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Anchor lock-off testing – improvements on equipment and interpretation

Essais de verrouillage des ancres - améliorations de l'équipement et de l'interprétation

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ABSTRACT: Pre-stressed anchors are indispensable elements in geotechnical engineering and represent a common technique for earth retention and slope stabilization. The installation of pre-stressed anchors offers several advantages compared to conventional systems, which result in an economic design along with technical improvements such as a reduction of deformations and construction time. Anchors for permanent use must be observed by means of a periodic safety assessment (e.g. endoscopic investigation, lock-off-testing). Especially lock-off-testing has become a standard procedure to determine the anchor lock-off load, defined as the load acting on the anchor (due to pre-stressing, temperature, or loading) at the time of testing. In this paper a new type of test device is introduced, which, in contrast to state-of-the-art test equipment, is specially designed for the execution of anchor lock-off tests. It consists of a hydraulic jack integrated in a nut, which can be applied on anchor heads with an external thread. In addition to an easier and more efficient load application, this device offers the possibility to directly determine the lock-off at the anchor head. Moreover, the paper presents first results of laboratory and field tests with this new device.

RÉSUMÉ : Les ancrages précontraints sont un élément indispensable en géotechnique et représentent une technique courante pour la rétention de terre et la stabilisation des pentes. L'installation d'ancrages précontraints offre plusieurs avantages par rapport aux systèmes conventionnels, qui se traduisent par une conception économique et des avantages techniques tels que la réduction des déformations et du temps de construction. Les ancrages destinés à une utilisation permanente doivent être observés au moyen d'une évaluation périodique de la sécurité (par exemple, endoscopie, essais de verrouillage). Les essais de blocage sont devenus une procédure standard, qui est utilisée pour déterminer la charge de blocage de l'ancrage, définie comme la charge agissant sur l'ancrage (due à la précontrainte, la température ou la charge) au moment de l'essai. Ce document présente un nouveau type d'équipement d'essai qui, contrairement aux équipements d'essai de pointe, est spécialement conçu pour l'exécution des essais de blocage des ancres. Il consiste en un vérin hydraulique inclus dans un écrou, qui peut être appliqué sur des têtes d'ancrage avec un filetage extérieur. En plus d'une application de charge plus facile et plus efficace, cet équipement offre la possibilité de déterminer directement le verrouillage de la tête d'ancrage. L'article présente les premiers résultats des essais en laboratoire et sur le terrain de ce nouvel équipement.

KEYWORDS: anchor testing, lock-off testing, serviceability of anchors, safety assessment

1 SAFETY ASSESSMENT AND TESTING OF ANCHORS

Anchored structures (see Figure 1) are substantial to geotechnical engineering, especially when it comes to the construction of excavation pits or infrastructure lines such as roads or railways. Because of their benefits (Sabatani and Pass and Bachus, 1999; Ostermayr and Barley, 2002) with respect to the construction of retaining structures, the support of building pits or the stabilization of slopes, anchors offer a wide range of applications. Particularly in the construction of roads in the Alpine region, which are characterized by the alignment, high cuts or the stabilization of embankments are common applications.

During the design life of structures, anchors are subject to load changes in practically all cases. In other words, the anchor load increases or decreases after pre-stressing and lock-off over time. While an increase in the anchor load can be attributed to a changing loading situation (e.g. slope movements, changes in traffic loads, temperature effects), a decrease in the anchor load is usually associated with creep or relaxation of the anchor. Because of this increase in the lock-off load, the (residual) anchor load may exceed the capacity (i.e. structural or/and geotechnical capacity) and consequently failure of an anchor could occur. Soon, a failure of an anchor will unavoidably lead to a redistribution of forces within the anchored structure and the stabilized soil body as well. Due to this force redistribution, individual anchors, anchor parts or structural components could gradually be overstressed, which might result in the overall failure of the structure triggered by the failure of an individual anchor.

