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# Experimental investigations on the installation and bearing behaviour of full displacement bored piles

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ABSTRACT: During the installation of full displacement bored piles, the drilling tool is screwed into the ground with high torque and contact force. In contrast to bored piles, the soil is not extracted but displaced. This leads to compaction of the soil around the pile and, thus, to an increase in bearing capacity. There are many different full displacement bored pile systems worldwide, which differ significantly in the design of the drilling tool. Both, the tool geometry and the drilling machine parameters as well as the existing ground conditions have a decisive influence on the soil mechanical processes in the immediate vicinity of the pile during installation. In particular, they affect the stress changes induced by the screwing process and the resulting zone of influence close to the pile. The displacement behaviour in turn determines the bearing capacity of the individual pile systems. As part of an ongoing research project conducted at the Chair of Geotechnical Engineering at the University of Siegen, the installation process and the bearing behaviour of different full displacement bored pile systems are systematically investigated under varying machine parameters and different ground conditions. The research is carried out using a methodical combination of small-scale 1g model tests, numerical simulations and large-scale in-situ experiments. This paper focuses on the small-scale model tests. For these tests, various model drilling tools were produced at a scale of 1:10. The drilling tools are used to install model piles under different boundary conditions in a test tank, which are then subjected to axial loading. Measurements were taken during the installation and the static loading of the model piles. The results achieved so far accurately reflect the installation and load-bearing behavior of different full displacement bored piles and offer a high degree of reproducibility.

KEYWORDS: Full displacement bored pile, drilling tool, installation, bearing behaviour, model tests.

## 1 INTRODUCTION

To create a full displacement bored pile, the drilling tool is screwed into the ground without any relevant soil extraction and without vibration. As a result, the soil in the vicinity of the pile shaft is completely displaced and compacted at the same time. After reaching the final depth, the drilling tool is unscrewed while the pile is simultaneously concreted. Screwing the drilling tool in and out of the soil leads to changes in the stress state and the relative density of the soil in the vicinity of the pile.

The internationally known pile systems “Atlas” and “Fundex” are firmly established in German regulations and standards. However, a large number of other full displacement bored pile systems have been established, which differ from each other particularly in the design of the drilling tool (Basu et al. 2010). Depending on the drilling tool, very different machine parameters (torque, contact pressure, etc.) are required to screw it into the ground. The drilling tool geometry, the machine parameters, the existing subsoil conditions and the interaction of all the parameters have a significant influence on the soil mechanical processes in the immediate vicinity of the pile during the installation of a full displacement bored pile. At the same time, these soil mechanical processes influence the resulting bearing capacity of the pile.

In the collaborative project LeVoresT of the Chair of Geotechnics at the University of Siegen and the two companies Jacbo Pfahlgründungen GmbH and Otto Quast Bauunternehmen GmbH & Co. KG, the installation process and the bearing behavior of various full displacement bored piles are being systematically investigated under varying machine parameters and different ground conditions. For this purpose, small-scale 1g model tests are carried out in combination with numerical calculations. The purpose of these is to gain a deeper understanding of the soil mechanical processes during the production of full displacement bored piles and their influence on the load-bearing behavior. The subsequent aim of the research project is to optimize the full displacement bored piles by specifically modifying the drilling tool.

As part of the project, the Atlas and Fundex pile systems (reference systems) and the Quast-VVB and Jac-V systems (initial systems) are being investigated. Their geometries are depicted in the following Figure:

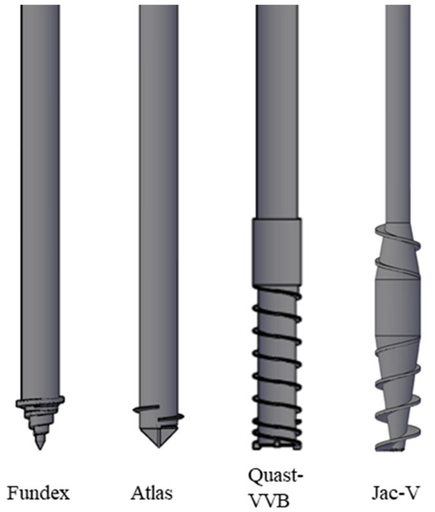

Figure 1. Pile systems investigated in the small-scale model tests.

