Retained water content of granular soils under elevated gravitational acceleration

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ABSTRACT: Knowledge of the retained water content above the water table in centrifuge models is critical as suctions within this partially saturated soil will result in an increase in the effective stress and thus strength of the soil. This paper presents the findings from a series of centrifuge tests performed to identify the desaturation process of wet soil models under elevated gravitational acceleration (g). Granular soil models, with varying levels of silt content, were prepared with a known water content and subjected to varying g-levels while being allowed to drain freely. The desaturation of the soil column was measured in real-time using an image-based measurement system. Deformations of the soil surface were recorded which enabled calculation of void ratio changes. Consequently, the saturation ratio of the soil mass was determined for each increment of g-level. Results show that the amount of water retained within the soil mass is highly sensitive to the grain size distribution of the soil. As desaturation continues, the consequential reduction in hydraulic conductivity slows the desaturation rate and results in the saturation ratio continuing to change over a prolonged period – this process is again sensitive to the particle size distribution of the soil. The study provides insight into the validity of a typical assumption that for coarse grained soil above the water table, which was saturated via capillary suction, completely drains once a targeted g-level is achieved.

1 INTRODUCTION

Geotechnical centrifuges are often used to model complex geotechnical problems, such as slope stability under rainfall conditions (Take & Bolton 2011, Askarinejad et al. 2012, Matziaris et al. 2015). In some cases, prototypes are in an unsaturated state with soil suctions (that cannot be effectively measured) contributing to the effective stresses and thus the shear strength of the soils. Knowledge of the initial conditions of a soil model is critical to evaluate its behaviour. The enhanced gravity field in a centrifuge model causes desaturation of the soil mass that affects soil suctions. Suctions strongly depend on the water content of the soil, which can be evaluated using a Soil Water Retention Curve (SWRC). Unsaturated hydraulic conductivity is also controlled by suction and is reduced significantly as suction increases.

Centrifugal acceleration causes desaturation of soil models which are initially in a fully or partially saturated state. A typical assumption is that granular soils drain completely under an increased gravity field. Signh & Kuriyan (2002) studied the impact of centrifugal acceleration on the development of the unsaturated state in a silty soil. Also, researchers have conducted centrifuge tests for the determination of the unsaturated hydraulic conductivity in sands (Nimmo et al. 1987) and silts (Singh & Gupta 2000). In this paper, the experimental results of soil drainage enabled by centrifugal acceleration are presented. Soil columns with different grain size distributions were subjected to a gradually increasing gravity field using the geotechnical centrifuge of the Nottingham Centre for Geomechanics (NCG), at the University of Nottingham, UK. To accomplish the objectives of the study, an experimental apparatus was designed and implemented which allows the real-time measurement of a soil's water content during centrifugal acceleration. Deformation of the soil surface was recorded, thus calculating changes in the void ratio. Therefore, variations in the soil's degree of saturation at different g-levels could be determined. Using this experimental setup, desaturation curves for different soils and at different g-levels were produced. The distribution of the water content and degree of saturation of the soil model was determined at the end of each centrifuge test by extruding soil samples from different depths and drying them in an oven. The final bulk water content of the soil mass was then compared with the values obtained by the oven drying samples.

2 METHODOLOGY

2.1 *Soils*

Three types of sand and two types of silty sand were used in the study, as described in Table 1. Leighton Buzzard (LB) sand, fractions C and E, and Congleton sand were used. LB-fraction C is a medium-gained sand while LB-fraction E and Congleton are fine-grained sands. The Congleton sand was mixed with a silty soil to make silty sand mixtures, with sand proportions at 90% (M_{90-10}) and 50% (M_{50-50}). Grain size distributions for all soils are presented in Figure 1. In Table 1, classification characteristics for these soils are shown. Coefficient of saturated permeability (k) was determined in the laboratory using either the constant-head (for LB-Fraction E sand) or the falling head (M_{90-10} and M_{50-50} mixtures) method. The determination of *k* for LB-Fraction C and Congleton sands was done using Hazen's approximation given by the following equation:

$$k = 100 \times D_{10}^2 \tag{1}$$

where k = coefficient of saturated permeability (in cm/s); and D_{10} = effective size (particle size at which 10% of particles are finer) in cm.

