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A LOW-COST MINIATURE IMMERSIBLE PORE WATER PRESSURE TRANSDUCER

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The ability to measure pore water pressure accurately in geotechnical models is vital for allowing researchers to quantify effective stress and, frequently, its temporal variation. The earliest use of electrical devices to measure pore water pressure in specific locations within a model employed a standard laboratory pressure transducer located outside the boundaries of the model connected to tubing inserted into the model. However, this technique was superseded by the development (some 40 years ago) of submersible miniature pore water pressure measuring devices that could be located within a model to measure pore pressure directly at specified locations. In particular, miniaturisation allowed these transducers to be used in small scale centrifuge models. This facilitated, across the full spectrum of geotechnical engineering modelling, both enhanced understanding of mechanisms, by permitting quantitative analysis, and validation of numerical techniques. The earliest miniature transducers, the PDCR81 device manufactured by Druck, rapidly became universally adopted by the geotechnical modelling community. The production of this device was halted about 10 years ago, but other manufacturers have developed similar miniature pore water pressure transducers. Whilst the newer devices have been demonstrated to be effective their unit cost is relatively expensive; owing to the low volume of manufacture. This can result in forced limitations in the number that may be in a model, or a reluctance to use them in zones of models where they might be damaged. The requirement for a cheaper but equally reliable device prompted the work described in this paper. This is now achievable because of the development for the consumer market of a mass produced robust, immersible pressure device that has a very low unit cost. The paper will describe the development of a miniature transducer, employing this device, that can be located within models in a similar way to the PDCR81.

INTRODUCTION

Pore pressure transducers are often used in physical modeling in geotechnics and are essential for inferring changes in effective stresses at key locations. Following the discontinuation of the Druck PDCR81 transducers there were a limited supply of pore water pressure transducers at the geotechnical research center at City, University of London. Wang et al. (2012) and Stringer et al. (2014) among others have both produced new transducers in response to the halt in production of the Druck PCDR81. The use of a cheap mass-produced pressure sensor by TE connectivity was deemed as a potential alternative pore pressure transducer (with the design of a suitable casing) that could be used to create a low-cost submersible pore pressure transducer for centrifuge modelling. This TE connectivity sensor has previously been used in centrifuge model testing as a wall mounted pressure sensor at the University of Western Australia (e.g., Fiumana et al., 2018).

Already proven its ability to work inflight under increased g-levels this paper details of the design of the PPT casing, the deairing and installation procedure to turn a pressure sensor into a submersible pore pressure transducer that can be used in centrifuge modelling.

TE CONNECTIVITY MINIATURE SMD PRESSOR SENSOR

The University of Western Australia have successfully used the TE connectivity pressure sensors in centrifuge modelling as surface mounted pressure sensors on buried structures (Fiumana et al., 2018). The TE connectivity pressure sensors are mass produced pressure sensor primarily used in divers' watches, pneumatic braking systems, and high accuracy electronic scales. TE connectivity manufacture 4 different pressure sensors to cover three absolute pressure ranges of 0 to 1,7 and 12 bar and in either high sensitivity or high linearity versions. The sensors available to purchase are shown in Table 1 (from TE connectivity data sheet). Irrespective of the sensor model the size and the construction of the sensors remains the same. Figure 1 also taken from the TE connectivity data sheet shows the dimensions of the pressure sensors. Importantly for the use of the pressure sensors as a submersible pore-water pressure transducer (PPT) the sensing element is housed in an anticorrosive and antimagnetic containing ring that is filled with silicone gel that allows for direct contact with water. The manufactures note that although the front of the senor is waterproof it is imperative that the back of the sensor is sealed to prevent water from getting to the contact pads on the back of the transducer as this will permanently damage the sensor. The most suitable sensor to be used as a pore-water pressure transducer in centrifuge modelling at City, University of London, with the design of a suitable casing and filter, is the MS5407-AM, a 7-bar high sensitivity transducer. The electrical properties of this transducer are shown in Table 2.

