The miniature wireless data-logger for pressure measurements in geotechnical applications

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TECHNICAL NOTE

The miniature wireless data-logger for pressure measurements in geotechnical applications

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KEYWORDS: centrifuge modelling; laboratory equipment; laboratory tests

INTRODUCTION

Stresses are applied or altered during construction, and the ground responds in the form of deformation. The engineering behaviour of the ground can be studied thoroughly when information is available on both the stresses and the strains. In cases where only stresses are known, strains can be predicted using powerful constitutive modelling. An adequate knowledge of the stress conditions is therefore essential for predicting the performance of ground with reasonable confidence. Various methods are currently used to measure stresses and strains in soils.

The water (or fluid) pressures can be measured using a pore pressure transducer, and total pressures using pressure cells, while displacement measurements can be used for strain measurements. Most transducers are excited using a.c. or d.c. power, and the output signals are collected through external data-loggers, which inevitably involve wiring, regardless of whether the measurements were made in the field or in the laboratory. Frequently, particularly in large-scale applications, the performance of the soil is influenced by the presence of buried cables. Excessive ground deformations can also lead to cable damage (McKenna *et al.*, 1975). In this respect the development of wireless sensors has great potential in geotechnical engineering. Wireless sensors would be beneficial in small-scale geotechnical centrifuge testing. In traditional geotechnical centrifuge systems the signals from the transducers are relayed to the external sources using electrical slip rings on the rotating shaft. This can involve high levels of noise, and this noise level has been reduced by converting signals to digital form 'in flight' using analogue-to-digital (AD) converters placed on the rotating arm close to the shaft. In small-scale geotechnical centrifuge modelling using laboratory centrifuges the electrical slip rings and associated wires within the centrifuge can interfere with the equipment's safety interlocks (e.g. Evans, 1994) as well as provide additional restraint on the models. Mitchell (1998) reviewed the range of applications of both large and small centrifuges for geoenvironmental applications, highlighting centrifuge work's suitability for problems of permeability measurement, consolidation and contaminant transport.

This technical note reports the early development of a miniaturised probe for pressure measurements for total pressure and pore water pressure. The probe consists of a pressure sensor, a power supply, an AD converter and a data-taker/data-receiver. The probe discussed in the paper allows the data to be stored at preselected intervals for subsequent downloading, although research continues on relaying the data using radio control for near-real-time monitoring. This technical note provides information on the design, calibration and possible use of the probe in a laboratory-based centrifuge.

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DEVELOPMENT, CALIBRATION AND ASSESSMENT OF THE MINIATURISED DATA-LOGGER

Equipment development

The data-logger consists of a pressure cell, a stamp-micro-controller, signal conditioning circuitry and a power supply. A miniaturised hollow stainless steel pod houses the power supply and stamp-micro-controller, and the pressure cell is mounted on the probe head. The pod can be easily opened in order to change the battery or to download data. Three different configurations were considered. Fig. 1(a) shows configuration 1, which has a flat head and uses an Ellison International Ltd PC18 type 5 bar pressure cell of 18 mm diameter. Configuration 2 has a tapered head shown in Fig. 1(b), to reduce possible boundary effects, and uses an FGP Ltd XPM10 type 10 bar pressure cell of 8 mm diameter. The pod diameter is 25 mm and the height is 90 mm in this configuration. Fig. 1(c) shows configuration 3, with a reduced probe height of 18 mm and diameter of 70 mm. It uses an Ellison International Ltd PC18 type 5 bar pressure cell of 18 mm diameter.

Both pressure cell types operate on the excitation of 7·2 V d.c. with a maximum output voltage of 100 mV. An operational amplifier is used to increase the maximum output voltage to 4·4 V. Analogue signals are converted to digital form using a 12-bit AD converter. A battery powers the circuit, giving the miniaturised data-logger a three week lifetime. The stamp-micro-controller controls the electronic system and data collection. The system switches 'ON' at predefined time intervals, collects data, and then switches to sleep mode, which saves battery power. The logging interval can be changed by the user. At present data are manually downloaded at the end of the test using Stamp-DAQ software by way of a serial port on the probe. However, research are continuing into the development of data transmission by way of radio signal.

