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Insight into interaction effects between reaction systems and test piles during static load tests

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ABSTRACT: During the loading procedure of static pile load tests the reaction system counteracts the movement of the tested pile. This bracing effect results in an overestimation of both, the pile stiffness and the measured pile resistance. Although this phenomenon is widely recognized by execution standards it lacks physical evidence. In this context, the present work reports lessons learnt from two large-scale field tests that aim to provide insight into the underlying mechanism. Moreover, the in-situ measurements serve as basis for calibrated numerical models. From the experimental results it can be inferred that a clear relationship between vertical pile load and horizontal pile shaft pressure exists. This holds true for both micropiles and Ductile Piles tested in tension. This observed tendency is supported by numerical studies. Moreover, it is found that the bracing effect on the normal stress mobilization distributes in a non-constant manner across the pile shaft.

1 INTRODUCTION

Considering their cost-effectiveness and simplicity in installation, micropiles and Ductile Piles have found wide application in geo-engineering problems with difficult access and poor ground conditions (Abbas et al., 2021; Dziwok et al., 2023). Use cases include, but are not restricted to rockfall protection systems, pile foundations and retrofitting of existing buildings.

Generally, the design of related structures requires a reasonable understanding of the pile performance under operating conditions (Poulos and Davis, 1980). The verification of piles is routinely carried out using static pile load tests (SPLTs) that provide information about the load-displacement behaviour and design parameters, such as the pile resistance at the ultimate limit state. The interpretation of results, however, is non-trival (Hirany and Kulhawy, 2002), mainly due to the complex behaviour of soils and limited control of site boundary conditions (Wroth, 1984).

In this context, it should be pointed out that the load transfer during a SPLT may influence the measured pile response as well. Pile loads applied to the pile head are typically transferred to the surrouding soil using a reaction device, resulting in bracing effects that counteract the pile movement. The latter induce unwanted stress concenterations along the pile shaft, especially in close vicinity to the reaction device. Consequently, they may have adverse effects on the fidelity of pile measurements (Latotzke et al., 1999). This holds true for piles tested in compression (Henke, 2020) and tension. Although most execution codes offer guidelines to reduce bracing effects to an acceptable limit, they are incositent, inherently empiricial and lack validation (Granitzer et al., 2022).

This contribution provides insight into bracing effects, and aims to serve as practical reference to engineers that have to assess their influence in SPLTs. Moreover, we study the numerical fidelity of novel stress recovery methods (Granitzer et al., 2024a). Scientific contributions are split into two parts: First, we present lessons learnt from SPLTs of one micropile and one Ductile Pile instrumented with tailor-made systems to monitor the development of shaft contact forces. Part two presents numerical studies focusing on the spatial distribution of shaft normal stresses.

2 BACKGROUND

2.1 Static pile load tests

SPLTs constitute an essential part of piling contracts, especially in projects with limited knowledge about the ground conditions (Randolph, 2003). While we acknowledge the existence of alternative (dynamic) pile testing methods, such as described in Rebhan et al. (2022), it is worth noting that their applicability in practice is constrained. The interested reader may refer to the German Geotechnical Society (DGGT, 2014) for a detailed discussion on relevant application limits.

According to EN ISO 22477-1;2 (2019, 2023), the primary aim of SPLTs is to evaluate the pile load-displacement behaviour. Principal components of the test equipement are shown in Figure 1. Depending on the test objectives, refined SPLTs may be executed using an advanced instrumentation, for example, to montior the load sharing between pile shaft and base or skin friction distribution (Monsberger et al., 2016).

