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Retrofitting load measurement devices on existing anchored structures

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ABSTRACT: Anchored structures are an essential part of infrastructure corridors, as they enable high cuts and the reinforcement of existing structures. As pre-stressed elements, anchors allow for economical construction with low-deformation, making them critical components for ensuring stability. Consequently, comprehensive monitoring is often required alongside inspections, especially when the reliability of the load-bearing elements is in question - e.g., due to creep or corrosion of metallic components. Based on research activities due to the ageing of such structures, several options have been investigated to retrofit load measurement devices to already installed pre-stressed anchors. In addition to different types of coupling methods, this paper presents first results from a trial in which, through the retrofitting of an external thread to strands, a new method for load monitoring is investigated. These methods are particularly useful when information about the current anchor load is lacking, as they provide better insight into the condition of the tension elements and, furthermore, the overall behavior of the structure. The paper shows some approaches already in use and the results of an initial test series, in which the potential of a new approach to amend a load measuring device to an already installed pre-stressed anchor is investigated and validated.

KEY WORDS: Anchor testing, Load monitoring, Existing structures, Asset management, Retrofitting.

1 ANCHORED STRUCTURES

Due to their ability to transfer large tensile forces into deeper or more competent strata, anchored structures using tension elements are often an economical design option in geotechnical engineering. Grouted anchors [1] & [2]], in particular, can be used to reduce deformations, allowing for more compact and slender geometries. Examples of such structures include newly constructed anchor and pilaster walls (Figure 1), as well as structures that have been subsequently anchored during refurbishment or repair (Figure 2).

Figure 1. Anchored pilaster wall.

Figure 2. Pre-stressed anchors used for the remediation of a cantilever retaining wall.

Over the designed service life of up to 100 years, such technically demanding structures require increased inspection and maintenance. In Austria, the specifications for structure operators are defined in the FSV guidelines [2]. The inspection procedure for anchored structures is identical to that for non-anchored retaining structures. On the one hand, the focus is on the surrounding terrain, drainage system and structural

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components, which are typically made of reinforced concrete. On the other hand, anchors undergo a more intensive assessment to determine their state of preservation. Inspections (or checks) are generally carried out every 3 to 6 years and must be performed manually and visually during on-site activities.

In addition, the special inspection of tension elements and anchored structures is described in detail in a separate working paper [5]]. The aim of these activities is not only to determine the current condition of the structure, but also to detect changes in the state of preservation or the development of damage patterns on the tendons, in order to assess their impact on safety and reliability.

At the end of such an inspection, and in addition to the assessment, recommendations for necessary measures are provided. Alongside the suggestion to carry out special inspections, this may include advices on implementing monitoring systems for the structure. The aim is, on the one hand, to gain a better understanding of the structure's behaviour , and on the other hand, to integrate these systems into alarm and warning plans - especially for severely damaged structures - in order to enable early response to potential or imminent failure.

2 INSPECTION AND DAMAGE IDENTIFICATION ON ANCHORED STRUCTURES AND TENDONS

As a structure ages, the requirements for inspection and maintenance increase in order to ensure an accurate and conclusive assessment of its condition. The regular performance of inspections [6]] enables the early detection of defects and thus forms the basis for a long-term, continuously optimized maintenance strategy. The scope of [2]] covers all structures in which anchorages [1]] have been installed. Therefore, this guideline includes a wide range of applications - from anchored retaining structures (see [5]]) to pier footings and anchored bridge abutments, as well as retrofitted anchored structures ([7]]). For inspection purposes, a distinction has to be made between the structure itself and the relevant structural components. In this context, the term "structure" also includes the adjacent terrain at the head or base of the structure.

Relevant structural components of anchored structures cannot be completely examined during inspections (i.e. they can only be examined to a limited extent). This is, on the one hand, due to the apparent free length and the bond length (see Figure 3) of a pre-stressed anchor, which are located in the subsoil and thus not accessible. On the other hand, for many structures, the anchor heads were sealed during construction and are therefore not directly visible.

As with other structures, damage or an increase in damage can also be observed over time on anchored structures and the installed tendons. In addition to damage to the structural components (e.g. concrete elements and shells), corrosion damage to the metallic components of pre-stressed anchors is particularly critical. For permanent anchors with a designed service life of up to 100 years, corrosion protection for all components must be ensured. When it comes to tension elements and anchored structures, a general distinction can be made between two types of corrosion.

