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Static and dynamic testing of pre-stressed grouted anchors

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ABSTRACT: Tension elements such as pre-stressed anchors are an essential component of geotechnical structures. Due to their adaptability to subsoil conditions, the possibilities of pre-stressing and the potential for optimisation of the structures, these geotechnical elements have been widely used. Examples range from temporary use in building pit support to permanent installation along cuts, embankments and retaining structures. In order to ensure safety and reliability, periodic inspections are required, during which the state-of-conservation is determined and necessary measures are derived. A sub-task in inspection is the determination of the current anchor load, which can be subject to ageing-effects or changes in actions and resistances. This paper presents a series of developments that are intended to simplify the performance of this activity. These are adaptations on the methods, the equipment used and options to replace or retrofit load measuring devices. When adapting the equipment, especially weight reduction and the process optimisation provides significant advantages compared to the state-of-art. In addition to simpler handling, the presented developments allow a detailed determination and interpretation of the load-displacement relationship, which could potentially enable a more in-depth interpretation of the acquired data. Furthermore, to the possibility of subsequently extending anchor strands and the use of dynamic excitation of anchor strands was investigated. Considering the increasing age and the associated decreasing state-of-conservation, this presents a significant contribution to sustainable and reliable constructions as well as the safety of road and rail infrastructure.

KEYWORDS: pre-stressed grouted anchors, testing, inspection, existing structures, maintenance.

1 PRE-STRESSED GROUTED ANCHORS AND STRUCTURAL INSPECTION

Due to topography or space limitations, engineering structures such as tunnels, bridges and retaining structures are an essential element in civil engineering. Especially in road and railway construction such assets are necessary to fulfil the requirements of route alignment. An overview on the number of existing structures is provided in ASFINAG (2012) and BMK (2023), whereby only the high-ranking road network and the railway network are analysed in more detail. Figures on the total scope of civil engineering structures are only available to a limited extent (Rebhan, 2017) or are associated with a certain degree of imprecision and lacking data quality. However, some interesting facts are that, the average age of the gravity retaining structures in the rail network is 79 years (basis 2022, see Rebhan et.al., 2023), and that newer forms of construction such as soil-nail walls within the ASFINAG road network have an average age of 26 years (basis 2022).

In Austria, due to its wide road and railway network as well as due to its Alpine topography, anchored structures (see Figure 1) commonly serve as a cost-effective solution for permanently stabilising deep cuts or steep slopes. Due to their ability to transfer tensile forces into deeper or more competent strata, anchored structures are often an economical design option in geotechnical engineering to reduce deformations and allowing for more compact and slender geometries.

Figure 1. Examples for anchored retaining structures, diagonally anchored element wall (top), segmented anchor wall (bottom).

Due to their mode of operation, pre-stressed grouted anchors (Ostermayr H. and Barley T., 2002) can transfer high (tensile) loads into load-bearing ground. This is made possible primarily by three components (see Figure 2). The anchor head (A) is connected to the structure and transfers (structural) loads to the ground via the apparent free length (C). The bond length (E) discharges these tensile forces via shear forces into the surrounding subsoil. In addition to utilising or activating more load-bearing and competent strata, this setup allows anchors to be pre-stressed by a longitudinally shortening of the apparent free length. This is achieved by applying a pre-load during the installation process, leading to tensile stresses in the tendon, which in turn are transferred to the structure via a force-fitting connection at the anchor head.

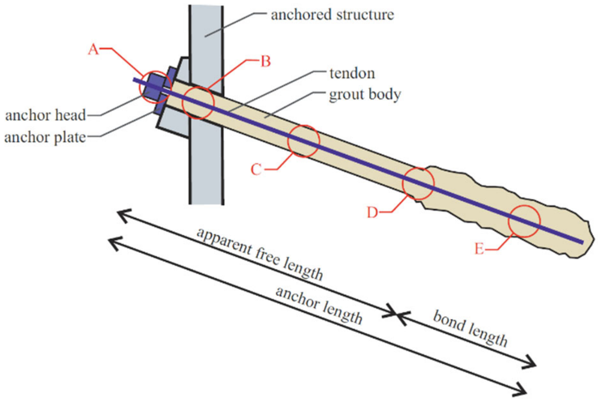

Figure 2. Schematic structure of a pre-stressed grouted anchor.