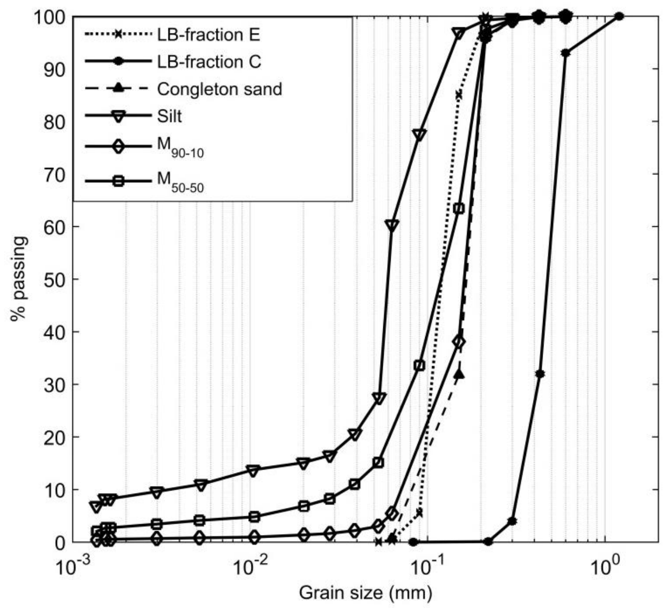

Figure 1. Grain size distribution of all soils.

Leighton Buzzard and Congleton are uniform sands with low uniformity coefficient (U) and very steep grading curves. Silty soil, used only for preparing sand/silt mixtures M_{90-10} and M_{50-50}, is better graded with more wide range of particle sizes. Grain size curves for M_{90-10} and M_{50-50} have been calculated based on the fractions of sand and silt.

Table 1. Characteristics of soils used in the centrifuge tests.

Soil ID	Soil name	D_{10}	U^*	k_{sat}
-	-	mm	-	m/s
1	LB-Fraction C	0.34	1.47	1.2E-2
2	LB-Fraction E	0.095	1.37	5.3E-5
3	Congleton	0.08	2.12	1.7E-3
-	Silty soil	0.0035	5.33	-
4	M_{90-10}	0.07	2.42	1.8E-6
5	M_{50-50}	0.036	4.17	1.0E-7

* Uniformity coefficient: $U=D_{60}/D_{10}$.

2.2 *Apparatus & model preparation*

A soil column apparatus for centrifuge testing was designed and implemented, as shown in Figure 2. It consists of a soil chamber, a measuring system and a top lid which seals the soil compartment. The lid is fitted with an LVDT for measuring surface displacement and spraying nozzles for applying soil wetting. The maximum height of the soil column is 500 mm, however this drops to 410 mm when LVDTs and spraying nozzles are used. The inner diameter of the chamber is 127 mm. A cone-shaped base assists with the extraction of water, which moves to a water tank through a fine filter, preventing soil from washing-out. The water removed from the soil is collected in a stainless steel tank which is connected to a standpipe. The water level in the standpipe therefore correlates to that in the collecting tank. A ventilation valve at the top of the tank ensures that air pressure inside the tank remains atmospheric during the test; therefore equal to the air pressure inside the measuring cylinder. Apart from the ventilation valve, the tank is sealed, thereby not allowing any loss of water due to evaporation.