Figure 1. Anchored retaining structure along an Austrian highway

Although the design process for ground anchors is regulated by Eurocode 7 (Austrian Standards Institute, 2009), the stability of anchored structures could be negatively affected by the failure of individual anchors, whether because of corrosion (e.g. Burtscher et. al., 2017) or other failure mechanisms. Within section 8.3, Eurocode 7 (Austrian Standards Institute, 2009) defines a special design situation which should consider "*the consequences of the failure of any anchorage*". In practice, however, this design situation is not clearly outlined and therefore barely examined. Additionally, other guidelines (e.g. Spring Singapore, 2010; British Standards Institution, 1994) provide rules for anchored excavation support and walls in general. Basically, these guidelines require sufficient redundancy of the system (in each construction phase) with respect to individual anchor failure and the subsequent force redistribution, without giving more details on the design procedure. Nevertheless, the design situation regarding ground anchor failure is often neglected in practice. This is most likely related to the complex three-dimensional (3D) stress states that occur within the structure when ground anchors fail.

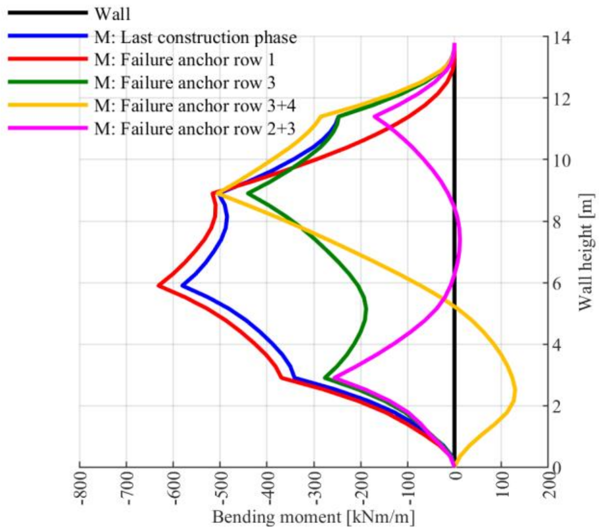

Figure 2. Changes in the bending moment of an anchored structure for different types of failure arrays of anchor rows (Daxer, 2020)

Recently conducted numerical analyses (Daxer, 2020) on the load redistribution of anchored retaining structures subjected to anchor failure clearly indicates a significant influence of anchor failure on the serviceability and ultimate limit state of such structures. The example in Figure 2 shows the bending moment distribution along the wall after the last construction phase (blue line) and its changes caused by the failure of different anchor rows (red, green, yellow and magenta line). While small changes in the bending moment (e.g. failure anchor row 3 – green line) lead to an increase in the wall deformations and thus mainly affect the serviceability of the structure, larger increases in the bending moment (e.g. failure anchor row 3+4 – yellow line) can result in a significant load redistribution within the reinforced concrete (RC) structure. On the one hand, this load redistribution is also reflected in higher deformations of the structure, but it could also lead to an overstressing of the structural components and thus result in a failure or collapse of the structure itself. As expected, larger deformation increments were observed for double-row anchor failure than for single-row anchor failure, with the anchor loads from the failed elements being transferred mainly to the closest anchors.

In agreement with Zhao et al. (2018), evaluations of these 2D analyses indicate that anchor failure close to the wall base and at the top of the retaining wall can be considered especially critical. While a significant decrease in the safety factor could be identified for failure near the wall base, internal forces were negatively affected by failure close to the wall base and failure at the top of the retaining structure, respectively.