However, this advantage of pre-stressed anchors, which is often decisive for their use, also means that significant parts of the structure are buried underground. On the one hand, this requires a precise, high-quality and controlled installation and, on the other hand, increased maintenance efforts. This can be seen in the regulations of the design process as for example Eurocode 7 (CEN/TC 250), requires to assess the consequences of the "*failure of a structural element such as a wall, anchor, wale or strut or failure of the connection between such elements*". Nevertheless, investigations addressing the load redistribution due to the failure of structural elements are rare and usually focus on numerical analyses and the failure of struts (whereas failure of ground anchors are scarce). In addition, a large number of these structures were, at least in Austria and the Alpine Regions, built before above-mentioned regulations and approaches were available. Therefore, questions regarding the effects of anchor failure often arise during the safety assessment of these structures.

Therefore, over the designed service life of up to 100 years a comprehensive inspection and maintenance is required. In Austria, the specifications for operators are defined in the FSV guidelines (FSV, 2022). 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 systems and structural components – mostly reinforced concrete. On the other hand, anchors undergo an intensive assessment to determine changes or deficiencies.

In addition to the periodical inspection every 3 to 6 years, special inspection of tension elements and anchored structures is described in detail in a working paper (AP33, 2022). The aim of these activities is not only to determine the current condition, but also to detect changes in the behaviour or the development of damage patterns on the tendons. At the end recommendations for necessary measures are given, ranging from special inspections, the shortening of the inspection interval to anchor lock-off-testing (see section 3) or the implementation of a monitoring system (see section 2). These steps aim to get a better understanding of the – site-unique – behaviour of the structure and to guarantee its reliability. Based on the damage potential and the relevance of anchored structures especially for infrastructure routes, a great deal of effort is required to ensure reliable structures and thus a safe and available road and railway network.

2 ANCHOR LOAD MEASUREMENT

As mentioned above, pre-stressed anchors are essential for the construction of infrastructure structures and must fulfil their function throughout their entire planned service life. For this reason, such structures are often equipped with appropriate monitoring systems. These range from simple geodetic measurements to full-surface monitoring (Kalenjuk et. al. 2021) to detect changes in geometry, usually misalignments, tilting or settlement. However, this type of monitoring only gives limited information on the behaviour of the tension elements. This is due to the pre-stressing force applied and therefore given low deformations that underlie this type of construction. As a result, changes in the pre-stressing force of anchors are additionally measured.

Considering this, either periodically performed lock-off-testing, as described in section 3, or permanently installed load measurement devices can be used. Latter range from simple analogue hydraulic pressure cells (see Figure 3) to digital devices and the attachment of fibre optic sensors along the entire tendon. The aim is to determine changes in the pre-stressing force and to deduce possible damage processes or evolving failure mechanisms. The following section deals with this topic with reference to its application to installed pre-stressed anchors. In newly installed anchors, reference can be made to current developments in Austria, which define the number of load measuring devices to be installed (Austrian Standards Institute, 2021), as well as to the possibilities for the planned installation of force measuring devices.

By monitoring the anchor force, changes (both decreases and increases) and their effects on the structure, are recorded in a timely manner. 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 (rain, wind, de-icing agents) affecting their durability and usability.

Figure 3. Hydraulic pressure cell with an analogue gauge used as an anchor load measurement device.

Various approaches are available to eliminate these potential limitations of already installed load measurement devices and to enable their retrofitting on anchors that are not yet monitored. On the one hand, the digitisation of existing systems (see section 2.1) can provide added value through a continuous time series. On the other hand, there are a number of methods (see sections 2.2 and 2.3) for retrofit measurement devices.

