Evaluating the response of new pore pressure transducers for use in dynamic centrifuge tests

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ABSTRACT: Over the past 30 years, the PDCR-81 pore pressure transducer has become a standard instrument for measuring pore pressures in centrifuge experiments. Following the retirement of this transducer and its reduced reliability, it has become vital to find an alternative sensor for use by the geotechnical modelling community. In this paper, the response of the 2Mie pressure transducer is compared against that of a PDCR-81. The sensors were tested in a number of configurations, both with and without filters, and in the presence of fluids with elevated viscosities which are common in dynamic centrifuge experiments. From these tests it appears that subject to appropriate filter selection, the 2Mie transducer produces comparable results to a PDCR-81.

1 INTRODUCTION

The use of Pore Pressure Transducers (PPT) within physical geotechnical models is very common and necessary to infer effective stresses at key locations during experiments. When carrying out reduced-scale testing in a centrifuge, the size of the transducer becomes important and lead to the design of the miniaturised PDCR-81 PPT, previously manufactured by Druck, which has been accepted over the years as a standard instrument for use in centrifuge modelling. Following the discontinuation of the PDCR-81 sensor, it has become necessary to source alternative sensors of a similar overall size which can isolate the pore pressure component of the total stress. One candidate transducer is the 2Mie, manufactured by Keller.

In this paper, the results from a number of experiments are presented which aim to benchmark these sensors against the response of the existing PDCR-81 sensor in order to provide confidence that these sensors can be used in future dynamic centrifuge testing.

2 DESCRIPTION OF TRANSDUCERS

The two miniaturised transducers being compared in this paper are shown in Figure 1. The two transducers are of similar dimensions; the existing PDCR-81 transducers being approximately 6 mm in diameter and 12 mm in length, while the assembled 2Mie transducers are 7 mm in diameter and 11 mm in length.

Both types of transducer measure pressure via the deflection of a thin, flexible diaphragm. The diaphragm on the PDCR-81 transducer is mounted on a glass cylinder to reduce sensitivity to stresses acting on the sides of the instrument (Fig. 3). However, the measuring element on the 2Mie transducers is part of a silicon chip which is mounted within a cavity in the main body of the instrument and is protected from side stresses by the space between the chip and instrument sidewalls, which is filled with a rubbery compound as shown in Figure 2.
To reject the effective stress component acting on the instrument face, a porous filter is placed in front of the diaphragm. While the filters on the PDCR-81 are often held in place by an adhesive, the 2Mie transducer is designed to be used with a replaceable filter, which is held in place by a threaded stainless steel cap. To prevent ingress around the sides of the filter, an o-ring seal is placed around the head of the filter. It should also be noted that the aspect ratio of the filters are quite different between transducers; those used in the PDCR-81 being approximately 6 mm in diameter and typically 2 mm thick, while those used in the 2Mie transducer are close to 4 mm in both diameter and thickness.

3 USE OF VISCOS FLUIDS IN DYNAMIC CENTRIFUGE MODELLING

It is well known that the time scaling associated with dynamic events (i.e. ground shaking) and seepage events (i.e. fluid flow during consolidation) are different. This issue is not normally of significance when carrying out experiments with clayey soils, given the relatively slow changes in soil behaviour due to seepage compared to the dynamic events which are occurring during the experiment. This however is not the case when sandy soils are tested during dynamic centrifuge experiments. Researchers conducting these types of test will often use fluids with elevated viscosity to slow down seepage events so that their time scaling falls in line with that of dynamic events. It is therefore important to understand the effects of fluid viscosity on the pressures being measured by the PPTs.

4 FREQUENCY RESPONSE

4.1 Comparison of response without porous filters

An initial series of tests were carried out to obtain the frequency response of the 2Mie relative to the existing PDCR-81 using the equipment set-up shown in Figure 4. In each test, both a 2Mie and a PDCR-81 PPT were placed within a plastic tube, sealed at both ends with rubber stoppers. After applying a vacuum to the tube, the stopper at the non-instrument end was pulled from the tube, creating a rapid change in pressure, followed by an oscillation in pressure within the tube, which typically decayed within 0.5 s. The oscillating pressure component is caused by the excitation of a natural vibration mode as the air rushes into the tube and was associated with a “popping” sound at the time the stopper was released. By varying the length of the tube, it was possible to alter the frequency of oscillation.

To obtain the frequency response, the signal (sampled at 50 kHz) was cropped to include only the portion containing the oscillating pressures and then analysed in the frequency domain (using FFT) to obtain the magnitude and phases of the pressure recorded by each transducer at the fundamental frequency for the current tube length. A “gain” was defined as the pressure magnitude recorded by the PDCR-81 divided by that of the 2Mie. Phase is defined such that a negative value indicates that the PDCR-81 lags the 2Mie. The results from these experiments are presented in Table 1. Very good agreement between the two transducers over the entire range of frequencies is observed.

