Bench-scale centrifuge testing to determine the hydraulic conductivity of clayey soils

G. Di Emidio[1,2], H. Peiffer[1,2], B. Malengier[3], P. Kišon[3], A. Bezuijen[1]
[1]*Laboratory of Geotechnics, Ghent University;* [2]*Geosound.be, Belgium*
[3]*Department of Mathematical Analysis, Research Group NaM[2], Ghent University*

Abstract: The purpose of this research is to validate a mathematical model for flow through saturated and unsaturated porous media using a bench-scale centrifuge for an accurate determination of the hydraulic conductivity (function of the saturation degree of a soil) within a limited time at a reasonable price. The aim of this paper is to show preliminary results of this investigation where the validation and calibration of the mathematical model is performed determining the hydraulic conductivity of saturated porous media, such as kaolin clay and glass porous filters, with a bench-scale centrifuge.

Keywords: centrifuge modeling, hydraulic conductivity, inverse problem

1 INTRODUCTION

Compacted clay covers and linings of waste-management facilities are often in unsaturated conditions. Typical applications where such circumstances may occur are landfill cover systems, as a result of seasonal fluctuations of temperature and moisture content and inadequately thick protection layers (Meer & Benson 2007; Mazzieri et al. 2009). These covers and linings have the purpose to contain polluted liquids that might spread into the surrounding soil and groundwater. The hydraulic conductivity of the clayey soil, commonly part of these containment systems, is the most important factor governing their sealing performance. The hydraulic conductivity mainly depends on the water content, dry density, and degree of saturation of the soil. The movement of moisture, and the spread of contaminant, takes place in the region surrounding the waste-containment area, which is mostly unsaturated (vadose zone). This requires the estimation of unsaturated hydraulic conductivity of the soils, to correctly design an efficient containment system (Fredlund 1995; Rahardjo et al. 1995; Gourley & Schreiner 1995; Singh & Kuriyan 2002).

Traditional analyses of the mechanical and hydraulic response of earth structures generally assume water-saturated conditions. This worst-case design approach limits optimization of the performance of the system under expected field conditions and thus may lead to overconservative designs. This is particularly relevant in the analysis of geoenvironmental systems, such as evapotranspirative landfill covers, as well as geotechnical systems, such as retaining walls with poorly draining backfill, embankments, and pavement subgrades (Zornberg & McCartney 2010). For a given climatic condition, the extent of desiccation strongly depends on the thickness and on the properties of the soil covering layers. The gravimetric water content of exhumed GCLs was found to be strictly correlated to the hydraulic conductivity (Meer & Benson 2007).

Various researchers have tried to evaluate unsaturated hydraulic conductivity of soils by conducting either laboratory experiments or in situ studies. These methods have been classified as direct methods and indirect methods. The direct methods are quite tedious and time consuming and require expensive experimental setups (Stephens 1996). Indirect methods, which employ volumetric properties of the soil and the soil-water characteristic curve (SWCC), are frequently adopted. Integration along the SWCC provides a measure of the quantity of water in the soil which can then be used to estimate the soil hydraulic conductivity (Ray & Morris 1995; Takeshita & Kohno 1995; Singh & Kuriyan 2002). Although some field and laboratory methods are available to measure the relationship between water permeability and suction of unsaturated soils (Fredlund & Rahardjo 1993), it is extremely difficult and time-consuming to measure the relationship accurately due to the low water permeability of the soils.

1.1 Centrifugal modeling

To overcome these limitations, centrifuge modeling is increasingly being used to study the groundwater flow through soils. A geotechnical centrifuge is used to conduct model tests to study geotechnical problems such as the strength, stiffness and capacity of foundations for bridges and buildings, settlement of embankments, stability of slopes, earth retaining structures, tunnel stability and seawalls. While conventional geotechnical centrifuges are used to reproduce the response of earth structure prototypes, the centrifuge developed in this study is used to accelerate flow processes.

