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A novel digital pore pressure transducer in geotechnical physical modelling

Z.J. Xu
Schofield Centre, Department of Engineering, University of Cambridge, Cambridge, United Kingdom, zx280@cam.ac.uk

X. Liang, N.G.L.H. Lee, S.C. Liu, S.K. Haigh
Schofield Centre, Department of Engineering, University of Cambridge, Cambridge, United Kingdom, xl539@cam.ac.uk, nglhl2@cam.ac.uk, sl2101@cam.ac.uk, skh20@cam.ac.uk

ABSTRACT: This paper presents the development and evaluation of a new digital pore pressure transducer (PPT) for centrifuge modelling. Motivated by the discontinuation and limitations of traditional analogue devices such as the Druck PDCR-81, the new digital PPT employs an MS5837 digital sensor within a compact stainless-steel casing and interchangeable porous filters for use in sand and clay. Calibration results show that the transducer responds consistently to applied pressures with stable offsets. Centrifuge testing further illustrates its ability to capture the overall evolution of pore pressures under both static and dynamic loading conditions. Although its sampling rate is lower than analogue PPTs, fast-logging at 300-500 Hz enables reliable measurement of seismic pore pressure cycles. Results indicate that the digital PPT provides a practical, low-cost, and robust alternative to conventional analogue PPTs for static and dynamic centrifuge modelling.

1 INTRODUCTION

Pore pressure transducers (PPTs) are essential instruments in geotechnical physical modelling, enabling the measurement of transient and steady-state pore water pressures in clay and sand under centrifuge loading. For decades, analogue PPTs such as the Druck PDCR-81 have been the standard choice for such applications. However, this product is no longer in production, and the available alternatives are relatively expensive and suffer from calibration drift, structural dimensional constraints, electro-magnetic interference and other limitations (Wang et al., 2012; Stringer et al., 2014; Ritchie et al., 2021). In this case, a compact, low-cost, and sensitive replacement for conventional analogue PPTs is needed.

Compact digital pressure sensors offer high precision, built-in temperature compensation, and direct digital output. Based on this, a miniature digital pore pressure transducer (PPT) was developed at the Schofield Centre, University of Cambridge. The device incorporates an MS5837 digital sensor, a stainless-steel casing, and modular porous filter tips to accommodate different soil types. Integrated communication through an I²C interface enables many PPTs to operate simultaneously within a single data-logging system.

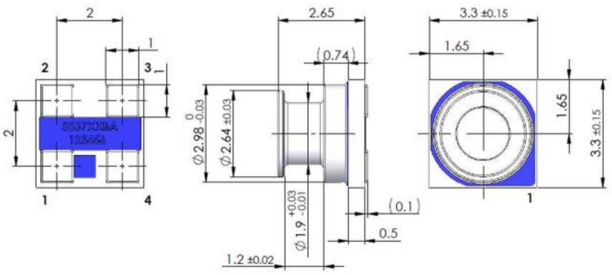
This paper presents the design, calibration, and centrifuge performance of the new digital PPT. The results are compared with those from the traditional analogue PPTs in static and dynamic conditions. The aim is to assess whether the new digital PPT can serve as a practical and reliable replacement for traditional analogue instruments in geotechnical physical modelling.

2 DESIGN OF THE DIGITAL PPT

The design of this new digital PPT is based on the MS5837 digital pressure sensor (TE Connectivity), which provides high-resolution absolute pressure measurements through an integrated piezoresistive element with on-chip temperature compensation. The package outline and pin configuration of the sensor are shown in Figure 1. Three versions of the sensor were fabricated, with full-scale ranges of 2 bar, 7 bar, and 30 bar, to accommodate different soil types and loading conditions.

The sensor body consists of a stainless-steel casing (6 mm in outer diameter and 14 mm in length) that houses an MS5837 chip and is sealed with epoxy resin to provide waterproofing and electrical insulation. The tip incorporates a rubber O-ring and a porous filter (ceramic for clay or sintered bronze for sand) to maintain hydraulic continuity and prevent soil intrusion. The modular filter design allows the same sensor to be used in either clay or sand simply by replacing the porous filter. Figure 2 and Figure 3 show the cross-section and overview of the new digital PPT.

Each MS5837 sensor communicates with a Teensy microcontroller via an I²C digital interface, and the microcontroller is linked to a multiplexer board that manages multiple sensors within a single data-logging system. This configuration enables simultaneous monitoring of several pore pressure locations, significantly improving spatial coverage in centrifuge model tests. The system has a logging frequency range of 0 to approximately 700 Hz, enabling reliable acquisition of static and dynamic signals across a broad spectrum, which is essential for monitoring transient pore pressure responses during centrifuge testing.