4.2 Influence of porous filters

As previously described, the transducers must be fitted with a porous filter to remove the influence of soil effective stresses on the recorded output. An analytical solution by Lee (1990) showed that
the response of diaphragm PPTs is affected by the presence of these filters, through which pore fluid must flow to deflect the sensing diaphragm. Hence the measured pressure became increasingly attenuated with increasing frequency, fluid viscosity and decreasing filter permeability. It should be noted however that if perfect saturation is achieved, then Lee's (1990) analytical solution indicates the expected attenuation to be less than 5% at 600 Hz, even when fluids with a viscosity of 50 cSt are used with a filter whose permeability was 4.2 D.

The importance of fully saturating PPTs was highlighted in the experimental study of Phillips and Sekiguchi (1991) who showed that the pressures recorded by partially saturated PDCR-81 PPTs at medium frequencies (i.e. 200 Hz) were significantly attenuated, even when high permeability filters were used in combination with water as the fluid.

In this section, the effects of the filter permeability, geometry and fluid viscosity on the frequency response of the transducers will be examined, and a list of filters used with the PDCR-81 and 2Mie PPTs is shown in Table 2.

In order to investigate the effects of the filters on the measured response, a number of tests were carried out using the experimental set-up sketched in Figure 5. To reduce possible impedance caused by gas bubbles behind or inside PPT filters, a number of processes were followed to obtain the best possible saturation of the filters and transducer. Specifically, all of the filters except C2 (which was sealed into the PDCR-81 PPT) were removed from the transducers. Note that the two sintered bronze filters had tapered sides and were held within the PDCR-81 PPT by an interference fit. The sides of these filters are impermeable due to the “smearing” which occurs when sintered bronze is cut. The PDCR-81 PPT with C2 filter was subjected to the same process as the individual filter elements. The filters were first “cleaned” by passing repeatedly between boiling water and isopropyl alcohol to attempt to remove any residues within the filters.

The filters were then dried by placing in an oven at 105 °C for a minimum of 12 hours. The filters were then placed in a sealed chamber to which a vacuum was first applied and then flushed with CO₂ (this step was repeated twice). Finally, the chamber was again placed under vacuum before the test fluid was introduced to the chamber. The internal cavity of the transducers were filled with fluid before inserting the filter element.

In each test, signals from three 2Mie PPTs and one PDCR-81 PPT was measured. Two of the 2Mie PPTs were attached to the PDCR-81 so that they were located in similar locations during the test. The PPTs were tied to the bolts inside the chamber to keep their position relatively central and their axis normal to the oscillating disc. The final 2Mie PPT was attached to a second bolt and used to verify that similar pressures were being recorded at different locations within the chamber. One of the 2Mie transducers within the cluster of PPTs was designated as the reference transducer and as such, no filters were placed in this transducer for any of the tests.

After completely filling the chamber with fluid, it was securely fastened to a “strong table,” in the orientation shown in Figure 5. A 12 mm thick plastic disc was attached to the vibrating end of a linear oscillator which was suspended above the pressure chamber, such that the disc was in contact with the chamber’s diaphragm. Harmonic pressure waves were created within the chamber by driving the oscillator with a frequency generator. It was expected that this set-up would allow the transducers to be compared across a wide range of frequencies up to and beyond the 1250 Hz discussed in Section 4.1. However, while the tests without filters showed close agreement at frequencies below 200 Hz, it was found that above this frequency, the data became highly scattered and inconsistent.

<table>
<thead>
<tr>
<th>ID</th>
<th>Filter material</th>
<th>Permeability D</th>
<th>PPT model</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Ceramic (Keller supplied)</td>
<td>1.2E-04</td>
<td>2Mie</td>
</tr>
<tr>
<td>C2</td>
<td>Ceramic</td>
<td>4.4E-03</td>
<td>PDCR-81</td>
</tr>
<tr>
<td>BF</td>
<td>Fine sintered bronze</td>
<td>3.0</td>
<td>PDCR-81</td>
</tr>
<tr>
<td>BC</td>
<td>Coarse sintered bronze</td>
<td>164</td>
<td>PDCR-81</td>
</tr>
<tr>
<td>PPF</td>
<td>Porous plastic</td>
<td>4.6</td>
<td>2Mie</td>
</tr>
<tr>
<td>PPC</td>
<td>Porous plastic</td>
<td>20</td>
<td>2Mie</td>
</tr>
</tbody>
</table>
between tests. As an example, the gain and phase measured using this setup using water and no porous filters is shown in Figure 6. A number of different phenomena could be responsible for this effect, such as resonance of the container walls, or the oscillator rocking at some natural frequency, causing the disc to oscillate about a horizontal axis as well as the intended vertical axis. As such, the comparison of the different PPT responses has been limited to the region where consistent results were obtained (i.e. below 200 Hz).

