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Calibration chamber for testing of a novel self-boring probe for in-situ ground investigation

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ABSTRACT: This work presents the development of a new cylindrical calibration chamber constructed at ETH Zurich (ETHZ) to test a novel self-boring probe for in-situ ground investigation, currently under development at ETHZ. The design of the chamber builds up on existing similar concepts for penetration testing, while adopting bespoke solutions for the needs of the self-boring probe. Initially, the chamber is used for proof-of-concept testing of an anchoring unit, which is part of the self-boring probe's mobility system. The inner dimensions of the chamber are 730 mm in height and 670 mm in diameter. Either zero-displacement or constant-stress conditions can be imposed along the lateral boundaries of the soil specimen. In the first case, the lateral boundary is the rigid wall of the calibration chamber, whereas in the second case, water pressure acts on a custom-made rubber membrane around the circumference of the soil, controlling the radial stress. Vertical stress is applied through a pneumatic cushion at the base of the chamber, while the top is restricted from movement. The chamber is equipped with central circular openings at the top and base plate. Through these the self-boring probe can be mounted to test its anchoring system and furthermore in a later testing stage, it can be pushed axially without tip-resistance interference in order to estimate exclusively the anchor capabilities. A bespoke pluviation system was developed to fill the chamber with sand. The paper discusses the development of the chamber, sample preparation and test procedure, presenting indicative preliminary results of anchoring unit tests in dry Perth sand.

1 INTRODUCTION

Calibration chambers have been predominantly used to test instruments for in-situ soil investigation, such as cone penetrometers or pressuremeters. The controlled environment of the chamber has been proven to be an effective tool, in comparison to large-scale field testing, which is essential for the development of such geotechnical probes and the derivation of correlations for geotechnical parameters (Schnaid & Houlsby, 1991). To date, various calibration chambers have been developed, differing in dimensions, stiffness, boundary conditions, sample preparation, and capability to handle saturated samples (Sweeney & Clough, 1990; Ajalloeian & Yu, 1998; Pournaghiazar et al., 2011; Ayala et al., 2020).

Since it is well known that the response of an instrument analysed in the chamber is strongly influenced by boundary conditions of the specimen (Salgado et al., 1998), a multi-purpose approach was targeted in this work with respect to the boundaries of the soil specimen. Two different boundary conditions are included in the design: zero radial strain (rigid wall chamber), or constant horizontal stress (flexible wall chamber) boundary condition. In this work, the calibration chamber was developed and constructed to test a novel self-boring probe for in-situ soil investigation developed at ETHZ (Alber & Anastasopoulos, 2020). As a first step, the anchoring unit of the probe is tested under controlled soil conditions in the chamber. The design of the chamber, as well as the sample preparation set-up, follows general features of existing calibration chambers, but is equipped with certain features, specific for the anchoring unit to be tested. Some initial results are presented herein, referring to preliminary tests for the anchoring unit in uniform, dry Perth sand, using the rigid wall calibration chamber setup.

2 DESIGN OVERVIEW

The design of the chamber and the air-pluviator as a sample preparation tool consist of several different components. *Figures 1* to *4* show the calibration chamber, the air-pluviator and their functional components.

2.1 Chamber

The calibration chamber encloses a soil specimen of 730 mm height and 670 mm diameter. In the case of the rigid wall boundary conditions, the soil is confined directly by the tank of the calibration chamber (*Fig. 1*). The latter is positioned on a pedestal construction, which allows for distribution of the weight of the entire assembly to a larger floor area, as well as for water and air pressure supply access below the chamber. Initial testing targets the anchor unit, whose response is tested first in a fixed position (discussed in this paper) and subsequently, while axially pushing the probe. Hence, the anchor is to be isolated from possible tip-resistance interference of the device. To achieve this goal, the probe is allowed to extend vertically through the chamber assembly, the top and base plates include a central circular opening, and all components inside the chamber are designed to be "donut-shaped".