Due to the expected scale effects, the results of the initial systems are related to those of the reference systems and thus the relative changes are considered. The initial systems will then further modified in the scaled physical and numerical model. The aim is to increase the load-bearing capacity by modifying the drilling tool, while it is essential to retain the installation ability of the pile systems. Afterwards, the modifications that have proven to be particularly efficient in the context of the aforementioned considerations will be produced as prototypes on the original scale and investigated with regard to their load-bearing behavior and installation capability in large-scale in situ tests. At the same time, the transferability to large scale will be investigated numerically.

The present paper focuses on the small-scale model tests conducted so far. First, the operating principle of full displacement bored piles is discussed. This understanding of the process is essential, particularly with regard to future drilling tool modifications. After that, the concept of the small-scale model tests is introduced and initial test results are finally presented.

## 2 OPERATING PRINCIPLE OF FULL DISPLACEMENT BORED PILES

In principle, full displacement drilling pile tools can be divided into short (e.g., System Fundex, Atlas or Olivier) and long systems (e.g., Omega, Quast-VVB or Jac-V).

### 2.1 *Short full displacement bored pile tools*

The drilling tools of the short systems do not have a displacement body. Below the steel pipe, there is a cutting head and/or a lost tip at the base of the tool. The Fundex system has a helical foot tip with a larger diameter than the shaft. By rotating the tip into the ground, the soil is compacted, especially below the tip. Once the final depth has been reached, the tip is released. Since only the steel pipe is pulled during concreting, there is no further compaction of the soil while the tool is being pulled. Consequently, the load transfer of Fundex piles is carried out predominantly via the base resistance. When an Atlas pile is screwed in, the cutting head on the tool displaces the soil to the side and no significant compaction takes place at the base of the pile. During concreting, the pipe and cutting head are screwed up backwards to form a helical concrete body. Due to lateral compaction effects during pile production and the formation of the helical concrete body, the load in Atlas piles is mainly transferred via the shaft resistance (DGGT, 2012; Kempfert & Becker, 2007; Porr Spezialtiefbau GmbH, 2024).

### 2.2 *Long full displacement bored pile tools*

A typical characteristic of the drilling tools used in long systems is the displacement body with a screw auger at the bottom, which loosens the soil, transports it upwards, and partially compacts it. In some cases, a screw auger is also located above the displacement body. A further distinction is made between progressive and fast displacement screw augers (see Figure 2).

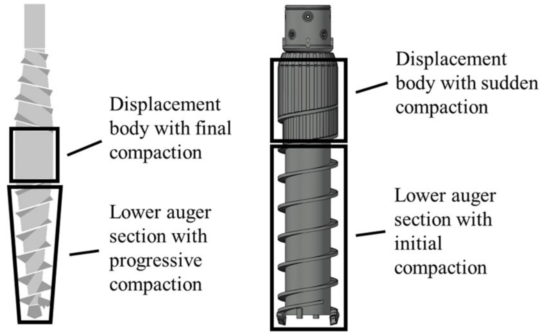

Figure 2. Difference between a progressive (left) and a fast displacement screw auger (right) – modified according to Larisch et al. (2012).

In progressive displacement augers, the diameter of the drilling tool increases conically and reaches its maximum at the height of the displacement body. The conical auger performs a large part of the total compaction of the drilling tool. The final compaction is performed by the displacement body. The conical counter-rotating auger above the displacement body lead to a recompaction of the soil while the drilling tool is being pulled. At the same time, loosening of the soil is prevented. In contrast, with fast-displacement augers, the diameter of the bottom auger is constant and as large as that of the displacement body. When a fast-compacting auger is screwed in, only partial compaction occurs in the lower part of the drilling tool. The majority of the compaction only occurs at the level of the displacement body (Larisch et al., 2012).

## 3 CONCEPT FOR SMALL-SCALE MODEL TESTS

The small scale 1g-model tests are carried out on a scale of 1:10. With that, the pile systems to be investigated have a maximum drilling tool diameter of 62 mm. All small-scale piles are manufactured with an embedment length of 1 m. The test tank consists of three segments and has a diameter of 105 cm with a total height of 210 cm. The third segment is not used for the 1:10 scale tests, resulting in a usable height of 160 cm for the tests.

