Development of a coaxial cell for porosity measurements during contact erosion experiments

T. Bittner, T. Bore, A. Scheuermann & M. Bajodek
School of Civil Engineering, The University of Queensland, Australia

K.J. Witt
Bauhaus Universität Weimar, Germany

Abstract: The rearrangement of soil particles during erosion, which is basically a transient mixing of base and filter particles, is accompanied by changes in porosity, leading to overall settlements which frequently can be severe for geotechnical structures such as levees. Therefore, not only the geometric and hydraulic boundary conditions, but also porosity changes are an important parameter that has to be observed during experiments. Classical approaches, like layer-wise analysis after the test, are usually not sufficient to allow any upscaling to technical dimensions. Furthermore, numerical approaches are under development allowing the computational modelling of hydro-mechanical problems in general. A decisive parameter governing both, hydraulic processes as well as the mechanical reaction, is the porosity. Former experiments have shown that Spatial TDR (Time Domain Reflectometry) is a promising technology for real time and spatial monitoring of porosity distributions. In order to use this measuring principle, an erosion experiment has to be designed and built to meet the requirements of this technique. The erosion cell itself serves additionally as the TDR-probe. Glass beads are used as an idealisation of a granular soil in order to minimise the effects of the grain angularity and different compositions of natural soils of varying sources, and thus allowing a high rate of repeatability. The data obtained in these experiments will help to get a better understanding about the progress of the erosion process and can be used for the calibration of numerical simulations.

Keywords: Contact erosion, porosity measurements, granular soils, Time Domain Reflectometry

1 INTRODUCTION

There are many geometric criteria regarding the onset of the internal erosion at the contact zone of two different soils, of which the best known is the one developed by Terzaghi (Fannin, 2008; Peck & Terzaghi, 1948). Additionally, hydraulic criteria were developed to meet the requirements of base/filter combinations that are beyond the specifications of the geometric criteria (Ziems 1969, Brauns et al. 1993). It has to be noted that all of this criteria are limited to the conditions under which they were developed, namely grain size distribution and the uniformity of the soils used or the boundary conditions of the equipment used (Sherard, Dunnigan, & Talbot, 1984). All these criteria have one important commonness: They are focussed on the onset, or, more precise, on the prevention of erosion, as this is an important part of geotechnical design (Schuler & Brauns, 1993). In some cases, a certain filtration length is accepted (Witt, 1993). But with that focus, the process beyond the onset of erosion is out of range.

In the case of geotechnical structures under construction which are under subject to hydraulic loading, it is the task of the engineer to develop a design which is safe against internal erosion. The difficulty is to meet this design requirements with the materials that are available.

With existing older structures or naturally built up soils, the situation is different. The geometrical design criteria are often not met in naturally layered soils and the numbers of failed earth-fill dams with poor or no control of erosion are considerable higher compared to those with a good control of erosion (Foster, Fell, & Spannagle, 2000).

As the initiation process within a structure is usually unnoticed, contact erosion can often only be detected after a certain progress, leading to changed flow characteristics or settlements that can pose a risk for the geotechnical structure. Therefore, it is mandatory to understand the mechanisms that induce and maintain the process of internal erosion. However, these mechanisms are not clearly understood (Bonelli, 2012).

The classical geometric and hydraulic filter criteria are more and more flanked by numerical models. The accuracy of these simulations is heavily dependent on the available data. Thus, experimental work is of great importance to get a better insight into the erosion process and to determine specific data required to calibrate numerical simulations.

An integrated approach of both, micro scale of the grains and pores and macro scale of the whole soil layers, is necessary to obtain a better insight. On the micro scale, recent studies showed that the porosity and the shapes and connections of the pores have a significant influence on the hydraulic conditions and the distribution of the flow velocity in the pores (Beguin, Philippe, & Faure, 2012; Bonelli, 2012; Harshani, Galindo-Torres, & Scheuermann, 2017). Thus, it is important to monitor the spatial distribution of the porosity and its alteration during the erosion process, as the hydraulic and mechanical properties are coupled and interdependent.

