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Behaviour of anchored structures at failure – physical testing and numerical modelling

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ABSTRACT: A large number of geotechnical procedures and methods are based on achieving a sufficient level of safety during the design phase. However, such approaches can only be used to a limited extent for existing structures, as a decrease in safety can generally be assumed. Therefore, damage and its effects must be modelled, and often only limited knowledge of the structure and the underground is available. This topic was analysed with reference to anchored structures, which often suffer considerable damage due to corrosion of the tendons or are affected by changes in earth and water pressure. Due to the lack of suitable modelling approaches and material laws, an experimental representation of a damaged anchored structure was carried out, accompanied by a series of numerical investigations. In this way, an attempt was made to determine the redistribution capability of both subsoil and structural components. The aim of these investigations was to identify methods and approaches for considering damage in the analysis of anchored structures. It became evident that an accurate depiction is only possible to a limited extent, requiring a number of assumptions. Based on this, a simple and practical method was subsequently derived to enable an assessment of damaged anchored structures.

1 ANCHORED STRUCTURES

Especially in Alpine regions, anchored structures (see Figure 1) commonly serve as a cost-effective solution for permanently stabilising deep cuts or steep slopes along infrastructure routes. Ensuring the reliability of these structures throughout their planned service life, which may reach up to 100 years, requires regular condition assessments (FSV, 2013). 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"*. However, past experiences highlight the multifaceted challenges in assessing the condition of anchored structures (e.g. Stadlbauer and Antony, 2019), affecting both geotechnical and structural engineers (e.g. Rebhan et al., 2022). Addressing the effects of damage on the (remaining) bearing capacity is of utmost importance in this context.

Figure 1. Example of an anchored structure along the railway network in Austria.

In general, there is a (current) lack of guidelines and regulations addressing how to deal with defective anchored structures and how damage to ground anchors affects the overall behaviour of the structure. In principle, damage to ground anchors (up to anchor failure) will result in a load redistribution within both the structural elements and the soil body.

Damage patterns range from structural defects such as concrete spalling, corroded reinforcement, and insufficient expansion joints to geotechnical and geological impairments such as deformations, wet-spots, or washouts, and even other specific damage. The latter usually relates to the tension elements and can influence the external load transfer of these elements (e.g., creep), but can also have an impact on the internal load-bearing capacity, as is the case with corrosion damage to the tendons.

2 NUMERICAL MODELLING OF DAMAGED ANCHORED STRUCTURES

As described, anchored structures are subject to aging, which is further exacerbated and accelerated by corrosion due to poor design, construction, or maintenance. This can lead to a reduction in the pre-stressing force or even a loss of function of the pre-stressed grouted anchors. Currently, only limited methods (see Stille, H & Broms B., 1976; Pong et al., 2012; Daxer, 2020; Zheng et al., 2021; Zhao et al., 2018) are available to assess the effects or the monitoring potential resulting from a loss of individual anchors on retaining walls. Although regulations and recommendations (Austrian Standards Institute, 2021) emphasise the need for redundant design for newly constructed structures, no comprehensive method has been described for existing structures to the authors' knowledge. The following section presents a novel approach that integrates numerical methods, high-order constitutive models, and three-dimensional considerations to simulate the effects of anchor failure.

To investigate load redistributions resulting from various anchor failure scenarios within the soil body, the concrete structure, and the remaining anchors, three-dimensional finite element analyses were conducted with the software PLAXIS 3D (Seequent/Bentley Systems, 2024). The three-dimensional finite element model has overall dimensions of 140 m in width, 60 m in height, and 25 m in depth. Prior to the construction of the retaining wall, the site featured a slope inclined at 20° with a height of 14.49 m. The soil body was modelled as a homogeneous stratum without groundwater.

The soil mass behind and beneath the wall was modelled using the Hardening Soil model with small-strain stiffness (Schanz, 1998; Benz, 2007). The concrete structure was idealized with elastic plate elements with interfaces on the earth-facing side. While the tendons were modelled with elasto-plastic node-to-node anchors, the grout bodies were idealized as elastic embedded beam elements. For more details on the parameters of the structural elements, reference is made to Munoz (2024).

The finite element analyses approximate the behaviour of the anchored structure throughout construction, during its normal service state, and under selected anchor failure scenarios. Therefore, a stage-wise installation was modelled, where each anchor in a row is pre-stressed to 500 kN. Anchor failure was simulated by deactivating the corresponding node-to-node anchors and embedded beam elements. The anchor axes are labelled A to E from left to right and the corresponding anchor rows are numbered 1 to 5 from top to bottom.