2.1 *Digitalization of load measurement devices*

Usually load measurement devices have been installed on a large number of anchored structures in order to confirm design assumptions and the resulting load-bearing behaviour, similar to the Observational Method (CEN/TC 250, 2013). In general load measurement devices available are analogue hydraulic pressure cells, as shown in Figure 3, which enable readings to be taken during an on-site inspection. As a result, only a spatial resolution of the monitoring data is available over time making it hard to derive trends or to investigate the influence of variable loads and temperature effects.

In order to enable a continuous time series of measurement data, both new and existing hydraulic cells can be digitised. As for example and described in Rebhan et. al. (2024), the installation of a digital pressure transducer is in most cases sufficient. This can also be linked to an analogue output, offering redundancy and the advantage of easy readability.

Figure 4. Time series of digitized anchor load cells in relation to temperature.

The result of such a digitisation of a load measuring device is shown in Figure 4 for three anchors and additional the air temperature is plotted. Furthermore, this kind of improvement to the equipment not only enables digital and continuous data recording, but also integration to early warning systems. As one can clearly see, there is a direct linkage between the air temperature (grey line) and changes in the measured anchor loads. More details on the approaches to interpreting this data are outlined in section 2.4.

2.2 *Retrofitting load measurement devices on anchor heads*

If load measurement devices are missing, or if additional monitoring is necessary, several retrofitting options are available. If the anchor head offers a thread, load measuring devices can be retrofitted with ease - using a force-locking mechanism similar to a lock-off test as shown in section 3. Alternatively, the existing tendon overhang can be used for attaching a measurement device. However, due to geometric boundaries, this is rarely feasible, necessitating the exploration of alternative solutions. Usually such approaches are to be customized to the situation and the type of anchor head.

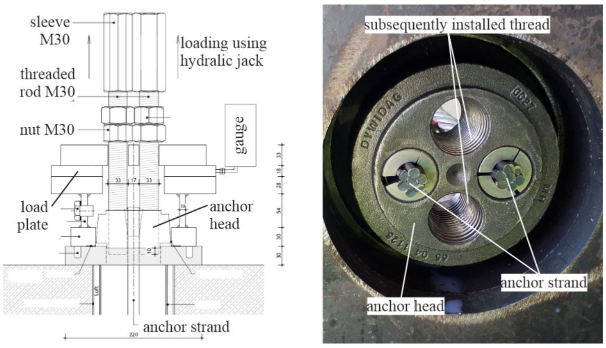

Figure 5. Example of retrofitting an anchor load plate on a partially occupied anchor head.

This retrofitting involves attaching an additional press chair to facilitate the subsequent lifting of the anchor head via two threaded rods. For the installation of these rods, a subsequently installation of threads within the anchor head has to take place, as shown in Figure 5. This approach was applicable in this particular case because only two strands were installed in a four-strand wedge plate, leaving two strand holes available. This enables the creation of a force-fitting installation of a new hydraulic load cell (IBG, 2019). However, this design is only possible if suitable contact points are available on the anchor head (e.g. free strand holes in the anchor head, internal threads, bayonet at the wedge plate, see Rebhan et. al. (2024)) allowing a properly and permanent coupling.

2.3 *Retrofitting load measurement devices on strands*

Many anchors do not have load measurement devices to carry out digitisation as described in section 2.1, and in most cases, the anchor head does not offer the possibility of retrofitting as shown in section 2.2. If rods were used as a tendon, the possibility of retrofitting an extension via the external thread is given. However, for permanent pre-stressed grouted anchors, and especially for anchor lengths of more than 30 m, strands are generally used for practical reasons. However, a force-fitting connection to strands is difficult. Although systems are available for coupling (e.g. bridge construction) this requires a planned strand overhang of several centimetres.