As a result, centrifuge modeling is increasingly being used to study problems involving groundwater flow through soil. From the point of view of groundwater flow modeling, one of the major advantages of using a centrifuge is that Darcy's velocity in a centrifuge model tested at N times Earth's gravitational acceleration (g) is N times the unit discharge in the prototype provided that the soil in the centrifuge model and the prototype soil have the same intrinsic permeability (Schofield 1980; Arulanandan et al. 1988; Oung et al. 2002; Singh & Kuriyan 2002; Sharma & Samarasekera 2007).

Centrifugal force has been used in a variety of applications both for saturated and unsaturated porous media. Stewart et al. (1967), Alemi et al. (1976), and Hagoort (1980) have used centrifugal force in measuring the hydraulic conductivity of soils. Bear et al. (1984) have presented a theoretical analysis of the approach to equilibrium of liquid in a deformable porous medium in a centrifugal field. Nimmo & Mello (1991) and Nimmo & Lewis (2002) presented the relevant analytical equations describing saturated flow under different experimental conditions. Van den Berg et al. (2009) provided a review of unsaturated hydraulic conductivity measurements with a centrifuge. They divide centrifuge techniques for measuring the relative permeability function into steady- and transient-state methods. In steady-state centrifuge experiments, the sample and fluids are subjected to a time-invariant centrifugal acceleration. Pressure and flow conditions at the inlet end face (the sample face closest to the center of rotation) are set so that steady-state flow conditions develop for the wetting fluid with time.

A steady-state method consists of centrifuging samples at different angular velocities or flow rates, reaching steady-state unsaturated flow conditions for each speed and determining the average water content. Using measured or calculated fluid pressures and measured flow rates, the relative permeability that corresponds to the measured average saturation is calculated. The steady-state approach has been widely used for measuring flow and transport parameters under partially saturated conditions . Two steady-state methods, internal flow control (IFC) and unsaturated flow apparatus (UFA), have been used for multiphase flow applications.

The transient experiment always consists of a period of time in which the centrifuge rotor is accelerating to the specified constant angular velocity and a period in which the angular velocity is constant. Because of capillary forces, there will be no production until the capillary pressure generated by the centrifugal acceleration exceeds the air-entry pressure. There are a limited number of examples in which transient flow centrifuge methods have been applied to vadose zone problems (Van den Berg et al. 2009).

1.2 Purpose of this investigation

Attempts to develop centrifugal setups were made in previous research (Wright & Conca 1994; Singh & Kuriyan 2002; Caputo & Nimmo 2005; Simunek & Nimmo 2005; Ferno & Graue 2009). However, these methods could be particularly expensive and greatly time consuming. To overcome this problem, the purpose of this research is to validate a mathematical model for flow through saturated and unsaturated porous media using a bench-scale centrifuge for an accurate determination of the hydraulic conductivity within a limited time at a reasonable price. The development of this innovative measurement technique is part of a broader research project, the project CENPERON (Centrifuge for the determination of the permeability of unsaturated soils). The aim of this paper is to show preliminary results of this investigation where the validation of the mathematical model and calibration of the instrumentation is performed determining the hydraulic conductivity of saturated porous media, such as kaolin clay and glass porous filters, with a bench-scale centrifuge with a maximum radius r_{max} = 171 mm and maximum speed of 16000 rpm.

2 THEORETICAL BACKGROUND

In light of the scope, we focus here on the theoretical background for transient measurements in a centrifuge to determine the hydraulic conductivity.

2.1 Classical formula's

For the hydraulic conductivity k, there is the classical formula for the falling head test,

$$k = \frac{L}{(t_2 - t_1)} \ln\left(\frac{H_1 + L}{H_2 + L}\right). \tag{1}$$

The derivation of this formula can be found in standard textbooks of soil mechanics (e.g. Budhu 2000). In it, t_1 and t_2 are two discrete time steps at which the height of the water column above the sample, H_1 and H_2 respectively, are measured. Furthermore, L is the height of the soil sample, and it is assumed that the bottom of the sample is kept at atmospheric pressure (by applying a datum, so hydraulic head is 0). Main assumption in the derivation of this formula is that $\frac{\partial}{\partial x}$ can be obtained from the equilibrium profile.