Different methods have been used for the determination of the porosity so far. A classical approach is the determination of the washed out fine fraction (Ke & Takahashi, 2014; Rochim, Marot, Sibille, & Thao Le, 2017). However, this method does not allow conclusions of the spatial distribution during a test. It is only possible to examine the soil sample layer-wise after the experiment or, as an extension, the monitoring of changes of the layer heights during the test (Ke & Takahashi, 2012). Depending on the experimental setup, conclusions of local changes of the porosity are feasible, but are limited to sections which can be monitored visually.

In order to determine porosity profiles of a sample before, during and after an erosion test, Sibille, Marot, and Sail (2015) utilised a gamma ray source and a scintillation counter. The drawback of this method, along with the hazard of radiation, is that the porosity can only be determined layer by layer.

Soil can be seen as a mixture of three different phases. An approach which takes advantage of the different dielectric permittivity of the solid, liquid and gaseous phases is based on high frequency electromagnetic methods such as TDR (Time Domain Reflectometry). The possibility to detect changes in one of the phases in a porous medium is premised on their dielectric contrast (Robinson, 2004). TDR has been successfully used to determine the water content and the density of soils (Drnevich, Ashmawy, Yu, & Sallam, 2005) and for the measurement of spatial porosity distribution along a rod probe (Scheuermann, Muehlhaus, Bittner, & Bieberstein, 2012).

In this paper, a newly developed experimental setup is introduced, which is designed to perform erosion tests in an optimised setting for electromagnetic measurement techniques. With this device, it is possible to determine the porosity profile along the soil sample in real time.

2 SPATIAL TDR

Considering soil as a porous media composed of solid, liquid and gaseous phases, it is obvious that the ratios of these fractions are subject to change during an erosion process or variations of the water content (drying, humidification). In various laboratory and field experiments, high frequency electromagnetic methods such as Time Domain Reflectometry (TDR) are currently used to assess water content and density. The measurement principle of TDR is based on the interactions of a high frequency electromagnetic field with the surrounding medium under test. The TDR-device, consisting of a pulse generator and an oscilloscope, emits a voltage step pulse via a coaxial cable into the probe built as a transmission line. At impedance discontinuities (e.g. the transition between cable and probe or sharp alterations of dimensions of the probe), the pulse is partly reflected. The remaining pulse travels further and is fully reflected at the end of the probe. The sum of the signals is shown by the TDR device’s oscilloscope.

The first and second reflection in the TDR signal serve as an indicator for the beginning and the end of the probe. The travel time of the signal between the two reflections is dependent on the dielectric permittivity of the medium under test and can be used easily to determine an average value of the porosity or water content by the tangent method (Huisman, Weerts, Heimovaara, & Bouten, 2002). A good approach for measuring moisture content and density using Time Domain Reflectometry (TDR) was developped in Siddiqui and Drnevich (1995) which was subsequently updated and further developed by Jung, Drnevich, and Abou Najm (2012).

However, there can be much more information found in a TDR signal than the travel time. Between the first and second main reflection, it contains a dielectric profile of the medium under test. The principle is to generate a permittivity profile out of the measured TDR signal. This is done by means of a simulation of the propagation of the TDR signal along the probe in the time domain using a numerical model (forward problem) based on the telegraph equations:

$$\left(L'(x)C'(x)\frac{\partial^2}{\partial t^2} + L'(x)G'(x)\frac{\partial}{\partial t} + \frac{1}{L'(x)}\frac{\partial L'(x)}{\partial x}\frac{\partial}{\partial x} - \frac{\partial^2}{\partial x^2}\right)V(x,t) = 0 \qquad (1)$$

Both capacitance *C'(x)* and effective conductance *G'(x)* are influenced by the spatial distribution of the soils properties along the probe. The inductance *L'(x)* is not a function of the soil but of the transmission line (the probe) and can therefore be considered as a constant for a uniform geometry and a given probe.

