The paper was published in the proceedings of the 11th International Conference on Scour and Erosion and was edited by Thor Ugelvig Petersen and Shinji Sassa. The conference was held in Copenhagen, Denmark from September 17th to September 21st 2023.

Experimental Investigation of Suffusion with X-ray Computed Tomography

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ABSTRACT

Suffusion, i.e. the transport of smaller particles through the pore space of the fixed particle skeleton of larger particles, is the prerequisite for all erosion processes. For the understanding of erosion processes in the soil, such as backward erosion (piping) as a failure mechanism for water retaining structures such as dikes, dams or measuring weirs, a better understanding of the mechanical and hydraulic processes in these is needed. X-ray computed tomography as an imaging technique allows a non-destructive examination of the inside of a soil sample on a micro level. With Mirco-CT devices, processes can be examined on particle level. For this purpose, particle shape and position, as well as the distribution of the phases in saturated soils, the water and particle phase within the soil, are analyzed. For the investigation of suffusion, a grain structure consisting of large glass spheres was flushed through with water, resulting in the smaller particles from the lower layers moved through the pore space.

INTRODUCTION

Erosion is defined as particle transport of the soil by external influences such as wind or water, whereby all particles in the soil can be transported and relocated. If, on the other hand, only the part of the soil that is not responsible for the structural capacity of the soil is transported and relocated, this is referred to as suffusion (Bundesanstalt für Wasserbau, 2013). Suffusion refers to the process in which the small particles of the soil (fine fraction) are transported by the water flow into the pore space of the larger particles (coarse fraction) of the soil and are rearranged. This phenomena is non-destructive which is defined with a mass loss but without a change in volume (Fannin and Slagen 2014). Internal suffusion takes place within a soil layer and is the prerequisite for any kind of suffusion and thus also for erosion processes. As the transport path of the moving particles is limited the process only last for a short time (Busch et al., 1995).

Since internal erosion on structures cannot be calculated, there is no verification procedure and the possible damage is usually prevented constructively by means of filters or interruption of the flow (Bundesanstalt für Wasserbau, 2013). Consequently, erosion processes such as backward erosion can usually only be assumed to be the cause of damage retrospectively.

For the investigation of erosion processes in the soil, a better understanding of the mechanical and hydraulic processes in it is necessary. Computed tomography as an imaging method enables the non-destructive examination of the inside of soil samples. Especially in materials science, computed tomography (CT) has been used for some time to examine structures on a particle level. In geotechnical engineering, on the other hand, this method has only recently been used for the investigation of processes at the particle level. Here the particle shape and position, as well as the distribution of phases in saturated soils, the water and particle phase within the soil are analysed. In addition, such CT investigations offer a possibility to validate numerical models such as the Discrete Element Method (DEM), because for numerical modelling an understanding of the physical processes must be available in order to make extensions and improvements to the models.

X-RAY TOMOGRAPHY

The theory of computed tomography (CT) was first described by the Godfrey Hounsfield in the early 1970s. The imaging procedure for the spatial visualisation of matter with different densities applied X-rays was introduced into medical practice in the same decade and is now also increasingly used in materials research. In computed tomography, layer images without superposition are generated and a three-dimensional CT image is created with a mathematical algorithm. In this way, even small differences in density can be clearly reproduced, allowing different materials to be distinguished from one another. Based on the different grey value ranges (density differences), a phase classification into soil particles, pore water and pore air is carried out in geotechnics. This is made possible because soil particles have a higher density compared to water and air. Another decisive factor is that the voxel number must be smaller than a particle in order to reflect the interface between particle and pore space. This allows the study of mechanical and hydraulic processes in soil on a grain-to-grain level (Milatz and Grabe, 2019).