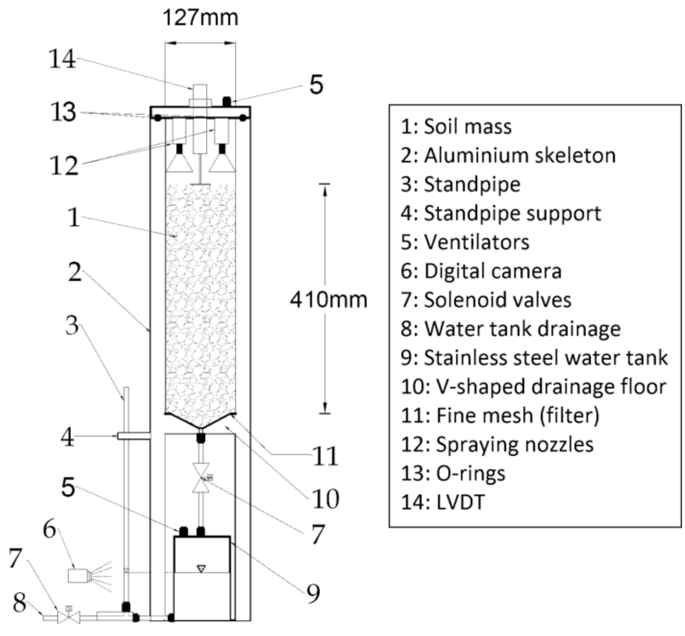

Figure 2. Soil column apparatus.

A digital camera is used to record changes of the water level in the standpipe, providing a measurement of the water volume within the water tank. The camera used was a Prosilica GC2450C with a resolution of 5 Megapixels and a recording rate of 15 Hz at full resolution, fitted with a 8 mm lens. The camera was fixed in front of the measuring cylinder providing images of the water level variation during the test.

Prior to centrifuge testing, calibration of the testing apparatus took place to: a) correlate the level in the standpipe to the water volume inside the water tank and b) determine the effect of water level variation due to the non-uniform enhanced gravity field which causes deflection of the free water surface in the centrifuge model. Water level changes within the standpipe were tracked at single pixel resolution using the image processing and analysis software ImageJ (Abramoff et al. 2004). This resolution corresponded to a water volume change, within the water tank, of 0.9 ml. Therefore, the accuracy of measurement was determined to be ±0.9 ml as determined by the calibration. This water volume corresponds to a change in moisture content of about 0.008% and depends on the soil type, model dimensions and g-level variations across the soil sample. It should be noted that this and all water contents quoted in this paper, which were derived from the centrifuge tests, refer to the bulk water content of the soil mass.

Soil models were prepared within the aluminium chamber to an initial height of 410 mm. The initial water volume, water content (w), void ratio (e), and degree of saturation (Sr) were determined, therefore measurement of the water volume extracted from the soil mass enabled calculation of the variation of the bulk water content during the centrifuge tests. Sandy models were prepared by pluviating dry sand into the aluminium tube, which contained a specific volume of water, from an average height of 0.5 m above the water level. Silty sand models were prepared by compacting the samples in 5 layers at a water content near proctor optimum. Water was then added from the bottom of the soil model until they reached near-complete saturation.

3 RESULTS & DISCUSSION

In Figure 3Figure 7, water content and degree of saturation variation due to increased gravity are presented, as well as the displacement of the soil surface. The gravity increment was done in the following order: 1-5-10-20-30-40-50-60g, with centrifugal acceleration determined at the middle of the soil sample. Soil models were subjected to each g-level until the settlement of the surface was less than 0.01 mm for at least 10 min. in model time. Corrected porosity and void ratio was determined based on the displacement of the soil surface, i.e. the volume change of the soil mass. Therefore the actual degree of saturation was determined.

The volume of the water tank is limited to 1500 ml, which is less than the volume of water removed from the soil. At stages during the tests, the solenoid valve connecting the tank to the soil was turned off and the tank was drained (by opening the downstream solenoid valve). This can be seen in Figures 3 & 5 as the steps in the data during the initial stage of spin-up.

For the coarser LB-fraction C soil (Figure 3), the desaturation occurs very rapidly even from 5g, and increments in g-level do not have much effect on water content after 10g. At the end of the test, LB-fraction C retained a water content w=2.5% corresponding to Sr=9.7%. This is evidence that even medium sands have the ability to retain a small amount of water when subjected to g.