For the simplified description of the wave propagation using the telegraph equations, some preconditions are to be met. This includes specific assumptions about the wave propagation itself as well as special requirements on the probe design. A more detailed description of probe design and wave propagation is given in (Huebner et al., 2005) and a comprehensive introduction of the inverse model in (Schlaeger, 2005).

TDR measurements can be made with one port in the reflection mode, which means the electromagnetic pulse can be fed only from one side into the probe, or with two ports in the transmission mode, where the measurements can be made from both ends of the probe. In the reflection mode, only the capacitance profile can be computed out of the TDR-signal, hence just one state parameter of the material under test can be detected, either the volumetric moisture content or the porosity. However, at fully saturated conditions, the volumetric water content can directly converted into changes in porosity (Scheuermann, 2012).

The setup presented here is limited to the reflection mode due to design reasons and the measurements are thus limited to porosity changes. As the erosion experiments are made on fully saturated samples in order to eliminate the permeability fluctuations of entrapped air, this means no restriction for the experimental setup. In this respect the use of glass beads with uniform dielectric permittivity as an idealisation of natural granular soils is further beneficial.

3 EXPERIMENTAL SETUP

3.1 General setup

The general setup equals a constant head permeability test with an upwards directed flow and can be seen schematically in Figure 3.1. The hydraulic boundary conditions are defined by the potential, which is defined by an adjustable overflow upstream and a fixed overflow downstream of the column. The water circulation system consist of a 100 litre water reservoir, a submerged pump, a valve for the control of the flow rate, the adjustable constant head overflow tank upstream of the erosion cell, the erosion cell with the downstream overflow and finally a flow meter. A detailed description of the coaxial erosion cell and its development is given in section 4. In order to reduce the flow resistance at high flow rates and to avoid head losses, all connecting hoses have an inner diameter of 32 mm. Therefore, the flow meter is placed downstream of the erosion cell, as it acts as a constriction. The setup has been used previously for fluidisation experiments and has been changed to meet the requirements of the erosion test setup presented here (Bittner, Bore, Wagner, Karlovsek, & Scheuermann, 2016).