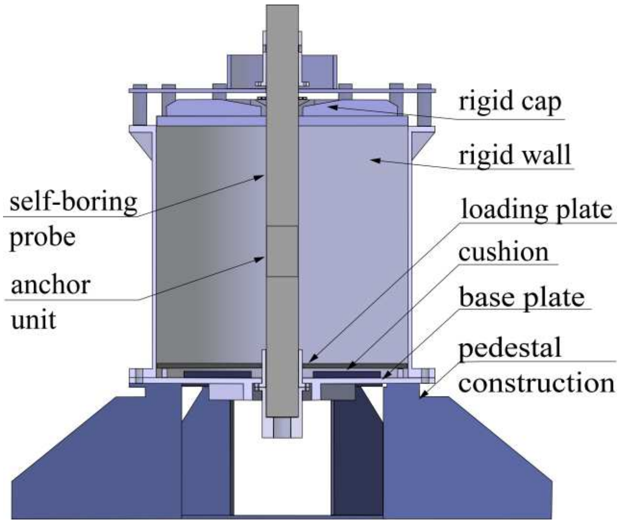

Figure 1. Rigid wall calibration chamber setup.

The top of the calibration chamber consists of a perforated rigid cap, directly in contact with the soil specimen. The vertical stress in the soil specimen is generated through a custom-made air cushion. The latter is sitting on the base plate of the chamber and is vertically pushing a rigid loading plate in the direction of the soil. The cushion can provide a maximum vertical force of 200 kN, which is a function of the supplied air pressure and its height (the increase of inflation leads to a decrease of the area of the cushion that is in contact with the plates). Hence, a calibration procedure was needed to quantify the force applied by the cushion. The latter was placed between the base and loading plate and the rigid cap with its load cells (see chapter 2.3) was directly fixed to the base plate (no calibration chamber tank was used for this set up). In this way, the force given by the cushion could be correlated to the air pressure and inflation height, using a similar configuration as in the final chamber test set up.

The flexible wall chamber setup includes a custom-made rubber membrane, through which water pressure is applied (also referred to as cell pressure) to the soil (*Fig. 2*). In this way, the lateral and vertical pressure can be applied independently. Another component of the flexible wall chamber is the movable specimen former, similar to the one of Pournaghiazar et al. (2011). The former serves as a jacket to hold the membrane in place during sample preparation and can be released manually once the cell pressure is enough for the specimen to remain stable on its own.

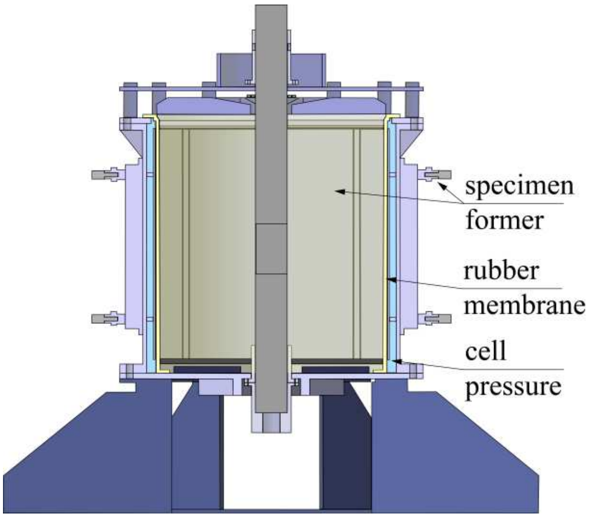

Figure 2. Flexible wall calibration chamber setup.

2.2 Air-Pluviator

Stationary pluviation was chosen for the preparation of the dry sand specimen, as it allows for a wide range of relative densities and for reconstitution of large specimens within a short time. Similar to the concept presented by Richards (2019), the air-pluviator consists of a hopper sitting on an additional tank (*Fig. 3*). The hopper has a perforated base plate, connected through roller supports to another perforated shutter plate, which is fixed to the tank. The two perforated plates have matching hole patterns. By moving the hopper on the rollers with respect to the shutter plate, the holes can be aligned to allow the sand to flow. Furthermore, a diffuser mesh is inserted in the pluviator tank to better disperse the sand flow. The perforated base plate of the hopper is equipped with an equilateral triangular grid of adjustable holes with possible diameters of 20 mm/10 mm/5 mm/2.5 mm, and a 60 mm spacing from the centre of the holes. The diffuser mesh has 5 mm wide squared openings and spacing between the centres of 8 mm.

A preliminary pluviation sensitivity study with Perth sand was performed by using measurement pots at different locations and heights in the chamber. The study showed that using this air-pluviator, the soil relative density is uniform over the height of the calibration chamber. This leads to the conclusion that the additional tank serves the purpose of creating sufficient distance between the hopper and the calibration chamber, so that the terminal velocity of the sand flow can be reached.

