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Simulation and numerical back analysis of the load redistribution associated with degrading anchored structures

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ABSTRACT: 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. These assessments are crucial for ensuring the reliability (durability, serviceability and load-bearing capacity) of such structures over their intended service life but represent challenging interdisciplinary tasks for engineers. In particular, assessing the condition of ground anchors and identifying potential damage to these elements is challenging yet of utmost importance for providing a reliable statement on the (remaining) load-bearing capacity. Currently, there is a lack of guidelines and regulations on how to deal with a reduced load-bearing capacity (or even failure) of ground anchors and how such damage patterns affect the reliability of the structure. This paper presents (planned) medium-scale laboratory tests investigating the load redistribution behaviour resulting from anchor failure in defective anchored structures. During the failure simulation, various measurements are performed to determine the load transfer and the load redistribution in the structure itself as well as in the retained soil body. Apart from deformation and force measurements, a novel earth pressure measuring system is introduced. This system allows horizontal loads to be recorded over almost the entire surface of the earth-facing side of the wall. Additionally, preliminary three-dimensional numerical analyses of the laboratory tests are presented. By validating these numerical models against the experimental results for large-scale numerical studies, some future recommendations on how to deal with degrading anchored structures should be given.

1 INTRODUCTION

Anchored structures (see Figure 1) commonly serve as a cost-effective solution for permanently stabilising deep cuts or steep slopes along infrastructure routes, especially in Alpine regions. Ensuring the reliability (durability, serviceability and load-bearing capacity) of these structures throughout their service life, which may reach up to 100 years, requires regular condition assessments (FSV, 2013). 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 to the ground anchors on the (remaining) load-bearing capacity is of utmost importance in this context.

Eurocode 7 (CEN/TC 250, 2013), 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"*. Despite this requirement, there is currently a 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 soil body. This redistribution is generally a three-dimensional problem, but also relies on the structural design (e.g. pilaster wall, element wall etc.).

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). Studies often focus on numerical analyses and the failure of struts (e.g. Pong et al., 2012; Zhang et al., 2018; Choosrithong and Schweiger, 2020), whereas studies on the failure of ground anchors are scarce (e.g. Zhao et al., 2018; Daxer, 2020).

This paper introduces (planned) medium-scale laboratory tests aiming to investigate the stress redistribution resulting from an anchor failure in defective structures. A test box facilitates the investigation by allowing the installation of an anchor supported wall while simulating individual anchor failure. During this simulation, various measurements are conducted to determine the loads and stress redistribution behaviour in the structure, the anchors and the retained soil body. Additionally, wall deformation and anchor force measurements are performed and a novel earth pressure measuring system is introduced, allowing the recording of horizontal loads over almost the entire surface of the earth-facing side of the wall.

Moreover, preliminary numerical studies to investigate the design of the test set-up are presented. Therefore, three-dimensional Finite Element Analyses in combination with advanced constitutive soil models have been performed.

The medium-scale tests serve two main purposes: Firstly, to illustrate the potential of full-surface recording of the horizontal earth pressure acting on the retaining wall. Secondly, the tests should validate the numerical models, which in a next step are used for large-scale applications. Thus, these research activities aim to provide future recommendations on how to deal with degrading anchored structures.

Figure 1: Anchored structure in Austria.

2 PLANNED LABORATORY TESTS

The test box in Figure 2 has internal dimensions of 1.0 m in width, 1.5 m in height and 3.0 m in length. 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 (see Figure 3) 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 a polytetrafluoroethylene film on the earth-facing sides.

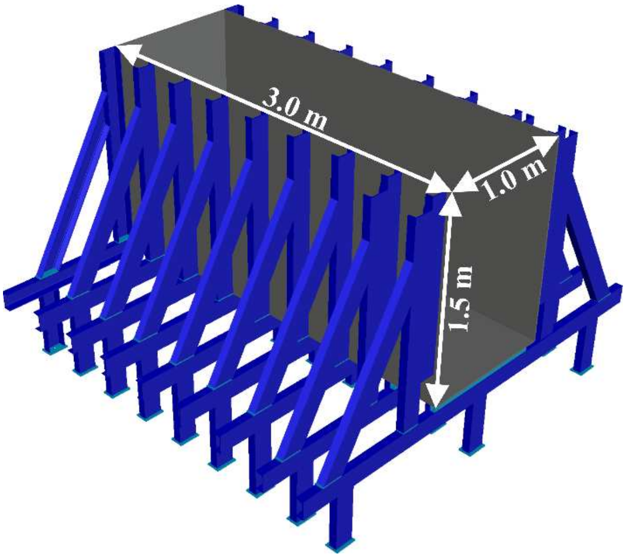

Figure 2: Test box with its dimensions.

