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New findings on the load-bearing behavior and innovative applications of ground screws

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ABSTRACT: In geotechnical engineering, ground screws are often associated with lightweight constructions and are used extensively for foundations of solar power plants worldwide. This paper presents innovative foundation designs using ground screws and discusses their load-bearing behavior. In addition to the normative classification of the different types of ground screws according to Eurocode 7, investigations into the load transfer using numerical methods and in-situ load tests are presented. Guidelines for the design of ground screws with small diameters of about 150 mm as well as with diameters of more than 400 mm are presented. Furthermore, a testing procedure with significantly reduced test time, requiring about only half of the testing program according to EA-Pfähle, is outlined. Ground screws with a large diameter can be classified as pile foundations and dimensioned analogously to driven steel piles. However, in contrast to conventional driven piles, screw foundations are installed without vibration meaning that they are often preferable when particular attention must be paid to noise emission and vibration. Currently the system is being tested for use for noise barriers or foundations along railway lines. Ground screws consist of only a prefabricated steel load-bearing element that is screwed into the ground and can be loaded immediately. There is no need for concreting, which not only significantly reduces mobilization and construction time, but also saves resources. That ground screws can also be reused, e.g. after temporary construction work, means that the impact to the environment during construction is also minimized. This complete recyclability of the foundation system renders it an attractive and innovative system for achieving sustainability goals.

KEYWORDS: ground screws, piles, foundation, numerical methods, load test, sustainability.

1 INTRODUCTION

Deep foundation techniques that enable fast construction are important, especially for infrastructure projects. Smart and innovative approaches are needed that enable construction without significantly restricting the existing infrastructure. At the same time, negative impacts on the environment must be avoided and people living nearby the construction site must be protected. The focus is on deep foundations that can be installed without long closure periods and cause hardly any noise or vibration emissions. Ground screws are one of these deep foundation techniques. They can be installed with minimal disruption under challenging geometric conditions and meet the above requirements. Ground screws are used worldwide for the foundations of lightweight structures, such as photovoltaic systems, and can have diameters in the range of micropiles. The large design, with a diameter of over 400 mm, is comparable to a driven steel pile and is already being tested for the foundations of noise barriers in the railway sector.

2 SPECIFICS OF GROUND SCREWS

2.1 *Small diameter of about 150 mm*

Ground screws with a small diameter of about 150 mm are installed in the ground with low vibration by rotating them and applying a torque force. The installation should be carried out using the full displacement method so that no soil is pushed upwards during the screwing process, but is displaced sideways. The torque at the pile head is recorded during installation as the so-called installation torque and is usually less than 25,000 Nm. The torque is not a constant value, but depends on the respective soil conditions and depth (Höppner & Boley 2022). The relationship between the installation torque and the load-bearing capacity is used for quality assurance purposes. If there is no competent layer below the ground surface and the installation torque is too low, the base element is extended with extension elements until the ground screw reaches the load-bearing soil layer and the installation torque increases significantly. Alternatively, the system can be designed and constructed as a floating foundation. The different elements of a ground screw are coupled by a connection bolt, see Figure 1.

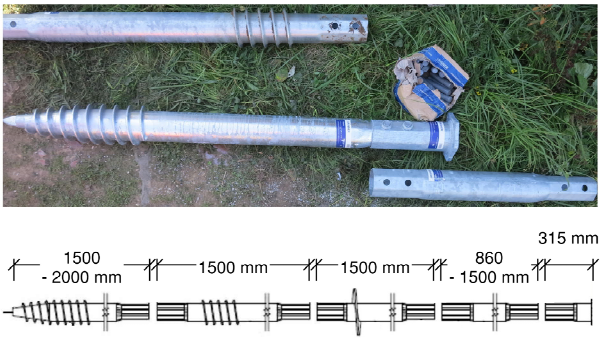

Figure 1. Assembly of the small ground screw.

2.2 *Large diameter over 400 mm*

In addition to the small-diameter ground screw, there is also a design with a diameter of approx. 406 mm, see Figure 2. This diameter is similar to that of conventional driven steel piles. In order to obtain sufficient tolerance for positioning the post of the noise barrier within the ground screw, the head area is converted into an approximately rectangular cross-section. This results in a transition area between the circular and rectangular cross-sections with stress peaks that can be relevant for the design and are discussed in more detail in Mölter et al. (2022). Similar to driven steel piles, ground screws can be installed from the road or railway track using a road-rail excavator and a hydraulic excavator attachment. The hydraulic equipment can apply a torque of up to 100,000 Nm, which causes transverse stress on the railway track when the work is carried out from the track.

