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A new centrifuge permeameter to examine the role of stress and scale in internal erosion

R.E. Stevenson, E.T. Bowman & C.C. Smith
Department of Civil and Structural Engineering, University of Sheffield, UK

ABSTRACT: Internal erosion, in particular suffusion, poses a significant and increasing threat to water-retaining earth structures globally, including embankment dams and levees. This process is influenced by both the stress level in the soil and the length of the seepage path. In this study a new centrifuge permeameter has been developed, allowing a significant stress gradient to be applied across the height of a soil column. For these tests, downwards seepage flow is applied to an underfilled, gap-graded silty sand. The migration of eroding fine particles through the soil is tracked using seven miniature pore pressure transducers. Eroded particles are quantified using turbidity measurements at the outlet. The final distribution of particles within the sample is verified by post-test dissection and analysis. As well as detailing the design of the new permeameter, this paper reports the results of these centrifuge experiments, demonstrating the importance of both hydraulic loading conditions and effective stress level on the initiation and development of suffusion.

Keywords: centrifuge modelling, internal erosion, dams and levees, suffusion

1 INTRODUCTION

Internal erosion is a major problem for water-retaining earth structures, such as embankment dams and levees, leading to loss in performance and potential collapse (ICOLD 2013). Suffusion, a type of internal erosion, is defined as the selective erosion of the finest soil particles under seepage flow. It is particularly difficult to identify in the field as it is accompanied by no volume change of the soil.

The susceptibility of a soil to suffusion is relatively well understood. It can be assessed using criteria suggested in the literature, including the Kenney and Lau (1985) and Kezdì (1979) methods, which are based on the particle size distribution of the soil.

What is less understood is the hydraulic and stress conditions needed to initiate suffusion within a soil. Moffat and Fannin (2011) found that, in permeameter tests, either an increase in applied hydraulic gradient or decrease in effective stress was needed to instigate suffusion. In a scale model of an internally eroded embankment dam, Horikoshi and Takahashi (2015) observed clogging of fine particles in more highly stressed areas in post-test dissection.

Marot et al. (2012) previously developed a centrifuge permeameter to study scale effects in internal erosion, focusing on establishing the influence of specimen length on critical hydraulic gradient and erosion rate in a clay sand. The permeameter introduced in this study can test longer seepage paths, with multiple pore pressure points. This allows the soil to be considered as a stack of interconnected layers, giving a spatial understanding of the erosion process. It also facilitates testing of stress gradients comparable to those experienced in-situ.

Previous studies have focused on a critical hydraulic gradient (i_{cr}) to initiate suffusion at the macro level, whereas at the micro level migration of individual particles is due to the fluid velocity applied to them (Wautier 2018). By exploiting the centrifuge scaling laws, this relationship can be examined in depth, as hydraulic gradient does not scale with centrifuge acceleration N, but fluid velocity does (Garnier et al. 2007).

2 CENTRIFUGE TEST DEVICE

To investigate suffusion, a new centrifuge permeameter has been developed for the 4m diameter 50gT centrifuge at the University of Sheffield. This permeameter allows for a significant stress gradient to be applied across a soil sample subjected to downwards seepage flow. The sample can be considered as up to six interconnected layers, thanks to the pore pressure transducers (PPTs) along the permeameter wall. Figure 1 shows a schematic of the centrifuge payload. Each of the key components will be discussed in the following sections.

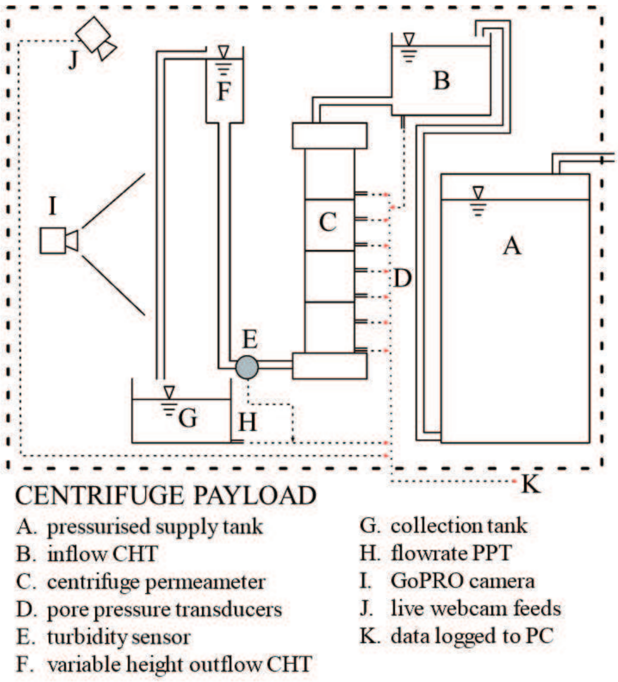

Fig. 1. Annotated schematic of the centrifuge payload configuration for suffusion testing.