In Sharma & Samarasekera (2007), this derivation is performed for a centrifuge set-up. This leads to the formula

$$k = \frac{L}{N(t_2 - t_1)} \ln\frac{(H_1 + L)(2r_0 + L - H_2)}{(H_2 + L)(2r_0 + L - H_1)}, \tag{2}$$

where r_0 is the distance from the centrifuge axis to the top of the sample, and N is defined as $N = (r_0 + L)\frac{\omega^2}{g}$, so it is the g-level at the base of the sample.

The normal practice is to set the g-level not at the base, but at the center of the sample (so $N = (r_0 + L/2)\frac{\omega^2}{g}$). Sharma & Samarasekera (2007) argue however that the pressure at the top should be correct, and hence argue that the g-level should be calculated at the center of the water layer. As the water level decreases, the g-level is calculated at the average position of the center of the water layer, so

$$N = \left(r_0 - \frac{H_1 + H_2}{4}\right)\frac{\omega^2}{g}. \tag{3}$$

In essence, this playing with the g-level serves to decrease N, and hence increase the hydraulic conductivity as computed by (2). We show in the experiments what the effect is.

The main source of error will be the startup and slowdown of the centrifuge if the water level cannot be measured inside of the centrifuge. The second main error will be due to the outlet hydraulic head which should be 0, but experimentally will differ somewhat due to the specific design. We can avoid these errors, by solving the full transient problem between t_1 and t_2, which with current computer models is straigthforward to do.

2.2 The transient model

The transient model is based on Darcy flow, in which the flux q is given by

$$q = -\frac{K}{\mu}\partial_r\left(p - \frac{\omega^2}{2}\rho r^2\right), \tag{4}$$

where K is the permeability, μ the dynamic viscosity, ρ the density of water, and r the distance from the center of the centrifuge. The hydraulic conductivity is defined as $k = \frac{K\rho g}{\mu}$ and a hydraulic head is introduced as $h = \frac{p}{\rho g}$. Assuming there is no more consolidation, we obtain for saturated flow

$$q = -k\partial_r\left(h - \frac{\omega^2}{2g}r^2\right), \quad \partial_r^2\left(h - \frac{\omega^2}{2g}r^2\right) = 0, \tag{5}$$

with conditions

$$h(t_1, r_0) = \frac{\omega^2}{2g}H_1(2r_0 - H_1),\ h(t_2, r_0) = \frac{\omega^2}{2g}H_2(2r_0 - H_2),\ h(\cdot, r_0 + L) = 0. \tag{6}$$

It follows that at a time t, with water level H, we have

$$h(t, r_0 + y) = \frac{\omega^2}{2g}\left(y^2 - y\left(\frac{H(2r_0 - H)}{L} + L\right) + H(2r_0 - H)\right),\ y \in (0, L). \tag{7}$$

In this, ω is a known function of t, while $H(t)$ must be determined, but is known at t_1 and t_2. We can connect the two times, by noting that

$$\dot{H}(t) = -q(t),\ H(t_1) = H_1. \tag{8}$$

This can be readily solved with a suitable ode method. The result will depend on k, which implies that the measured value of $H(t_2) = H_2$ allows to determine k with an optimization method.

It should be noted that the actual implementation needs to take into account the filter at the end of the sample, and requires careful measurement of the acceleration and deceleration of the centrifuge. A specific point of attention for the current implementation of the centrifuge, is that there is no datum at the outflow, and hence the boundary condition $h(\cdot, r_0 + L) = 0$ is not imposed. Removal of the datum allows for faster flow, and reduces the cost and complexity of the setup, which are important design parameters. This will lead to a partially saturated zone at the outflow. However, also when a datum is present, due to the filter at the end of the sample, the boundary condition will also not be exact. We can further assume that in normal circumstances the unsaturated zone will be neglectible, and have neglectible effect on the results. The model used can however be extended with an unsaturated zone, see Kačur et al. (2010). This requires an estimate of the soil retention curve, so the logical approach is to neglect the unsaturated zone first to determine a first estimate of the hydraulic conductivity, and then estimate the soil retention curve via a drainage experiment, after which the estimate of the hydraulic conductivity can be improved using the more detailed model.

