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Tactile Pressure Sensors to analyse Anchor Wall Behaviour in mid-scale Experiments

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ABSTRACT: Material ageing, such as corrosion of reinforcements or damage to geotechnical tension elements, can lead, among other effects, to load redistribution mechanisms at the interface of structure and the adjacent soil. These mechanisms are difficult to capture, as analytical calculations are not practical and three-dimensional numerical simulations, utilizing advanced constitutive laws require sufficient monitoring data to validate the calculations. Consequently, it is difficult to determine the reliability of damaged structures. To improve existing knowledge in this field, a test setup simulating an anchor wall was developed, to provide calibration data for numerical studies and to evaluate load redistribution mechanisms at the soil-structure interface in general. In this context, newly developed Tactile Pressure Sensors (TPS) were tested for their suitability as an additional monitoring tool, to record changes in compressive stress at the interface and consequently, to complement conventional monitoring devices used for deformation and force measurements. Such TPS can enable the visualization of an approximate compressive stress distribution across the entire interface, utilizing 576 individual sensing elements over an area of 1.50 m² to monitor changes in stress. Thus, additional data is provided to improve the evaluation of load redistribution mechanisms and to be used as validation data for numerical models.

KEY WORDS: tactile pressure sensors, piezoresistive sensors, geotechnical testing, experiment, validation.

1 INTRODUCTION

Anchored retaining structures are commonly used as an economical solution for the long-term stabilization of steep slopes or deep cuts along infrastructure routes. To ensure their reliability - encompassing durability, serviceability and load-bearing capacity - regular maintenance and inspection is essential throughout their intended service life [1][2]. These inspections often reveal damage, and in some cases, failure of the metallic tension elements. Corrosion represents the most significant challenge for pre-stressed ground anchors and reinforced concrete structures in general, which can lead to significant damage (up to failure) of the tension elements, affecting the load-bearing behavior of the structure. This may lead to a redistribution of forces, both within the retained soil and the structure itself. This redistribution can ultimately result in the failure of additional (adjacent) ground anchors and unexpected deformations of the retaining structure.

Currently, engineers are dealing with limited guidelines and regulations to assess such effects, caused by damage or failure, impacting the load-bearing capacity and, consequently, the safety of the structure. In this context, complex three-dimensional numerical models, regardless of their resource intensity, are inevitable to provide a reliable safety assessment. Such models are essential to determine the probability of critical failure mechanisms and their location within the soil body, which is mandatory for many existing anchored structures. To provide valid calculation data, these numerical models must be calibrated accordingly and therefore require a suitable amount of measurement data, e.g. on deformations and stresses. As such data is usually not sufficiently available for existing structures, it is necessary to evaluate the expected behavior of the structure in the event of an anchor failure differently. For example, in mid-scale experiments, which combined with numerical models allow for an upscaling of the results to come up with recommendations concerning the assessment of existing structures possibly at risk. Based on this consideration, it would also be highly beneficial to consider an appropriate monitoring concept for future structures.

This paper describes a mid-scale test facility for simulating anchor failures and investigating the resulting load redistribution effects in the soil body and at the soil-structure interface. The studies provide more information on the sensitivity of anchored structures to tension element failure and help identify critical areas for potential future monitoring. To improve the quantity and quality of data obtained from the experiments, a newly developed measurement system is presented. These, so called Tactile Pressure Sensors (TPS), should enable an approximate two-dimensional recording of the stress field at the soil-structure interface and thus provide an extended amount of data for the calibration of numerical models and the interpretation of the experiment itself. The content includes an initial assessment of the capabilities of the TPS mentioned. Accordingly, an investigation of the sensors' performance under geotechnical constraints, considering the boundary conditions in the test setup, took place. Additionally, first results for the simulation of an anchor failure, monitored by classic load cells and displacement transducers, are presented.

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2 TACTILE PRESSURE SENSORS

Standard earth pressure cells only provide a punctual recording of the compressive stress at the soil-structure interface, whereas the pressure distribution itself ideally needs to be monitored in a two-dimensional way. Thus, the evaluation of the problem in its entirety requires an alternative measurement system which provides a higher measurement resolution and consequently a better database to examine load redistribution effects due to anchor failure.