Calibration of the probe

The pressure cells were calibrated using the manufacturer's standard procedures. The calibrations were then checked by subjecting the probes to known pressures. The miniaturised probe was placed inside a water-filled hydraulic chamber and the pressure was ramped from 50 kPa to 450 kPa over three days. The pressure was measured using the probe and an existing sensor in the hydraulic chamber.

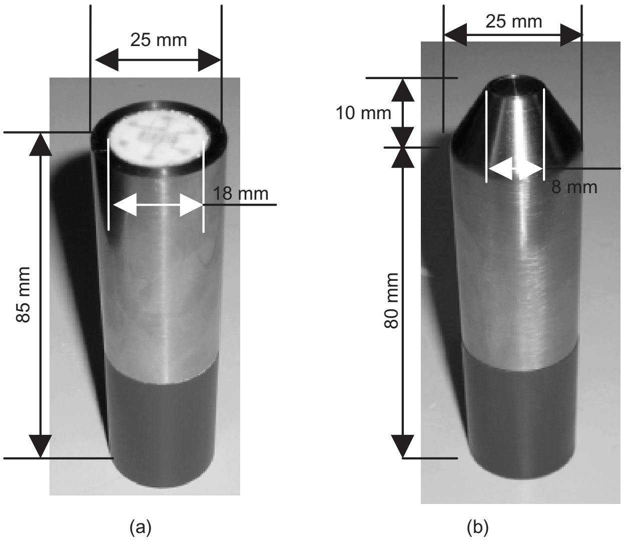

Fig. 1. Miniaturised probe configurations: (a) configuration 1; (b) configuration 2; (a) configuration 3

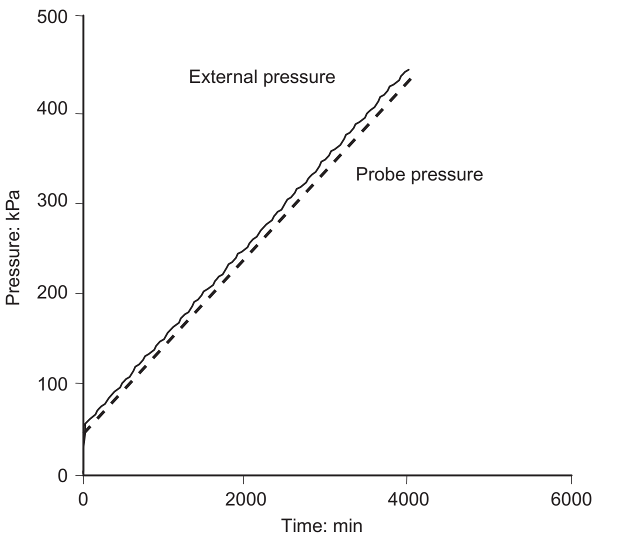

Fig. 2. Probe pressure and external pressure measurements against time

Fig. 2 shows the pressure measured by both the probe and the existing sensor, plotted against time. Aside from a slight offset in the measurement, the probe measured the pressures accurately. This good agreement paved the way for the assessment of the device in geotechnical applications.

Assessment of the miniaturised data-loggers

The miniaturised data-logger was tested in a clay deposit subjected to a known consolidation pressure. A 250 mm diameter by 500 mm high consolidation chamber (Fig. 3) was used for this purpose. The chamber was instrumented with two XPM10 type pressure cells located diametrically opposite on the cylindrical surface, 75 mm above the base. A pressure cell was also located on the chamber base. The consolidation pressure was measured using a standard pressure transducer located on the pressure line connecting the regulated air supply to the chamber. A displacement gauge measured the clay compression. The readings were taken using a DT50 data-recorder. The probe was located in the chamber with its pressure cell facing upwards (Fig. 4(a)). The chamber was filled with 21·5 kg of commercially available speswhite kaolin slurry (prepared at 1·5 times liquid limit) to a height of 300 mm. The slurry was subjected to a small vertical pressure for a short period; subsequently the pressure was increased to 200 kPa and the slurry was allowed to consolidate.