3 EXPERIMENTS

3.1 Materials

A commercial processed kaolin Rotoclay HB (Goonvean, St. Austell, UK) was used in this investigation. This kaolin clay was chosen as reference material because it has been largely used in previous research. Table 1 shows some properties of this clay determined in Di Emidio & Verástegui Flores (2012). Deionised water, produced using a water purification system, was used to prepare the samples and as reference permeant solution. The Electrical Conductivity of deionized water was EC $\leq$ 3.9 μS/cm and the pH was about 7.6.

The samples consists of a mixture of kaolin clay and deionized water. The amount of water in the mix was set to two times the liquid limit of the clay to obtain a slurry (w = 2 x 59% = 118%). In order to created suitable reconstituted samples (Fearon & Coop 2000), the clayey soil and the water were mixed in a dough mixer for 15 minutes until a homogeneous distribution was observed. Next, the slurry was poured in the glass centrifuge tubes using a vibratory table to remove air bubbles. Then, the sample was housed in an outflow glass reservoir.

3.2 Instrumentation

The centrifuge used for the experiments is a Laboratory bench-scale centrifuge type Sigma 3-18. This setup is equipped with two microprocessors for the independent control of the rotor recognition and the overspeed signal. The speed is continuosly controlled by these microprocessors with an accuracy of 1 rpm to a maximum

Property	Value	Unit
Specific gravity	2.64	
Liquid limit	59.00	%
Plasticity index	21.00	%
pH of 1:5 extract	5.4	
Electrical conductivity of 1:5 extract	303	μS/cm
Cation Exchange Capacity	1.38	meq/100g
Exchangeable cations:		
Na^+	0.45	meq/100g
K^+	0.10	meq/100g
Ca^{2+}	0.93	meq/100g
Mg^{2+}	0.56	meq/100g
Soluble salts:		
Na^+	1.44	meq/100g
K^+	0.21	meq/100g
Ca^{2+}	1.00	meq/100g
Mg^{2+}	0.81	meq/100g
Ca^{2+}	0.93	meq/100g
Cl^-	1.79	meq/100g
$SO4^{2-}$	1.33	meq/100g
HCO^{3-}	$\leq$ 0.10	meq/100g

Table 1. Physical and chemical properties of kaolin clay

of 16000 rpm. The duration of centrifugation, acceleration and deceleration curves can be set. The centrifuge is dotated with four buckets. Uneven loading of oppositely located buckets may lead to imbalance, in that case the drive automatically switches off and an imbalance warning message is diplayed. The maximum radius from the central rotor to the base of the buckets is 171 mm.

The soil sample is housed in a fully closed system where a constant pressure prevails. This closed system is constituted by a Duran glass tube (LSB Inner tube, inner diameter 21.55 mm x height 85 mm) containing the soil sample. This tube is screwed to a screw cap which is provided in the screw cap of an outlet reservoir (LSB centrifuge, glass thread GL 60, out diam. 62.3 mm x height 110 mm). The soil container tube is provided with a Borosilicate glass 3.3 Vitra POR filter welded to the tube with a nominal pore size 1 μm - 1.6 μm (class 5, ISO/4793 = P1,6), thickness about 2.55 mm to 3 mm, a diameter of about 21.55 mm. The glass containers are provided of a sufficiently thick wall (3 mm) resistant to centrifugal forces.

The necessary length sizes (e. g. height of the soil) were measured using a Vernier caliper (accuracy 0.01 mm). The mass of the soil, inlet and outlet water were measured by means of laboratory scales (accuracy 0.01 g). For the determination of the center of gravity (COG) of the soil into the tubes, two digital scale professional mini balances were used. The tube is placed horizontally on two sharp holders placed on the balances. The weight of the tube in two points is recorded and the center of gravity is calculated by means of the equilibrium of forces.

3.3 Experimental procedure

The testing program of this research consisted of four series of hydraulic conductivity tests on the Vitra POR glass filters welded to the tubes, on saturated and unsaturated kaolin samples and finally imbibition of the soil samples in the centrifuge. In this paper preliminary results on the glass filters and on the saturated kaolin samples will be illustrated in order to show the validation and calibration of the mathematical model and the suitability of the instrumentation.

