DOI: 10.3217/978-3-99161-057-1-067

Inspection as a basis for structural health monitoring

Stefan S. Grubinger[1], Stefan L. Burtscher[2, 0000-0002-5469-9596], Peter Huber[0009-0003-1935-4108], Morris Tutschku[2, 0009-0007-0114-171X], Matthias J. Rebhan[3, 0000-0002-0638-6202]
[1]recordIT GmbH, Griesgasse 1, 8020 Graz, Austria
[2]Rocket NG GmbH, Austria
[3]Institute of Soil Mechanics, Foundation Engineering and Computational Geotechnics, Faculty of Civil Engineering Sciences, Graz University of Technology, Rechbauerstraße 12, 8010 Graz, Austria
email: grubinger@tugraz.at, stefan.burtscher@rocket-ng.at, peter.huber@rocket-ng.at, morris.tutschku@rocket-ng.at, rebhan@tugraz.at

ABSTRACT: To effectively monitor engineering structures such as bridges, tunnels, and retaining walls, comprehensive knowledge of load-bearing behavior and load transmission mechanisms is essential. This knowledge allows for the assessment of its behavior and the identification of damage mechanisms. A thorough and clear documentation of regular inspection forms the foundation for this. It is important not only to capture damage patterns and visible defects but also to determine their origin and precise location. This information aids in the development of monitoring processes, the selection of measurement variables, and the implementation of monitoring technologies. The paper addresses the progress on how a documentation process of inspections is carried out to serve as a basis for a valid monitoring of such structures. Therefore, the use of digital models and a standardized description of damage in combination with a precise localization on the structure is described in the beginning. Such documentation provides valuable insights into load-bearing behavior and possible underlying damage mechanisms. Additionally, the development of suitable monitoring systems that serve as key parameters for structural inspection is demonstrated. The interaction and exchange of information between inspection and monitoring are emphasized, including clear visualizations and meaningful data overlays, to offer valuable benefits for building owners and inspection personnel.

KEY WORDS: Inspection, SHM, monitoring data, structural behavior.

1 INSPECTION OF CIVIL ENGINEERING STRUCTURES

Inspections are an essential part of the maintenance strategy for residential and industrial buildings (see [1] & [2]) as well as for infrastructure such as bridges and tunnels (see [3] & [4]). While the former is usually carried out by the building owner, the latter are part of the responsibilities of the owners of the infrastructure (road or railway) or those responsible for maintenance. Due to its geographical location in the center of Europe and its alpine topography, Austria places special demands on the routing of its road and railway network and the associated infrastructure. Therefore, a large number of engineering structures to secure cuts and slopes (see Figure 1), cross mountains and span valleys.

Figure 1. Gravity wall along the Semmering railway line.

The majority of the routes required for this purpose, especially along the high-level road network, were built between 1960 and 1980, while other structures (e.g. along the Semmering railway line [5]) are already more than 150 years in service.

Figure 2. Visual inspection method.

Aside from the erection and the ongoing maintenance, inspections, as shown in Figure 2, are essential to ensure the reliability of these structures and, consequently, their roadworthiness, usability and safety. The principal task lays in generally on a manual visual inspection, which includes the load-bearing and non-load-bearing components and structural elements required for safety.

DOI: 10.3217/978-3-99161-057-1-067

1.1 Goals, methods and guidelines

In general, for inspection, a distinction can be made between ongoing tasks by internal personnel and inspection and testing by trained specialist personnel. These inspection activities are carried out periodically and usually conclude with a report. Thus, providing information on the state of preservation, includes necessary steps for maintenance and serves as the basis for subsequent testing and inspection intervals.

Planning documents are required as the basis of inspection to define the scope and provide the necessary structural and safety-related information, defining the tasks for the inspection personnel. Furthermore, these documents provide the basis for recording information of the on-site activity during the inspection process. Examples hereof are damaged areas, image numbers, changes compared to the forerun inspections or in general changes in the state of preservation.

Depending on the asset to be analysed, different guidelines and regulations apply in Austria. These are issued by the FSV and are to be regarded as the state of the art:

- Road bridges - RVS 13.03.11 [6];
- Anchored retaining walls - RVS 13.03.21 [7];
- Road tunnel - RVS 13.03.31 [8];
- Gantries - RVS 13.03.51 [9];
- Retaining structures - RVS 13.03.61 [10];
- Noise barriers - RVS 13.03.71 [11], and
- Trough - RVS 13.03.81 [12].

In general, manual and visual inspections are carried out, which are performed by the inspection personnel directly on site. Various smaller tools and instruments are used to carry out such activities on structures. Depending on the type of structure and asset, these range from cameras and plans to observation instruments (binocular or crack magnifier) and tools such as hammers and spanners.

