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ARTICLE

Application of a structural monitoring on segmental tunnel linings

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Abstract
The prediction of the structural behavior and the internal forces acting in segmental tunnel linings is a difficult task and contains uncertainties. In situ measurements within structural monitoring are the only possibility to assess the results under realistic boundary conditions. However, no standardized structural monitoring method for segmented lining exists and consequentially setting up a new monitoring project requires an increased effort. Therefore, in this paper, first, an analysis of experiences in reported monitoring projects is done. Then, a report on a current monitoring project carried out by the authors and the experiences made are presented. Based on these, suggestions are given to facilitate future applications of structural monitoring on segmental tunnel linings regarding conceptualization, instrumentation, installation, operation, and data evaluation.

KEYWORDS
in situ measurements, monitoring, precast concrete segments, structural behavior, structural monitoring, tunnel lining, tunnelling

1 | INTRODUCTION

The calculation and prediction of the structural behavior of segmental tunnel linings (STLs) is a challenging engineering task, because[1–3]:

- Action and resistance cannot be separated clearly.
- Uncertainties regarding the ground properties exist.
- Different interactions and non-linear effects govern the structural behavior even in the serviceability state.

Therefore, simplified assumptions are required for calculations. Depending on the chosen calculation method and the assumptions made, the predicted stresses and internal forces in the segmented lining can vary significantly.[4–7]

In structural design, reliable and safe predictions regarding the limit states are ensured by considering unlikely loading situations and safety factors. However, because of the existing uncertainties, in some cases, more detailed investigations regarding the real structural behavior, the stress state, and the internal forces in segmented linings, are required—pursuing one or more of the following objectives[8–10] (Figure 1).

In situ measurements are necessary for these investigations, as it is the only chance for tests on full-scale under realistic boundary conditions. It is very difficult, if not impossible, to fully reproduce these conditions in the laboratory or in simulations.[11] For these in situ measurements, that are pursuing the mentioned objectives and capturing the structural behavior over a long period, the term "structural monitoring" is used.

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Objectives	Tasks/Goals	Key Questions
Research	- Advance state of the art - Improve calculation methods - Increase structural reliability - Reduce material consumption	- How does the structure behave in reality? - How good is the agreement between measurement and calculation?
Surveillance	- Surveillance of the structural behaviour - Surveillance of the development of stresses and internal forces	- Is the lining able to sustain high loads within the serviceability state?
Design Check	- Checking of calculation results - Checking the actual reliability of a structure	- What is the actual stress state in a specific period? - Does it match the predictions?

FIGURE 1 Scope of structural monitoring projects.

Although, for structural monitoring of other engineering structures, various recommendations and guidelines (e.g. for concrete structures,[12] bridges,[9,13,14] geotechnical structures[15]), standards (e.g. for geotechnical structures[16]) as well as many experiences and state-of-the-art reports (e.g. for concrete structures,[17] bridges[18–21] and geotechnical structures[22,23]) exist, this is not the case for STL. For structural monitoring of STL-reported projects that are rare, technical recommendations are limited and universal guidelines do not exist. The reason therefore could be that tunnel construction by placing concrete segments is a relatively new method compared to conventional excavation methods, although its share has increased in the last few decades.[24,25]

Despite the existing know-how on structural monitoring for different engineering structures, the concepts cannot be adopted for segmented linings as they stand. In fact, it is necessary to consider i.a. the differences in the load bearing behavior (e.g. STL are loaded immediately and permanently with great shares of the final loading). Moreover, the pursued objectives have to be considered to develop the monitoring specifications.

In the following, the state-of-the-art regarding structural monitoring of STL, reports from literature as well as experiences made by the authors in a current structural monitoring project are presented. Based on this, general recommendations on how to carry out structural monitoring on segmented linings are given to facilitate future applications. The focus lies on linings with precast concrete segments, as this is the state-of-the-art.

2 | STATE-OF-THE-ART: STRUCTURAL MONITORING OF SEGMENTAL TUNNEL LININGS

2.1 | Standards, guidelines, and general recommendations

To the best knowledge of the authors, no standard directly addresses the structural monitoring of STL. Regarding European standards, Eurocode 7[16] gives general recommendations regarding measurements of geotechnical structures. Eurocode 2[26,27] does not include structural monitoring of concrete structures. Appendix-D of Eurocode 0[28] brings together structural design with measurements giving some very general recommendations. EN-ISO-18674[29,30] covers geotechnical monitoring by field instrumentation. Other recommendations are given in Ref. [8,10]. Altogether the following is specified:

- The monitoring specifications depend on the boundary conditions of the tunnel and need to be adapted for changing loading situation.[8]
- The measurement system must be able to detect the geotechnical behavior, also on the long term.[16]
- The monitored sections should be selected carefully, be geotechnically uniform, and representative.[8]
- Redundancy (more measurements than required) and diversification (several measurement systems for the same parameter) in monitoring systems are important.[8,30]
- All potentially influencing factors have to be recorded for further analyses if needed.[30]
- Using robust sensors for the rough environment is necessary.[30]

In any case, structural monitoring should only be applied, if there is a valid reason for it,[15] as it is very laborious, which might not be appropriate without a valid reason.

Although addressing bridges, in the opinion of the authors, the general workflow proposed in Ref. [9] is, if adapted appropriately, most suited for any structural monitoring of STL, because it also considers required work steps beyond the actual measurements. The necessary tasks[8,9,12,30] are assigned to the corresponding steps (Figure 2).