1-g falling head hydraulic conductivity tests were performed on the samples analyzed (glass filters and kaolin soil) in order to obtain reference values of their hydraulic conductivity. Next, particular scenarios were analyzed utilizing centrifugation. Initially, the tube glass filters were analyzed by adding a water column on top and then by fixing the permeation driving force by imposing an acceleration on the specimen through a series of adjustable rotation speeds (100 rpm, 200 rpm, 300 rpm, 600 rpm and 900 rpm). After prescribed intervals of time of centrifugation, the amount of expelled water was measured and the hydraulic conductivity was computed following Sharma & Samarasekera (2007) and the mathematical model proposed here.

A second series of tests were performed on saturated kaolin samples. Fully saturated slurries of kaolin and deionized water were consolidated in the centrifuge with a free outflow right boundary (away from the center of the centrifuge) with increasing rotational speeds (100 rpm, 200 rpm, 300 rpm, 600 rpm and 900 rpm). After a prescribed time of centrifugation, the first measurements of the characteristics of the soil (sample weight and height, center of gravity) were obtained, as well as the amount of expelled water and remaining water on top. Then, the centrifugation was restarted up to the end of primary consolidation. This procedure was continued for a number of rotational speeds (100 rpm, 200 rpm, 300 rpm, 600 rpm and 900 rpm). Next, the centrifugation started again at 900 rpm rotational speed, with a water column on top of the sample and a free outflow right boundary. After prescribed time intervals of three and fifteen minutes, the centrifugation was stopped and the sample characteristics and the amount of expelled water were measured, in order to calculate the hydraulic conductivity of saturated kaolin samples at the end of consolidation.

4 RESULTS AND DISCUSSION

4.1 Hydraulic conductivity of the glass filters

Figure 1 shows the hydraulic conductivity of the glass filters in the centrifuge compared to the falling head hydraulic conductivity test. The hydraulic conductivity of the four filters centrifuged at different rotational speeds (100 rpm, 200 rpm, 300 rpm, 600 rpm, 900 rpm) were computed using Sharma & Samarasekera 2007 and the transient mathematical model proposed here.