Digital tools for carrying out a structural inspection are generally not defined. Only specifications for integrating the inspection results into corresponding databases are given. Furthermore, within the area of monitoring [13] topics such as IoT (Internet of Things) and, briefly, the necessary digitalisation of measurement and monitoring tasks and the management of data and results are addressed.

1.2 Damage and damage symptoms

In order to enable a diagnosis of the structure and the resulting statement on the state of preservation, it is necessary to record defects and damage continuously on the structure to be inspected. Some examples are given in Figure 3.

Due to the wide-ranging and interdisciplinary approach to civil engineering structures, it is difficult to provide a schematic collection of damage patterns and defects in such structures. However, the literature (see [14] to [17]) provides comprehensive descriptions and lists that can be used as a basis. In such a categorisation, a general distinction must be made between damage and defects relevant to load-bearing capacity and those relevant to durability.

A distinction can be made between structural, geotechnical and geological damage patterns. In addition to a differentiation, however, an interdisciplinary and interactive approach is required in order to recognise the underlying causes of the damage so these can be addressed during maintenance.

Figure 3. Examples for damages found during inspection of civil engineering structures; reinforcement corrosion and concrete spalling (top); shift and misalignment within a construction joint (center); erosion and unguided surface flow (bottom).

1.3 Climate change

Austria's topography, the dense road and railway network and the increasing average age of the infrastructure are a major challenge for long-term maintenance. In addition to the approximately 2,300 km of high-ranking road network and 5,000 km of railway lines, there are also around 125,000 km of lower-ranking road network [3]. In terms of motorways, there are around 250 km per million inhabitants, which means that the high-ranking road network is around 50 % larger than the EU average.

In addition to an increase in loads and traffic, climate change will also have a direct impact on structures as a perceptible manifestation of climate change. These are superimposed by geological and geotechnical effects such as increasing water

 DOI: 10.3217/978-3-99161-057-1-067

supply due to heavy rainfall events or the increase in natural hazards such as mass movements and rockfalls.

The effects of climate change can be summarised as '*long-term changes in temperature and weather patterns*' Figure 1. Gravity wall along the Semmering railway line. Among other things, this will have an impact on road and railway infrastructure. These changed boundary conditions influence the durability of the infrastructure substance due to increased thermal and hydraulic stress and changed environmental conditions. At higher temperatures, the saturation vapour pressure of the atmosphere increases and more and more water vapour can be held in the air (+ 7% per 1°C). This intensifies the greenhouse effect and increases the risk of short-term extreme precipitation (see [18] & [19]). The intensity of these events can for example exceed the capacity of existing drainage systems, leading to both direct damage to the structure and indirect damage with respect to surface erosion and sediment transport. Increased extreme precipitation is also accompanied by an increasing risk of gravitational natural hazards such as rockfall, which, in addition to the direct risk in the area along the infrastructure, can also have a corresponding impact on the functionality of engineering structures due to an impact. [20]

The increase in damage patterns, damage intensity and defects in combination with the increasing age of structures and the rise in traffic and loads pose new challenges for those responsible for maintaining structures. In 2021, the European Commission drew up a technical guideline to ensure the climate compatibility of infrastructure [21], which defines that the primary goal must be to make '*infrastructure climate-neutral and climate-resilient*'.

1.4 Digital inspection

In addition to the advantages that a digitalisation can offer, it is also important to adapt working methods to newly created possibilities in order to generate a corresponding increase in time and quality. Preparation by the inspection staff will remain essential, but the approach will take a different form. For the most part, the collection and collation of (meta) data will no longer be necessary and a stronger focus on existing issues and damage will be possible.

Figure 4. Using digital inspection tools to reduce workload and to improve information transfer.

However, it is not only the preparation that changes, the form of the inspection also changes when digital solutions are used. For example, due to standardisation and the use of existing inspection results, personnel will play a much stronger role as a controlling element. This results from the fact that a software-supported inspection specifies or can specify defects or damage and structures and thus provides a framework for recording in the field.

A number of benefits can be generated through the digitalisation of structural inspection. The biggest and usually most decisive point is the potential for savings in terms of on-site inspection time. In addition to the monetary savings, this can also result in shorter closure times, which could lead to massive improvements in route availability, especially if a total closure is required. In addition, software solutions using digital devices on site creates a standardised and less error-prone structural inspection, from which reports and documentations can be created with little effort or information and characteristic parameters can be further processed digitally. In addition, photorealistic 3D models (e.g. from photogrammetry) depict the current condition of a structure more comprehensively and allow a comparison between different inspection periods.