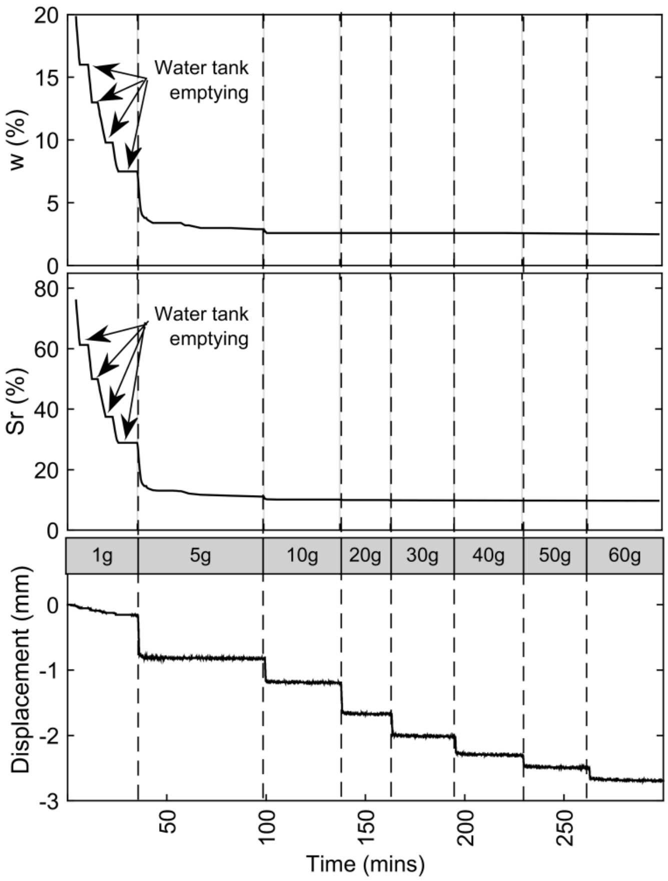

Figure 3. Desaturation curves for the *Leighton Buzzard sand, fraction C* (model scale). Displacement axis refers to the surface displacement of the soil mass.

Finer sands, like LB-fraction E (Figure 4) and Congleton (Figure 5), tend to retain more water during increased gravity. Also, increments of g-level cause more severe desaturation. The retained values for LB-fraction E were w=3.0% (Sr=9.9%); for Congleton sand they were w=3.4% (Sr=14.2%).

For the silty sands, the retained water increases significantly and reaches w=4% for the $M_{90\text{-}10}$ and

w=11% for the M_{50-50}, corresponding to degrees of saturation of Sr=18.9% and Sr=48.4%, respectively.

As desaturation continues, the considerable reduction in hydraulic conductivity slows the desaturation rate and results in the saturation ratio continuing to change over a prolonged period. This process is sensitive to the particle size distribution of the soil, as silty sands tend to desaturate much slower than clean sands.

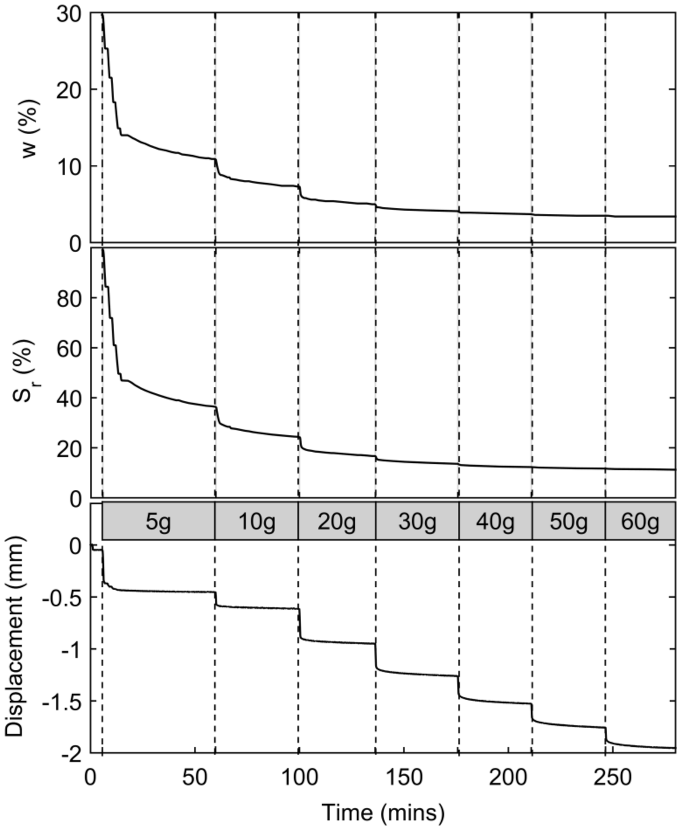

Figure 4. Desaturation curves for the *Leighton Buzzard sand, fraction E* (model scale). Displacement axis refers to the surface displacement of the soil mass.