2 TESTING OF ANCHORS AND INSPECTION OF ANCHORED STRUCTURES

Regarding the safety assessment of anchors and anchored structures in Austria (e.g. Scharinger et. al., 2017; Schäfer et. al., 2013), the normative rules of EN 1537 (Austrian Standards, 2015) are supplemented by the requirements given within the RVS guidelines (FSV, 2013). To ensure the capability of an anchor or the function of a preliminary anchor system design, three different test types - namely, investigation, suitability and acceptance tests - are performed. During the service life of an anchor, the anchor load can either be observed with an installed monitoring system (e.g. load cell, see Figure 3 left) or lock-off-tests are performed. While a monitoring system, such as the load cells, offers the possibility to survey the anchor load over a longer period (depending on the monitoring interval), a lock-off-test (see Figure 3 right) only determines the load acting on an anchor at the time of the test.

Figure 3. Determination of the anchor load during service life, anchor load cell (left), lock-off-test on an anchor (right)

As mentioned above, performing a lock-off-test solely indicates the anchor force 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 influences into account, however, an accurate statement on the condition of an anchor or its functional efficiency can be made by using a lock-off test.

Research (e.g. Burtscher et. al., 2017; Hunkeler et. al., 2005) and the results of recent safety assessments on anchors have shown that anchors, and especially the anchor head, are often subject to increased exposure to de-icing agents and salt and are therefore highly susceptible to corrosion damage. The detection of such damage using the results of lock-off-tests is usually not possible. In addition to a lock-off-test, endoscopic examinations (Huang-Jiun, 2018) can therefore provide further information on the 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.

Despite the above-mentioned lock-off-testing or the readout of anchor load cells, the structural integrity of the structure itself is evaluated during the safety assessment (Hanel and Prehn, 2006) and inspection. Besides – mostly durability related – damages to an anchor (e.g. Burtscher et. al., 2017; Ebeling et. al., 2013), an increasing number of corrosion damages on reinforcement elements (e.g. Rebhan et. al., 2017; Hunkeler et. al., 2005) can be observed. On the one hand, this type of damage is associated with the altering of concrete and is usually triggered by frost wedging or by design and construction defects (e.g. insufficient concrete cover and honeycombing). On the other hand, an increase in cracks and spalling of concrete elements can also be the result of overstressing or load redistributions caused by changes in the anchor load.

3 ANCHOR TESTING EQUIPMENT

Chapter 1 of this paper discussed the necessity of testing anchors and anchored structures as well as its influence on the safety of these structures. Complementary information on anchor testing and the inspection of anchored structures was given in chapter 2. This chapter gives a brief overview of the state-of-the-art in lock-off-testing of anchors. Moreover, a new apparatus for this type of test is presented.

3.1 *Anchor lock-off-testing – state-of-the-art*

As shown in Figure 3 (right) and Figure 4, the apparatus currently used to perform a lock-off-test on anchors generally consists of a hydraulic jack (hollow piston), a press chair, a temporary pulling head as well as a displacement and load measurement unit. In addition, such a test can usually only be carried out on testable anchors, whereas (mostly) temporary anchors are not designed to perform a lock-off-test.

Figure 4. Apparatus used for anchor lock-off-testing; state-of-the-art solution using a hollow piston

The temporary pulling head provides the force-fitting connection between the anchor head and the hollow piston hydraulic jack. Depending on the anchor type, the configuration of the anchor head and the design of the anchor recess, different types, and designs of the temporary pulling head (anchor bell) are required. When planning or implementing this temporary pulling head and press chair, the geometrical requirements (e.g. the anchor recess or the area of the base plate) and the additional elastic expansion of these components must be considered. In addition, it must be feasible to attach a displacement measurement unit as close as possible to the anchor head. This requirement is necessary to determine the anchor head movement which results in the detection of the lock-off and the determination of the lock-off load. It may also be necessary to consider the deformations of the structure separately from those of the anchor head in order to give a clear statement on the behavior of the anchor.

Currently used methods to perform lock-off tests on pre-stressed anchors depend on heavy equipment, as shown in Figure 4. This procedure mainly uses long stroke hydraulic cylinders, which are also used for the pre-stressing of the anchor. In lock-off tests, only a minor stroke is needed to establish a detectable gap between the anchor head and the anchor plate. Hence, by reducing the large stroke of the currently used hydraulic cylinders to the required stroke, a lightweight and compact design can be realized. Due to these limitations and disadvantages of the currently used test equipment, a new method for static anchor lock-off testing was developed.