DESIGN OF THE CITY, UNIVERSITY OF LONDON PORE WATER PRESSURE TRANSDUCER

The design of the pore-pressure transducer casing is inspired by the Druck PDCR81 with several similarities between the designs. Figure 2 shows the design of the City, University of London pore water pressure transducer. The design of the casing ensured that the overall size was as small as possible however, this was largely dictated by the size of the pressure sensor itself. The Druck PDCR81 has an overall length of 19mm and a diameter of 6.4mm. The City, University of London PPT has an overall length of 18mm and a diameter of 9.5mm; a potential limitation in the use of the TE sensitivity pressure sensors. The City, University of London PPT shell is manufactured from stainless steel rod on a CNC lathe. The two sections of the PPT casing are joined together using an adhesive potting compound, this provides a robust adhered joint but also prevents water penetration into the contact pads of the transducer through the cable exit port. Water is prevented from penetrating beyond the diaphragm by the use of an O ring which is placed between the containing ring of the transducer itself and the fabricated PPT casing. The porous stone is made from Celleton V1; a silica-based ceramic with a 1micron pore size and an air entry value of 2 bar. It is supported by the containing ring and is secured in place using a very small amount of epoxy resin around the perimeter of the stone. These stones are the same size and thickness as the porous stones used in the Druck PDCR81 transducers. Manufacturing new stones proved difficult owing to the practical problem of the tendency of the material to fracture when machined. Special precautions when machining the material were necessary because of the health implications related to generation of silica dust. In view of this, the new filters were manufactured by a specialist ceramic supplier (Precision Ceramics) who were able to grind the new porous stones to an accuracy of ±0.1mm.

Table 1. TE connectivity pressure sensor models available

		High sensitivity versions			High linearity versions		
Carrier	Full scale pressure	Product code	Full span cycle	Linearity	Product code	Full span cycle	Linearity
Ceramic	1 Bar	MS5401-AM	240 mV	±0.20 % FS	MS5401-BM	150 mV	±0.05 % FS
	7 Bar	MS5407-AM	392 mV	±0.20 % FS			
	12 Bar				MS5412-BM	150 mV	±0.05 % FS

Table 2. Electrical characteristics of the TE connectivity MS5407-AM selected for the City, University of London pressure tansducer

Model	Parameter	Min	Typ	Max	Unit
MS5407-AM	Operating pressure ranges	0	-	7	Bar
	Full-scale span (FS)	322	392	462	mV
	Sensitivity	46	56	66	mV
	Linearity		±0.15	±0.40	% FS
	Operating temperature range	-40	-	125	°C
	Zero pressure offset	-40	0	40	mV
	Pressure hysteresis	-	-	±0.20	% FS
	Temperature hysteresis	-	0.3	0.8	% FS
	Repeatability	-	-	±0.20	% FS
	Bridge resistance	3	3.4	3.8	kΩ
	Temperature coefficient of resistance	+2'400	+2'900	+3300	ppm/°C
	Temperature coefficient of span	-1'500	-1'900	-2'300	ppm/°C
	Temperature coefficient of offset	-80	-	+80	µV/°C