The presented tests in the calibration chamber are performed on a wished-in-place self-boring probe. The probe is mounted centrally in the chamber before starting the filling process. In order to avoid shadow effects around the circumference of the probe, a dummy elongation of the same diameter is placed on top of the probe, extending up to the shutter plate.

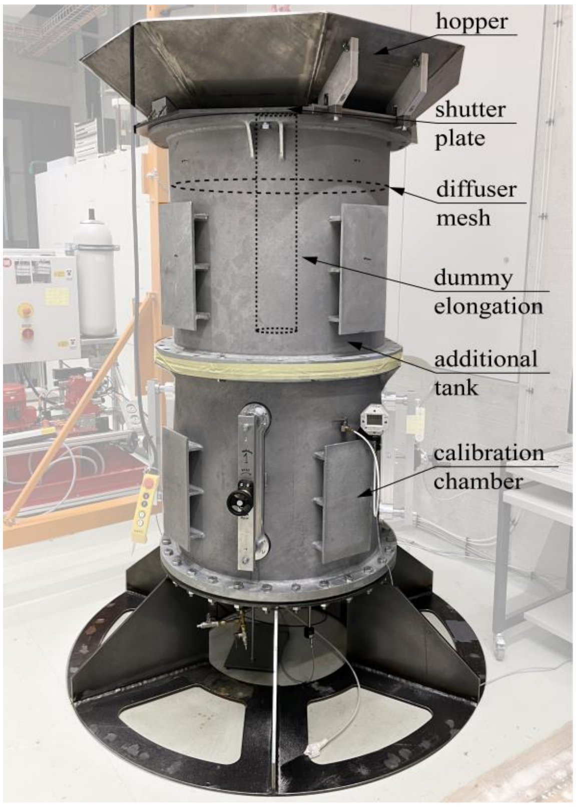

Figure 3. Stationary air-pluviator for sample formation.

2.3 Control and measurement devices

The chamber is fitted with control and measurement devices. The cell pressure in the membrane, as well as the air pressure in the cushion, are controlled and measured by pressure regulators and gauges. The top cap of the chamber (*Fig. 4*) incorporates three load cells, which are positioned at an angle of 120° around the central axis of the chamber and record the vertical stress reached at the top of the specimen. Three linear varying displacement transducers (LVDTs) are mounted underneath the loading plate to measure the inflation height of the air cushion, which corresponds to the vertical deformation of the soil cylinder. Furthermore, these transducers can detect any tilting of the loading plate. In the case of the rigid wall chamber, the inner wall of the chamber is equipped with tactile pressure mapping sensors in the direction of monitoring the horizontal stress in the soil.

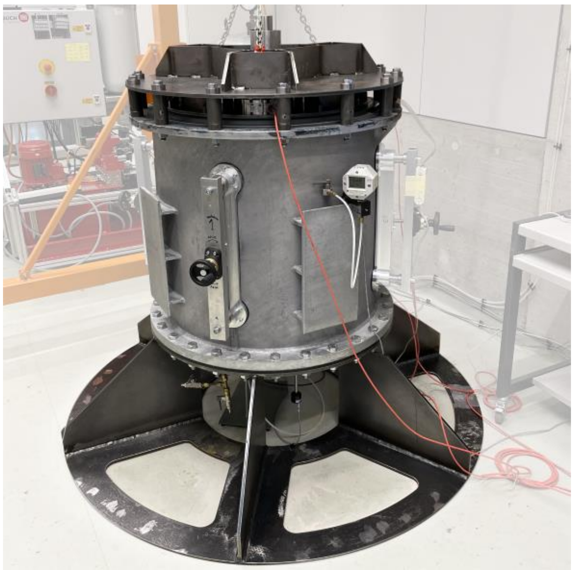

Figure 4. Calibration chamber during test.

3 TEST PROCEDURE

The test presented in this work is a preliminary evaluation of the anchor unit of the self-boring probe. The latter has a diameter of 100 mm and comprises four rectangular steel boxes, placed at intervals of 90° around the longitudinal axis of the probe. These boxes act as anchors, as they are pushed horizontally in the surrounding soil with the target of generating enough reaction force for the autonomous subsurface movement of the probe (Alber and Anastasopoulos, 2020).