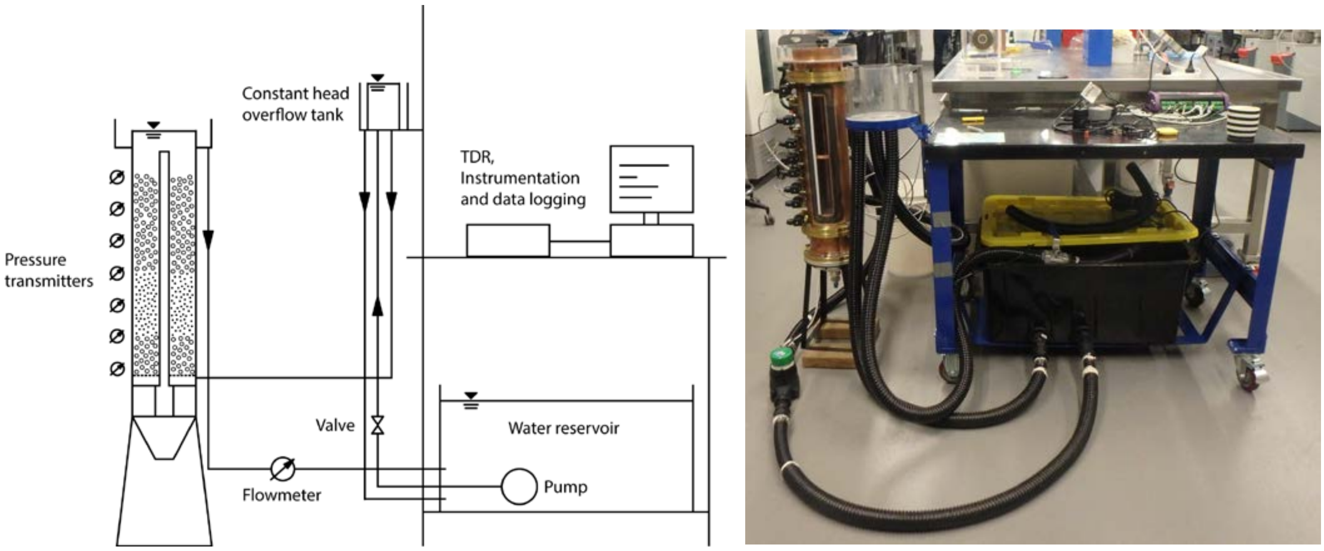

Figure 3.1. Schematic and photograph of the experimental setup with the coaxial erosion cell.

The vertical distribution of the hydraulic potential is measured with 14 pressure transmitters WIKA A-10. According to the data sheet of the manufacturer, they have an accuracy of 0.5 %. They are installed vertically in a distance of 25 mm to 50 mm in the side wall of the cell. The hydraulic gradient can be calculated out of the vertical distance and the difference of the hydraulic head. The flow rate is measured with a displacement flowmeter ManuFlo MES20-S-T. According to the data sheet, the accuracy is 1.5 % and the repeatability 0.3 %. The measurements of the hydraulic potential and the flow rate are automatically recorded every 10 s by a Data Taker Geologger DT85. With these two hydraulic parameters, a comprehensive analysis of the hydraulic behaviour of the soil during the erosion process can be made.

3.2 Materials

In the experimental setup presented here, beads of soda-lime glass are used as an idealisation of granular material instead of natural sand and gravel. With a density comparable to quartz based soil grains, glass beads offer the advantage of being free of influences like grain angularity and density variations which are typical for soils of different sources. Therefore, glass beads are a common replacement for erosion tests (Scheuermann et al., 2012; Sibille et al., 2015; Tomlinson & Vaid, 2000). The properties of the glass beads used in the tests presented here can be found in Table 1. The two fine fractions serve as base materials, the coarse fractions are used as filter.

Table 1. Properties of the glass beads used in the experiments

Diameter/Tolerance	Roundness	Colour	Grain density	Application
0.3 – 0.425 mm	≥ 70 %	Clear	25 kN/m^3	Base II
0.425 – 0.6 mm	≥ 70 %	Red	25 kN/m^3	Base I
2.0 mm ± 0.2 mm	90 %	Blue	25 kN/m^3	Subbase filter
6.0 mm ± 0.3 mm	≥ 90 %	Clear	25 kN/m^3	Filter D
8.0 mm ± 0.4 mm	≥ 90 %	Clear	25 kN/m^3	Filter A

4 COAXIAL EROSION CELL

4.1 Design

In former experiments, a five-rod probe with a quasi-coaxial arrangement was inserted into an erosion cell (Scheuermann et al., 2012). As a drawback of this device, the distribution of the electromagnetic field is not fixed to the boundaries of the cell.

To avoid this issue, the cell itself acts now as a probe for the electromagnetic measurements by using its metallic walls as a conductor for the electromagnetic field. Coaxial arrangements have been used for the dielectric characterisation of liquids (Kaatze & Feldman, 2005) and soils (Wagner et al., 2013). The soil samples are either prefabricated or prepared directly in the cell.

The novelty of the coaxial erosion cell presented here is that the main intention is to observe the spatial and temporal changes of the density condition of the material under test in the cell during the measurements. The force that induces these changes is the water flow, hence the cell has to be optimised for the electromagnetic measurements as well as for the required hydraulic boundary conditions.

