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Experimental investigation of internal fluidisation due to a vertical water leak jet in a uniform medium

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Abstract

This paper presents an experimental study on internal fluidisation which can occur in the soil outside of a leak in a buried water distribution pipe. The study proposes an experimental method of measuring excess pore pressure and flow velocity in an uniform glass beads medium surrounding the leak. One flow rate of 2 l/min at a fixed leak diameter of 3 mm was used in the experiments. The results showed large velocities directly outside the inlet (in the fluidised zone), which decreased rapidly with increasing distance. The surplus pressure in the bed rises to a maximum value at the top of the fluidised zone, after which it decreases towards the top of the bed.

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Keywords: Leak-soil interaction; Internal fluidisation; Pitot tubes.

1. Introduction

Pipes in water distribution systems are susceptible to water leaks that cannot be directly observed due to the pipes being buried. In the US alone, water lost through leaks is estimated to be 26 x 10^6 m^3 per day [1], and throughout the world water losses are estimated to be over 32 x 10^9 m^3 per annum [2].The World Bank estimates that the water lost in the world amounts to over 8 billion US $ in revenue per year [2]. In addition to the loss of water and revenue, some leaks have been reported to have caused damage to nearby structures by weakening the soils on which they are founded [3].

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Recent research has shown that a leak in a water distribution pipe may internally fluidise the soil directly outside the leak if a sufficient flow rate is present [4,5]. This fluidisation is described as the process whereby a granular medium is transformed into a fluid-like state [6].

Fluidisation is known to occur under various conditions, including the removal of sand in coastal environments [7,8]; for pile driving [9,10]; due to leakage through sheet piles [11]; and in biological reactors and wastewater treatment for the mixing of substances [12]. However, the occurrence of fluidisation outside leaks in water pipes has only recently become the subject of investigations by researchers [4,5,13,14,15].

Van Zyl et al. [5] experimented with a leak directed vertical upwards in ballotini (glass beads). The authors identified three zones in the leak-soil interaction space: a fluidised zone outside the leak with particles moving at high velocity to a terminating head, a mobile bed zone where tightly packed particles move slowly back to the origin of the jet and a static bed zone. The study found that the majority of the mechanical energy in the leakage jet is dissipated through the orifice and the two inner (fluidised and mobile bed) zones. Surplus pressure in the fluidised zone increased rapidly and reached a maximum at the terminating head. Finally, the study concluded that substantial pressures may be sustained within the pipe without the fluidised zone extending to the surface of the ballotini bed. This concurs that leaks directed upwards may not become visible on the soil surface, making them more difficult to detect.

Alsaydalani [4] and Alsaydalani and Clayton [6] conducted experimental studies on internal fluidisation using different types of sands. They increased the flow rate until internal fluidisation initiated, which was found to be the point where the seepage force exceeds the buoyant weight of the particles located in a wedge shape above the orifice. The seepage force that controls the onset of internal fluidisation was found to be dependent on the flow rate, particle size, sphericity, bed height and permeability.

The aim of this study was to experimentally measure the flow and pressure distribution outside a vertical jet in a ballotini medium. The study is an extension of Van Zyl et al. [5] and the same ballotini was used. The work consisted of two phases: 1) the development of an experimental setup allowing measurements to be made in a three-dimensional grid in the ballotini bed, and 2) measurements of the flow and pressure distribution inside the bed for a test case.

The next section describes the experimental setup, followed by the methodology of measuring pore and pressures, after which the results of the experiment and a discussion of the results are presented.

2. Experimental setup

The experimental setup (Fig 1) consisted of a glass tank with a central inlet in its base and four overflow holes in its walls, and was filled with glass ballotini. The inlet on the tank was a vertically drilled circular hole in its base and was fitted with a bored stainless steel tube, through which the water flowed. The tube had a diameter of 3 mm for a length of over 10D to ensure uniform flow. Water was directed via valves and a flow meter to the inlet, simulating a pipe leak. The overflow holes in the walls of the tank maintained a static water elevation of 449.5 mm in the tank. The glass ballotini was used as an idealised soil medium with uniform smooth particles, replicating soil which surround a buried water main. Ballotini was used as it reduced the complexity of real soils. The diameters of the particles varied between 0.6 and 0.8 mm as shown in Fig 2.