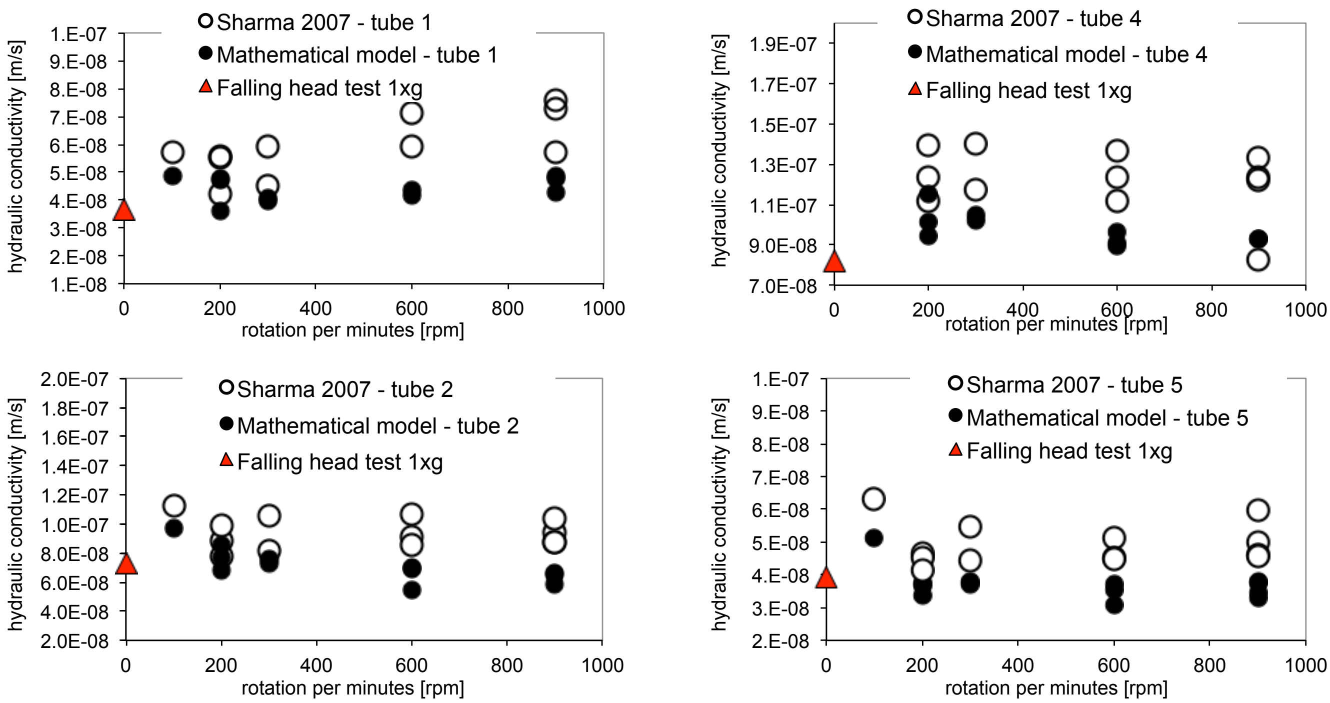

Figure 1. Hydraulic conductivity of glass filters in tube Nr. 1, Nr. 2, Nr. 4, Nr. 5: falling head (1xg) and centrifuge tests (Nxg). Comparison of analysis with the mathematical model with the Sharma computation referred to the COG of the water column above the soil

As expected, the hydraulic conductivity of the filters was constant independently on the rotational speed imposed (as shown in Figure 1). The hydraulic conductivity, in fact, is independent on the applied hydraulic gradient, which is the ratio between the hydraulic head on top of the sample and the sample thickness.

As illustrated above, and as shown in Figure 1, the computed hydraulic conductivity of the filters based on the centrifuge tests was consistent with the hydraulic conductivity of the same filters obtained with the 1-g standard falling head hydraulic conductivity test. On the other hand, as also shown in Figure 1, the hydraulic conductivity computed using Sharma & Samarasekera (2007) was slightly higher and showed a larger spread. The reason of this behavior is likely due to the fact that Sharma & Samarasekera (2007) refer their calculation of N to the COG of the water column above the sample, as shown above with equation (2) and that they do not take into account the acceleration and deceleration of the centrifuge which is taken into account by the model proposed here.

To verify these assumptions, the hydraulic conductivity was computed calculating N of Sharma referred to the base of the sample instead to the COG of the water column above the sample. As a result, the hydraulic conductivity computed with Sharma & Samarasekera (2007), referred now to the base of the filter, is lower compared to the hydraulic conductivity computed calculating N using the COG of the water column above the filter (Figure 2). This hydraulic conductivity is lower and tends to approach the hydraulic conductivity computed with the model that better resemble the hydraulic conductivity measured with the 1-g falling head standard method. Nevertheless, these differences are small and not crucial in our application.