It should also be mentioned that structural inspections can provide the foundation for implementing structural health monitoring. Through the appropriate collection, evaluation, and interpretation of inspection results, it becomes possible, to have the fundamental information required for a structural health monitoring system readily available. Furthermore, based on the results of structural inspection and the analysis of findings over time, it is possible to determine whether the structure can remain in operation with monitoring, whether restrictions are necessary, or whether demolition, reconstruction, or strengthening are necessary.

In addition to these advantages, there are also disadvantages associated with a digitalisation measure - or generally a change and adaptation of existing processes. On the one hand, these relate to usability and the utilisation of digital solutions by users. However, this can be very easily remedied with an appropriate software solution (UX and UI design see Figure 4). On the other hand, the pervasive and sustainable use of digital solutions often requires adjustments to databases, data structures and standardisation. In Austria, there is largely a lack of specifications relating to the use of digital products for structural inspection of infrastructure. Nonetheless, a corresponding trend and a corresponding willingness to implement such solutions and procedures can currently be recognised among a number of structural owners and maintainers.

2 MONITORING OF CIVIL ENGINEERING STRUCTURES

An essential component of the safety assessment of civil engineering structures can be created by the systematic consideration of monitoring data. This can give an inclusive insight into the behaviour of the structure or the triggers responsible for damage or a change in the structures reliability.

However, in order to be able to utilise such information comprehensively, it is necessary to plan a monitoring system accordingly. The following briefly discusses possible measured variables, the timing of monitoring and the digitalisation of

DOI: 10.3217/978-3-99161-057-1-067

existing measuring equipment. This serves to enable a holistic view between inspection and monitoring.

2.1 Behavior of the structure

The decisive factor when carrying out monitoring is the correct selection of the measured variable to be recorded. Due to the size and extent of engineering structures and the frequent interaction between the object and its surroundings, measurement data of the terrain is often the first choice. For example, data from satellite measurements or LIDAR measurements in the vicinity of the infrastructure can be used for this purpose. Such data offers information on areas that are otherwise difficult to access or overviews of the structure and the terrain, deformations can already be derived.

Monitoring is also usually carried out by attaching sensors or transducers. These are usually attached directly to the structure or to relevant component regions. A range of different measured variables [13] can be used to analyse the terrain, the structure or individual components. These are often also related to the requirements or statements from the structural inspection - such as questions regarding load-bearing behaviour or load transfer. In addition, the overall behaviour of the structure must be considered when selecting measured variables or generally when defining the monitoring concept.

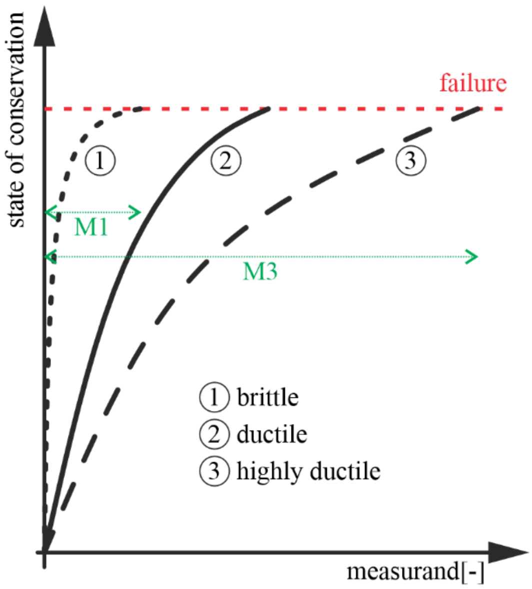

Figure 5. State of preservation with respect to a measurand depending on the behavior of the structure.

In addition to the arrangement of the sensors, the time component must also be thought of when planning a monitoring system. This is related to the behaviour of the structure and can be seen schematically in Figure 5. This shows the change in a possible measured variable depending on the state of preservation of the structure. The greater the damage to the structure - i.e. the greater the decrease in the state of preservation - the greater the change in a possible measured variable used for monitoring.

The extent to which a measured variable increases until the structure fails is strongly influenced by the behaviour of the structure. While all structures should exhibit ductile behaviour, this may only be the case to a limited extent, especially in the case of brittle structures. An example of this is the reduction in the load-bearing capacity of a concrete cross-section that is damaged by corrosion of the main reinforcement [22].

This aspect means that the possible, recordable and detectable measured variable of a value is defined accordingly by the behaviour of the structure. As a result, during the planning of a monitoring, it is necessary to estimate how large the possible, still available supply of a measured variable is and whether the quantity is still sufficient to enable meaningful and accurate monitoring.