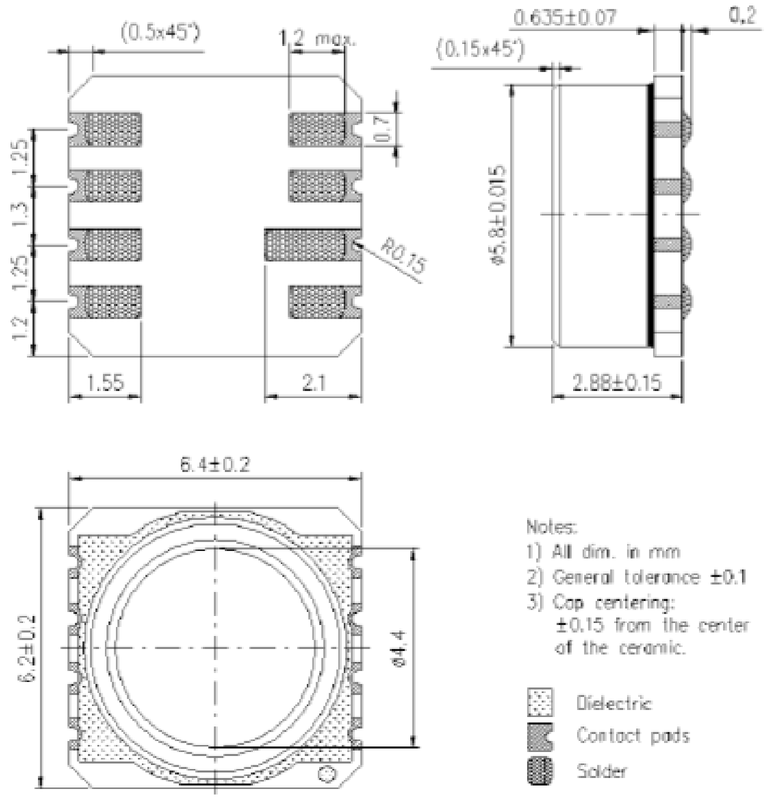

Figure 1. Drawing with dimensions of the TE connectivity pressure sensors

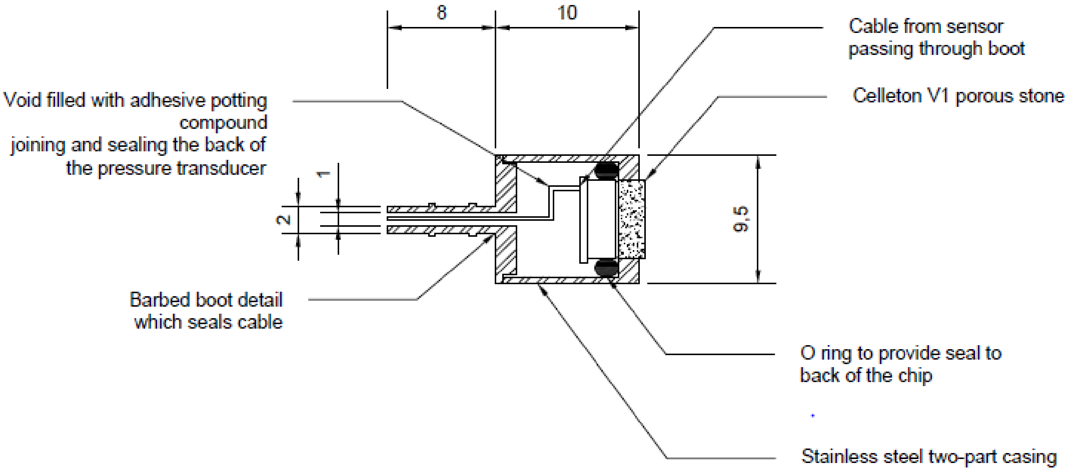

Figure 2. A cross section through the City, University of London Pore water pressure transducer highlighting key features, note that the dimensions shown are in millimeters.

At City, University of London centrifuge instrumentation is connected to the data acquisition system using a LEMO connectors. Finding a low-cost four core cable to connect the LEMO connector and PPT with a similar diameter to the Druck PDCR81 cable also proved to be challenging. Manufacturers of suitable cables tended to require minimum orders of 1000m of cable with an associated excessively high cost. A more economical solution was found by manufacturing a homemade cable from 29swg strain gauge cable and heavy wall Teflon tubing with a 0.4mm wall thickness and 1.75mm outer diameter (supplied by Adtech). The strain gauge cable was pulled through the Teflon tubing to create a 'low-cost' small diameter four core cable. It was found to be possible to stretch the Teflon tubing over the barbed detail of the boot of the PPT thereby preventing water entry into the cable portion of the transducer. As a secondary measure a sterling silver jump ring was secured over the Teflon tube and the tail of the PPT and this was then covered with a heat shrink tubing to ensure a seal around the boot of the PPT. Figure 3 is a photograph of a City, University of London PPT next to a Druck PDCR81 for comparison of size.

