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Tracing water movement in the capillary fringe

-A laboratory study to determine the horizontal water movement in the capillary fringe with resistivity and image analysis

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Abstract

The capillary fringe is a small zone on top of the ground water table where a low capillary tension keeps soil pores with water up to a certain level. Normally, calculations in hydrogeology consider that the capillary fringe only has vertical movement like the unsaturated zone in comparison to the ground water zone, which only has horizontal movement. Today's usage of pollutants in the environment is a threat to a clean groundwater supply. It is therefore of interest to study the movement in the capillary fringe since the pollutants must pass it before contaminating the ground water.

This master thesis will describe experiments and observations of the movement of a dye tracer when it is passing the capillary fringe. The movement will be observed with both image analysis and resistivity measurements to determine the flow path of the dye. The aim of the study is to find if there is horizontal movement in the capillary fringe, and try to see how it is affected by different gradients of the saturated zone.

To be able to conduct experiments on the movement in the capillary fringe a special aquarium with access to control the water level and gradient of the saturated zone is used. A Brilliant Blue dye is inserted into the sand and the movement of the dye is observed with both resistivity- and image analysis to obtain the flow path. The images for the image analysis are converted using Adobe Photoshop into black and white images and put in a template created in Adobe Illustrator showing the levels of the saturated zone and the capillary fringe. The resistivity is measured before the experiment begins to obtain the background resistivity in the aquarium. The background resistivity value is removed from the resistivity values collected during the experiment, and the presented resistivity images show only the change of resistivity in the experiment at the investigated time.

The experiments are done with three different gradients on the saturated zone to see if there is a difference in the flow path dependent on the gradient. The investigated gradients are 0.48, 0.90 and 1.79 degrees.

The result of the image analysis shows a large horizontal movement in the capillary fringe, and the horizontal speed is increasing with a steeper gradient.

The resistivity images show a similar movement as the image analysis but results are only reliable in the beginning of the experiment when the dye tracer travels in the part where resistivity data is obtained. It is recommended that in future studies the resistivity model should be changed to one with more data measurements.

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1 Introduction

1.1 Background

The capillary fringe is usually ignored in traditional hydrology and hydrogeology. There are a number of reasons for this. It is considered that transport in the capillary fringe is only vertical, which is the same flow direction as the unsaturated zone. It is contrary to the saturated zone, which has mainly horizontal flow.

Horizontal velocity in the capillary fringe is usually ignored due to that the capillary fringe is significantly smaller than the groundwater aquifer below. However in shallow aquifers the transport in the capillary fringe will be of greater importance to the aquifer. This aquifer type is very common in Sweden, and the capillary fringe will therefore affect the total transport significantly.

Today's usage of pollutants in the environment is a threat to a clean groundwater supply. Therefore it is important to investigate and observe the groundwater transport process in the capillary fringe since all pollutants must pass it to contaminate the groundwater.

1.2 Outline and objectives of the study

Studies of the capillary fringe have shown possibility for horizontal water movement within it. The objective of this project is to find out if the studies are correct and if it is possible to trace how water and solutes move across the capillary fringe. The following research questions will be investigated:

- Is it possible to observe a horizontal movement in the capillary fringe and how large is this movement compared to the vertical movement?
- If there is a horizontal movement, how is it affected with different magnitude of the groundwater hydraulic gradient and is there a connection between the speed of the horizontal movement and the slope of the gradient?

It is also of interest to find out if it is possible to combine image analysis with resistivity analysis to observe the movement in the capillary fringe.

1.3 Previous studies

Previous studies have confirmed that dye tracer and resistivity analysis can be useful to detect flow paths in soils. The following studies have investigated flow movement in a soil with image analyses and resistivity measurements.

Koestel et al. (2009) conducted an experiment with the aim of proving that Brilliant Blue can be used as an electrical tracer. They also wanted to determine if there was a possibility to combine an electrical resistivity survey with a photographic image analysis to determine the dye tracer concentrations in an unsaturated soil. The experiment was conducted in a lysimeter with a diameter of 16 cm and a height of 140 cm, which was filled with an undisturbed horizontally layered sandy soil. 212 electrodes were used along the sides of the lysimeter at different depths to obtain the resistivity values. They applied dye with a concentration of $2.5 g/cm^3$ with an infiltration system consisting of 484 needles on top of the lysimeter. The image analysis was conducted by acquiring an image of every layer they removed of the soil after the experiment.

The result of the experiment was that a joint application of a geoelectrical and photographic methods has a variety of benefits. The Brilliant Blue staining patterns can be used to benchmark the geoelectrical images, and vice versa. The Brilliant Blue images can also be used to constrain inversion problems in the geoelectrical survey. The advantages of a Brilliant Blue imaging can be combined with the advantage of a geoelectrical imagine and offer an improvement in characterization of the transport process in the unsaturated zone.

Another study made by Kim et al. (2010) has conducted experiments with the aim of tracing the solute transport in an undisturbed forest soil profile. The solute transport is traced with Brilliant Blue solution and recorded with photography and a geoelectrical survey. The experiment was conducted in a forest where two holes were drilled to 90 cm depth and one meter apart and equipped with electrodes ten cm apart. Brilliant Blue dye tracer with a concentration of $5 g/cm^3$ was inserted between the two boreholes. The investigation area was flooded three times with a 100 l dye solution before the area was excavated to a depth of 150 cm. The different layers of the excavation were recorded with image analyses.

The result from the study was that the first 30 cm in a sandy loam and the image analysis shows the infiltration is mainly dominated by matrix flow. The next layer of soil was loamy sand to a depth of 20 cm, and the image analysis shows the infiltration was mainly macropore flow along the structural interfaces. The last layer of soil was a sandy soil with a depth of 100 cm, and the image analysis shows the infiltration was mainly macropore flow along the quartz or mica veins.
The electrical resistivity measurements successfully detected the matrix flow, but could only detect the macropore flow in a regional scale and not in an individual scale. The study shows that it is possible to use image analysis and resistivity measurements together to trace the transport process in a soil.

2 Theory

2.1 Capillary fringe

Above the groundwater level there is a low capillary tension that keeps soil pores almost completely full with water up to a certain level. This is the tension-saturated zone or the capillary fringe, which is situated between the saturated and unsaturated soil zones. This layer is of interest for a couple of reasons. It has a vertical extent, which affects the overlaying soil water profile and the surface runoff (Ward & Robinson, 2000). This determines how much of the rainwater that will infiltrate to groundwater and the amount that will be surface runoff. It also has a rate of capillary flow, which makes it possible for the soil to provide water for root zone and evaporation from the soil surface.

The capillary fringe is dominated by adhesion and cohesion (Kasenow, 2001). Adhesion is the molecular attraction between the solid surface and the fluid. Cohesion is the attraction between molecules of the fluid. Field measurement made by Ronen et al. (2000) in an aquifer showed that the distribution of water in the capillary fringe had a compact structure, and there was an abrupt change of water content with an increasing height over the saturated zone. This shows that the capillary fringe has a well-known limit of capillary rise where the soil pores are almost filled with water.

Horizontal water movement in the capillary fringe has been studied with simulations in a model conducted by Ronen et al. (1997). The result of the simulations showed that a soil with a compact structure and a hydraulic gradient in the saturated zone has horizontal water movement within the capillary fringe. The water content at the top of the capillary fringe may predict the beginning of the lateral flow.

The thickness of the capillary fringe is equal to the air entry value, the suction necessary for air to enter the largest pores (Ward & Robinson, 2000). The thickness of the capillary fringe is therefore dependent on the size of the sedimentary material in the soil where it is more extent with a smaller grain size in the soil. For typical values of capillary rise in different soil types see table 1.

Table 1: ***Typical values of capillary rise in different soil types (modified from Kasenow, 2001).***

Soil types	Grain Size (mm)	Capillary rise (m)
Silt	0.05-0.02	2.00
Coarse Silt	0.1-0.05	1.06
Fine Sand	0.2-0.1	0.43
Medium Sand	0.5-0.2	0.25
Coarse Sand	1.0-0.5	0.14
Very coarse sand	2.0-1.0	0.065
Fine Gravel	5.0-2.0	0.025

2.2 Water movement in soil

2.2.1 Saturated zone

In the saturated zone the soil pores are completely filled with water. Most of the water movement in the saturated zone takes place in interstices so that the resistance to flow is imposed by the soil material. The main water flow tends to be located in areas where the interstices are large and well connected. The water in the saturated zone move manly to the hydraulic gradient where it moves from a high pressure area to a low pressure areas, and the direction of the water seams to follow the path of least resistance (Ward & Robinson, 2000). The direction and the rate of the flow in the saturated zone in a porous medium may be calculated from the prevailing hydraulic gradient and the hydraulic conductivity of the material using the Darcy's equation.

The water flow (Q) is equal to the hydraulic conductivity (K) multiplied with the cross-sectional area of the material (A) multiplied with the hydraulic gradient $\left(\frac{dh}{dl}\right)$. In large open aquifers the groundwater table is assumed to form a plane where dh/dl is the slope of the plane.

$$Q = K \bullet A \bullet \left(\frac{dh}{dl}\right)$$

The Darcy equation states that the water movement in a porous media is proportional to the difference in the height of the water tables between two points and inversely proportional to the flow length between them. The flow is also proportional to the hydraulic conductivity and the cross sectional area of the porous media.

The Darcy law says the following about water movement:

- If there is no height difference of the ground water levels between the points there will be no water movement in the porous media.
- If there is a height difference between the points there will be a water movement from the higher water level to the lower water level.
- If the water level increases between two points the water speed will increase between them.

An alternative way to calculate groundwater flow is the Dupuits formula, which is based on Darcy's equation.

The water flow (Q) is equal to the hydraulic conductivity (K) multiplied with the width of the aquifer (B) divided by the length (L) of the aquifer times two and multiplied by the square of the water level in one basin $\left(h_1^{\,2}\right)$ minus the water level of the other basin $\left(h_2^{\,2}\right)$.

$$Q = \frac{K \bullet B}{2 \bullet L} \bullet \left(h_1^{\,2} - h_2^{\,2}\right)$$

(Raghunath, 1967)

The Dupuit formula also calculates the water movements between two points in a porous media. In an unconfined aquifer there is both horizontal and vertical movement. The Dupuit formula assumes that the water head is constant along the vertical direction, which is only true if there is no vertical movement. The water movement in the porous media is therefore treated as a one-dimensional problem in the formula. In the Dupuit formula the groundwater table is assumed to have a hyperbolic surface.

The hydraulic conductivity in both equations is a property of the soil that describes the ease of fluid movement through it with the dimension length/time. The coefficient is dependent both on the fluid and matrix properties. The matrix properties that are relevant are grain size distribution, specific surface, shape of grain and porosity. The fluid properties that are relevant are viscosity and density (Bear, 1972).

2.2.2 Unsaturated zone

The soil pores in the unsaturated zone is not completely filled with water and only contain water to some degree, this is the degree of saturation, which refer to the portion of pore volume filled with water.

The soil water in the unsaturated zone moves in response to a number of forces. Gravity does not have to be the dominant force and, therefore, the unsaturated water movement can be in any direction. The main forces for the water movement from the surface are infiltration and evaporation, and groundwater recharge and capillary rise from the bottom layer of the unsaturated zone. This leads to that the general water movement is in a vertical direction in the zone and the water is moving either upwards or downwards (Ward & Robinson, 2000).
The Darcy's equation have showed us how water movement in saturated conditions is dependent on the hydraulic gradient, but is it also applicable for water flow in unsaturated conditions. It is described in unsaturated conditions as:

The macroscopic velocity of water (v) is equal to hydraulic conductivity (K), which in unsaturated conditions varies with the water content (θ) multiplied with the hydraulic gradient $\left(\frac{\delta h}{\delta l}\right)$ comprising the change in hydraulic head (h) with the distance along the direction of flow (l).

$$v = K(\theta) \bullet \left(\frac{\delta h}{\delta l}\right)$$

The hydraulic conductivity in the unsaturated zone is highly dependent on the degree of saturation, due to that the fluid are constrained to smaller flow channels when the soil pores have less water in them. This means the hydraulic conductivity will decrease when there is less water in the soil pores.

2.3 Resistivity analysis

Resistivity is a geophysical measuring method. The common goal with geophysical methods is to obtain information of the subsurface geology. The techniques used to achieve this may differ in a geophysical survey but it will almost always consist of three steps: surveying, data processing, and data interpretation (Palacky, 1987).

2.3.1 Basic resistivity theory

The resistivity analysis is a method where electrical current is introduced into the surface of a soil. The potentials of the electrical current are measured to determine the subsurface resistivity distribution. The collected data from the obtained resistivity distribution will be used to create a model of the subsurface resistivity (Loke, 2010). The obtained resistivity is compared with resistivity values for different types of soils and rocks to determine the subsurface. There are different types of electrical currents that can be used but the most common one is direct current or an alternating current with low frequency.

The normal setup for a resistivity analysis is to insert steel electrodes into the surface in a line. The electric current is applied between two electrodes and another pair is used to measure the potentials. Increasing and decreasing the length between the electrodes changes the depth of the electrical current and larger subsurface volumes can be investigated.

Resistivity (ρ) is a property parameter for how the material conducts electrical currents. It is the inverse of electrical conductivity (σ).

$$\rho = \frac{1}{\sigma}$$

The resistivity can also be described with Ohm's law if the resistivity is measured between two electrodes in a defined cross-section through a homogeneous media. The resistance (R) is measured as the voltage (U) divided by the current (I).

$$R = \frac{U}{I}$$

The resistivity is also proportional to the cross-sectional area (A) and the length (L) between the electrodes. The resistance is then expressed as:

$$R = \frac{\rho \bullet L}{A}$$

(Hambley, 2005).

Combining these equations the resistivity can now be expressed as:

$$\rho = R \bullet \frac{A}{L} \Rightarrow \rho = \frac{U}{I} \bullet \frac{L}{A}$$

If a geometric factor (K) is introduced which is dependent on the length between the electrodes and cross-sectional area the equation can be written as:

$$\rho = K \bullet \frac{U}{I}$$

The geometrical factor is dependent on which type of resistivity survey you are conducting. In the most common electrical survey with a four electrode arrangement where the electrical current is injected between one pair of electrodes and measured in another pare the potential difference (ϕ) is given by

$$\phi = \frac{\rho \bullet I}{2 \bullet \pi} \bullet \left(\frac{1}{r_{C1P1}} - \frac{1}{r_{C2P1}} - \frac{1}{r_{C1P2}} + \frac{1}{r_{C2P2}} \right)$$

Where C1, C2 are two electrodes with electrical current injection and P1, P2 is the voltage difference at two different electrodes. With this setup the geometric factor will be as followed

$$k = \frac{2 \bullet \pi}{\frac{1}{r_{C1P1}} - \frac{1}{r_{C2P1}} - \frac{1}{r_{C1P2}} + \frac{1}{r_{C2P2}}}$$

(Loke, 2011).

2.3.2 Resistivity in different earth materials

A satisfying resistivity survey is not easy to obtain. To be able to make prediction of the subsurface in a resistivity analysis, the fundamental electric properties of different earth materials must be known. Most studies of the electric properties have been done in a laboratory with samples collected from the field (Palacky, 1987). These studies gave a specific range of resistivity values for different types of soils and rocks (see figure 1). The resistivity varies substantially to the resistivity of the field survey, since in the field there will be a mixture of different materials. Many different types of material have the same resistivity and are overlapping. This makes it difficult for the geophysicist to make an assumption of the ground identification if he lacks rudimentary knowledge of the physical properties of the ground and its surroundings (Palacky, 1987).