2.2 Timing of measurement

The behaviour of a structure in relation to the measurable value also results in a temporal influence on the monitoring. Similar to the quantity of the measurand to be recorded, a brittle or ductile structure also has an effect on the time available until failure occurs. This is shown schematically in Figure 6.

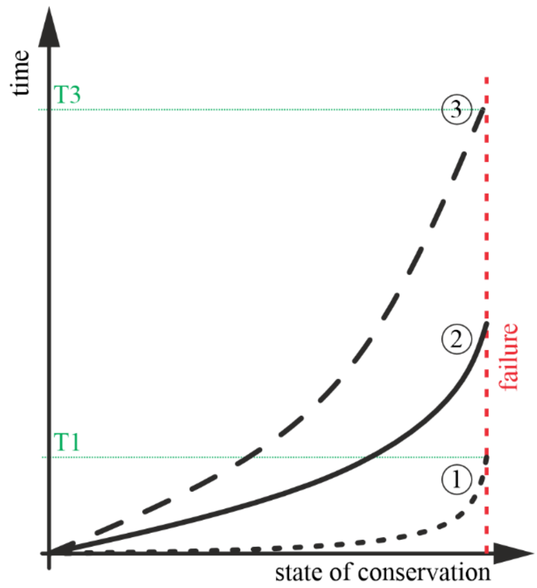

Figure 6. Timely installation of a monitoring system with respect to the state of preservation depending on the behavior of the structure.

This shows that, depending on the behaviour of the structure or the effects of damage, there are different time periods that indicate a decrease in the state of preservation. This can have a considerable influence, particularly with regard to the implementation of monitoring as a measure following a structural inspection. If the time period is too short, only a limited statement can be made about the behaviour of the structure. Meaning that it is not possible to differentiate between temperature-related and damage-related behaviour of the structure. This in turn means that a planned monitoring can only make a small contribution to the structural inspection.

2.3 Digitalization of existing measurement equipment

When implementing monitoring concepts, classic approaches applicable to new structures or the monitoring method can only be used to a limited extent. The subsequent installation and calibration of sensors and monitoring equipment on existing structures is often only possible to a limited extent due to accessibility. A particular problem with existing structures is the unknown construction effects and the limited observation

DOI: 10.3217/978-3-99161-057-1-067

time compared to the age of the structure. In particular, the assessment of load-bearing behaviour, load redistribution and the delimitation of seasonal effects therefore usually requires a combination with redundancy and an overdetermination of the measurement concept in order to correctly characterise the structure's behaviour. Another aspect of monitoring tasks on existing structures is the reactivation or digitalisation of existing measuring equipment.

The aim of monitoring must always be to create a valid database which, in combination with appropriate testing and inspection of the structure, can be used to identify the load-bearing behaviour and possible damage mechanisms of the structure. One innovative application example is the digitalisation of hydraulic force measuring devices on pre-stressed grouted anchors. The current anchor force (see [23]) is one of the main parameters of an anchored structure. As a rule, force measuring devices have to be installed during the pre-stressing process of the tendon, making a retrofitting of such a measuring device not often possible.

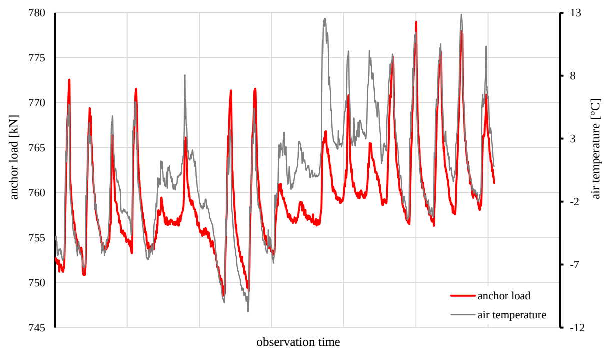

Figure 7. Time-period of a subsequently digitalized anchored load plate.

Digitising the measured value readings, as shown in Figure 7 and described in more detail in [24], enables permanent data recording and provision for existing force measuring systems. Temperature and seasonal anchor force changes and the resulting effects on the structure can be reliably recorded thanks to continuous recording. This makes it easier to interpret the measurement data and represents a significant improvement on the current practice of periodic and manual readings.

3 INTERLINK INSPECTION TO MONITORING

The previous chapters have attempted to provide a brief insight into the inspection and monitoring of engineering structures. These topics are usually directly linked, but are currently usually considered separately. While the inspection of the objects is carried out and documented regularly, monitoring is usually only used for structures that already show a deficit in their behavior or corresponding damage.

