A new device for the measurement of negative pore water pressures in centrifuge models

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ABSTRACT: Recent advances have allowed the direct measurement of matric suctions in soils above the "false ceiling" of 100kPa through the use of high air-entry porous filters and a rigorous saturation programme. Although the Druck PDCR-81 has proven to be useful in measuring matric suctions, the high mortality rate of the devices modified for use as a tensiometer has led to the development of a new tensiometer for application in centrifuge models. This paper describes the evolution of this device's design, the saturation procedure, and an application in which the device is used to observe pore pressures in clay embankments.

1 INTRODUCTION

The technology for the measurement of positive pore water pressures in centrifuge models has been standardised in the Druck PDCR-81, and is a routine aspect of centrifuge modelling (König et al., 1994). Negative pore water pressures corresponding to water held in tension above the water table have historically been ignored in both field testing and physical modelling due to the difficulty of measurement and the complexity of analysis. Recent advances in the field of unsaturated soil mechanics have generated more lifelike consititutive models, and improvements in the measurement of soil suctions required to validate them.

Techniques for the measurement of soil suction can be subdivided into the categories of direct and indirect measurement. The direct measurement of soil suction relies on the direct observation of the pore water pressure. Indirect measurements, on the other hand, rely on a calibration between observations of a more readily available parameter and soil suction. Measured parameters for which calibration relationships have been established include relative humidity (psychrometer), the moisture content of filter paper in contact, and the electrical resistance or thermal conductivity of porous blocks (Ridley and Wray, 1995). The application of the indirect methods to the in-situ measurement of soil suction within centrifuge models are either hampered by long equilibriation times (porous blocks, filter paper), or are not ideally suited to measurement of in-situ suctions (filter paper). The direct method of suction measurement has the advantage of being able to measure both positive and negative pore water pressures.

2 DIRECT SUCTION MEASUREMENT

2.1 *Maximum attainable suction*

The direct measurement of soil suction is most commonly performed using a tensiometer consisting of a porous filter, a water reservoir, and a pressure measurement device. Water held in tension within soil pores will cause water to pass through the porous filter and create a tensile stress in the water reservoir as measured by the pressure sensor. Once at equilibrium with the pore water pressure in the soil, the flow of water will cease and the pore water pressure will be equal to the tension in the reservoir. Traditionally, the use of tensiometers was thought to be limited to pore water pressures no smaller than -100kPa. Using a rigorous programme of filter saturation and high air-entry filter elements, several researchers were able to briefly measure negative pore water pressures lower than –100 kPa (Mair, 1979; Standing, 1991). Ridley (1993) went on to investigate the conditions under which a device was able to withstand negative water pressures below –100kPa. Motivated by these observations, Marinho and Chandler (1995) have summarised the results of various experimental studies of the tensile strength of water from other disciplines, reporting most estimates in excess of several MPa, yet orders of magnitude less than the theoretical value. The disparity between theory and practice has been proposed to be a result of cavitation nuclei trapped within crevices of the solid surface containing the water under tension (Harvey et al. 1944). These researchers have proposed that the cavitation nuclei can be forced to dissolve and reduce in size if subjected to large pressures, thereby increasing the achievable tensile strength of the liquid – container system.

The maximum sustainable tension within a tensiometer is also a function of the air-entry value of the filter element. If the pressure difference between the tensiometer reservoir and the soil being measured exceeds the air entry value, air will be drawn into the water reservoir. Once bubble growth has been initiated, external changes in pressure acting on the device will result in the expansion or contraction of the air void and the pressure measured within the tensiometer has the potential to be detached from reality (Ridley, 1993).