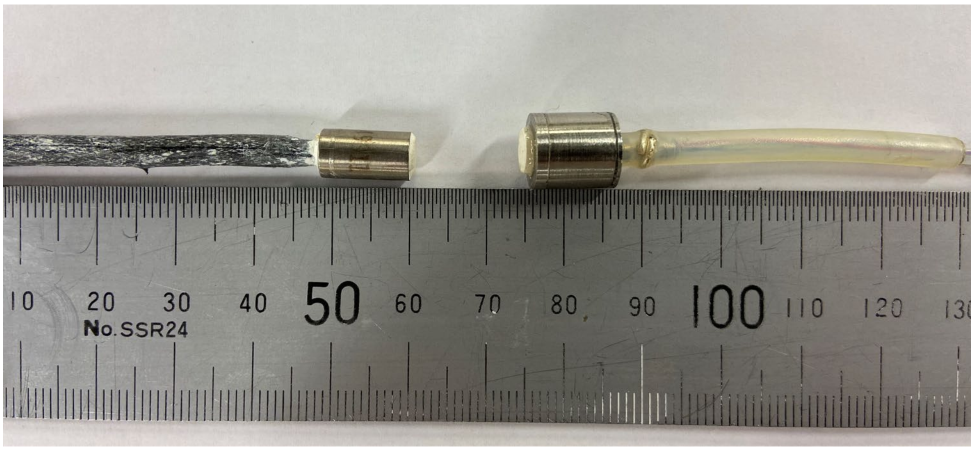

Figure 3. Shows a side-by-side photograph comparison of the Druck PDCR81 and the City, University of London PPT.

At City, University of London it has been common practice to install pore pressure transducers into a clay centrifuge model after it has been consolidated and subsequently swelled to its final effective stress in the hydraulic press. A similar system to that used previously has been adopted for the new transducers. Ports were machined into the centrifuge strongbox walls at appropriate locations at positions appropriate to the particular application. These ports are plugged during the consolidation period and prior to the installation of the pore pressure transducers. When installing the pore pressure transducers the plugs are removed and a guide is installed into the ports, a thin-walled seamless stainless-steel cutter is then used to create a horizontal bore through the strongbox wall to the mid-point of the soil sample. Using a 'slurry gun' a small amount of speswhite kaolin clay slurry at a water content of twice the liquid limit is placed at the end of the bore. A de-aired PPT is then placed into end of the bore and the void behind the PPT is filled with clay slurry using the slurry gun. Once full of slurry the port is sealed; this is achieved by using a standard Swagelok plumbing fitting on the PPT cable as seen in Figure 4. The seal is created by using a rubber tube which is compressed by a washer when the plumbing fitting is tightened over the cable. Once the pore pressure transducers are installed and sealed the soil sample is left to consolidate for a further

48 hours in the hydraulic press. This system has been found to provide a reliable seal with the strongbox and is essentially the same system that is used whilst deairing and calibrating pore pressure transducers.