However, in order to be able to implement monitoring in a targeted manner, the content and results of inspection must be included. This can be seen schematically in the cycle in Figure 8. The cycle without monitoring refers to the classic inspection of a structure, in which the relevant data and information on the structure and its condition are collected in the course of an on-site activity in order to enable a subsequent assessment. This usually takes place in a purely visual and manual manner. The data and information collected is therefore purely about damage patterns or changes in the state of preservation recognizable on the surface of the structure or its surroundings. If there is no major damage and no extensive changes in the behavior of the structure can be detected, the inspection process is completed for the period in question and no further activities are required.

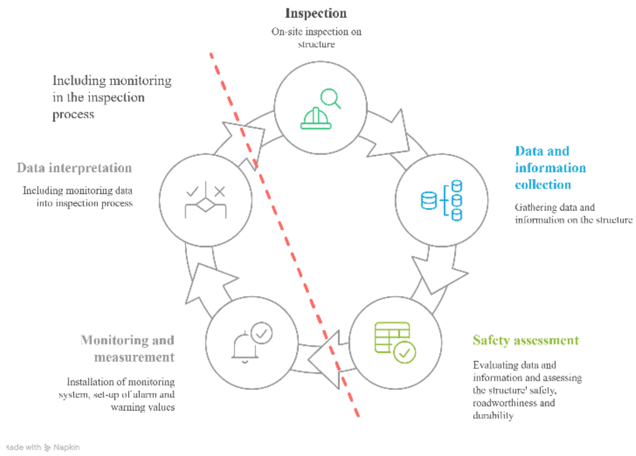

Figure 8. Schematic process of interlinking monitoring processes into the cycle of structural inspection.

The aim of the inspection is to be able to make a statement about the load-bearing behaviour of the structure and thus about its state of preservation. If this is not possible, special tests in the form of a material analysis or an in-depth inspection of the structure can be carried out. However, these often only provide information about the progression of damage (e.g. carbonation) or provide characteristic values for materials or components. A statement about the load-bearing behaviour of the structure and, for example, the interaction with the subsoil can only be given to a limited extent.

Monitoring of the structure can be used for this purpose. This can be used to make a statement about the behaviour of the structure by recording measured values and interpreting them accordingly. In relation to the building inspection or rather the assessment of the construction, a valid statement can be made about the load-bearing behaviour, load transfer mechanisms or, for example, a number-based assessment of the load and stress levels of components.

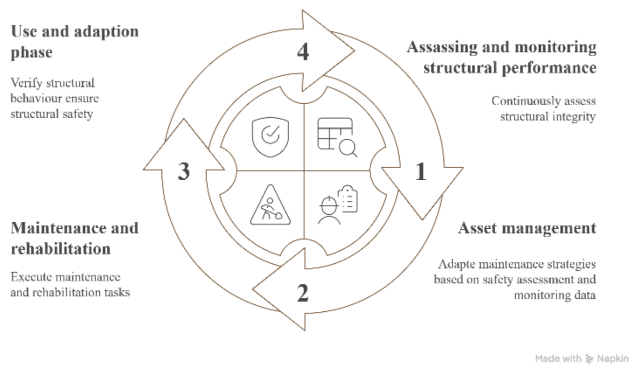

Figure 9. Ongoing circle on assessing data and information including asset management, maintenance and use phase.

DOI: 10.3217/978-3-99161-057-1-067

If this relationship is now considered over the entire service life of a structure, it can be seen, as shown in Figure 9. Ongoing circle on assessing data and information including asset management, maintenance and use phase., that this results in a continuous process. Beginning after construction with a continuous recording and observation of the behaviour of the structure, which can be carried out either by inspection or supplemented by monitoring.

Based on this, the necessary processes are planned and implemented in the asset management in order to be able to carry out maintenance. Here, both smaller measures can be derived from the inspection (e.g. flushing the drainage) and larger measures (e.g. replacing the edge beam) can be implemented. The whole process is completed by a phase of utilisation which is not associated with any restrictions and in which the structure is in a sufficiently good condition to be used safely and reliably.

This brief and schematic illustration shows the possibilities in which the inspection of structures and their monitoring are linked. It also shows that monitoring is usually implemented as a measure or as a reaction to an inspection. It is therefore essential that the results are communicated and transferred to the monitoring of the structure in order to enable the two processes to interact and integrate with each other.

4 EXAMPLE – ANCHORED STRUCTURES

The approach described in the previous chapter can be explained using a practical example. An anchored construction as shown in Figure 10, which has a height of 9.00 m and a total length of approx. 240 m. The wall was constructed in three stages, with individual concrete elements anchored by two anchors (diagonally). It is not possible to tell from existing planning documents whether there is a transverse force-locking connection between the elements in vertical and horizontal direction.