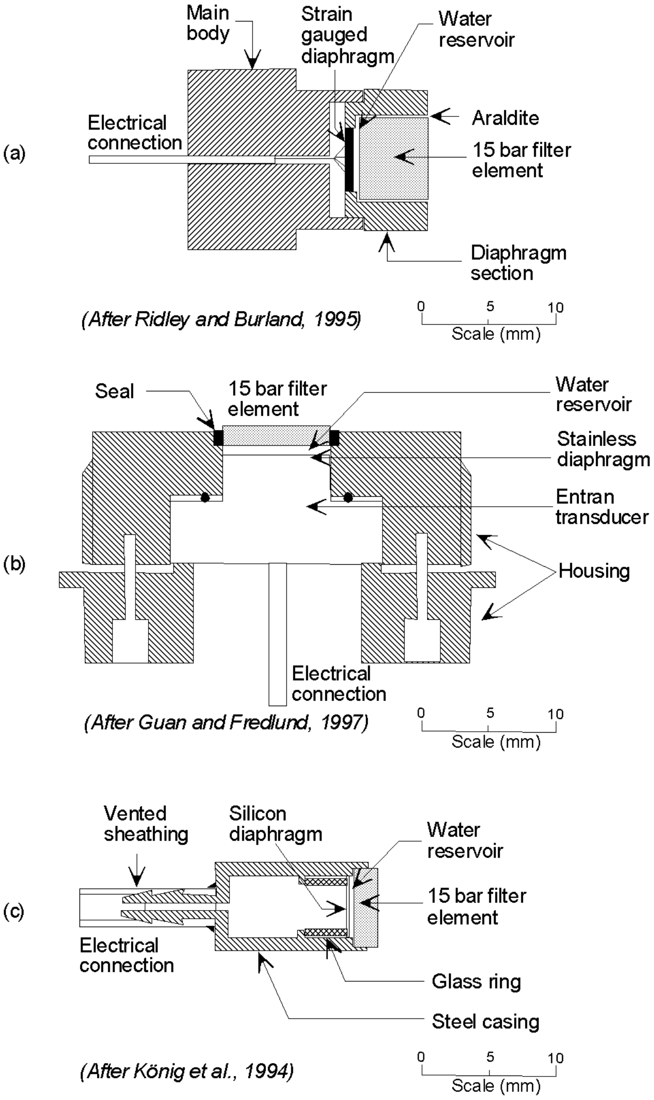
2.2 *Tensiometer design*

The principles of maximising the sustainable tension in tensiometers have been applied successfully to measure high soil suctions. The Imperial College tensiometer described by Ridley and Burland (1995) allows the insitu measurement of soil suction to 1500 kPa. The device consists of an integral strain gauged diaphragm and filter element housing sealed to a 15 bar air-entry value ceramic filter (Figure 1a).

Similarly, the tensiometer developed at the University of Saskatchewan has observed soil suctions up to 1250 kPa when saturated under six pressure cycles between 12000 kPa and –85 kPa (Guan and Fredlund, 1997). The high air-entry ceramic is sealed into one half of a detachable housing. Assembled underwater, the other half of the housing acts as a compression fitting and seals a commercial pressure transducer into the water reservoir (Figure 1b).

Despite the reduction in size from a previous design of the Imperial College tensiometer (eg. Ridley, 1993), these two devices are still too bulky for inclusion into centrifuge models.

The current standard in pore pressure measurement in centrifuge models is the Druck PDCR-81. This device consists of an instrumented silicon diaphragm supported on an internal glass cylinder and connected to a porous filter by a steel outer casing (Figure 1c). Using a high-range version of this device fitted with a 15 bar air-entry porous ceramic filter and saturation at a pressure of 2000 kPa, Ridley (1993) was able to measure suctions as high as 1370 kPa. Although well suited to the measurement of positive pore pressures, three design features conspire to make the Druck transducer not ideally suited for the measurement of high suctions. Ridley (1993) has reported that large outward diaphragm displacements associated with large negative pressures can compromise the integrity of the connection between the diaphragm and the supporting glass cylinder. As a consequence, water is free to enter the vented device, making the resulting pressure measurements suspect for both positive and negative pore water pressures.