Soil investigations in the laboratory are usually based on the fact that equations are set up from the results of measurements of forces and deformations at the sample edges, which are supposed to reflect the material behaviour of the soil. However, the assumption is that the soil can be described as homogeneous, which means that it is only considered macroscopically. With the help of computed tomography, soil samples can be analysed non-destructively at the particle level, as CT scanning allows microscopic soil structures to be identified, enabling the investigation of soil mechanical processes at a grain-to-grain level. Computed tomography has been introduced to geotechnical engineering in the 1980s. CT imaging provides a powerful method for understanding and spatially arranging the different soil phases and their interaction, and primarily involves the study of pore space and its distribution. CT imaging is used to study hydraulic and mechanical processes in soil at the microscopic level to improve the understanding of macroscopic behaviour. Especially the investigation of time-related processes in three-dimensional space with stepwise CT scans offers new possibilities.

The computed tomographic investigations in the present work were carried out with the micro CT μCT35 from the company SCANCO Medical.

EXPERIMENTAL SET UP

The experimental setup consists of a sample holder with base and plug, syringe pump, stepper motor, motor control board and a Raspberry Pi computer.

The cylindrical polyoxymethylene copolymer sample holder has an opening in the base area which is connected to the electrically controlled syringe pump. The connection is made via rubber hoses and connectors as well as a ball valve. The suffusion is triggered by pumping water in the sample holder using the syringe pump, which is driven by the stepper motor and the motor control board run by the Raspberry Pi.

The sample holder area for the sample has an inner diameter of 12mm and a height of 12mm. A filter stone is inserted below the particles to ensure that the particles do not enter the irrigation channel and that the water flows as evenly as possible over the cross-sectional area into the sample (see Figure 1).

Material. Monodisperse SiLibeads spheres made of soda-lime glass from SIGMUND LINDNER GmbH are used as test material. Two different particle sizes are used, with the small particles (SiLibeads SOLID Micro glass beads) having an average diameter of 0.25mm and the large particles (SiLibeads glass beads type M) having a diameter of 2mm.

Figure 1: Syringe pump (left) connected to the sample holder (right) in the CT scanner.

Scan parameters. The scan parameters for the CT scans are listed in table 1. For the first scan, the integration time is set to 800 ms and then reduced to 600 ms due to time constraints.

Table 1: Settings for the µCT35 CT device

Description	**Parameter**	**Value**
General	Specimen holder type	U80802
	Mode	Convert to DICOM
X-ray settings	Acceleration voltage	70 kVp
	Current	114 µA
	Intensity	8 W
CT-Scan settings	Resolution	High
	FOV/Diameter	20.5 mm
	Voxelsize	10 µm
	Slice	232 mm
	Integration time	600 ms
	Avergage Data	2

Experimental procedure. The glass beads are trickled into the water column of the saturated sample container. Start by trickling in a layer of large particles with a mass of 3g. Then fill the pore space with small particles with a mass of 0.2g and finally fill with the large particles so that the plug presses against this top layer when it is closed.

With the syringe pump, between 200mm^3 and 400mm^3 of water is injected into the sample from the bottom in a hydraulic step. Control by means of a PYTHON script regulates the flow velocity to 0.002m/s. The PYTHON script was developed by Dr.-Ing. habil. Marius Milatz from the Institute of Geotechnics and Construction Management.

First, the initial state of the sample is recorded in a first CT scan. Then water from the syringe pump flows through the sample from bottom to top and a CT scan is taken. The whole process is repeated in 3 hydraulic steps. In each first and second step 200mm^3 of water are injected and in the third 400mm^3.

RESULTS

In the 3D images (Figure 2) of the sample before (left) and after (right) the injection of water, a rearrangement or upward movement of the small particles can clearly be observed.