Figure 10. Segmented anchor wall.

In the course of an inspection of the wall, a number of damage patterns were identified, which primarily affect the durability of the entire structure as well as that of the concrete components. Two examples of this are given in Figure 11. These show two symbolically recorded cracks, which can be found in a similar way along the entire wall. The cracks have a width of 0.2 to 0.5 mm.

Some cracks are located in the area of the installed anchoring elements, as shown in the picture, while others are scattered across the entire surface of the wall. In general, the cracks are characterised by sintering and moss-like growth was also visible, which indicates that the cracks have been present for some time.

No damage could be visually detected on the tensile elements of the structure (strand anchors), only slight signs of corrosion on the external components could be detected. In general, the structure was in an inconspicuous condition and only limited moisture damage, water leakage or other geological failure mechanisms could be found in the adjacent area.

Figure 11. Cracks along the concrete structure and adjacent to the anchors.

In general, this structure can be assumed to be in a good state of preservation, but there is a lack of information, particularly with regard to the anchorage, its function and the associated effects on the load-bearing behaviour. In order to obtain this information, special inspections [23] such as an endoscopic examination of the anchor head area and a lift-off check of the tension elements would be the first option. However, this is not possible on all structural anchors due to the non-liftable design of the tension elements, but it was possible to carry out subsequent digitisation on six structural anchors with existing force measuring equipment.

The monitoring data (Figure 7) shows that there is a clear correlation between the temperature and the anchor force, even over a longer period. This indicates that either the structure, the measuring device or both together exhibit temperature-

 DOI: 10.3217/978-3-99161-057-1-067

dependent behaviour. However, as there is no inexplicable change in the anchor forces, it can be assumed that there is no massive damage to the structure which is therefore behaving as it was designed intentionally.

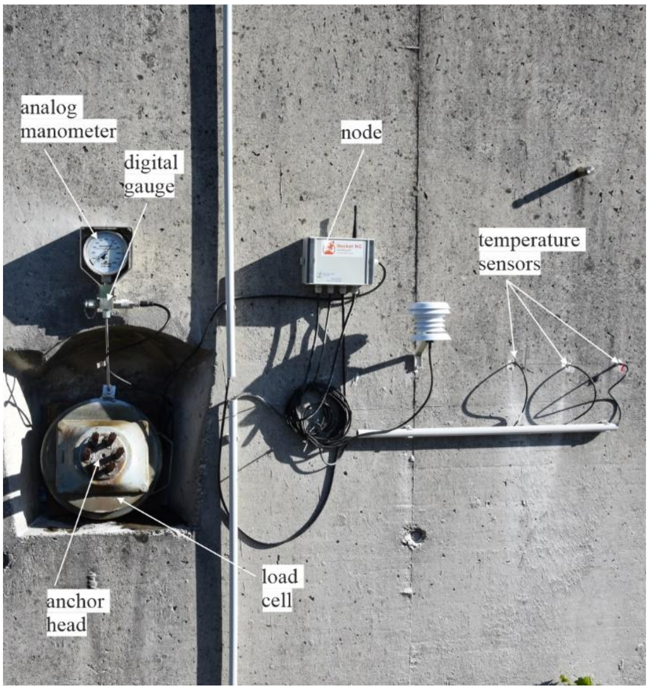

Figure 12. Anchor wall, anchor head and scheme of monitoring positions and sensors.

Such investigations were possible because the structure already had force measurement equipment (see Figure 12) that could be included in the monitoring. Whether this takes the form of digitisation or continuous readings is merely a question of the desired accuracy or a resource-related one. If this had not been possible, a variety of other measurement systems would have been applicable, which are briefly described below:

Classical deformation monitoring, for example by attaching measuring points, could possibly provide a statement about the temperature-related behaviour of the structure. However, this only provides a limited possibility of deducing an increase in damage, as only a limited distinction can be made between temperature-related fluctuations and a change in deformation. In particular, only periodic recording of the wall (e.g. on a weekly or daily basis) and not recording the entire surface of the structure means that only very limited detailed information can be provided. Current approaches such as full-surface monitoring of the wall surface and the resulting derivation of overall deformations could provide a remedy here, but are not yet considered state of the art.

As there were no signs of extensive deformation of the object in the course of an inspection of the rear area of the structure, no major changes in the stresses on the structure due to earth or water pressures can be assumed. On the one hand, this would rule out a change in the above-mentioned structural deformations and, on the other hand, would also put geotechnical measuring equipment such as inclinometers or extensometers in their place as far as the detection of a change in the structural behaviour as a result of damage is concerned.