Tactile Pressure Sensors have been used in geotechnical experiments since the 1990s [3] and have been part of many experiments and publications since [4][5][6]. Due to their low-profile architecture and the amount of measurement points per area, they can be generally applied to determine the stress distribution between two structures. In geotechnical engineering such measuring equipment is used to determine the soil-structure interaction or the load transfer between two soil bodies in various setups, especially in geotechnical centrifuge testing [7][8]. According to previous experiences made with such sensors, the technology seemed to be suitable for the given task. Unfortunately, well-known TPS, although applicable in terms of metrological performance, did not meet the requirements of the planned testing series. Mainly caused by limitations in terms of geometry, robustness and high costs. Thus, it was necessary to find an alternative system which better addresses the requirements resulting from soil-structure interaction within the mid-scale experiment.

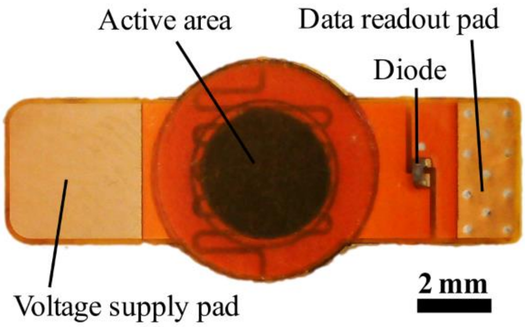

Figure 1. Sensor design.

The chosen TPS, developed by sendance GmbH, leverages the physical principle of piezoresistivity for pressure detection. The core sensing element consists of a circular 0.1 mm thin layer of piezoresistive material, with a diameter of 3.5 mm, that electrically connects two electrodes. The simplified sensor design is shown in Figure 1. Under compressive stress, the sensor's electrical resistance diminishes from values exceeding MΩs to tens of kΩ. During measurement, a 3.3V supply voltage is applied to one electrode. The other electrode is connected to a microcontroller with a 12-bit Analog-to-Digital Converter (ADC) and a 20 kΩ reference resistor connected to ground (GND). This voltage divider configuration allows the microcontroller to measure the voltage change resulting from the sensor's resistance variation, caused by the compressive stress acting on the piezoresistive material. To ensure a more uniform pressure distribution on the piezoresistive material and enhance the system's robustness, the TPS and its wires are encapsulated in a silicone coating, achieving a total thickness of 1 mm. To compensate for the production variability of sensors and to achieve more accurate readings, each sensor is individually calibrated. The sensors are usually calibrated by 36 load-steps spread over the range of 0 to 500 kPa or lower, depending on the area of interest. At each load-step, the corresponding ADC value, and the acting compressive stress in kilopascals are recorded. These calibration data pairs each define one calibration point, which collectively form the calibration curve.

This data is subsequently stored within the readout electronics, and linear interpolation between the individual calibration points is used to determine the pressure corresponding to any measured ADC value not directly provided by the calibration points themselves. As the devices are tailor-made, the sensors can be arranged in any formation, limited only by the space required for wiring. Figure 2 shows a TPS example with a 4x4 grid formation, used for small-scale testing to evaluate sensor performance. In general, each sensor row (horizontal) shares one supply line and each column (vertical) shares one readout line to minimize wiring amount and complexity. Only one supply and one readout line are active at any given time, allowing for a sequential readout of the sensors with a rate of up to 150 Hz using Bluetooth®. To prevent crosstalk between sensors, which means they would influence each other's readings, a diode is added to each sensor.

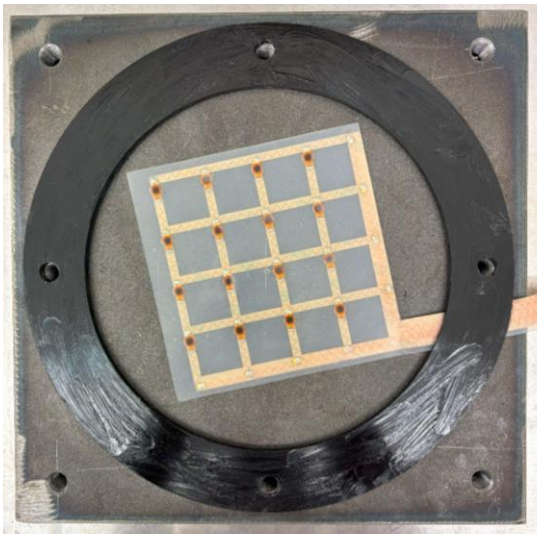

Figure 2. TPS for performance testing (small-scale), placed on pressure chamber baseplate.

