Dynamic testing of pre-stressed grouted anchors – concept and feasibility study

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ABSTRACT: The assessment of pre-stressed grouted anchors represents a significant challenge; nevertheless, it is imperative for ensuring the safety and reliability of anchored structures. In conjunction with load measurement apparatus, anchor lock-off tests are frequently utilised as a cutting-edge technique to ascertain variations in the presently implemented anchor load and to deduce deviations. However, due to the considerable effort involved, this type of investigation is associated with high costs, intensive personnel deployment and can influence the usability of the structure or its surrounds. The present paper discusses the use of dynamic excitation to determine the state-of-conservation of pre-stressed grouted anchors. The fundamental premise of this theory is predicated on the notion that a modification in the anchor load results in a concomitant shift in the eigenfrequency, a phenomenon that can be objectively measured. A preliminary investigation was conducted in a laboratory setting to ascertain the feasibility of the proposed experiment. The experiment was conducted under idealised conditions, and a clear correlation was observed between the excitation and the response of the tensile element. Subsequent field tests demonstrated that the proposed concept is both feasible and offers further potential. The objective of this paper is to present preliminary findings with the aim of generating a further basis for improvement. The objective of this study is to demonstrate that such developments could assist in addressing the challenges posed by an ageing infrastructure.

1 ANCHORED STRUCTURES AND TENSION ELEMENTS

Due to the topography of Austria a vast number of civil engineering structures are essential for the routing of roads and railways. In addition to bridges, tunnels and natural hazard protection structures there are also retaining structures necessary.

Anchored structures as shown in Figure 1 commonly serve as a cost-effective solution for permanently stabilising deep cuts or steep slopes, at least during the construction phase. Especially due to their ability to transfer large tensile forces into deeper or more competent strata, anchored structures are often an economical solution in geotechnical engineering. Pre-stressed grouted anchors as defined in EN 1537 (Austrian Standards Institute, 2015), can be used to reduce deformations, allowing for more compact and slender overall design and geometries (e.g., cross sections). Examples for such structures range from newly erect structures, as well as a subsequent us of tensile elements in refurbishing existing structures.

Pre-stressed grouted anchors are a crucial element when it comes to the load-bearing and the function of anchored structures. Eurocode 7 (CEN/TC 250), for example, requires assessing 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*".

Figure 1. Example for anchored structures in Austria.

Despite this requirement, a lack of specifications addressing how to deal with defective anchored structures can be seen. Especially regulations on how damage to ground anchors affects the overall behaviour and function of the structure are omitting.

Therefore, ensuring reliability throughout their planned service life of up to 100 years, requires a regular condition assessment. However, past experiences highlight the multifaceted challenges in assessing the condition (state-of-conservation) of anchored structures (e.g. Stadlbauer and Antony, 2019). However, addressing the effects of damage to anchors on the (remaining) load bearing capacity is of utmost importance in this context.

2 INSPECTION AND TESTING OF ANCHORED STRUCTURES

Like everything, civil engineering structures are subject to ageing processes, where natural degradation of building materials is superimposed and accelerated by external influences (mechanical and chemical damage). This will reduce the structures reliability and therefore affects the function and the availability of the structure. Consequently, a comprehensive and periodic inspection of the structures has to be carried out, in order to determine the effects of damage on the condition of the structure and to be able to derive the necessary maintenance.

2.1 Inspection of anchored structures

In Austria, the procedure to be used for the inspection of civil engineering structures is described in the FSV regulations (see FSV, 2022 for example). In addition to a step-by-step inspection, which must take place periodically, the scope of these inspections is also specified in detail. As a rule, a close-up inspection, as shown in Figure 2 (a) and (b) by appropriately trained personnel is sufficient to determine possible changes in the state of conservation and subsequently to be able to derive their effects on load-bearing, serviceability and roadworthiness.

For example, cracks and damaged areas on the structural components are assessed, possible damp patches and the condition of the drainage are determined and the surrounding terrain is included in the on-site inspection. In the case of geotechnical structures such as anchored structures, it is clear that buried components (e.g., foundation and anchorage) that cannot be directly inspected, are particularly difficult to assess.