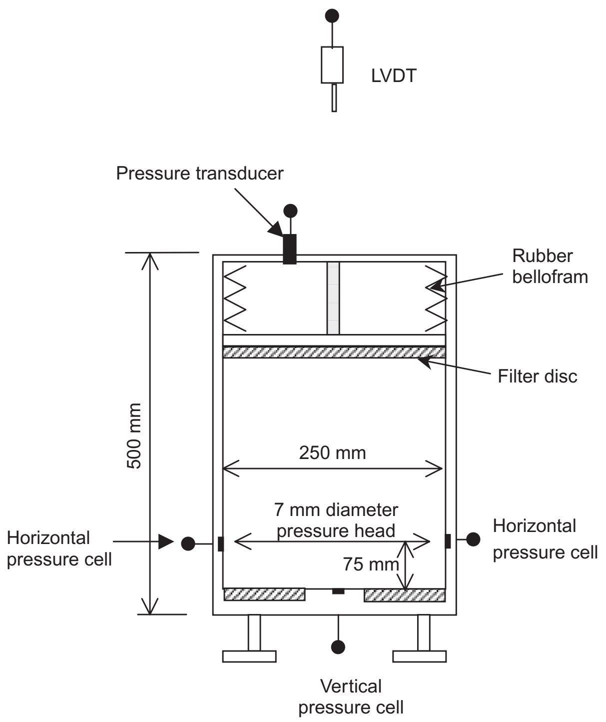

Fig. 3. Testing chamber

Various tests were performed, including a repeat test. The effect of changing the probe head shape was examined using probe configuration 2. The probe was located in the clay as shown in Figs 4(a) and 4(b), where the probe was allowed to rest on the base of the chamber, slightly away from the pressure cell located on the consolidation chamber itself. The ratio of the probe height to the clay bed thickness, H_p/H_c, was around 0·3 at the beginning of the tests. This ratio has a significant influence on the pressure measurements. In one of the subsequent tests, the probe configuration 3 was located in the clay bed as shown in Fig. 4(c). In order to avoid the probe sinking into the clay slurry, two 250 mm diameter filter papers were placed on the top surface of the slurry when the chamber was filled to 150 mm height of slurry. In this case the ratio H_p/H_c reduced to 0·06 when the clay was in slurry form.

