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Design of a model scale plate anchor instrumented with excess pore water pressure transducers for centrifuge modelling

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ABSTRACT: Anchoring systems supporting floating offshore renewable energy (ORE) facilities experience variable loads over the facility lifetime which can change the geotechnical properties of the surrounding soil and the capacity and response of the anchoring system. In normally and lightly overconsolidated fine-grained soils, beneficial consolidation effects from the dissipation of excess pore pressures generated from loading is a key mechanism in whole-life analysis. Beneficial consolidation effects can lead to increases in strength and stiffness of the soil, resulting in increases in anchor capacity and reductions in the required design anchor size. To enable local measurement of the build-up and dissipation of excess pore water pressure around deeply embedded plate anchors, as a result of whole-life loading, a bespoke model plate anchor instrumented with a pore water pressure transducer, has been designed and manufactured in collaboration with MSMT Solutions.

This paper describes the design of the instrumented model plate anchor and its initial validation for future use in 1-g and high-g environments in measuring the build-up and dissipation of excess pore water pressure around the plate anchor when embedded in normally consolidated fine-grained soils. This initial validation demonstrates the prototype capability of detecting small changes in pore pressure, and the resulting dissipation.

1 INTRODUCTION

Numerical studies have reported the effects of sustained loading and consolidation in the load capacity of plate anchors embedded in normally and lightly overconsolidated fine grained soils (e.g. clays). Larger observed increases in the consolidated plate anchor load capacity are attributed to the formation of a water-filled gap beneath the plate anchor. This leads to a non-symmetrical consolidation above and below the plate, which creates a zone of hardened soil above the plate anchor, altering the overall failure mechanism and plate anchor capacity (Han et al., 2021; Kwa & White, 2023; Singh & Chatterjee, 2018).

Ongoing research on the physical modelling of plate anchors and their load capacity increase under sustained or cyclic loading presents new challenges regarding the instrumentation required to effectively monitor the physical changes around the anchor. Localised consolidation around buried structures is complex to monitor due to the nature of the phenomenon and the type of instrumentation needed to measure pore water pressure changes around the anchor. Such setup must meet the following conditions to enable effective monitoring:

- Be placed close enough to the region with expected changes in pore water pressure.
- Be positioned far enough away to avoid creating boundary effects on the buried structure.
- Require few or no support structures since they cause additional boundary effects.
- Remain at a fixed known location during the entire test.

Although the physical modelling of plate anchors embedded in fine grained soils has previously been conducted in geotechnical centrifuges (e.g. Wang, 2023; Wang et al., 2025; Zhou et al., 2020), pore pressure measurements around the anchor were either not measured (Zhou et al., 2020) or have not been conclusively presented due to technical challenges associated with pressure transducers built into the anchor (Wang, 2023; Wang et al., 2025).

Previous research on dragged anchors has also explored the use of built–in transducers to measure position and rotation of anchors during centrifuge tests (e.g. Robinson et al., 2018; Sharif et al., 2024). However, these studies did not include the measurement of pore water pressure and the pore pressure transducers used were based on commercially available printed circuit boards (PCB) which are challenging to fit on small and thin anchor models. This paper therefore describes the development of an instrumented model plate anchor with built-in pore water pressure transducers capable of reliably measuring excess pore water pressure during geotechnical centrifuge tests.

2 CONCEPTUAL DESIGN

The purpose of the instrumented plate anchor is to investigate the generation and dissipation of excess pore water pressure that sustained loading generate on a deeply embedded plate anchor. Figure 1 illustrates two different failure mechanisms associated with plate anchors. Anchors embedded close to the surface tend to mobilise a wedge of soil extending to the surface. In contrast, plate anchors embedded at greater depth (e.g. at or deeper than 2 times their diameter or width) develop a flow – around failure mechanism.

This deep failure mechanism led to the decision to position the pore water pressure transducer on the top face of the plate anchor at a raised location (not flushed with the top face) enabling it to capture changes in pore water pressure within the mobilised clay. Figure 2 shows the final location of the top pore water pressure transducer in the prototype.