Depending on the largest particle of the material under test, the dimension of the probe has to be designed accordingly to the Representative Elementary Volume (REV) (Robert, 1998). The useable frequency bandwidth is coupled with the dimensions of the cell. The larger the cell, the lower is the upper frequency. This is leading to a compromise in the design of the cell between the required dimensions and the achievable frequency range.

The cell is made of commercially available rigid line components produced by the company Spinner GmbH. The great advantage is that the cell is comparatively cost effective to assemble in a workshop. Especially readily available conical transitions between the cell and a cable as a connection to the TDR device can be used. The drawback is that only a limited range of dimensions is at choice. The cell can be seen in Figure 3.1.b on the left side of the table and in Figure 5.1 filled with glass beads during an experiment.

In order to control the initiation and the progress of the erosion process, an inspection window with a height of 420 mm and a width of 40 mm is mounted in the outer wall of the cell.

4.2 Calibration

The inversion procedure will provide the apparent permittivity profile from the TDR waveform. The final step is the computation of the porosity profile. Two methods can be used here. The first consists of a specific material calibration. Previous measurement of apparent permittivity with known porosities were performed in order to derive an empirical equation. This can be done with tests of different glass beads mixtures with known porosities. Mixtures of different sizes are leading to low porosities (Scheuermann, 2012). High porosities can be achieved by fluidisation (Bittner et al., 2016). Alternatively, mixing rules (Sihvola, 1999) can be used for materials with known dielectric properties like glass beads and water to get a function of dielectric permittivity and porosity. The Bruggeman-Hanai-Sen (BHS) model has proven its applicability for saturated glass beads (Jung et al., 2012; Sen, Scala, & Cohen, 1981).

In this study, the BHS model is used, as the dielectric properties of the media under test are known. A material specific calibration should be taken into account, if particles of different shapes or dielectric permittivity are used, e.g. natural soils.

5 EROSION EXPERIMENTS

5.1 Experimental procedure

With the base and filter materials listed in Table 1, four base/filter combinations are possible, as the 2 mm beads are exclusively used as a subbase filter to keep the base material in place. In the preliminary tests, three combinations were tested, Base I and Filter A as well as Base II in combination with Filter A and D. All combinations are geometrically unstable.

5.1.1 Hydraulic boundary conditions

An upwards directed flow was applied in all tests. Two different schemes of the hydraulic potential as a boundary condition were used. In the first scheme, the hydraulic potential was increased stepwise for 1 cm every 10 minutes until base and filter were fully mixed.

In the second scheme, the increase of the potential is coupled to the response of the erosion process. Until the erosion process has started, which was marked by the first movements of the base particles, the hydraulic potential was increased 1 cm every 5 minutes. After the onset of particle movement, the potential was kept constant until no further progress of the erosion process was noticeable. Then, the potential was again increased by 1 cm and so on until a complete mixing of the base particles with the filter was achieved.

5.1.2 Preparation

The glass beads were inserted layer-wise into the cell. Each layer consisted of beads of the same size, in other words, there were no mixtures of beads of different diameters during the setup. All beads were trickled dry into the cell which resulted in porosities between 0.36 and 0.40, regardless of the beads' diameter. The porosity of each layer was determined by means of the volume, calculated out of the layer height, and the dry mass.

Saturation of the fine base material was achieved through a concurrent increase of the water level during the setup. The water level was controlled in way that the top layer of the base particles was moist, but no free water surface was present. The capillary forces ensured a complete saturation, while entrained air was able to escape from the pores. This procedure turned out to work better than the previously used one, where the beads were trickled into the already water-filled column (Bittner et al., 2016).

5.2 Initial results

5.2.1 Hydraulic measurements

A good impression about the behaviour and the progress of the erosion process can be seen in the typical results of the preliminary experiments. For the illustration, the combination of Base II and Filter A according to Table 1 and the hydraulic boundary conditions of the second scheme was chosen. The setup of the experiments and the development of the erosion process can be seen in Figure 5.1. The initial height of the base was 8.5 cm and of the filter 17.5 cm.