2.1 Rigid walled permeameter

Figure 2 shows a detailed view of the permeameter device itself. The soil sample is held in the acrylic cylinder, with an internal diameter of 77mm. The number of stackable sections used determines the height of the sample, up to a maximum of 250mm. This relatively large height to diameter ratio allows both the initiation and spatial progression of the internal erosion to be investigated, due to the ability to track local erosion and clogging events. PPTs are installed flush with the inside wall of the device with a vertical spacing of 35mm. The sections are sealed with O-rings and held together with 3 steel tie rods.

Water is delivered to the top of the cell and distributed evenly over the soil using a showerhead-style acrylic disk. The soil sample sits on top of an inserted 125μm aperture wire mesh (sized at the smallest grain size of the coarse soil). This is supported by a sunburst pattern acrylic disk, which allows the removal of fine particles due to the seepage flow, without collapse of the force-carrying, coarse soil matrix.

The water and eroded particles flow into the conical base section and exit the device through an 8mm diameter outflow pipe.

2.2 Water supply system

To ensure that small air bubbles do not disrupt the suffusion mechanism, deaerated water is used for testing. As passing water across the centrifuge slip-rings would introduce air, water is deaerated in an 18 litre pressure vessel on the payload using the nitrogen purging method (Butler et al. 1994).

The flow through the sample is controlled by the head difference between two constant head tanks (CHTs) – B and F in Figure 1. The outflow CHT can be lowered in in flight using a servomotor controlled from the centrifuge office. The maximum extent of the outflow CHT in flight is 200mm. In between test stages the inflow CHT can be manually raised and the outflow CHT returned to its original position. The next stage then begins at the same applied hydraulic gradient (i_{app}), taking into account the variation of acceleration with model height. The maximum head difference achievable in the current configuration is 800mm. The water supply to the inflow CHT is adjusting using a pressure controller.

The outlet CHT overflows into the collection tank, where the flowrate is measured from the change in water depth using a PPT in the base of the vessel. For very low flow cases, a smaller vessel can be placed inside this tank for more precise measurements.

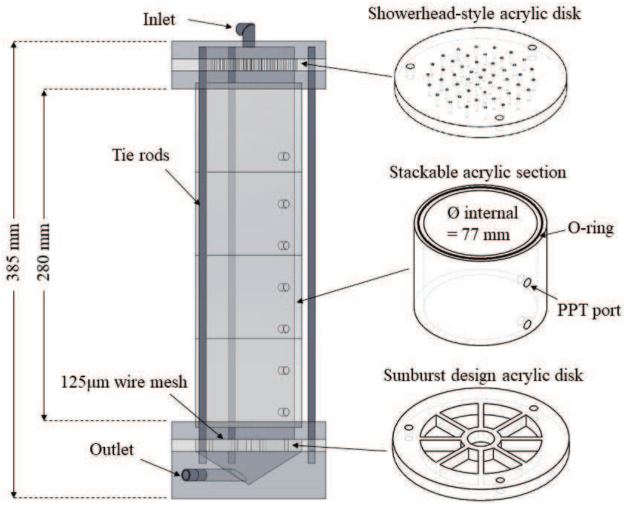

Fig. 2. Centrifuge permeameter (dimensions at model scale)

2.3 Instrumentation

In total there are nine PPTs in the payload, two in the water supply system and seven in the permeameter itself. These EPB-PW transducers have a sensor diameter of 6.4mm, and are fitted with 6μm ceramic porous stones (StrainSense 2017).

At the outlet point of the permeameter cell an inline turbidity sensor (DFRobot 2020) has been fitted over a clear glass section of pipe. This logs the turbidity of the effluent water, helping to identify the onset of suffusion. The data from both the PPTs and turbidity sensor is monitored live in LabVIEW from the control room.