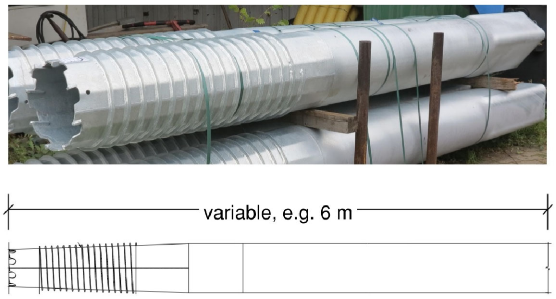

Figure 2. Assembly of the ground screw.

3 GUIDELINES FOR THE DESIGN

With regard to the design of ultimate limit states, DIN EN 1997-1 provides the European standard and is extended by the National Annex DIN EN 1997-1/NA and DIN 1054 in Germany. According to these standards, the limit value of pile resistance may generally be determined either from the results of soil testing or by pile load tests.

The ground screw with a diameter of more than 400 mm is designed in the same way as a conventional driven steel pile. Vertical load transfer is achieved via the mobilized pile skin friction and pile tip pressure. The pile tip pressure is not usually taken into account in the design, although pilot projects have documented the formation of a soil plug at the open tip. When applying empirical values for pile skin friction and pile tip pressure, it is important to take into account the model factors in accordance with EA-Pfähle (2012). The procedure is similar to that for conventional driven pipes. In accordance with FGSV Guideline 552 (2018), the application of skin friction is only recommended from 2.0 m below the ground surface.

In the case of layered ground conditions or increased requirements for horizontal displacement, the approval for testing ground screws in situ requires design based on the modulus of subgrade reaction method. The horizontal subgrade reaction can be approximated from the static modulus of stiffness per layer with ks = Es/D. A linear increase over the first three meters should be assumed. On slopes, sufficient soil resistance must be available, otherwise the horizontal subgrade reaction must be reduced or neglected.

For ground screws with small diameters, dimensioning based on pile parameters has not yet been standardized. The recommendations of the Working Group on Piles EA-Pfähle (2012), in its current version, do not contain a description of the ground screw system. Consequently, no empirical values for dimensioning are given. The complex geometry compared to other pile types makes it difficult to describe the load transfer. In particular, for designs with large helix diameters and multiple helices, the respective share of the load transfer can only be determined by complex instrumentation of test piles. A subdivision into tip resistance and skin friction does not describe the actual bearing behavior with sufficient accuracy. The determination of pile resistance from load tests is therefore the standard procedure. It should be noted here that dynamic load tests on ground screws are not yet part of the generally accepted technical standards, which is why these must be carried out as static pile load tests. Static pile load tests are carried out in accordance with the EA-Pfähle (2012). For static axial pile load tests under compression, DIN EN ISO 22477-1, is also available. This is also applicable in accordance with the current version of DIN 1054, which has been introduced by some federal states for building control purposes. The regulations of EA-Pfähle (2012) and DIN EN ISO 22477-1 are largely identical in content. There are only marginal differences that are not relevant in practical terms. Additional specifications may be included in a general type approval for ground screws.

In addition to empirical values and test loads, it is also possible to calculate the pile bearing capacity numerically. In this case, the influence of pile manufacturing on the pile bearing capacity must be taken into account, see EA-Pfähle (2012) and recommendations of the working group “Numerical Modelling in Geotechnics” (2014). With regard to the second generation of Eurocode 7, new possibilities for design could arise in the future.

The inner load-bearing capacity of ground screws is designed according to the standards of Eurocode 3, regardless of diameter.

4 VERIFYING THE LOAD-BEARING CAPACITY OF GROUND SCREWS

4.1 *Pile load testing*

Before the test load is applied, the required length of the prefabricated ground screw is estimated on the basis of soil investigations. It is recommended that the pile be embedded at least 1.20 m into the load-bearing soil layer. Based on this preliminary estimate of the length, a test load is applied to verify the external load-bearing capacity. The test load and load program are based on EA-Pfähle (2012), although a reduction in the test duration from approx. 5 hours to 2.5 hours is only permitted for ground screws with a small diameter of about 150 mm. The corresponding load program for a shortened compressive or tensile load in the axial direction is shown in Figure 3 (Deutsches Institut für Bautechnik 2023). Larger ground screws must be tested like a conventional pile. The load program can be taken from the EA-Pfähle (2012), for example. The test load not only determines the design value of the resistance of the ground screw at the start of the construction project, but also checks the load-bearing capacity of the structural piles during the construction project. The testing of the structural piles is carried out with a test load at the design load level and must be performed on 3% of the ground screws with a small diameter, but at least two ground screws per homogeneous soil layer.