The results show that for the finer soils, centrifugal acceleration at 60g can cause only partial desaturation, with a final Sr of almost 50%. This reduces significantly for coarser soils, becoming only 19% for the M_{90-10} mixture. On the other hand, sandy soils show a rather unexpected high degree of saturation after being subjected to 60g, having a degree of saturation of 10%. Based on the fact that hydraulic conductivity reduces significantly under partially saturated conditions, decreasing water content causes drainage to take longer to occur.

The results illustrate the existence of a residual value of moisture content for each soil at different g-levels. These values are shown in Table 2 Table 3, in terms of both w and Sr. After a g-level increase, an initial sharp reduction of the bulk w occurs, followed by an asymptotic reduction towards a constant value. This is more obvious for coarser soils; the time required to reach the steady state value of w for finer soils is considerable.

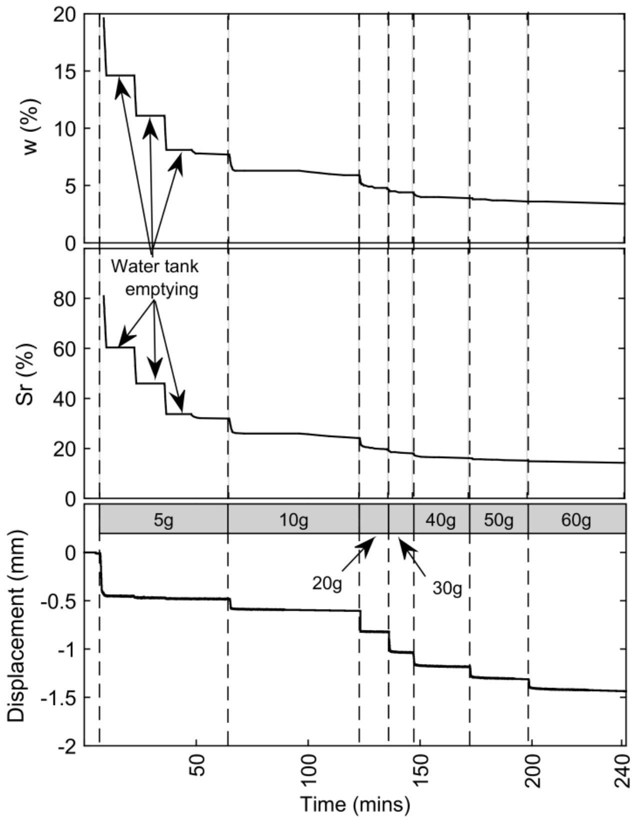

Figure 5. Desaturation curves for the *Congleton sand* (model scale). Displacement axis refers to the surface displacement of the soil mass.