Oxygen corrosion refers to a chemical process in which iron and steel materials oxidize when they interact with oxygen and an electrolyte (e.g. water). The product of this process is commonly referred to as rust. This rust layer is generally very porous and, in contrast to other reaction products (e.g. the pyrolysis layer of burned wood), provides little or no protection against the progression of the process. The corrosion can only be halted by removing one of the reaction partners (oxygen or water) or by passivating the surface. In contrast to oxygen corrosion, stress corrosion cracking typically occurs in pre-stressed steel elements under prolonged tension. These stresses can result either from an externally applied load or from internal constraints. Additionally, hydrogen atoms, which may be produced from oxygen corrosion, penetrate the metal lattice. This slight disturbance in the metal's microstructure forms a crack capable of growth under the influence of tensile stresses. These chemical reactions and processes can occur in pre-stressing steels, which are sensitive to such damage. In the case of high-strength steels, commonly used for tendons, the process is referred to as hydrogen-induced stress corrosion cracking. In contrast such a process generally does not produce any significantly recognizable damage pattern during propagation, and can therefore not be clearly identified by the reaction products.

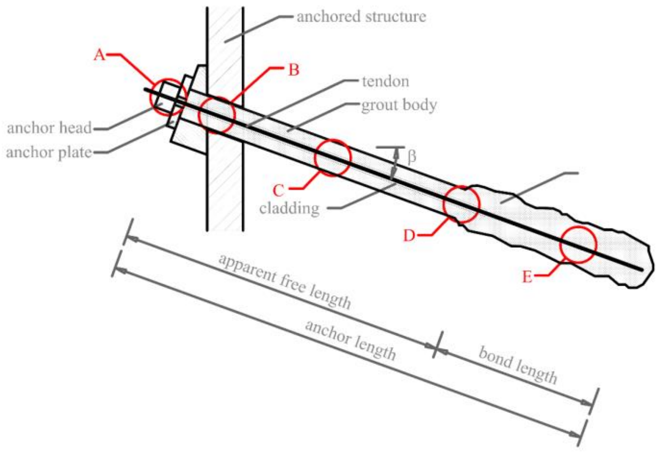

Figure 3. Parts of a pre-stressed anchor.

In the absence of corrosion protection and when environmental conditions are conducive to corrosion, uniform surface corrosion can affect the entire cross-section. This is mainly observed on exposed steel components, strands and bars with insufficient corrosion protection. In contrast to uniform surface corrosion, pitting corrosion occurs at points where the corrosion protection is absent or inadequate in certain areas of the cross-section. This corrosion phenomenon is typically found in improperly manufactured or cracked grout bodies. In chloride-contaminated environments (e.g. de-icing agents), such phenomena are also more likely to occur. This process begins in a relatively small area on the surface and spreads relatively quickly into the interior, significantly reducing the cross-section locally.

As mentioned above, corrosion damage to anchored structures and tendons mainly occurs in unprotected or inadequately protected areas of the structure. Some of these areas are a result of the design itself, while others stem from the manufacturing process or associated weaknesses and deficiencies.

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Figure 4. Corroded tension elements of the external parts of strand anchors.

Corrosion damage to insufficiently protected outer surfaces of the anchor (Figure 3 area A) can lead not only to a visual impairment of the anchored structure but also to a loss of load-bearing capacity of individual tendons or even the failure of an entire anchor over time. However, due to the often rather massive design of the anchor head components, some reserves remain. Improperly filled anchor head niches or protective covers often lead to increased corrosion, which can manifest as the release of reaction products or visible rust plumes. As shown in Figure 4, exposed components of the anchor, which are subjected to weathering and environmental conditions, are particularly susceptible to corrosion. Such damage can usually be detected by a visual inspection of the anchor head.

The most critical point is found in the section directly behind the anchor head (Figure 3 area B). Defects in the inner anchor head can occur during construction, but also due to ageing or volatilization of the corrosion protection material. The absence of corrosion protection at the anchor head (see Figure 5) can be considered severe damage to both the tendon and the anchored structure.