A total of three test series were carried out, with the fluid being changed from water to solutions of methyl cellulose with viscosities of 10 and 50 cSt. Between test series, the filter elements were cleaned and re-saturated with the new fluid, using the processes previously described. The results from these tests are presented in Figure 7. Note that the difference in y-axis scaling.

From the plots, it is apparent that the choice of filter is relatively unimportant when water is being used as the pore fluid; the results indicating that the pressures recorded by the C2 filter (PDCR-81 PPT) were attenuated by approximately 1% at 180 Hz and showing a small phase lead of 2°. The C1 filter results in Figure 7(a) have been disregarded since the stone is known to have dried out slightly between saturation and testing and therefore is thought to have been affected by partial saturation of the filter.

Increasing the fluid viscosity clearly affects the measured response; with a fluid viscosity of 50 cSt, the recorded pressures were reduced to approximately 40% at 100 Hz with the coarser ceramic filter (C2), while even the higher permeability filters showed significant attenuation; the filters with permeabilities as large as 19.9 D (with water) were attenuated by nearly 20% at 200 Hz, while the coarsest filter (BC) attenuated the pressures by 5% at 200 Hz. The frequency response when the C1 filter (2Mie PPT) was used indicates some unexpected behaviour, especially in the phase lag, which reaches its greatest value between 10 and 25 Hz before decreasing in magnitude, eventually becoming very small at 200 Hz. This response suggests that the recorded pressures arise from a mechanism alternate to fluid flowing through the filter. It is possible that the pressures arising from

![Figure 6. Response of transducers in water without porous filters.](image)

![Figure 7. Frequency response of transducers with porous filters against a 2Mie without filters.](image)
fluid migrating through the filter reduce to zero at about 200 Hz, while the second mechanism results in pressures being generated behind the filter which are in phase with the oscillating pressures in the main chamber, but attenuated to approximately 20%. This could be explained by oscillating deflection of the filter or O-ring seal allowing pressure to be felt by the diaphragm even without fluid flow through the filter. This would, of course, be undesirable because filter deflection could be caused by effective stress or total stress.

Table 2 indicates that the permeability of the fine bronze (BF) and Porous Plastic Filters (PPF) were reasonably similar and as such can provide some indication of the importance of the filter length. Comparing the responses of the two filters with the 50 cSt pore fluid (where filter effects were greatest) it was observed that the longer filter in the 2Mie transducer resulted in an increased level of attenuation by approximately 50% compared with the PDCR-81. This ratio is lower than expected since the PPF filter was approximately twice the length of the BF. However, this could arise from the sealing detail of the transducers. While the BF filter is essentially sealed at the side walls, the PPF allows some radial flow. It is possible that fluid is moving within the cavity in which the filters are placed, acting to increase the apparent permeability of the filter slightly. Therefore, it follows that while the increased length of the Keller filter does increase the level of pressure attenuation at a given frequency, this effect may be reduced if the fluid can flow radially within the filter, especially for low permeability filters, where decreasing the effective path length through the filter would greatly increase the overall flow rate.

5 USE IN A DYNAMIC CENTRIFUGE EXPERIMENT

In the previous sections, it has been demonstrated that the 2Mie PPT provided comparable results to the existing PDCR-81 transducer. A final sequence of testing was carried out to compare the pressures recorded by the two transducers during an actual dynamic centrifuge test. These tests were performed on the 1 m radius beam-centrifuge at the University of California, Davis. A simple sand profile was pluviated within a rigid container (internal dimensions: 559 (L) × 279 (W) × 182 mm (H)) using Ottawa sand (e_{min} = 0.55, e_{max} = 0.87, D_{50} = 0.21 mm) to a depth of approximately 10 cm and relative density of 45%. The pluviation was interrupted after placing an initial 2 mm layer of sand to place a number of PPTs in two clusters (shown in Fig. 8). The PPTs were placed so that the diaphragms were parallel to the direction of shaking (i.e. instrument axis is perpendicular to shaking), and with the pairs of instruments in the cluster facing each other (i.e. D-BF and K-PPC faced each other). The model was flushed with CO2 and then saturated with a solution of methyl cellulose (viscosity of 50 cSt). After reaching the designated acceleration of 50 g, a number of strong shaking events were conducted on the model, with data being sampled at 4096 Hz. These events included a number of simple sinusoidal excitations at 100 Hz with differing amplitudes, a scaled 1989 Loma Prieta earthquake (pk-pk acceleration = 8.8 g) and a scaled 2010 Chile earthquake (CCSP station, pk-pk acceleration = 104 g).