The accuracy of the TPS is influenced by several factors, including the homogeneity of the applied pressure, the utilized pressure range, and the duration of the applied load. Consequently, the accuracy of the system must be determined within the field of application.

To evaluate the performance of the sensors under geotechnical conditions and to confirm the suitability of the TPS for the intended application within the mid-scale tests, some information on performance evaluation is provided in the following chapters. The focus is on the precision (repeatability) of the system's measurements, including soils.

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3 TEST SETUP & METHODS

Mid-scale model tests on anchor failure are conducted in a test box (see Figure 3) with dimensions of 1.00 m (width), 1.50 m (height) and 3.00 m (length). Within the test box, a retaining wall is constructed using nine individual steel elements arranged in a 3 x 3 grid, rigidly connected in both horizontal and vertical directions. The retaining wall is backfilled with gravel (4/8 mm rounded grains). To simplify the assembly process, the ground anchors are represented by horizontally installed bracing units (struts) placed outside the soil body. These struts, which are subjected to compressive loads, rest on a horizontal abutment in front of the retaining wall. Each strut can be individually pre-stressed by applying torque, allowing for different test configurations. Individual struts are released to observe the system's response during the failure simulation. Force measurements, using load cells, are taken at each of the nine contact points between the retaining wall and the struts to capture the resulting force redistribution. Additionally, displacement transducers were installed to monitor wall deformation. These measurements have not been incorporated into this study, as the primary focus lies on the load redistribution.

Figure 3. Test setup during assembly.

Figure 3 illustrates the test set-up during the assembly process. The labelling scheme is as follows: from left to right, the axes are labelled A to C, while from bottom to top, the anchor rows are designated 1 to 3. For example, the central anchor is labelled B2. Additional details on the set-up can be found in [9].

Although the change in force, measured by the installed load cells, already allows some interpretation of the mechanical processes during the experiment, providing more data, to e.g. validate a numerical model for post-processing purposes, would be highly beneficial Furthermore, more data would be crucial to come up with a comprehensive conclusion about the occurring load redistribution effects.

Consequently, it was decided to integrate the previously described TPS into the testing facility, positioned at the soil-structure interface (see Figure 3), to analyze the acting compressive stresses. For this purpose, a sensor arrangement was designed which allows for 64 sensors on each of the nine individual steel elements (see Figure 4) which results in 576 individual measurement points evenly distributed over the entire back-side of the retaining wall, covering an area of 1.50 m². Compared to the force measurements with just nine load cells, the TPS enables an approximately two-dimensional analysis of the stress field at the soil-structure interface and therefore allows a detailed interpretation of spatial mechanisms caused by the load redistribution within the soil body (e.g. arching effects) due to anchor failure.

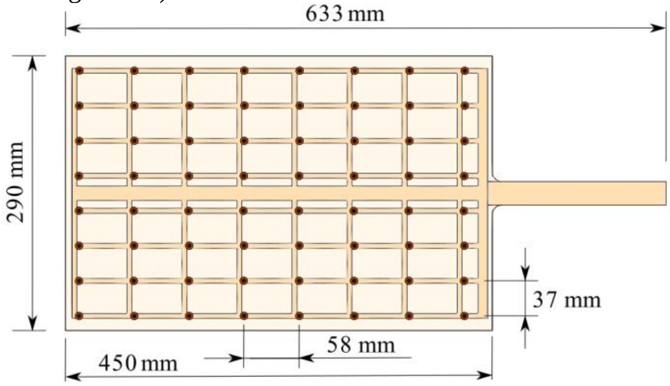

Figure 4. TPS configuration for mid-scale test.