As a result, only measured values that consider the structure itself remain possible. As this is an existing structure, the installation of earth pressure cells or the determination of the change in strain in the reinforcement, for example, is only possible to a limited extent, at great expense and with a possible falsification of the structure's behaviour. Nevertheless, the cracks already encountered on the front of the structure, for example, would be suitable for monitoring. Particularly with regard to a possible load redistribution between the tension element, which could indicate damage to these, would possibly manifest itself in the crack pattern of the structural components. Monitoring of the cracks on the front side would be recognisable in the event of a significant change in the cutting forces resulting from an anchor failure or a reduction in the prestressing force. A similar approach can also be used for corrosion-damaged angular retaining walls [24], for example, to show a redistribution between individual reinforcement elements.

5 CONCLUSIONS & SUMMARY

The aim of this article is to highlight the similarities between structural inspection and monitoring. The duality of this topic must be considered, which makes a significant contribution to a comprehensive understanding of the behavior of damaged infrastructure structures, whereby a distinction can be made between structural, geotechnical and geological damage patterns. In addition to a differentiation, however, an interdisciplinary and interactive approach is also required in order to recognize the underlying causes of the damage so that these can be addressed in the course of maintenance if necessary.

On the one hand, the structural inspection and the resulting information on damage and damage processes form the basis for the planning and implementation of monitoring and the interpretation of monitoring data. On the other hand, monitoring can significantly improve the level of data and information on the behaviour of a structure. This is a great added value in the assessment of the structure, especially for structures in a poor condition, but also for objects with missing documentation.

The aim of this article is to highlight the similarities between structural inspection and monitoring. The duality of this topic must be considered, which makes a significant contribution to a comprehensive understanding of the behaviour of defective infrastructure structures, and the relationships presented here are intended to show that considerable added value can only be generated through interdisciplinary and targeted cooperation and the exchange of information in both structural testing and monitoring. Only in this way it is possible to obtain a comprehensive statement about structures and thus subsequently guarantee their safety and reliability. Only in this way can a sustainable, durable and resilient infrastructure be made possible, which, in addition to appropriate usability, also has a certain resistance to climate change-related effects, whereby a distinction can be made between structural, geotechnical and geological damage patterns. In addition to a differentiation, however, an interdisciplinary and interactive approach is also required in order to recognise the underlying causes of the damage so that these can be addressed in the course of maintenance if necessary.

DOI: 10.3217/978-3-99161-057-1-067

REFERENCES

[1] ÖNORM B 1300, 2018. Objektsicherheitsprüfungen für Wohngebäude - Regelmäßige Prüfroutinen im Rahmen von Sichtkontrollen und zerstörungsfreien Begutachtungen - Grundlagen und Checklisten. Austrian Standards. Wien.

[2] ÖNORM B 1301, 2016. Objektsicherheitsprüfungen für Nicht-Wohngebäude - Regelmäßige Prüfroutinen im Rahmen von Sichtkontrollen und Begutachtungen - Grundlagen und Checklisten. Austrian Standards. Wien.

[3] BMK (2023). Statistik Straße und Verkehr. Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. Abteilung IV/IVVS1 – Planung, Betrieb und Umwelt. Vienna.

[4] Rebhan, M.J., Grubinger, S.S, Schüppel A, Deutinger S, Schwarzenberger G. (2024). Advances in the digital documentation of railway tunnel. ITnA-reports – 12th international conference tunnel safety and ventilation. Volume 107, Graz.

[5] https://www.unesco.at/kultur/welterbe/unesco-welterbe-in-oesterreich/semmeringeisenbahn

[6] RVS 13.03.11, 2021. Überwachung, Kontrolle und Prüfung von Kunstbauten – Straßenbrücken. Richtlinien und Vorschriften für das Straßenwesen. Österreichische Forschungsgesellschaft Straße – Schiene – Verkehr (FSV). Wien.

[7] RVS 13.03.21 Geankerte Konstruktionen. Verfügbar unter: https://www.fsv.at/shop/produktdetail.aspx?IDProdukt=e65a7d2a-7e23-4312-a865-2f909c7b3c5c [Abgerufen am 27.01.2025].

[8] RVS 13.03.31, 2021. Überwachung, Kontrolle und Prüfung von Kunstbauten – Straßentunnel. Richtlinien und Vorschriften für das Straßenwesen. Österreichische Forschungsgesellschaft Straße – Schiene – Verkehr (FSV). Wien.