In the model tests, the soil mechanical processes during the installation of different pile systems are investigated by installing earth pressure sensors in the vicinity of the piles. In addition, small-scale pile load tests are carried out on various full displacement bored pile systems. Poorly-graded sand ($C_u$ = 2.61, $D_{50}$ = 0.49) is used as test soil and can be installed in different relative densities in dry condition using a specially designed air pluviation system. Depending on the drop height, different relative densities $I_D$ of the test soil can be set in the tank (see Table 1). The total mass of the installed sand is recorded. In addition, core sampling methods are used. The achieved relative density is checked by using the determined masses. The following three relative densities are used in the small-scale model tests:

Table 1. Drop heights and relative densities used in the tests.

| Drop heights [cm] | Relative densities $I_D$ [-] |
|---|---|
| 5 | 0.42 ± 0.02 |
| 25 | 0.55 ± 0.02 |
| 75 | 0.70 ± 0.02 |

Also, the cone tip resistance $q_c$ is measured over the entire depth of the tank using an electric penetrometer. This was done to check whether the sand was installed with a constant relative density over the depth. The following figure shows the average cone tip resistance $q_c$ for two drop heights over the depth in the test tank.

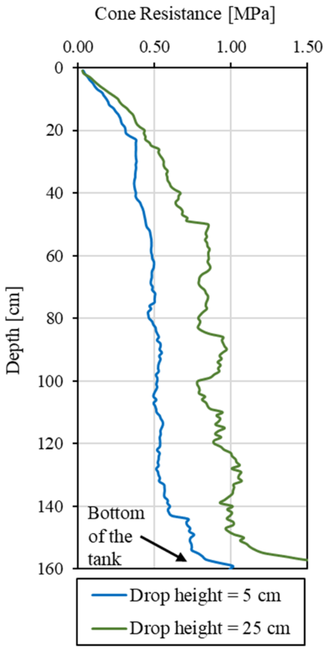

Figure 3. Cone tip resistance $q_c$ measured across the depth of the test tank for two different drop heights.

Constant cone resistance $q_c$ -profiles are apparent from a depth of approximately 40 cm to a depth of 140 cm where disturbances from the tank bottom occur.

The lower part of all small-scale drilling tools is made of plastic and the shaft is made of aluminum. The small scale drilling tools can be seen in Figure 4. In terms of the accuracy of the manufacturing processes, the small-scale tools are as similar as possible to the original large-scale tools. Further information on the test concept can be found in Kuhlmann (2024).

Figure 4. Small-scale full displacement bored pile tools on a scale of 1:10: from left to right: Fundex (Ø 40/56 mm), Atlas (Ø 45/62 mm), Quast-VVB (Ø 60 mm), Jac-V (Ø 60 mm).

In order to simulate the screwing process as accurately as possible, a drilling rig was equipped with measurement technology and data acquisition software. The exact setup can be seen in Figure 5. The data acquisition system enables machine parameters (rotational speed, insertion speed, contact force and torque) to be recorded with centimetre precision.

Figure 5. Modified drilling rig for screwing in small-scale drilling tools.

A Pagel E1F anchor and injection mortar is used for the model piles, as it has high early material strength and good flow properties. Once the final drilling depth has been reached, the mortar is injected through a concreting slot in the drilling tool.

The load required for the static load test was applied to the pile head by a hydraulic cylinder. The load is measured using a load cell connected between the hydraulic cylinder and the pile head, and the pile settlement is recorded using three displacement transducers. The pile is then gradually loaded up to a limit settlement of 0.1·D.

## 4 RESULTS OF THE SMALL-SCALE MODEL TESTS

So far, the Fundex system has been tested in several series of experiments for three different relative densities. The Atlas, Quast-VVB and Jac-V systems have already been tested in sand with a relative density $I_D = 0.42$. In addition, the Quast-VVB system was investigated in a sand with a relative density $I_D = 0.55$. The manufacturing parameters were recorded in all tests. In addition, the horizontal and, in some cases, vertical stress changes occurring in the vicinity of the pile during pile installation were measured and evaluated. All test piles were subjected to static loads tests at the end.

### 4.1 *Machine paramters*

All pile systems were screwed in with a penetration speed of approximately 1 cm/s and a rotational speed of approximately 7 rpm. The necessary contact forces and torques were recorded for each test. For the Fundex pile, contact pressures between 2,500 and 5,000 N were required, depending on the relative density (see Figure 6). In addition, a maximum torque between 110 and 145 Nm was needed (see Figure 7). There is a notable increase in the contact pressure and torque required for the production of the "Fundex, $I_D = 0.68$" pile compared to the "Fundex, $I_D = 0.42$" pile. When comparing the contact pressure and torque required for the "Fundex, $I_D = 0.42$" and "Fundex, $I_D = 0.55$" piles, there is unexpectedly only a slight difference.