1	GND	GROUND
2	VDD	POSITIVE SUPPLY
3	SCL	I2C CLOCK
4	SDA	I2C DATA

Figure 1. Package outlines and pin configuration of the pressure sensor (reproduced from TE Connectivity, MS5837-30BA Pressure Sensor Datasheet, 2025).

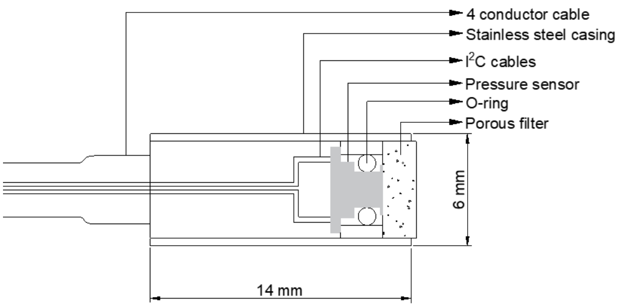


Figure 2. Cross-section of the new digital PPT.

Figure 3. Overview photograph of the new digital PPT.

3 CALIBRATION

A water column calibration test was conducted to verify the linearity and stability of the new digital PPT, as the transducer outputs absolute pressure without atmospheric correction. The calibration was carried out at the Schofield Centre, University of Cambridge, using a dedicated calibration system (Wang et al., 2012) equipped with functions for de-airing, saturation, and pressure regulation. All PPTs were placed in a common chamber, where the input water pressure, controlled by applied air pressure, was adjusted to various levels. An integrated data acquisition system (DAS) was used to record the measurements.

The stability of digital PPTs with different measuring ranges and soil types was assessed, including 2-, 7-, and 30-bar clay PPTs and a 7-bar sand PPT. The input water pressure was gradually increased from 0 to 100 kPa in discrete manual steps, and the corresponding outputs of the digital PPT were recorded for calibration. During the test, the PPT exhibited an immediate response to a sudden rise in pressure, with no detectable delay relative to the pressure regulation system, indicating that the porous filter was fully saturated. The calibration results are presented in Figure 4, where the output pressure from the new PPT exhibits an almost linear relationship with the input water pressure. The slope of the linear fitting line and the coefficient of determination (R^2) are both approximately equal to 1.0, indicating excellent measurement linearity and stability. The offset values show only a small variation, ranging from −101.3 to −97.7 kPa, and remain consistent across sensors with different ranges and tip types, which means that the zero-pressure offset is stable and can be easily corrected.

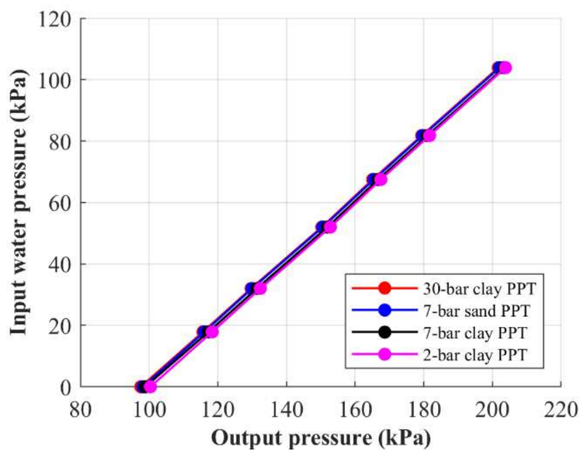


Figure 4. Calibration of the new digital PPTs.

4 STATIC TESTING

A centrifuge test was conducted using the new digital PPTs in a clay model and their performance was evaluated during the swing-up phase. The clay model was prepared by mixing Speswhite kaolin powder to a water content of twice the liquid limit (120%) and the sample was consolidated to a certain maximum stress by the consolidometer. Two new digital PPTs (sampling at 50 Hz) and one Druck PDCR-81 PPT (sampling at 100 Hz) were installed at different depths for comparison. The water table was set to about 27 mm below the ground surface level. The centrifuge was then accelerated from 1 g to 60 g. The responses of three instruments during centrifuge acceleration can be seen in Figure 5.

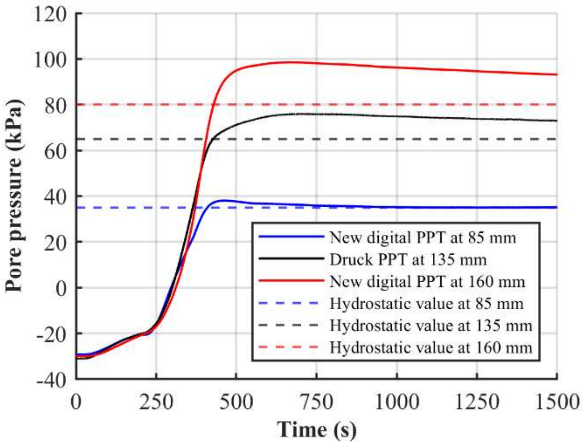


Figure 5. Pore pressure responses in the clay model during swing-up phase.