It was assumed that the less permeable layers of the base material, consisting of comparatively small particles, and the developing mixture zone, characterised by a low porosity through mixing of particles of different sizes, rule the progress of erosion. This is confirmed by the records of the hydraulic potential along the cell (Figure 5.2). A degradation of the potential was found mainly in the named layers. After the onset of erosion, the gradient in the base layer remained nearly constant, whereas the further increased potential was degraded mainly in the developing mixture zone. It is apparent that the discharge remained nearly constant due to the decreasing permeability of the extending mixture zone. In other words, the extension of the mixture zone regulates the erosion process. In this special case, this leads to a kind of self-healing process for a given hydraulic head, which comes with the cost of having settlements of the filter.

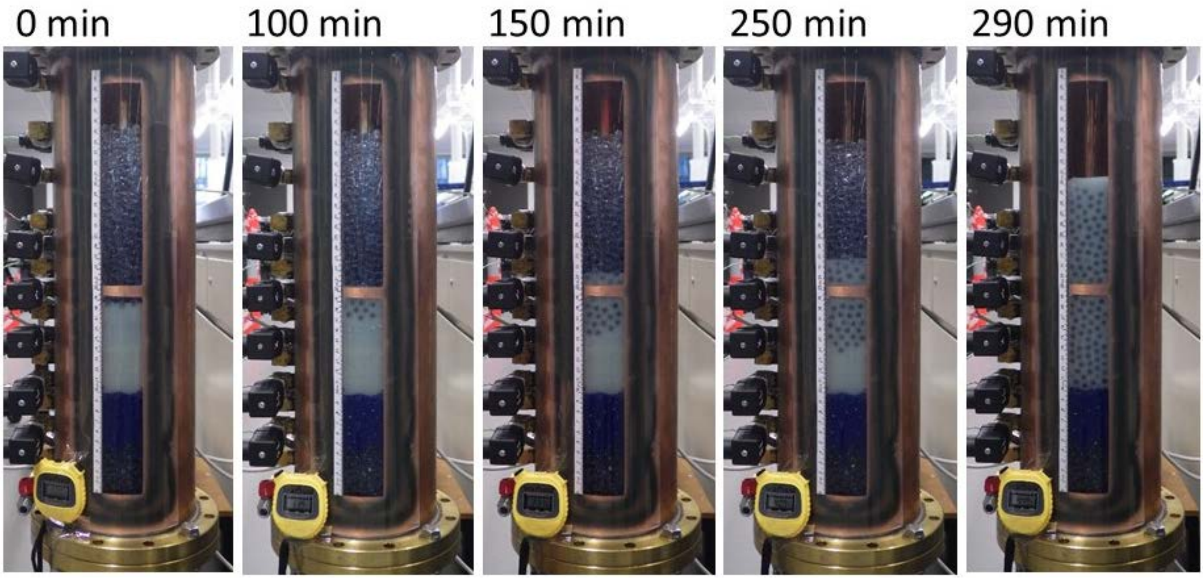

Figure 5.1. Development of the erosion process at different time steps. Note the settlements of the filter and the formation of the mixture zone.

