensors |
| Wind/ventilation | Anemometers |
|  | Aneroids |
|  | Air composition tester |
| Water ingress/flow | Water level sensors |
|  | Water velocity sensors |

7 | PRACTICE SPECIFIC BASICS IN TUNNEL MONITORING

7.1 | Data acquisition-transmission

7.1.1 | Sampling frequency, data storage, data transmission

Generally, the sampling frequency depends on the kind of measured variable which has to be recorded. For vibration measurements (accelerations or vibration velocity) and generally dynamic measurements, higher sampling frequencies (>100 Hz) are required than for geodetic or quasi-static inclination measurements. However, sampling frequency has to be defined in advance, during planning the monitoring task. Beside the individual measured variables, the possibilities of different sampling frequencies on a logging system have to be considered. In most cases, the application of different sampling rates on a measuring system is limited.

7.1.2 | Data storing local and remote

Although prices of storage media have decreased significantly, data storage of long-term monitoring tasks can still be a challenge. Especially in case of live measurements, high sampling rates are required. Figure 6 shows a storage-requirement estimate for different sample rates and channel amounts, based on a memory depth of 16 bits.

A few comments are worth of being mentioned:
a continuous storage of a large number of channels with higher sampling frequencies (>100 Hz) can be a challenge for long-term monitoring data storage,

TABLE 6 Measuring techniques and types of sensors used in monitoring of tunnel structure performance based on the work of Bien (2019)

| Physical or chemical quantity | Measuring techniques and sensors |
|--------------------------------|----------------------------------|
| Linear displacement           | Geodetic techniques             |
| Mechanical sensors            | Inductive sensors               |
| Vibrating wire sensors        | Capacitive sensors              |
| Eddy current sensors          | Fiber optics sensors            |
| Laser techniques              | Radar techniques                |
| Extensometers                 | Hydraulic sensors               |
| Angular displacement          | Inclinometers                   |
| Fiber optics sensors          | MEMS sensors                    |
| Strain/stress                 | Electrical resistance gauges    |
| Load cells                    | Fiber optics sensors            |
| Vibrating wire sensors        | Hydraulic piezometers           |
| MEMS sensors                  |                                  |
| Vibration velocity and        | Piezoelectric sensors           |
| acceleration                  | Capitive sensors                |
| Inertial sensors              | Inductive sensors               |
| Radar techniques              | Laser techniques                |
| Geophysical seismic testing   | MEMS sensors                    |
| Crack opening                 | Mechanical sensors              |
| Inductive sensors             | Fiber optics sensors            |
| Vibrating wire sensors        |                                  |
| Degradation processes         | Acoustic emission sensors       |
| Chloride level sensors        | Sensors of pH level             |
| Corrosion sensors             |                                  |

- a full raw data transfer is hardly possible, if no wired data connection is available, specific solution can be the users basis for triggering.

These define criteria have to be fulfilled in order to save the data. Data that does not meet these criteria are otherwise permanently deleted.

The criteria that determine whether data is stored or permanently deleted can range from simple threshold value criteria to complex links of multiple sensors.

For storage itself, hard disk systems without moving parts are recommended (SSD hard disks). These are less sensitive to external influences. For storage on “flash” cards, it should be noted that these often have a limited number of read/write cycles. This can lead to increasing error susceptibility with increasing age.

7.1.3 | Data transmission

In the field of data transmission enormous developments have taken place in the last decade. These relate to both network coverage and availability, especially in tunnels, as well as the bandwidth itself. The development has its origin in the GSM standard with only a few kbit/s and reached today a good coverage of 4G (LTE) and bandwidth of up to 100mbit/s.

However, these high bandwidths represent “optimal values”. With greater distance to the next base station or heavily loaded base stations, the “real” values can be

FIGURE 4 General scheme of monitoring system implementation
considerably lower. This is also influenced by the geometry of the tunnel (e.g., blind spots due to vertical and horizontal tunnel alignment curvature).