In addition to the two types of damage in the anchor head area, corrosion processes can also occur along the entire anchor length. Likewise, ageing effects on the grout material can occur along the entire apparent free length, potentially leading to corrosion of the tension element (Figure 3 area C). Due to the load transfer from the tendon into the underground along the bond length and the associated tensile stresses in the grout body, cracks may develop. These cracks create damaged areas in the corrosion protection (Figure 3 area E), serving as potential sources for corrosion. Especially in the transition zone between the apparent free length and the bond length (Figure 3 area D), cracks occur more frequently due to the strong increase of the stresses in the grout body [8]].

Figure 5. Corroded strands within the anchor head area.

Furthermore, if design documents or long-term monitoring data are available, the inspection of the structure can usually be carried out by trained personnel without major difficulties. However, if no or only limited geological, geotechnical and structural information is available at the time of inspection, a more detailed investigation is required to make a reliable assessment of the structure's condition.

3 MONITORING OF ANCHORED STRUCTURES

As already mentioned, it is often necessary to implement appropriate monitoring measures during the maintenance phase of a structure, especially if significant defects are identified. In addition to deformation monitoring, the pre-stressing force is a key parameter for anchored structures. Throughout the service life of an anchor, the anchor load can either be observed with installed monitoring systems, or assessed by performing lock-off-tests. While a monitoring system, such as load cells, offer the possibility to survey the anchor load over a longer period (depending on the monitoring interval), a lock-off-test only determines the load acting on the anchor at the time of testing.

3.1 Anchor Lock-Off-Testing

Regarding the safety assessment of anchors and anchored structures in Austria (e.g. [7] & [9]), the normative rules of EN 1537 [1] are supplemented by the requirements outlined in the RVS guidelines [3] and a Working Paper [4]. To ensure the capability of an anchor or the functionality of a preliminary anchor system design, three different test types - namely, investigation, suitability and acceptance tests - are performed. A lock-off-test solely indicates the load currently applied to an anchor. In general, the anchor load depends on a variety of factors and can be influenced by daily and seasonal fluctuations (e.g. temperature, groundwater), but can also vary due to damage (e.g. corrosion) or creep effects. Taking these factors into account, however, a lock-off test can provide an accurate assessment of the anchor's condition and functional efficiency.

Research (e.g. [10] & [11]) and the results of safety assessments on anchors have shown that anchors, especially the anchor head, are often exposed to de-icing agents and salt, making them highly susceptible to corrosion damage. Such damage is usually not detectable through the results of lock-off tests. Therefore, in addition to a lock-off-test, endoscopic examinations [12] can provide valuable insights into the

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condition of an anchor. Especially the visual inspection of the anchor head area can help to detect manufacturing defects or corrosion damage in the anchor head.

Besides – mostly durability related – damages to an anchor (e.g. [10] & [13]), an increasing number of corrosion damages to reinforcement elements (e.g. [11]] & [14]]) can be observed.

The result of an anchor lock-off test can be seen in Figure 6. This load-deformation-diagram illustrates the compression and slippage of the test setup (green line) alongside with the elastic elongation of the anchor strand. The intersection point, marked by the two equalisation lines in Figure 6, represents the point where the anchor head lifts off the anchor plate (or the structure), which defines the currently applied anchor load.

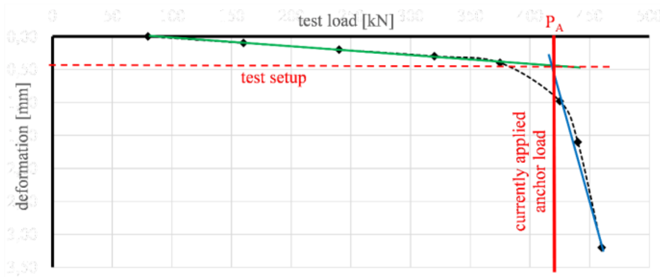

Figure 6. Deformation-load-diagram of an anchor lock-off test.

In comparison to the test loads in a suitability or acceptance test of anchors (e.g. [1], [15] & [17]), the determine of the lock-off load is not described in normative or design regulations. As this load reflects the current state of the anchor and is therefore subject to change over time, making it therefore often necessary to define the lock off load PA in advance based on knowledge and experience. The number of strands or the diameter of the bar, for example, can provide information on this and define the limits and boundaries for such tests in combination with a preceding endoscopic surveillance of the anchor head and a stepwise load increase during the testing process.