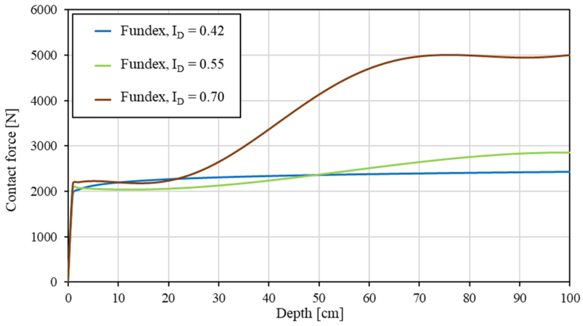

Figure 6. Trends showing the required contact forces for the installation of small-scale Fundex piles in three different relative densities.

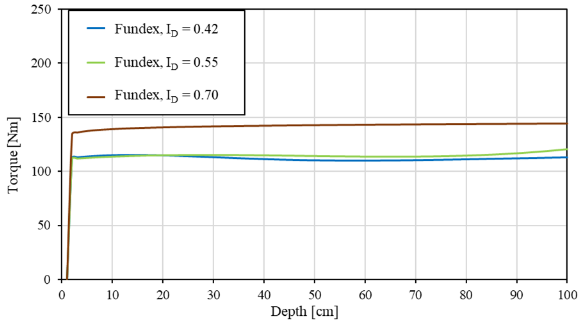

Figure 7. Trends showing the required torques for the installation of small-scale Fundex piles in three different relative densities.

Figure 8 and Figure 9 show trend curves which were derived from the raw data of the respective installation parameters. These were used for better conciseness. A comparison of the different pile systems under the same ground conditions clearly shows that the long full displacement drilling tools (Quast-VVB, Jac-V) require significantly higher contact pressure than the short tools (Fundex, Atlas). Both the required contact pressure and the required torque increase significantly with increasing screwing depth in the Quast-VVB and Jac-V systems. The required contact force and torque remain approximately constant during the installation of the Fundex and Atlas piles. In contrast to the Atlas pile, the Fundex pile requires higher contact pressure, while the Atlas pile requires higher torque. Both appear plausible when considering the tool geometry of the two systems. The maximum torque required for the long displacement tools is also higher than that for the short tools.

A comparison of the installation protocols for the small-scale piles with those for piles on the real construction site is planned.

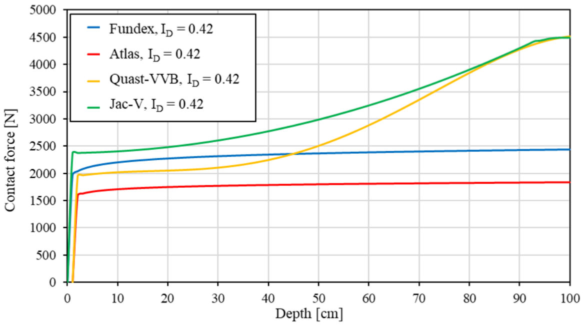

Figure 8. Trends showing the required contact forces for the installation of various small-scale full displacement bored pile systems in a relative density $I_D = 0.42$.

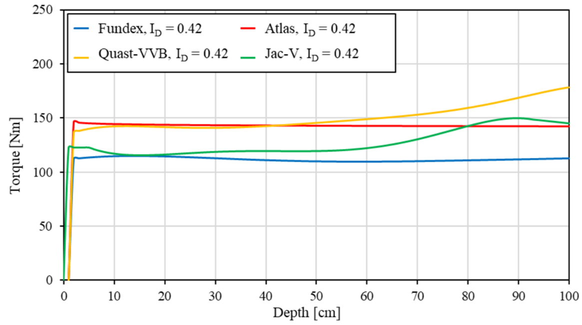

Figure 9. Trends showing the required torques for the installation of various small-scale full displacement bored pile systems in a relative density $I_D = 0.42$.