The TPS system must be calibrated and tested in the geotechnical environment to obtain accurate sensor readings within the mid-scale model. While the entirety of the grid is encapsulated in silicone, the sensors are exclusively present in specific regions of the sensor grid, which causes the TPS to be inhomogeneously stiff. Areas where sensors are situated exhibit a higher stiffness than areas without any sensors present. Thus, applying stress to the TPS by e.g. a stiff loading plate doesn't allow for an accurate calibration or repeatable testing. Single-point calibration/testing on the other hand, with e.g. a load-stamp, would result in a significant testing effort. In addition, the use of a load stamp would prevent reliable repeatability, as the stamp would have to be positioned at the same spot on the sensor (diameter = 3.5 mm) each time, which cannot be guaranteed with a manual process, as was observed in preliminary studies.

Therefore, the testing and calibration is performed using a calibration chamber, designed to apply air pressure to the sensor grid. This approach satisfies the need for an evenly distributed compressive stress on the system (isobaric stress state), which is not affected by any inhomogeneities in the system's stiffness, which could possibly lead to a misinterpretation of the applied stress. Additionally, air pressure is well controllable, and the calibration steps can be chosen flexibly. Concerning measurements incorporating soils, a membrane was introduced to enhance the calibration chamber's suitability. This advancement allows air pressure, distributed by the membrane, to act across the soil grains, onto the TPS. This prevents additional air pressure being applied to

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the system, which could act between the grains, although all loads should only be transferred by the soil grains themselves.

First tests to evaluate the TPS' accuracy were performed under load application by air pressure only - without any soils incorporated - to assess the sensors' performance under fully controllable and repeatable conditions. This ensured benchmark measurements that reflect the pure performance of the TPS in the pressure chamber, without the effects of uneven loading from soil grains, etc. This data can later be used for comparison with measurements of the TPS in soils to put the sensors' performance in different environmental conditions into perspective.

Subsequently, the systems suitability for application in the geotechnical environment was evaluated. Thus, soil samples with different grain size distributions (GSDs) were prepared to investigate the maximum grain size (D_{max}) suitable for the TPS, as well as to generally analyze differences in performance due to the GSD. Sample preparation aimed for very narrow GSDs to isolate the critical grain size. Furthermore, angular grains were utilized for the tests, as these may cause more distortion in the sensor readings compared to round grains and thus represent a 'worst-case' scenario in terms of sensor performance and robustness, which provides the most information concerning the overall performance of the TPS.

4 FIRST TESTS AND RESULTS

Preliminary studies concerning the TPS performance are shown below. All described tests were executed in the previously mentioned pressure chamber, using a 4x4 grid (16 sensors), which is illustrated in Figure 2. To characterize the TPS for the use under geotechnical constraints, the systems accuracy must be investigated in terms of precision and trueness, according to [10]. The outlined experiments mainly focus on the precision of the TPS, also defined as the repeatability of measurements. In addition to the studies concerning the TPS, initial experiments simulating anchor failure within the mid-scale test facility were carried out. The results of these tests are also presented and discussed below.

4.1 Preliminary studies - TPS

In the following, the term 'representative sensor' always refers to one and the same sensor on the grid to ensure comparability of different measurements. The presented measurements were carried out by applying air pressure on the sensors.

First, all 16 sensors were calibrated, according to the calibration procedure, described in chapter 2. Afterwards the first test series was performed, which consisted of four individual tests with 10 load cycles – loading and unloading – of the entire sensor grid.

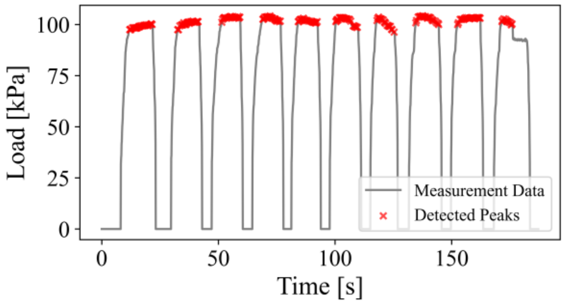

Figure 5. Recorded load-cycle for a representative sensor.

Figure 5 illustrates the recorded measurements for a representative sensor at a maximum pressure of 100 kPa, for one individual test.