3.2 Anchor load monitoring

By monitoring the anchor forces, any changes (both decreases and increases) in the anchor force and their resulting effects on the structure, or the potential failure of the anchor, should be recorded in a timely manner. This is necessary to comply with the requirement of Eurocode 7 [17], Chapter 8.3, which states that '*the effects of anchor failure must be taken into account*', even though there are limited specifications in terms of standards and calculation methods (see [18], [19] & [20]) for how this requirement should be addressed.

For this purpose, anchor load measuring devices are used, typically installed during the construction of the structure. In addition to electrical force measuring devices (e.g. eddy current) or traditional systems based on strain gauges, hydraulic measuring devices as shown in Figure 7 are commonly used.

Such measuring devices are usually installed at the anchor head and are equipped with analogue reading devices. However, the accuracy of these readings is often limited, influenced by factors such as viewing angle and accessibility. Additionally, these measuring devices are usually exposed to weathering, ranging from temperature changes, rain and wind to harsh environmental conditions like snow, frost and the effects of de-icing agents used during winter maintenance.

Figure 7. Anchor load plate installed during the construction of the structure.

4 RETROFITTING LOAD MEASUREMENT DEVICES ON PRE-STRESSED ANCHORS

If assessing the state of preservation, the results of a lock-off test or the need for more comprehensive information on the behaviour of an anchor require it, digitising existing measuring equipment or installing force measuring devices may become necessary.

The following sections present various approaches for implementing such measures, as well as the key considerations related to planning, execution and data interpretation.

4.1 Digitalization of load measurement devices

Force measuring devices installed on structures, such as shown in Figure 7, usually feature only an analogue reading, limiting their ability to provide close-meshed time series or assess temperature-related behaviour of the structure. To address this limitation, the digitalisation and real-time collection of measurement data have therefore been increasingly used for such existing elements.

Although force measuring devices can already be digitised during installation - i.e. during the production of the anchorage - this was often not done, or the technology was not yet available at the time the anchorage was installed. In the following, however, the digitalisation of already installed anchor load plates is briefly discussed - a possibility to add digital data acquisition to almost all installed and still functional devices.

Figure 8 shows an example where an existing anchor load plate with an analogue reading device was upgraded with a

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digital data acquisition unit. The exact implementation steps involved are listed in [21]]. In addition to digitising the anchor load measurement, environmental factors such as the outside temperature, humidity and structural temperature at different depths should also be recorded to gain a comprehensive understanding of the structure's behaviour.

Figure 8. Digitization of an already installed anchor load plate.

This type of digitisation process, combined with the installation of both analogue and digital data acquisition systems, can offer significant added value for the structure and inspection personnel. While the analogue reading allows for a fast check of functionality and a direct determination of the anchor force, the digital interface enables the collection of comprehensive time series data on the behaviour of the anchor. An example of this is shown in Figure 9.

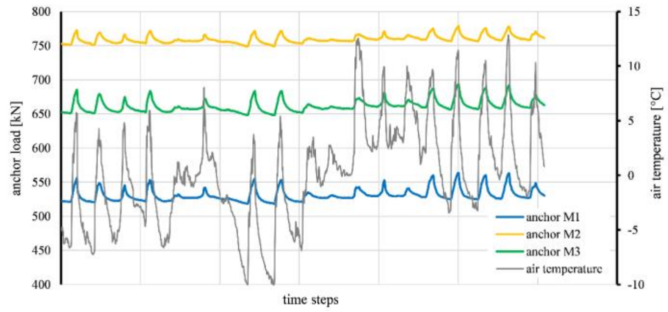

Figure 9. Time series of digitized anchor load cells in relation to temperature.

The diagram shows the recorded anchor loads of three anchors (M1 to M3) alongside the measured air temperature (from -10°C to +13°C) over an observation period not further defined here. A clear correlation between changes in air temperature and the recorded anchor loads can be observed. Furthermore, the anchor load responds almost immediately to changes in temperature, suggesting that these variations are largely attributable to the thermal expansion of the measuring device or the structural elements of the wall.

4.2 Retrofitting load measurement devices on anchor heads

If no load measurement devices are present on a structure, or if additional pre-stressed anchors are to be equipped with such systems, several retrofitting options are available. If the anchor head offers a thread (either internally in the wedge plate or externally), a force measuring device can be retrofitted relatively easy - enabling a short-circuit setup similar to a lock-off test. Alternatively, the existing tendon overhang can be used for attaching a measurement device. However, this is rarely feasible with existing anchorages in Austria, necessitating the exploration of alternative solutions. Two such approaches are briefly described below.