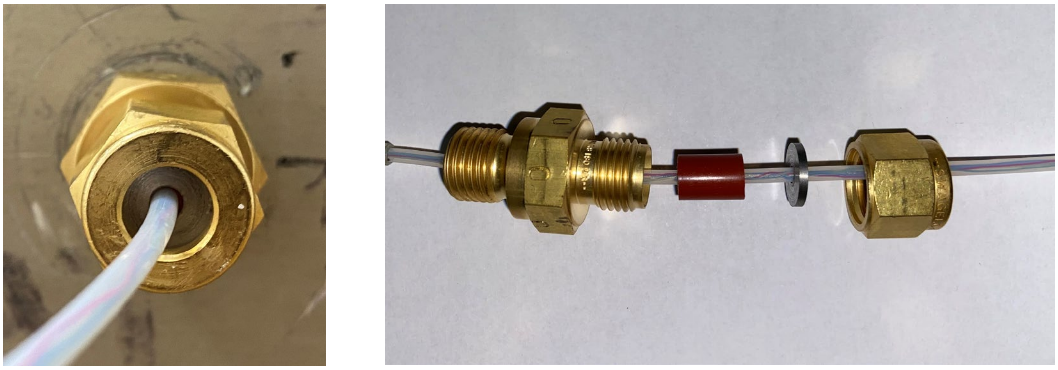

Figure 4. Shows a photograph of the of the Swagelok sealing system assembled and connected to the strongbox (left) and the components of the sealing system (right).

PERFORMANCE OF THE CITY, UNIVERSITY OF LONDON PORE WATER PRESSURE TRANSDUCER

Testing pressure transducers without porous stones at 1G

Prior to the manufacture of multiple pore pressure transducers and the placing of the porous stones the performance and the stability of the TE connectivity pressure transducers were assessed. These tests where carried out using an air compressor, an air-water interface, and a pressure cell such that the pore pressure transducers were held under a constant water pressure of 400kPa for a period of 5 working days. The water pressure in the test cell was measured and recorded using the centrifuge data logging system connected to the pore pressure transducers and a Druck digital pressure indicator used for calibrating pressure transducers. Over this period the maximum variation in water pressure recorded in the pore pressure transducers was less than 3kPa and the same variation in water pressure was also recorded by the Druck digital pressure indicator. The average water pressure readings over the 5 day period varied less than 0.5kPa between the pore pressure transducers and the digital pressure indicator. These tests highlighted that these pressure sensors have very little noise or drift when subjected to a constant pressure.

Saturation of porous stones

When used as a pore water pressure transducer instead of a water pressure transducer there needs to be a porous filter to prevent clay from damaging the sensor. Essential to getting a good response in the pore pressure transducers is to fully de-air and saturate the porous stones. A two-chamber system was developed to de-air, saturate and calibrate 8 pore pressure transducers at a time. The de-airing and calibration equipment is shown in Figure 5. In the left chamber the pore pressure transducers are installed and sealed using the Swagelok fittings and subjected to a vacuum to fully de-air; once de-aired the valve is closed to maintain the vacuum. Distilled water is placed into the right hand chamber and subjected to a vacuum and deaired, once de-aired the right hand chamber is closed keeping this chamber under a vacuum. The connecting valve between the chambers is then opened to flood the pore pressure transducer chamber with distilled de-aired water. The vacuum in the left hand chamber is then released so that the distilled de aired water saturates the porous stones. As a secondary check the pore pressure transducers are again subjected to a vacuum to determine if any air remains in the porous stones. In all tests, there was been no visible air bubbles removed from the pore pressure transducers; indicating that the system is suitable for de airing and saturating the porous stones. Once de-aired the pore pressure transducers were calibrated in the left hand chamber using the Bishop ram where the water pressure is recorded by both the pore pressure transducers and the Druck digital pressure indicator. The calibration of the pore pressure transducers with and without the porous stones was found to be very similar; indicating that the de-airing system is effective and that the pore pressure transducers are fit for purpose. When subjecting the PPT to a rapid increase in pressure the response of the PPT and the Druck DPI was instant. There was no measurable lag between the PPTs and the DPI when taking a reading every second again satisfying that the stones were fully saturated and they are fit for use as a PPT in a centrifuge experiment.