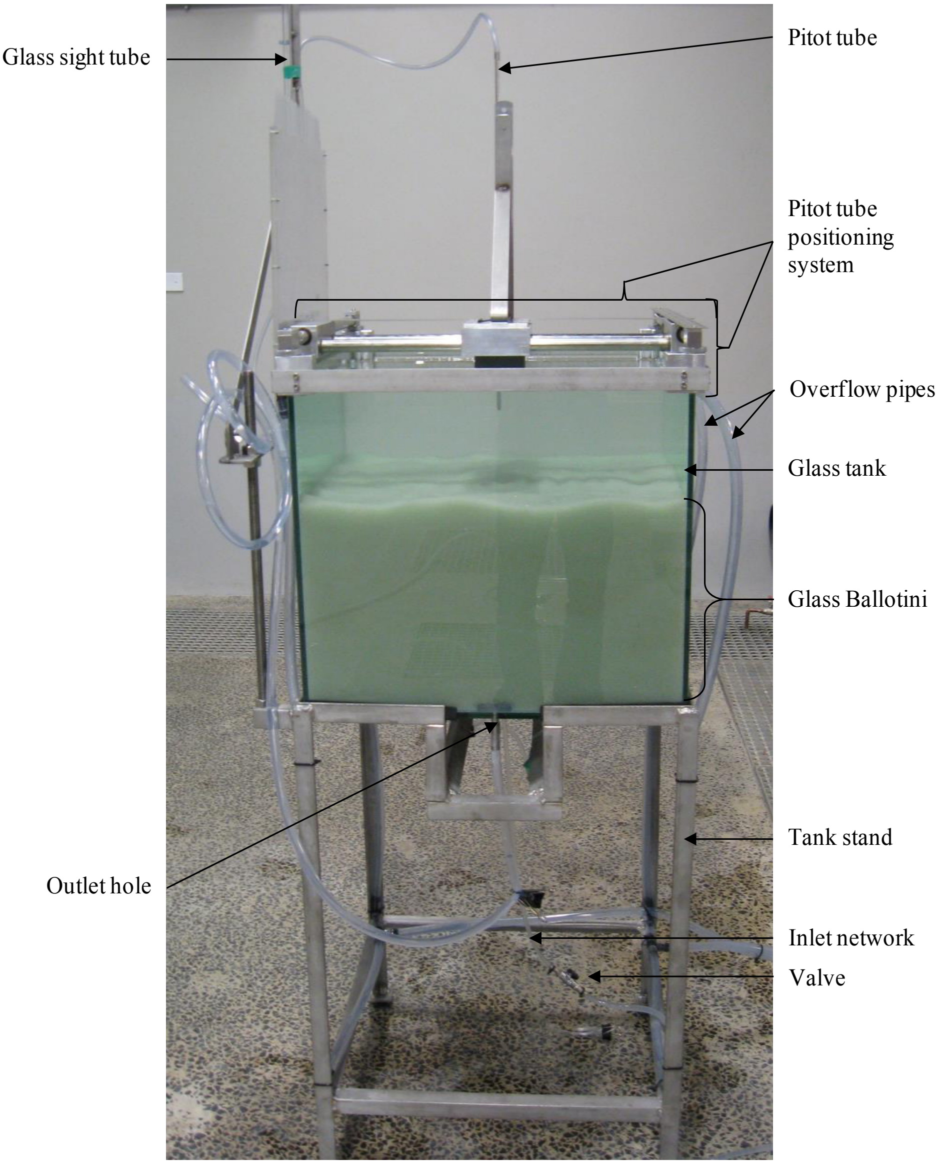

Fig 1: Complete view of the experimental setup showing: the glass tank filled with saturated ballotini supported by the tank stand; the Pitot positioning system placed on top of the glass tank; and the inlet network system and the overflow pipes.

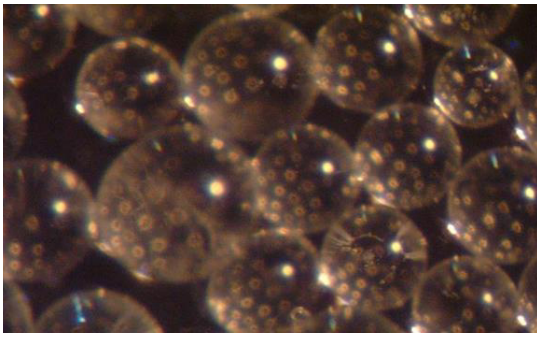

Fig 2: Image of the glass ballotini (glass beads) used as the idealised soil medium in the experiments [13].