(After Ridley and Burland, 1995)

(After Guan and Fredlund, 1997)

(After König et al., 1994)

Figure 1. Tensiometers for the measurement of high soil suction, a) Imperial College tensiometer, b) University of Saskatchewan tensiometer, c) Druck PDCR-81.

The second concern pertains to the risk associated with creating a seal between the porous filter and the body of the instrument. The measurement of positive pore water pressures simply requires a saturated porous filter to be press fitted into the tip of the sensor. In this measurement application, any short-circuit path around the periphery of the filter element will not be of a sufficiently large size to detract from the purpose of the filter – separation of the pore water pressure from the total stress applied to the face of the filter element. For the case of measuring negative pore water pressures, any short-cut path around the filter will limit the measurable suction to its air-entry value, potentially much less than the air entry value of the filter material. As a consequence, the reliable measurement of negative pore pressures using the Druck PDCR-81 requires a seal between the porous filter and the outer housing. Experience has shown that there is considerable risk associated with both the initial sealing operation (excess epoxy bonding the diaphragm to the filter), and the subsequent extraction of a porous filter for replacement.

The high pressures required to saturate the tensiometers also have a potential to cause problems with the use of the Druck PDCR-81. Small holes in the vented sleeving of the device, although watertight under working pressures, are susceptible to water entry under the high water pressures associated with saturation. These pressures, sustained for periods of an hour during the cyclical saturation process, have resulted in several older devices being lost to electrical malfunction.

3 TENSIOMETER DEVELOPMENT

The high mortality rate of Druck PDCR-81 devices modified to measure soil suctions has prompted the development of a new, more robust, device to measure negative pore water pressures in centrifuge models. Design considerations for this device included the need for a small physical size to limit the disturbance to the model, a minimisation of the volume flow of water required to measure suctions, a diaphragm resilient against both tensile and compressive loadings, and the ability to safely change the filter element.

The three tensiometers as configured in Figure 1 have been designed to maximise the possible suction measurement attainable. Equipped with 15 bar air-entry value ceramic filters, these devices have been subjected to water pressures in excess of 2000 kPa in order to exceed the air entry value of the filter during saturation. In this manner, the air-entry value of the ceramic filter not only dictates the maximum attainable suction value, but also the required range of the pressure measurement transducer. Many applications require the measurement of suctions in the low suction range below 300 kPa. The use of a smaller range transducer would increase the accuracy of suction measurements in this range, as long as the reduced maximum pre-pressurisation pressure did not inhibit saturation.

The initial design of the new tensiometer consisted of a 7 bar range Entran EPB stainless steel diaphragm pressure cell embedded into a brass housing. An interchangeable filter cap could then be sealed to the device keeping the epoxy seal as far away as possible from the pressure sensitive diaphragm (Figure 2a). Although this device had the advantage of an interchangeable cap, the high water pressures associated with the saturation process tended to crack the acrylic cylinder. Once cracked, a short-cut path was created for air-entry into the water reservoir, thereby rendering the device useless for the measurement of negative pore water pressures.