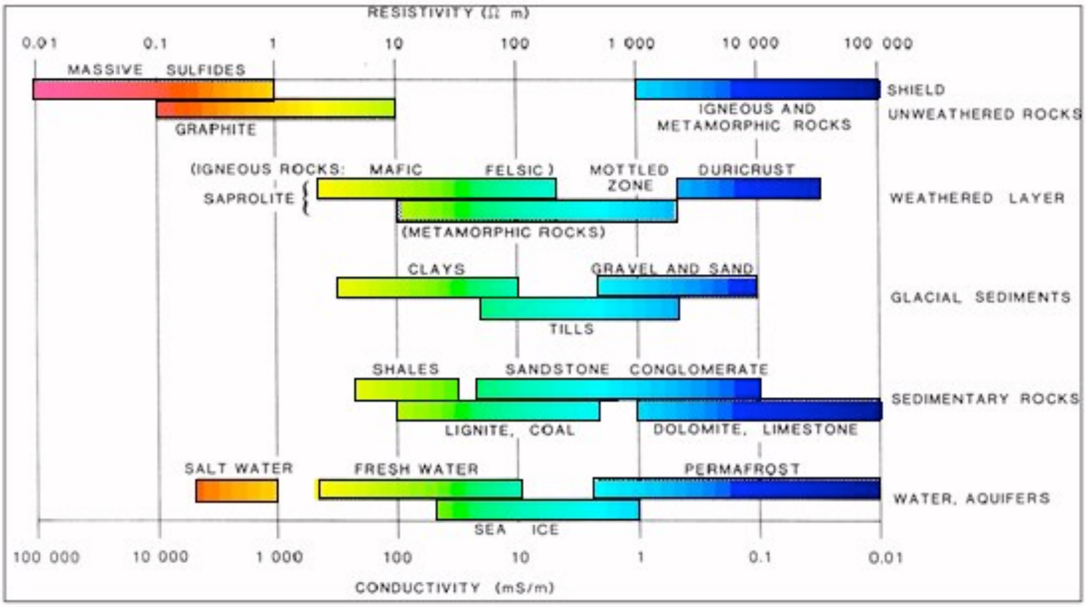

Figure 1: ***Typical ranges of resistivity in earth materials (modified from Palacky, 1987)***

Most of the rocks and unconsolidated materials have high resistivity when they are dry and work as isolators. This means it is mainly the amount and properties of the water that determines the resistivity in the material. There are other factors affecting the resistivity, the content of clay and metallic material but they do not affect it in the same degree.

The unconsolidated materials contain small particles and pore space. Therefore the resistivity in the materials mostly depends on the water and clay content. The particles material works as an isolator, which means the conductance mainly, take place in the pore space. This means that it is the porosity and saturation of water that determines the resistivity.

The rocks resistivity value mainly depends on the amount of faults and fractures in the formation. The rock material itself works as an isolator and the electric conductivity mainly travels in the faults.

2.3.3 Data acquisition

The equipment for a resistivity analysis consists of a current transmitter and a voltmeter. The electrodes are inserted into the earth and are connected with a cable to the equipment. In a survey with many electrodes a multi core cable is connected to the equipment. The current transmitter and the voltmeter are also connected to an electrode selector and a computer. The computer collects the data of interest.

There are different types of electrode arrangements that are used in a resistivity survey and each has both strengths and weaknesses. One common array in a four-electrode surface arrangement is the gradient array, using multiple current electrode combinations. Surveys have proofed that it resolution is good and it behaves well in terms of sensitivity to noise ratio (Dahlin and Zhou, 2006).

2.3.4 Data inversion

The goal of a resistivity survey is to obtain a model of the subsurface resistivity distribution. The measurement collected from the survey has resulted in data from the boundary of the object. The purpose of the inversion is to determine the true subsurface resistivity from the collected data.

There is no direct way to solve the problem, normally an iterative process is used. An initial model of the subsurface is created; the model is mathematically determined for the given electrical properties of the collected data in so-called "forward problem". But to complete the inversion process the measured data needs to be adapted into the created model in a so-called "inverse problem" (see figure 2). This iterative process continues until the model fits the collected data to an acceptable degree.

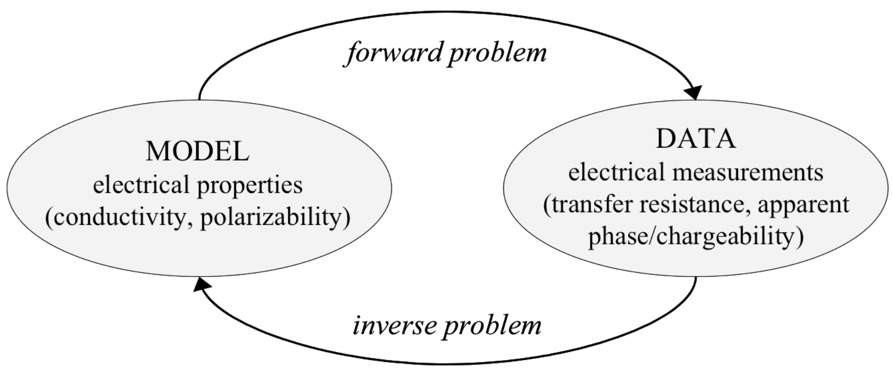

Figure 2: ***Image of the electrical forward and inverse problem (modified from Rubin & Hubbard, 2005*).**

2.3.5 Data interpretation

Interpretation of a 2D resistivity model is associated with some typical phenomena that are affected by the theories behind resistivity measurements. Some typical problems with the method that should be considered are:

- The ends of the final resistivity model have less data points and the model is strongly affected by the boundary condition of the inversion model.

- The resistivity method needs a conductive top layer to inject the electric current into the soil. Problem with bad electrode contact will give less accurate data.

- The resistivity model loses its resolution exponentially with the depth.

2.4 Dye tracer and image analysis

Dye tracers are a valuable method for investigating the effect of soil heterogeneity, water and solute transport pattern in soil and aquifers (Flury and Flühler, 1995).

2.4.1 Brilliant blue FCF

A good dye tracer for tracking flow path of water and solute transport in a soil need to fulfill three criteria's. These are; it should be easily visible in the soil, it should have transport properties similar to that of water, and the compound itself should not be toxic, or create a harmful process in later stages. Tests made on Brilliant blue FCF shows it fulfils all the three criteria's (Flury and Flühler, 1994).
Brilliant blue FCF is highly soluble in water compared to other dye tracers. When it is inserted in a soil it is adsorbed by the soil particles and the flow path can be identified. Due to its solubility to water the adhesion is low and is it easily washed out by water. One of the main advantages with Brilliant blur FCF as a dye tracer in soil samples is its good visibility against the color of the soil's background (Flury and Flühler, 1995).

2.4.2 Collecting Images

Normally digital cameras use the RGB color space. In this color space, the images are built up out of three colors, red (R), green (G) and blue (B). These values can be in a range of 0 to 255 if the image is saved in a 8 bit format, black is represented of R = G = B = 0 and white is represented with R = G = B = 255. A perfect image without color cast for grey shades should have a equal value of R, G and B. A satisfying image also needs the right exposure. One way to achieve images with the right exposure is to use a grey card. The grey card is photographed and if it is correctly exposed the values for all the colors should be 128.

To be able to determine a relationship between dye concentration and the RGB values in the images, a calibration test must be conducted. In the calibration test known amounts of dye, water and sand are mixed and photographed under the same conditions as the experiment. With the calibration test is it possible to determine the correct concentration of the dye in the experiments.

To acquire good image results with the camera it is important to focus the optics correctly. This makes it possible to collect fine details to the image. It is also important to reduce possible reflection in the image to obtain a satisfying image quality.

3 Methodology

The experiments are performed in a laboratory environment where dye is infiltrated into sand. The dye is traced with both resistivity- and image analysis to determine the flow path in the sand with special interest to the movement across the capillary fringe.

Due to small size laboratory environment the normal resistivity acquisition tools will not fit in the environment, therefore specially designed resistivity equipment is created to make the acquisition possible.

The tests to determine the flow in the capillary fringe will consist of multiple experiments with different angle of the gradient. A modified aquarium, which is described below, is used as a basin for the experiment. A special infiltration system is needed to control the dye tracer injection.

The layout of the experiment is: the camera records the movement of dye in the soil formation at the side if the aquarium. It is also in interest to see if the movement of the dye is homogenous throughout the width of the basin. Therefore five parallel resistivity lines will be used to trace the whole width of the basin. The resistivity images will also help to determine if the images from the image analysis is a correct representation of the movement.

3.1 Aquarium setup

The aquarium has the dimensions 1.5*0.5*0.5 m. Two smaller basins with a width of 10 cm were created on each short side to visualize the water levels and to create the possibility to pump water between the basins and establish a gradient. The walls of the basin consist of a perforated plastic board. They are covered with geotextile to prevent sand from reaching the two basins at the side and still have water passing it. The cross section of the tank can be seen in figure 3 and the actual aquarium can be seen in figure 5. The area in the middle of the aquarium is the investigation area, which is filled with sand in these experiments.

3.2 Resistivity setup

A suitable and water proofed measuring equipment is created for the aquarium. It is based on plastic boards with the dimension 122*7*3 cm. A line is cut out of the boards and 32 holes are drilled in the line with a distance of 35 mm between each other. The electrodes are placed in the holes and one electric cable is led to each electrode. The volume of the line in the plastic board is filled with a special plastic called Araldite DBF, which is water resistant to minimize risk of short circuit. The electric cables connected to the electrodes are also covered with a special Teflon plastic coverage to minimize electric short circuit when the cables leaving the board. The layout of the resistivity boards in the aquarium can be seen in figure 4.

3.3 Sand setup

The sand used in the experiment has a grain size 0.3-0.7 mm. This sand is chosen because it has the requested hydraulic properties to fit in the experiment. It has a capillary fringe on 13 cm, which is thick enough to be able to locate movement within it and there is also room in the aquarium for a saturated and an unsaturated zone. The sand is also tested for the hydraulic conductivity to be able to determine the flow in the saturated zone. This is done with both the Darcy's equation and the Dupuits formula.
The Darcy equation is rewritten to as follows to determine the hydraulic conductivity:

$$Q = K \bullet A \bullet \left(\frac{dh}{dl}\right) \rightarrow K = \frac{Q \bullet dl}{A \bullet dh}$$

The Dupuits formula is rewritten as follows to determine the hydraulic conductivity:

$$Q = \frac{K \bullet B}{2 \bullet L} \bullet \left(h_1^2 - h_2^2\right) \rightarrow K = \frac{2 \bullet L \bullet Q}{\left(h_1^2 - h_2^2\right) \bullet B}$$

The test results of the sand can be seen in table 2.

3.4 Camera setup

The camera used in the experiment is a Nikon d2X. The camera is placed approximately three meters away from the aquarium. The camera is focused on the glass of the aquarium and cardboard peaces have been placed out in the lab to decrease the reflection in the glass of the aquarium.

3.5 Infiltration system setup

To obtain a good homogenous infiltration of the dye a special infiltration pipe has been constructed. The pipe is a plastic pipe with a length of 0.5 m and diameter of 1.5 cm. Small holes with a diameter of 0.5 mm are drilled every second cm throughout the pipe to get a homogenous infiltration over the whole length. Two separate hoses are connected to both sides of the injection pipe to minimize pressure losses throughout the pipe. The hoses are connected to a pump with an adjustable injection rate. After the first experiment the injection pipe is modified with one extra hole closer to the window to decrease the travel time of the dye to the window.

3.6 Experiment setup

A pump located in the right basin pumps water to the left basin to create a gradient. The water levels on both basins are measured and the pump rate is adjusted to get the right height of the gradient. Another pump is installed in the right basin and is connected to a level gauge to ensure a stable level of the right basin. This pump will withdraw the same amount of water that is injected with the dye to keep the amount of water constant in the aquarium.

Before each experiment water is sprinkled on the sand to get homogeneous packing. The injection pipe is placed in the sand and buried precisely below the top of the sand about 40 cm from the right edge. The five-resistivity boards are placed over the injection pipe on top of the sand. They close together in the center of the aquarium. During pre tests of the resistivity measurement a problem with bad electrode contact occurred. To avoid the problem soaked Wettex rags are positioned under the electrodes to increase the contact. The experiments have five parallel resistivity lines in the bottom of the aquarium to obtain resistivity values in the lower parts of investigation area. The data from these lines is not taken in to consideration in this project due to a problem in the resistivity model program. The top of the aquarium is also covered with plastic film to decrease evaporation from the experiment area. For a better overview of the layout see the cross section in figure 3 and the planar view in figure 4.

The injected dye is mixed with tap water and has a concentration of $4g/cm^3$ and a measured conductivity of $1050\mu S/cm$. The conductivity in the tap water was $350\mu S/cm$.

Before the dye infiltration starts a pre-investigation of the resistivity is measured to see the apparent resistivity values through the formation. A gradient array is used to obtain the resistivity measurements. When the experiment starts the measurements of the resistivity is measured in all the lines. The measurements can only be done in one line at the time and each measurement took 11 min except in experiment three where a software update in the resistivity instrument made it possible to perform the measurement in 8 min. The outline of the resistivity measurement is to investigate the lines in the following order; one, two, three, four, five and three one more time. This cycle was repeated during the whole experiment to collect the resistivity measurements. This means that in experiment one and two there was a 66 min time lapse between every investigation in the lines except line three where the time lapse is 33 min. Line number three was investigated twice to see the movement with a shorter interval and therefore with a higher accuracy. In experiment three the time lapse was decreased to 48 min in all the lines except number three where the time laps was 24 min.

An interval of one picture every third minute was chosen to obtain a good overview of the dye movement.