Webcam feeds show the movement of the variable height outflow CHT and water level in the inflow CHT, as well as giving an overview of the whole centrifuge package. A GoPRO Hero 7 camera is trained on the sample taking photographs every minute. These images can be interrogated post-test to identify any soil movement, for example the formation of pipes or local settlement.

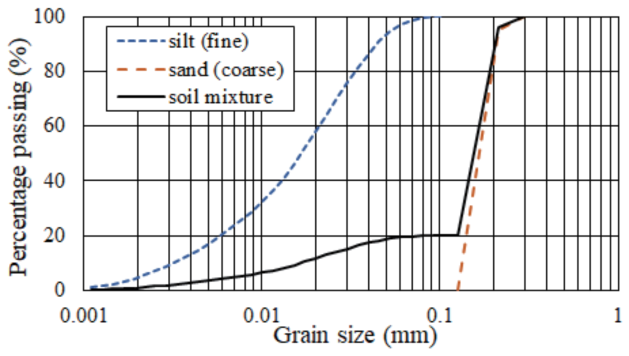

Fig. 3. Particle size distribution of the chosen underfilled, gap-graded soil and its constituent parts.

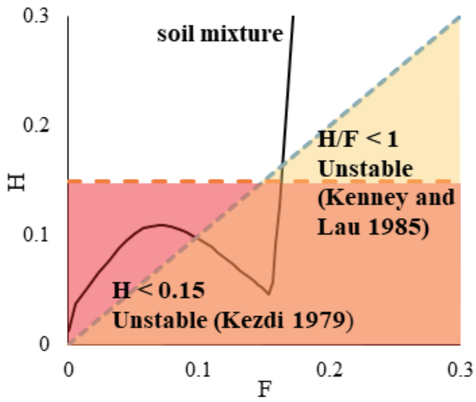

Fig. 4. H/F diagram of the gap-graded soil chosen for testing, showing the Kenney and Lau (1985) and Kezdì (1979) boundaries.

3 EXPERIMENTAL PROCEDURE

3.1 Test material

For the first set of experiments in this device, a gap graded soil consisting of a mix of fine sand and silt was tested. The particle size distribution in Figure 3 shows the soil has a fines content of 20%, meaning it is underfilled (Skempton and Brogan 1994). The fine particles can be considered rattlers, sitting loosely in the void spaces, and not contributing to stress transfer through the soil. Typically, suffusion tests consider a gravel/sand mixture, but in this case the grain size has been scaled down while preserving the shape of the curve, ensuring that the assumption of laminar flow is valid even at a centrifuge acceleration of N=40.

Figure 4 shows that the tested soil can be considered unstable according to both the Kezdì (1979) and Kenney and Lau (1985) criteria, as the H/F curve dips well into the unstable zone. The soil has a H/F_{min} value of 0.29.

3.2 Sample preparation

Batches of the sand/silt mixture are prepared at a 10% moisture content. The sample is prepared by moist tamping 15mm layers of soil into the permeameter device to a target relative density of 70% ($e = 0.58$) according to the method from Ladd (1978).

Once the sample reaches the desired height, a layer of free-draining coarse sand fills rest of the cell. This provides overburden pressure and aids the homogeneous distribution of water across the sample surface. The sample is then flushed with CO_2 to remove the oxygen, and then saturated with deaerated water under a very small upward flow overnight.

3.3 Multi-stage seepage flow

The sample is placed on the beam and connected to the inflow and outflow CHT, which are initially level, giving no flow through the sample. The package is accelerated to 40-g. Once at test acceleration, the outflow CHT is lowered under external control and flow through the sample commences.

The hydraulic gradient applied to the sample (i_{app}) is calculated by the difference in height of the two CHTs divided by the sample length. Table 1 shows the increments of applied hydraulic gradient, Δi_{app}, for each test. Each increment is held constant for 2 minutes. Once the outflow CHT has been lowered its maximum extent, the centrifuge can be spun down and the inflow CHT raised for the next stage of testing.

4 TEST RESULTS

For these preliminary tests, two samples of different heights have been prepared and tested with different i_{app}, as described in the previous section. The details of these tests are summarised in Table 1. All tests were nominally undertaken at 40 times Earth's gravity (N=40) as measured to 1/3rd of the height of the sample.