Flow velocities and pore pressures at points inside the ballotini bed were measured using two types of Pitot tubes (Fig 3), i.e. L-shaped and straight tubes. The Pitot tubes consisted of single tubes, having one opening at the nose. The noses were fitted with glass tubes that tapered down to an inner diameter of 0.5 mm, preventing the ballotini from entering the Pitot tube. A length of clear PVC tube connected the top of the Pitot tubes to an incremented glass sight tube, with which the stagnation pressure head at the Pitot tube's nose was taken.

The Pitot tubes were secured and positioned in the ballotini bed by a positioning system (Fig 4) mounted on top of the glass tank. The system positioned the Pitot tubes three-dimensionally in the X,Y,Z directions shown in Fig 4 inside the ballotini bed, and it also allowed this position to be tracked.

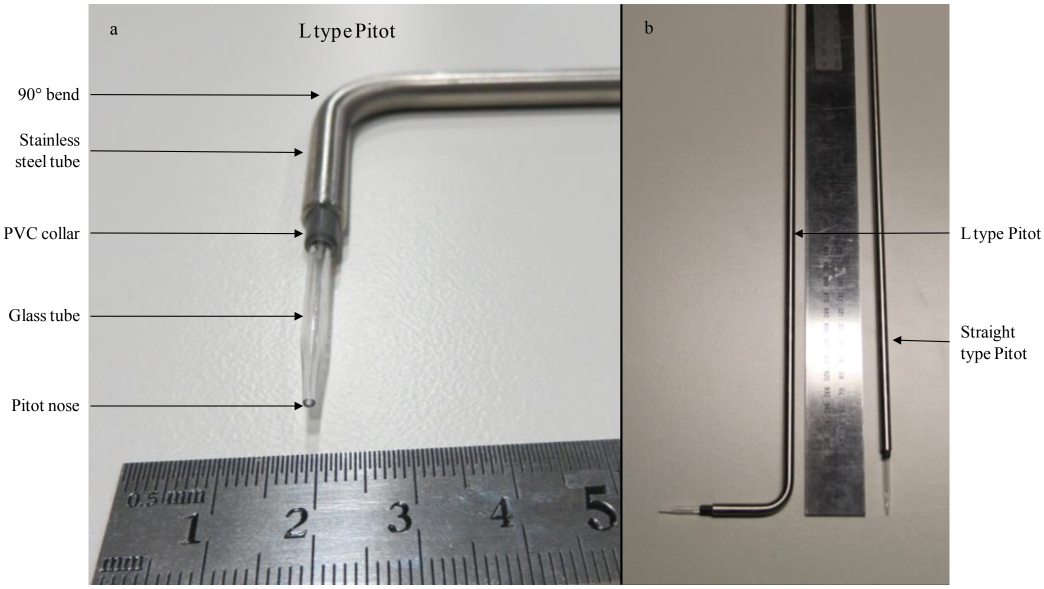

Fig 3: (a) Nose detail of the L type Pitot tube, which is the same as the straight type Pitot tube, except for the 90° bend; (b) image of the L type and the straight type Pitot tubes.