3.2 *Proposed design*

The lock-off tests have to be performed at the location of the permanently installed anchors. Therefore, the equipment needs to be carried by hand and has to be applicable to achieve the geometrical constraints to guarantee the accessibility and mounting on the anchor head, which varies between different anchor types. For this reason, a ring-shaped design of a hydraulic cylinder was found to be most suitable.

Figure 5 shows a cross-sectional view of the proposed hydraulic cylinder. The cylinder is attached to the anchor head via an internal thread. To apply the test force to the anchor, a hydraulic piston is actuated by applying a hydraulic pressure of up to 700 bar in the primary chamber. To retract the piston, a pressure of 30 bar is applied in the secondary chamber to overcome the friction of the seals.

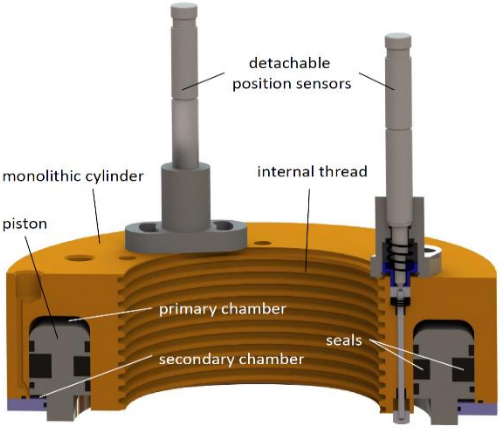

Figure 5. Cross-sectional view of a newly developed anchor lock-off testing equipment specialised for threaded anchor heads

Figure 5 shows schematically the principle. A hydraulic hollow piston, which is designed as a nut, is screwed onto an anchor head, which is used to apply a load on the anchor head until a lock-off takes place. To ensure a force-fitting connection between this nut and the anchor head, an internal thread is used, which offers a direct application of the test equipment on the anchor head, without the need for a temporary pulling head (or other force-fitting equipment) as shown in Figure 4. However, this results in limiting the use of the equipment to one type (or geometry) of anchor head. Nevertheless, using this kind of equipment, a wide range of benefits can be addressed, which range from ease of application due to a reduced weight, to digitalization of the anchor lock-off-test process, to the improvement of the determination of the actual acting anchor load. Additionally, related to the design, a visual inspection of the anchor head, the installed anchor strands and the wedges is possible due to the nut-shaped design of the test equipment.

3.3 *Force and displacement measuring*

In order to use this equipment to perform anchor lock-off tests in Austria, it must meet the requirements of ÖNORM EN ISO 22477-5 (Austrian Standards Institute, 2019) and be capable of performing such a test according to test method 1.

Therefore, three easily detachable LVDT displacement sensors are arranged on top of the hollow piston cylinder in a 120°-symmetry to measure the stroke of the cylinder. Due to the dimensional constraints, an integrated solution was hard to implement. The sensor heads measure the stroke of the cylinder via the stroke of a pre-loaded measuring piston. Additionally, the hydraulic pressure of the primary chamber is measured at the inlet. For the determination of the applied force on the anchor, the measured pressure (p) and the known piston surface (A) are multiplied (see Eq. 1).

$$F = p * A \tag{1}$$

In addition to the classic lock-off test to determine the currently applied anchor force, the concept presented is also able to perform long-term tests such as the determination of the creep rate or the critical creep load for existing anchors using a pressure stabilization.

3.4 *Physical demonstrator*

For the verification and validation of the above mentioned concept, a physical demonstrator was developed and built, which can be used under both, laboratory and field conditions on one type of anchor. To allow for the widest possible range of test objects, an anchor with four strands (ANP-Systems, 2018) was selected. The physical demonstrator was also adapted to the geometrical relationships between the anchor head and the anchor plate to allow the test equipment to be mounted on any possible installation type of this anchor system. The result of this development work can be seen in Figure 6.