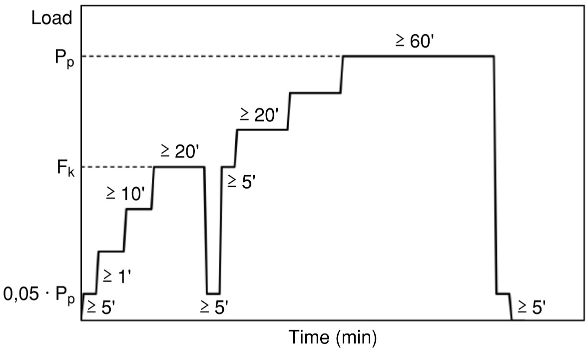

Figure 3. Pile load test with reduced testing time (Deutsches Institut für Bautechnik 2023).

4.1.1 *Pile load testing equipment*

For axial and cyclic test loads, a loading system consisting of a beam supported on each side by a shorter beam with two anchored abutments is used. Ground screws can be used as reaction piles, see Figure 4. The system is connected to the test pile via a hydraulic cylinder with a load cell. A compressor and automatic load control are used to maintain a constant load.

To measure vertical displacements, an optical displacement sensor is attached to a reference system made of aluminum profiles. Depending on the direction of displacement or measurement, the laser of the displacement sensor must be aligned with a measuring point plate magnetically attached to the side of the head of the ground screw. The displacement is always measured at the height of the load application point.

During the pile load tests, the displacement measurement is coupled with the force measurement. This enables the simultaneous recording and assignment of force and displacement.

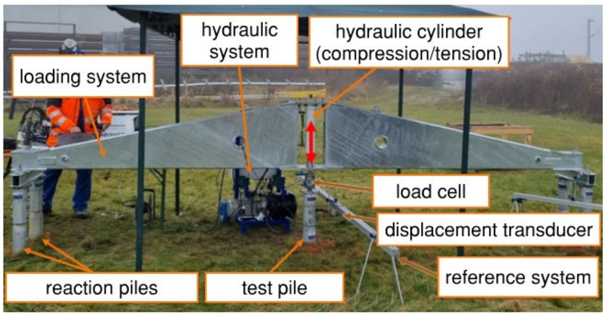

Figure 4. Pile load testing equipment.

4.1.2 *Results of the load tests on ground screws for the foundation of noise barriers*

As part of a pilot project, axial and horizontal load tests were carried out on ground screws before the deep foundations for the noise barrier were constructed. For the axial load tests in the direction of compression, the load system shown in 4 was used. For the horizontal load tests, two ground screws were coupled and pulled toward each other so that an abutment structure was not required. A digital spirit level was also installed to measure pile head rotation. The load was applied in stages in accordance with the specifications for EA-Pfähle (2012), and the load-time and displacement-time diagrams were documented. A special characteristic of noise barriers is the horizontal loading. For this reason, test loads were applied in the horizontal direction. Even with a horizontal load of approx. 27 kN, the displacement at the pile head was only 1.2 mm. According to the static calculation of the noise barrier, a horizontal head displacement of the screw foundation of up to 20 mm is acceptable. The influence of alternating stresses on the screw foundation due to suction and pressure loads was investigated in research work (Boley et al. 2023). Further detailed investigations into the load transfer of screw foundations were carried out by Höppner (2021), for example.

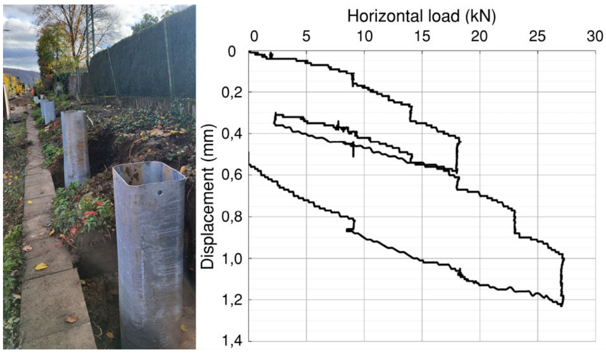

Figure 5. Ground screw foundations for noise barriers and result of horizontal pile load test.

4.2 *Numerical simulation of the displacement process*

The numerical simulation of ground screws poses challenges with regard to the functionality of screw. During the installation of the ground screws the displacement process leads to compaction, which causes an increase in the horizontal stresses in the ground (Xiong et al. 2024). This generally mobilizes a higher skin friction around the screw foundation. A simulation of ground screws using the Wish-in-Place method is therefore not suitable.

In this study, the applicability of three different simulation methods for numerically simulating the displacement processes of ground screws was examined and the advantages and disadvantages of each individual method were determined, see Figure 6. The investigations in this phase were carried out according to the “trial and error” principle, whereby the following findings and results were obtained.