In this paper the proof-of-concept testing of the anchor unit in the rigid wall calibration chamber is described. The test procedure can be divided in three phases: specimen preparation; consolidation to the desired stress level; and anchor expansion. Firstly, the 10 cm diameter probe is placed inside the empty calibration chamber, so that the anchor unit is positioned at mid-height of the chamber. Using the air-pluviator, the chamber is uniformly filled with Perth sand at an average relative density $D_r = 80\%$, corresponding to voids ratio $e = 0.54$. In the second phase, the dense sand specimen is subjected to an average vertical stress of around 100 kPa. The test is concluded by the third phase: the four anchor boxes are pushed in the surrounding soil. Each of the anchors has been calibrated beforehand without soil by means of a load cell. Therefore, the recorded force-displacement relation of the anchor unit represents the response in the soil without the effect of internal friction.

4 PRELIMINARY TEST RESULTS

During the consolidation process, the loading plate was pushed up by the air cushion, experiencing a vertical displacement of 1.4 mm (average of the three LVDTs). No tilting of the loading plate was observed. Based on the cushion calibration, the stress at the bottom of the chamber was estimated at 135 kPa. At the top of the chamber, a stress of 80 kPa was recorded by the load cells at the end of the consolidation phase. This indicates a significant stress gradient between the bottom and the top of the chamber (higher than the effect of self-weight of the soil, which is around 12 kPa), due to friction at the chamber side walls. The pressure mapping sensor, placed on the inner side wall of the chamber at the height of the anchor unit, measured a horizontal stress of 65 kPa at the end of the consolidation process.

Figure 5 depicts the pressure-displacement response of the four anchors during their expansion. It can be observed that, on average, the anchors start expanding at a stress of about 50 kPa. This “lift off” stress gives an indication of the initial horizontal stress, which needs to be overcome for the anchor to start moving. This value is slightly lower than the horizontal stress indication given by the pressure mapping sensor. Furthermore, it can be seen from *Fig. 5* that by the end of the expansion phase, the anchors achieved a displacement of 0.57 mm, reaching an anchoring stress of 800 kPa. This shows that in the given chamber stress field, which corresponds to 6 m of overburden pressure in dense Perth sand, the anchor unit is able to fully mobilize its maximum available capacity in terms of force.

During the anchor expansion, no considerable change in the load cells at the top and the LVDT’s at the bottom could be observed. However, the pressure mapping sensor increased its measured horizontal stress to 75 kPa at the end of the anchor expansion. This means that around 1.3% of the stress increase at the anchor - soil interface reached the inner wall of the calibration chamber.

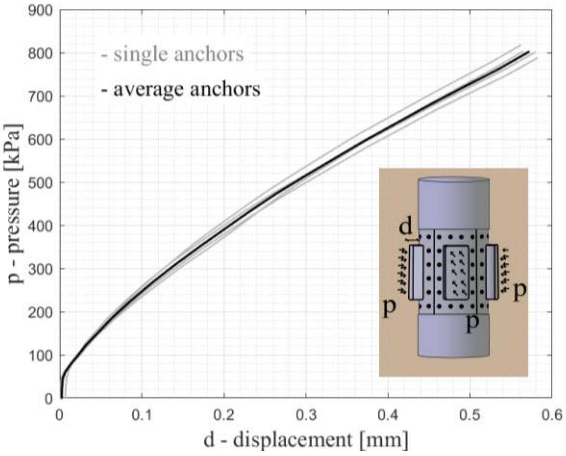

Figure 5. Average anchor expansion response.

5 CONCLUSIONS

The designed rigid wall calibration chamber proved to be a suitable and efficient environment for conducting preliminary anchor unit tests in the framework of the self-boring probe development. More anchor tests are envisaged in order to analyse the functionality and performance of the anchor unit at different stress levels and relative densities.

In terms of chamber applicability, the preliminary test shows that a reduction of the interface friction between the sand and the inner side wall of the chamber is beneficial for its performance, as it will decrease the stress gradient between its top and base, allowing for better control of the overall stress field. Furthermore, the preliminary test highlighted the importance of the pressure mapping sensors along the height of the calibration chamber, as they offer valuable information on the stress field and the “lift off” stress of the anchor unit.

Following the rigid wall chamber tests, the plan is to evaluate the anchor response under constant horizontal stress as the soil specimen‘s boundary conditions, using the flexible rubber membrane.

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