The four most important steps in Figure 2 are:

1. Selection of the reference values;

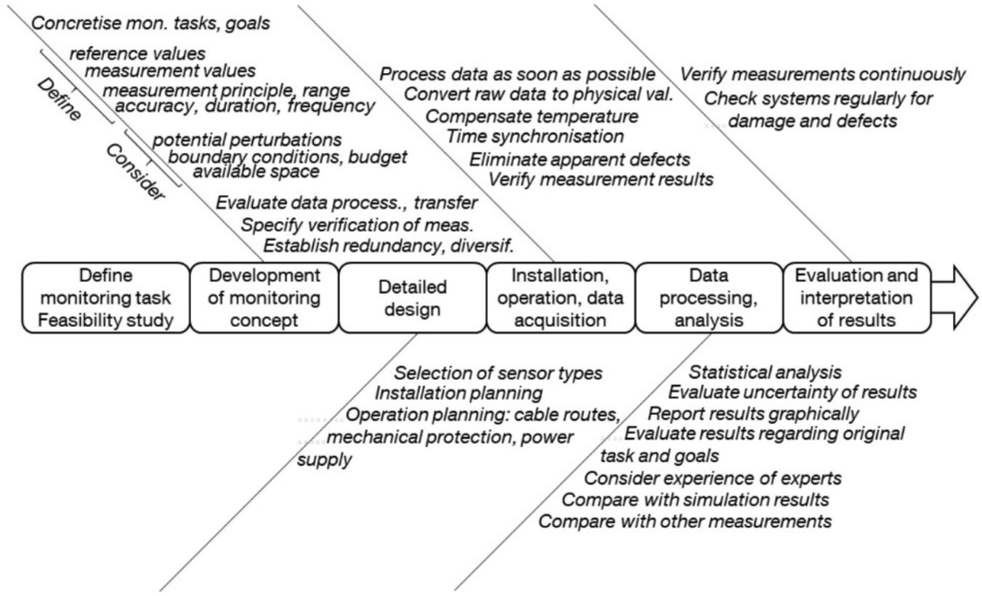


FIGURE 2 Workflow for monitoring projects, following.[9]

2. Selection of the measurement values and
   a. Their measurement duration, frequency, accuracy, sensor types, etc. according to the objectives.

The reference values are the physical counterparts of the monitoring tasks and objectives. The measurement values are actually measured on the structure and related to the reference values. Both can, but do not have to be the same, for example, if the reference values cannot be measured directly with reasonable effort.

3. Ensuring redundancy and diversification
4. Creating verification options

These two latter aspects are already emphasized here, although they are covered extensively later. Having the option to compare data and verify results is very valuable in case of unclear results and for further analyses.

2.2 | Review of case histories

In the last few decades, some structural monitoring projects on STL with different purposes and objectives were reported. In the following an overview of selected projects matching the following criteria is given:

- Use of prefabricated segments made out of concrete, as this is the state-of-the-art.[31]
- Measurements are suited to capture the structural behavior, the internal forces, and the stress state of the segmented lining in order to fulfill the objectives in Figure 1.
- Technical details regarding the monitoring are reported.

Due to the first criterion, some older monitoring projects (e.g., Ref. [32,33]) were not considered, as a few decades ago steel segments were state-of-the-art. Monitoring projects, where only geotechnical parameters (e.g. settlements, earth pressure) were measured, are neglected due to the second criterion as the structural behavior of the lining, which includes kinematics or internal forces, remains unclear. However, these measurements, if carried out additionally, deliver further information for analyses.[34]

Table 1 contains the 12 considered structural monitoring projects. Most of them had a research purpose, two were carried out for survey reasons and three were additionally used to check design assumptions.

The subsequent comments on the case histories follow the list of the most important steps in Section 2.1.

2.2.1 | Reference values and measurement values

To capture the structural behavior in all projects strains, stresses or internal forces are reference values. Stresses and internal forces cannot be measured directly. Therefore, 11 projects used strains as measurement values and only one[46] pressures (pressure cells) in the joints and on the extrados (Figure 3).

2.2.2 | Measuring the measurement values

Vibrating wire sensors (VWS) is the most used strain sensor type, followed by strain gauges[52] and fiber optic sensors (FOS).[50] The structural behavior of STL is three-dimensional. This makes it important to measure

TABLE 1 Structural monitoring case histories.

Tunnel	Country	Literature	Objective(s)
Linea 1 Metro Napoli	Italy	35–38	Research
Linea 6 Metro Napoli	Italy	39–41	Research
Botlek Railway Tunnel	Netherlands	42,43	Research
2nd Heinenoord Tunnel	Netherlands	42–45	Research
New Schlüchterner Tunnel	Germany	46	Research, check design
Koralmtunnel	Austria	47	Research, check design
Fildertunnel	Germany	48	Survey
Cross Rail Thames Tunnel (CTT)	United Kingdom	49,50	Research
Diabolo Tunnel	Belgium	51,52	Research, Survey
Liefkenshoek Rail Tunnel	Belgium	52,53	Research
Line 9 Barcelona	Spain	54	Research, check design
Boßlertunnel	Germany	55	Survey

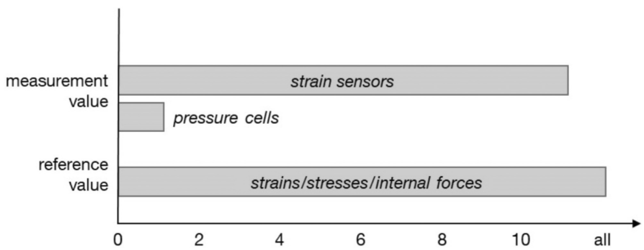


FIGURE 3 Reference and measurement values in case histories.

strains in tangential and longitudinal directions and to consider the lateral strains.[35,36]

2.2.3 | Redundancy and diversification

Data evaluation can be challenging but facilitated with a redundant and diversified measurement system.[52] Additional measurement values can be collected, for example, by the TBM steering system (grout pressure and jacking forces[35]) or by deformation measurements.

2.2.4 | Verification

To verify the measurements and to analyze the structural behavior further, additional full-scale tests with three complete rings in laboratory[43] and in a single-segment testing setup on site[35] were carried out.

2.2.5 | Further aspects

All projects aim to capture the stages during assembly and first loading after leaving the TBM shield precisely. Measuring during the assembly is possible, especially with wireless sensor systems.[35,43] It was shown that these early stages are of particular relevance for the structural behavior,[43] because the structural behavior during this period is highly unpredictable.

If the measurement duration is long and continued after the early stages, considering the long-term behavior (creep and shrinkage) of concrete becomes relevant.[35,50] As the creep and shrinkage strains are normally not of interest, they have to be separated from the measurements. This can be challenging[55] because of their large natural scatter and their magnitude that is not neglectable compared to the total strains, especially at low concrete age.[35,56,57] Material tests are required to get accurate results.[50] Concrete creep depends on the loading history. Therefore, also in long-term monitoring, the early stages have to be measured accurately.

If the monitoring project is long-term, natural temperature changes occur. Because of, for example, restrained deformations, temperature compensation can be quite challenging and is discussed extensively in many reports.[35,50,52]

Figure 4 summarizes the mentioned properties of the case histories graphically.