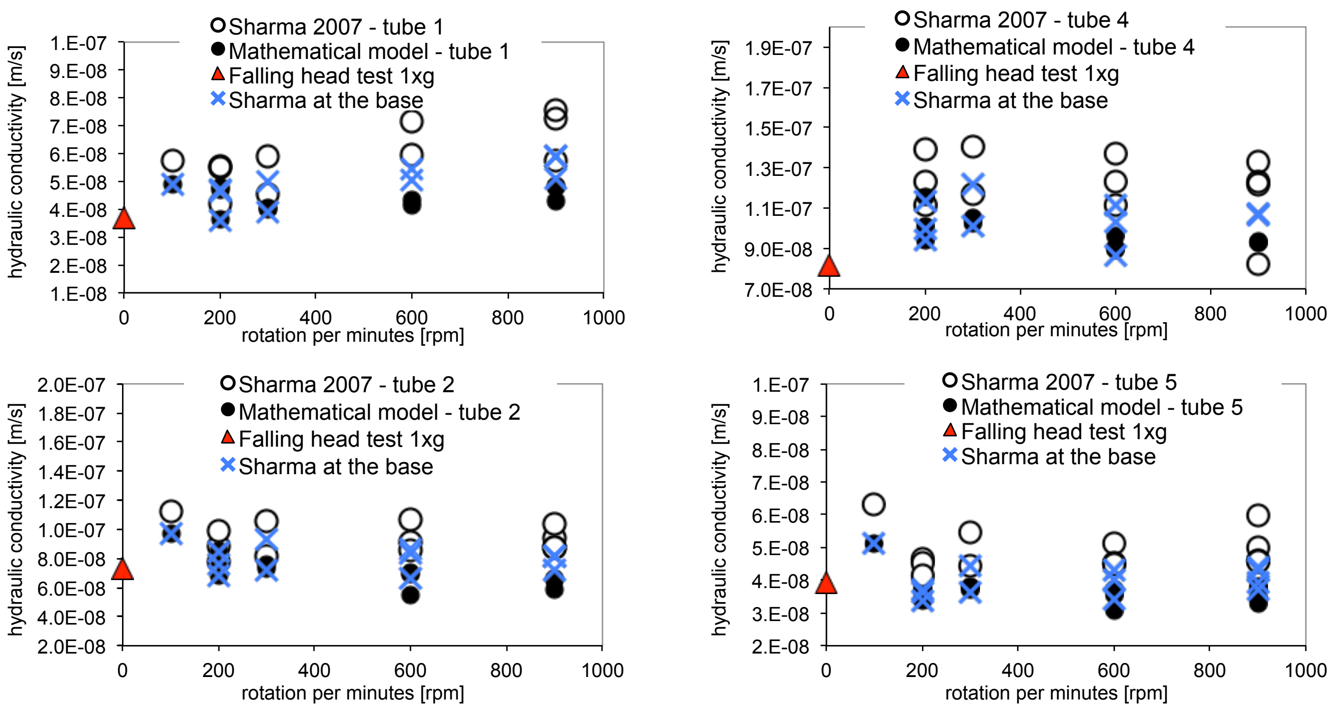

Figure 2. Hydraulic conductivity of glass filters in tube Nr. 1, Nr. 2, Nr. 4, Nr. 5: falling head (1xg) and centrifuge tests (Nxg). Comparison of analysis with the mathematical model with the Sharma computations referred to the base of the filter

4.2 Hydraulic conductivity of the saturated kaolin clay samples

Figure 3 shows the hydraulic conductivity of the saturated kaolin sample in the centrifuge at the end of every consolidation step. Four kaolin samples were consolidated simultaneously using 5 different rotational speeds, as listed in Table 2.

The hydraulic conductivity was again computed using Sharma & Samarasekera (2007) and the mathematical model. As shown in Figure 3, the hydraulic conductivity of the soil decreased with increasing rotational speed. The reason of this behavior is due to the decrease of the void ratio of the soil. Mesri & Olson (1971) showed that a direct linear relationship exists between the logarithm of hydraulic conductivity (log k) and the logarithm of void ratio (log e). Data from GCLs tested by Petrov & Rowe (1997) exhibit a similar relationship, although Petrov & Rowe (1997) indicated that an equally good linear relationship exists between the logarithm of the hydraulic conductivity, log k, and the void ratio, e. The void ratio, which is controlled by the state of stress in

speed	N
rpm	–
100	1,5
200	6,0
300	13,6
600	54,3
900	122,3

Table 2. Rotational speed and N computed in the center of gravity (distance from the rotatory axis r = 135 mm) of the consolidated saturated kaolin samples

a soil sample, describes the total amount of void space in the specimen. One of the methods to decrease the hydraulic conductivity of clays is to reduce the void ratio that can be achieved by applying high effective stresses to consolidate the soil. In centrifuge modelling, the increase of the rotational speed increases the driving force applied on the sample and, as a consequence, decreases its void ratio. Therefore, the increase of the rotational speed causes a decrease of the hydraulic conductivity of the samples analyzed here.