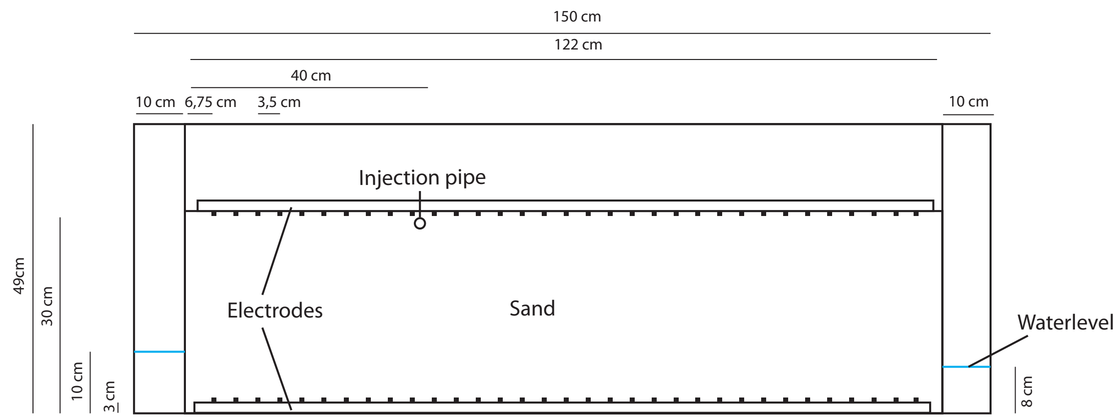

Figure 3: ***Cross section of the aquarium with the placement of the two basins, injection pipe and the electrode boards.***

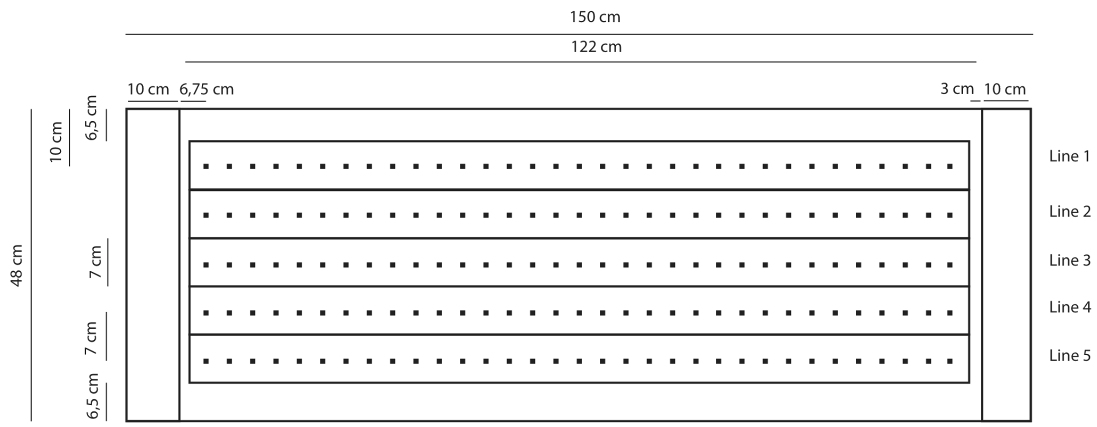

Figure 4: ***Planar view of the aquarium with the electrode board placement.***

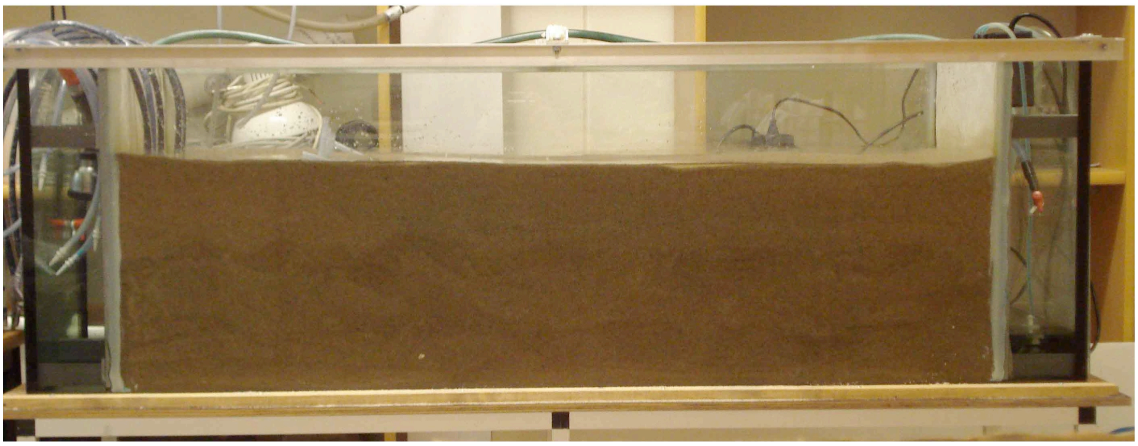

Figure 5: ***Photo of the aquarium with the experiment area filled with sand and the two basins at the sides.***

3.7 Resistivity data analysis

Two programs are used for the resistivity analysis, which are Erigraph and Res2Dinv. The apparent resistivity data collected during the dye tracer infiltration is merged together in a time-laps routine in Erigraph. The routine subtracts the resistivity measured in the pre-study and results in an image of the changes in the apparent resistivity caused by the injection of the dye tracer.

The merged apparent resistivity is inverted into a model with resistivity values in Res2Dinv. Different model parameters have been tested to improve the model quality.

The model from Res2Dinv is opened in Erigraph to change it into an image representing the increase or decreases of resistivity through the formation. A palette where blue color describes a decrease and a red color describes an increase of resistivity is chosen to illustrate these changes. These images will show a 2D assumption of the resistivity in a 3D environment.

3.8 Image analysis

The images are recorded in the raw format with the camera. Every tenth image is used in the study to show how the solution moves in sand in a 30 minutes interval. The images are modified into black and white in Adobe Photoshop and a template with the borders is created in Adobe Illustrator. The image and the template are then put together to show the movement across the formation.

4 Results

4.1 Test of the hydraulic conductivity in the sand

The sand used in the experiment is tested in advance to acquire the specific properties. The tests are made in the aquarium measuring the circulating water flow, measuring the depth in each basin and calculating the hydraulic conductivity with both Darcy's and Dupuits formula can be seen in table 2.

Table 2: ***Pre test of the sand where the hydraulic conductivity is calculated with both Darcy's and Dupuits formula.***

Flow (m^3/day)	Average height	Area (m^2)	Height left basin (m)	Height right basin(m)	Gradient (dh/dl)	Darcy's formula (m/day)	Dupuits formula (m/day)
0.0720	0.0530	0.0149	0.0595	0.0465	0.0102	475	268
0.0720	0.0615	0.0190	0.0670	0.0560	0.0086	440	272
0.0720	0.0700	0.0231	0.0755	0.0645	0.0086	363	239
0.0720	0.0930	0.0341	0.0980	0.0880	0.0078	270	198
0.2333	0.0960	0.0356	0.1210	0.0710	0.0391	168	124
0.2304	0.0780	0.0269	0.1010	0.0540	0.0367	233	162
0.0285	0.0780	0.0269	0.0810	0.0750	0.0047	226	156
0.0576	0.0780	0.0269	0.0835	0.0720	0.0090	238	165
0.0950	0.0490	0.0130	0.0590	0.0390	0.0156	467	248

4.2 Color calibration test

A color calibration test has been conducted to be able to determine the dye concentration in the acquired images. 12 images with different dye concentration and amount of dye tracer have been mixed with the sand and photographed to use as a reference. Examples of the calibration test are seen in figure 6 and 7.

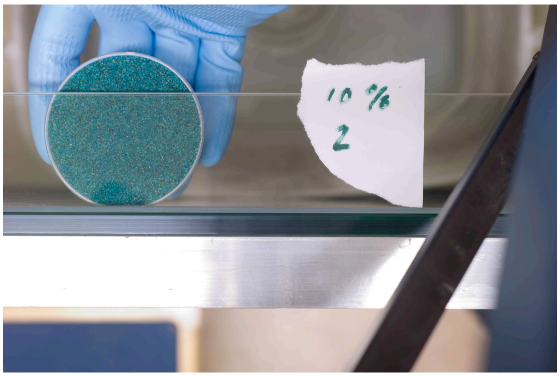

Figure 6: ***Calibration test with a dye concentration of 2 g/l and a dye tracer content of 10%.***

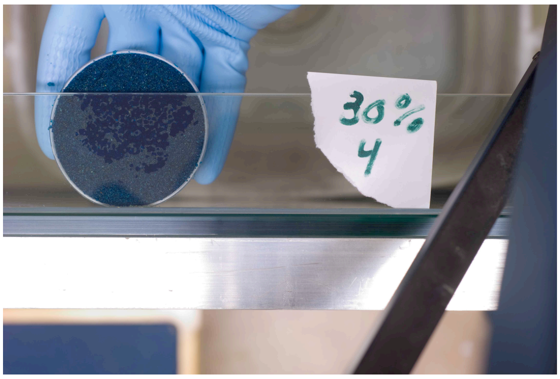

Figure 7: ***Calibration test with a dye concentration of 4 g/l and a dye tracer content of 30 %.***

4.3 Image analysis presentation

The pictures from the image analysis are presented in the following order. The first image presents the original picture of the experiment. The second image shows how the picture is transformed into the template where the capillary fringe is revealed. The images shown represent the situation after one and three hour after the experiment has started.

The last image reveals how the dye tracer moves in the solution in 30 min intervals during the entire experiment.

All the modified images can be seen in appendix A, B and C.

4.4 Resistivity image presentation

Two lines of the resistivity measurements are presented in the results; these are line three and five. These lines are chosen to represent the results because line three has a higher resolution due to its shorter interval and line five is located closest to the windows where the image analysis is taken.

The resistivity images of the other lines can be seen in appendix A, B and C.

4.5 Experiment 1

In experiment one the gradient head difference is set to be 2 cm between the basins, which corresponds to an angle of 0.90 degrees. The water pumped from the left side to the right side is measured to be four liters per hour and the level of the saturated zone will be 10 cm in the left basin and 8 cm in the right basin of the aquarium. The infiltration rate of the dye tracer is two liters per hour.

4.5.1 Image analysis

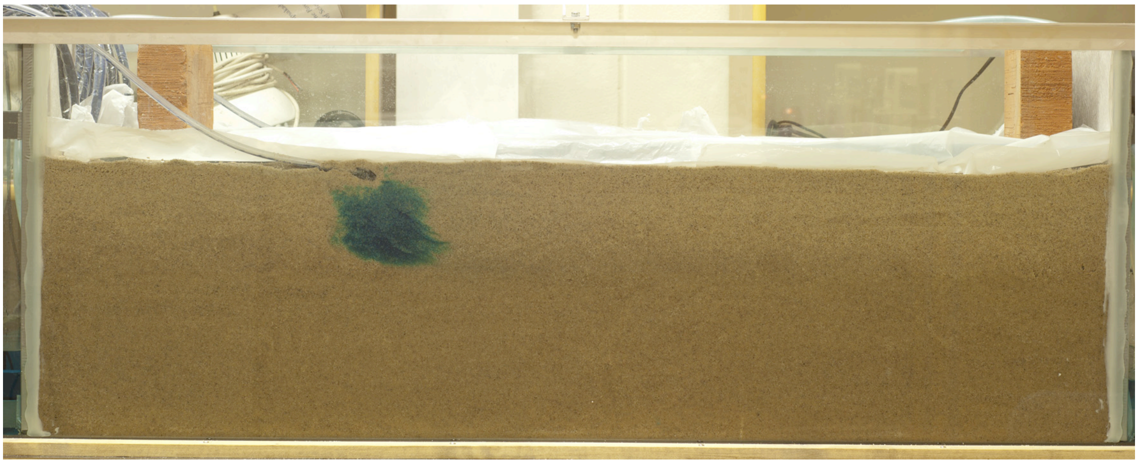

Figure 8: ***Image from the experiment one hour after start.***

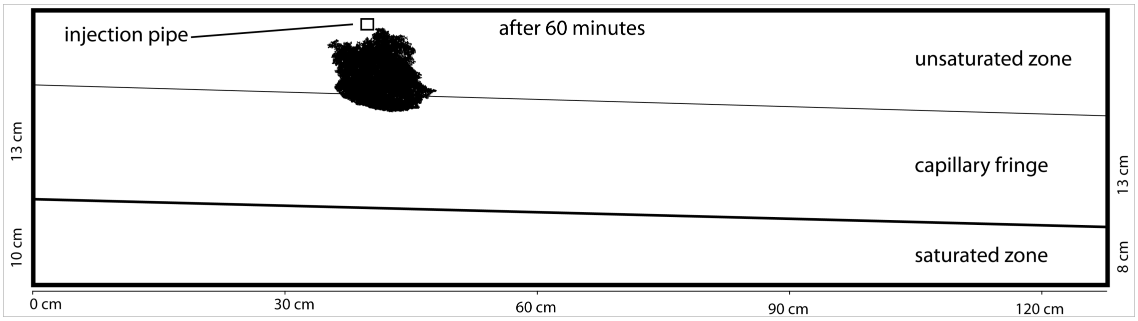

Figure 9: ***Modified image of the experiment one hour after start.***

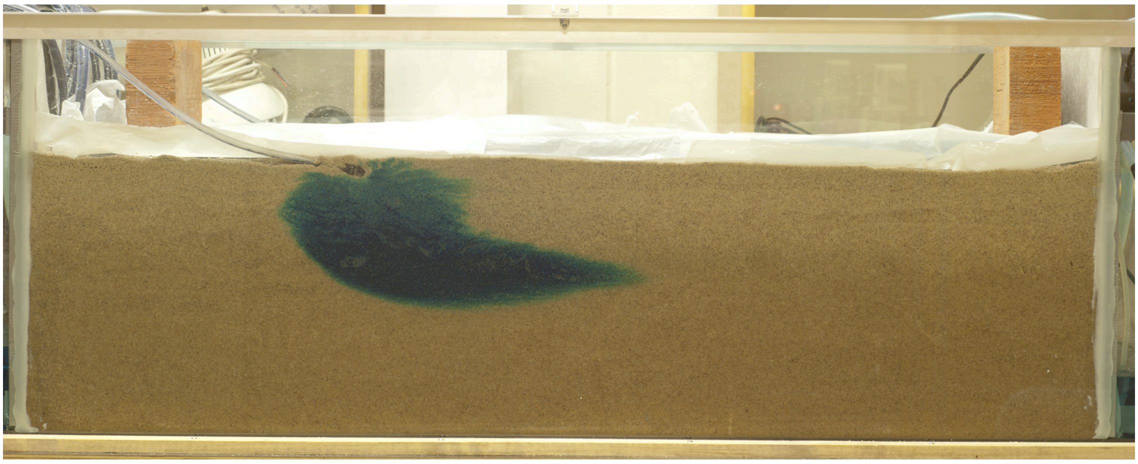
Figure 10: ***Image from the experiment three hours after start.***

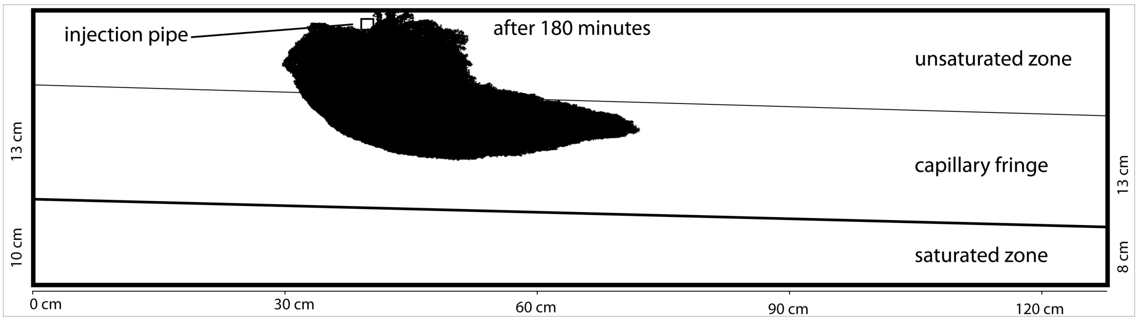

Figure 11: ***Modified image of the dye movement three hours after start.***

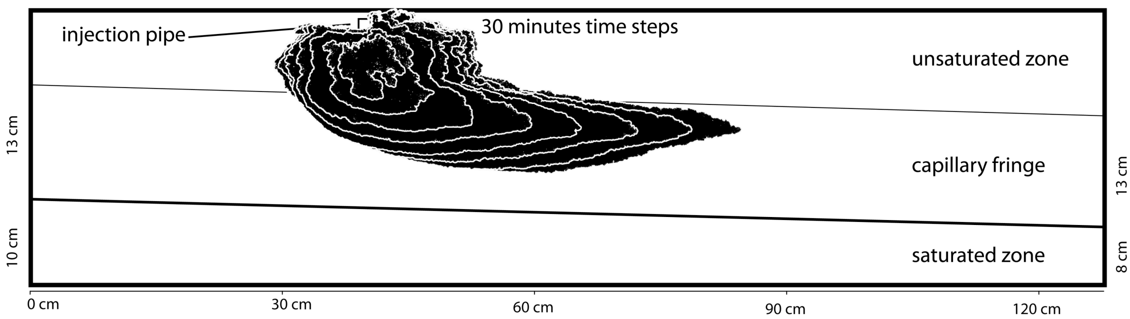

Figure 12: ***Modified image of the dye movement with 30 min time step.***

4.5.2 Resistivity analysis

Line 3

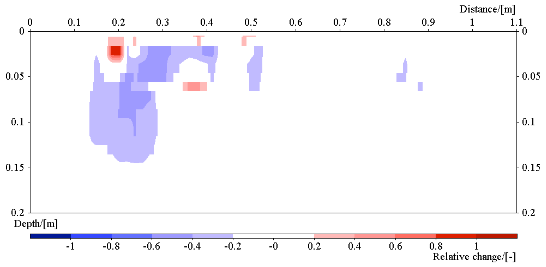

Figure 13: ***Image of the resistivity change in line 3. Time step 1, ca: 33 min after start.***