3 | THE MONITORING OF PROJECT U5 AND EXPERIENCES MADE

3.1 | Project presentation

In 2020, the authors had the chance to start a long-term structural monitoring on a newly build STL in

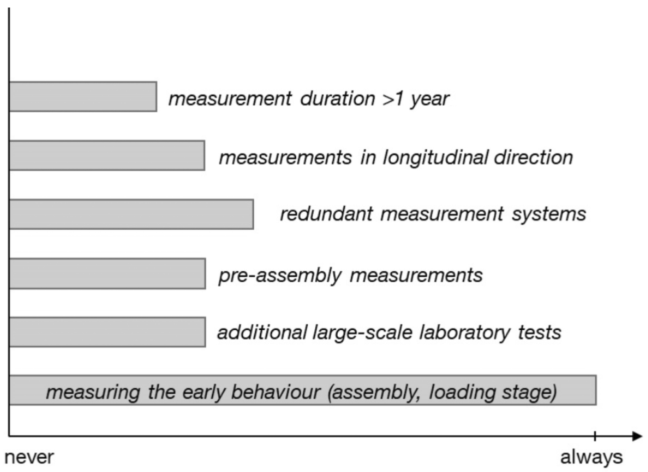


FIGURE 4 Properties of case histories.

Frankfurt(Main), Germany, that is still being continued. Two tunnel tubes of about 850 m in length with an outer diameter of 6.80 m[58] were constructed. In structural design, the engineers had to consider the underpassing of an area with several high-rise buildings already build or planned. These load cases resulted in the prediction of high internal forces in the STL. This structural monitoring surveils the development of the internal forces in the STL over several years and detects changes by using instrumented segments assembled into two measurement rings.

3.1.1 | Monitoring concept

In the monitoring concept (Figure 5), the internal forces are the reference values to capture the structural behavior and strains are the measurement value. Following mechanical and material laws, a method was developed to back-calculate the internal force from the related strains. To validate the concept, to calibrate the back-calculation method, and to test the monitoring setup, small- and full-scale laboratory tests were performed.

The monitoring concept is redundant and diversified. Also, further measurements were carried out to verify the results, including measurement of the in situ deformations and steering data from the TBM, in particular, the jacking forces.

3.1.2 | Instrumentation and installation

One measurement ring was placed right under the future position of a planned 175 m tall skyscraper and one in an undisturbed position as reference.

Due to the good experiences regarding the long-term reliability and the achievable accuracy the measurement rings were equipped with full-bridge strain gauges and VWS for strain measurements. By using two different sensor types diversification was achieved.

In the tangential direction, 13 cross-sections were instrumented (Figure 6, Figure 7). Each cross section consisted of three strain sensors. Because only two strain sensors are needed to back-calculate normal forces and bending moments, with a third sensor redundancy, is ensured. The equipped cross sections were placed in locations that were considered suitable to capture the structural behavior.

In the longitudinal direction, two segments were equipped with VWS. Both segments included two equipped cross sections, each equipped with two longitudinal VWS in line with the axes of the TBM hydraulic jacks, one at the upper and one at the lower reinforcement to back-calculate the longitudinal normal forces and to benefit from averaging.

The strain gauges were welded on the reinforcement bars, and the VWS placed in the segments' center line and tied on a thin supporting plate. Every segment included a covered cast-in cable box on the inner surface to store the sensor cable ends.

Since connecting cables were used outside the segments, they were not placed in the tunnel bottom because of the rough traffic. Because the stress state in the key segment is the most disturbed, it was not instrumented and placed in the tunnel bottom.

After instrumentation and casting the segments were stored for about 1.5 years. The first ring was installed (Figure 8) on 21/07/2020 and the second on 14/05/2021. Measurements started right after ring assembly.

3.1.3 | Back-calculation method, calibration, and validation

A method to back-calculate from strains (measurement value) to internal forces (reference value) and a procedure to validate and calibrate the monitoring was developed. The development process and the back-calculation method are explained in more detailed in Ref. [59] and only the most important concepts are presented here.

In this and probably in most structural monitoring projects, the internal forces resulting from structural loads like earth pressure or buildings on the surface are of interest. These structural loads cause instant strains and corresponding stresses. However, the long-term strain measurements record all types of strains (concrete creep and shrinkage, and temperature strains).

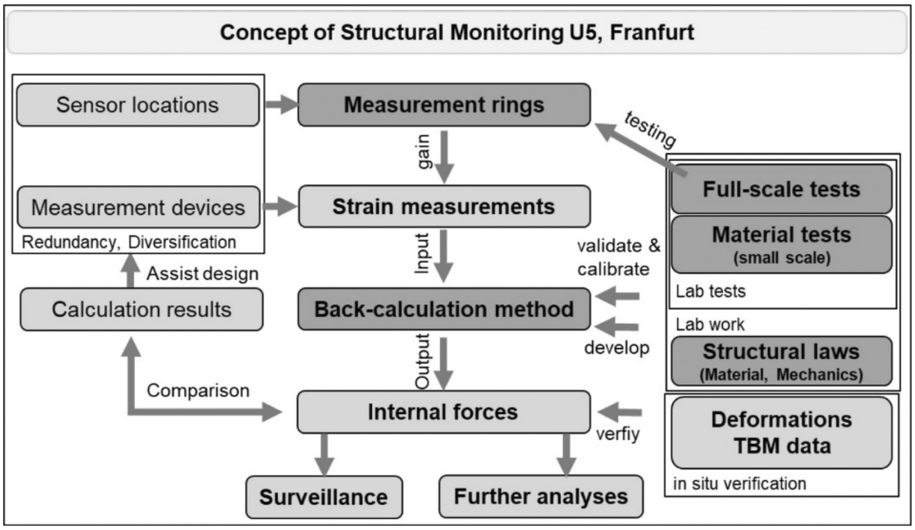


FIGURE 5 Monitoring concept U5.

FIGURE 6 Instrumentation details U5; left: vibrating wire sensor, right: welded strain gauge.

These have to be quantified and separated from the total measured strains to get the instant strains required to back-calculate to the internal forces (Figure 9).