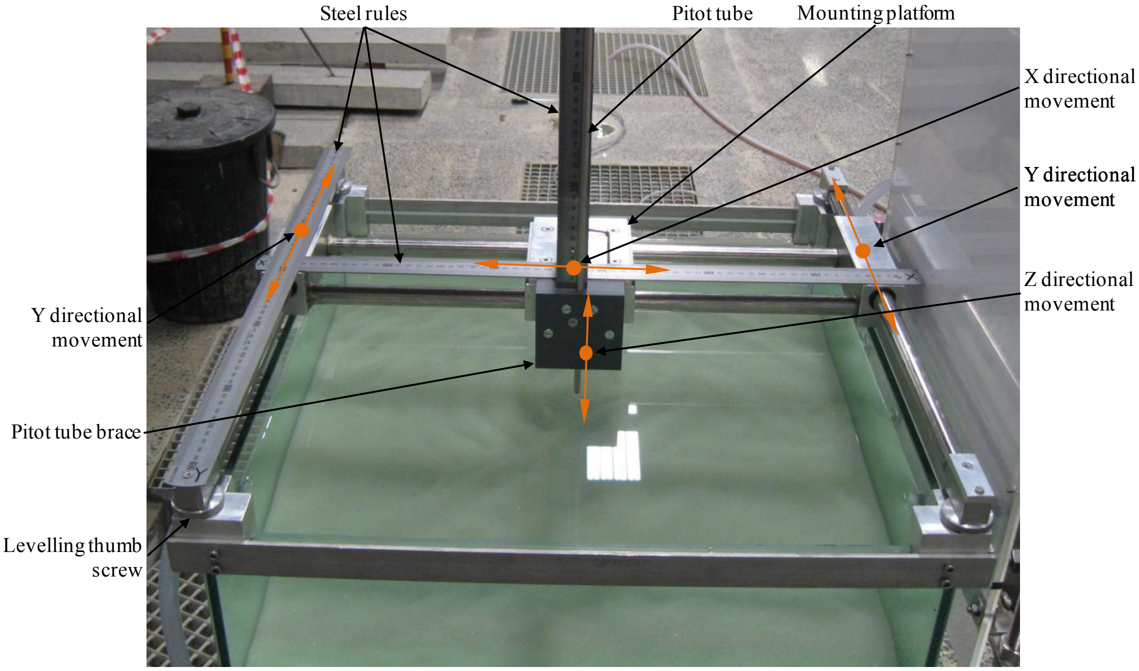

Fig 4: Image showing the top of the glass tank supporting the positioning system. Also shown is the three dimensional movement (in orange) of the Pitot tube.

It was assumed that the internal fluidisation was symmetrical about any vertical plane passing through the centre of the orifice. Measurements were taken at 10 mm and 20 mm intervals on a grid layout along the YZ plane (Fig 5 (a)). At each point, Pitot tubes measurements were taken in three directions as shown in Fig 5 (b).

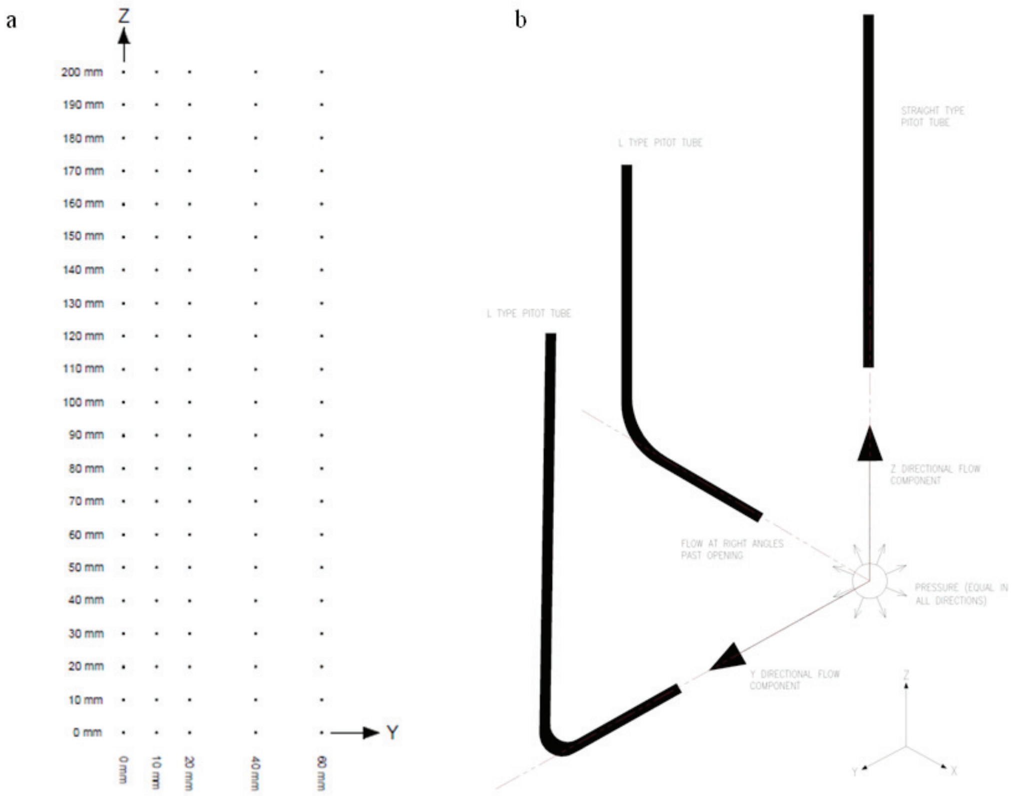

Fig 5: (a) Illustration of the measurement points along the YZ plane where at each point three measurements were taken; (b) illustration of the placement of the two types of Pitot tubes at each measurement point to record the total Z pressure, total Y pressure and the pore pressure.