As a rule, the strand overhang was cut to 15-20 mm after the tensioning process in order to install the anchor head cover and the necessary corrosion protection. This length is unsuitable for standard coupling systems in order to ensure a force-fitting connection by means of a clamp. But, such a length would be sufficient for a screw connection, as well-known in common steel construction. In a series of laboratory tests, the possibility of cutting a thread onto already installed strands was performed. The first result is shown in Figure 6.

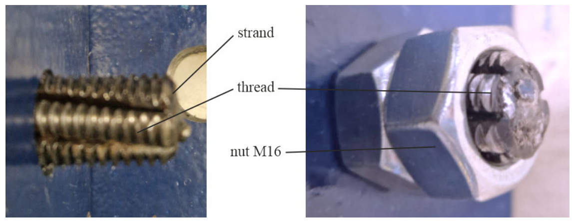

Figure 6. Subsequently applying an external thread to anchor strand, external thread (left), nuts screwed on.

A fine thread M16x1 (core diameter 14.92 mm) was cut onto a strand with an outer diameter of 15.6 mm. The test installation demonstrated that even with low pre-stressing forces on the strand and a resulting small wedge bite, the thread could be successfully reamed on. The thread on the strand overhang allowed a force-locking connection using a nut or a sleeve as shown in Figure 6 right. Obviously, the admissible load of such a connection depends on the length of the thread, the pitch and the condition of the strand. This feasibility study was successful and revealed the following points:

- It is possible to ream an external thread onto the overhang of installed, pre-stressed and wedged anchor strands;
- There is no unacceptable mechanical damage to the high-strength steel strands due to cold forming during the reaming process of thread cutting;
- It is possible to achieve a force-fitting connection;
- An externally applied thread can be used to attach threaded nuts for further use.

This approach is currently under investigation and should be suitable for lock-off tests as well as the retrofitting of load measurement devices.

2.4 *Monitoring data and interpretation*

The aim of all methods described in this section is to generate data on the anchor load and thus to draw conclusions about the behaviour and any changes in the load-bearing behaviour of the structure. The reasons for this can be manifold and range from ageing or damage to load changes or geological mechanisms. In addition to data acquisition, it is necessary to interpret the data in order to be able to give insights into causes and to take the necessary steps regarding potentially required maintenance. Various effects must be considered and a certain time-period is required to determine the behaviour under normal conditions.

Figure 4 shows that there is (in general) a daily fluctuation of the measured load which can range from 20 to 50 kN. This illustration additionally shows that there is a correlation between the fluctuation in load and air temperature. This can be caused by the structure itself, but also by the measuring system and the metal components of the anchor head. In order to enable an appropriate data interpretation, a corresponding time-period of generally more than 4 months is necessary to evaluate this behaviour. In addition, influences such as traffic loads or changes in groundwater can also have an effect on the results.

3 ANCHOR LOCK-OFF TESTING

The currently applied anchor load can, in addition to load measurement devices, also be determined by using anchor lock-off testing (Schäfer F., 2013). In general, a distinction between three different test types - namely, investigation, suitability and acceptance tests - can be made. While the systems as described in section 2 offer the possibility to survey the load over a longer period, a lock-off-test only determines the current load acting on an anchor at the time of testing.

The anchor load depends on a variety of factors and can be influenced by daily and seasonal fluctuations, but can also vary due to damage (e.g. corrosion) or creep effects of the subsoil. Compared to the use of anchor load measurement devices, performing a lock-off-tests solely indicates the currently applied anchor load. As shown in Figure 7, the apparatus used generally consists of a hydraulic jack (hollow piston), a press chair, a temporary pulling head, as well as a displacement and load measurement unit.