Figure 6. Physical demonstrator of a new anchor lock-off-test equipment

The physical demonstrator of the proposed design has a weight of 14.3 kg, making it suitable to be carried by hand and mounted on the anchor head by a single person. Furthermore, the displacement sensors as well as the hydraulic cables are easily detachable and therefore allow for an ergonomic handling of the equipment. The supply and control unit for operating the test cylinder is shown in Figure 9. With the ability to provide a hydraulic pressure of up to 700 bar and implemented force and displacement control capabilities, it allows to run pre-defined test cycles with a high accuracy.

3.5 *Laboratory testing*

The physical demonstrator was tested under laboratory conditions. For this purpose, an anchor test rig (see Figure 7) was used in which the corresponding number of strands and an anchor head was installed. These were attached to the “A-side” of the anchor test rig (as marked in Figure 7) and pre-stressed by a hollow piston jack installed on the “B-side”. This test set-up gave the opportunity to simulate different pre-stressing loads on the system and therefore enabled to validate the displacement measurement unit and the control unit. Some of the results of one test are shown in Figure 8.

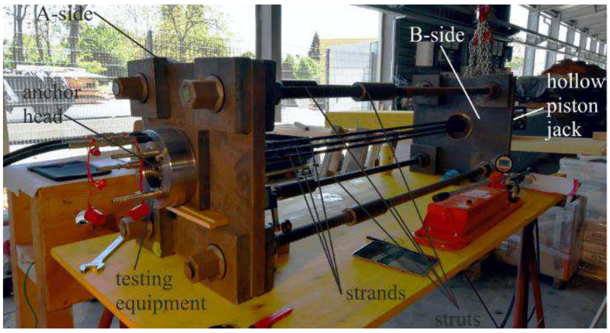

Figure 7. Laboratory Tests using and anchor test rig

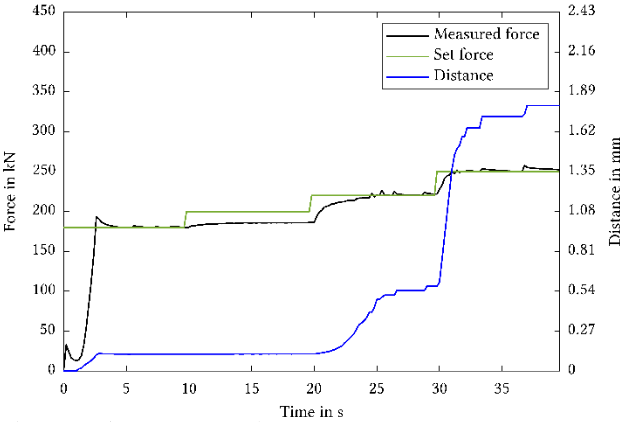

Figure 8. Laboratory test results

In the test, the “A side” of this test rig represents the structure – e.g. a concrete wall or a sheet pile wall – and offers the possibility to perform different test settings such as the installation of various anchor head types or the testing of new remediation methods (see IBG, 2019). While the opposite side of the rig (see B-side in Figure 7) simulates the beginning of the tendon bond length (L_{tb}) of an anchor, the distance between the “A-side” and the “B-side” can be adjusted to represent the tendon free length (L_{tf}) of an anchor. However, given by the geometrical limits of this test rig, only a tendon free length of 2.00 m was considered, resulting in a limitation of the applicable load of 300 kN. This load was applied using the hollow piston jack on the “B-side” of the anchor test rig, followed by a lock-off-test using the equipment described.

In these laboratory tests, the applicability and functional suitability under laboratory conditions could be investigated and validated. Within the scope of a test series, the pre-defined load of a (pre-stressed) anchor installed in the anchor test rig was checked, as exemplary shown in Figure 8. In addition to this functional test, the installation process of the equipment on an already installed and pre-stressed anchor was investigated and a first software for data recording and visualization was tested. Furthermore, the methodology was validated by a state-of-the-art software for anchor testing (Codestruction GmbH, 2020).