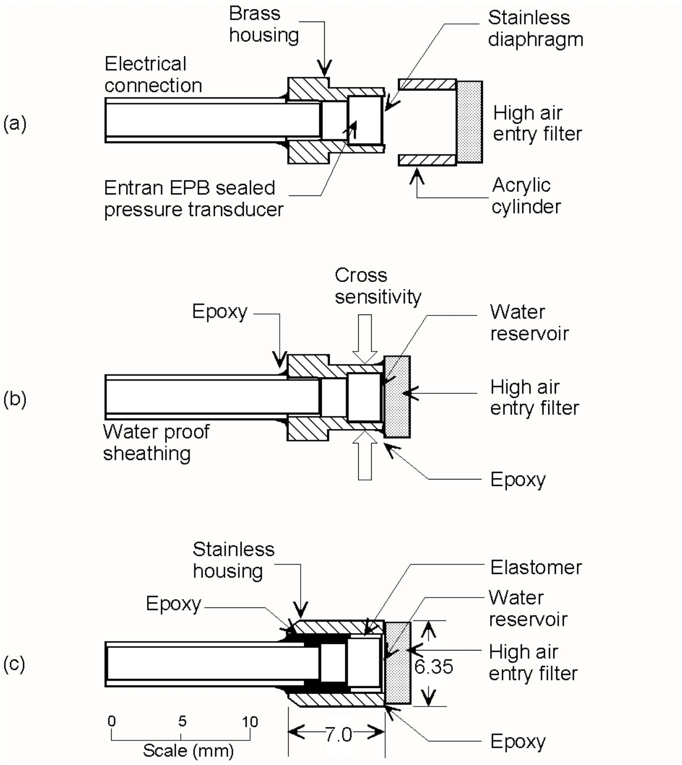


Figure 2. Design evolution of new tensiometer, a) filter cap, b) direct seal, c) isolated internal sensor.

The second design, illustrated in Figure 2b, dispensed with the interchangeable cap concept and bonded the porous filter element directly to the end of the brass housing. Although this greatly increased the risk of accidentally bonding the diaphragm to the porous element, the stainless diaphragm proved to be resilient to this eventuality. Once fully saturated, this design resulted in successful measurements of negative water pressures below –100kPa, but demonstrated undesirable features in deviatoric stress fields. Further investigations revealed that even small cross-axis forces on the brass, by pinching the device between the thumb and forefinger, for example, are transferred to the pressure cell causing the diaphragm to deflect. In situ use of the device, therefore, would no longer measure pore pressure, but rather an unacceptable mixture of pore pressure and effective stress.

A third and final design was formulated in an attempt to isolate the internal pressure sensor from the total stresses applied on the device. This design, illustrated in Figure 2c, consists of a thick, rigid, stainless steel casing attached to the pressure sensor at the base of the sensor whilst leaving a gap around the sensitive face to isolate it from the casing. This gap was then injected with an elastomer to infill the space, thereby eliminating a potential space where air bubbles are likely to be trapped. In addition, the presence of the elastomer in the cavity around the commercial transducer will prevent any excess sealant from the filter attachment process from creating a load transfer mechanism between the device and the outer case. Any radial deformation of the exterior shell of the device will therefore be dissipated in the elastomer, thereby successfully isolating the device from its surroundings.

4 EXPERIMENTAL METHODOLOGY

The filter element separating the stress components at the measurement face of a suction probe is itself a porous material, and is therefore, subject to the same laws regarding flow in unsaturated porous media as the soil in which it is embedded. In this manner, if the filter element is not saturated, the pressure recorded has the potential to be no longer representative of the pore pressures within the soil mass, with the unsaturated hydraulic conductivity increasing response times.

4.1 *Initial Saturation*

The initial state of the suction probe consists of an air dry filter element sealed to the base of the device, creating an air-filled void between the filter element and the pressure sensing diaphragm.

The initial saturation procedure attempts to saturate the air dry porous filter element to as high a degree of saturation as possible. Once filled with deaired water, the saturation chamber is rotated through 90 degrees to allow the installation of the suction probe without wetting the porous filter. The chamber is then evacuated and the device is allowed to come to equilibrium (Figure 3a). The saturation chamber is then rotated through 90 degrees, slowly introducing water to the porous filter whilst under a vacuum (Figure 3b).

4.2 *Pre-pressurisation*

To increase the degree of saturation of the filter element, and dissolve potential cavititation nuclei, a programme of cyclical application of positive and negative water pressures has been applied to the device (Figure 4). This cyclical saturation process is often referred to as pre-pressurisation, as it entails pressure cycles prior to the measurement phase.

The magnitude of the positive water pressure cycles are limited by the allowable over-range of the measurement diaphragm. The base device has a full-scale range of 700kPa, with an over-range limit of 1400kPa. To ensure the device was not damaged in the pre-pressurisation process, positive pressure cycles were limited to a maximum pressure of 1000kPa.