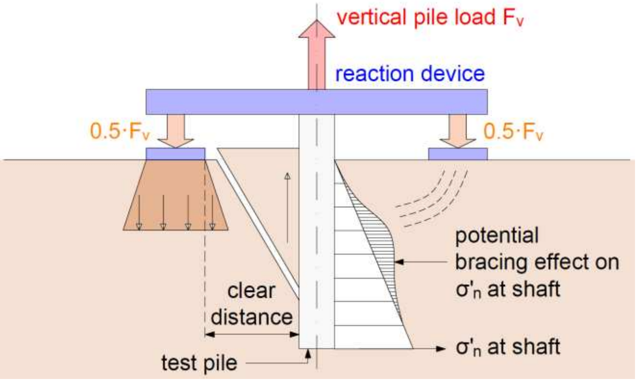

Figure 1. Schematic representation of static tension pile load test as well as bracing effect on shaft normal stresses.

Irrespective of the pursued in-situ measurement aims, the interpretation of data shall account for relevant factors, such as the pile loading rate (Randolph, 2003), monitoring intervals or changes in the pile material behaviour (England, 2012).

2.2 Bracing effects

Overall, considerable uncertainty exists in the ability to estimate the intensity and significance of bracing effects on the measured pile response. This mutual interaction decreases with increasing clear distance (CD) between the test pile and the reaction device; compare Figure 1. Thresholds of the minimum clear distance (MCD) documented in the literature, however, do not appear to be supported by sufficient physical evidence and deserve closer scrutiny. In this respect, Kitiyodom et al. (2004) report a relatively stiffer test pile response compared to 'non-influenced test piles', even for cases where the MCD is selected in accordance with relevant specifications. Likewise, Latotzke et al. (1999) provide experimental evidence that bracing effects are determinant at small displacements and lead to an overestimation of the pile bearing capacity that may be as high as 70 %. Granitzer et al. (2022) document a similar, but less pronounced trend for micropiles. In addition, it is pointed out that bracing effects are more pronounced for short piles with low slenderness ratio L_{pile}/D_{pile}.

The authors firmly believe that a more detailed understanding of the underlying mechanism is crucial to refine specifications concerning bracing effects, in the sense that they allow engineers to select MCDs with confidence and deploy practicable equipment.

3 FULL-SCALE FIELD TESTS

In this section, we present lessons learnt from two field test series carried out by the Graz University of Technology. The experimental campaigns focus on the analysis of different pile installation techniques, a novel pile testing method and the interpretation of results. Moreover, selected results serve as basis for numerical studies presented in section 4. As a novelty, one micropile and one Ductile Pile are equipped with measurement devices that capture changes in the horizontal load acting on the pile shaft.

3.1 Micropile test field in Graz

The installation and testing of micropiles, especially in the context of protective structures designed to mitigate natural hazards, pose a significant challenge for both on-site personnel and engineers engaged in the validation process. This has motivated the research project 'DAT' (Rebhan et al., 2021), which has made several attempts to enhance the framework conditions for relevant stakeholders. As integral part of 'DAT', micropile field tests have been conducted at the test site 'Inffeldgasse'. The adopted tension pile testing methods encompass SPLTs and a novel method based on impact pulse loading (Rebhan et al., 2022).

Figure 2 displays the arrangement and positions of the test micropiles. Three different micropile types are installed along axes 1-3, with the aim to compare their load-displacement response under similar boundary conditions. Axis 4 features the installation of a recently developed double corrosion-protected self-drilling micropile (Rebhan et al., 2023). The micropiles installed along axis 5 are utilized to study the micropile performance under impact pulse loading.

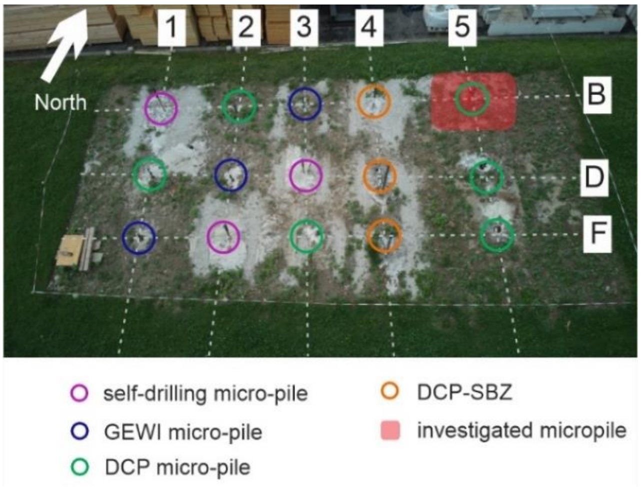

Figure 2: Overview of test field 'Inffeldgasse'. The red-marked micropile (5-B) is used for numerical studies.