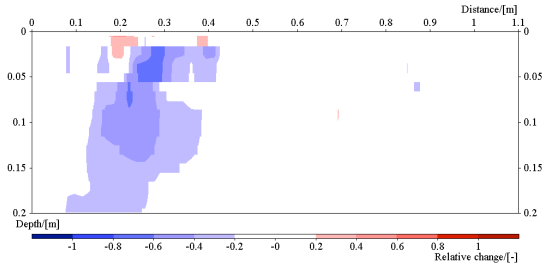

Figure 14: ***Image of the resistivity change in line 3. Time step 2, ca: 66 min after start.***

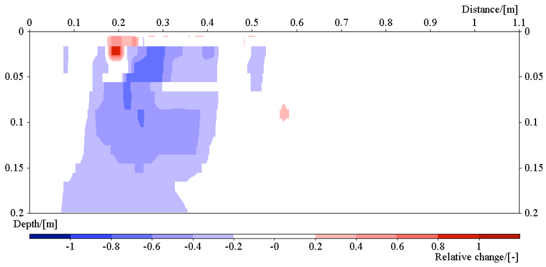

Figure 15: ***Image of the resistivity change in line 3. Time step 3, ca: 99 min after start.***

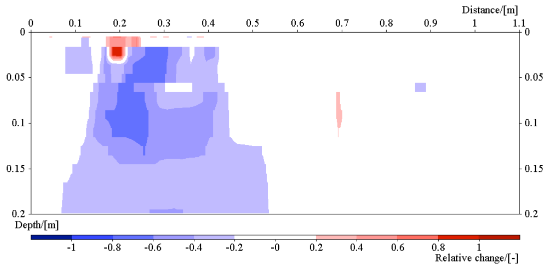

Figure 16: ***Image of the resistivity change in line 3. Time step 4, ca: 132 min after start.***

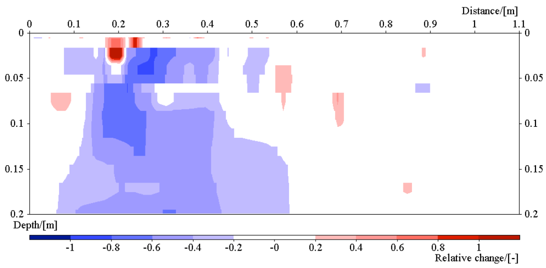

Figure 17: ***Image of the resistivity change in line 3. Time step 5, ca: 165 min after start.***

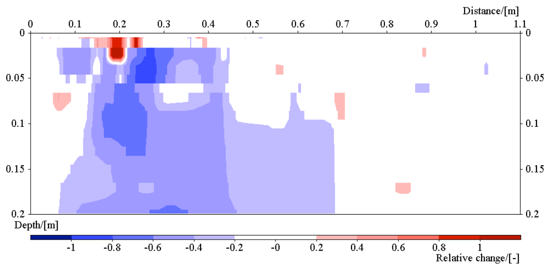

Figure 18: ***Image of the resistivity change in line 3. Time step 6, ca: 198 min after start.***

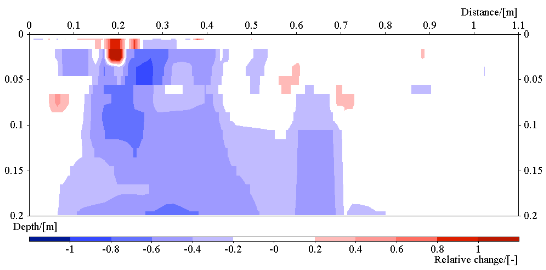

Figure 19: ***Image of the resistivity change in line 3. Time step 7, ca: 231 min after start.***

Line 5

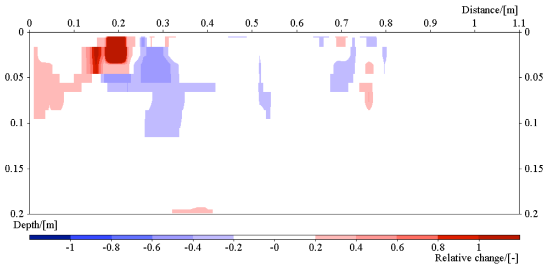

Figure 20: *Image of the resistivity change in line 5. Time step 1, ca: 55 min after start*

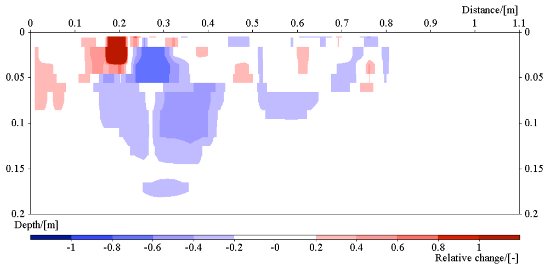

Figure 21: *Image of the resistivity change in line 5. Time step 2, ca: 121 min after start*

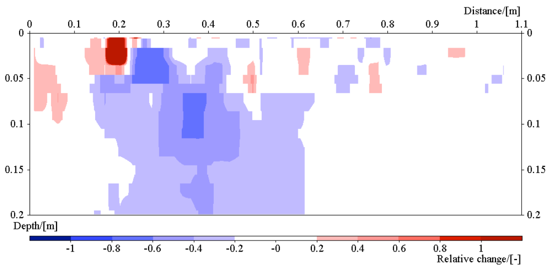

Figure 22: *Image of the resistivity change in line 5. Time step 3, ca: 187 min after start.*

4.6 Experiment 2

In experiment two the gradient head difference is set to be 4 cm between the basins, which corresponds to an angle of 1.79 degrees. The water pumped from the left side to the right side is measured to be eight liters per hour and the level of the saturated zone will be 12 cm in the left basin and 8 cm in the right basin of the aquarium. The infiltration rate of the dye tracer is two liters per hour.

4.6.1 Image analysis

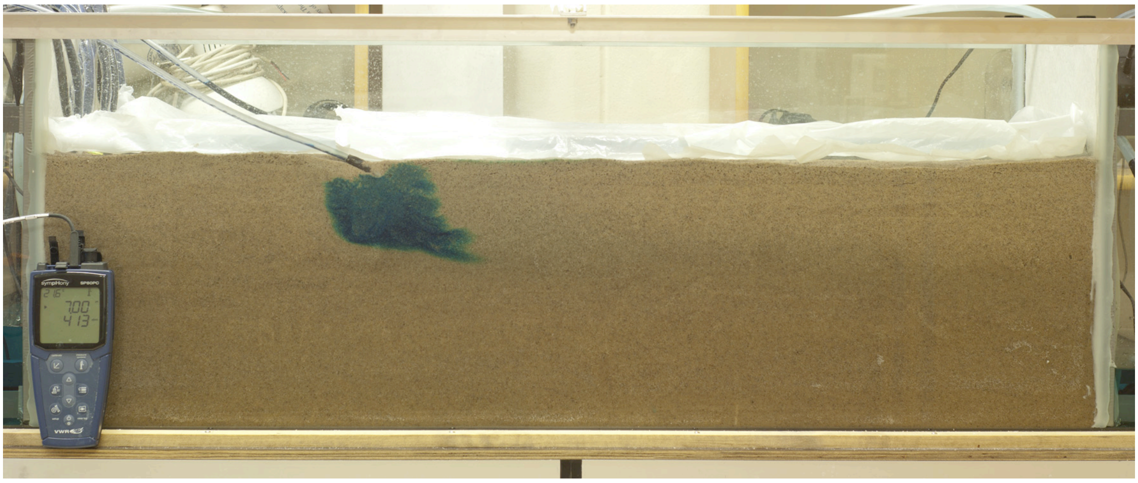

Figure 23: *Image from the experiment one hour after start.*

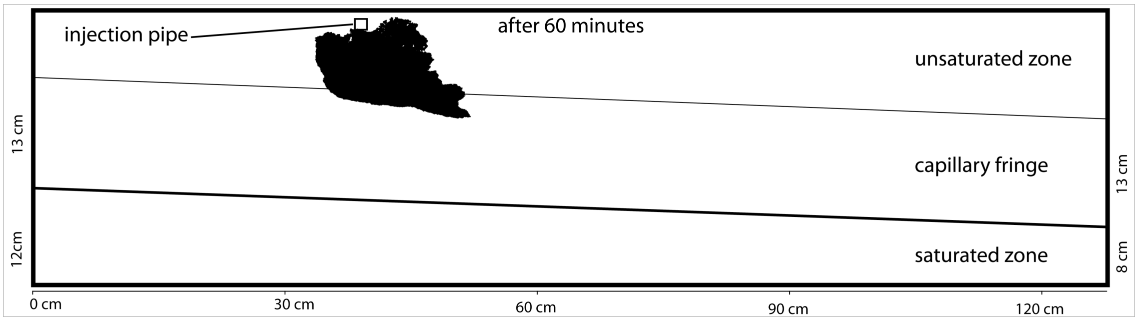

Figure 24: ***Modified image of the dye movement one hour after start.***

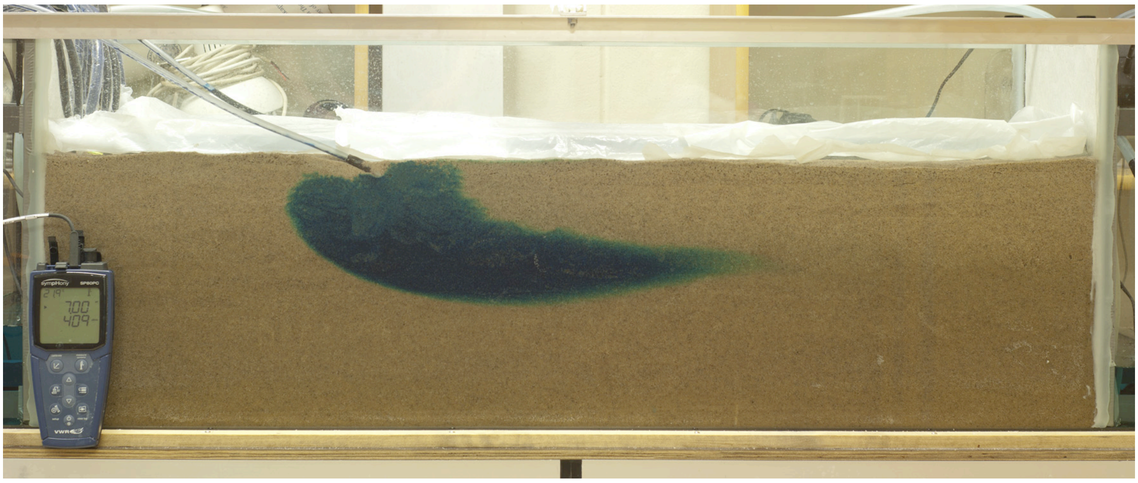

Figure 25: ***Image from the experiment three hours after start.***

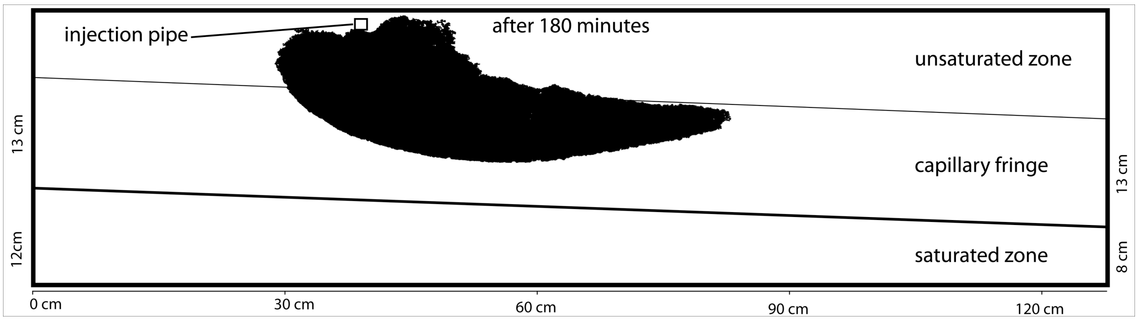

Figure 26: ***Modified image of the dye movement three hours after start.***

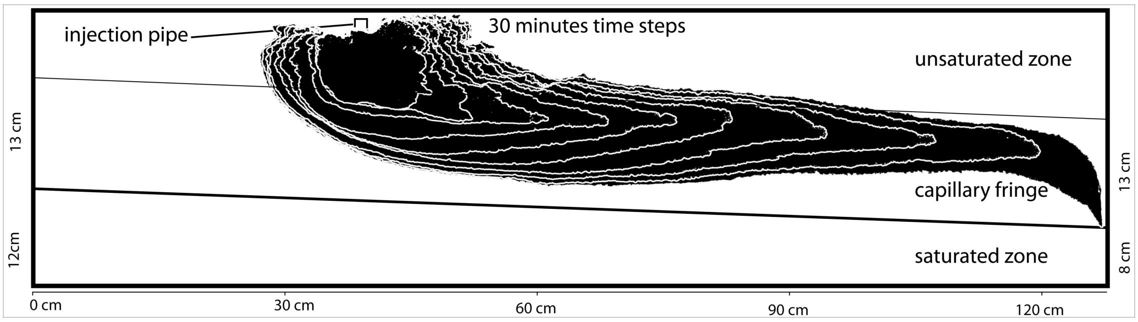

Figure 27: ***Modified image of the dye movement with 30 min time step.***

4.6.2 Resistivity analysis

Line 3

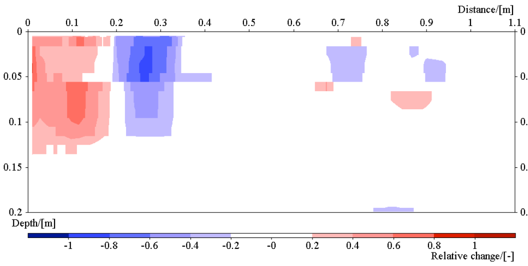

Figure 28: ***Image of the resistivity change in line 3. Time step 1, ca: 33 min after start.***

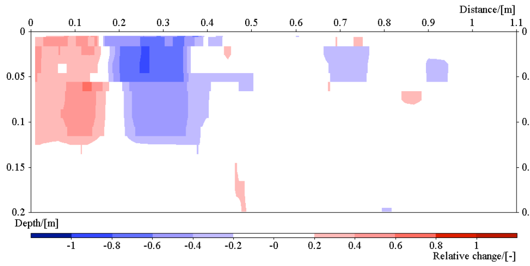

Figure 29: ***Image of the resistivity change in line 3. Time step 2, ca: 66 min after start.***

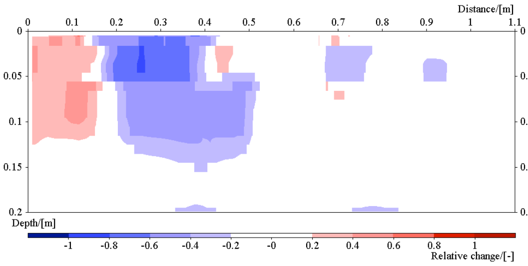

Figure 30: ***Image of the resistivity change in line 3. Time step 3, ca: 99 min after start.***

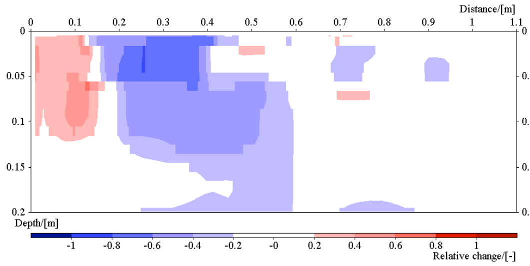

Figure 31: ***Image of the resistivity change in line 3. Time step 4, ca: 132 min after start.***