Permanent transmission of the raw data can therefore not be guaranteed with conventional mobile radio technology. As a result, it must be decided during the monitoring planning process which data should be available online. The following fundamentals for data transmission have to be considered:

- transmission of minimal data to check the functionality of the whole system or single sensors. To do this, only single values may be transmitted at relatively large intervals (e.g., 3 times a day). This can be guaranteed even in the worst transmission conditions (GSM standard with few kbit/s).
- Periodic transmission of single values to check a limit or alarm criterion. Data is therefore transmitted periodically, usually every few minutes.
- Partial transfer of raw data for further evaluations/interpretations. In this case, depending on a selected trigger threshold, raw data is transmitted. This can usually only be achieved with 3G or 4G cellular standard.

The transmission of the full raw data is usually only possible with wired or proprietary data connections (unidirectional radio antennas with base station). In recent years, fiber optic cables are often used in tunnel structures where transmission over 10–20 km is possible without significant bandwidth lost. The corresponding interfaces at the beginning and end of the fiber optic cables (routers) provide the translation between fiber optic transmission and conventional LAN transmission.

### 7.2 Engineering monitoring techniques

#### 7.2.1 Vibration-/acceleration

Vibration and acceleration measurements can be classified as indirect measurement methods. This means that they can both provide only indirect and relative statements about the stiffness behavior of a structure. The basic equation is:

$$ F_0 = \frac{1}{\pi} \sqrt{\frac{k}{m}} $$

With $F_0$, natural frequency; $m$, mass; and $k$, stiffness of the system.

Since mostly the mass ratios or in particular modal masses are unknown, the (modal) stiffnesses can only be indirectly and relatively inferred. The damping properties of the surrounding soil also add incomplexity since the soil properties and the soil structure interface are governed by variability and randomness. However, the advantage of this kind of measurements is the rather easy application. Figure 7 offers a few typical applications.

**FIGURE 5** Operation scheme of monitoring system supported by knowledge-based expert system, according to Bien (2019)

**FIGURE 6** Storage requirement estimation
Accelerometers are usually easier to mount on exposed locations such as tunnel walls or structural parts due to their smaller size. With regard to the measurement principle of accelerometers, both capacitive and piezoelectric sensors are widely used. For capacitive sensors, the principle is based on the movement of capacitor plates by external acting acceleration. This causes a capacitance change of the capacitor from which the applied force and acceleration (see Equation (1)) can be derived. For piezoelectric acceleration sensors, the measuring principle is based on the same-named effect. The acting force causes the crystals of the ceramic core shifting against each other. This displacement causes an electrical voltage, from which the acting force or acceleration can be calculated.

For vibration velocity sensors (geophones), whose origin comes from the earthquake field, the measuring principle is based on a coil with a moving magnet in the core. This movement induces a voltage in the coil, which is proportional to the externally induced vibration velocity. Due to this measuring principle, the size of the construction is usually larger than with acceleration sensors.

The advantage of these measuring sensors is the handy application. The sensors must be simply attached to the tunnel wall or floor.

The output of acceleration or vibration velocity sensors are usually volts (±10 V), and charge amplifiers for the capacitive acceleration sensors are necessary.

The disadvantage of this kind of sensors is that high sampling rates (>100 Hz) are necessary and, secondly, that the results need to be further interpreted. Direct statements about damage of a structure cannot be derived from the results.

7.2.2 | Inclinometers

Inclination sensors can be used for quasi-static measurements as well as for dynamic measurements. On the one hand, the results of inclination measurements can directly indicate movements, but on the other hand, they can also be interpreted by further calculations for deformations (bending line of a structure). Inclination sensors determine the position angle of an object with respect to the gravitational field of the earth. The application possibilities for these sensors are manifold: on cranes and excavators, for example, the inclination angle of the boom is detected to prevent the machine from tipping over. Tilt sensors can be used for both quasi static and dynamic measurements.