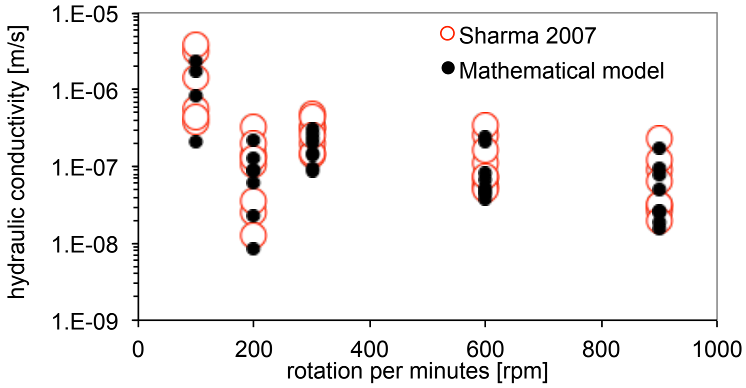

Figure 3. Hydraulic conductivity of saturated kaolin clay: falling head at the end of the test and centrifuge tests

It should also be noted that the centrifugal acceleration and the effective stress are not constant along the sample height. They increase in fact with increasing the distance from the rotatory axis and with the depth along the sample. As a consequence, the void ratio at the base of the sample is expected to be lower compared to the top of the sample. Therefore also the hydraulic conductivity is not homogeneous: at the base of the sample it is expected to be the lowest.

The spread of the results for every rotation speed (figure 3) is due to the fact that the values refer to different samples, with different void ratios. The computed hydraulic conductivity corresponding to the last consolidation step of 900 rpm was compared to the falling head hydraulic conductivity test performed at the end of the tests on the same samples. As shown in Figure 4, the hydraulic conductivity of the soil samples computed with the mathematical model was consistent with the hydraulic conductivity obtained with the falling head test and

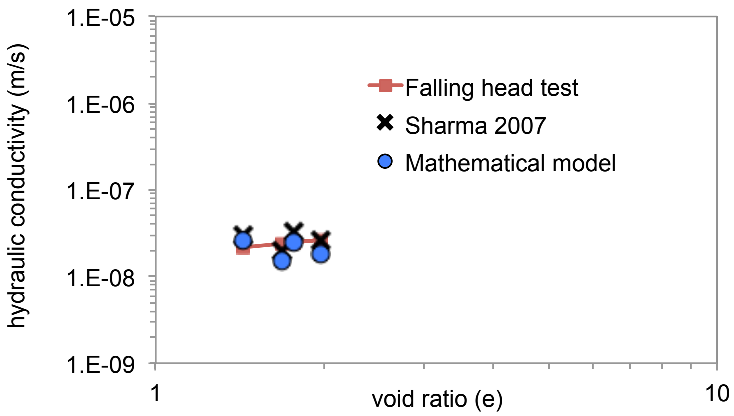

Figure 4. Hydraulic conductivity of kaolin samples: falling head (1xg) and centrifuge tests (Nxg)

the hydraulic conductivity computed using Sharma & Samarasekera (2007). These preliminary results are very promising in view of future application of centrifuge modeling for the determination of the hydraulic conductivity of low permeable soils.

5 CONCLUSIONS

The purpose of this research is to validate a mathematical model for flow through saturated and unsaturated porous media using a bench-scale centrifuge for an accurate determination of the hydraulic conductivity within a limited time at a reasonable price. Preliminary results of this investigation where shown here with the aim to validate and calibrate the mathematical model proposed and the instrumentation. The hydraulic conductivity of saturated porous media, such as kaolin clay and glass porous filters, was determined by centrifuge modeling using a small radius bench-scale centrifuge.

The hydraulic conductivity of the glass filters at different N-g levels (with N from 1.5 up to 122.23) computed with the mathematical model proposed here was consistent with the falling head hydraulic conductivity determined in a 1-g field. As expected, the hydraulic conductivity of the filters was constant independently on the rotational speed imposed.

The hydraulic conductivity of the soil samples computed with the mathematical model was consistent with the hydraulic conductivity obtained with the falling head test and the hydraulic conductivity computed using Sharma & Samarasekera (2007). These preliminary results are very promising in view of future application of centrifuge modeling for the determination of the hydraulic conductivity of soils. More research is needed to validate the model for unsaturated hydraulic conductivity tests.

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