4 FIELD TESTING

Besides a scientific approach on an improved design of an anchor test equipment under laboratory conditions, field tests were carried out to verify the function and the usability of the physical demonstrator described in chapter 3.

Therefore, in addition to the laboratory tests, on-site tests of the equipment have been performed (at a construction site), which consisted of a soldier pile wall along with an anchored pillar that was utilized for the construction of a building bit. This pillar (see Figure 9) was anchored by using strand anchors (ANP-Systems, 2018) with a spacing of approx. 2.00 m, an anchor length of approx. 15 m, a bond length of approx. 7 m and an anchor load of up to 400 kN. For scientific purposes, these temporary anchors were equipped with an externally threaded wedge plate to enable the use of the test equipment.

Figure 9. Field Testing of the developed anchor test equipment

The purpose of these field tests was to apply the test equipment under practical conditions. The use of the test equipment on anchor heads manufactured under site conditions was investigated. One of the main focuses was on damaged external threads (which can occur as a result of pre-stressing the anchor). Another focus was on how to deal with a contamination of the anchor heads e.g. by grout washing. Additionally, given by the fact, that the stroke of the test equipment is limited with 5 mm (due to its compact design) the use under site conditions (e.g. manufacturing tolerances, damages and degeneration of the threat of an anchor head) have been validated in this first field tests.

Figure 10. Testing equipment with additional installed displacement sensors (orange caps) in the field tests

By applying the physical demonstrator on three anchor heads, it was shown that the system can accommodate slight deformations of the external thread of the anchor head. In addition, by determining the pre-stressing force of these anchors, a validation of the overall concept could be carried out in order to demonstrate that the concept works under practical circumstances.

Furthermore, the measuring and recording devices as well as the developed site software were examined during these field tests. In addition to the pressure reading (used to determine the test load), the arrangement of the three displacement transducers (see orange caps in Figure 6) and their mode of operation were examined.

5 OUTLOOK

The test equipment presented is to be further developed in the course of the ongoing research project NAT and tested through further laboratory and field applications. In addition to the necessary requirements for a more precise and comprehensive definition of the lock-off-testing and the associated boundary conditions, the application of this method to a variety of anchor systems will be investigated. Currently, the test set-up can only be used for anchors that have an external thread and thus, the test equipment is undergoing a further development for the application on other types of anchor heads. This improvement is required since in Austria, however, a large number of different anchor systems were installed starting in the 1970s. In addition to their different manufacturing processes and designs, they also differ in the geometry and the type of the anchor head. Only a very small number of existing anchors allow the use of the test equipment presented here. However, the equipment can be adapted accordingly by minor modifications, such as the attachment of adapter pieces or the use of special coupling devices. These modifications will enable a variety of anchor systems of different periods and manufacturers to be tested.

However, this development must also be accompanied by an adaptation of the regulations and standards. Currently, there are no (sufficient) technical regulations in Austria which define the scope and implementation of anchor lock-off-testing, the test procedure itself and the break-off criterion to be applied.

6 CONCLUSIONS

Within this paper, the necessity of anchor testing and anchor monitoring has been highlighted. On the one hand, anchored structures are usually built in quite sensitive areas – e.g. traffic lines – and therefore exhibit a high damage potential if such structures fail. On the other hand, different failure modes and causes of damage to anchors can be identified during the inspection and the checkup of anchored structures.

One major part in the safety assessment of anchored structures is the determination of the anchor load. In this paper, a newly developed anchor testing device has been presented. Using this device, it is possible to carry out lock-off-tests on anchors easily, quickly and purposefully and thus detect possible changes in the load-bearing behavior of the anchor or influences on the reliability of the structure.

7 ACKNOWLEDGEMENTS

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