3 MECHANICAL SPECIFICATIONS

The instrumented model plate anchor is based on previously designed models at Geotechnical Centrifuge Facility at The University of Southampton, which were tested under monotonic and cyclic load at 100 g. However, these earlier models did not include a built-in pore water pressure transducer and were used to investigate the ultimate capacity of the anchors under sustained load. The original anchors were designed to be lightweight and capable of withstanding monotonic pullout forces of up to 1000 N. They also incorporated a versatile docking cap, allowing either in-flight mechanical gripping with a metallic clamp or a docking force using ferromagnetic top plate and an electromagnet. Figure 3 shows the overall dimensions of the instrumented plate anchor.

The plate anchor diameter was selected as 60 mm with a hollow shaft of 10 mm diameter. The shaft serves as both a structural element connecting the plate anchor with the robotic actuator and as a conduit for electronic wiring. The total length of the assembly is 240 mm, providing sufficient clearance from the strongbox base to minimise boundary effects, while also allowing adequate space at the top for docking with the robotic actuator.

Stainless Steel grade 316 was selected as the manufacturing material due to its excellent corrosion resistance, high strength and non-ferromagnetic properties, ensuring that magnetic docking occurs only at the designed magnetic cap.

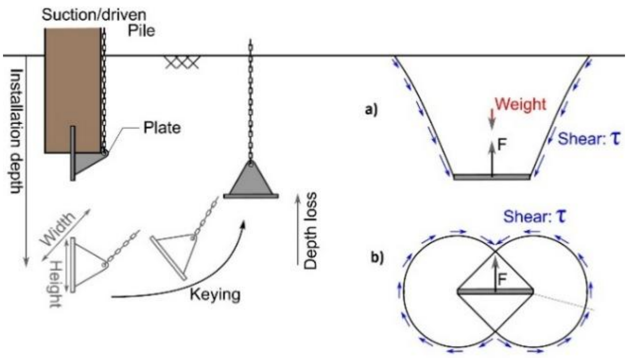

Figure 1. Plate anchor and its failure mechanism. a) Shallow plate – anchor. b) Deep plate – anchor. Modified after Cerfontaine et al., 2023

Figure 2. Close-up view of the top pore water pressure transducer located 5 mm above the top face of the anchor.

4 SIGNAL PROCESSING

The pore water pressure transducers were designed with a capacity of 3000 kPa. The design and manufacture of the instrumented plate anchors was carried out by MSMT Solutions.

Two digital pressure transducers are installed on the anchor, located on the top and bottom faces of the plate. These are connected to a custom–made PCB located outside the anchor, where the signal is conditioned and amplified. The PCB is designed to accept a wide input supply voltage (0 to 30 V), which is converted to a regulated 3.3 V rail. Pressure sensor signals are processed by an onboard microcontroller and converted to an analogue output via a high precision Digital to Analogue Converter (DAC). Figure 4 show a view of this PCB.

Data acquisition is performed using a DigiDAQ datalogger (Gaudin et al., 2009), where the analogue signal is recorded and transmitted digitally through a network card to the onboard PC in the geotechnical centrifuge.