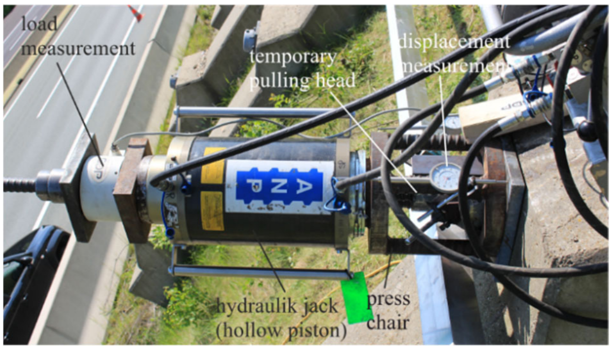

Figure 7. Apparatus used for anchor lock-off testing using a hollow piston state-of-the-art equipment.

The temporary pulling head provides the force-fitting connection between the anchor head and the hydraulic jack. Depending on the anchor type, the configuration of the anchor head and the geometry, different types of the pulling head (often referred to as anchor bell) are required. The result of an anchor lock-off test can be seen in Figure 8. Such a load-deformation-diagram illustrates the compression and slippage of the test setup (green line) alongside with the elastic elongation of the anchor strand. The blue line describes the linear-elastic behavior of the tendon due to a small increase in load exceeding the currently applied anchor load. Therefore, the intersection point, marked by the two equalization lines, represents the point where the anchor head lifts off, defining the currently applied anchor load. In comparison to the test loads in a suitability or acceptance test of anchors (Austrian Standards Institute, 2015), the lock-off load P_A is not described in normative or design regulations. As this load reflects the current state of the anchor and is therefore subject to changes over time. This load has to be defined in advance of the test and can usually be estimated, as the number of strands or the diameter of the bar can provide information on this. Thus, defining the limits and boundaries in combination with a preceding endoscopic investigation of the anchor head and a stepwise load increase during the testing process.

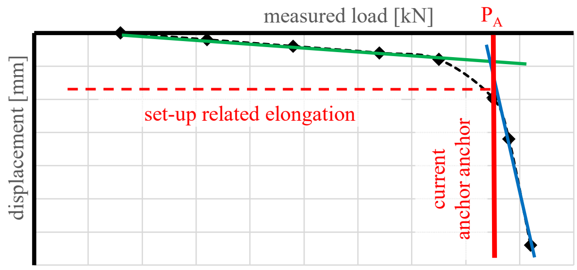

Figure 8. Schematic load-deformation-diagram as a result of an anchor lock-off-test.

Most methods for lock-off tests use heavy equipment with long stroke hydraulic jacks, which are also used for the pre-stressing process. However, in lock-off tests, only a minor stroke is needed to establish a detectable gap between the anchor head and the anchor plate. In Austria, the testing procedure is described in AP33 (2022) and states that Method 1 according to Austrian Standards Institute (2019) is to be used for the performance of lock-off tests, which is characterized by a gradual load application and a measurement of the anchor head displacement. Such a method - based on the determination of individual points of the force-displacement diagram as shown in Figure 8 - is associated with a certain degree of imprecision. New approaches such as those shown by Rebhan et. al. (2021) also enable continuous data acquisition. On one hand, this enables a more accurate statement about the load currently applied, but also offers approaches to carry out a more comprehensive evaluation of the behavior of the anchor tested.

4 DYNAMIC TESTING OF ANCHORS

In section 2 and 3 it was shown, how load measuring devices and anchor lock-off tests can be used to determine changes in anchor force. However, anchor lock-off tests usually involve a high level of personnel and financial expenditure in order to carry out the tests and to enable access only offering a momentary insight into the behaviour of the structure. Furthermore, since testing can take 30 to 60 minutes, a reduction in the required effort would be an advantage.

Next to improving the equipment used, a different type of testing could also be a huge improvement. In a series of research activities, the use of dynamic testing on pre-stressed anchors was investigated. The aim was to determine the response of the anchor as a consequence of controlled dynamic excitation and, as a result, to derive changes in the applied anchor load and subsequently to be able to infer damage and defects. The setup required for this is shown in Figure 9 top and consists of three main parts. The excitation is achieved by a drop weight, which exerts a tendon-orthogonal impact on the overhang. The impact and the response of the system are recorded by an accelerometer. These two elements are force-fitting coupled to the strand overhang using a clamping device.