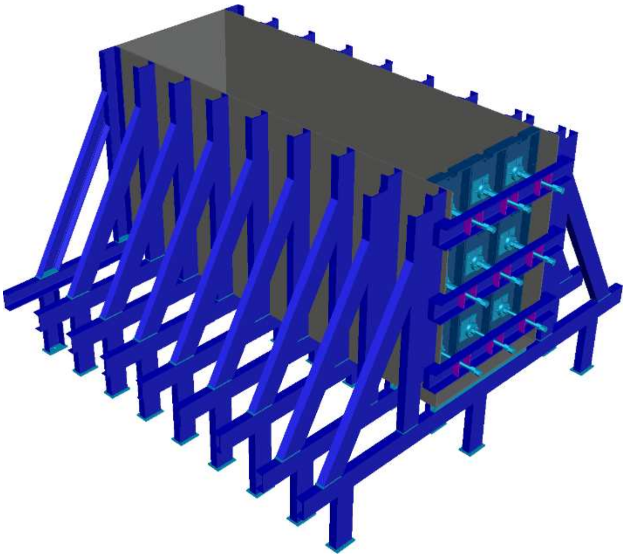

Figure 3: Constructed retaining wall with bracing units.

The modelled retaining wall comprises nine individual steel elements (see Figure 4) with dimensions of 330 mm in width and 490 mm in height, arranged in a 3 x 3 grid. To simulate various types of anchor walls, these elements can either be rigidly connected by bolting (to form a continuous wall) or can be unconnected to act as individual elements. In this context, a soft interlayer can also be introduced between the elements to prevent force transmission. Additionally, the thickness of the elements can be adjusted by adding multiple steel plates, allowing for the simulation of varying wall stiffness.

To simplify the test set-up and construction process, while reducing the uncertainties in the model, the ground anchors are simulated by horizontally installed bracing units (under compressive loads; see Figure 4) in front of the wall. These units (each with a length of approximately 300 mm) can be pre-stressed through a connection to the steel frame via cross-beams. Additionally, a surface load on top of the retained soil body allows for an increase of the stress level within the soil body and the bracing units.

The failure simulation involves releasing individual or multiple bracing units to investigate the resulting stress redistribution. Throughout this process, various measurements are taken to determine the load transfer and stress redistribution in both the structural elements as well as the retained soil body. In addition to measuring the wall deformations and forces (within the bracing units), a novel earth pressure measuring system (see Section 2.1) is introduced.

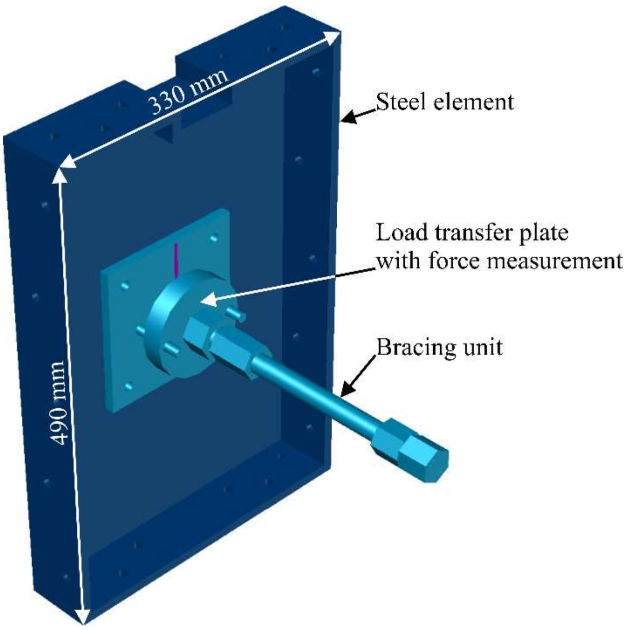

Figure 4: Steel element with bracing unit.

2.1 Earth pressure measurement

To assess the earth pressure and its distribution as well as the potential redistribution at the interface between the wall and the soil body resulting from a simulated anchor failure, each of the nine elements is equipped with a measuring grid (as depicted in Figure 5). This 3 mm thin grid, referred to as sendance-grid, measures 290 mm in width and 450 mm in height, and features 64 pressure sensors. Therefore, a total of 576 pressure sensors enable the measurement of the horizontal earth pressure across almost the entire 1.5 m² surface.