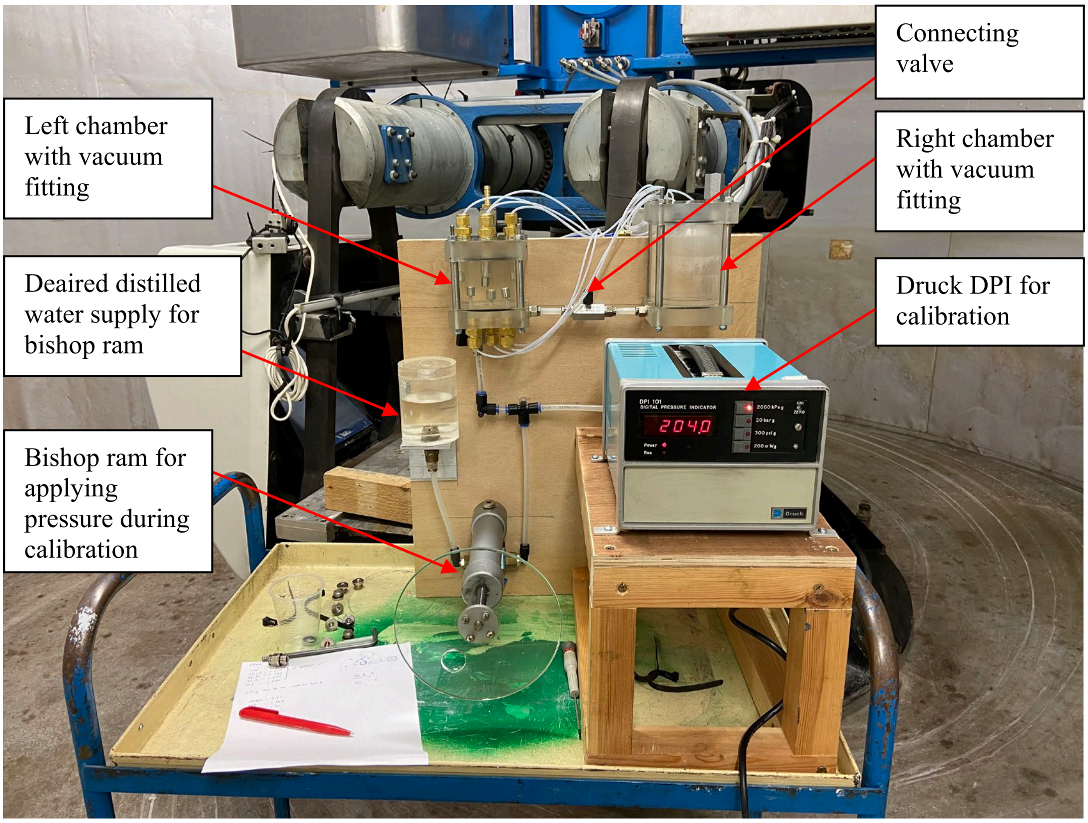

Figure 5. A photograph of the deairing and calibration apparatus developed.

Testing the City, University of London PPT's inflight

A demonstration centrifuge test was conducted to determine the performance of the City, University of London pore pressure transducer in-flight using a Speswhite kaolin clay model. This was prepared by mixing Speswhite kaolin powder supplied by Imerys Ltd with distilled water to a water content of twice the liquid limit (120%). This model was consolidated to a maximum stress of 500kPa and swelled to stress of 250kPa. Eleven pore pressure transducers were installed at a various horizons in the manner described above. The Speswhite kaolin model containing pore pressure transducers was placed on to the centrifuge swing and a ground water regime was imposed using a standpipe connected into the base drain of the centrifuge strongbox. The height of the water table was set to 10mm below the ground surface level. The centrifuge was then accelerated to 100g for 2 working days (44 hours of increased g level). The response of the pore pressure transducers were recorded every second during the centrifuge acceleration procedure and then every 5 minutes for the next 44 hours. The response of one of the instruments to the acceleration of the centrifuge can be seen in Figure 6 whilst the final ground water profile at the end of the 44-hour centrifuge test is shown in Figure 7.