Therefore, by using additional inspection methods (AP33, 2022), it is possible to draw conclusions about the functionality of the structure based on its overall condition.

Figure 2. Inspection of anchored structures, equipment used (a), hands-on inspection (b), investigation of an anchor head using endoscopy (c), corrosion damage at the anchor head area (d).

One example is given in Figure 2 (c) where an endoscopic investigation is used to check the condition of the corrosion protection at the anchor head and determine the condition of the tendons in this area as shown in Figure 2 (d).

2.2 Damage of anchored structures and tension elements

An essential part of inspection is the identification of existing defects and damage patterns. In the case of anchored structures and in addition to the damage of (reinforced) concrete such as exposed reinforcement, spalling or cracks mostly corrosion damage of the tensile elements in one of the most common damage.

Besides – mostly durability related – damages to anchors (e.g. Burtscher et. al., 2017 & Ebeling et.al., 2013), an increasing number of corrosion damage to reinforcement elements (e.g. Hunkeler et.al., 2005 & Rebhan et.al., 2017) can be observed. The tensile elements must be addressed accordingly as a relevant component to load-bearing of the anchored structure. The tendons, as well as the structure itself, are exposed to enormous external influences during their service life, resulting in high demands on the durability of the structure. In addition to geotechnical damage patterns, this is reflected in frequently observed corrosion damage of the tendon in various forms as shown in Figure 2 (d). Such a reduction of the tendons cross-section caused by corrosion can lead to an increase in (tendon internal) stress and thus to a reduction in capacity. The resulting effects, such as a change in pre-stressing force or, if the load-bearing capacity is exceeded, failure, can have a negative impact on the stability of the anchored structure.

Therefore, it is necessary to determine the condition of the structure itself but also a change in the state of conservation or mutation in damage patterns. Furthermore, the damage‘s influence on the safety and reliability of the tendon have to be adressed properly.

Research (e.g., Burtscher et. al., 2017 & Hunkeler et.al., 2005) and the results of safety assessments 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 can usually not be detected through lock-off-testing, as described in section 3.1, yet solely limiting the results to the area of the anchor head with an endoscopic investigation (see Hung-Jiun, 2018 and Figure 2 (c) and (d)).

3 LOCK-OFF-TESTING AND MONITORING

Relevant structural components of anchored structures cannot be completely examined due to the installation within the subsoil. Usually this is limited to the area of the anchor head as illustrated by the sections A and B in Figure 3. The apparent free length and the bond length of a pre-stressed anchor are located within the subsoil and thus are not accessible for a visual inspection. Additionally, especially for older anchors, the anchor heads were sealed during construction and are therefore not directly visible and accessible.

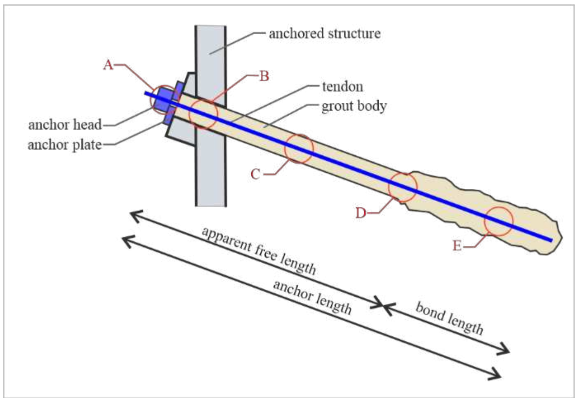

Figure 3. Schematic of a pre-stressed grouted anchor.

Consequently, the only way to determine the function and effectiveness of an anchor is to measure the applied pre-stressing force or its change. Lock-off-tests can be used for this purpose, enabling a short-term determination of the currently applied anchor load. In addition, this component can also be monitored by attaching appropriate measuring instruments over a longer period of time in a monitoring process.

3.1 Lock-off-testing of pre-stressed grouted anchors

In literature the lock-off test (Witt, 2011) is described as to extend the tendon by socketing it in such a way that a hydraulic jack (Figure 4 (a)) and load cell can be mounted above it. This testing procedure is further described in AP33 (2022) and states that test method 1 according to EN ISO 22477-5 (Austrian Standards Institute, 2019) is to be used, which is characterised by a gradual load application and a measurement of the anchor head or component displacements. It must be ensured that the anchor head locks off the anchor plate.