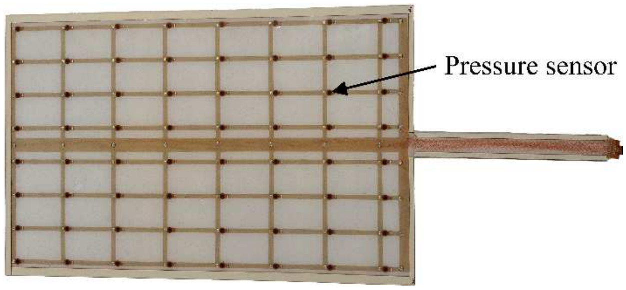

Figure 5: sendance-grid with 64 pressure sensors.

The pressure sensors employed in these studies leverage the piezoresistive effect (Fiorillo et al., 2018) and possess a measurement capability within the range of 25 kPa to 500 kPa. Each sensor consists of a sheet of piezoresistive material with a diameter of 3.6 mm and a thickness of 0.1 mm, connected to solderable electrodes. In order to minimise the number of required supply and readout wires, the sensors are arranged in a grid formation, and each sensor is equipped with a diode to effectively prevent crosstalk. To enhance robustness against environmental factors such as humidity and provide restoring force to the meander wires (Plovie et al., 2018) connecting the electrodes after stretching, the entire sensor grid is encapsulated into an ecoflex elastomer matrix. For calibration, pressure is applied sequentially to each sensor and data pairs of pressure and sensor resistance are then used for interpolation.

In a preliminary study, a square-shaped sendance-grid measuring 200 mm, equipped with 64 pressure sensors, was employed within a cube-shaped steel box with an edge length of 200 mm. The box was filled with sand (0 – 2 mm grain size) and the sensors were placed between the load transfer plate and the soil. The sendance-grid underwent stepwise pressure application up to 75 bar using a hydraulic jack. Figure 6 shows the (inhomogeneous) stress distribution (0 kPa to 200 kPa) for the maximum load step, revealing stress concentrations in the lower left corner. These concentrations most likely arise from imperfections from both the manufacturing process of the steel box and an inaccurate installation of the soil body, compounded by tilting of the load transfer plate. However, as this study was preliminary, aimed to gain initial insights into the behaviour of this new measurement system, no further improvement of the test set-up or extensive data analysis were performed.

There are still some open questions, such as the behaviour of the sendance-grid under shear forces. Although the grid appears to be more robust, it is still unclear if problems arising for similar sensor systems (e.g. Palmer et al., 2009) can be overcome. However, these first tests indicate the enormous potential for full-surface measurements of horizontal loads.

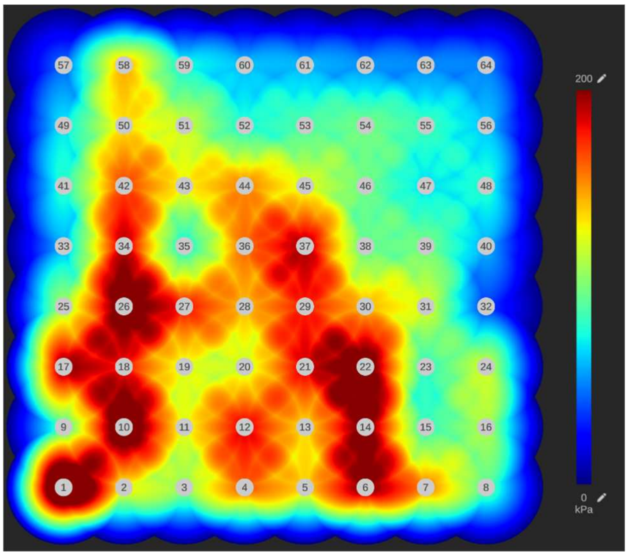

Figure 6: Stress distribution of the preliminary study on the sendance-grid (blue = 0 kPa; red = 200 kPa).

3 NUMERICAL ANALYSES

Preliminary numerical analyses were conducted using PLAXIS 3D, V22 (Seequent/Bentley Systems, 2022) to accompany the design of the test box. The FE model, depicted in Figure 7, uses the Hardening Soil Small model (Schanz, 1998; Benz, 2007) for a realistic representation of the soil body. For this model, the same dimensions as specified in Chapter 2 are discretised. Approximately 94250 (10-noded tetrahedral) elements were employed to discretise the geometry. The base plate, rear wall and side walls are modelled using plate elements (blue surfaces in Figure 7) with their displacements constrained in all directions (green dots in Figure 7). The retaining wall is represented by nine individual plate elements, rigidly connected for these preliminary studies. Each of the nine elements is supported by a fixed-end-anchor, representing a bracing unit (black dots with arrows in Figure 7). A surface load (grey surface in Figure 7) of 200 kPa is applied on top of the soil body to investigate the effects of increasing the stress level. Interface elements have been modelled to reduce frictional influence between the soil body and the box/wall elements. The interface between the test box and the soil was modelled frictionless. In case of the wall, an interface strength equivalent to 2/3 of the friction angle (φ' = 40°) was assumed. To allow for a relative movement between the wall and the box, custom connections (yellow lines in Figure 7) have been employed. The increased flexural rigidity resulting from the design of the wall elements (see Figure 4) is considered through beam elements (purple lines in Figure 7).