### 4.2 *Earth pressure measurements in the pile vicinity*

In various axes in the cross section of the tank earth pressure sensors have been placed in distances according to Figure 10. These sensors were used to measure the horizontal stress changes in the vicinity of the pile as well as the vertical stress changes at a distance of 4·D below the pile base. Preliminary tests have shown that vertically arranged pressure sensors have no influence on the load-bearing capacity of the pile. In all tests evaluated so far, no stress changes can be measured at the edge of the container.

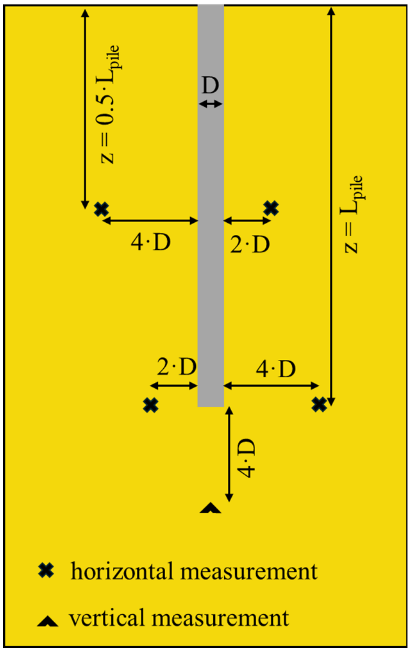

Figure 10. Positioning of earth pressure sensors in the test tank.

The results of the horizontally measured stress changes presented in this chapter are average values. Also, the results refer exclusively to stress changes caused by pile installation, whereby the existing stress level is constant, thus set to zero and not taken into account.

Table 2 shows the horizontal stresses measured by the sensors during the installation of a Fundex pile in three different relative densities of the sand. As expected, the horizontal stress changes during the installation of a Fundex pile at $z = L_{pile}$ are significantly higher than at $z = 0.5 \cdot L_{pile}$. Despite different relative densities, the stresses at $z = 0.5 \cdot L_{pile}$ are in a similar, low range for all three variants. On the other hand, the horizontal stress changes at $z = L_{pile}$ decrease with increasing relative density. These results will be verified in further tests.

Table 2. Measured average values of changes in horizontal earth pressure at a distance of 2·D from the pile after installation of Fundex piles in different relative densities.

| | Stress changes [Pa] | |
|---|---|---|
| $I_D$ [-] | $z = 0.5 \cdot L_{pile}$ | $z = L_{pile}$ |
| 0.42 | 4,792 | 18,417 |
| 0.55 | 4,293 | 9,130 |
| 0.68 | 3,192 | 6,581 |

Figure 11 to Figure 15 show the average values of all horizontally and vertically measured stress changes for various full displacement bored pile systems in the same relative density over time. The stresses were measured throughout the entire installation process. The initial maximum values correspond to the point in time when the tool base or the displacement body passes the sensor level. At $z = 0.5 \cdot L_{pile}$, the stress changes drop to almost zero after the tool has passed. In the area of the pile base, a maximum is reached during screwing in, which drops slightly after the rotary drilling rig is stopped. The subsequent strong decrease is caused by loosening of the tip. When concreting the pile, no stress changes are visible horizontally at $z = L_{pile}$ and vertically below the pile base. However, at the pile $z = 0.5 \cdot L_{pile}$ still large changes during screwing out are observed. The horizontal stress changes measured at a distance of 4·D from the pile are significantly smaller than the changes measured at a distance of 2·D.

The horizontal stress changes in vicinity of the pile at $z = L_{pile}$ during the installation of the Fundex, Quast-VVB and Jac-V systems are more than twice as large as those caused by the installation of the Atlas system. However, at $z = 0.5 \cdot L_{pile}$, the installation of the Atlas pile results in the significantly largest stress changes after pile installation. Below the pile base, though, a reduction in vertical stresses was observed with the Atlas system. These results may indicate increased shaft resistance and low base resistance of the Atlas pile. The magnitude of the vertical stress change for the other three systems is in a similar range, but the Fundex system shows a slightly lower value. The second increase in horizontal stresses at the middle of the pile during the concreting of the Quast-VVB and Jac-V systems is due to the displacement body and the counter-rotating augers above, which lead to a recompaction of the soil.