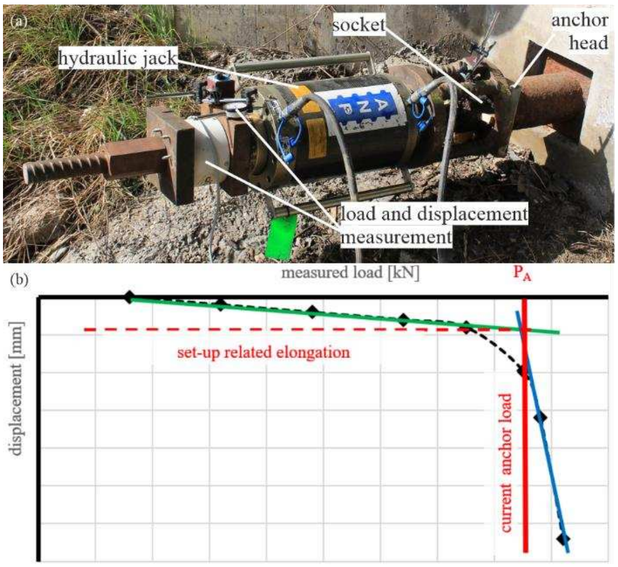

Figure 4. Anchor lock-off-testing, equipment used (a), schematic load-displacement diagram of a test (b).

The result is a load-displacement diagram as shown in Figure 4 (b) in which the respective displacement measurements on the anchor and the comparison with those of the structure are plotted for different load levels. The intersection point, which is marked by the two equalisation lines (green and blue line in Figure 4(b)), represents the point where the anchor head locks off the anchor plate. This load reflects the current state of the anchor (P_A) and is therefore subject to change over time.

However, such a method - based on the determination of individual points of the load-displacement diagram - is associated with a certain degree of imprecision. However, approaches and equipment such as those shown by Rebhan et. al. (2021) also enable continuous data acquisition and recording. This enables a more accurate statement about the load currently applied to the anchor, but also offers approaches to carry out a more comprehensive evaluation of the behaviour of the tension element. For example, changes in the elastic behaviour of the anchor (blue line in Figure 4 (b)) could be used to deduce damage or increases in damage such as corrosion of the strands and tendons. As a result, a more precise statement could be made regarding the development of the anchors reliability or new approaches for monitoring and safety assessment could be developed.

3.2 Monitoring

Using monitoring, changes (both decreases and increases) in the anchor load and their resulting effects on the structure, or the potential failure of the anchor, can be recorded in a timely manner. For this purpose, next to lock-off-testing, anchor load measuring devices (load cells) are used, typically installed during the construction of the structure.

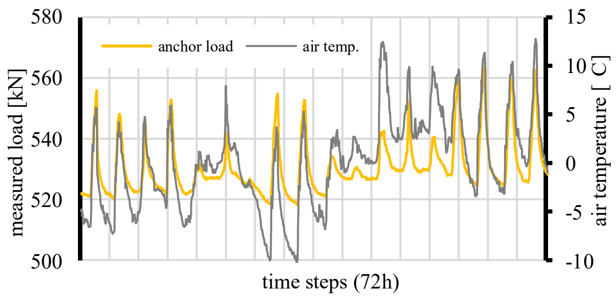

Figure 5. Time series of temperature related changes in anchor load.

Such measuring devices are usually installed at the anchor head and are at least 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 exposed to weathering, ranging from temperature changes, as shown in Figure 5, rain and wind to harsh environmental conditions like snow, frost and the effects of de-icing agents used for winter maintenance.

4 CONCEPT DYNAMIC TESTING OF PRE-STRESSED ANCHORS

Section 3 gave a short insight into how lock-off-testing and monitoring can be used to determine changes in anchor load. These tests usually involve a high level of personnel expenditure in order to carry out the tests and to enable access only offering a momentary insight into the behaviour of the structure. During testing, a reduction in the required effort would be an advantage, as improving the equipment (Rebhan et. al., 2021) used, can lead to a reduction of the work load and also the interpretation of the test results.