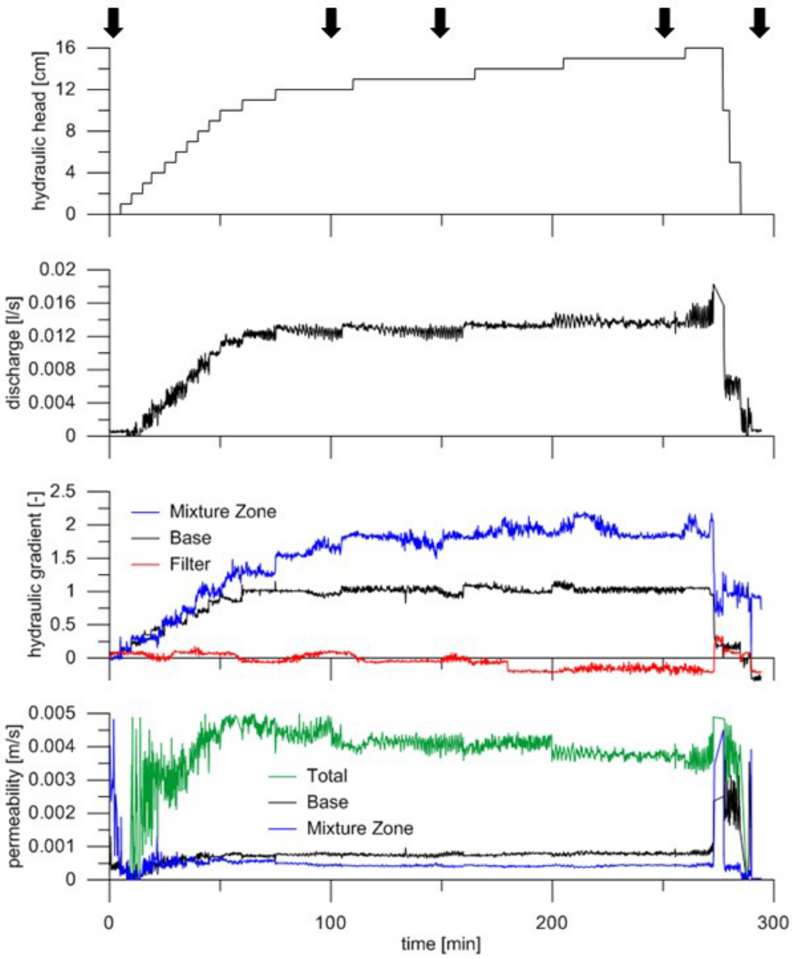

Figure 5.2. Hydraulic parameters. The arrows are showing the time matching to the pictures in Figure 5.1. Note that the peak values of discharge and permeability are cut off between minute 273 and 277, as they are out of the range of the graphs.

5.2.2 Porosity measurements

A comparison of the porosity profiles at different time steps can be seen in Figure 5.3. Before the onset of erosion, the porosity is nearly uniform over the full length of the column, as all layers consist of monodisperse glass beads. After the onset, the formation and elevation of a mixture zone can be seen, which is characterised by a lower porosity due to the mixing of different sized beads. The porosity of the mixture zone as a control of the TDR measurements was estimated by means of the visible changes in the layer heights monitored through the inspection window, which might be not the same for the overall area of the column. The fractions of base and filter above and below the mixture zone were regarded as unaffected by the mixing. That might not be the case for the filter, which experienced settlements. This leads to slightly lower porosities for the mixture zone than measured, as can be seen in Figure 5.3.