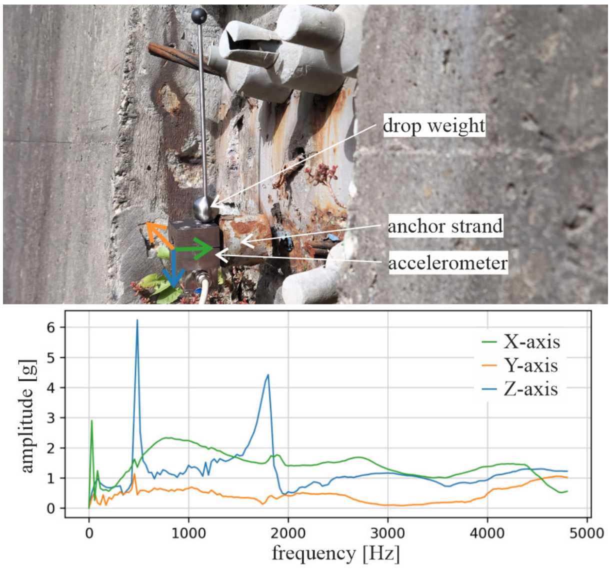

Figure 9. Dynamic testing of pre-stressed anchors, testing equipment used on-site (top), spectrum of a performed test (bottom).

With this type of test, several things can be examined. A distinction can be made between absolute measurements, to determine the current anchor load, and relative measurements, showing changes in relation to the initial state. This must be considered when interpreting the data and when defining the measurement concept and is of great interest, especially with regard to interpretation and timing of the investigation. In addition, geometric relationships can be examined and conclusions about possible damage can be drawn. For this interpretation the frequency of a stand wave (similar to a guitar string) can be considered, as given in Formula (1).

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}} \qquad (1)$$

This simple mathematical description of the vibration of an ideal (no damping, no stiffness) model with both ends considered to be fixed, shows the influencing factors on the determined eigenfrequency f_n. The different modes (eigenfrequencies) can be described by the factor n while the linear mass density (constant) is considered with the factor μ. Furthermore, the geometry is described by the length L and the factor T considering the tensile force within the string. Using such an approach, the following observations could be made:

- Determination of the apparent free length (L in Formula (1) shown in Figure 2) as long as the eigenfrequency f_i is known and the tension T (pre-stressing force) is known;
- Specifying the pre-stressing force (tension T in Formula (1) or P_A in Figure 8) if the eigenfrequency f_i and the apparent free length L are known;
- Measuring the eigenfrequencies f_i as long as the apparent free length L and the pre-stressing force T are given.

However, this would require that the approach given in Formula (1) for a free-swinging string can be converted to a pre-stressed anchor. On the one hand, this is of course only possible to a limited extent due to the assumptions that damping is not considered and that a stiffness-related behaviour of the system is absent. On the other hand, this would require sufficient knowledge of the boundary conditions. Investigations (e.g. Fabris et. al., 2019) have shown, that the determination of the apparent free length can only be carried out correctly to a limited extent and that the area of the bond length and thus the area under compression can only be determined with restrictions. Additionally, it is difficult to clearly determine the individual tensile force during the pre-stressing process due to production-related reasons such as using one hydraulic jack for multiple tendons. Furthermore, fluctuations in material properties (e.g. modulus of elasticity) will have an influence on these considerations.

Furthermore, it has to be assumed that the application of a dynamic excitation at the overhang results in a limited transfer of the vibration into internal sections of the anchor – especially the transition from the anchor head area to the apparent free length. In the case of strand anchors, this is caused by the clamping of the strands using wedges, which results in a force-fit connection usually extending over several centimetres of the strand. With bar anchors, this is defined by the size and tightening of the nuts. This could lead to a possible interference of the dynamic signal which has to be considered in the interpretation of the results.