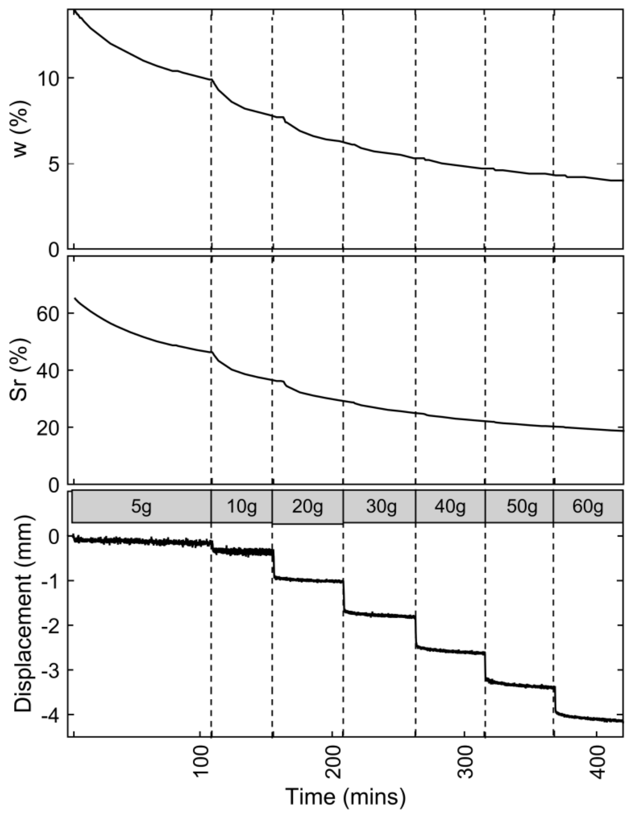

Figure 6. Desaturation curves for the *M_{90-10} mixture* (model scale). Displacement axis refers to the surface displacement of the soil mass.

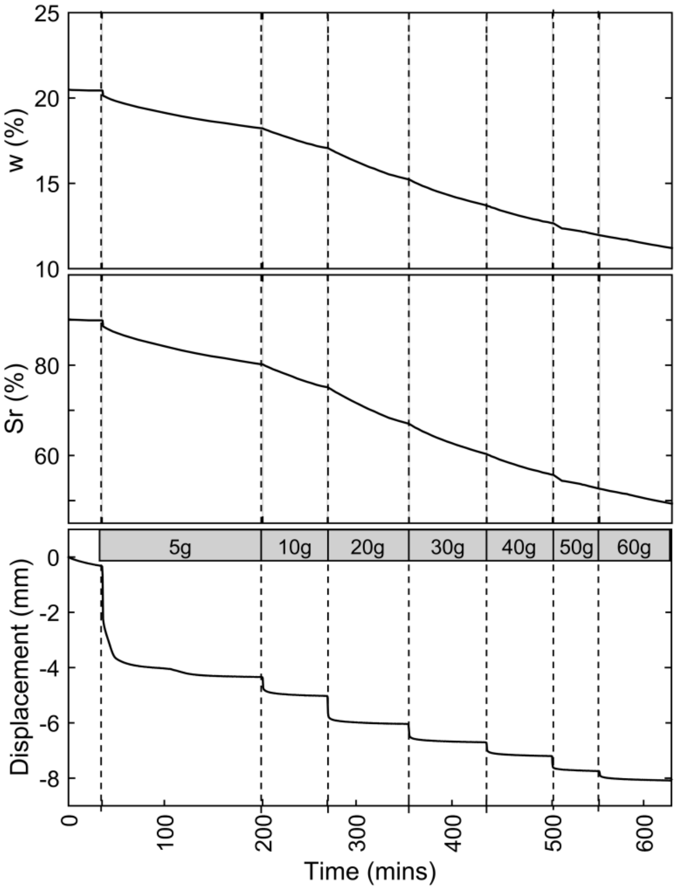

Figure 7. Desaturation curves for the $M_{50\text{-}50}$ *mixture* (model scale). Displacement axis refers to the surface displacement of the soil mass.

Table 2. Retained values of bulk gravimetric water content at different g.

Soil ID	*Initial*	*5g*	*10g*	*20g*	*30g*	*40g*	*50g*	*60g*
1	25.9	2.9	2.6	2.6	2.6	2.6	2.6	2.5
2	29.4	10.9	7.3	5.0	4.1	3.7	3.5	3.4
3	24.2	7.7	5.9	4.8	4.4	3.9	3.6	3.4
4	13.9	9.9	7.7	6.3	5.3	4.7	4.2	3.9
5	20.5	18.2	17.1	15.3	13.8	12.7	12.0	11.0

Table 3. Retained values of degree of saturation at different g.