The void ratio e is calculated as the ratio of the volume of the pore space (water phase) to the volume of the glass spheres with

$$e = \frac{V_{Pore\ Space}}{V_{Glass\ Spheres}}.$$

The pore number over the depth of the sample (see Figure 3) shows a wavelike progression, which can be explained by the placement of the large particles in layers. The void ratio is not a marcoscopic soil parameter, as is normally the case, but a particle-scale value. It is low when the

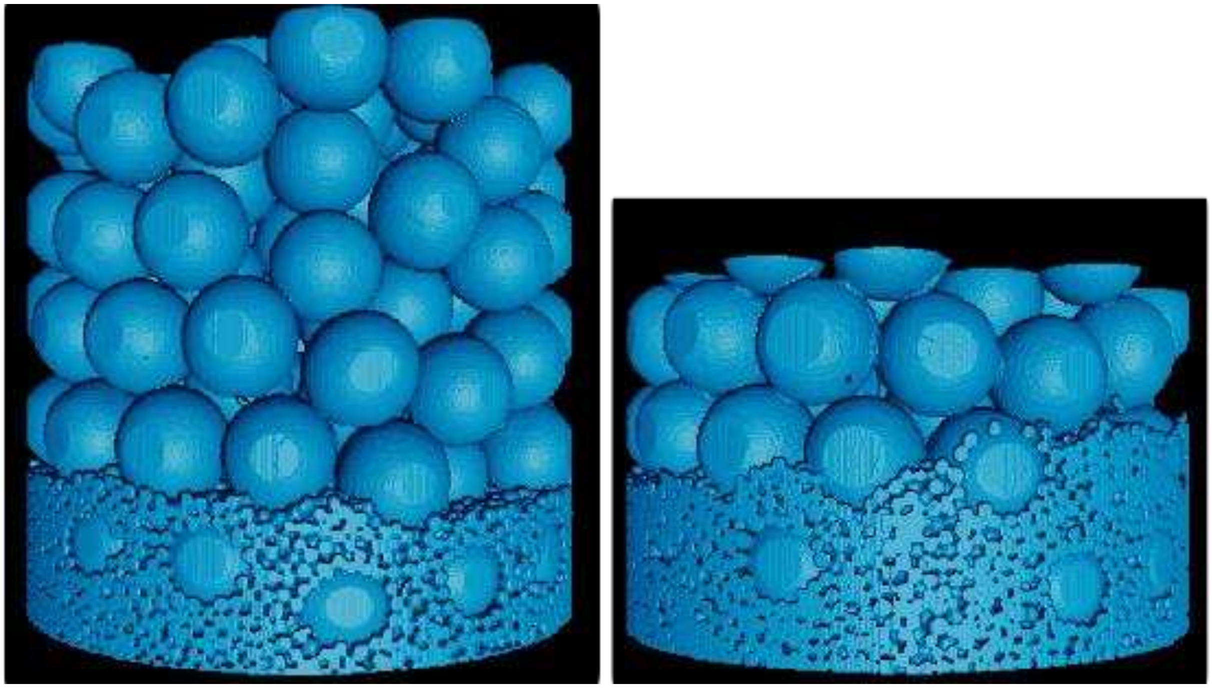

Figure 2: 3D image of the start (left) and end (right) of the experiment.

maximum diameter of a layer of large particles is reached in the cross-sectional area. When the volume centre of mass of the large particles is reached in a cross-sectional area, the void ratio is at its lowest; above and below this, the void ratio increases accordingly. The deflections in the x-direction are regular and are repeat approximately every 2 mm, which corresponds to the diameter of the large particles.

The shape of the curves of the three following CT scans are similar to those of the initial state. After the first hydraulic step with an input of 200 mm^3 of water into the system (red curve), the void ratio in the lower part of the sample is clearly lower than in the initial state. Comparing the CT images of the first two scans, a difference in quality is noticeable (see Figure 4). The integration time was set to 800 ms in the first scan, which makes it easier to distinguish the small particles from the pore water and also results in a different ratio of particles and water in the phase segmentation. With a lower integration time, more voxels appear to be assigned to the particle phase, resulting in a lower void ratio. Nevertheless, the difference between the blue and red curves is not constant over the entire height, indicating a change in void ratio over the depth of the sample after the first hydraulic step. In the following scans, the shift from the minimum to higher areas of the sample can be seen. This indicates that the small particles were transported upwards.