The micropile ($L_{pile} = 4.0$ m) placed at the intersection of axes 5-B, designed as GEWI-pile with SAS thread bar ($D_{bar} = 32$ mm) and installed using the percussive drilling technique with temporary casing and lost bit, deserves special attention, as it serves as a focal point to investigate bracing effects. For this purpose, two horizontally-oriented load cells at micropile depths of 50 and 130 cm are mounted on a steel rod segment (Figure 3). To accommodate their instrumentation, a PVC pipe with a length of 150 cm is inserted during installation along the uppermost micropile section to provide lateral borehole support (Figure 3a). Within this section, borehole stability is achieved without grout injection, maintaining an open annulus between the ground and the steel rod. Once the remaining grout material has cured, the instrumented steel rod segment is connected to the grouted hollow bar using a coupling element (Figure 3b). In the next step, the PVC casing is carefully withdrawn, allowing for the simultaneous filling of the open annulus with sand. To establish sufficient force closure between the steel rod and the ground, the filled sand material is slightly compacted prior to commencing the measurements.

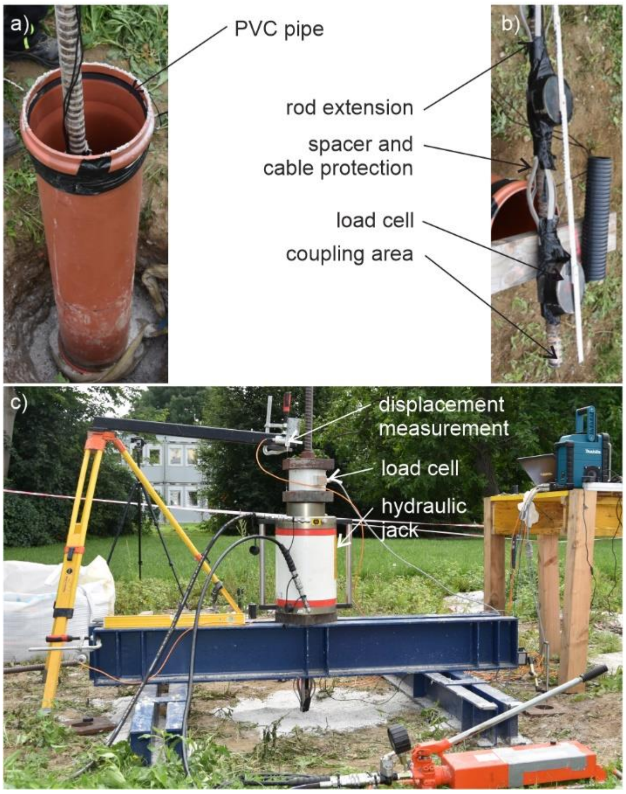

Figure 3: Details of micropile instrumentation and set-up for SPLT: a) PVC pipe, b) horizontally-oriented load cells mounted on steel rod and c) entire testing set-up.

Figure 3c shows relevant parts of the testing set-up. The hydraulic jack used to generate the pile load is placed on a symmetrically arranged reaction system, composed of a reaction beam and two abutments (CD = 5·D_{pile}). Vertical displacements of the pile head and the reaction frame are monitored by displacement transducers and draw-wire sensors, placed outside the influence zone of the reaction system.