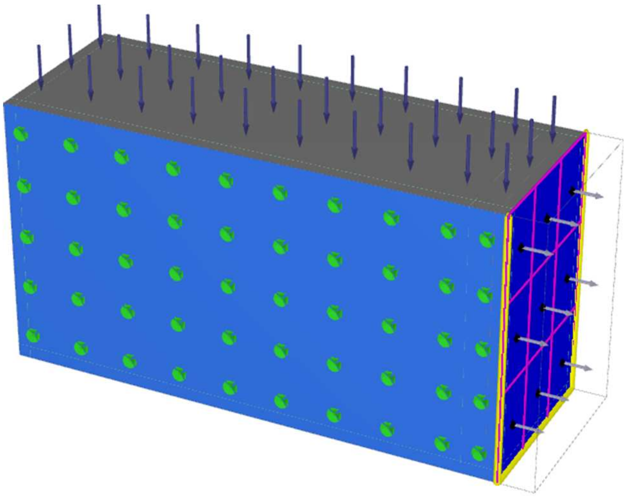

Figure 7: PLAXIS 3D model.

Figure 8 illustrates the results of individual anchor failure in terms of changes in the effective normal stresses σ'_N acting at the interface between the retaining wall and the soil body. The figure compares the stress conditions before (left) and after (right) simulating the anchor failure – specifically, simulating the failure of the centred anchor in axis B. Additionally, the black dots represent the positions of the anchors (bracing units), showing their (compressive) forces and the associated increases (percentage) in the right figure.

For the frictionless box (prior to simulating anchor failure), the computed earth pressure distribution across the width of the wall is (as expected) very homogeneous and increases linearly with depth. However, the application of the surface load introduces some stress concentrations in the upper 15 cm. In the right figure, it becomes apparent that the earth pressure in the area next to the failed anchor decreases significantly and redistributes to other locations, primarily to the (stiffer) areas around the remaining anchors.

The top anchor in axis B shows the maximum increase in anchor force (21%). Additionally, other anchors in the top row experience a 15% increase, similar to the 16% increase observed in the anchors adjacent (left and right) to the failed one. The anchors in the bottom row show the lowest increase, ranging from 3% to 4%. Summing the anchor forces from Figure 8 (left) yields a total of 113.57 kN, compared to the sum of 112.04 kN from Figure 8 (right). Consequently, the difference of the „total“ anchor force is 1.53 kN. Thus, 10.03 kN (11.56 kN - 1.53 kN) from the force in the failed anchor are redistributed to the remaining anchors, while 1.53 kN are transferred (redistributed) to the soil.