The determination of the long-term strain components is not at all straightforward for concrete, because of the natural scatter in long-term material behavior and the subsequent uncertainties regarding their prediction.[60] However, with a suited model[57] and corresponding laboratory tests[61] the prediction turned out to be accurate.

Mathematically Figure 9 corresponds to Equation (1).

$$\varepsilon_i(t) = \frac{\varepsilon_{\mathrm{tot}}(t) - \varepsilon_{\mathrm{c}\Delta\mathrm{T}}(t)}{1+\varphi(t,t_0)}, \tag{1}$$

where ε_{i} are the instant strains, $\varepsilon_{\mathrm{c}\Delta\mathrm{T}}$ are the temperature components, φ is the creep coefficient, t is the current time, and t_0 is the time of loading. According to test results, shrinkage is negligible because of the high concrete age at assembly.

Because the structural loads on a tunnel lining develop and change with time[62] and the creep behavior depends on the load, by superposition[63] (Figure 10, right) equation 1 becomes a linear equation system and if solved yields the internal forces at any time.

Apart from the material properties, also sensing technology (e.g., measurement errors) can have an influence on the back-calculation results. To investigate this and to test the developed back-calculation method, an extensive validation and calibration laboratory program was carried out, with small-scale, and full-scale tests in the tunnel segment testing rig (Figure 11). Also, the accuracy of back-calculations was quantified with these tests.

A complete analysis of the observed internal forces and the structural behavior, is currently in preparation.

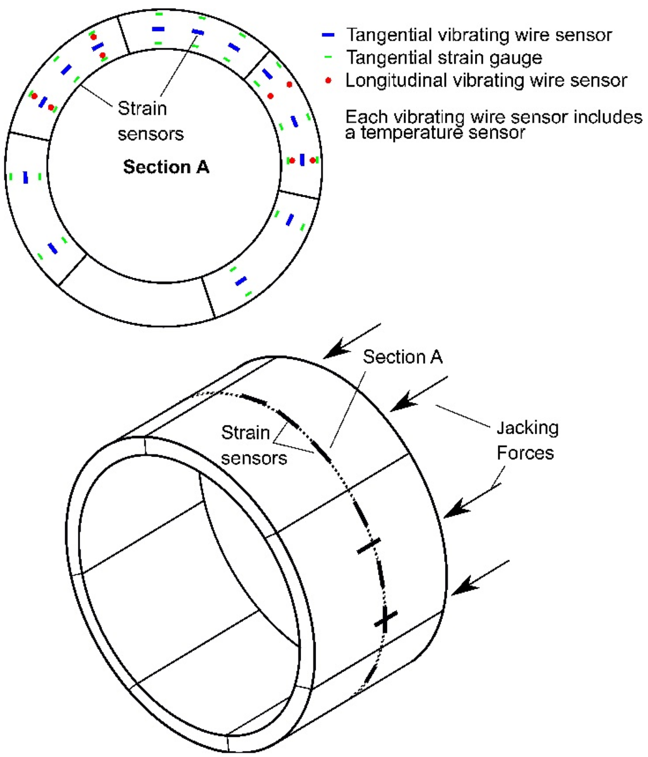


FIGURE 7 Instrumentation of a U5 measurement ring.

A first analysis is presented in Ref. [64]. However, to explain the back-calculation method a numeric example is given, showing the back-calculation from total strains measured in situ at a strain gages sensor pair in the crown of measurement ring 2, 1 year after the assembly (Figure 10).

The different strain components are quantified to get the instant strains. As mentioned, shrinkage is negligible. Relative temperature change during 1 year is small and due to the temperature compensation of the sensors and the small expansion constraint also this component is negligible in this example. The creep matrix takes the load changes over time into account. Solving the matrix equation yields the instant strains. The strain distribution[65] is calculated and through numerical integration, the back-calculation to the internal forces is completed and finalized by computing the accuracy of the results. Then, by spline interpolation, the distribution of internal forces along the STL circumference is calculated.

3.1.4 | In situ verification of results

To verify the back-calculation results under realistic conditions they were compared to other available in situ measurements:

- In situ deformation measurements of the equipped rings
- Jacking forces registered by the TBM steering system

During the first days, conventional geodetic measurements were not possible because the measurement rings were not in the view field. Therefore, the deformations were measured with inclinometers during this time.

3.2 | Experiences made at U5

The experiences made at U5 can be sorted into three different categories (Figure 12).

3.2.1 | Experience regarding calibration and validation

The extensive calibration and validation experimental program helped to increase the monitoring quality significantly. The best example, therefore, is concrete long-term behavior. It was explained earlier that an accurate determination of strains caused by long-term behavior is important but difficult. However, long-term materials tests can reduce the uncertainties significantly[61]—even more if the in situ conditions can be reproduced realistically in the laboratory, for example, with full-scale tests, realistic load levels, and climatic conditions. Although these tests were tedious and costly, they were a huge benefit for the monitoring quality.

3.2.2 | Experience regarding instrumentation

The chosen strain and temperature sensor quantity, types, and positions in tangential and longitudinal directions turned out to be suited for the monitoring goals. However, longitudinal sensors in all segments would have been useful regarding the longitudinal behavior. Good experiences were also made with the system's accuracy, long-term reliability, and the chosen frequency of about 0.0015 Hertz, although a slightly higher frequency would have been beneficial during the first hours after ring assembly.

3.2.3 | Experience regarding in situ installation and operation

Because of the redundant and diversified concept, it was possible to compensate for some defects and damage that occurred unfortunately. The in situ verification options strengthened the reliability of the results.

FIGURE 8 Installation of measurement rings U5.