Peak values were detected and marked with a red cross. Determining the mean value of the peak values per load-cycle, results in 10 measurements per sensor, per test, which corresponds to 160 values for the entire TPS. To simplify these results, only one mean value was calculated per sensor and test across all peak values. Subsequently, an average value was calculated from the measurements of all 16 sensors, representing the entire system, assuming a smeared performance as relevant. This approach represents an evaluation of the overall performance of the TPS, while studies on individual sensors are presented later.

Table 1 shows the mean value $\bar{p}$ (measured compression stresses) for each individual test, as well as the global mean value μ, the standard deviation σ, and the relative error δ across all tests, at certain pressure levels PL, for the entire TPS.

Table 1. Preliminary evaluation of TPS performance

PL [kPa]	$\bar{p}$ [kPa]	μ [kPa]	σ [kPa]	δ [%]
100	98.56 91.20 100.31 95.18	96.31	4.01	3.69
200	195.30 193.32 199.86 194.58	195.27	2.85	2.37
300	290.73 297.81 294.72 298.79	295.51	3.42	1.50

First tests showed good results with a maximum relative error of 3.69 % at a pressure level of 100 kPa as well as 2.37 % and 1.50 % at 200 and 300 kPa respectively. Furthermore, the calculated standard deviations show a good consistency of the measurements.

To extend these first investigations, additional studies were conducted. As part of these studies, predefined load steps were performed and the corresponding ADC outputs from the TPS were analyzed. This allowed for a more descriptive interpretation of the sensor performance and avoided any distortion of the measurements due to linear interpolation and statistical processing of the test results. Thus, six tests were performed with load steps evenly distributed over a range of 0 to 300 kPa, resulting in one curve per sensor per test (run).

Figure 6 shows the measurement results for a representative sensor for all six runs labeled Run 1 to Run 6. The results can be considered promising as the curves show good repeatability, which is consistent with the results shown in Table 1. Especially at higher pressures, from 200 kPa onwards, the agreement of the individual measurement points is good, while at pressures below 100 kPa a certain deviation can be observed, which, however, is not critical. These results agree well with the previous observations, which confirms the initial assessment of the overall TPS' precision.

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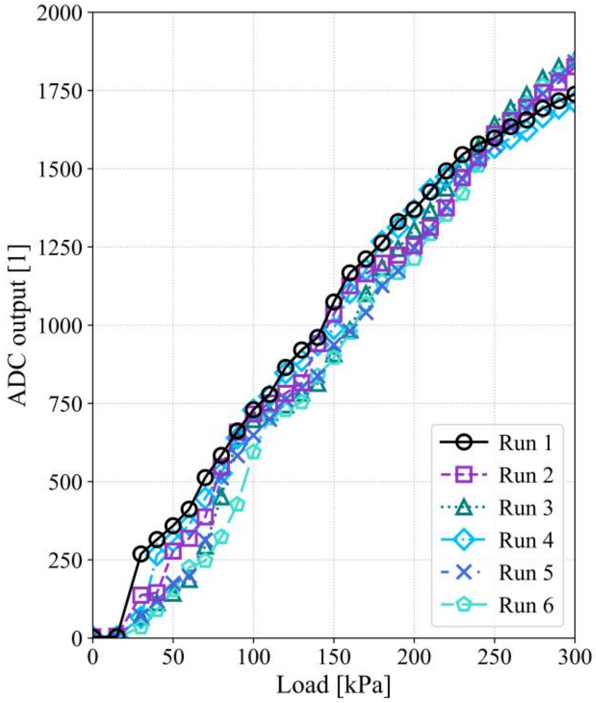

Figure 6. Precision test without soil for a representative sensor.

Proceeding with the test series, the TPS' performance was evaluated incorporating soils, simulating the application of the system at the soil-structure interface. The aim of these investigations was to evaluate the influence of soils with different maximum grain sizes on the accuracy of the sensors and to compare these findings with the results shown in Figure 6. To allow for comparison between the different test series the following studies were performed in line with the previously described procedures, apart from including a membrane, as explained in chapter 3. This test series should allow a statement related to the maximum tolerable grain size without a drastic reduction in sensor performance, which is considered mandatory to evaluate the applicability of the TPS in the mid-scale experiments. All tests were carried out with the same TPS system used previously.