Figure 5 shows hydraulic conductivity for test 1 (T1). There is a sudden increase in hydraulic conductivity at around $i_{app} = 0.3$, corresponding to the onset of suffusion. After this point, the hydraulic conductivity for each layer gradually decreases indicating some clogging. This process is more pronounced in the lower levels of the sample, towards the end of the seepage path.

In contrast, Figure 6 shows the results for a longer sample (T2) where much smaller steps of applied hydraulic gradient were taken. The onset of suffusion occurs at a much lower $i_{app} = 0.1$, and is much more pronounced towards the bottom of the sample. This lower i_{cr} with smaller Δi_{app} agrees with the results from Rochim et al. (2017). In T2 almost all the layers show an increasing permeability with hydraulic gradient, indicating ongoing suffusion. Only layer 4 shows any evidence of clogging, as the permeability reduces.

For both samples, all the layers show a sudden increase in hydraulic conductivity at the same time, regardless of their position, suggesting that suffusion initiation is independent of effective stress level for this underfilled material, but T2 shows a clear trend of higher hydraulic conductivity towards the end of the seepage path, meaning a higher net migration of fines out of these layers. In both of these tests, the effluent water was observed to be cloudy, confirming that suffusion had occurred. There was no observable settlement of the sample in either test.

Table 1. Testing conditions and sample geometry.

Test	Sample height (mm)	Number of layers	Scaled seepage path (m)	Δi_{app}	i_{cr}
T1	131	3	5.2	0.05	0.3
T2	225	6	8.4	0.01	0.1

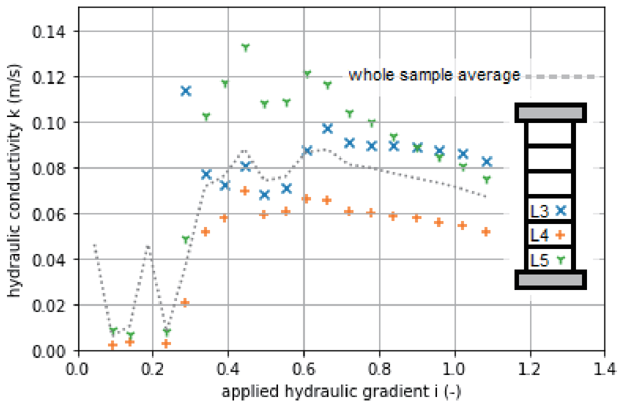

Fig. 5. Hydraulic conductivity of each soil layer for T1

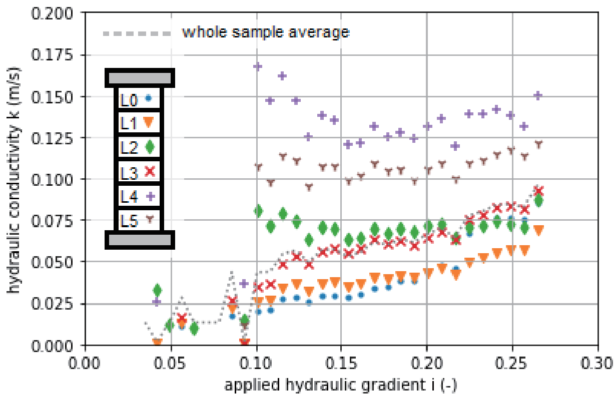

Fig. 6. Hydraulic conductivity of each soil layer for T2

5 CONCLUSIONS

A new centrifuge permeameter has been developed for the 4-m diameter UoS 50gT centrifuge, allowing the investigation of the role of effective stress level, seepage path length and hydraulic loading on internal erosion. Samples with a diameter of 77mm and a seepage path length of up to 250mm can be tested.

Preliminary tests have been undertaken on an underfilled, suffusive soil. The initiation and progression of suffusion has been clearly tracked using local pore pressure measurements. The results show that i_{cr} for the onset of suffusion is dependent on Δi_{app} with erosion happening at a higher i_{app} when the increments are larger.

In forthcoming experiments, a variety of sample configurations and hydraulic loading conditions will be investigated. Alternative soil mixes with different fines contents will be used to build a better understanding of the response of under- and overfilled materials. Various g-levels in the centrifuge can be used to provide a "modelling of models" approach to investigating the influence of seepage path length in relation to particle size and effective stress level.

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