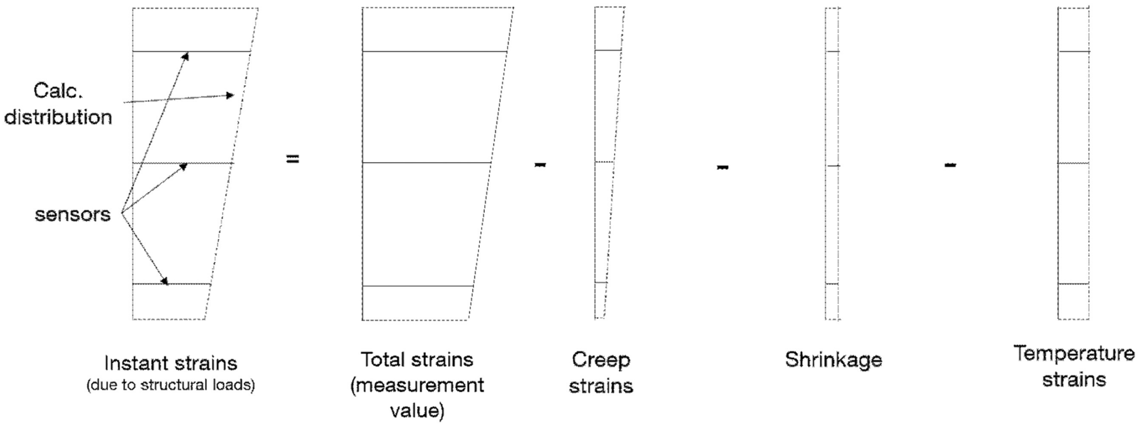


FIGURE 9 Separation of strain components.

To get a complete insight into the structural behavior measurements should start prior to the ring assembly. However, this was not possible due to the cables required for data transfer and the power supply of the sensors.

4 | BEST PRACTICE AND FURTHER DEVELOPMENTS

A structural monitoring project is individual and its specifications and requirements depend on the corresponding circumstances and objectives. Because of this, standardization seems not applicable. However, some recurring tasks, challenges, and corresponding solutions can be found for any structural monitoring project. To facilitate the implementation of future structural monitoring, based on the previous chapters recommendations are given. For convenience, this chapter is divided into four sections roughly following the workflow in Figure 2.

4.1 | Development of a structural monitoring concept for segmented linings

A well-though-trough monitoring concept is crucial, as corrections at a later stage are either impossible or costly. Some recurring general principles are presented (Figure 13).

To achieve the objectives in Figure 1, internal forces are suitable reference values, because they give an immediate overview of the structural behavior over time and are easy to compare with calculation results.

Strains are the best measurement value,[35,42,50,66] and strain sensors are the better choice over pressure cells (on the outer surface or within joints). Pressure cells can experience arching effects in the hardening grout, the conversion from pressures to internal forces is difficult and it is not possible to measure tangential stresses and tension.[34] In addition, strain sensors are generally small and have no significant influence on the structure.

Redundancy and diversification are required in every monitoring. Redundancy is achieved by placing more sensors than required by structural mechanics, and diversification by using different (strain) sensing techniques.

The monitoring results should be verified by other measurements, that are related to the reference value, for example, full-scale laboratory tests, in situ deformation measurements, or TBM steering data. Especially the strain measurements in the longitudinal direction can be verified by comparison with the TBM jack forces. Additional pressure cells on the outer surface, although not

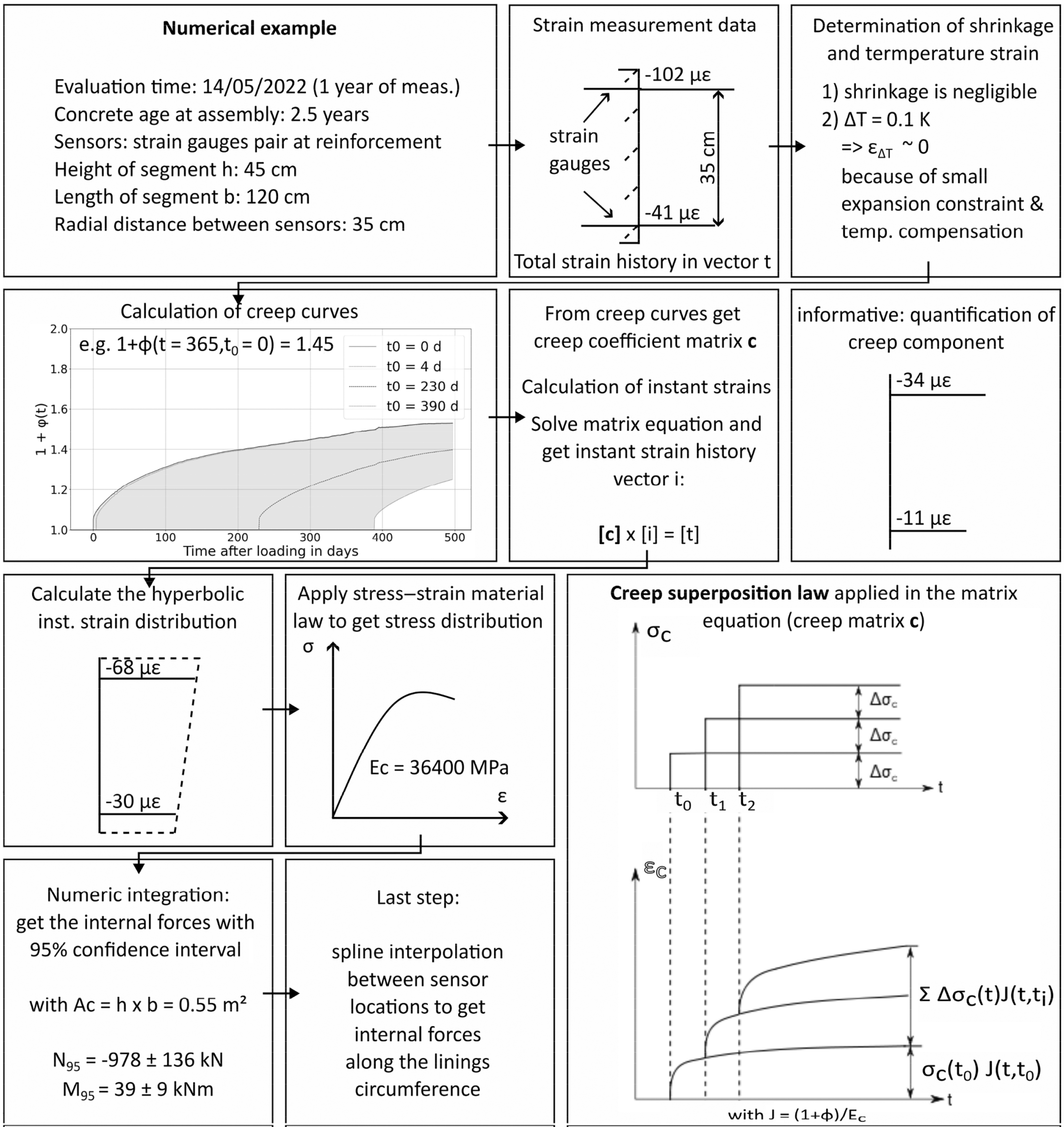
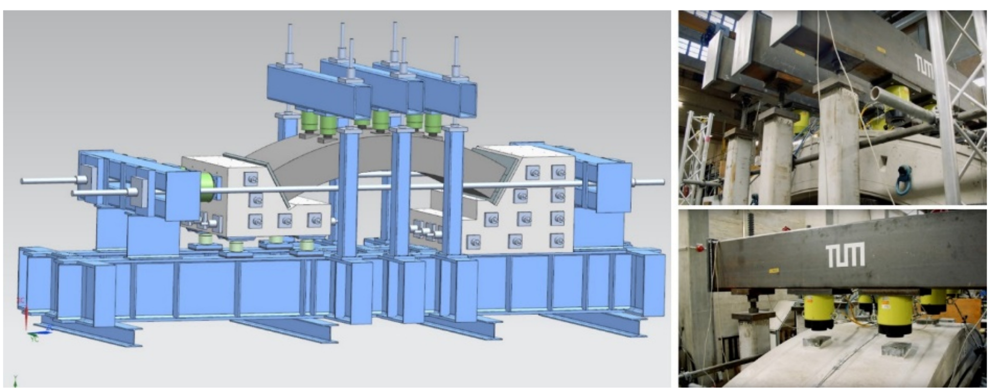