During the SPLT, the pile load is increased in six loading steps over a period of around 60 minutes. For brevity, the measured vertical pile head load (F_v), horizontal cell load (F_h at pile depth of 0.5 m) and pile head settlements, shown in Figure 4, are constrained to a detailed view of two characteristic loading steps. The results infer that F_v and F_h simultaneously increase, giving a first indication of notable bracing effects on the 'mobilized' shaft normal stresses. It could be expected that these normal stresses are more determinant for fully grouted micropiles, that is, in cases where the compacted sand inside the open annulus is replaced by grout material.

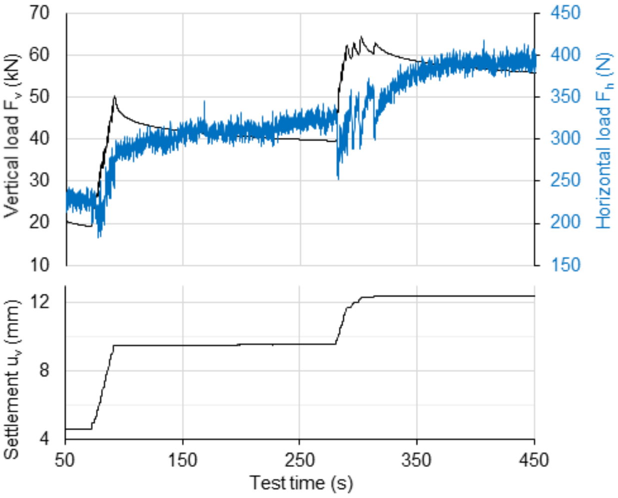

Figure 4. Micropile test results with detailed view of two representative loading steps: (top) vertical head load, horizontal shaft load and (bottom) settlements over time.

Although the results provide experimental evidence of the bracing effect on the mobilized micropile shaft normal stresses, insight into the role of the MCD is beyond the capabilities of this field test. Essentially, it should be noticed that this would require a more detailed experimental campaign with varying CDs. In addition, the following obstacles and critical aspects could be identified in the course of this study:

- The instrumentation of piles with load cells for assessing bracing effects on the pile response is non-trivial, mainly due to the fact that they have to be installed after pile installation.
- In the present case, the horizontal load cells are not aligned with the steel rod geometry; hence, they represent a possible anomaly with respect to the pile resistance mobilization during the SPLT.
- To capture the shaft normal stress mobilization with higher fidelity, a more realistic representation of the in-situ stress field and contact conditions between the micropile and the ground is required.

Future work at Graz University of Technology will therefore examine the applicability of flexible stress sensors that have the potential to capture the spatial distribution of shaft normal stresses as well.

3.2 Ductile Pile test field in Vienna

A conceptually similar field test is carried out near Vienna, with the difference that bracing effects are studied with respect to one Ductile Pile. The SPLT is executed using the patented Pile HAY Proof-System® (Hayden and Kirchmaier, 2010) shown in Figure 5. As a key characteristic of this system, the pile shaft and the pile base are loaded in two opposing directions (bi-directional). In this way, skin friction and shaft base resistance can be measured separately.

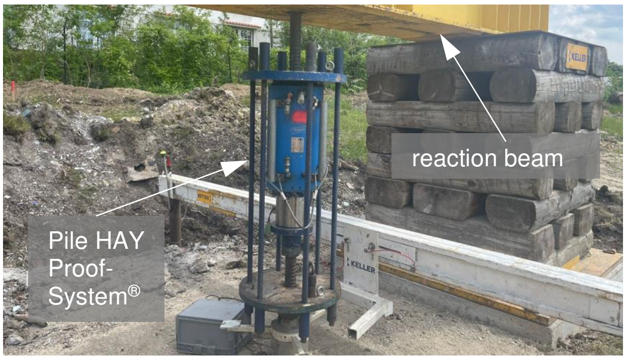

Figure 5: Entire testing set-up for bi-directional loading of instrumented Ductile Pile, with Pile HAY Proof-System® and horizontal reaction beam used for subsequent SPLT.