After removing the sample from the consolidometer, the clay was under suction, and the recorded pore pressure was roughly -30 kPa. This negative pressure confirms both the expected soil state and the ability of the PPTs to accurately capture suction. During the early swing-up phase, as the acceleration increased from 1 g to 10 g within 240 s, all sensors exhibited a similar rise in pore pressure while still under suction. This consistent response indicates that the sensors were fully saturated, and they did not introduce measurable hydraulic delays. From 10 g to 60 g, both the new digital PPTs and the Druck PPT responded immediately and simultaneously. They recorded pore pressures higher than the expected hydrostatic values. This transient excess pressure is characteristic of the rapid loading during swing-up, reflecting the undrained compression of the clay. Following this phase, the excess pore pressures dissipated gradually over a further 1000 s. All sensors showed a progressive approach toward the expected hydrostatic values. The shallower sensor (installed at 85 mm depth) approached hydrostatic conditions within this period, whereas the deeper sensors (at 135 and 160 mm) continued to exhibit residual excess pore pressure due to the longer drainage path and slower dissipation rate. Overall, these observations demonstrate that the new digital PPT performs comparably to the traditional analogue Druck PPT in capturing both the short-term and longer-term pore pressure evolution under static centrifuge loading.

5 DYNAMIC TESTING

5.1 Sand models

A dynamic centrifuge test using sand models was conducted to compare the dynamic responses of the new digital PPT and the Druck PDCR-81. The new PPT (sampling at 83 Hz) and the Druck PPT (sampling at 6000 Hz) were installed at the same depth of 38 mm below the surface of saturated loose sand, both mounted flush against the outer wall of an aluminium pile. The model was tested at 63 g, and a sinusoidal input motion of 63 Hz, 2 V amplitude, and 10 cycles was applied, corresponding to a 1 Hz earthquake at prototype scale. After 10 seismic cycles, the pile moved away from the PPTs. As shown in Figure 6, during seismic loading, the readings from the new PPT were nearly 17% higher than those from the Druck PPT. This difference is likely related to the limited sampling rate of the digital PPT, which is only slightly above the excitation frequency and therefore less capable of capturing the peaks recorded by the 6000 Hz analogue sensor. In the post-earthquake phase, the readings from both the new and Druck PPTs were closely aligned, and both effectively captured the transient suction response induced by the pile movement. These results confirm that the new digital PPT maintains practical applicability in dynamic testing.

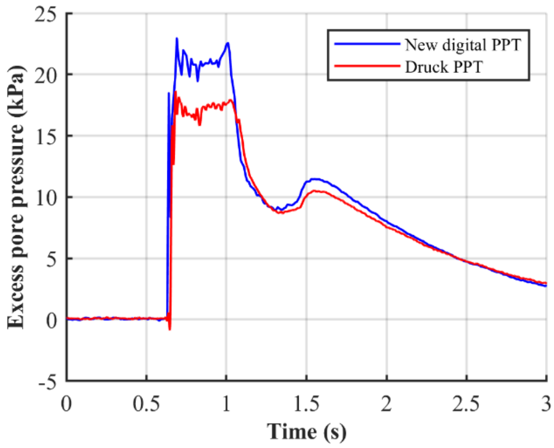


Figure 6. Dynamic excess pore pressure responses in the sand model.

5.2 Clay models

A more recent dynamic centrifuge test with clay models was carried with the improved fast logging rate of 300-500 Hz. The model investigated the seismic behaviour of a rigid box tunnel buried in a clay stratum, where the new digital PPTs were installed underneath the tunnel as shown in Figure 7. The model was tested at 80 g, with sinusoidal earthquakes (EQ3 to EQ5) applied at 80 Hz, equivalent to a 1 Hz earthquake at prototype scale.

Figure 8 compares the dynamic response recorded in this test with that from an earlier test in the series using analogue PPTs. In previous tests, transient spikes in excess pore pressure were observed during each shaking cycle, accompanied by an overall buildup throughout the shaking period that increased with shaking intensity. These trends were captured reasonably well by the digital PPTs. Although the digital instruments recorded data at a lower rate than the analogue PPTs (sampling at 6000 Hz), the peak cyclic pore pressures measured by the digital PPTs fell within the range expected from the tests using analogue PPTs. The overall buildup of pore pressure across the shaking cycles was also consistent with the applied shaking amplitude.

These results indicate that the new digital PPT can effectively respond to high-frequency events. However, several sources of uncertainty lie outside the transducers' inherent functionality, including the limited sampling rate and the need to synchronise the digital PPT data with the analogue data.