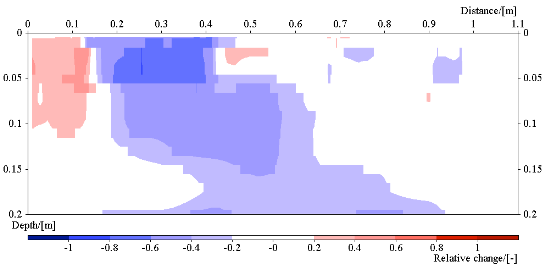

Figure 32: ***Image of the resistivity change in line 3. Time step 5, ca: 165 min after start.***

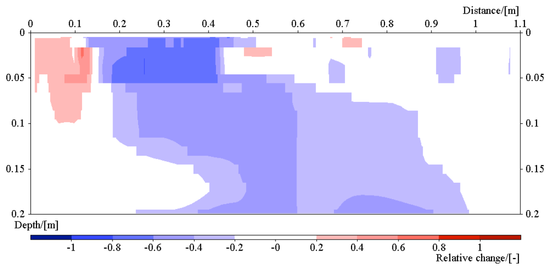

Figure 33: ***Image of the resistivity change in line 3. Time step 6, ca: 198 min after start.***

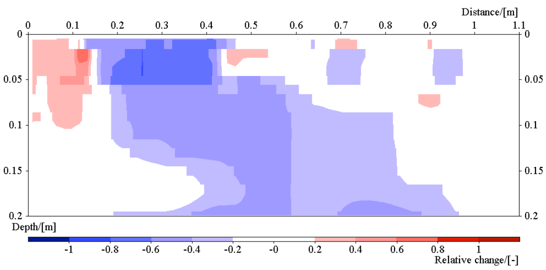

Figure 34: ***Image of the resistivity change in line 3. Time step 7, ca: 264 min after start.***

Line 5

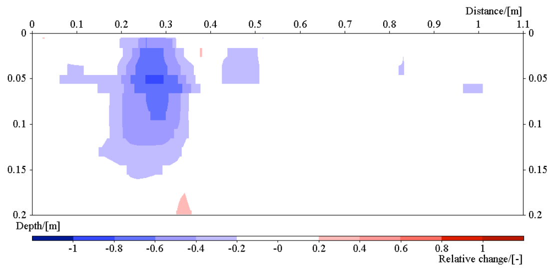

Figure 35: ***Image of the resistivity change in line 5. Time step 1, ca: 55 min after start.***

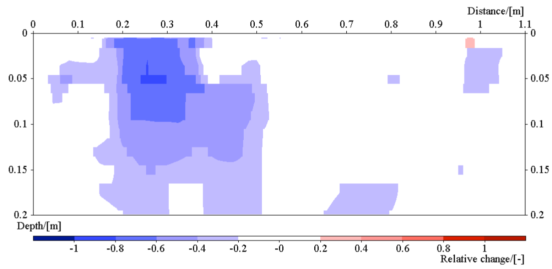

Figure 36: ***Image of the resistivity change in line 5. Time step 2, ca: 121 min after start.***

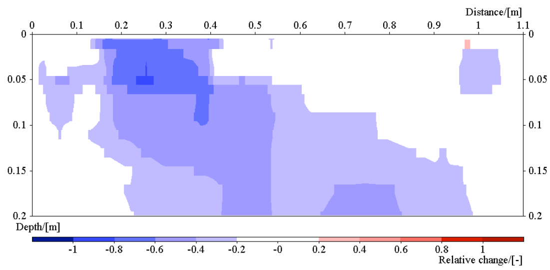

Figure 37: ***Image of the resistivity change in line 5. Time step 3, ca: 187 min after start.***

4.7 Experiment 3

In experiment three the gradient head difference is set to be 1 cm between the basins, which corresponds to an angle of 0.48 degrees. The water pumped from the left side to the right side is measured to be two liters per hour and the level on each side of the saturated zone will be 9 cm of the left side and 8 cm on the right side. The infiltration rate of the dye tracer is two liters per hour.

4.7.1 Image analysis

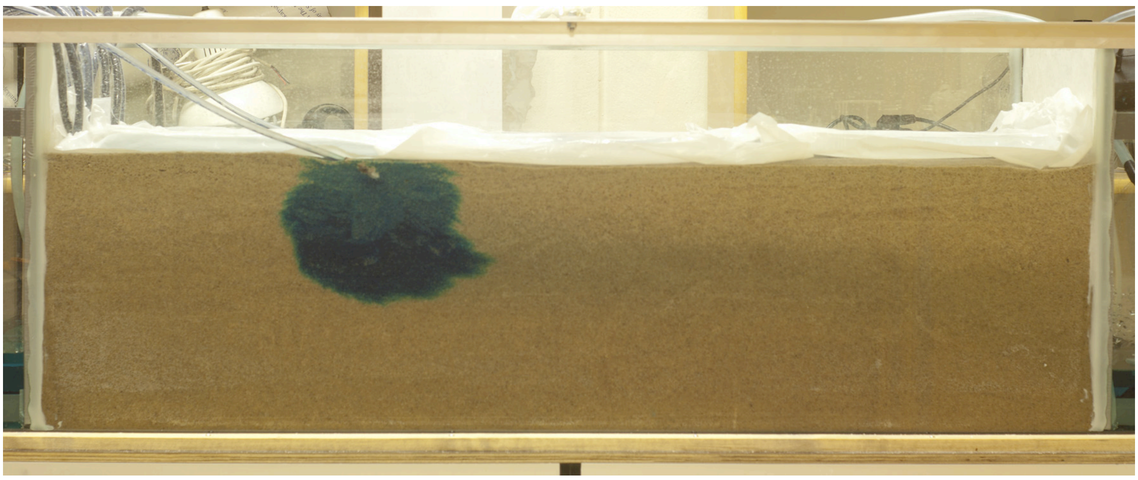

Figure 38: ***Image from the experiment one hour after start.***

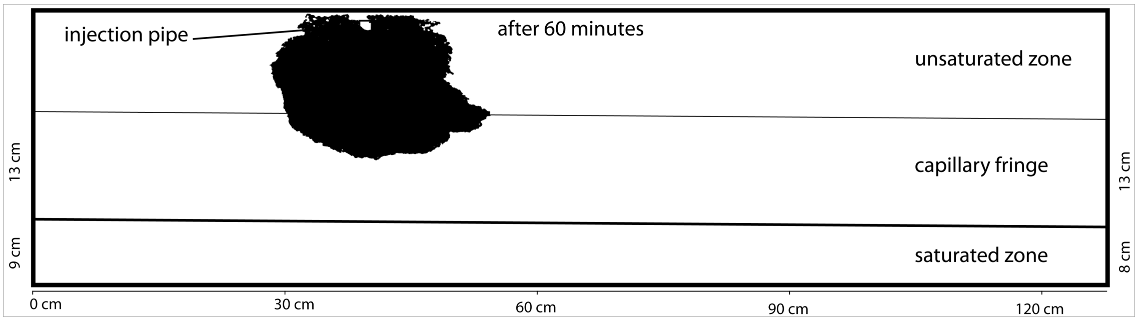

Figure 39: ***Modified image of the dye movement one hour after start.***

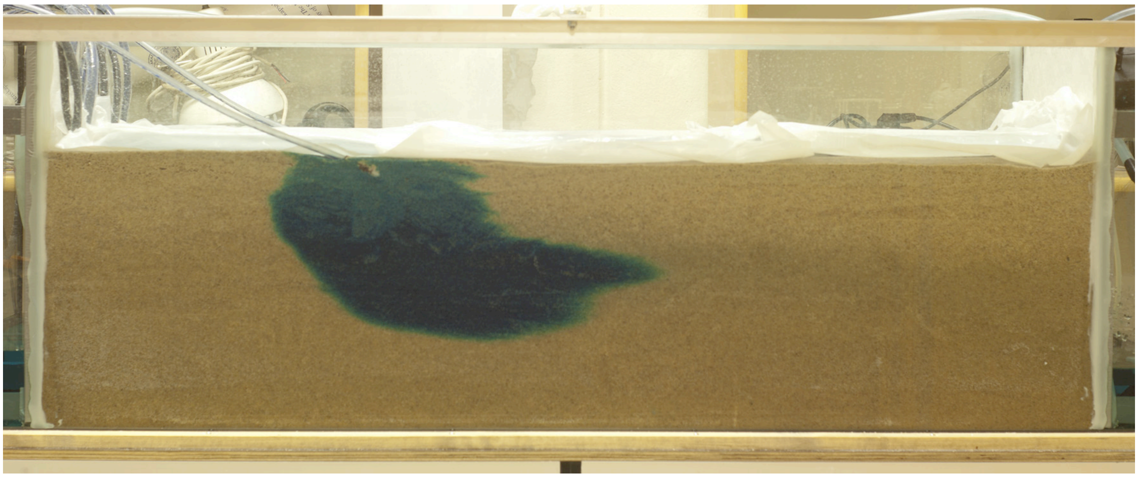
Figure 40: ***Image from the experiment three hours after start.***

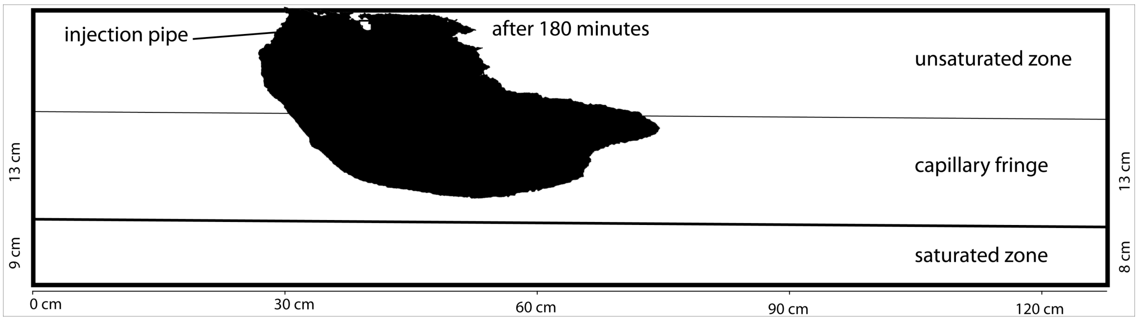

Figure 41: ***Modified image of the dye movement three hours after start.***

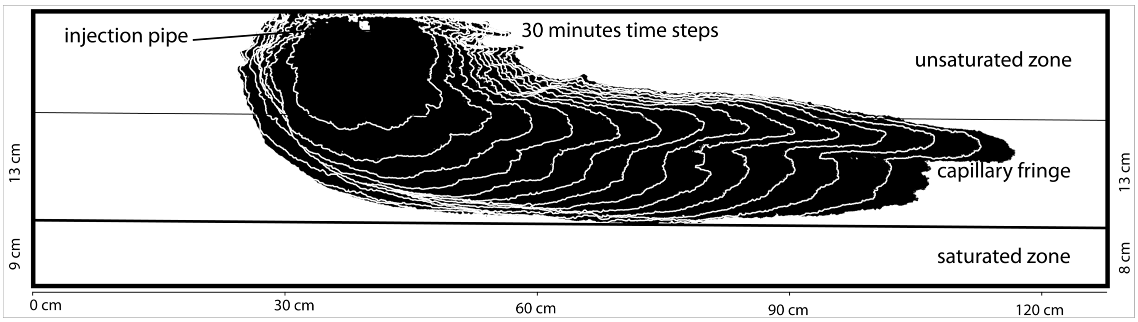

Figure 42: ***Modified image of the dye movement with 30 min time step.***

4.7.2 Resistivity analysis

Line 3

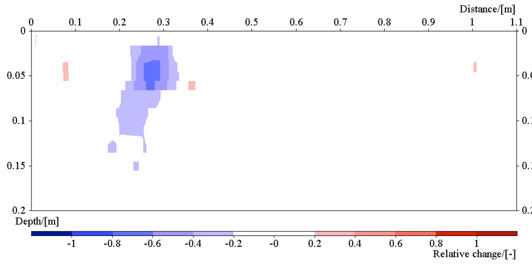

Figure 43: *Image of the resistivity change in line 3. Time step 1, ca: 24 min after start.*

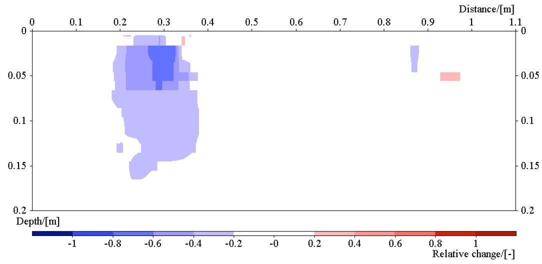

Figure 44: *Image of the resistivity change in line 3. Time step 2, ca: 48 min after start.*

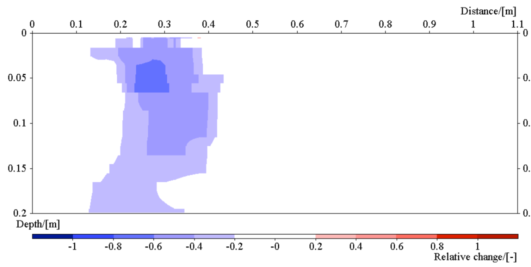

Figure 45: *Image of the resistivity change in line 3. Time step 3, ca: 72 min after start.*

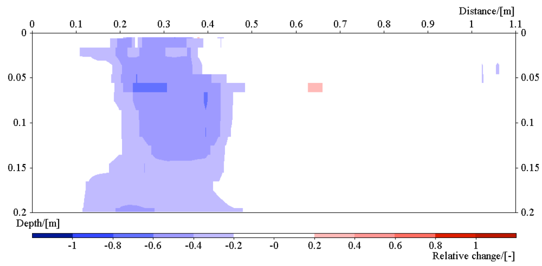

Figure 46: *Image of the resistivity change in line 3. Time step 4, ca: 96 min after start.*

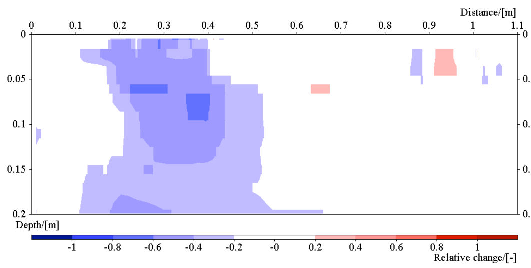

Figure 47: *Image of the resistivity change in line 3. Time step 5, ca: 120 min after start.*

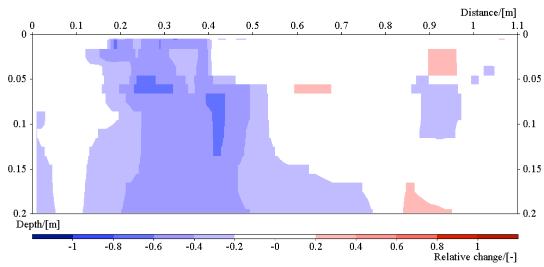

Figure 48: *Image of the resistivity change in line 3. Time step 6, ca: 144 min after start.*

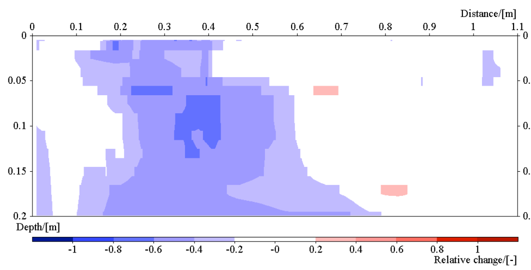

Figure 49: *Image of the resistivity change in line 3. Time step 7, ca: 168 min after start.*