3. Results and discussion

3.1. Velocity distribution

The measured velocity distribution is shown in Fig 6 (note that only one half was measured, the other half is shown as a mirror image for illustrative purposes). The largest velocities were found in the fluidised zone in a vertical direction just outside the inlet opening. Here, the largest velocity was 5.24 m/s situated at the inlet and decreased to less than 2.4 m/s near the top of the fluidised zone. Outside of the fluidised zone the velocities were substantially smaller.

It was found that some of the velocity vectors near the inlet were directed down towards the inlet. In particular the vectors from Y,Z points of (20,10) and (20,20) show this. These two vectors, as well as a number of other vectors in this bed region, indicate the flow dynamics near to the inlet, where the flow from the top of the fluidised zone circulates down towards the inlet. This circulating flow is generally located in the mobile bed zone, which surrounds the fluidised zone.

The height at which the fluidised zone terminated (typically at the vortex movement) was estimated by inserting the straight type Pitot tube into the ballotini bed from directly above the inlet, until the point when a distinctive scramble noise could be heard. The noise was due to the ballotini colliding with the Pitot tube. This fluidisation height was found to be 27 mm as illustrated in Fig 6.

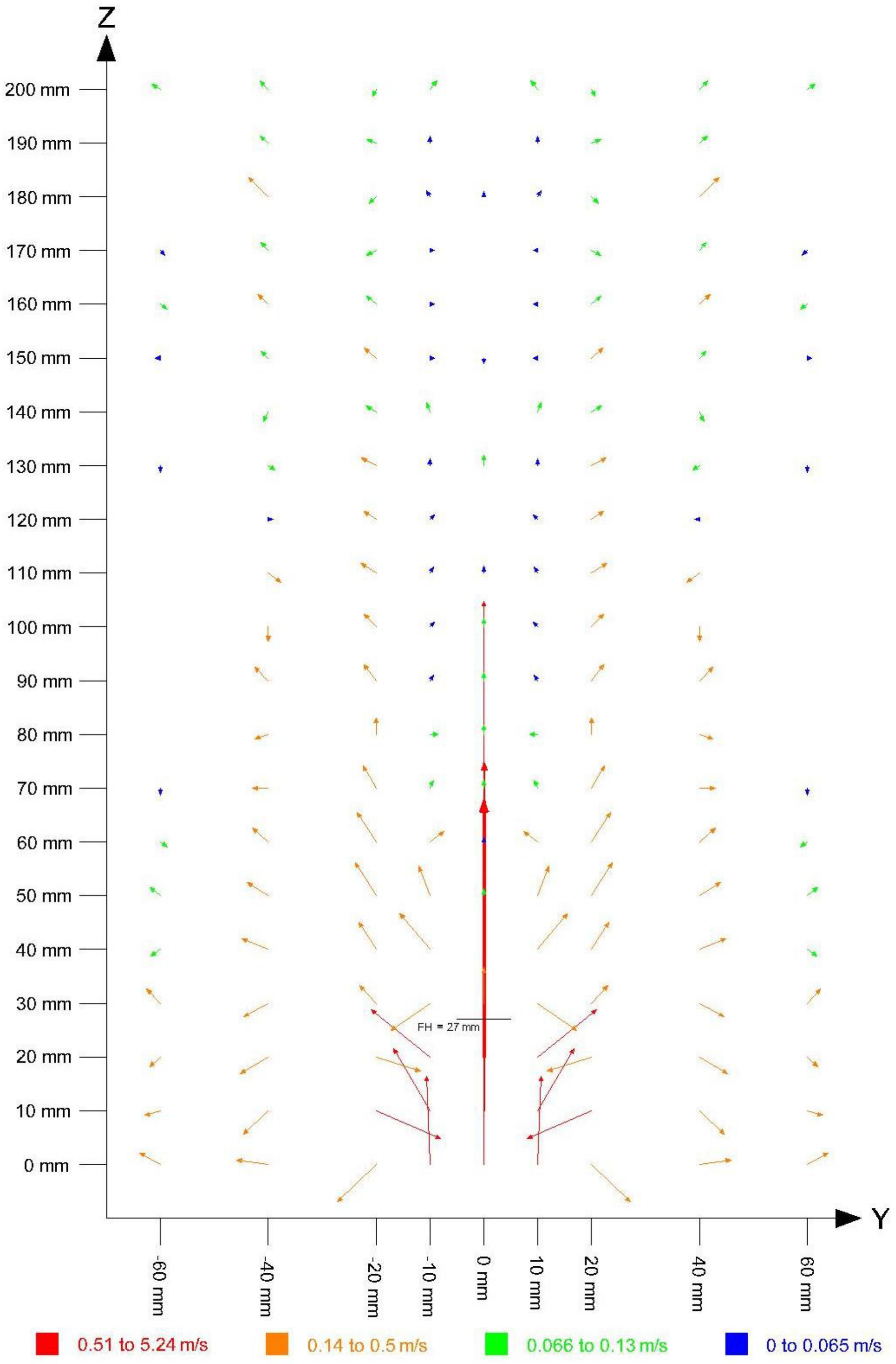

Fig 6: Velocity vector plot in the ballotini bed measured using the Pitot tubes. The one side of the plot is a reflection of the measured side, thus they are perfectly identical.