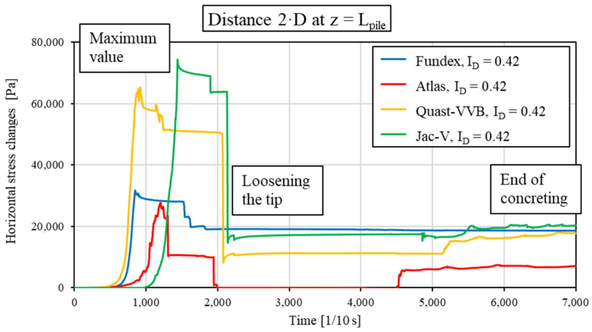

Figure 11. Average values of changes in horizontal earth pressure at a distance of 2·D at $z = L_{pile}$ during installation of various pile systems in a relative density $I_D = 0.42$.

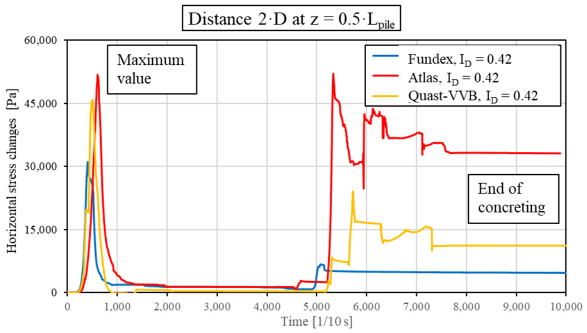

Figure 12. Average values of changes in horizontal earth pressure at a distance of 2·D at $z = 0.5 \cdot L_{pile}$ during installation of various pile systems in a relative density $I_D = 0.42$.

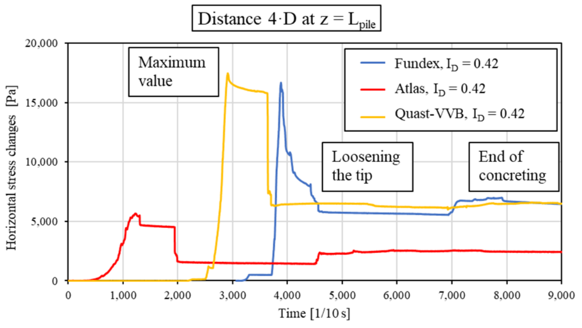

Figure 13. Average values of changes in horizontal earth pressure at a distance of 4·D at $z = L_{pile}$ during installation of various pile systems in a relative density $I_D = 0.42$.

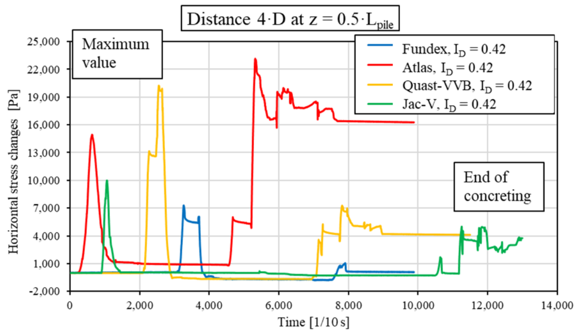

Figure 14. Average values of changes in horizontal earth pressure at a distance of 4·D at $z = 0.5 \cdot L_{pile}$ during installation of various pile systems in a relative density $I_D = 0.42$.

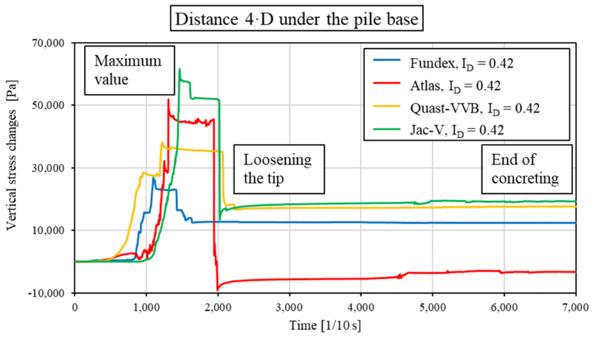

Figure 15. Average values of changes in vertical earth pressure at a distance of 4·D under the pile base during installation of various pile systems in a relative density $I_D = 0.42$.

The stress curves measured by the sensors correspond to expectations from the installation process. Taking into account the different drilling tool geometries, the results appear plausible. There are also significant differences between the pile variants.

## 4.3 *Static load tests*

Figure 16 shows the results of two static load tests on Quast-VVB piles with a relative density of $I_D = 0.55$. The load-settlement curve for both piles is very similar, confirming the excellent reproducibility of the tests.