Figure 10 shows the first retrofitting possibility, which involves attaching an additional press chair to facilitate the subsequent lifting of the anchor head via two threaded rods. This enables the creation of a load short circuit through the installation of a new anchor load plate. However, this design is only possible if suitable contact points are available on the anchor head (e.g. free strand holes, internal threads, bayonet at the wedge plate) that allow the anchor head to be properly engaged. In this particular case, the approach was possible because only two strands were installed in a four-strand wedge plate, leaving two free strand holes. Threads were cut on-site into these unused holes to accommodate the threaded rods.

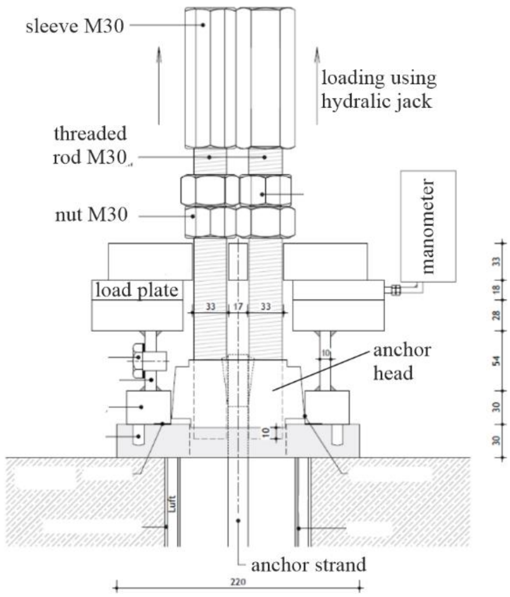

Figure 10. Example of retrofitting an anchor load plate on a partially occupied anchor head.

The figure below shows a special type of anchor known as a wire anchor. Its distinctive feature is that the wires within the drill hole are bundled by a rod attached in the centre. This system, referred to as a PZ anchor [22], allows for relatively straightforward attachment of a new load short circuit and the retrofitting of an anchor load plate, due to the presence of a fine-threaded rod at the anchor head.

Both options share a common factor in that they involve considerable effort. Sufficient expansion paths must be available to enable a load short circuit and the geometric requirements for attaching an anchor load plate must also be met. It should also be noted that such interventions, such as the on-site installation of threads in installed wedge plates, represent a significant impact on the system. This may raise concerns not only regarding liability but also with respect to durability and integrity. Nevertheless, in cases where

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significant changes in anchor loads are suspected, the added value of enabling anchor load measurement typically outweighs these concerns and becomes the primary focus of such investigations and considerations.

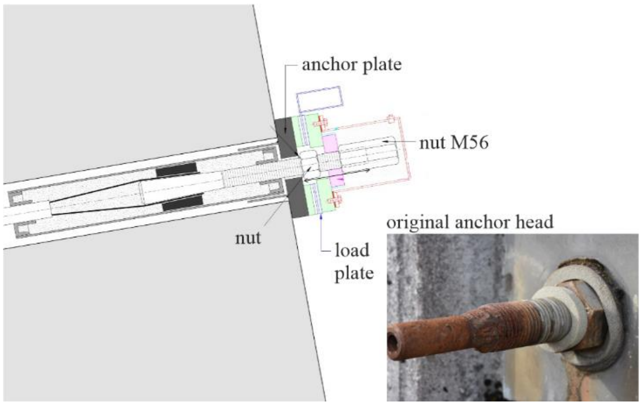

Figure 11. Example of retrofitting an anchor load plate for tensile elements or anchor heads with threaded component.

4.3 Retrofitting load measurement devices on anchor strands

Often, there is insufficient strand overhang, the wedge holes of an anchor head are occupied and other structural components required to create a force-locking connection are unavailable. As a result, the options listed in Chapter 4.2 for retrofitting an anchor load plate to existing pre-stressed anchors may not be feasible. Nevertheless, to accurately assess the behaviour of the structure, it would be beneficial to obtain information about any potential changes in the pre-stressing force.

One possible option is to cut an external thread on the existing strand overhang. From a practical point of view, this section of the tendon is usually 15 - 20 mm long, which may allow a fine thread to be screwed on and subsequently a threaded nut to be fitted. An example for testing purposes is shown in Figure 12 and Figure 13. A fine thread M16x1 (core diameter 14.92 mm) was screwed onto a strand with an outer diameter of 15.6 mm. The manufacturing test demonstrated that even with low pre-stressing forces on the strand and a resulting small wedge bite, the thread could still be successfully installed.