Five samples with different grain size distributions were utilized, allowing a continuous increase in D_{max}. The samples were mainly coarse grained (angular grains) and contained little to no fine grains. All samples were artificially prepared by sieving a large soil sample into different GSDs, which ranged from 0/0.8 mm, with D_{max} = 0.8 mm, to 2/4 mm, with D_{max} = 4 mm and D_{min} = 2 mm.

Figure 7 illustrates the results for this test campaign, comparing a representative air pressure curve (Run 1), labelled as 'Air', from Figure 6, with five curves including soils with different GSDs. The curves differ in the lower load range, up to ~ 100 kPa, whilst the repeatability seems to improve with pressure levels above 100 kPa. Both effects have also been identified in the previous tests.

The results show good repeatability, and the influence of grain size appears to be negligible up to a D_{max} of 2 mm. Though, grain sizes above 2 mm seem to cause a change in sensor performance. Curve 2/4 (orange) shows significantly lower ADC outputs, from 150 kPa and onwards, than all other curves. In general, it is assumed that the silicone coating of the TPS acts like a thin load distribution layer, which provides good sensor performance if $D_{max} \leq 2$ mm, as these measurements agree well with the air pressure reference curves. However, the load distribution effect of the silicone doesn't appear to be suitable for dealing with larger grain sizes.

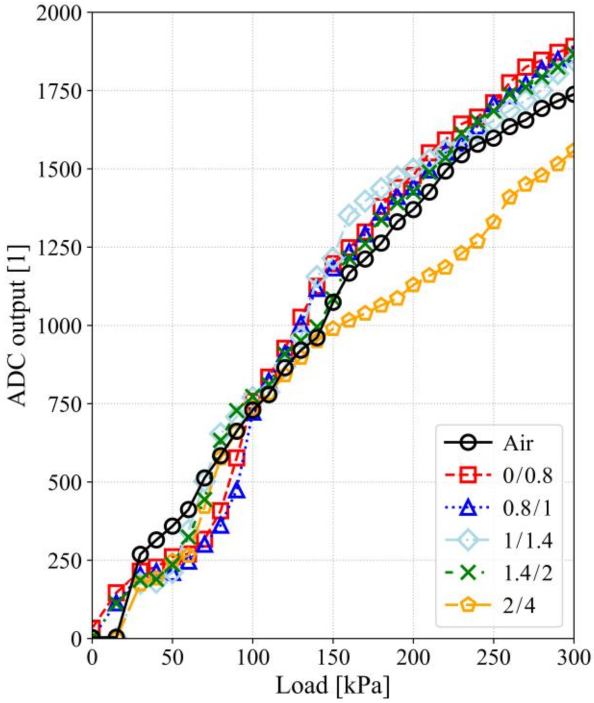

Figure 7. Influence of grain size (angular grains) on sensor curve for a representative sensor.

To summarize, the preliminary investigations on the sensor performance have shown the potential of the system for its application in the geotechnical environment. Soil with a grain size below 2 mm does not seem to negatively affect the sensor performance. However, it will be necessary to implement some kind of load distribution layer to improve the TPS for the application in larger grain sizes. As the material used in the mid-scale tests has a grain size above 4 mm, it is essential to adapt the TPS accordingly. This allows its application within the setup and enables the collection of more spatial information on load redistribution mechanisms.

4.2 Mid-scale test facility

Figure 8 and Figure 9 present the initial evaluations of anchor failure simulations, conducted by setting the compressive load along individual struts to zero. Both figures show the modelled retaining wall, with the steel elements arranged in a 3 x 3 grid, following the labelling scheme from Figure 3. The failed anchor is marked with a red cross, and the changes in load, both in percentage and absolute terms, are shown for all remaining anchors. The failure simulations started from nearly identical stress states, with anchor rows 1, 2 and 3 pre-stressed to approximately 7 kN, 5 kN and 2 kN, respectively.

Figure 8 illustrates the first failure simulation, which assumed the central anchor B2 to fail. The results clearly show that the load redistribution following the failure of anchor B2 is almost symmetrical. In absolute terms, the majority of the redistributed load is transferred to the adjacent anchors on the

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left (A2) and right (C2), rather than those above (B3) or below (B1). The largest increase, considering absolute terms, occurs at anchor A2, which increases by 0.95 kN, a 20% rise from its pre-stressing load of about 5 kN. However, in percentage terms, the largest increase is observed at anchor B3, which experiences a 24% increase from its pre-stressing force of approximately 2 kN (equivalent to an absolute increase of 0.52 kN). The anchors located in the corners (i.e. A1, C1, A3 and C3) play a minor role in the load redistribution.