Figure 2 presents the normalised anchor forces for the failure of the anchors B3, C3, and D3 (failure at the same time). The normalised anchor force represents the ratio between the anchor forces after the final construction stage and after anchor failure. The horizontal axis represents the axis (A to E), while the different lines correspond to the individual anchor rows (1 to 5). Since anchors B3, C3, and D3 failed, only values for A3 and E3 (triangular symbols in Figure 2) are shown for anchor row 3.

For the remaining anchor rows, normalised anchor forces are provided across all anchor positions. The figure shows that the increase in anchor forces is nearly symmetrical in the horizontal direction. Similarly, the vertical distribution is almost symmetrical, as indicated by the nearly overlapping lines for anchor rows 2 and 4, as well as rows 1 and 5. The maximum increase in anchor force of approximately 4% is relatively minor, corresponding to an increase in anchor force of roughly 20 kN.

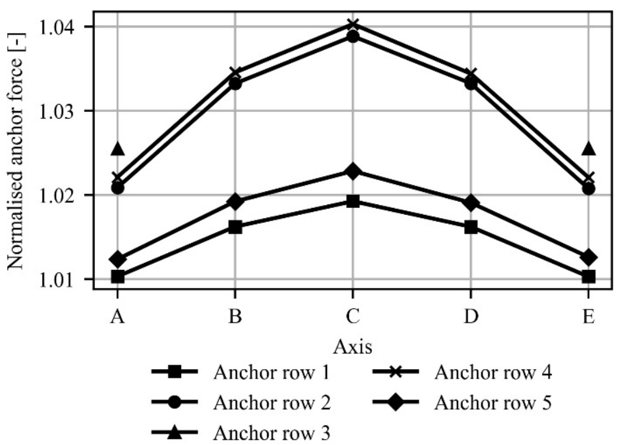

Figure 2. Normalised anchor forces after failure of anchors B3, C3, and D3.

3 MID-SCALE TESTING OF DAMAGED ANCHORED STRUCTURES

Experimental studies investigating the load redistribution due to the failure of structural elements such as struts or ground anchors are rare; some exceptions are, e.g. Stille and Broms (1976), Itoh et al. (2016), Zheng et al. (2021). To overcome this, a test set-up was developed to simulate anchor failure and its effects at a mid-scale size. The test box used is shown in Figure 3 and has internal dimensions of 1.0 m in width, 1.5 m in height, and 3.0 m in length.

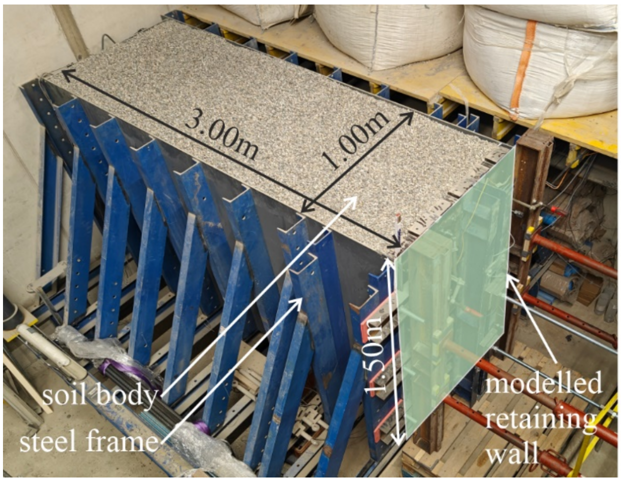

Figure 3. Test box with dimensions.

A robust steel frame integrates the box composed of the base plate, rear wall, and side walls. This configuration allows the construction of a retaining wall in front of the retained soil body (which consists of gravel). To mitigate frictional influences, the base plate, rear wall, and side walls are coated with polytetrafluoroethylene on the earth-facing sides.

The modelled retaining wall comprises nine individual steel elements (Daxer, 2024) with dimensions of 330 mm in width and 490 mm in height, arranged in a 3 × 3 grid. To simulate various types of anchor walls, these elements can either be rigidly connected by bolting or remain unconnected to act as individual elements.