Soil ID	*Initial*	*5g*	*10g*	*20g*	*30g*	*40g*	*50g*	*60g*
1	100	11.0	10.1	10.0	10.0	9.9	9.8	9.7
2	98.3	36.4	24.3	16.7	13.6	12.3	11.7	11.2
3	100	31.6	23.8	19.7	18.0	15.9	14.8	14.2
4	66.7	46.3	35.9	29.4	24.6	21.9	19.5	18.5
5	86.9	79.6	74.9	67.4	61.0	56.1	53.5	49.0

At the end of each test, the distribution of the gravimetric water content within the soil mass was determined by extruding soil samples from different depths and drying them in an oven. These are shown in Figure 8 and reveal a more or less uniform distribution in coarse soils. In finer soils (mixtures $M_{50\text{-}50}$ and $M_{90\text{-}10}$), w and S_r increased moving from the top to bottom of the soil column. This shows accumulation of the water within a zone near to the bottom of the soil mass. This zone starts from about half the height at the $M_{90\text{-}10}$ mixture while at the $M_{50\text{-}50}$ the zone starts at the upper layers. At sandy soils, a more even distribution appears and no water seems to be gathered near the bottom.

Comparison of the final bulk water content with the values determined by oven-drying samples for each soil is illustrated also in Figure 8. The empty symbols in the graph correspond to the bulk water content of the soil mass at the end of each test as they were determined by the measuring system of the soil column apparatus. The comparison shows that the determined mean moisture content for each soil lies between the minimum and maximum values of its moisture profile. In the case of $M_{90\text{-}10}$ mixture, the determined bulk water content is close to its minimum boundary while for Congleton sand it is close to its maximum boundary. However, there is a good agreement between the two types of results which provided evidence of the reliability of the measuring method using the soil column apparatus.

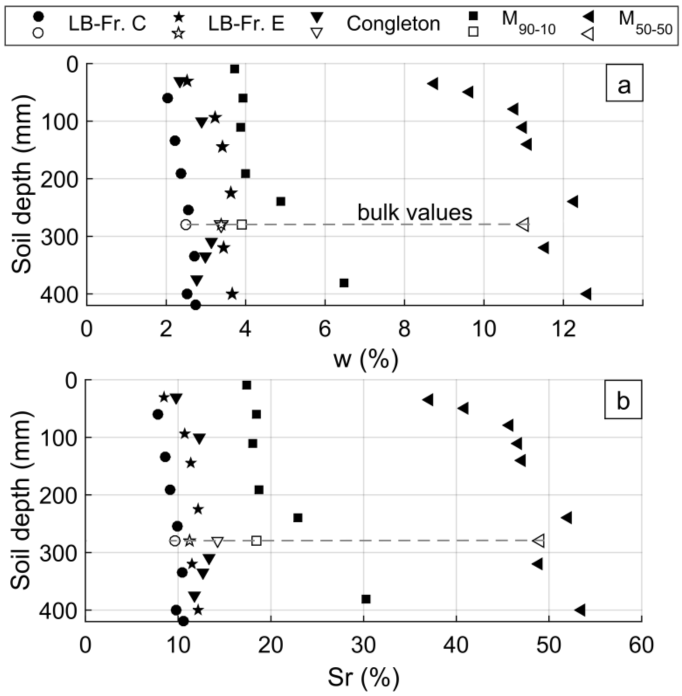

Figure 8. (a) Distribution of the water content, and (b) degree of saturation with depth at the end of centrifuge spinning. The empty symbols located on the dashed line correspond to the bulk values of w and respective S_r and were determined by using the measuring system of the soil column apparatus.

4 CONCLUSIONS

The desaturation of soils which occurs in an increased gravity field was studied in this paper. A series of tests were performed in soils with varying grain size, ranging from medium sand to silty sand.

A soil column apparatus was designed which allows for accurate and real-time measurement of the retained water content within the soil mass under increased gravity. The accuracy of the apparatus was checked by comparing the calculated retained water content with that obtained from sample drying.

Results showed that even coarse soils do not completely dry when subjected to centrifugal acceleration, retaining a degree of saturation *Sr* between 9.7% and 14.2% for sands and 18.9% to 48.4% for silty sands even after a prolonged period. The desaturation rate decreases and the amount of retained water increases for finer soils. The retained water content under these circumstances causes partially saturated conditions, with enabled soil suctions influencing effective stresses and shear strength. Therefore, it is important to take into account, for certain circumstances, the unsaturated conditions that occur in wet soils when they are subjected to elevated gravity in a geotechnical centrifuge.

5 ACKNOLEDGEMENTS

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