A nominal 3 bar air-entry stone was fitted to a the body of a new tensiometer, and wetted under a vacuum. The maximum attainable suction was then determined by allowing water to evaporate from the filter element, thereby creating tension in the water reservoir. If the measurement system was perfectly saturated, the suction would increase until the air entry value was realized at a value above 300 kPa. As shown in Figure 5, evaporation from the face of the filter element resulted in a suction of only 80 kPa. The initial saturation process, therefore, is not sufficient to fully saturate the measurement system.

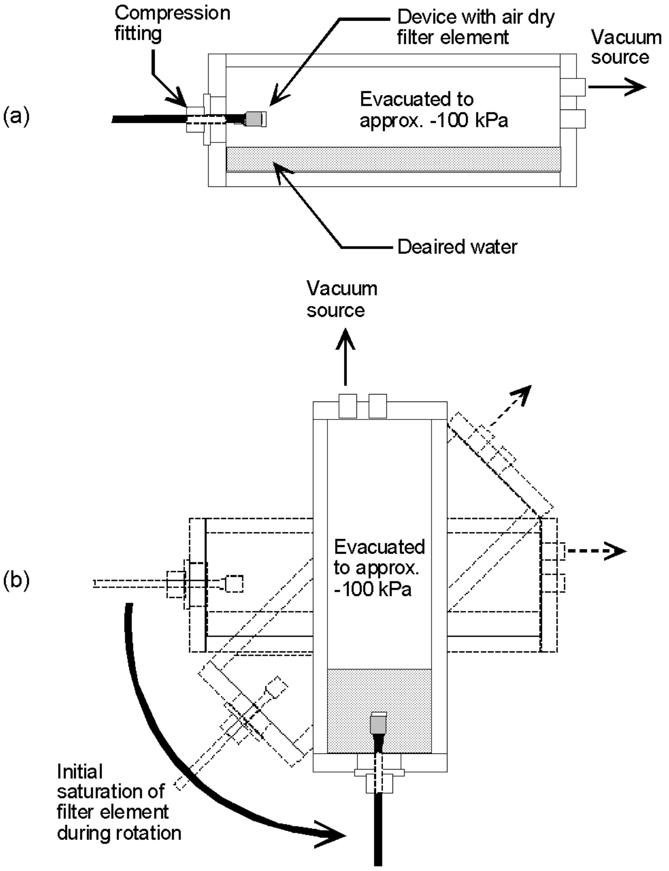


Figure 3. Initial saturation of porous filter element, a) de-airing of water and evacuation of chamber, and b) saturation.

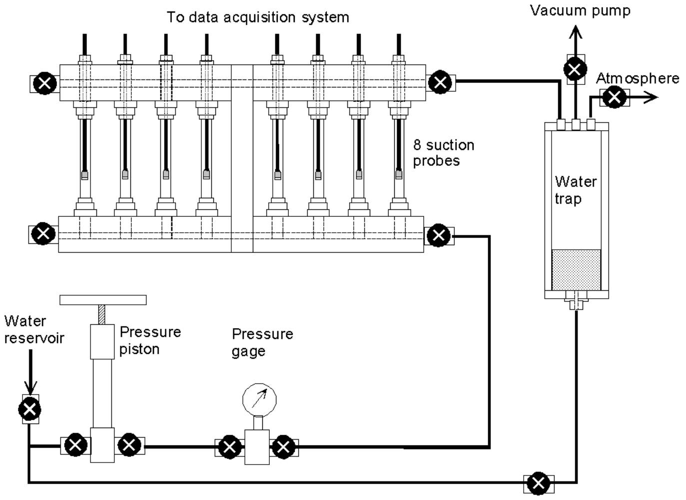


Figure 4. Pre-pressurisation apparatus for the simultaneous saturation of eight tensiometers.