To simplify the test set-up and construction process, while reducing the uncertainties in the model, the ground anchors are simulated by bracing units in front of the wall. These units can be pre-stressed through a connection to the steel frame via cross-beams. The failure simulation involves releasing individual or multiple bracing units to investigate the resulting stress redistribution.

At the transition zones between the wall elements and the bracing units, load cells were installed as shown in Figure 4. K-181 (Lorenz, 2025) cells were used for this purpose, which were additionally equipped with a radial bearing to enable the bracing units to rotate.

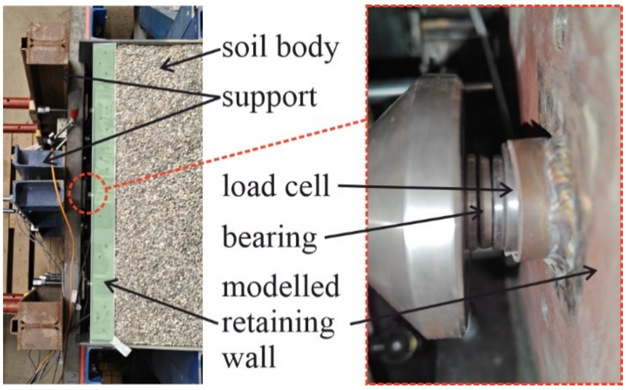

Figure 4. Load cell installation at the transition zone between the wall element and the bracing unit.

Several test series were conducted to investigate how the (complete) failure of an anchor affects the surrounding anchors. One of the results can be seen in Figure 5, where the failure of the central anchor (B2) was simulated. The initial load on this anchor was 5 kN. This figure shows the nine wall elements and illustrates the increase in the measured forces in absolute terms (kN) and in relation to the initial situation (%).

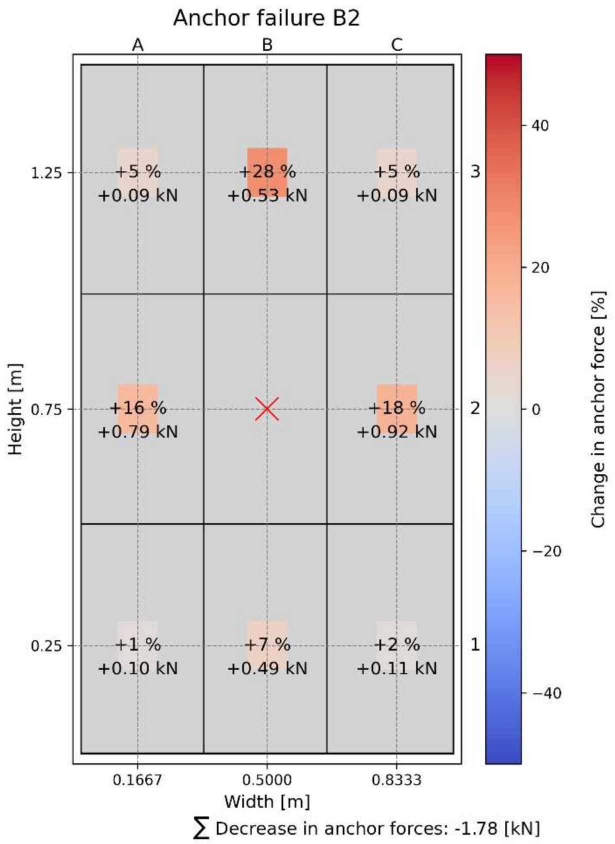

Figure 5. Measured load redistribution due to the failure of the central anchor B2.

What can clearly be seen is that a load redistribution to the surrounding anchors took place. A large proportion (28%) is transferred to the anchor directly above (B3), and an almost equal distribution to the two lateral anchors (A2 and C2) can be seen. Only a small amount of the load is transferred downwards or across the diagonal. Only part of the initial load of 5 kN was redistributed to the remaining anchors, with 1.78 kN absorbed by the soil body or dissipated through friction effects.

4 CONCLUSIONS

The essential role of anchored structures in ensuring the availability and safety of infrastructure routes in Alpine regions emphasises the significance of conducting regular condition assessments. In order to accomplish this interdisciplinary engineering task, knowledge of the effects of damage and the resulting load redistribution is necessary. The investigations presented have shown that, at anchor failure, a significant load transfer to the surrounding tension elements takes place. This has also been demonstrated in a similar way in numerical investigations, yet further improvements are needed to contribute to practical use in structural inspection.

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