Nowadays available sensors typically use either liquid-based mechanisms or mechanical spring mass systems. Microelectromechanical systems typically use spring-mass systems that determine the deflection of small test masses as a function of the position.

Liquid-based systems use either the reflection or refraction of a light through the liquid level or a resistance measurement or capacitance measurements as a function of the position of the liquid. Especially in the case of liquid-based systems, the dynamic resolution is limited to lower (<50 Hz) frequencies.

The number of inclination sensors necessary to approximate a bending line sufficiently depends on the degree of a function (usually the polynomial) with which the bending line can be sufficiently approximated. If a third order function is necessary to describe the bending line sufficiently, at least N + 1, (4) inclination sensors are necessary to estimate the bending line. This means that a mathematical model (analytical or FEM) of the structure exists in advance.

The output from analog inclination sensors is predominantly a voltage signal (e.g., ±5 V) or a current output, for example, 4–20 mA.

The advantage of inclination sensors is, similar to acceleration sensors, the comparatively easy applicability.
of the sensors. The disadvantage of these sensors is that further calculations are necessary to determine actual deformation of a certain structure.

### 7.2.3 Strain gauges

Metall based strain gauges, which represent most of the strain gages available, are based on the change in resistance due to length and cross-sectional change of metal. If a DMS is stretched, its resistance increases. If it is compressed (negative strain), its resistance decreases. The output of strain gauges is the resistance, which is proportional to strain. The resistance is a value that cannot be measured directly. The measurement is usually done as a bridge circuit (analogous to a Wheatstone bridge) with either quarter, half or full bridge circuit used. An important point along with strain gauges is the application to the structure. The aim is to attach the strain gauges in such a way that they are fully connected in a frictionally manner and reflect every movement of the structure. This generally adapts very well to a structure such as steel, with appropriate pretreatment (see Figure 8). For this purpose, usually high-strength adhesives (often 2 components) are used.

When applying strain gauges to a structure like concrete the following points are important to note:

- the surface must be sufficiently smooth so that the strain gauge is well connected the entire surface of the structure.
- The surface must be free of dust so that the adhesive finds sufficient primer to produce a frictional connection to the structure.

An important issue with strain gauges is temperature sensitivity. This is due to the cables and the strain gauge itself. Since the measurement is based on a resistance measurement, changes in the resistance value of the cables are mistakenly interpreted as strains/compressions. This can be counteracted by the measurement as a full bridge. In this case, the cable resistance is compensated by corresponding additional lines. Another source of problems may be direct temperature acting on the strain gauge itself, such as sunlight, which will lead to resistance changes in the strain gauge, which are not due to real strain/compression of the structure. This can be controlled in the practice by housing the strain gauge by means of adhesive and metal foil.

The advantage of strain gauges is related to price. The individual strain gauges usually cost only a few euros, so that many sensors can be used to minimize errors by averaging. The disadvantage lies in the application on the structure. This can certainly be associated with considerable work to prepare the structure surface.

### 7.3 Optical monitoring techniques—3D laser scanning

#### 7.3.1 Concept

3D laser scanning has become a standard test method in tunnel monitoring in addition to traditional surveying methods, thus creating new possible survey applications. Unlike using a total station, at which single points are measured with high precision, 3D laser scanning acquires the position \((x, y, \text{and} \ z\text{-coordinates})\) of millions of points reproducing the scanned surface in detail. Because of its holistic approach for acquiring the geometrical parameters of the surrounding area actively (by the emission of laser light), distance-based, quickly (a few minutes per scan), in 3D and in high resolution, laser scanning has become an essential measuring method during tunnel drive as well as long-term monitoring of existing tunnel structures. Thanks to its high resolution, 3D displacement measurement can be performed by comparison of the scanned cavity geometry at various times. Nowadays, online observation of critical areas using automatic measuring is state of the art. Altogether, 3D laser scanning helps ensuring the design lifetime of the structure by recognizing changes in the geometry full-faced at an early stage, thus allowing a near-term damage repair.