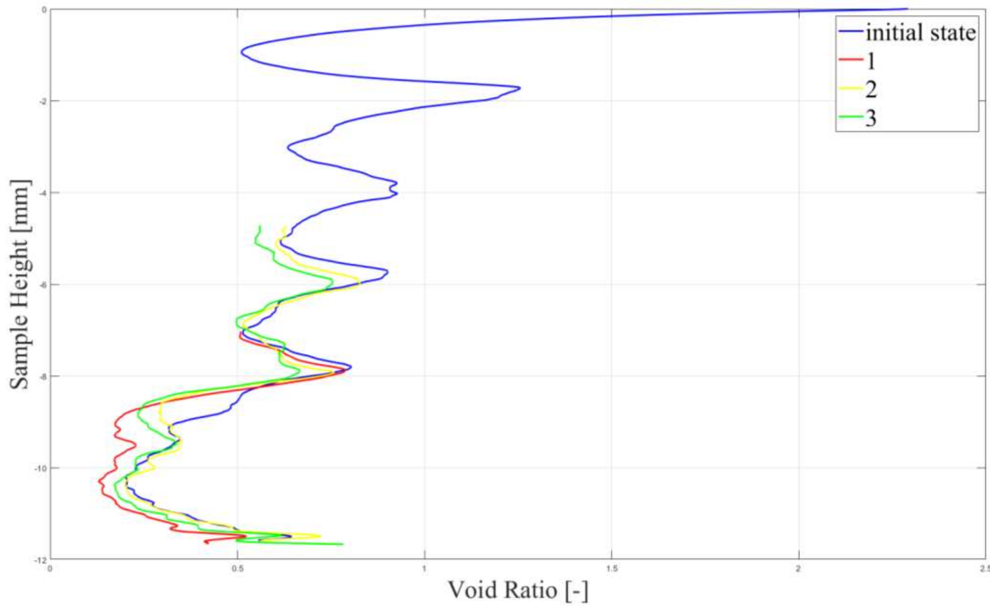

Figure 3: Void Ratio development over the depth of the sample for the initial condition and the 3 following CT scans after the hydraulic steps.

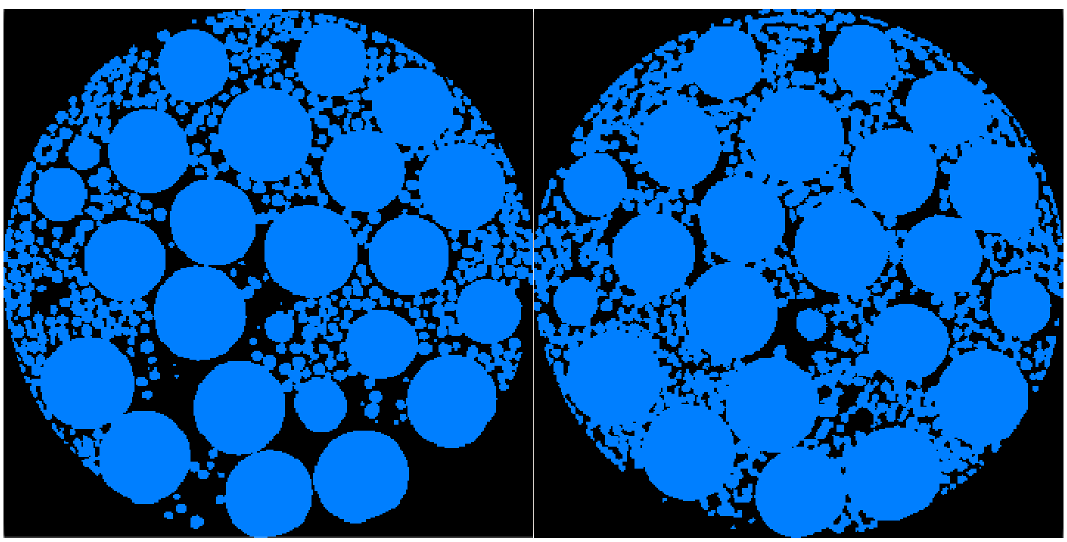

Figure 4: Comparison of the quality of the CT scans initial condition (right) and condition after the first hydraulic step (left) of the cross-sectional area at a depth of -9 mm.