In order to circumvent these disadvantages of conventional state-of-the-art testing and monitoring, the application of dynamic testing was considered in a series of investigations. The aim was to determine the response of a pre-stressed anchor as a consequence of a controlled dynamic excitation and to derive changes in the applied anchor load and subsequently to be able to infer damage and defects. To enable this, the strand overhang is dynamically excited to determine changes in the eigenfrequency.

The setup required is shown in Figure 6 (a) consisting of three main parts. The equipment is mounted force-fitting by half-shells clamped to the strand overhang. The excitation is achieved by a drop weight exerting the tendon using an impact orthogonaly to the axis of the anchor strand. The impact and the response are recorded by an accelerometer attached to the mounting device.

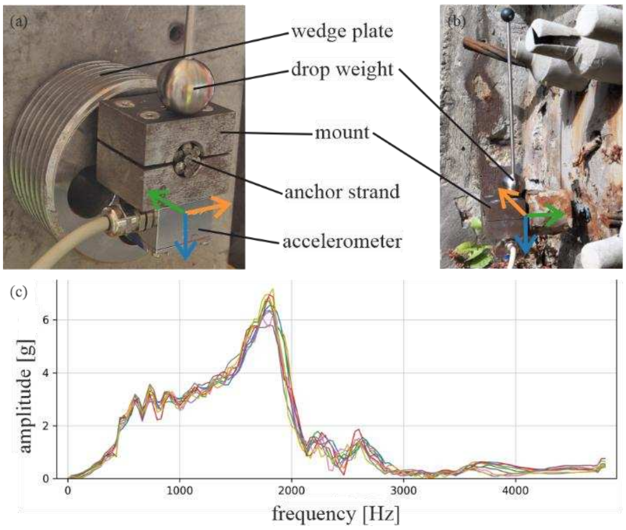

Figure 6. Dynamic testing of pre-stressed anchors, testing equipment in a lab test (a), field test (b), measurement results of a repeated field test (c).

Using this approach and the gatherred measurement results, parameters of a pre-stressed grouted anchor under investigation can be derived.

First of all, a distinction can be made between absolute measurements – e.g. determining the current applied anchor load (P_A in Figure 4) – and relative measurements. Later outlining changes in the response to the dynamic excitation and therefore changes of the anchor load in relation to the initial state. This is of great importance, as it influences both the interpretation and the timely application.

Similar to the anchor load also geometric constraints of the anchor can be examined. For example, the apparent free length (Figure 3) could be determined to supplement missing information on existing structures.

For such interpretations the frequency of a stand wave (similar to a guitar string) can be considered, as given in Formula (1).

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

Using such a description of the vibration shows the influencing factors on the determined eigenfrequency f_n. The factor n defines the different modes while the linear mass density - seen as a constant - is substituted by the factor μ. Furthermore, the geometry is described by the length L and the factor T considering the tensile force within the system. Therefore, the apparent free length (L) as well as the current applied anchor load (T) could be dirived for different eigenfrequencies.

However, this idealised system is not considering any damping or stiffness within the modell and is based on the boundary that both ends are completely fixed. By including the stiffness of a tendon into the system and a free swinging system. Furthermore, it has to be assumed that the application of a dynamic excitation at the strand overhang results in a limited transfer of the vibration into internal sections of the anchor – especially the transition to the apparent free length. For strand anchors, this is caused by forcefit wedging the strands over several centimetres at the wedge plate. This could lead to a interference of the dynamic signal which has to be considered in the interpretation of the results or to a complete suppression of signal transfer.

However, by abstracting the strand overhang as a cantilever the natural vibration of the anchor head area can - with identical assumptions as above - also be derived, as shown in Formula (2).

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

For this, two terms describing the behavior of the 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 being described for the relationship f_n/f_i, simplifying the application of the formulation. From a physical and mechanical point of view, this approach can be used to gain knowledge about the behavior of an anchor and to identify possible changes such as damage or a change in loading.

Figure 7 illustrates first results when deriving the spectrum of frequencies from the measurement data shown in Figure 6 (c).