An FE simulation of full displacement processes without restrictions in the displacement depth can usually be realized with the coupled Euler-Lagrange method. The coupled Euler-Lagrange method is generally only used in research projects (Staubach et al. 2025) that justify this effort, whereby it is limited in terms of the choice of program used and the underlying material laws. Simulations using this method are far more time-consuming and therefore not best suited for practical applications.

The program PLAXIS is an FE tool that is often used in practical applications worldwide. Here we explain the simulation options for screw foundations using this program.

A simulation of the full displacement of a screw with the PLAXIS program using dynamic mesh generation methods can only be implemented up to a limited displacement depth. This program considers an absolute displacement by using a forced displacement, which requires a reset of the displacements after each simulation phase. This makes it more difficult to evaluate the ground screw foundation at a later stage. This method was therefore not considered ideal compared to the method with volume expansion.

The simulation method with volume expansion is relatively flexible compared to the other methods mentioned and worked relatively well in the program PLAXIS. This simulation method requires a starting volume element with relatively small dimensions in the FE model. If the dimensions of the starting volume element are too small, this could lead to a long calculation time and an incorrect estimation of the desired foundation diameter (percentage input of the volume displacements in PLAXIS). Also, a too large dimensioning of the starting volume element leads to a wrong estimation of the stress state and possibly a pore water pressure in the subsoil as well as the soil properties after the displacement. The mesh elements around the ground screw foundation need to be taken into account during mesh generation. These should be relatively large in the radial direction to prevent the overlapping of mesh points due to displacement, which would lead to numerical errors in the calculation.

The displacement process leads to an increase in pore water pressure in low-permeability soils, causing groundwater flow in the subsoil. Since the consolidation process occurs simultaneously with the displacement process, this should be taken into account in the simulations. A simulation as “consolidation” in the PLAXIS program essentially considers the flows and drainage in the vertical direction. However, due to the horizontal displacement process, horizontal flows must also be taken into account, which is only possible using the coupled hydromechanical simulation method in the PLAXIS program. The coupled simulations are only available in the Ultimate version of PLAXIS.

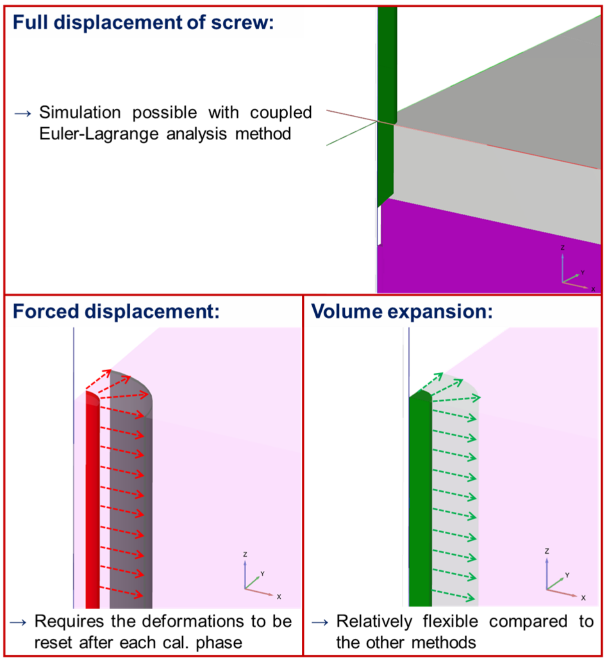

Figure 6. Methods for the numerical simulation of displacement processes.

5 CONCLUSIONS

Currently, pile load tests are a key part of foundation work with ground screws. This is set to change in the future, with the number of pile load tests being reduced, because real-time monitoring of installation parameters, such as the installation torque, allows conclusions to be drawn about the ground conditions and the load-bearing capacity of each individual ground screw. Research on the relationship between installation parameters and load-bearing capacity is presented, for example by Souissi et al. (2020). In this context, the FE simulations are also important for understanding the load-bearing behavior. The coupled Euler-Lagrange method allows simulation of the full displacement process of the ground screw foundation, but it's not practical because of time-consuming and limited choice of program and material laws. A simulation using the PLAXIS program, taking volume expansions into account, is generally useful for investigating the effects of the displacement process on soil parameters and stresses in the subsoil. Installing the screws leads to compaction of the subsoil and an increase in horizontal stresses in the subsoil as a result of the displacement process. This usually activates higher skin friction around the screw foundation, which improves the load-bearing capacity of screw foundations.

In addition to the structural aspects, the environmentally friendly installation and removal process is also worth highlighting. The ground screws can be recycled after removal or reused in following projects after quality control. The reusability of ground screws is particularly advantageous for temporary construction projects and innovative in terms of sustainability.

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