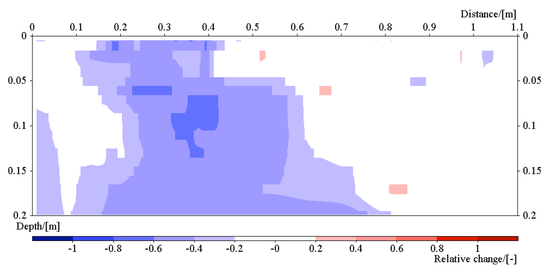

Figure 50: *Image of the resistivity change in line 3. Time step 8, ca: 192 min after start.*

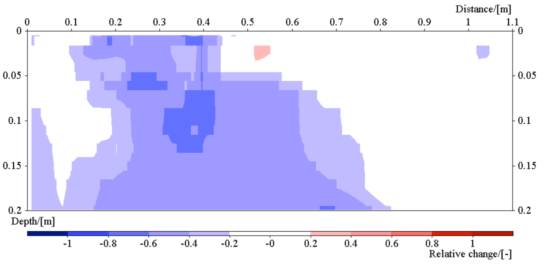

Figure 51: ***Image of the resistivity change in line 3. Time step 9, ca: 216 min after start.***

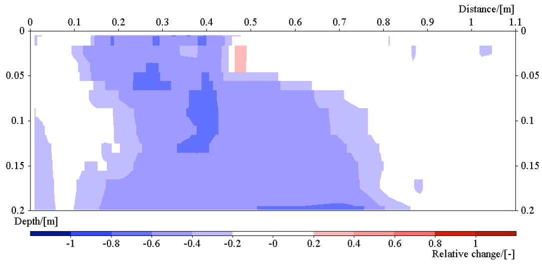

Figure 52: ***Image of the resistivity change in line 3. Time step 10, ca: 280 min after start.***

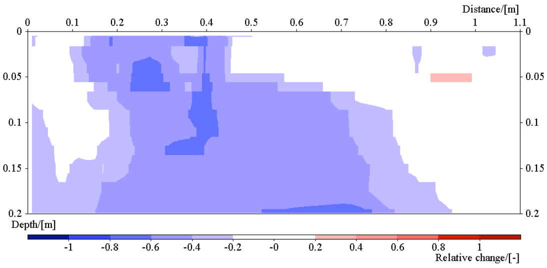

Figure 53: ***Image of the resistivity change in line 3. Time step 11, ca: 350 min after start.***

Line 5

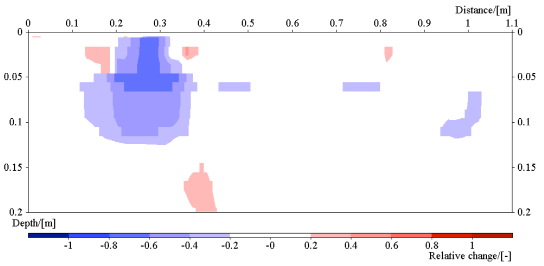

Figure 54: ***Image of the resistivity change in line 5. Time step 1, ca: 40 min after start.***

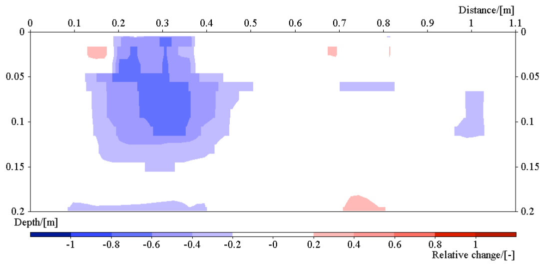

Figure 55: ***Image of the resistivity change in line 5. Time step 2, ca: 88 min after start.***

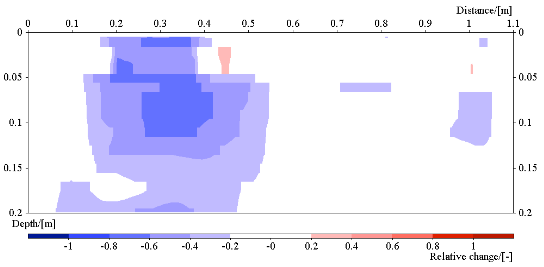

Figure 56: ***Image of the resistivity change in line 5. Time step 3, ca: 136 min after start.***

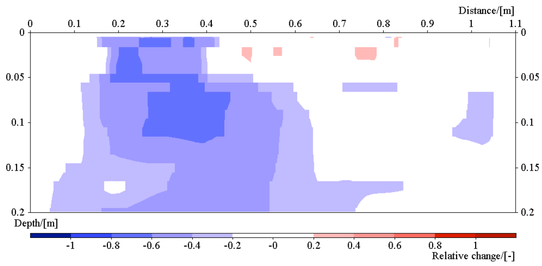

Figure 57: ***Image of the resistivity change in line 5. Time step 4, ca: 184 min after start.***

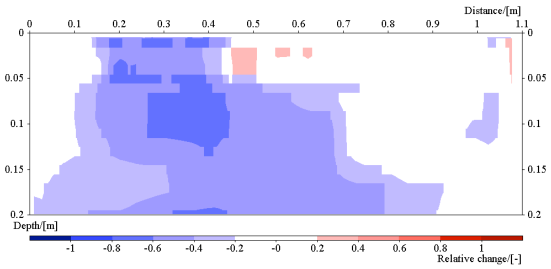

Figure 58: ***Image of the resistivity change in line 5. Time step 5, ca: 296 min after start.***

4.8 Image analysis at specific time

The following images show the images of the different experiments at a specific time. This makes is easier to see differences in the dye pattern between them. The time steps that are presented are two, three and four hours after the start of the experiment. To illustrate the flow pattern in relation to the capillary fringe, the images include the water level and the level of the capillary fringe of experiment one, even though they differ between all three experiments. Experiment one is chosen since its gradient is between the other two gradients.

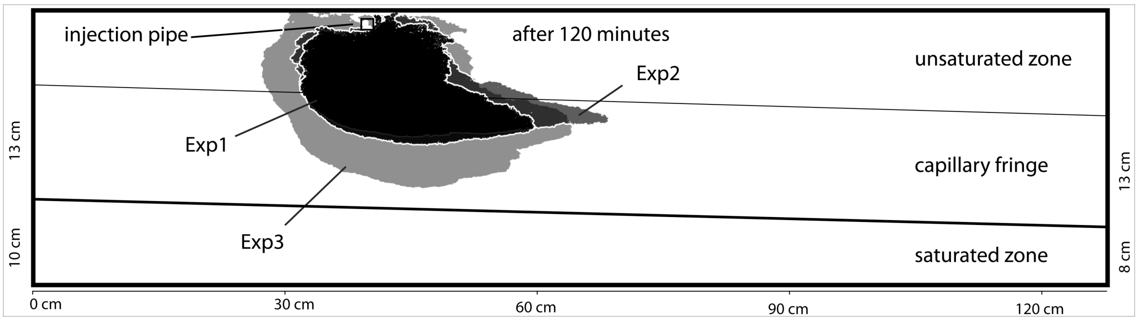

Figure 59: ***Image of the dye movement in the three experiments 120 min after the start.***

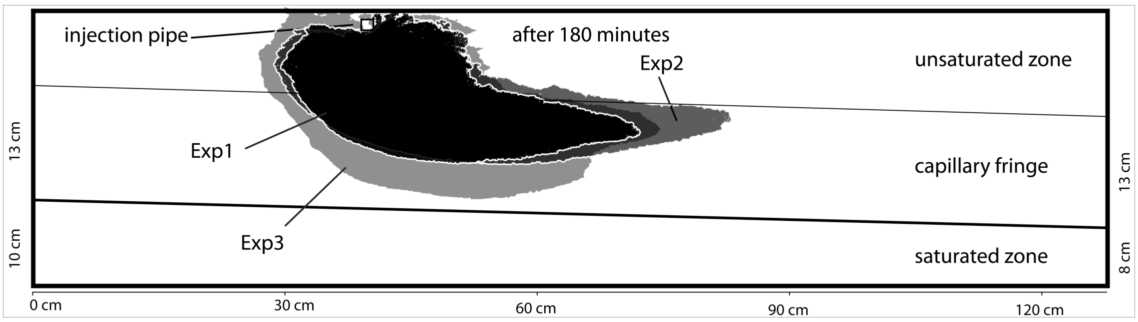

Figure 60: ***Image of the dye movement in the three experiments 180 min after the start.***

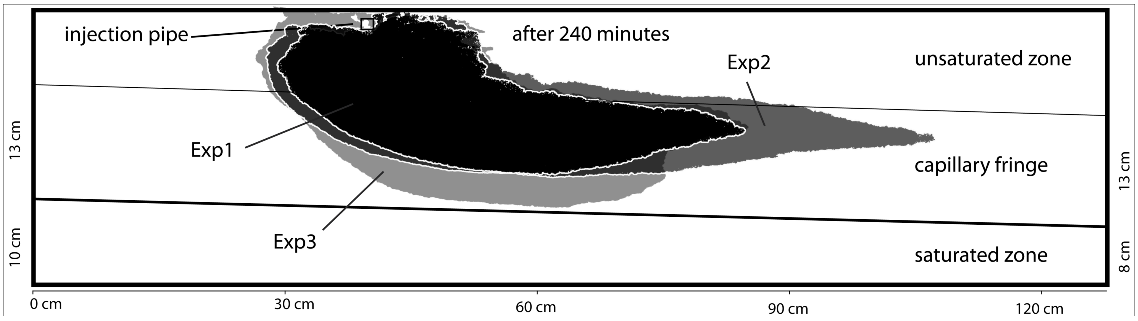

Figure 61: ***Image of the dye movement in the three experiments 240 min after the start.***

4.9 Speed differences between the experiments

The following table contains in the first column the measured speed of the of the dye tracer front in the images. Column two contains the calculated speed of all fluid movement, both infiltrated dye tracer and the circulating water in the aquarium. It is calculated that the fluids move with the same speed both in the saturated zone and the capillary fringe since the capillary fringe was observed with a high horizontal movement. The last column presents the measured speed in comparison to the calculated speed of each experiment. All the calculations can be seen in appendix D.

Table 3: ***Results of the measured speed, calculated speed and the percentage of the measured speed compared to the calculated speed.***

Experiment nr	Measured speed (cm/h)	Calculated speed (cm/h)	Measured speed / Calculated speed (%)
Experiment one	6.7	13.5	49.7
Experiment two	9.1	22.1	41.4
Experiment three	5.3	8.8	60.1

5 Discussion

Analyzing the resistivity images you will notice that the distance in the figures in only 1.1 m. This is caused by the electrode layout, which has this value as the maximum distance between the electrodes. On the left side the first electrode is 13 cm away from the basin border, this means that the injection pipe will be located just before 0,3 m in this figures.

In a comparison of the resistivity and the image analysis of the dye movement in all directions around the injection pipe there is a good relationship between the methods. Both methods show the same movement during the whole experiment in a radius of 25 cm around the injection pipe.

To get a reliable comparison between the investigation methods of the dye tracer in the horizontal movement in the capillary fringe experiment two is the best experiment to use. This is because of the dye movement takes place in the area where the resistivity models were obtained. The dye movement is similar in both methods. They show both the same thickness of the horizontal movement and how far the dye front has traveled up to three hours after the experiment start. After this time is the comparison not reliable because the dye front is outside the area where resistivity model loses sensitivity.

With this comparison made it is expected that the two methods will present the same result if the resistivity method is changed to obtain more resistivity values in the aquarium. This study will then present the same result as Koestel et al. (2009) that the two methods can be used together to trace water movement in soil.

Examining column one in table three and compare how fast the measured dye front is moving in comparison to each other the general pattern of an increasing speed of the movement is observed with a steeper gradient. The dye front is moving 26 % faster in experiment one compared to experiment three, and it is 72 % faster in experiment two compared to experiment three. These results show a large horizontal movement in the capillary fringe, which is increasing with a steeper gradient of the saturated zone.

As mentioned, this study shows a large horizontal movement in the capillary fringe, which is the same result as the simulations made by Ronen et al. (1997). The horizontal movement is so large that it should not be ignored in ground water calculations. The result from this study shows that there should be more investigation on the horizontal movement in the capillary fringe to be able to determine a general pattern. When this is done a model for the water movement in the capillary fringe should be created which can be used in groundwater calculation. One general conclusion is the hydraulic properties in the capillary fringe are more similar to the saturated zone then the unsaturated zone. It should therefore be treated as a part of the saturated zone rather then the unsaturated zone that it is treated as today.

In table three the third column shows the speed of the movement in the capillary fringe in comparison to a calculated speed of the movement of all the fluids in the aquarium. This value differs between the experiments and can be an indication of that it is easier for the fluid to move in the capillary fringe with a lower speed due to less friction. It might also be an error because the model of the calculated flow is incorrect which gives a misleading value. Experiments on the speed in the capillary fringe are necessary to draw conclusions of a general pattern.

When examining figures 59, 60 and 61, where the dye movement of the experiments is presented in the same figure, an important thing to remember is experiment one is not equal to experiment two and three due to the new hole in the injection pipe. This has affected the length of the dye front in experiment one and will most likely give a misleading length of the dye movement compared to the other experiments. One obvious reason why the speed of the movement in experiment one is incorrect to the other experiments is that the dye front in the experiment is equal to experiment three where the gradient of the saturated zone is half as high. If you compare experiment two and three you will see the difference in horizontal compared to vertical movement with the different gradients. The higher the gradient is the faster is the movement in the capillary fringe, specifically the movement in the upper part.

One big issue with the resistivity analyses and the modeling made by the model used in the study is that the investigation has limited sensitivity in the lower parts of the sand closer to the basins. This makes the resistivity analysis loses it quality and is not a certain investigation and the dye tracer path cannot be traced in this parts. Because of this the resistivity analyses is not that reliable in the final phrase of the experiment.

The resistivity images generally contain some disturbance. An example is that there should not be any red areas indicating an increase in resistivity in the images. But many of the images still contain some red area, which is a disturbance. If the disturbance is in the higher area of the image it might be caused by bad electrode contact. An example of a disturbance that might be bad electrode contact can be seen in e.g. figure 15. If it is in a lower area of the image it's uncertain what's causing the disturbance. In some figures e.g. figure 28 to 34 there is a large area of disturbance. When the disturbance is this large it is most likely the operator who have disturbed the sand composition between the background measurements and the normal measurements. The resistivity images in experiment one contain generally lots of disturbances. The noises make it harder to analyse the dye movement and makes less accurate data quality.

Experiment one was unfortunately stopped before the dye reached the right basin or the saturated zone. This makes it hard to determine if the dye will reach the saturated zone before the horizontal movement has moved it to the right basin. A lot of the dye movement is horizontal in the upper layer of the capillary fringe and there is only a small movement in depth during the experiment. The experiment is also different with the change of a new hole is drilled in the injection pipe closer to the glass which makes the dye reach the window faster in the other experiments. To be able to compare this experiment with the other experiments in the length of the dye movement at a specific time this experiment should be done one more time with the new hole in the injection pipe.

Experiment two has the highest gradient, and has also the most movement in the capillary fringe. In the figures you can easily see that the major dye movement takes place in the top layer of the capillary fringe. The horizontal movement is so fast in this experiment with a four cm gradient and the dye reaches the right basin before it reaches the saturated zone. Because of the fast horizontal movement the experiment is stopped and there is no time to see if the dye front might have moved slowly downwards and at some point hit the saturated zone.