#### 7.3.2 Functioning, accuracy and limitations

Laser scanning is an active, distance based imaging technique measuring the travel times of laser rays from the laser device that are reflected from the surface and detected again by the scanner unit. For scanning from
shorter distances (up to ca. 150 m), continuous wave (CW) lasers with modulated amplitude are used. Thereby, distance is measured through the phase displacement of the emitted and received laser beam. Using CW-lasers, the position of up to 1,000,000 points/s can be detected with a precision of up to 1 mm.\textsuperscript{52,53}

The design of modern scanner equipment shows small dimensions and low weight, thus the system is highly portable and applicable in narrow spaces. Most of the devices allow the operation in wet environment at a wide temperature-range commonly between −20 and 55°C. Since it is an active system, surveying with a laser scanner can be performed in poor light conditions, which is of great advantage in tunnel surveying, whereas heavy dust can cause interfering reflections and influence the measurement in a negative way. Nevertheless, free view to the investigated surface is necessary. Installations, vehicles, irregular geometry. Produce shadows, covered or shaded areas are not recorded. Multiple scans at different viewing angles generally reduce these data gaps.\textsuperscript{54}

In addition to position location, imaging laser scanners also record an intensity value for each point and therefore provide information about the type of surface depending on its reflective properties. However, the 3D point clouds do not provide image data that also may be useful in terms of interpretation and damage detection. For that purpose, imaging methods, like photogrammetric techniques, are suitable.\textsuperscript{55} Nevertheless, a laser scanner can be upgraded by integrated cameras recording the color information of the surveyed points, thus assigning color information to the laser data.\textsuperscript{53}

In general, by performing laser scanning, large point cloud datasets are generated in a short time. This is why point cloud management—including automated processing and analyzing procedures—is of great importance. Modern device and analysis software technology generally are supporting these requirement that is, Reference 56.

### 7.3.3 Geometry inspection and comprehensive documentation possibilities

One of the standard scopes doing regular inspection by laser range measurement recording the 3D geometry of the tunnel is to monitor the clearance zone of an operative railway tunnel. This is nowadays done regularly by the operating companies using laser-equipped rail-cars that can be driven at speeds of 10 to 30 km/hr. This provides a complete documentation of rock face, tunnel lining and different installations (installed components concerning ventilation, light, signs as well as exposed support measures like anchor heads etc.). Referring to control and invoicing function, this information can be of great assistance for maintenance, repair works and cost estimation that is, Reference 57.

By delivering 3D full-surface information, detection, visualization and analysis of cracks and other defects in concrete and masonry tunnels as indications of structure degradation at an early stage is possible (see also\textsuperscript{55}). Crack development can be recorded via multiple scans. The orientation information and crack opening widths as well as possible water ingress can easily be derived, that is, Wang et al.\textsuperscript{58} Depending on the perspective and crack characteristic, also crack depth can be monitored. In a final stage, the extent of the measures and behavior of restructuring actions—that is, thickness of shotcrete support layers—can be monitored by 3D laser scanning providing a good basis for modeling and postcalculations (Sánchez\textsuperscript{59}).

### 7.3.4 Displacement measurements

Next to geotechnical and operational applications\textsuperscript{60} like generating block models for rock mass analysis or data basis for maintenance,\textsuperscript{58} laser scanning is increasingly used for 3D displacement analysis during tunnel driving or inspection of existing tunnel structures. The displacement is determined via multiple scans at variable time intervals depending on the existing strain rate. Usually, reference points are measured in addition to the laser scan through an optical-trigonometric survey according to the principal of free stationing. In this way, every scan can be localized in the project or global coordinate system and be compared with one another. Thus, verification of displacement with an accuracy of 1 to a few mm is possible.\textsuperscript{52}