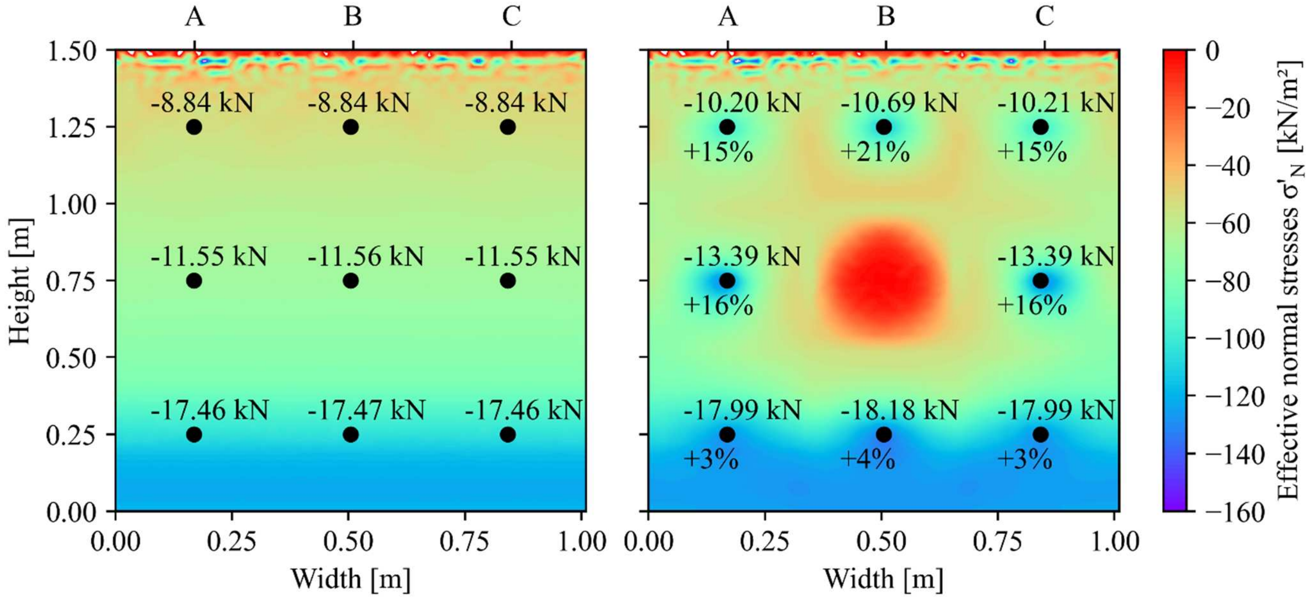

Figure 8: Effective normal stresses σ'$_N$; left: Before anchor failure; right: After anchor failure.

Figure 9 shows the observed earth pressure distributions over the wall height in axes A (dashed line), in the centre between A and B (denoted as A|B; dotted line) and B (solid lines).

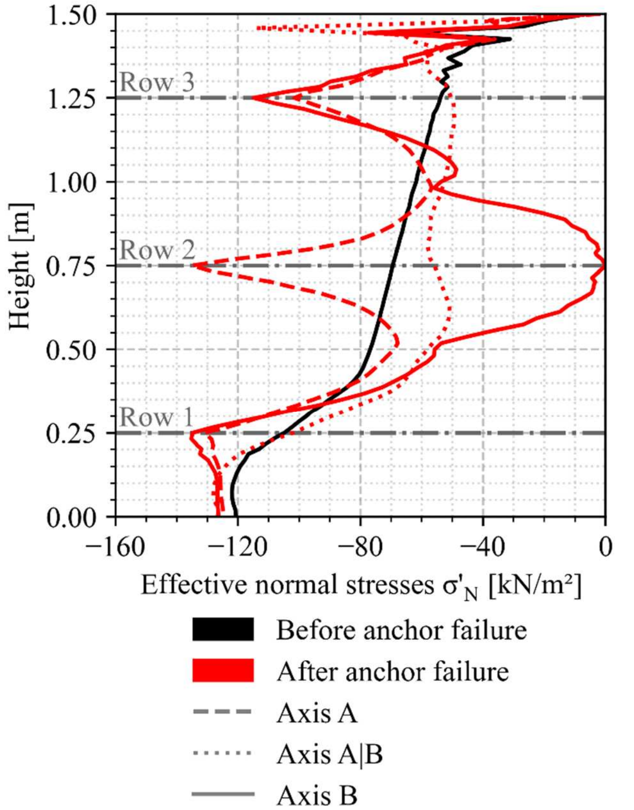

Figure 9: Effective normal stresses σ'$_N$ in the axes A, A|B and B.

4 CONCLUSIONS

This paper addresses the crucial but challenging task of assessing the behaviour of anchored structures. The lack of guidelines and regulations regarding reduced load-bearing capacity or failure of ground anchors underscores the need for comprehensive research. The planned medium-scale laboratory tests described aim to investigate the load and stress redistribution resulting from anchor failure(s) in defective structures.

The proposed sendance-grid for measuring horizontal earth pressures represents an innovative approach, enabling nearly full-surface measurements and offering significant potential for understanding the load distribution and load redistribution. Despite some open questions, such as the behaviour of the grid under shear forces, this system promises to improve the accuracy and reliability of measurements for various geotechnical engineering applications. For example, the sendance-grid has the potential to provide experimental insight into the development of normal stresses along the shaft of test piles during static pile load tests. To date, this research aspect has been addressed by means of parametric studies based on numerical methods, notably without validation from experimental results (Granitzer et al., 2022).

Preliminary numerical analyses illustrate the potential of the planned tests to simulate anchor failure and investigate the resulting redistributions. The observed stress redistributions around the failed anchor and the associated changes in anchor forces provide valuable insights into the behaviour of the structure under simulated failure conditions.

This research does not only aim to contribute to the understanding of load and stress redistributions in defective anchored structures, but also seek to provide recommendations regarding the management of such structures. By validating numerical models using the test box measurements, it is believed that the numerical analyses can be used for large-scale applications. Thus, this work endeavours to bridge the existing gap in guidelines and regulations, offering insights that improve engineering practices related to the assessment and maintenance of anchored structures.

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