Comparing the cross-sections of the last CT scan with those of the initial state, it is evident that the small particles have migrated up to a depth of -7.8mm in the container (see Figure 5 2nd row). In both the 2nd and 3rd row images, the comparison is shown at a depth of -11.55mm. While the small particles migrate upwards due to the water flow, the large ones sink downwards. Therefore, in the 3rd row image on the right (after all three hydraulic steps) twice as many large particles can be counted compared to the initial state. It can thus be concluded that the particles above also have started to move. This can be clearly be seen in the top two rows of images by the change in the positions of the large particles in the upper area of the sample.

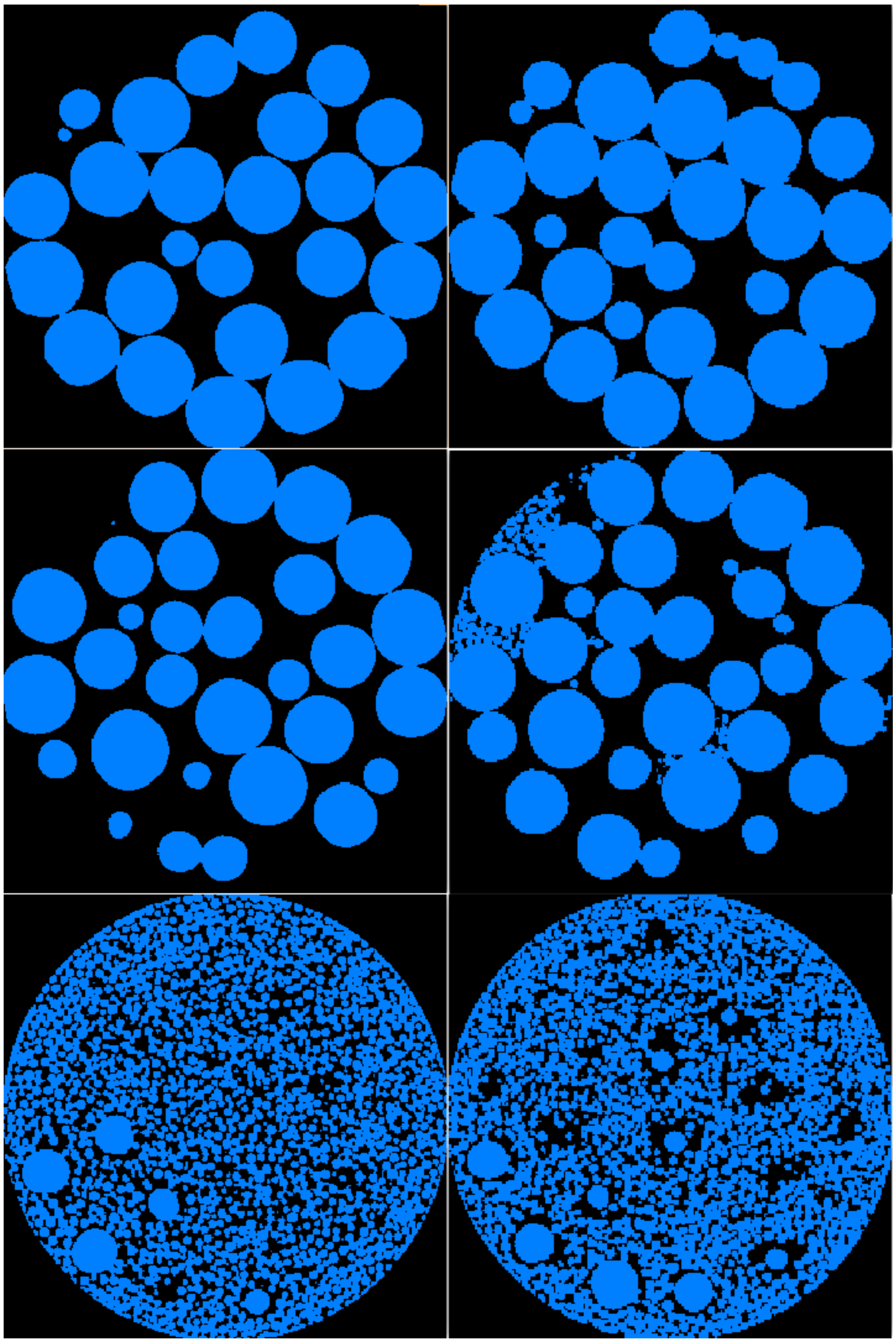

Figure 5: Comparison CT scans initial state (left) and state after three hydraulic steps (right) from the cross-sectional area at a depth of -5.10mm (top), -7.80mm (middle) and -11.55mm (bottom) from the sample.

CONCLUSION

The experiments showed that the suffusion process can be studied using CT experiments. By injecting water step by step through the syringe pump, the small particles from the lower area of the sample migrate upwards through the pore space of the large particles. The change in the position of the small particles can be identified from the curves of the void ratio over the depth of the sample, as well as from the CT scans. They do not migrate uniformly upwards across the cross-section but follow preferred paths through the particle skeleton of the large particles.

In contrast to the original definition of suffusion, there is no solid non-destructive particle skeleton in the sample. The spherical particles with a high degree of roundness of ≥ 0.98 are difficult to consolidate and the monodisperse glass spheres have a large particle volume to particle diameter ratio. The void ratio is therefore relatively large, as the pore spaces in the upper region of the sample, where no small particles are present, cannot be filled. Nevertheless, the glass spheres offer advantages because they come very close to being spherical and the properties of the individual spheres are comparable to each other. For the subsequent numerical simulation, both the spherical shape and the same material properties of the individual particles play an essential role.

The exact change in position caused by the flow through the sample cannot be reproduced with the CT image, only the final position can be seen. A CT image is always only a static image of a moment in time, while suffusion as such involves a dynamic process. Due to the stepwise flow through the sample and the subsequent sinking of the particles, only the static final state and the associated rearrangement of the particles by suffusion and subsequent deposition can be investigated.