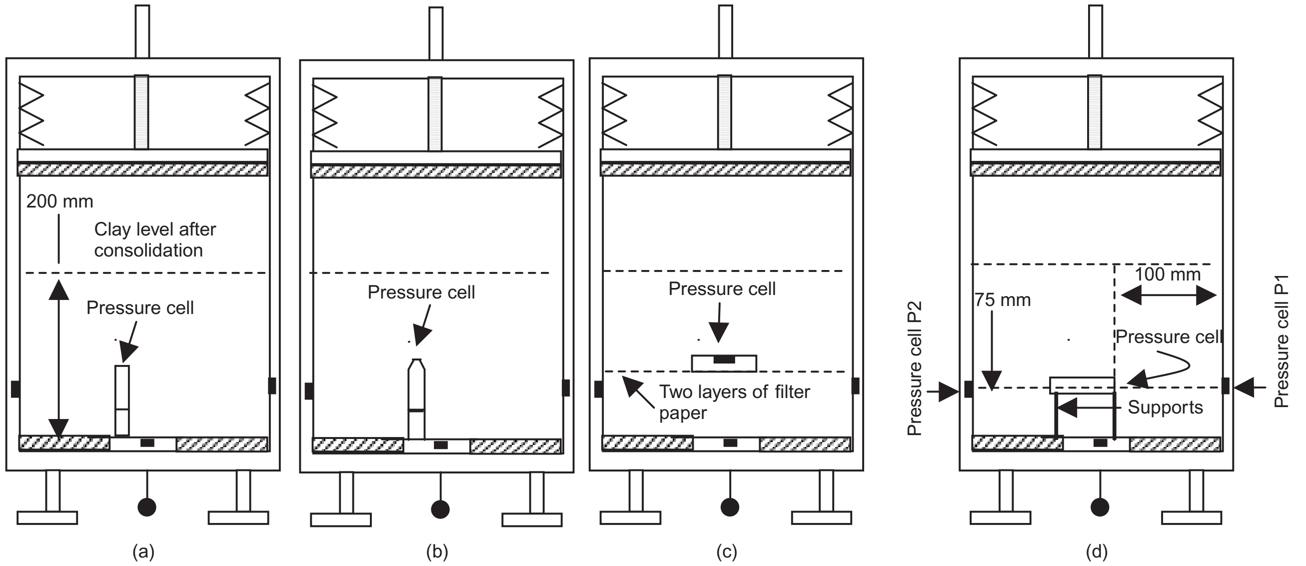

Fig. 4. Probe positions in the testing chamber

The slender probe (configuration 1) was also used to measure the lateral pressures in the clay bed. It was located horizontally at 75 mm above the base, with the probe head facing one of the pressure cells located on the chamber (Fig. 4(d)). A thin wire cradle supported the probe to prevent the probe position moving away from the location of the pressure cells located on the consolidation chamber. Once again the clay was consolidated to 200 kPa for four days.

Geotechnical centrifuges are frequently used to perform geotechnical modelling tests. Existing instrumentation is often complex and installation is time consuming, owing to the problems associated with signal retrieval. Verifying the transducer's ability to perform under elevated gravitational acceleration will have a significant impact on the way centrifuge tests are performed with this probe. Note that it is not proposed that the probes described be buried in clay models in centrifuge testing. The intention is to simplify the data collection using the proposed probe in standard laboratory centrifuges. As part of the work, the probe was tested in a benchtop laboratory centrifuge in order to assess its performance under elevated gravity.

RESULTS AND DISCUSSION

In Test 1 the probe was placed in a one-dimensional loading chamber filled with clay slurry consolidating under 200 kPa. The clay gained strength during consolidation, causing the side friction between the clay and the chamber to increase. Thus the vertical pressure at the base of the sample reduced significantly. The vertical pressure measured at the top and the pressure measured using the pressure cell located at the base were used to determine the approximate pressures at the heights where the probe pressure cell was located. This was carried out assuming that the pressure varies linearly from the top to the bottom, although variation is non-linear. The relevant vertical compression of the sample was taken into consideration in such calculations. Fig. 5 shows the pressures measured by the probe together with the evaluated pressure plotted against displacement. The difference between the two pressures was significant and was confirmed by a repeat test, which also validated the repeatability of the probe measurements. The change in the shape of the probe head (from 'flat' to 'tapered') failed to rectify the problem, as shown in Fig. 6. Owing to difficulties encountered with the continuous displacement measurements the relevant pressures are plotted against time in this case.

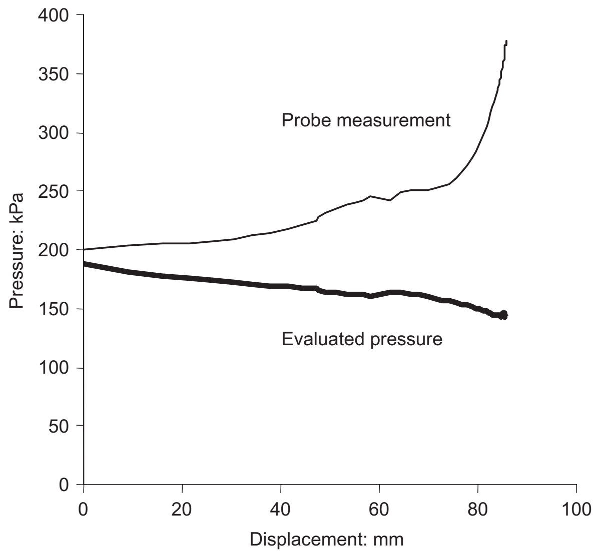

Fig. 5. Probe pressure readings and evaluated pressure against vertical displacement (flat probe head)