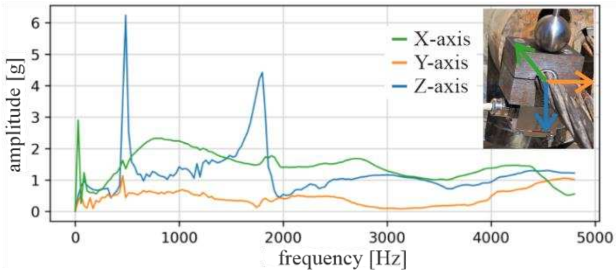

Figure 7. Spectrum derived from field measurement data.

The shown peaks occuring along the excitation direction (blue line, z-axis in Figure 7), at approximately 500 and 1,800 Hz. As Figure 6 (c) show a high degree of reproducibility of the measurement data. It is therefore possible to repeat the measurement periodically during inspections. This process enables the deduction of changes in the currently applied anchor load to a change (shift) in the spectrum. Consequently, this process also enables the determination of changes in the eigenfrequencies.

Based on this, the concept described could be used as a testing process for pre-stressed grouted anchors to determine changes in the currently applied anchor load. Additionally, the determination of multiple parameters, including the apparent free length, the damping, and alterations in stiffness could be possible.

In addition to these possibilities, such an approach can reduce the effort involved in anchor testing, and is capable to be carried out on all anchor systems with sufficient strand overhang. Nevertheless, attention must be paid to a forcefit coupling, in order to guarantee reproducable measurement results over a long periode of inspection and testing.

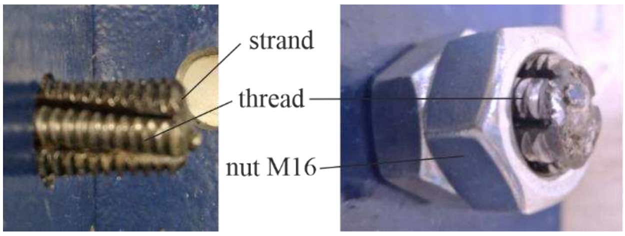

Figure 8. Subsequently applied external thread to an anchor strand.

Such a forcefit coupling between the measuring device and the strand overhang could be ensured, for example, by means of a thread. Figure 8 shows a feasibility study in which a thread was applied to a pre-stressed strand, enabling a controllable and repeatable connection. Additionally this could enable the permanent dynamic recording of the pre-stressing force as a monitoring.

5 CONCLUSIONS & OUTLOOK

Anchored structures using pre-stressed grouted anchors are widely used to stabilise slopes and deep excavations due to their efficient transfer of tensile forces into competent ground and therefore enabling slender structural designs. The planned service life of up to 100 years makes a systematic condition assessment and associated inspection necessary.

Conventional inspection procedures rely on visual and close-up inspections of accessible components, while buried elements remain largely inaccessible. Durability-related damage and defects, particularly corrosion of tendons and anchor heads is increasingly observed, reducing the tendon cross-section, increasing internal stresses, altering pre-stressing forces, and ultimately compromising the load-bearing capacity of the element and the structure.

Although such damage can be detected using state-of-the-art inspection methods as endoscopic examinations, lock-off testing, and monitoring, these examinations are very costly and can only be performed to a limited extent on all types of pre-stressed grouted anchors. To overcome the limitations of conventional methods, a dynamic testing concept for pre-stressed anchors is proposed.

This approach uses controlled dynamic excitation of the strand overhang and measures the response to identify eigenfrequencies. Changes in these frequencies can be related to variations in the currently applied anchor load, and can additionally offer the possibility to determine the apparent free length, stiffness and damping distributions. These measurements could provide both absolute and relative indicators on the condition of the system.

Initial testing demonstrated a reproducible frequency spectra, indicating the method's suitability for periodic inspections as well as long-term monitoring. Overall, the presented concept on dynamic testing offers a promising, low-effort complementary technique for assessing the condition of pre-stressed grouted anchors to be used in detecting degradation. Furthermore, this could provide valid and crutual information on the state-of-conservation of anchored structures and therefore increase the realibility of these structures and increase the availability of roads and railways.

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