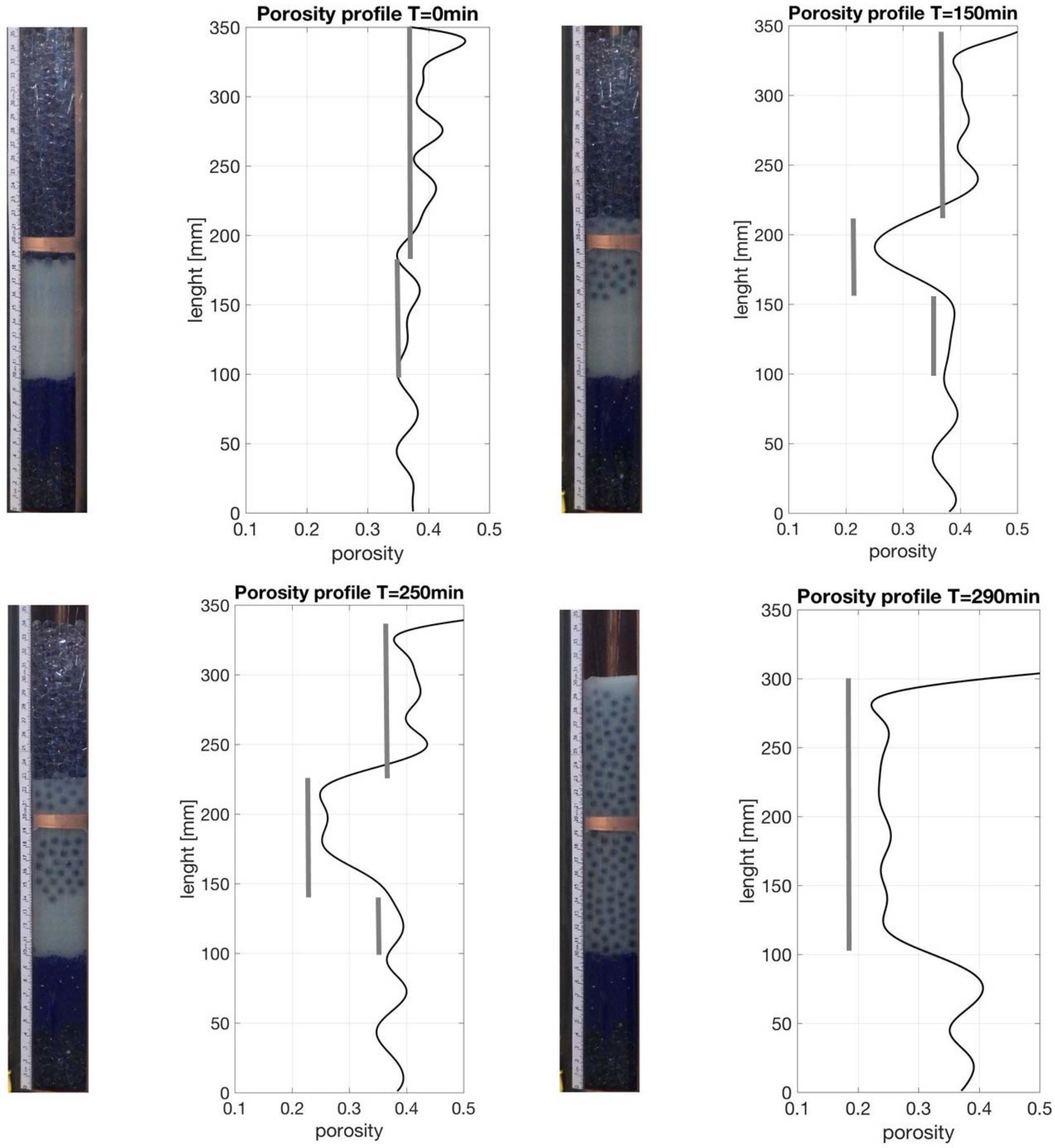

Figure 5.3. Comparison of the development of the mixture zone in the cell and the porosities determined by the layer heights with the porosity obtained with Spatial TDR. Note that both the boundaries of the mixture zone as well as the alterations in the overall height can be detected in the porosity profile with a resolution of approx. 2cm.

6 CONCLUSIONS AND OUTLOOK

A new type of cell for erosion experiments was developed which enables real-time measurements of the spatial porosity distributions by means of Spatial TDR, and preliminary experiments were carried out.

The contact zone of base and filter and the mixture zone are the determining factor for the onset and the progress of contact erosion. In the case of an upwards directed flow, a kind of self-healing behaviour can be noticed if settlements can be tolerated.

The work on the inversion of the TDR-signals is in progress. First results are showing the alterations in the porosity profile according to the progress of the erosion process and the formation of a mixture zone.

Due to the early stage, there is a need for repeated measurements in order to validate the data obtained so far. Special attention will be payed to the interface of base and filter. Additionally, further experiments are planned with added superimposed loads. This will allow studying the development of the base/filter combinations under extended boundary conditions.

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