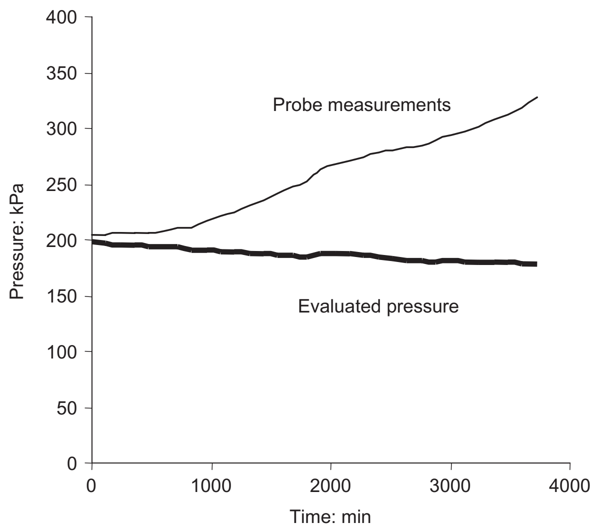

Fig. 6. Probe pressure readings and evaluated pressure against time (tapered probe head)

In these tests the loading applied at the top of the chamber was though a rigid boundary condition. In another test, not reported here, a water-filled flexible bag was located between the sample and the top plate, and it again showed a significant variation between the measured and evaluated pressures.

In the aforementioned cases the probe was measuring the actual pressures close to the pressure head, although the differences are due to the bearing resistance developed at the tip of the probe. Fig. 7(a) shows a sketch of the probe in the chamber. The ratio H_p/H_c increased from 0·3 at the start of the loading to 0·5 by the end of the loading. A steel plate was located on top of the clay, creating a rigid boundary condition: therefore the clay below was subjected to an equal amount of compression. Since the probe was rigid it generated a significant amount of bearing at the probe head. This situation can be compared with a rigid pile failing on an 'end bearing', although any mobilisation of side friction between the probe and the surrounding clay has no relevance here, since what happens in the clay above the probe head determines the relevant pressure measurements. Fig. 7(b) shows a possible vertical pressure distribution on a horizontal plane above the probe. It can be reasonably assumed that the vertical pressure away from the probe head may be equal to the evaluated pressure measurements. At the end of the tests the difference between the vertical pressures was as high as 200 kPa. This difference corresponds reasonably with the possible end-bearing pressure, assuming a pile failure mechanism with the undrained shear strength of the clay around 30 kPa.

The probe with thin base (configuration 3) significantly reduced the problem outlined above. Referring to the previous statement, the probe was allowed to float in the slurry at 150 mm above the base. As the consolidation progressed, the position of the probe changed, although the subsequent examination revealed that the probe remained horizontal until the end of the test, and the position of it was approximately 100 mm above the base. Fig. 8 shows the probe measurements and the linearly interpolated pressure measurements taken using the pressure cell located at the base and in the loading chamber. The pressures recorded by the probe were very similar to the estimated values and give confidence for future applications of the probe. The problem encountered in the above cases still persists with the flat probe, but the consequences are minimal.