### 7.3.5 Additional comments

3D laser scanning enables rapid, cost-effective, high resolution and full-coverage documentation of the tunnel geometry of the tunnel lining and therein located installations. By performing multiple scans at different times, changes in tunnel structure can be detected in real time. Defects and risk potentials can be identified at an early stage and necessary measures can be taken at an early stage that has a positive effect on the life-cycle increasing the service lifetime of the tunnel structure and reduces maintenance costs. This is why laser-scanning technology has gained increasing significance in recent years. This development is supported by further automation of absolute position and image overlays, steadily increasing position accuracy, the advancement of software algorithms...
for data analysis and interpretation as well as the possibility for online monitoring and control.61

7.4  |  Geodetic measuring methods

7.4.1  |  Absolute measurement systems

Over the recent past, it has become good practice to perform 3D displacement monitoring using total stations. For this conventional monitoring approach individual tunnel cross sections are equipped with 5–7 prisms, which are distributed over the cross section and whose spatial position in terms of 3D-coordinates is repeatedly determined by total station measurements (see Figure 9).

\[ \sigma_x = 1 \text{mm} \quad (1) \]

For the determination of the displacements, measurements are performed in each epoch from stations along the tunnel’s longitudinal axis to reference points and to the cross-section points. The first category of measurements is used to transfer the 3D-coordinates from the reference points to the instrument’s station. Subsequently, these coordinates are further transferred to the cross-section points using the measurements of the second category. The measuring configuration and the used instruments must be selected in a proper way that allows to achieve a standard deviation for the coordinates of the latter points. Repeating this general procedure at consecutive epochs allows to derive the displacements as coordinate differences of the cross-section points.

To estimate the coordinates of the monitored cross-section points \( \hat{x} \), first the 3D-coordinates of the total station \( \hat{x}_{\text{TS}} \) need to be estimated. Between consecutive epochs, similar locations of the total station should be chosen. This enables the canceling or the diminishing of influences on the measurement results that are related to the instrument’s position by difference building between the epochs (see Equation (2)). In general, the stationing should be in the longitudinal tunnel axis, as this allows a balanced azimuthal distribution of the measurements and avoids sightings along the tunnel walls which are prone to refraction effects.

Common principle is to determine the coordinates \( \hat{x}_{\text{TS}} \) by free-stationing using reference points with estimated 3D-coordinates \( \hat{x}_{\text{ref}} \) in the project’s coordinate system (see Figure 10). These reference points are selected in the neighborhood of the total station (10–90 m, [62]) and are in general determined starting from or part of the tunnel’s underground geodetic network. They have to meet particular stability conditions with monthly movement rates below 1 mm.62 As the upper limit between consecutive instrument stations is at the order of ~100 m, an interlinked observation scheme of the cross sections is adopted (see Figure 10). Thus, reference points are commonly used for the coordinate’s determination of successive instrument stations.

Two reference points are sufficient for solving unambiguously the coordinates of the total station \( \hat{x}_{\text{TS}} \) within a single free-stationing. However, it is mandatory to choose a higher number of such points in order to check for the stability of the reference points and to meet the imposed accuracy (see Equation (3)) as well as reliability conditions. This implies solving an over-determined free-stationing, which constitutes an adjustment problem. As a result one obtains 3D-station coordinates for the \( j \)-th epoch \( \hat{x}_{\text{TS},j} \) and the corresponding covariance matrix \( S_{\hat{x}\hat{x}, \text{TS},j} \).

Starting from \( \hat{x}_{\text{TS},j} \), measurements to the cross-section points allow to determine their coordinates \( \hat{x} \) by solving the first basic geodetic problem. The covariance matrix \( S_{\hat{x}\hat{x}, \text{TS},j} \) is considered in the law of covariance propagation for deriving the covariance matrices of the monitored points \( S_{\hat{x}\hat{x}, j} \). The square root of the main diagonal elements of this matrix gives the standard deviation of the corresponding coordinates, thus allowing a direct assessment if the accuracy criteria given in Equation (1) is fulfilled.