FIGURE 10 Numerical example (left), Creep superposition law (right) according to Ref. [63].

FIGURE 11 Tunnel segment testing rig.



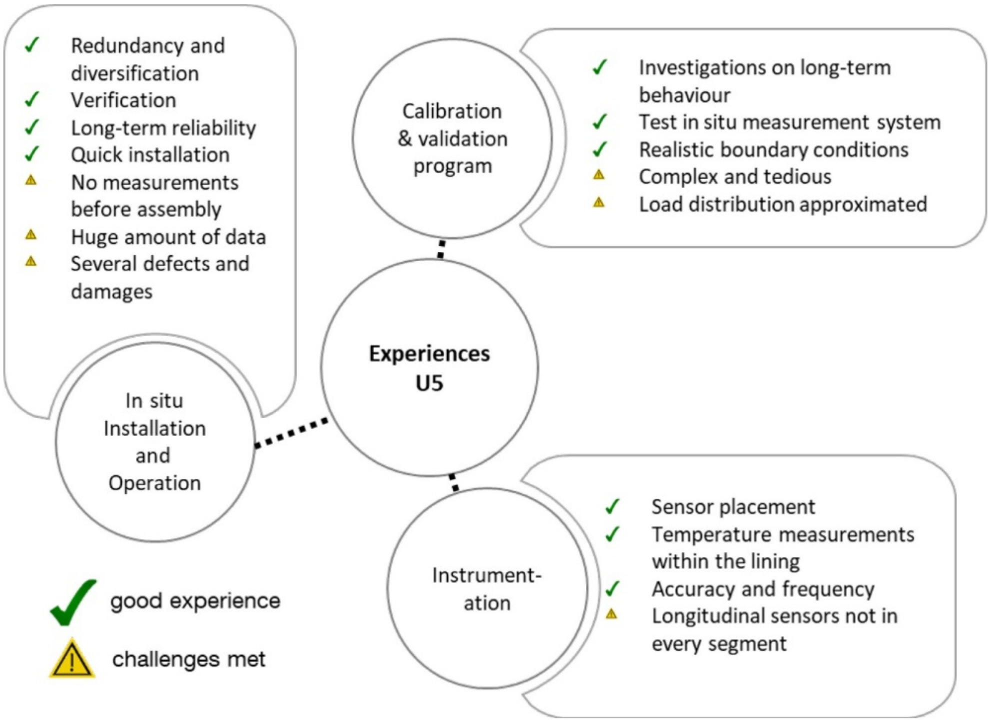


FIGURE 12 Experiences at U5.

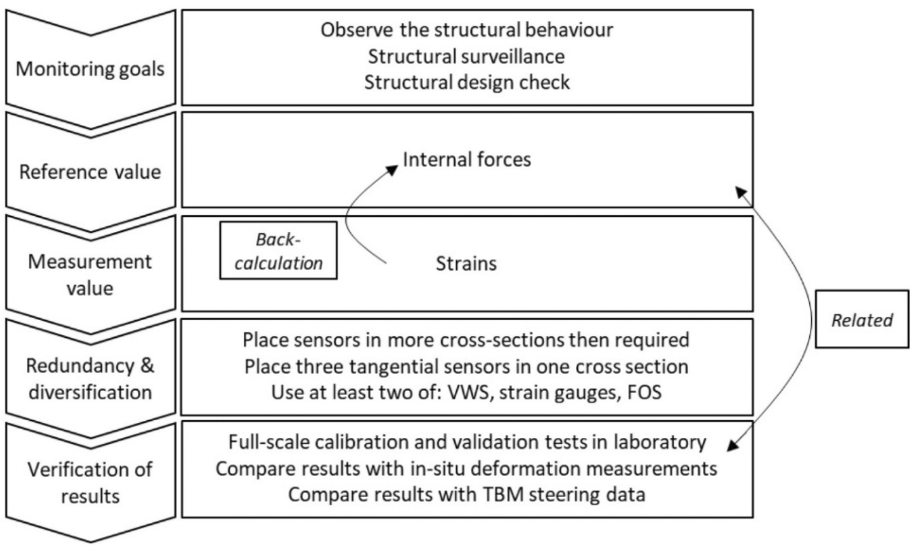


FIGURE 13 Development of monitoring concept.

suited as the main measurement value, might still be a suitable verification option.[34]

In situ deformations and internal forces are related to each other and can be used for verification. Deformations can be measured, for example, by laser scans,[52] displacement transducers in joints, inclinometers, or geodetic measurements.[67] The comparability between strain and deformation values is ensured by time synchronization, similar sensor positions, and sufficient accuracy. As a reference, also the initial form of the STL right after assembly should be measured. Attention should be given to the very first hours during which in both, strains and deformations the changing rates are high and easier to assess. However, it has to be considered, that during this period the boundary conditions are rough and the available space is limited due to the construction process.