The excess pore pressure recorded by the 2Mie PPT, K-PPC during the Chile CCSP event is shown in Figure 9. While the pairs of facing instruments typically recorded similar excess pore pressures, there appears to be some differences between PPTs fitted with coarse stones which did not face each other, suggesting some spatial variation in the model. The excess pore pressures recorded by the PPTs, K-PPC and D-BF are compared for two short time intervals in Figure 10(a) and (b) and represent the key features of the complete record. In both plots it can be seen that the temporal variation in pressure was similar in shape for both PPTs. While Figure 10(b) shows a portion of the shaking where the measured pore pressures were very comparable in magnitude (the difference in the
two recordings being less than 0.5 kPa), this was not the case in Figure 10(a), where differences of up to 4 kPa were recorded during the three downward spikes which occur at 1.625, 1.63 and 1.635 s. These spikes are likely indicators of shear-induced dilation and while the difference in magnitudes is not satisfactory, the mechanism of soil behaviour would still be recognised from the recorded pressures.

6 FURTHER CONSIDERATIONS

The results presented have so far indicated good performance of the 2Mie transducers up to 200 Hz, with consideration of filter material being most important when elevated viscosity fluids are being used. The results of Section 4.2 suggest that where possible, filters with high permeability should be used in these cases. However, attention must be paid to the grain size distribution of the soil profile being tested to ensure that soil will not intrude into the filter, since this will change the permeability of the chosen filter. Additionally, it may be important to consider the stiffness of the filter material, with two potential mechanisms affecting the measured response discussed by Kutter et al. (1990). The first concerns deflection of the diaphragm under increased total stress. When the filter is infinitely stiff (Fig. 11(a)), increases in total stress do not cause any deflection, and an increase in pore pressure results in pore fluid flowing into the filter. However, if the filter is relatively flexible (Fig. 11(b)) an increase in total stress causes the filter to deflect, and compress the fluid behind the filter. If the increase in total stress is partly caused by a rise in effective stress, then this effect can result in an overpressure being recorded initially, with fluid then flowing out of the transducer. The second mechanism involves axial compression of the filter, which will change the stress distribution and therefore pore pressures at the measuring face of the transducer. While the size of the filters means that central deflections of the filter will be much smaller for the 2Mie transducer than the PDCR-81, the compact size of the 2Mie diaphragm may still render the device susceptible to these effects and requires further investigation.

The removable cap on the 2Mie PPT is an attractive feature, especially for researchers using solutions of methyl cellulose. If these solutions are not effectively cleansed from the filters after testing, then the response of the PPT can be degraded as the methyl cellulose residues can block parts of the filter. The ability to remove the filter easily is advantageous since the instrument can be properly cleaned, and the filter then either subjected to more thorough cleaning, replaced. However, it must questioned whether the hole in the cap will affect the measured pore pressures—for example, would the clay within the hole consolidate evenly with the rest of the clay matrix? Additionally, Kutter et al. (1990) discusses the use of hemispherical stones as a way of obtaining a more representative value of pore pressures in clays by increasing the surface area of the filter. In some cases it may therefore remain desirable to fix the porous filters in place to allow the 2Mie PPT to be used without the cap, and therefore allow different filter shapes to be fitted. Finally, the authors believe that at present, the cap is over-designed, and it may be desirable to investigate a housing modification where the threaded areas are made shorter and the wall thickness reduced.

Figure 10. Difference in pore pressure recorded by K-PPC and D-BF.

Figure 11. Under and overpressures caused by filter stiffness.
slightly, which may help to reduce some of the effects mentioned in this paper.

7 SUMMARY AND CONCLUSIONS

The tests described in this paper were designed to compare the performance of the 2Mie pore pressure transducer manufactured by Keller against the PDCR-81 transducer which has been widely used by the centrifuge modelling community. In air, and without a porous filter, it has been shown that the two transducers have nearly identical response up to at least 1250 Hz. Further testing indicates that in the presence of the porous filters, the frequency response is hardly affected at frequencies up to 200 Hz with water as the pore fluid. However, if the viscosity of the pore fluid is elevated, the permeability of the porous filter becomes increasingly important. Low permeability ceramic filters appear to unacceptably attenuate the signal at even moderate frequencies when a pore fluid with 50 cSt viscosity is being used.

So far, it appears that the 2Mie transducer provides a reasonable alternative to the PDCR-81 transducer for frequencies less than 200 Hz in sand. It is however recommended that when conducting experiments with elevated viscosity fluids that researchers use porous filters with the highest permeability possible which does not allow ingress of the soil. Researchers are also advised to consider the stiffness of their porous filters, which may cause additional effects if too compliant.

This study has implicitly assumed that response of the PPT is governed by the flow of water through the porous filter. Further study is required to investigate the response time in low permeability soils, such as clays where the flow of fluid may be more restricted by the soil than the porous filter.

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