The coordinate differences between consecutive epochs, \( j \) and \( j - 1 \), or between the actual epoch and a reference epoch, provide the absolute 3D-displacement vectors \( \mathbf{d} \):

\[ \mathbf{d} = \hat{x}_j - \hat{x}_{j-1} \quad (3) \]
Additionally, the covariance matrix of the displacement vectors, $S_{dd}$, is estimated from the covariance matrices of the coordinate vectors in the single epochs:

$$S_{dd} = S_{xx} + S_{xx}^{-1}$$  \hspace{1cm} (4)

This enables to perform a statistical test in order to check the global statistical congruency between the geometries of the cross section determined in the two epochs.\(^63\) The used test value is given by:

$$T = d^T S_{dd}^{-1} d$$  \hspace{1cm} (6)

and is central $F$-distributed under the null hypothesis $H_0$ that no deformations occurred between the two epochs:

$$H_0 : E\{d\} = 0$$  \hspace{1cm} (7)

If the test value exceeds the $(1-\alpha)$-quantile of the corresponding $F$-distribution the null hypothesis can be rejected at the significance level of $(1-\alpha)$, thus indicating that the geometry of the cross section represented by the measured points significantly changed between the epochs. In a subsequent localization phase, the displaced points are identified by assessing the contribution of each point to the mean gap between the geometries determined in the two epochs (Niemeyer,\(^64\) (p. 592 for further details on the method of mean gap components).

Some typical results of this monitoring activity are:
- sum vectors of the deformations (see Figure 11),
- influence area diagrams,
- settlement velocity diagrams,
- time-deformation diagrams.

### 8 CONCLUSION

The paper presents a review of testing methods and a classification of strategies and tools in terms of technologies and techniques applied to the monitoring of tunnels. In particular, the topic is contextualized through a brief introduction in Chapter 1, followed by defect taxonomy and degradation mechanisms in Chapters 2 and 3, respectively. Chapters 4 and 5 are related to monitoring strategies and...
technologies. Nondestructive and semi-destructive techniques are also used as the basis for classification of monitoring methods. Chapter 6 presents a few concepts related to the implementation and operation of tunnel monitoring according to both international expert knowledge and practical experience in Austria. Chapter 7 discusses basic concepts related to data-acquisition transmission, engineering, optical and geodetic monitoring techniques. Chapter 8 introduces aspects related to the monitoring of tunnels during rehabilitation. Concluding remarks, references and research projects finally close the paper in Chapter 9, 10, and 11, respectively.

The research and survey related with this project show for example:

- the taxonomy of monitoring plays a very important role for the monitoring tasks in tunneling and allows a very good overview of the damage mechanisms, the possible detection systems and monitoring tasks,
- furthermore, the overall task of tunnel monitoring could be worked out very well in this article. In addition to defect classification, knowledge of the mechanisms of degradation, the choice of monitoring strategies and the use of different monitoring technologies is of high importance, this includes also the implementation and operation of the monitoring system,
- furthermore, it could be shown that the monitoring of the interlocking of several disciplines like for example, of the NDT of the SDT, from geodetic measuring methods to information processing. This was also demonstrated by case studies,
- As demonstrated in the last section “Monitoring of tunnels during rehabilitation”, the monitoring tasks and strategies as well as the choice of sensor are very dependent on the external boundary conditions, in this case the site conditions during a tunnel rehabilitation. In this section, the procedure for choosing an optimized monitoring concept for the repair of existing natural stone or masonry tunnels could be presented.

In addition, the following recommendations stem from the discussions about tunnel rehabilitation. In particular, the following solutions result to be the best possible ones in terms of attainable performance and cost:

- the use of displacement transducers (vibration lateral sensors), inclination transducers in combination with strain sensors, in case of an evaluation length of <100 m.
- The use of fiber optic sensors (Bragg systems) in combination with convergence measuring belts or the use of Brillouin in case of an evaluation length of >100 m.
- The use of fiber optic sensors (Bragg systems) in combination with convergence measuring belts (possibly in combination with displacement transducers), for an extensive monitoring, in case of an evaluation length of >100.

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