Also, the investigation of the preferential flow path is of interest. Nguyen et al. (2019) showed that there are preferential flow paths at the edge of the sample container. Figure 5 middle shows the same phenomena, the smaller particle which moves through the water flow accumulate at the wall of the sample container.

In addition, the settling velocity after Stokes of the smaller particles is about 0.2 m/s which is greater than the flow velocity with 0.002 m/s and also the flow velocity in the pore spaces. This can lead to a settling of the smaller particles after the water injecting and alter the position of these particles.

Fundamentally, computed tomography offers considerable analytical potential for the study of erosion processes. It can be used to examine a sample and the changes in individual particles caused by a flow and also to explore the interior of the sample in a non-destructive manner. For the calibration of particle-scale numerical models such as Discrete Element Method (DEM) coupled with Computational Fluid Dynamics (CFD), these CT experiments are a good option.

For further investigations of erosion processes using computed tomography, the sample preparation must be optimised so that the large particles form a rigid skeleton through whose pore space the small particles can migrate. One possibility would be to print a particle skeleton using a

3D printer to ensure a certain reproducibility of the experimental procedure. Alternatively, the large particles would have to be compacted so that they do not move during the course of the experiment. Another option is to use a different CT scanner with a higher resolution. Among other things, synchrotron radiation CT scans like the one at DESY (PETRA III) have a much shorter scan time and could thus better investigate dynamic processes such as erosion. As well as a device which has a place for a permanent solution for the water pressure inside the sample inside the x-ray chamber.

As a short-term alternative, a simplification of a 3D problem to a 2D problem that can be analysed by Particle Image Velocimetry (PIV) would be the next step.

ACKNOWLEDGEMENTS

The authors acknowledge the funding of this research by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) in the framework of Research Training Group GRK 2462: Processes in natural and technical Particle-Fluid-Systems at Hamburg University of Technology (TUHH).

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