Figure 6 shows the trend of one of the pore pressure transducers over time, all pore pressure transducers showed the same trend and only is shown for clarity. Initially after removing the sample from the press the soil is in suction and this is recorder by all the transducers the recorded pore pressure varied between -95kPa and -45kPa. During the acceleration of and the running of the centrifuge the pore pressure transducers recorded an initial rapid increase in pore water pressure and over time the rate of increase of pore pressure reduces until the centrifuge model reaches equilibrium with the standpipe water supply. Across all transducers there was a delay in response of the pore pressure transducers. This could be due to two main reasons; firstly, the sensors are sold with a working range of 0-7bar absolute pressure, the soil theoretically should, prior to spin up on the centrifuge, be under a suction 250kPa. This means that the transducer may have been out of range and could not record the changes in pore water pressure during this time. Secondly there may have been cavitation in the pore pressure transducers. Although every effort is made to deair and saturate the porous filters it is not possible to say all the air is removed and secondly the speswhite model is made with distilled water which has not been de-aired both of which could lead to cavitation. If cavitation occurred, when the pore pressure was smaller than -95 kPa only the vapour pressure was being measured until the pore pressure increased above -95 kPa. This is a potential limitation of the device however, a Druck PDCR81 transducer would suffer the same limitation.

The measured ground water profile determined from the array of PPTs at different horizons at the end of the demonstration test was very close to the theoretical ground water profile as seen in Figure 7. Towards the bottom of the model the measured and theoretical values of pore water pressures are essentially the same. Towards the top of the sample the measured pore-water pressure is slightly less than the theoretical values meaning the gradient of the ground water profile was less than hydrostatic as can be seen from the equation of the line of best fit. This can be explained as the sample had not reached equilibrium yet and that if the centrifuge model was left for longer on the centrifuge the PPT's would read closer to the theoretical values of pore-water pressure. Nevertheless, the results obtained from the demonstration experiment was very promising and highlighted that it is possible to create a low-cost submersible PPT using a TE connectivity pressure sensor that can measure the pore water response to inflight consolidation.

CONCLUSIONS

These tests show that the City, University of London PPTs can:

- Be produced using mass produced ‘low-cost’ components
- Provide stable and reliable measurements of pore water pressures
- Potentially measure negative pore water pressures smaller than 90 kPa
- Be used to monitor the changes in pore water pressure during consolidation and swelling of a centrifuge model inflight
- Observe the imposed ground water regime of a centrifuge model

To date a total of 15 PPT’s have been produced in a couple of weeks with the components of each transducer, cables and connectors costing less than £100 each (not inclusive of machining and assembly time). To buy 15 pore pressure transducers it would cost in the region of £25,000. This PPT solution can save a considerable amount of money and has the added benefit of inherent flexibility when designing centrifuge tests. Buying the sensor independently allows for pore pressure transducers to be incorporated into geotechnical structures as in the University of Western Australia (e.g., Fiumana et al., 2018) and to be buried as submersible PPT’s to suit the specific geotechnical problem. The only limitation so far in comparison to the Druck PDCR81 is the increased size of the PPT body and the potential influence this has on the geotechnical problem.

To date the most used City, University of London PPT has been pressured for approximately 450 hours. Over this time there is no visible signs of deterioration of the PPT and from the results obtained there is no change in PPT output stability or sensitivity. However there has not been sufficient testing time to fully assess the long-term performance and reliability of the City, University of London PPT. With the testing schedule planned over the next year at the multi-scale geotechnical research Centre at City, University of London there will be the opportunity to assess the long-term performance of the new PPTs, and their response to a variety of different geotechnical construction events.