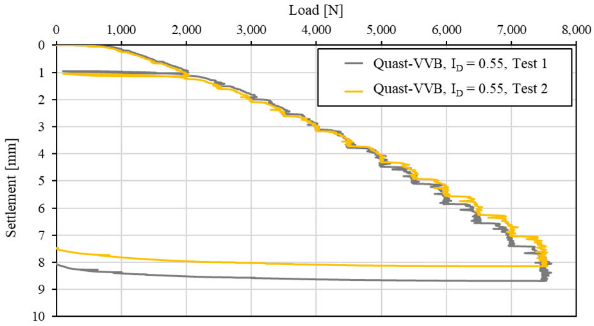

Figure 16. Results of two static load tests on Quast-VVB piles in a relative density of $I_D = 0.55$.

A variation in the relative density of the soil led to the expected results of the pile load tests (see Figure 17). Despite the very similar manufacturing parameters in the "Fundex, $I_D = 0.42$" and "Fundex $I_D = 0.55$" tests, there is a significant difference in the resistances achieved.

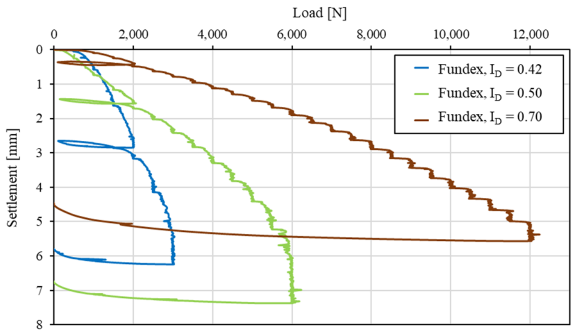

Figure 17. Results of static load tests on small-scale Fundex piles in three different relative densities.

The long full displacement bored pile systems Quast-VVB and Jac-V achieved significantly higher resistance than the Fundex and Atlas systems (see Figure 18). This corresponds both with the results from the installation protocols and with the results of the measured earth pressure changes. In addition, the load-bearing behaviour of the Quast-VVB and Jac-V systems is very similar. The Atlas pile settled significantly less than the other systems until a load level of approximately 2,500 N. However, at higher load levels, the Atlas system experienced a much faster increase in settlement compared to the Quast-VVB and Jac-V systems. The initially small settlements could indicate the large skin friction of this pile type, which was already fully mobilised at small load levels and could not be increased further with increasing load level.

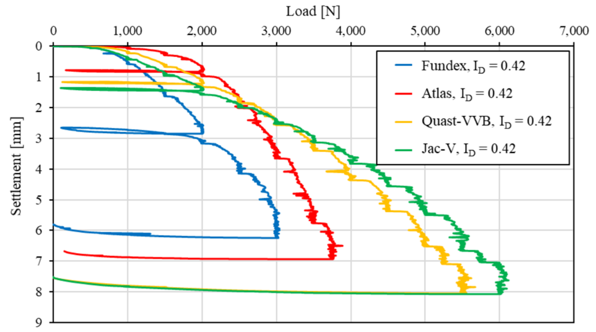

Figure 18. Results of static load tests on various small-scale full displacement bored piles for a relative density $I_D = 0.42$.

The significantly higher resistance achieved by the Quast-VVB and Jac-V systems compared to the Atlas and Fundex systems in small-scale test loads demonstrates the potential of these systems.

## 5 CONCLUSION

The geometry of the drilling tool, the machine parameters, and the existing soil conditions have a significant influence on the soil mechanical processes in the immediate vicinity of the pile during the installation of a full displacement bored pile. The bearing behavior of these systems is particularly influenced by the geometry of the drilling tool and varies significantly. Both the installation-related changes in the soil and the bearing capacity of the various systems have not yet been sufficiently researched. At the same time, there is potential for optimization of the drilling tool itself, which is being investigated as part of the LeVoresT project.

A concept for small-scale tests was developed to record the soil mechanical changes in the vicinity of the pile during installation. Furthermore, it is possible to perform a static load test on the small-scale test piles. Initial small-scale tests show promising and reproducible results. In particular, it can be emphasized that the bearing behavior under real conditions could be reflected in these, thus verifying the used method.

In the future, further tests will be carried out with small models in combination with numerical calculations. The results will then be confirmed by large-scale tests on site.

## 6 ACKNOWLEDGEMENTS

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