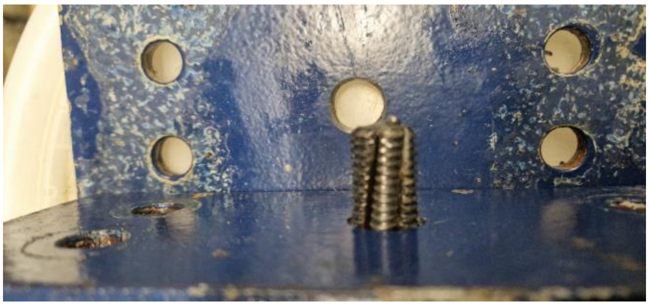

Figure 12. External thread retrofitted to a pre-stressed anchor strand.

The embossed thread on the strand overhang allows for the creation of a force-locking connection between the strand, which would otherwise only be gripped by friction, and other structural elements. An example of this can be seen in Figure 13, where two nuts were screwed onto the embossed thread of the strand to facilitate a tensile test.

Figure 13. External thread used for the application of a threaded nut on an anchor strand.

The result of a series of tests showed that a force-locking connection can be achieved by installing an external thread onto the overhang of already installed anchor strands. Obviously, the amount of load that can be transmitted depends on the length of the thread, the pitch and the condition of the strand. More detailed investigations are currently underway. Nevertheless, this first series revealed the following points:

- It is possible to emboss an external thread onto the overhang of already installed, pre-stressed anchor strands;
- There is no unacceptable mechanical damage to the high-strength steel strands due to cold forming during the cutting process;
- With sufficient strand overhang, it is possible to achieve a force-locking connection;
- An externally applied thread on strands can be used to attach threaded nuts for force input or transmission.

This approach therefore enables the creation of a subsequent force-locking connection with the individual strands of a pre-stressed anchor. This can facilitate the installation of threaded rods to extend the strands, simplifying the execution of lock-off testing or enabling the retrofitting of force measuring devices, as shown in Chapter 4.1 and 4.2.

Furthermore, innovative and new measuring devices, such as the e-Bolt [23]], could also be implemented in anchor technology. This system consists of a nut that, in addition to securing and transmitting loads, also serves as a measuring device. Such systems are already used in various measurement applications, for example to measure the pre-load force of dynamically stressed objects like noise barriers along railways. Beyond retrofitting force measuring devices, this technology could also enable the digitization of anchor force measurement.

5 CONCLUSIONS & SUMMARY

There are several methods to assess the condition of anchored structures, particularly the condition of the tension elements. In addition to traditional structural inspections, monitoring data is often used. Typically, geodetic surveys, readings from existing measuring devices and, if necessary, special tests to determine the material properties are used to record any changes regarding the state of preservation of anchors and anchored structures.

Since lock-off testing is associated with higher personnel costs and potential restrictions, such as road closures or other impacts on the availability of infrastructure, it is usually

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conducted on a limited number of anchors and at periodic intervals. If such tests are not possible, for example due to the shape and type of anchorage, or if a continuous time series of the currently applied anchor load is required, retrofitting a force measuring device may be an appropriate solution.

One of the most common options is to attach anchor load measurement devices directly to the anchors under consideration. However, this is only possible if such provisions have already been accounted for during the planning stage. These measuring elements can be enhanced with continuous data acquisition by digitising the measuring devices, providing comprehensive information on the behaviour of the structure. In addition to possible seasonal influences such as temperature, monitoring can also be implemented in order to detect damage processes or imminent failure of single elements or the anchored structure itself.

Current investigations and research activities in this area indicate that, in addition to various methods of coupling to the anchor head construction of pre-stressed anchors, it is also possible to retrofit anchor load measurement equipment by subsequently cutting threads onto the strand overhang. This approach allows for the use of a force-locking mechanism to attach measurement devices or to enable additional lock-off testing.

This article has attempted to compile a comprehensive overview of the available options for retrofitting anchor load measurement solutions. Given the decline in the state of preservation of anchored structures and tension elements, along with their frequent use in geotechnical engineering, such retrofitting solutions are expected to receive increasing attention in the future.

ACKNOWLEDGMENTS

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