Due to the different pile type and testing set-up, the instrumentation used for examination of the bracing effect is modified. Contrary to the micropile, where a coupling element is used to connect the steel rod segment (with load cells) to the grouted hollow bar, the load cells are directly attached to the Ductile Pile; see Figure 6. After pile construction, the soil is excavated to a depth of 2 meters to provide access to the shaft. During the SPLT, the bracing effect is examined via three load cells at a depth of 140 cm.

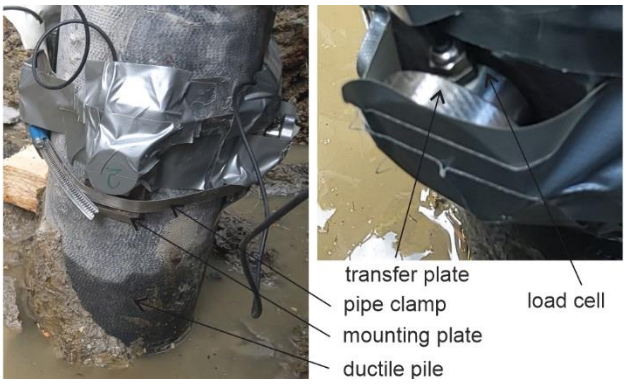

Figure 6. Measurement device mounted on Ductile Pile to investigate horizontal loads resulting from bracing effect.

As could be expected, a similar relationship between F_h and F_v could be observed; cf. 3.1. Interestingly, all load cells measure similar F_v-values, indicating a symmetrical distribution along the circumference (not shown here for brevity). Interested readers can refer to Böhm (2023) and Hayden et al. (2024) for a detailed documentation of in-situ measurements.

4 NUMERICAL STUDIES

To study bracing effects on the shaft normal stresses, the SPLT described in 3.1 is back-calculated using different pile modelling techniques. Contrary to in-situ measurements, this allows for the direct analysis of normal stress distributions across the shaft. In addition, three different techniques for normal stress recovery employed with a recently developed embedded FE model (Granitzer et al., (2024b) are validated for the first time considering complex soil stress conditions.

4.1 Analysis scenario and model description

All simulations are executed using the FE code Plaxis 3D (Bentley Systems, 2023). The calibrated soil model parameters, phase simulation sequence and ground water conditions, along with the geometry of the testing set-up, are adopted from Granitzer et al. (2022); see Figure 7. In this paper, the authors use this model to examine the CD-influence on the micropile tensile resistance (R_t), and report notable bracing effects for MCD < $5 \cdot D_{pile}$.

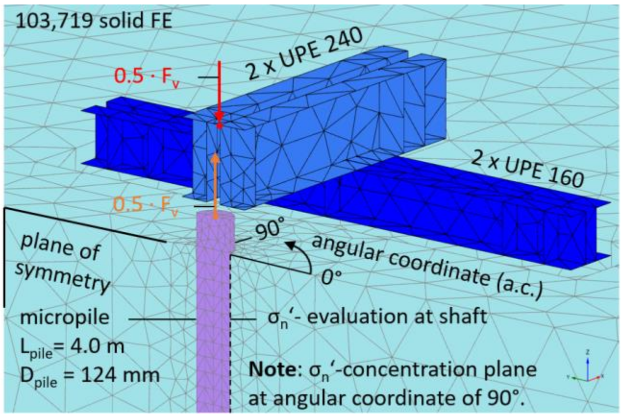

Figure 7. Detail of geometry and mesh topology (SFEA). Note: For clarity, interface elements are not shown.