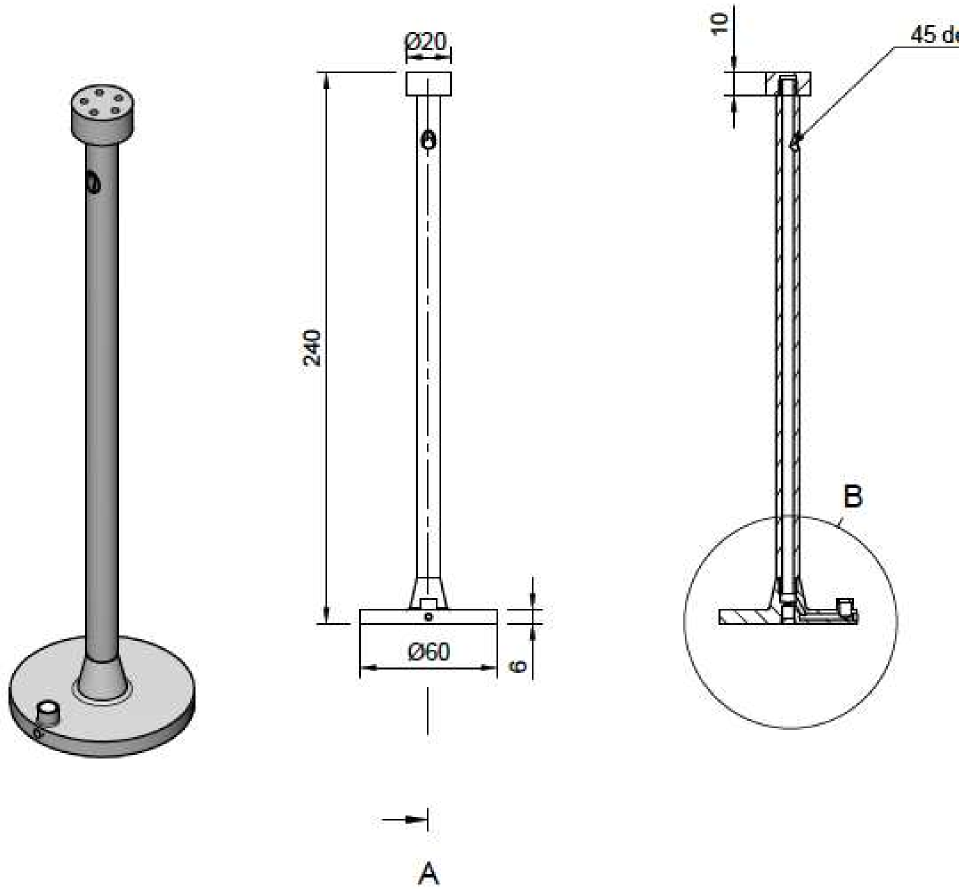

Figure 3. Overall dimensions of the developed instrumented plate anchors.

5 PROTOTYPE TROUBLESHOOTING

A few technical limitations were identified in this first prototype when combined with the DigiDAQ system, which was subsequently addressed at the Geotechnical Centrifuge Facility. The primary technical limitation arose from the DigiDAQ system being optimised for low-power sensor and strain-gauge instrumentation rather than for supplying power to external PCBs, resulting in insufficient available current for the custom-made board. Each instrumented plate anchor draws around 270 mA (two transducers and two PCB per anchor) while a DigiDAQ unit can supply a total current of up to 350 mA across all eight channels. This resulted in power loss during the initial trials involving two instrumented anchors and additional sensors (e.g. load cells and other pressure transducers).

To resolve this issue, a minor modification was implemented with MSMT to allow the PCB to be powered by an independent 12 V DC power supply. This approach provided a stable power source and significantly improved the reliability of the output signal from the instrumented model plate anchor.

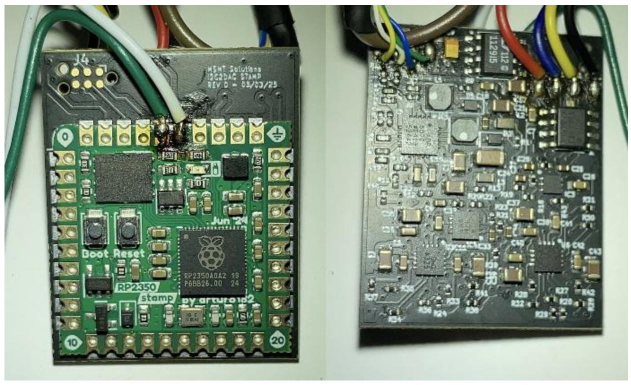

Figure 4. Front and back view of custom-made PCB.

6 CONCLUSIONS

This paper has presented the development and initial validation of an instrumented model plate anchor designed to measure the excess pore pressure generated during sustained and cyclic loading of plate anchors embedded in clays during geotechnical centrifuge tests. The motivation for such instrumentation arises from the need to better understand the mechanisms of the non-symmetrical consolidation response around embedded plate anchors that leads to increases in plate anchor capacity.

The initial conceptual design approach was based on the reported deeply embedded anchor failure which presents a flow – around mechanism where a shear zone forms around the plate anchor. This led to the decision to locate the top pore water pressure transducer at a raised position to capture the pore water pressure generated in this region.

The initial testing of this first prototype highlighted a power supply limitation associated with the custom electronics and their integration with the existing DigiDAQ–based setup.

Subsequent performance of the sensor shows that this instrumented plate anchor provides a robust experimental tool for measuring excess pore water pressure generated around buried structures (e.g. plate anchors) which otherwise could be challenging to observe. Future work will focus on a systematic testing in geotechnical centrifuge test to investigate soil consolidation effects around the anchor and its contribution to changes in loading capacity.

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