Generally, all available data should be saved for further data evaluation. If measurement results remain unclear one should ask: "Can I think of a hypothesis that is consistent with the data?".[15]

4.2 | Instrumentation

Instrumentation is an important part of any structural monitoring. First one needs to decide how the measurement values, here the strains, can be measured. Prior to the selection of the sensor type, the required measurement range, accuracy, and resolution are defined. Modern strain sensor technology achieves almost every requirement for tunnel structures. It also has to be considered if concrete cracking could occur and how it would affect the measurements.

VWS, strain gauges, and FOS can be used for strain measurements. VWS are reliable, water-resistant, have a good long-term stability[47] and, if they consist of a long base length, they are a good choice to back-calculate normal forces, that are expected to vary only moderately. However, good experiences were also made with strain gauges, that are relatively easy to use, flexible, stable, and enable temperature compensation. FOS allows measurements along a fiber, therefore, cover a large area, and can easily be used for crack detection.[68] In any case, before application, calibration test and proof of long-term reliability are recommended.

In almost every case, it is also necessary to measure the temperature within the lining. An accuracy of 0.1 K is sufficient in cases, where the thermal expansion coefficient of strain sensors and the lining material are similar.

A proposed sensor placement is shown in Figure 14. If FOS are used the fiber is intended to connect the positions. Ideally, at least two neighboring rings are instrumented to capture force redistribution in a longitudinal direction. Every segment should include sensors in longitudinal and tangential directions. To account for transverse strains, they should be placed in the same cross-sections. If the measurement devices cannot be protected properly, the keystone should remain unequipped and placed in the tunnel bottom.

In the tangential direction, the number of sensors needs to be high enough to capture potential non-uniformities. Three cross-sections per segment seem suitable in most cases. Sensors should be placed close to both surfaces and in the center line to account for bending moments and normal forces as well as to ensure redundancy.

In the longitudinal direction, two cross-sections per segment should be equipped with longitudinal strain sensors in line with the hydraulic jacks, to consider potentially irregular jack force application and moments in the longitudinal direction. The strain sensor should be placed near the upper and lower reinforcement to benefit from averaging.

Obviously, available budget, time, and space will play a role in instrumentation.

4.3 | Installation and operation

In situ installation and operation have to be planned carefully (Figure 15).

The start of measurements should be prior to assembly. This is necessary to get a complete picture of the structural

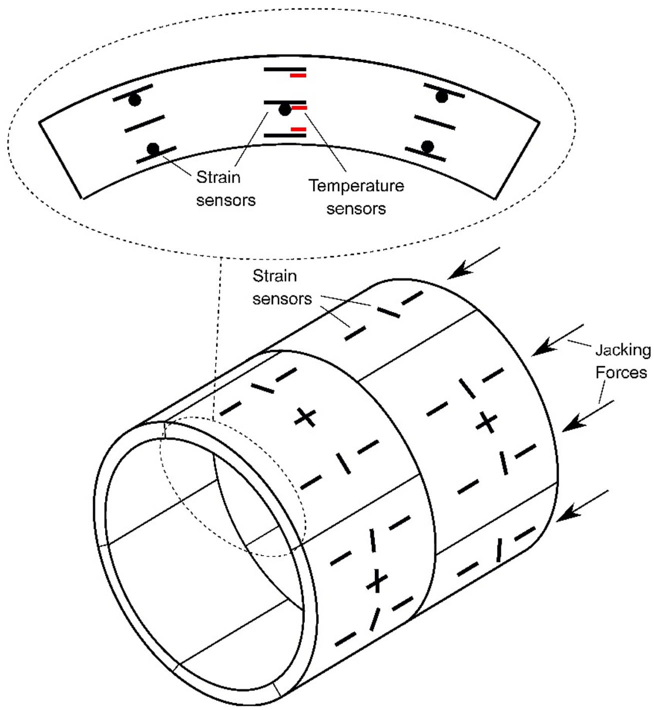


FIGURE 14 Proposed sensor placement.

behavior and the loading history. This can be accomplished with wireless sensors or by reference measurements in undisturbed and constrain-free conditions prior to assembly. However, if this is not possible, the start of measurement should be as soon as possible after the assembly but never after the next advancement of the TBM.

A graded frequency setting is recommended to control the amount of measurement data. In the beginning, where the load changes quicker, at least one complete measurement every 10 minutes is recommended. After a couple of months, with stable conditions one measurement per day is sufficient. If several different measurement systems are used, time and frequencies are synchronized to facilitate data processing.

To avoid damage to the measurement system mechanical protection, warning signs and regular checks are advisable. Repair of embedded sensors is normally not possible, and replacements on the inner surface require additional calibration to fit the new sensors into the original system.

Communication with the engineers on site is important to refine the workflow and time scheduling.

4.4 | Back-calculation method: Data processing and evaluation

The procedure of data evaluation and processing is depicted in Figure 16. In a sensitivity analysis, it was

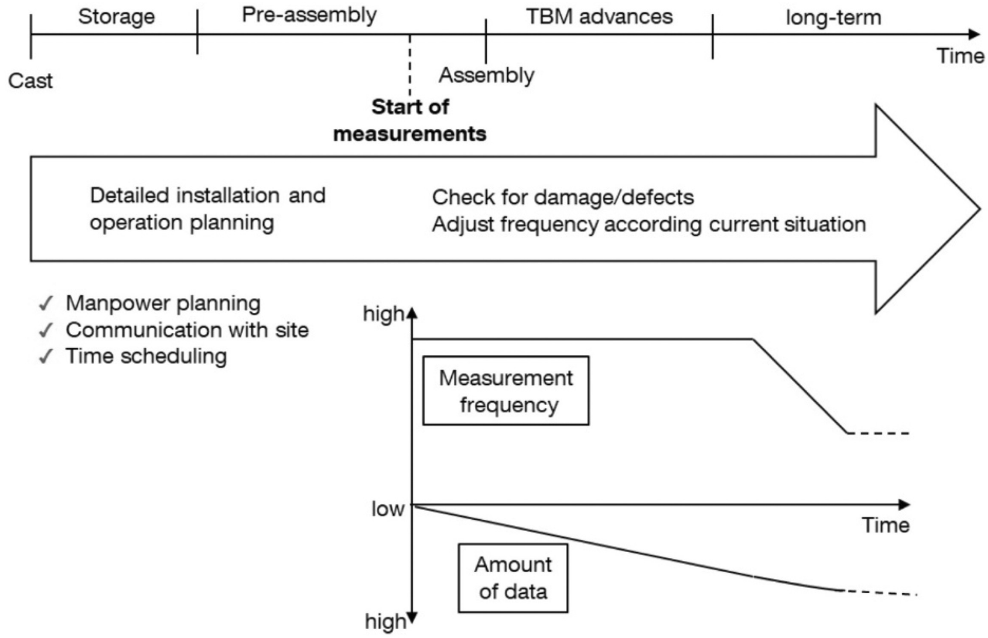


FIGURE 15 Installation and operation procedure.