In the present study, the pile is modelled by means of (i) the standard FE approach (SFEA), composed of zero-thickness interface FEs attached to linear elastic solid FEs, as well as (ii) the embedded FE model with interaction surface (EB-I) proposed by Granitzer et al. (2024b). For the EB-I, three different normal stress recovery methods (NRCs) are adopted to limit the frictional shaft resistance, namely, the penalty, local and non-local NRC. Conceptually, the normal stresses are recovered from solid Gauss points (local, non-local) and displacement increments of the pile and soil domain (penalty). The interested reader may refer to Granitzer et al. (2024a) for implementational details.

4.2 Back-calculation and validation

To validate the different pile modelling approaches, the first set of analyses is devoted to the back-analysis of the load-settlement curve. Figure 8 compares the measurements to the computed micropile response. The results confirm that all pile models are in good agreement with the measurements, particularly for $F_v < 80$ kN. While the local and non-local approach yield very similar results along the full range of loading, however, the penalty NRC slightly underestimates the mobilized pile resistance between $F_v = [80, 100]$ kN.

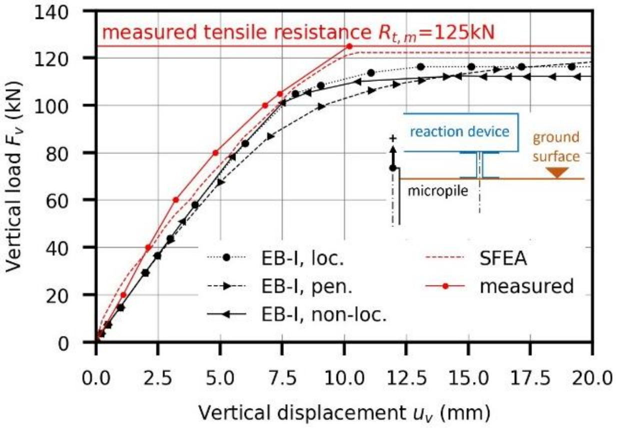

Figure 8. Validation of load-displacement behaviour.

Table 1 compares the tensile resistance in terms of absolute and relative metrics. Simulation results refer to the final converged increment of the analysis before failure. In all cases, the simulations capture the in-situ recordings with sufficient accuracy and a maximal deviation of 9 %. It can therefore be confirmed that the pile response is captured in an acceptable manner.

Table 1. Validation of tensile resistance ($R_{t,m}$=125 kN).

Pile model	EB-I, loc.	EB-I, pen.	EB-I, non-loc.	SFEA
R_t (kN)	116	121	114	122
$R_t/R_{t,m}$ (%)	93	97	91	98

4.3 Shaft normal stress distribution

The next analyses focus on the spatial σₙ'-distribution across the shaft. For clarity, we will refer to the plane in direction of the CD (at an angular coordinate of 90°) as σₙ'-concentration plane; compare Figure 7.

Figure 9 displays the σₙ'-distribution obtained with the SFEA. To increase the numerical resolution, σₙ' is plotted across half of the pile shaft and to a pile depth of 2.0 m, that is, the bond zone (grouted hollow bar) is only partially displayed. To examine bracing effects on the σₙ'-mobilization, the same boundary value problem is solved without reaction system as well, conforming to the idealized 'non-influenced test pile' case; cf. 2.2. The results infer that bracing effects lead to a notable increase of σₙ' in close vicinity to the σₙ'-concentration plane. This tendency is not suprising as it can be explained by the relatively small distance between the abutments and micropile shaft. Likewise, this result showcases that bracing effects are more determinant in the upper pile section, identified by a non-axisymmetric σₙ'-distribution. Peak values along the σₙ'-concentration plane are expected to be more pronounced for higher vertical loads. To some extent, these observations contradict the in-situ measurements mentioned in 3.2, which indicate very similar values for the horizontal load cells placed at angular coordinates of 0° and 90°.