Next to an interference this could also result in a complete suppression of the signal transfer into the apparent free length. Therefore, it could be useful to change the system and consider the overhang as a cantilever. The natural vibration of such a system can - with identical assumptions as above - also be derived for this case, as shown in Formula (2).

$$f_n = \frac{\beta_n^2}{2\pi L^2}\sqrt{\frac{EI}{\mu}} \qquad (2)$$

In addition to Formula (1), two terms describing the behaviour of a cantilever compared to a free-swinging string are added. Next to the bending stiffness EI, the natural frequency sought by the eigenvalue parameter β_n has to be considered which can be described for the relationship f_n/f_i, simplifying the application of the formulation.

Although this mathematical consideration of a dynamic excitation has its limitations, it shows that, at least from a physical point of view, it is possible to gain knowledge about the behaviour of an anchor and to identify possible changes such as damage or a change in loading. The results of an initial test series in Figure 9 bottom show that very useful and reproducible results can be generated. The following advantages were identified in the course of the investigations and initial studies:

- Determination of multiple parameters of a pre-stressed anchor by a single testing system is possible;
- Reduction of testing effort due to smaller equipment and reduction of installation time is given;
- Reduction of test duration due to a faster dynamic testing method of the tendons can be achieved;
- Applicability of the testing system is independent of the design of the anchor head and is only limited by the geometric boundaries of the strand overhang.

These advantages are accompanied by disadvantages and requirements that have to be considered in a further development. On the one hand, an adequate overhang is necessary to enable a force-fitting connection. On the other hand, the mathematical processing in Formula (1) and (2) shows that there are a number of factors that must be considered - in particular, damping and the influence of the clamping to guarantee a reproduceable test.

Nevertheless, the approach presented offers a new way of testing and assessing anchored structures which, through further development and the use of appropriate data analysis methods (e.g. Gasser et. al., 2025), can provide deeper insights into their behaviour. In addition, the system could be applicable as a monitoring system, thus contributing to the anchor load measurement described in section 2.

5 CONCLUSIONS & SUMMARY

This article presents a number of possibilities to determine the load currently applied to pre-stressed anchors. Due to the fact, that relevant structural components of anchored structures cannot be examined during inspections this is one main task while performing a safety assessment (Rebhan et. al., 2017). In addition to damage to the structural components, corrosion damage to the metallic components of pre-stressed anchors is particularly critical. Next to a reduced reliability of the structure, this can also affect the availability of infrastructure corridors. Furthermore, ageing will be superimposed by climate change effects such as increased rain events and changes in dry and frost periods.

A number of options are available to determine a change in the current acting load on a pre-stressed anchor. These range from lock-off tests and monitoring devices to approaches using dynamic testing. One of the biggest problems is that the boundaries and limitations of already installed anchors have to be considered especially due to restrictions in liftability of the anchor head and the arrangement of measurement equipment. For this reason, one part of this article has pointed out possibilities and approaches for anchor load measuring equipment to be retrofitted and digitised. Research on lock-off tests has furthermore shown that a considerable advantage can be created by improving the equipment. For example, continuous data acquisition instead of point-by-point data generation, which offers the possibility to determine changes in the behaviour of the anchorage.

The investigation of a new approach on testing of anchors showed that the use of a dynamic excitation at the strand overhang has the potential to provide information about changes in the behaviour. To make this possible, a comprehensive scientific and practical study has been performed. In particular, the effects of the geometry of the overhang as well as the influences of damping and the transmission of the dynamic excitation must be included through mathematical (numerical) and experimental modelling. However, it has been shown that such a concept can provide an essential component for both testing and monitoring of pre-stressed anchors. In view of the increasing age of these structures and the resulting decrease in the state-of-conservation, this is essential to ensure their reliability and safety.

6 ACKNOWLEDGEMENTS

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