Probe configuration 1 was also used to measure horizontal pressures. The pressure cell of the probe was oriented opposite pressure cell P1 located on the loading chamber with the probe tail end facing pressure cell P2. The distance between the probe's head and P1 was 100 mm (referred to as passage 1) and that for P2 and the tail of the probe was 65 mm (and referred to as passage 2). Fig. 9 shows the pressure measurements recorded by P1 and P2 and the probe plotted against vertical compression. The differences in the pressures can be explained using a simple arching mechanism developed in the passages between P1 and the probe's head and P2 and the tail end of the probe (Fig. 10). The width of the passage determines the degree of arching. In this respect the arching effects in passage 1 will be less than those in passage 2, and consequently the pressure measurements by P1 will be higher than those of P2. The experimental evidence reported in Fig. 9 supports this argument. The pressure cells located on the chamber walls experienced 'at rest' pressures. However, owing to the difference in the pressures in passage 1 and passage 2 the probe will attempt to move horizontally, making the head, where the pressure cell is located, become the active front, and consequently the clay adjacent to it would move with it. This justifies the decrease in the probe's pressure measurements compared with P1, yet the pressures remain above those of P2.

The ability of the probe to perform under elevated accel-

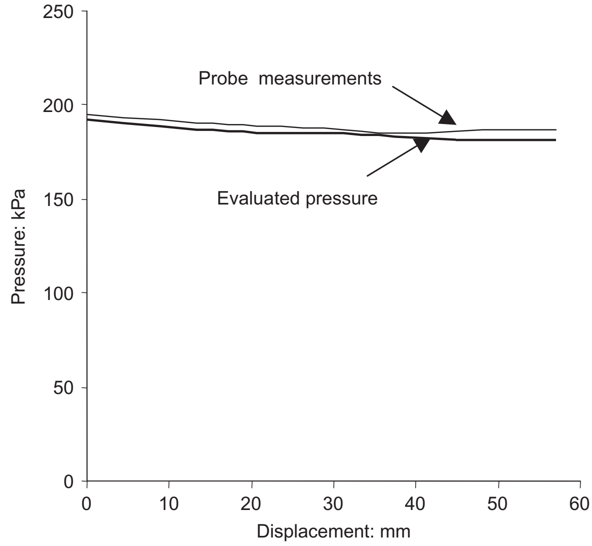

Fig. 8. Flat probe pressure readings and evaluated pressure against vertical displacement

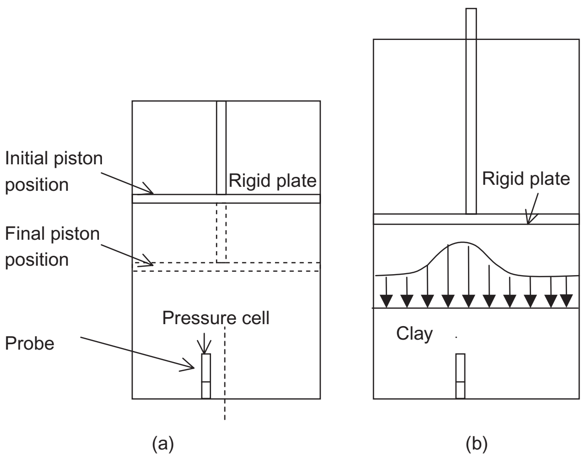

Fig. 7. Probe location and vertical pressure distribution in the clay bed

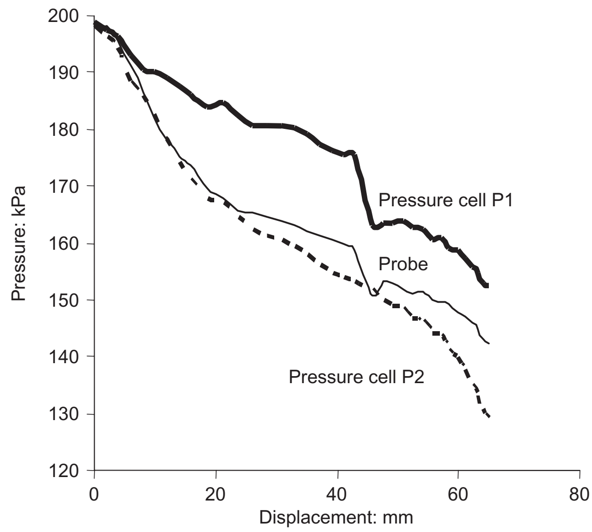

Fig. 9. Probe pressure and external pressure cell readings with vertical displacement