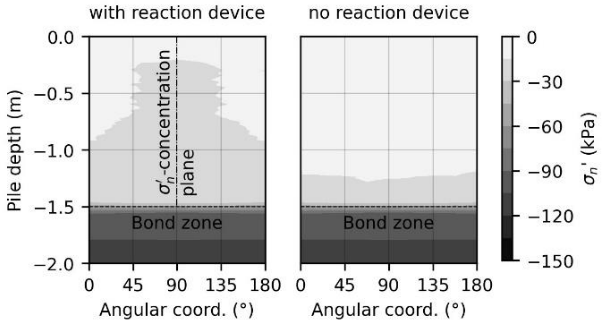

Figure 9. σ_n'-distribution at pile shaft (SFEA, $F_v = 40$ kN).

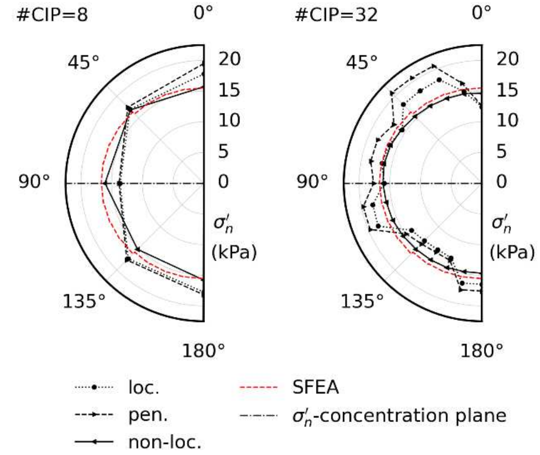

Figure 10. σ_n'-distribution at pile depth of 0.5m.

Figure 10 studies the potential of the three different NRCs to capture the circumferential σₙ'-distribution at a pile depth of 50 cm. The EB-I results are obtained with 8 and 32 circumferential coupling points (# CIP); compare Granitzer et al. (2024b). In analogy to the SFEA benchmark in Figure 9, σₙ' distributes in a non-constant manner for the EB-I models, with increasing values towards the σₙ'-concentration plane.

Additionally, Figure 10 shows that the number of circumferential coupling points influences the σₙ'-magnitudes; this holds particularly true for the local and penalty approach. Moreover, both NRCs produce singular values that become more distinct with increasing circumferential coupling point number. These limitations are lifted by the non-local NRC that shows an exceptional agreement with the SFEA and suppresses unwanted singularities in the σₙ'-field.

5 CONCLUSIONS

This work assesses the influence of the reaction system on the test pile response during static pile load tests.

Sufficient understanding of this bracing effect is instrumental for accurately interpreting the results of SPLTs and manufacturing efficient testing set-ups designed for challenging terrain conditions. A plea is made for the standardization of the operation, equipment and the interpretation of SPLTs to obtain maximum benefit from them.

To experimentally evaluate bracing effects on the pile response, two large-scale field tests are executed. In this context, this work investigates different pile types (micropile, Ductile Pile) and testing set-ups for force input and measurement of horizontal forces acting on the shaft. Both piles are instrumented with horizontal load cells placed at different positions along the shaft, whereas the underlying operational procedures are described in detail. The results show a clear relationship between the vertical pile load and the horizontal cell load resulting from bracing effects. Limitations and future lines of research concerning the employed testing set-up are highlighted as well.

To gain insight into the spatial σ_n'-distribution mobilized along the shaft, one micropile in-situ test is back-calculated employing different pile modelling approaches. In all cases, the measured tensile resistance is captured with reasonable accuracy. Likewise, the numerical results showcase that bracing effects result in a non-axisymmetric σ_n'-distribution, with peak values mobilized in vicinity of the so-called σ_n'-concentration plane. In addition, the performance of three normal stress recovery techniques employed for a recently developed embedded FE model with interaction surface is examined for the first time under non-axisymmetric stress field conditions. The results indicate that the non-local NRC yields relative merits compared to the local and penalty NRC, both of which suffer from singularities. It is therefore recommended to deploy the non-local NRC in future work.

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