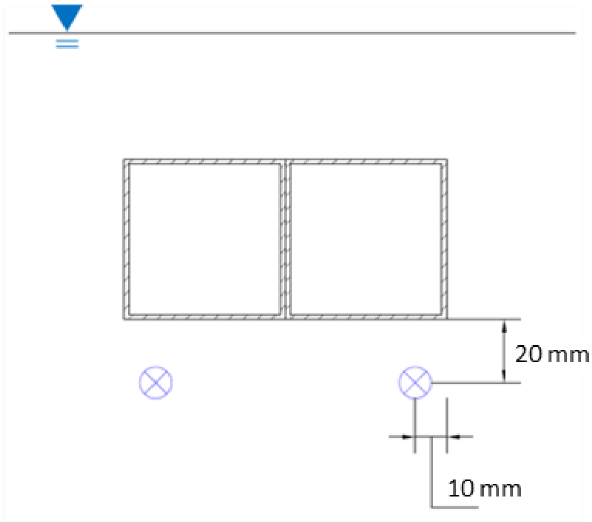


Figure 7. Clay model schematic with PPT locations.

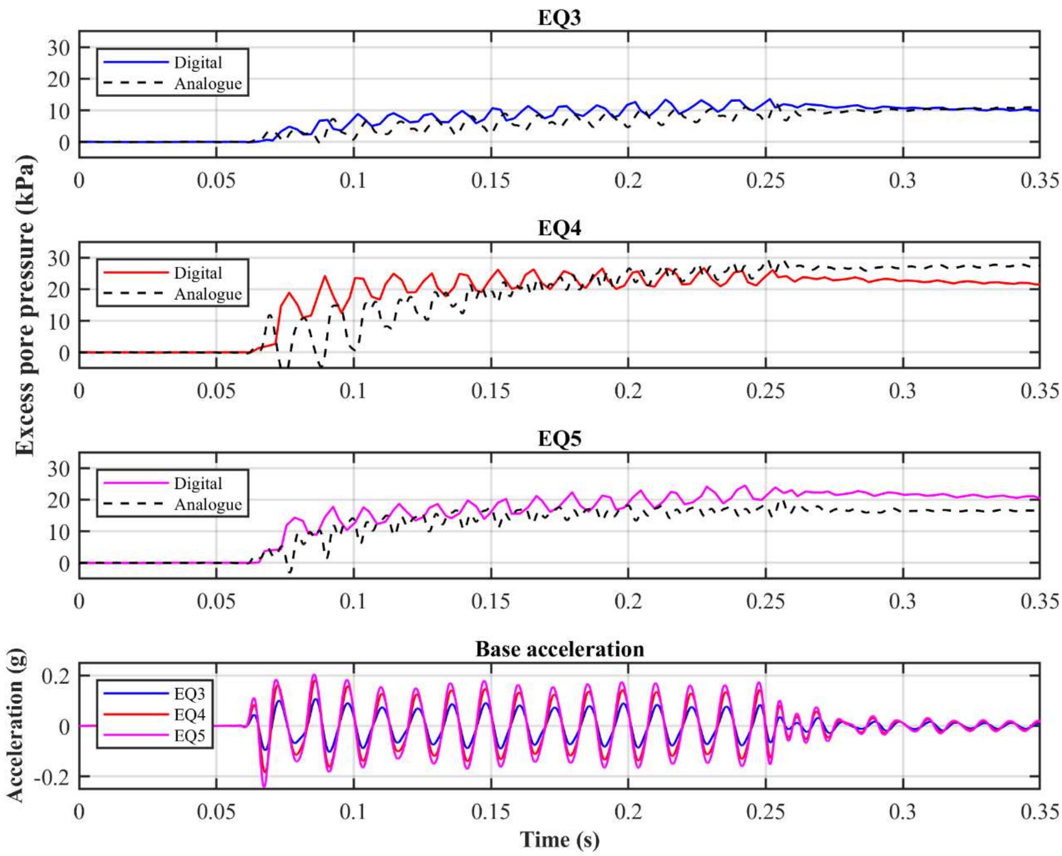


Figure 8. Dynamic excess pore pressure responses in the clay model.

6 CONCLUSIONS

This study presents a new digital pore pressure transducer (PPT) and assesses its behaviour through a series of experiments. Calibration results show stable offsets, linear pressure response behaviour. In static centrifuge tests, the digital PPT recorded swing-up loading effects and excess pore pressure dissipation in close agreement with the Druck PDCR-81. Although the device has relatively low sampling resolution compared to analogue PPTs, dynamic tests demonstrated that the sensor could capture the main trends of cyclic pore pressure generation in both sand and clay model.

To date, more than 20 digital PPTs have been produced and used in multiple centrifuge tests. The cost of each transducer, including cables and connectors, is less than £ 40, excluding labour cost and time. The PPTs remained in good condition during these tests, with no evidence of damage and no change in output stability or sensitivity. These results show that the new digital PPT is a robust, low-cost, and practical alternative for routine use in geotechnical physical modelling.

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