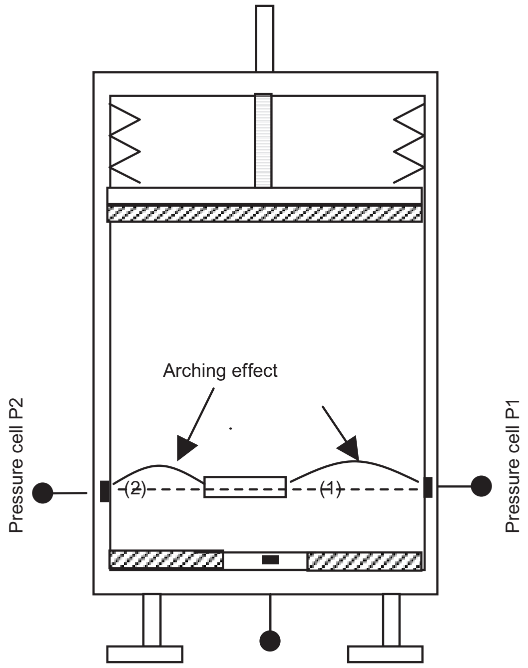

Fig. 10. Probe position and arching effect during Test 5

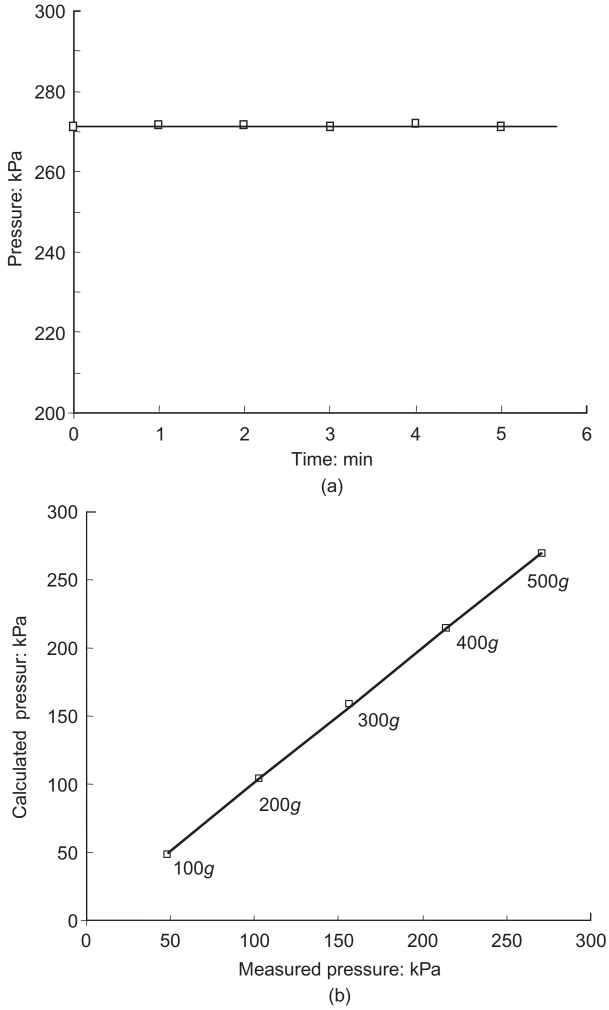

Fig. 11. Probe performance under elevated acceleration

eration was also examined using a laboratory centrifuge. The laboratory centrifuge used in the present study has four cups having 0·75 l capacity each. The maximum radius of the rotation is approximately 21·8 cm. The probe with configuration 3 (Fig. 1) was located at the base of one of the cups and filled with a column of water. The other three cups were filled with water, and it was ensured that the masses were equal within a tolerance of 0·1 g. Fig. 11(a) shows the pressure measured by the probe under a gravitation of 500*g* and its stability with time. Fig. 11(b) shows the relationship between the calculated pressure and the measured pressure using the probe. The pressure was calculated using the centrifugal acceleration and the height of water column above the probe in the cup. Consideration was given in the calculation of the pressure to the varying nature of acceleration along its radius. Fig. 11(b) shows excellent agreement between the calculated and measured pressures.

APPLICATION OF THE PROBE

The miniaturised probe and data-logger operate well under severe acceleration, reading and storing the pressures for subsequent downloading. The data-logger in the present configuration is used for pressure measurements. However, the technique reported here would also allow many other forms of measurement to be taken and recorded, including displacement, pH, electrical conductivity, strain, noise level and temperature. Understandably each of these would demand slightly different forms of electronic configuration inside the probe.

One imminent application of the probe is in centrifuge testing. Obviously, the boundary effects when the probes are buried in the soil bed are a concern, as under elevated acceleration the thickness of the probe will be significant. However, the merit of the probe refers to the use of it in centrifuge as a means to an 'on-flight' data collection unit. Celorie *et al.* (1989) used a falling-head permeameter cell in a laboratory centrifuge to measure water flow and contaminant transport in kaolin. Sharma & Samarasekera (2007) and Singh & Gupta (2002) have used a laboratory-based centrifuge for permeability measurements. The flow in and out of the sample was measured by taking digital photographs through a window located on the centrifuge. Khanzode *et al.