3.2. Pressure distribution

Fig 7 shows the increase in excess pore pressure in the ballotini bed due to the leak flow. The line in the graph represents the pressure measurements vertically above the inlet. As shown in Fig 7, the maximum pressure head in the ballotini bed of 110.6 mm was found to occur directly above the inlet at height Z=20 mm. Thus the maximum pressure exists near the top of the fluidised zone where the ballotini bed is in suspension due to the jet flowing through the inlet. The graph also shows how the pore pressures rapidly decrease from the maximum pressure point with increasing height.

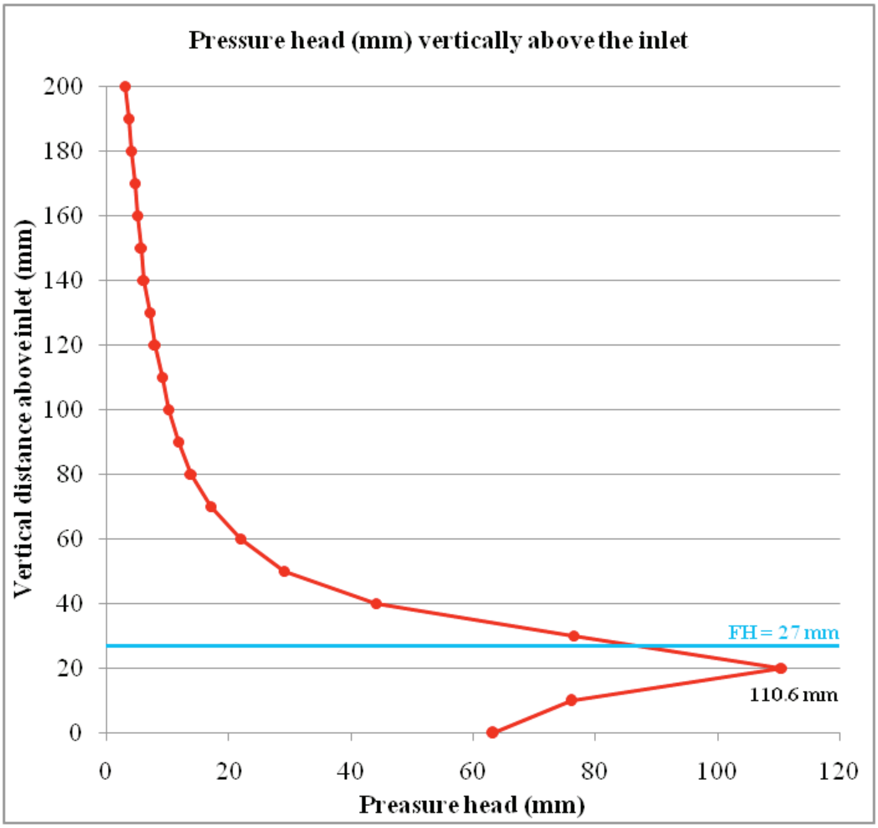

Fig 7: Pore pressure head measurements between elevations 0 to 200 mm vertically above the inlet.

4. Conclusion

An experimental technique to measure pore pressures and flow velocities outside a leak in a ballotini bed is proposed. The following conclusions can be drawn from the study.

- Large vertical velocities were found in the fluidised zone, up to 5.2 m/s at the inlet which decreased to less than 2.4 m/s at the top of the fluidised zone. Outside of the fluidised zone the velocity never exceeded 0.8 m/s, illustrating how rapidly the velocities decrease in the ballotini bed.

- The maximum pore pressure of 110.6 mm was found to be near to the head or top of the fluidised zone. Outside of the fluidised zone the pressures decreased rapidly. Above a height of 100 mm the excess pore pressure reduces linearly with height.

- The internal fluidisation occurring outside the leak rapidly reduces the available energy in the fluid, and this is likely to reduce the probability of a leak reaching the soil surface in the field – thus making it more difficult for the leak to be found.

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