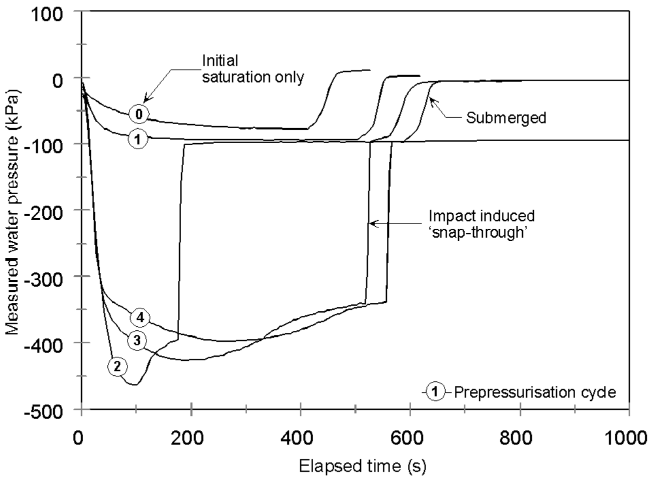


Figure 5. Air-entry characteristics of new device with saturation effort.

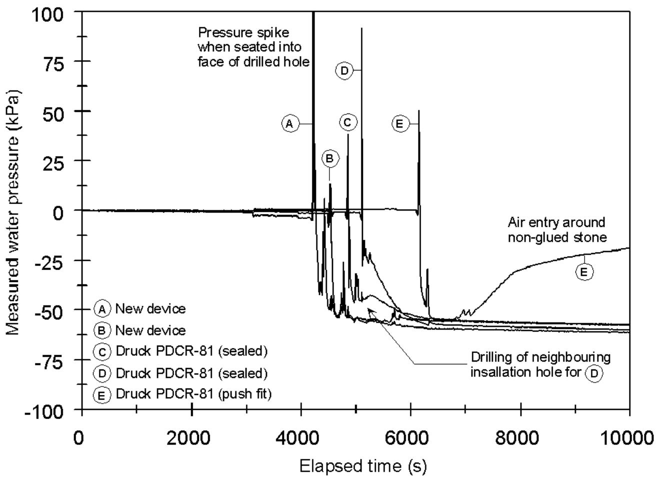


Figure 6. Installation of tensiometers into clay model initially at 60 kPa of suction.

The device was then inserted into the pre-pressurisation apparatus (Figure 4), in which it was subjected to a series of four cycles consisting of 60 minutes at both –100 and 1000 kPa. Although the first pre-pressurisation cycle improves the device's ability to measure suctions, it is only after the second pre-pressurisation cycle that the device is capable of measuring suctions to the air-entry value of the porous filter (Figure 5). Once the air-entry value has been exceeded, air slowly migrates into the water reservoir, expanding a bubble which subsequently reduces the tension within the water chamber. A quick 'snap-through' to –100 kPa occurs when the bubble is of a sufficient size to fill the water chamber, with the resulting pressure on the diaphragm being the pressure in the bubble. As shown in Figure 5, the time required for tension breakdown varies with the following saturation cycles, but breakdown from high suction could be initiated at any time by impact loading.

5 CENTRIFUGE APPLICATION

5.1 *Tensiometer insertion*

A block of Speswhite Kaolin clay was consolidated under K_0 conditions to a maximum vertical stress of 500 kPa. Upon reaching equilibrium with this stress, the pressure was reduced in increments of roughly 75 kPa, allowing for pore pressure equilibriation at each stage. Before the final unloading increment of 60 kPa was applied, all water sources to the clay were removed. The resulting clay block was removed from the consolidometer, and five suction probes were installed in sequence using an auger. A hole was drilled, a small bead of soil slurry was attached to the porous filter, and the tensiometer was seated into the end of the augered hole. Once in place, the tensiometer was backfilled with a slurry.