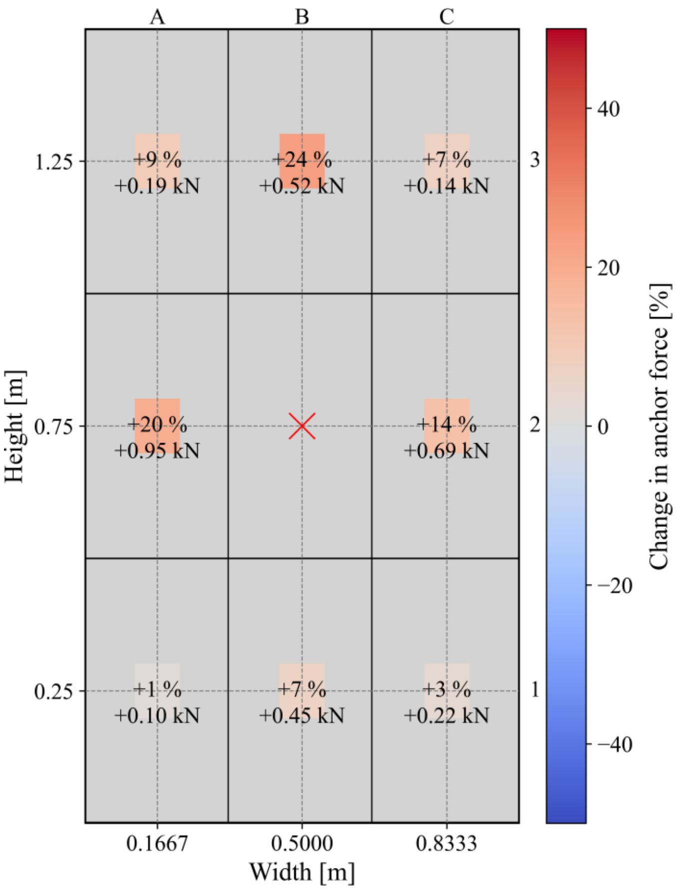

Figure 8. Failure simulation of anchor B2, adapted from [11].

In contrast, Figure 9 shows that the load redistribution following the failure of anchor A2 is more complex. The majority of the redistributed load is again transferred to the adjacent anchor on the right (B2), which increases by 1.23 kN, corresponding to a 28% increase from its pre-stressing load. However, anchor C2 experiences a significant load decrease of 1.04 kN, or -24%, from its pre-stressing load. Similar to the load redistribution pattern of the failed anchor B2 (see Figure 8), the maximum percentage increase occurs at the anchor directly above the failed element. In this case, anchor A3 shows a 50% increase from its pre-stressing load, which corresponds to a 0.60 kN increase.