[9] RVS 13.03.51, 2021. Überwachung, Kontrolle und Prüfung von Kunstbauten – Wegweiserbrücken. Richtlinien und Vorschriften für das Straßenwesen. Österreichische Forschungsgesellschaft Straße – Schiene – Verkehr (FSV). Wien.

[10] RVS 13.03.61, 2021. Qualitätssicherung bauliche Erhaltung, Überwachung, Kontrolle und Prüfung von Kunstbauten, Nicht geankerte Stützbauwerke, Österreichische Forschungsgesellschaft Straße-Schiene-Verkehr, FSV, Wien.

[11] RVS 13.03.71, 2021. Überwachung, Kontrolle und Prüfung von Kunstbauten – Lärmschutzbauwerke. Richtlinien und Vorschriften für das Straßenwesen. Österreichische Forschungsgesellschaft Straße – Schiene – Verkehr (FSV). Wien.

[12] RVS 13.03.81, 2021. Überwachung, Kontrolle und Prüfung von Kunstbauten – Wannenbauwerke. Richtlinien und Vorschriften für das Straßenwesen. Österreichische Forschungsgesellschaft Straße – Schiene – Verkehr (FSV). Wien.

[13] RVS 13.03.01, 2022. Überwachung, Kontrolle und Prüfung von Kunstbauten – Monitoring von Brücken und anderen Ingenieurbauwerken. Richtlinien und Vorschriften für das Straßenwesen. Österreichische Forschungsgesellschaft Straße – Schiene – Verkehr (FSV). Wien.

[14] Stahr, M., 2011. Bausanierung: Erkennen und Beheben von Bauschäden, 5. Aufl., Wiesbaden: Vieweg+Teubner Verlag / Springer Fachmedien Wiesbaden GmbH Wiesbaden.

[15] Weber, S., 2013. Betoninstandsetzung: Baustoff - Schadensfeststellung - Instandsetzung, 2. Aufl., Wiesbaden/s.l.: Springer Fachmedien Wiesbaden.

[16] Deutscher Beton- und Bautechnik-Verein e.V., 2017. Ist-Zustandserfassung von Parkbauten in Betonbauweise: Merkblatt 39, Berlin: Eigenverlag DBV.

[17] Schrepfer, T., Gscheidle, H., 2007. Schadenfreies Bauen: Schäden beim Bauen im Bestand, Zugriff im Juni 2019, https://www.irb.fraunhofer.de/schadis/s_inhalt.jsp?band=Sfb41

[18] ÖWAV 2020. ÖWAV-ExpertInnenpapier Klimawandelanpassung Wasserwirtschaft - Pluviales Hochwasser/Oberflächenabfluss. Wien: Österreichischer Wasser- und Abfallwirtschaftsverband (ÖWAV).

[19] Stocker et. al., 2017. Klimaänderungen 2013, Naturwissenschaftliche Grundlagen, Beitrag der Arbeitsgruppe I zum Fünften Sachstandsbericht des zwischenstaatlichen Ausschusses für Klimaänderungen (Ipcc), Deutsche IPCC-Koordinierungsstelle.

[20] Glade, Thomas & Bell, Rainer & Dobesberger, & Embleton-Hamann, & Fromm, & Fuchs, Sven & Hagen, & Hübl, Johannes & Lieb, & Otto, Jan-Christoph & Perzl, & Peticzka, Robert & Prager, & Samimi, Cyrus & Sass, O. & Schöner, & Schröter, Dagmar & Schrott, Lothar & Zangerl, & Zeidler, A., 2014. Der Einfluss des Klimawandels auf die Reliefsphäre. 10.1553/aar14s557.

[21] Commission Notice 2021. Technical guidance on the climate proofing of infrastructure in the period 2021-2027. Verfügbar unter: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021XC0916(03). [Abgerufen am 27.01.2025].

[22] Rebhan, M.J. (2019). Korrosionsschäden bei Winkelstützmauern. Dissertation. Graz University of Technology. Institute of Soil Mechanics, Foundation Engineering and Computational Geotechnics. Graz.

[23] AP33 (2022). Arbeitspapier Nr. 33 – Sonderprüfmethoden für geankerte Konstruktionen und Zugelemente, Österreichische Forschungsgesellschaft Straße – Schiene – Verkehr. Vienna.

[24] Rebhan et. al. 2024. Erfassung der Vorspannkraft bei bestehenden geankerten Konstruktionen – Abhebeversuche, Nachrüstung und Digitalisierung von Kraftmesseinrichtungen zu Monitoringzwecken. Mitteilung des Instituts für Geomechanik und Geotechnik, Technische Universität Braunschweig. Messen in der Geotechnik 2024. 22./23. Februar 2024. Heft Nr. 116.