In experiment three the dye reaches the saturated zone in the end of the experiment, but it is not infiltrating into the saturated zone before the experiment is stopped. It looks more like it is floating on the saturated zone. If you look closely in appendix C in the three last images you will see that it reaches the saturated zone somewhere between 360 and 390 min after the start of the experiment and in the last image of the experiment 420 min after the start of the experiment it is floating on the saturated zone. To make some estimation of how long the horizontal movement is before it reaches the saturated zone you have to use this experiment and look at the point where it starts floating on the saturated zone. In this case with this gradient the dye will move approximately 30 cm horizontally when it passes the capillary fringe. It is unfortunately not entering the saturated zone and the experiment is stopped before it has the time to do so. Another interesting fact is that it is not the front of the dye tracer that is first to vertically pass the capillary fringe to the saturated zone. It is instead somewhere in the middle of the dye movement where this happens. This means there will still be a large transport of dye in the capillary fringe. There is unfortunate some kind of layering in the middle of the capillary fringe which is most likely affecting the dye movement pattern.

This study shows a similar result as the previous studies made. It is useful to use both image analysis and resistivity measurements to track movements in the soil. Unfortunately there is need for a better resistivity model in this study, which can investigate a larger area of the experiment. When it’s used will it be possible to make a better comparison with the result of the previous studies.

6 Conclusions

With only three experiments performed it is hard to estimate definite conclusions of the exact movement in the capillary fringe. Only the gradient is changed in these experiments, the result might differ when other parameters are changed in the experiment. The general conclusions from this study are:

- There is a rapid horizontal movement in the capillary fringe and the horizontal speed is dependent on the gradient of the saturated flow. A higher gradient of the saturated flow creates a faster horizontal movement in the capillary fringe.
- Estimations of the horizontal movement of the dye when it's passing the capillary fringe to the saturated zone have been difficult to obtain because of the large horizontal movement. One experiment with a gradient of 0,48 degrees shows a 40 cm horizontal movement in a capillary fringe of 13 cm.
- The resistivity images give only a reliable result in the beginning of the experiment. Another resistivity protocol and model must be used which can obtain more data closer to the edges of the aquarium.
- The hydraulic properties of the capillary fringe are more similar to the saturated zone then the unsaturated zone. It should therefore be treated as a part of the saturated zone rather than the unsaturated zone that it is treated as today.

7 Future studies

It is recommended to conduct more experiments to determine the movement in the capillary fringe. It is recommended to do the experiments with different approaches to check its influence on the result.

- It is recommended to do more investigations to get an even better view of how the water moves across the capillary fringe. Because of the large horizontal movement it is interesting to try smaller gradient then 0,48 degrees.
- It is recommended to vary the injection flow of the dye tracer to see if it affects the flow path across the capillary fringe.
- It is recommended to analyse the concentration of the dye tracer in the experiments to see if there is a difference in concentration in the capillary fringe.
- Another resistivity software with a 3D model should be used, which takes the geometry of the aquarium into account, to obtain a better resistivity model of the experiment.

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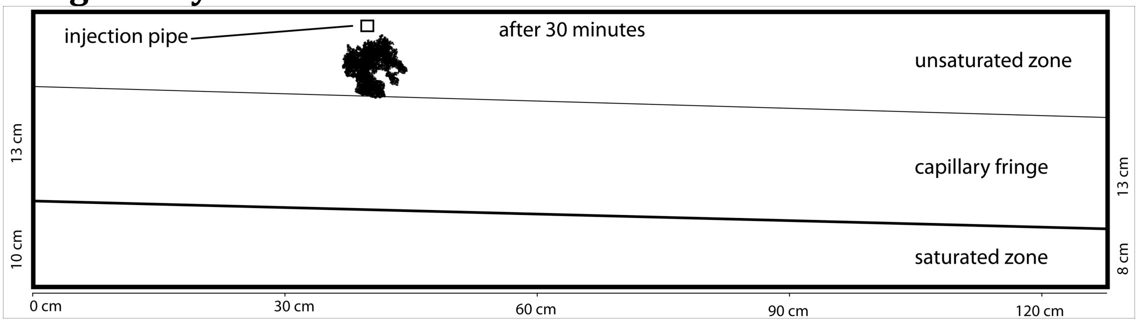
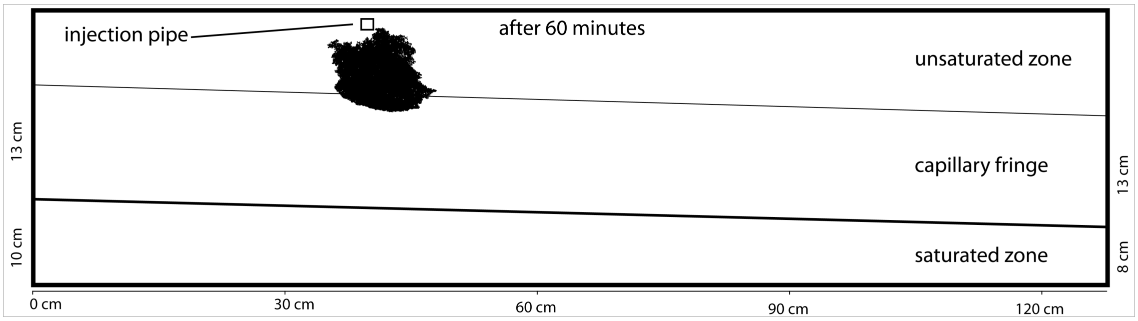
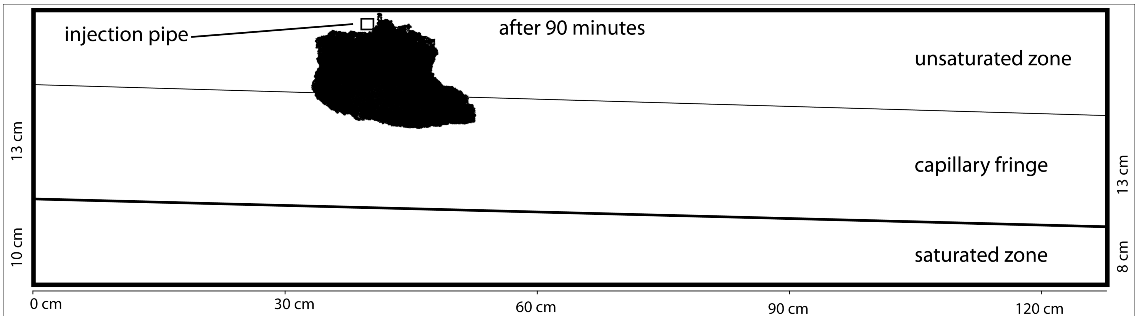
Appendix

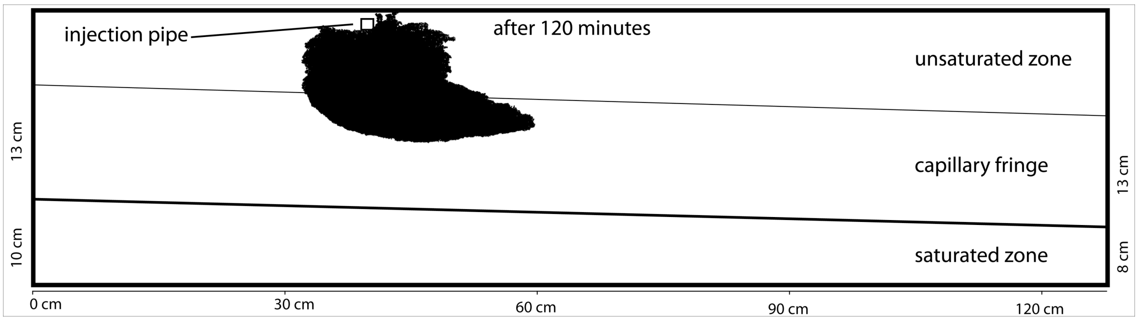
A: Experiment 1

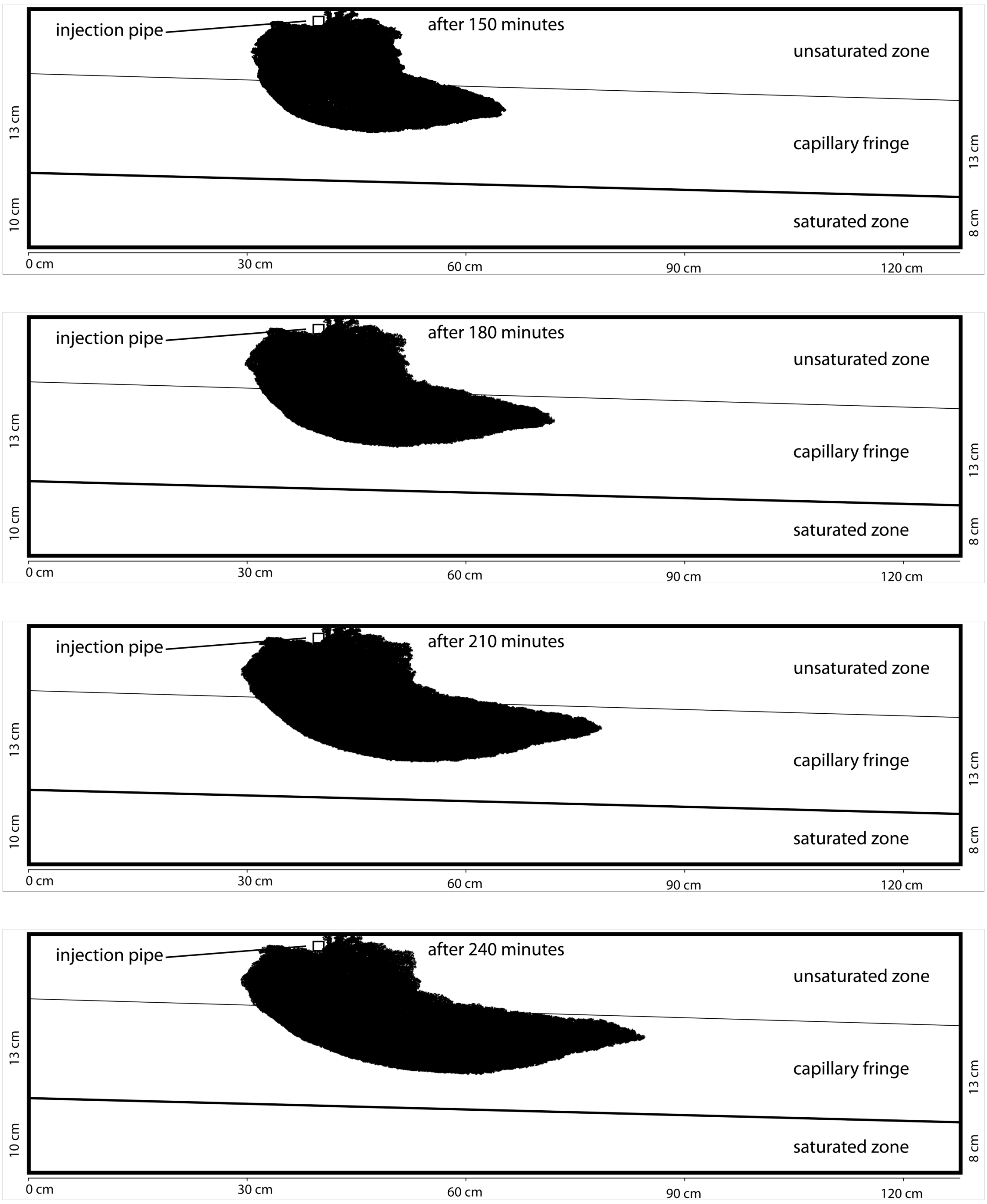
Image analysis:







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after 150 minutes
unsaturated zone
capillary fringe
saturated zone
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10 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm
injection pipe
after 180 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
10 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm
injection pipe
after 210 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
10 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm
injection pipe
after 240 minutes
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120 cm

Resistivity images:

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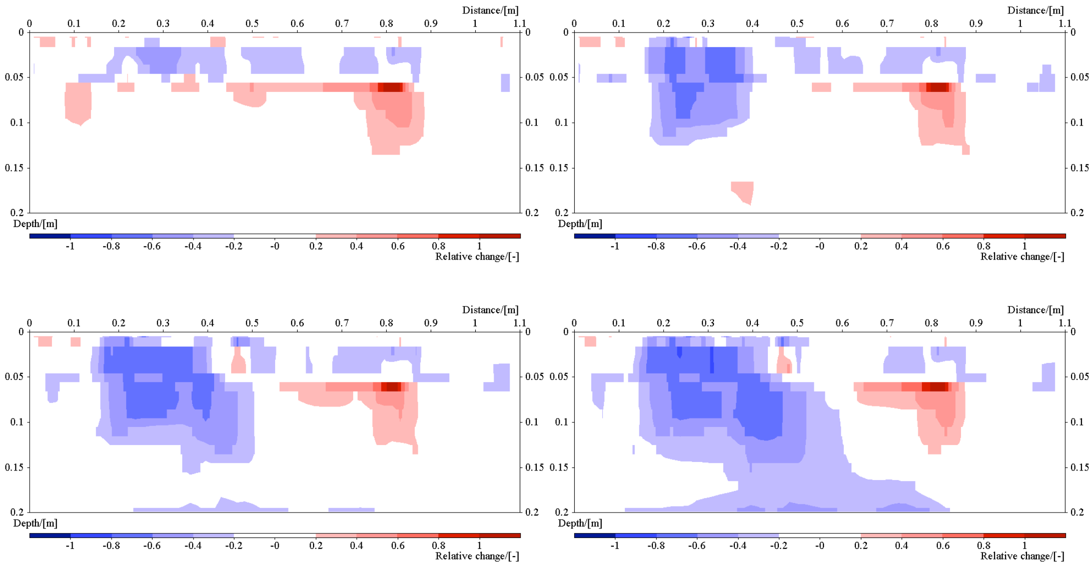

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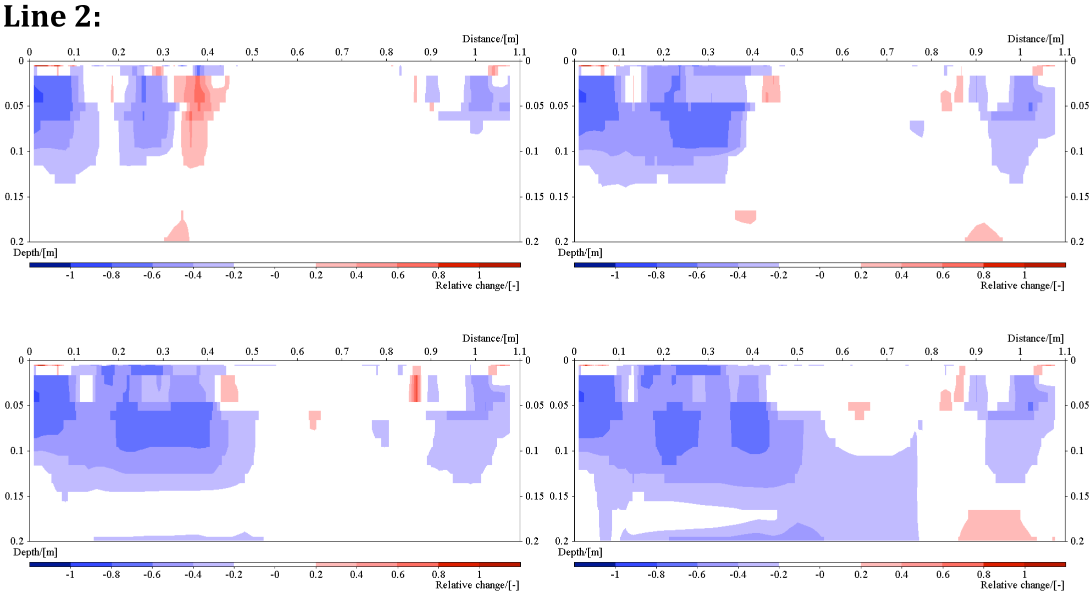