During the drilling process, previously installed tensiometers neighbouring the hole recorded pore pressure fluctuations. As shown in Figure 6, both the new devices and the sealed Druck PDCR-81 devices quickly record an equilibrium suction of 60 +/-2kPa. The close correspondence of the measured suctions with the unloading increment validate the assumption that the small volume of wet material backfilling the installation holes is not enough to appreciably change the global suction value of a massive block of consolidated clay. The Druck PDCR-81 device which did not have a sealed stone initially measured the correct value, but then was subject to air-entry around the periphery of the stone (Figure 6). Once air has entered the system, the measured value of pressure is unreliable for the measurement of soil suctions. The response of this probe illustrates the necessity of sealing between the filter element and the main body of the Druck PDCR-81.

5.2 *Model embankments*

The interaction between climatic conditions and pore water pressures within natural slopes, cut slopes, and embankments is an important consideration for stability. Natural slopes in the residual soils of Hong Kong and Singapore, for example, exist in an unsaturated state and are subject to infiltration induced slope failures. Cut slopes have a decreasing factor of safety with time, as the suctions associated with unloading slowly dissipate after construction. Embankments are, by very nature, unsaturated due to their construction from compacted fill and location above the local phreatic surface. In each of these cases, soil suction plays a pivotal role in determining the stability of a slope. Centrifuge models of slopes, therefore, must incorporate tensiometers capable of measuring the range of suctions appropriate to the degree of saturation of the soil.

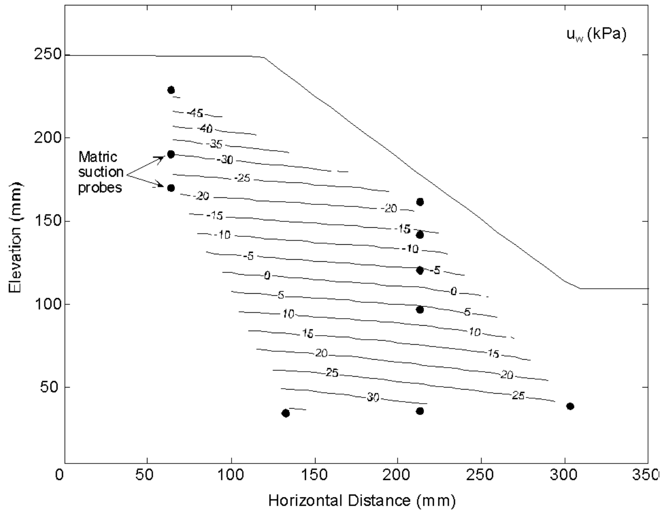


Figure 7. Pore water pressure contours in a model embankment (kPa)

A model slope was created from saturated Speswhite Kaolin clay for testing in the centrifuge. Ten matric suction probes were fitted with 1 bar nominal air-entry ceramic filters, saturated in two batches in the pre-pressurisation apparatus (Figure 4), and inserted into an overconsolidated clay model. The model was inserted into an environmental chamber designed to control the relative humidity boundary condition of the air above the surface of the embankment. Once accelerated to 60g, the model was allowed to dissipate the consolidation induced excess pore water pressures. The observed pore water pressures at the end of the consolidation phase of testing are shown in Figure 7 as interpolated contours of pore water pressure. From Figure 7 it can be easily seen that the entire embankment portion of the model is subjected to negative pore water pressures – pressures which cannot be ignored.

6 CONCLUSIONS

Although the Druck PDCR-81 has proven to be useful in measuring soil suctions, the high mortality rate has lead to the development of a new tensiometer for application in centrifuge models. This new device bridges the conflicting goals of providing a robust seal to the filter element and being capable to routinely change the porous filter element to suit the air-entry value requirements of the measurement application.

Rather than attempt to measure the maximum possible tension with the highest air-entry ceramic filter, a robust programme of initial and cyclic saturation has been presented in which two filter elements of nominal air-entry values of up to 3 bar have been saturated under a reduced saturation pressure. This reduction allows the use of pressure transducers which correspond more closely to the normal working range of pressures to be expected in centrifuge models, with the intention of improved accuracy.

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