* (2002) used laboratory centrifuge for establishing soil-water characteristics. Once again the measurements were taken after bringing the centrifuge to a halt. The probe proposed in this paper offers a viable and reliable means of data collection in a small laboratory centrifuge. The study currently in progress at Queen's University Belfast uses this device for in-flight data collection during a permeability test in laboratory-based centrifuges.

CONCLUSIONS

A probe with a miniaturised internal data-logger has been developed and checked for soil pressure measurements in a soil bed. The probe performance was initially examined in the laboratory environment. The flatter probe performed most satisfactorily. The probe performed well under severe gravitational acceleration, generating a possible application in centrifuge testing, to drastically reduce the complex data collection system currently adopted. The present device was developed only for pressure measurements (including pore water pressure), although it can be easily modified for strain measurements as well as others. The research continues, to advance the device further in order to incorporate radio transmission.

REFERENCES

Celorie, J. A., Woods, S. L., Vinson, T. S. & Istok, J. D. (1989). A comparison of sorption equilibrium distribution coefficients using batch and centrifugation methods. *J. Environ. Qual.* **18**, No. 3, 307–313.

Evans, D. C. (1994). *Contaminant migration through intact and damaged clay liners*. PhD thesis, University of Cambridge.

Khanzode, R., Vanapalli, S. K. & Fredlund, D. G. (2002). Measurement of soil-water characteristic curves for fine-grained soils using a small-scale centrifuge. *Can. Geotech. J.* **39**, No. 5, 1209–1217.

McKenna, J. M., Eyre, W. A. & Wolstenholme, D. R. (1975). Performance of an embankment supported by stone columns in soft ground. *Géotechnique* **25**, No. 1, 51–59.

Mitchell, R. J. (1998). Centrifugation in geoenvironmental practice and design. *Can. Geotech. J.* **35**, No. 4, 630–640.

Sharma, J. S. & Samarasekera, L. (2007). Effect of centrifuge radius on hydraulic conductivity measured in a falling head test. *Can. Geotech. J.* **44**, No. 1, 96–102.

Singh, D. N. & Gupta, A. K. (2002). Modelling hydraulic conductivity in a small centrifuge: Reply. *Can. Geotech. J.* **39**, No. 2, 488–489.