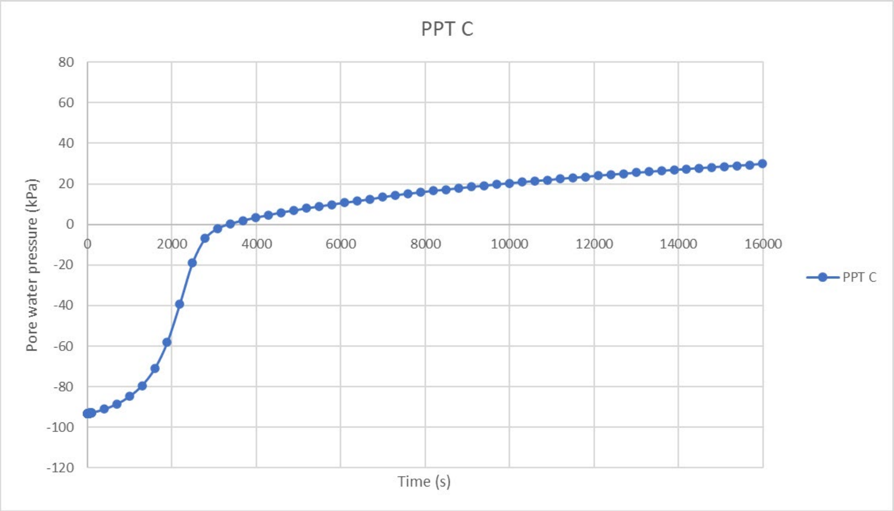

Figure 6. Response of a City, University of London PPT to the acceleration of the centrifuge

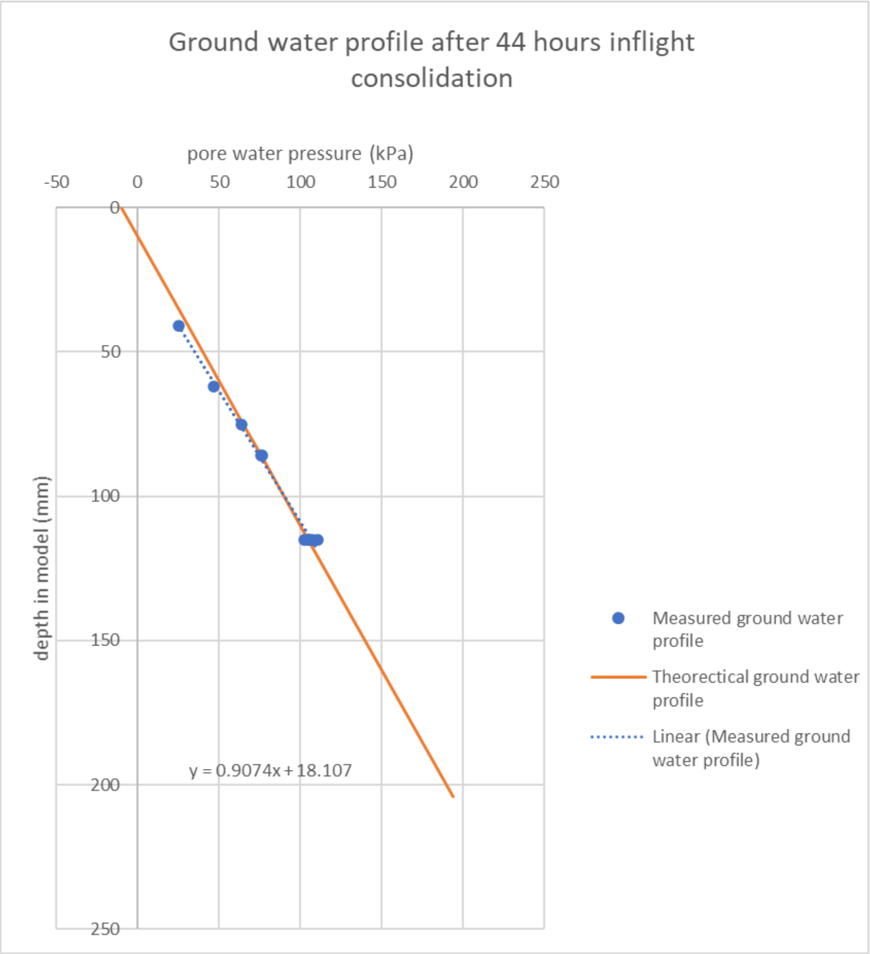

Figure 7. Ground water profile recorded by PPT after 44 hours of inflight consolidation

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