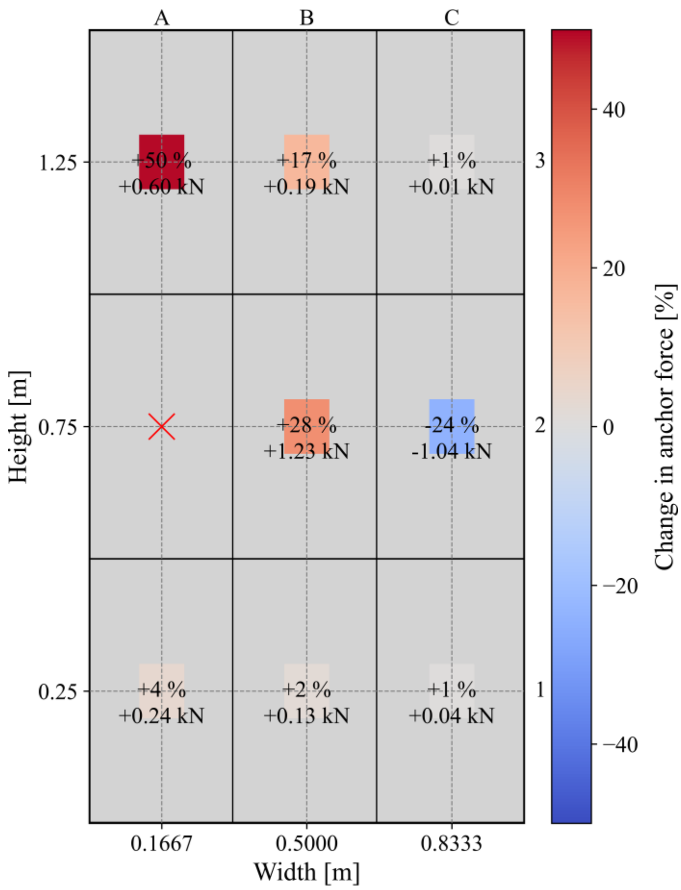

Figure 9. Failure simulation of anchor A2, adapted from [11].

As the measurement concept of the previously described tests only allowed for the evaluation of total force acting on the nine steel elements, future experiments need to conduct additional instrumentation to evaluate load redistribution effects in its entirety. It is therefore planned to integrate 576 Tactile Pressure Sensors to analyze the compressive stress distribution at the soil-structure interface. This will not only allow the experiments to be evaluated in a comprehensible way but also provides enough data to calibrate a numerical model of the setup. and to perform a robust back analysis. As a result, parameter and sensitivity studies can be carried out within the numerical model. Additionally, it is also possible to adjust the model scale if required.

5 CONCLUSIONS & SUMMARY

Preliminary tests of the presented Tactile Pressure Sensors (TPS) showed good sensor performance in terms of precision, with a maximum relative error of 3.69 % and a standard deviation of 4.01 kPa at a compressive stress of 100 kPa and even better results at 200 and 300 kPa. Based on these results, the TPS was further tested with soils to evaluate the applicability of the system for the planned experiments. On the one hand, these tests showed promising results, as soil grains up to a size of 2 mm could apparently be handled very well. On the other hand, larger soil grains unfortunately led to distortions in the measurements. As a result, in its current state, the stand-alone TPS did not appear to be suitable for the mid-scale experiments with 4/8 mm rounded grains. Consequently, simulations of anchor failure in the mid-scale test facility were not yet carried out as planned, which meant that first trials were

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monitored with only nine load cells. The performed simulations led to the observation of the following load redistribution mechanisms.

Loads released by a failing anchor were mainly redistributed to the adjacent anchors, while others did not show significant increases in load. Furthermore, some anchors experienced significant changes in their pre-stressing loads. Considering the design process of such retaining structures and the determination of the required bearing capacity of the anchors, increases in anchor force of up to 50 %, as observed, may be critical for the safety assessment of such structures.

Although these experiments have provided important information on the behavior of the anchor wall in the event of anchor failure, the test setup had some limitations that need to be addressed. In particular, the presented approach of monitoring experiments with only nine load cells considerably limits the possibilities for interpreting the tests, as the amount and resolution of measurement data is not sufficient to spatially evaluate load redistribution effects. Furthermore, these effects should ideally be evaluated in terms of stress, not force, at the entire soil-structure interface to observe mechanisms such as e.g. arching effects within the soil body. Although this cannot be achieved completely, even with the presented TPS, the approximate area coverage with 576 sensors is a considerable improvement compared to point measurements and may allow for an assumed stress field.

Though the Tactile Pressure Sensors were not yet applicable, further trials are planned to prepare them for the upcoming experiments. To reduce the TPS' sensitivity to grain size, the concept of an additional load distribution layer between the TPS and the soil will be focused. For this purpose, a variety of elastomers with different thicknesses and stiffnesses will be considered. The aim of these studies is to identify an elastomer which offers good load distribution effects if applied to 4/8 mm rounded grains but also allows for a good measurement resolution. Additionally, it will be important to gain more knowledge concerning the sensors' performance, not only in terms of precision but also concerning trueness. Consequently, new testing rigs are in progress to allow for an appropriate testing procedure. As the TPS is fully characterized and the necessary load distribution layer is identified, the mid-scale testing will continue as planned.

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