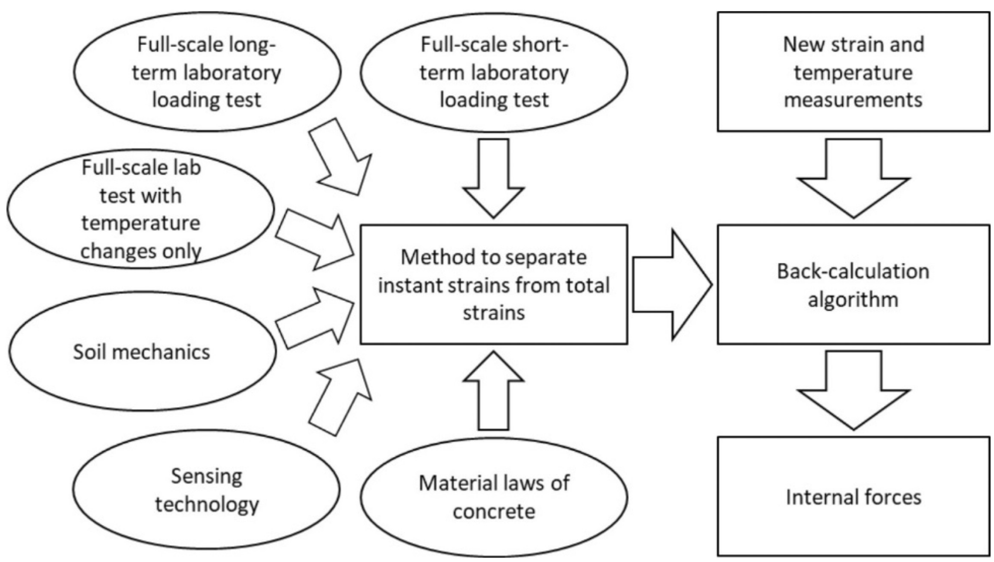


FIGURE 16 Development of back-calculation method.

investigated which parameters have the biggest impact on the results and have to be determined accurately.

First, the back-calculation method from instant strains to internal forces has to be set up carefully and ideally tested in full-scale tests. This allows taking mechanical relations like the strain distribution function, the scatter of material parameters, and issues regarding the measurement system (measuring errors, imprecise sensor application, straight sensors in a curved segment, etc.) into account. Also, with experimental data, it is possible to determine the accuracy of the back-calculation, as a result without the corresponding accuracy is not very meaningful.

Second, the long-term strains, in particular creep strains (and with early age concrete also shrinkage), need to be known as precisely as possible. Temperatures changing with time can be an issue if changes and gradients are large, if the sensors' temperature compensation is poor, or if thermal expansion is highly restrained.

To take these time-depended effects into account an extensive calibration and validation laboratory program is inevitable. The closer the program reproduces reality the better. This is why laboratory tests are recommended in full-scale with the complete in situ measurement system under realistic load levels. Also, these experimental results can be incorporated into the back-calculation accuracy determination.

Next to a precise determination, strategies to minimize the influence of long-term strains are advantageous. If the concrete age at first loading is high, creep and shrinkage strains are lower.[38] This is why, the equipped segments should be cast as early as possible. By using steel segments, creep could be eliminated completely. This is, however, not a good approach as the structural behavior is different from concrete segments, for example, because of the different long-term behavior in the longitudinal direction.

The back-calculations get complicated, if cracking occurs, due to the contribution of concrete in tension as the full-scale test for the U5 project showed. If cracking is expected, this has to be considered in sensor selection and placement. Identifying crack formation is relatively easy, as the tensional stresses are redistributed in the crack area. A sudden strain increase (in sensors applied to the reinforcement bars) or decrease (sensors on cracked concrete) indicates cracking. However, to additionally perform back-calculations to internal forces in a cracked area it is necessary to know both the tensional strains in concrete and in the reinforcement bars. Since it is not known a priori where cracks will form, either several discrete sensors have to be placed in line or FOS has to be applied. Additional calibration and validation tests with crack formation are recommended in this case, in which also the concrete strain distribution over the segments' height should be investigated.

5 | CONCLUSION AND OUTLOOK

Several applications for structural monitoring of STL exist. When carrying out a structural monitoring project a broad variety of aspects has to be considered. Standards on structural monitoring of STL are not available and also not applicable, but general recurring principles were elaborated based on a recent structural monitoring project carried out by the authors and by confirming their experiences with similar case histories. Summarized, for structural monitoring of STL the following aspects are the most important to consider:

- A well-thought-out monitoring concept has to be set up first to determine reference values, measurement values (and how to measure them), as well as strategies to ensure redundancy, diversification, and verification.
- Sensor specifications (type, position, accuracy, etc.) highly depend on the structural behavior of the segmental lining and were suggested.
- The measurements are carried out starting from right after installation and during the operation of the system. An appropriate installation and operation is required for a successful project.
- Data evaluation includes several recurring steps, parameters, and mechanisms, which were presented. An evaluation method brings all these aspects together. To ensure its applicability and to optimize the quality of the results additional (full-scale) laboratory tests are highly recommended. Also the accuracy of the results can be determined through these tests.

Of course monitoring data is already a result by itself and can be used, for example, for structural surveillance. However, monitoring can also be part of broader applications. Numerical models, that are established from monitoring data,[69,70] enable further studies of already existing tunnels or updating and checking of design assumptions of tunnels currently under construction.

In this paper, experience-based recommendations were given to facilitate future applications of structural monitoring for both, as a stand-alone task and as part of a broader application.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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