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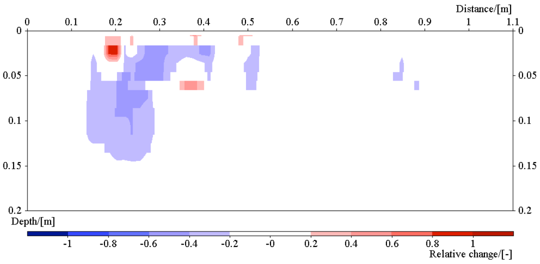
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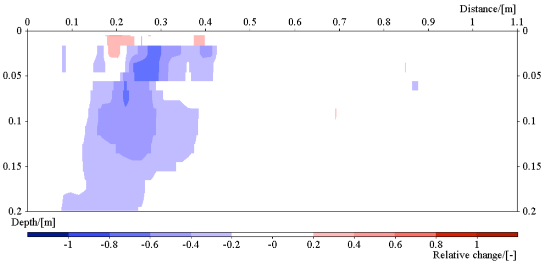
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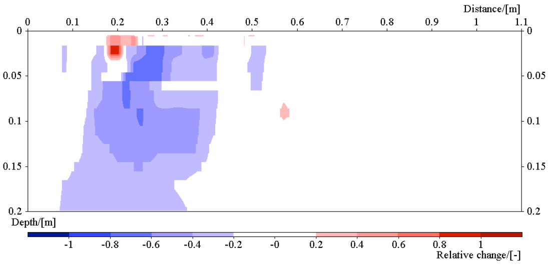
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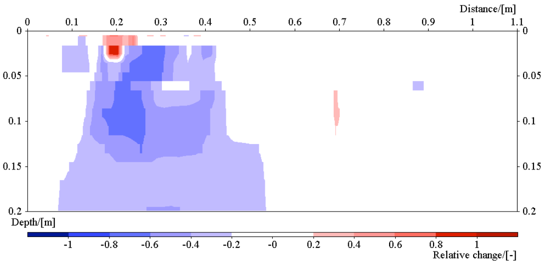
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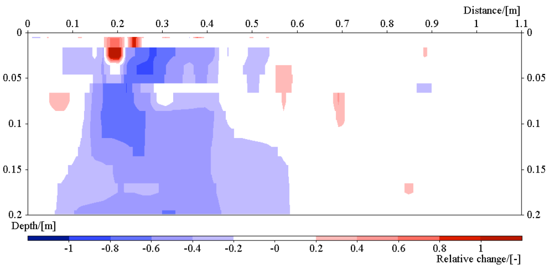
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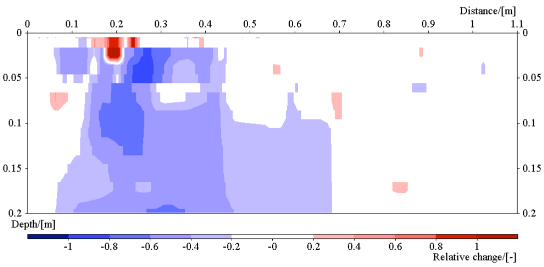
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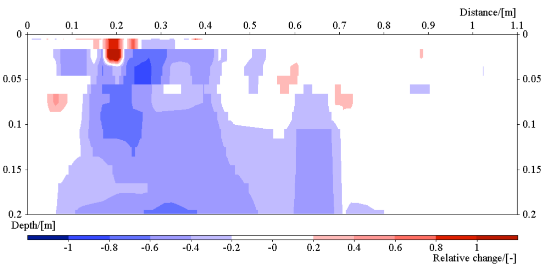
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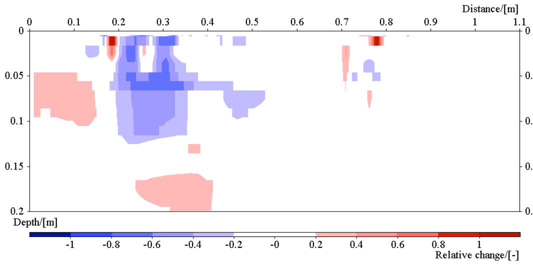
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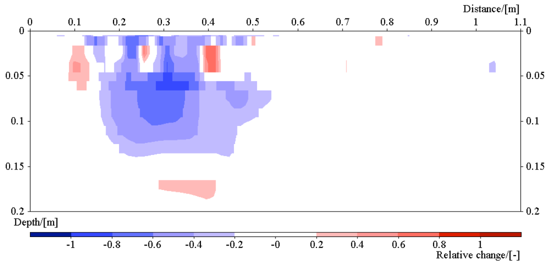
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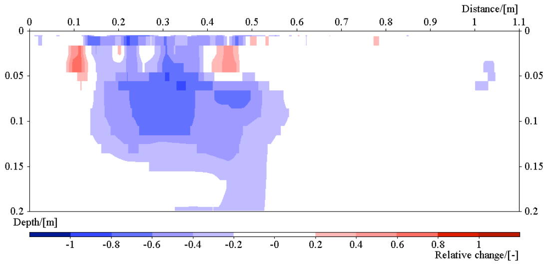
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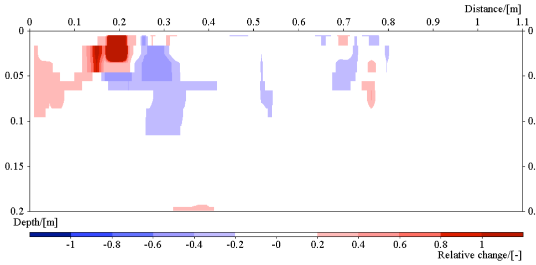
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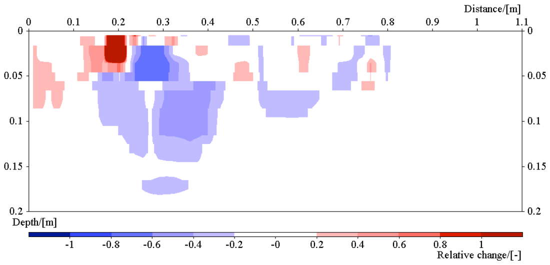
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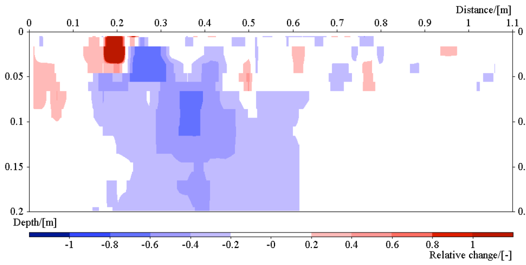
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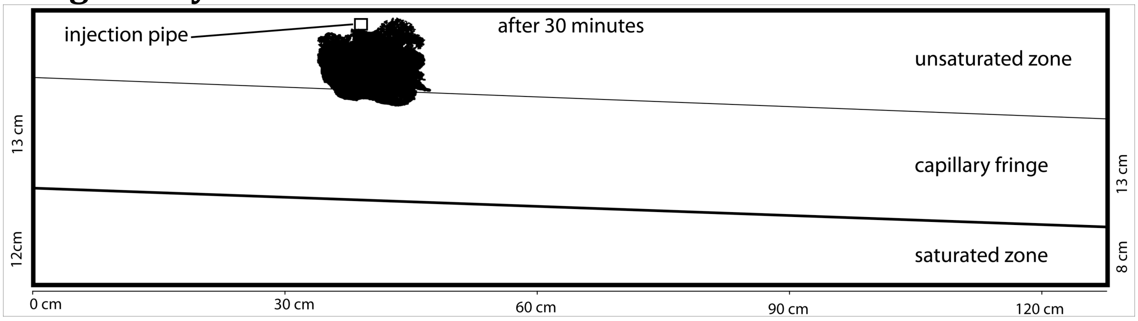
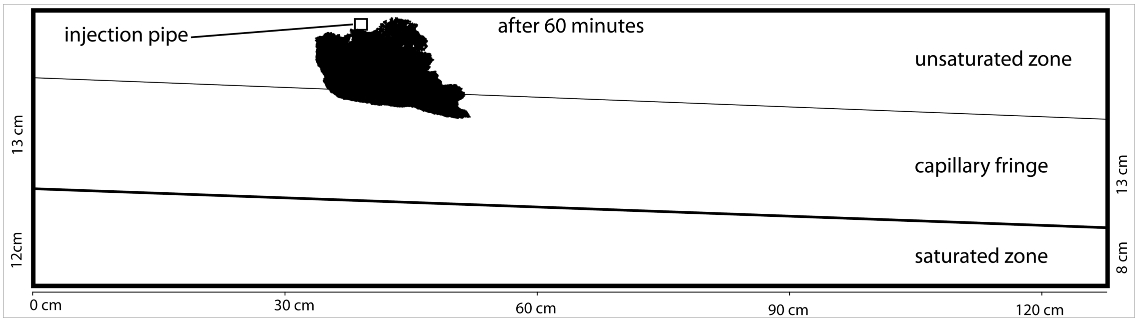
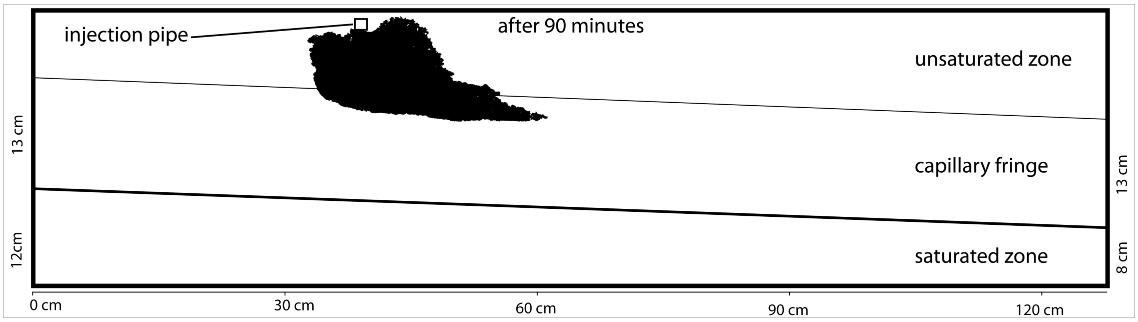
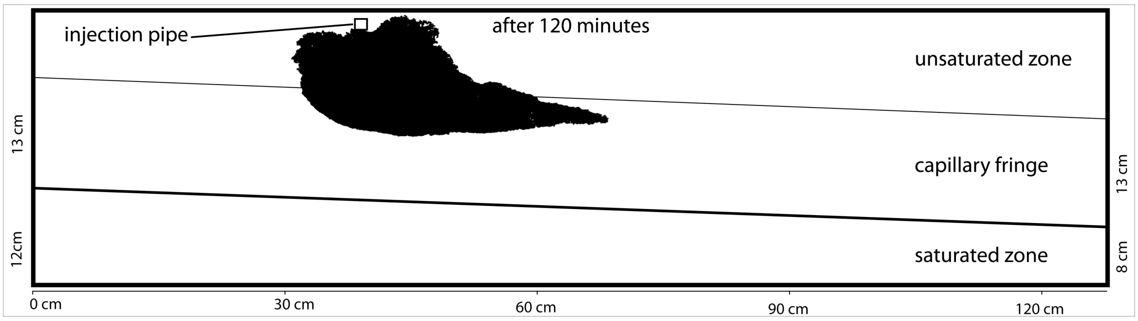
B: Experiment 2

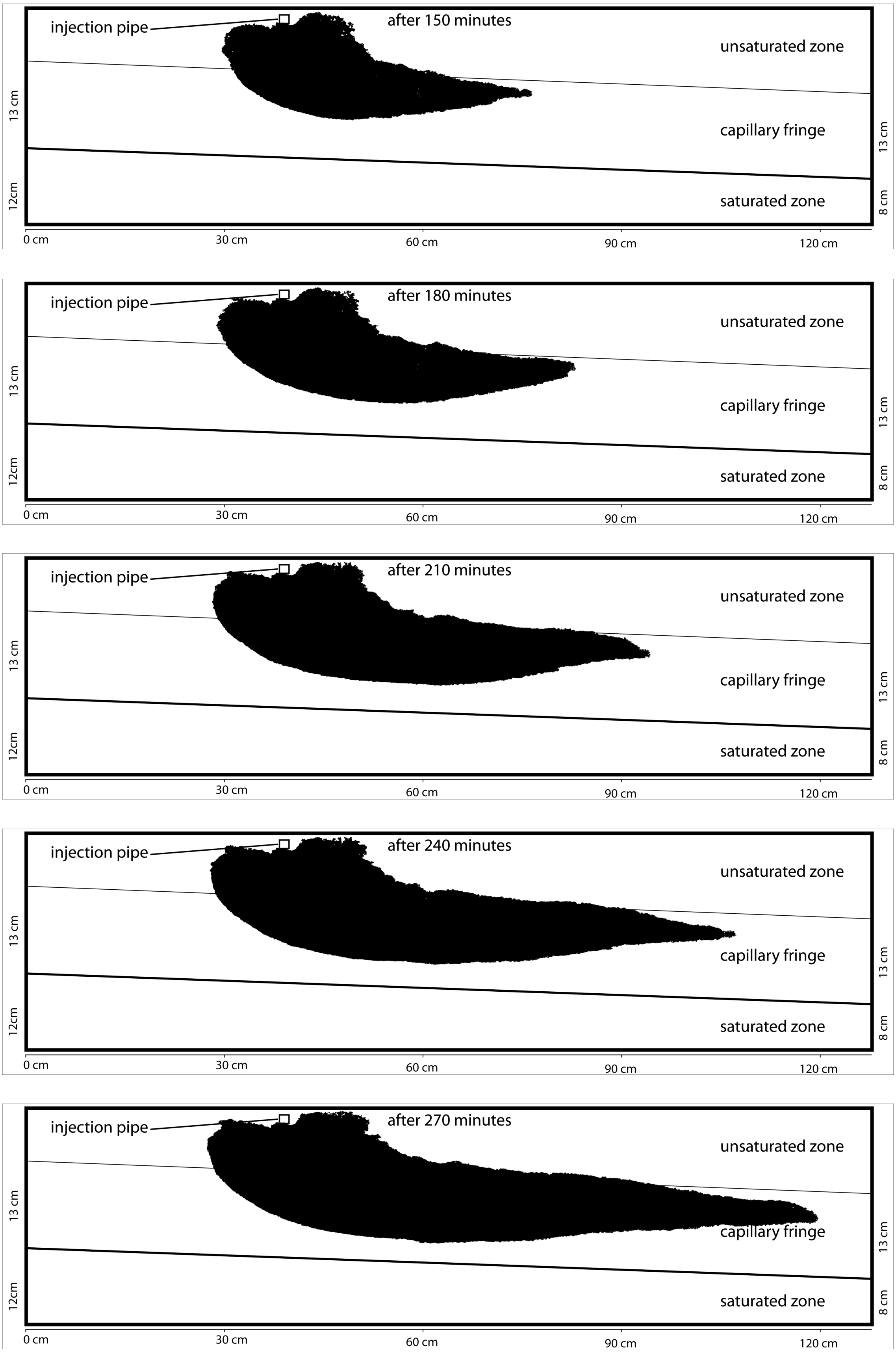
Image analysis:







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after 150 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
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30 cm
60 cm
90 cm
120 cm
injection pipe
after 180 minutes
unsaturated zone
capillary fringe
saturated zone
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12cm
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8 cm
0 cm
30 cm
60 cm
90 cm
120 cm
injection pipe
after 210 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
12cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm
injection pipe
after 240 minutes
unsaturated zone
capillary fringe
saturated zone
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90 cm
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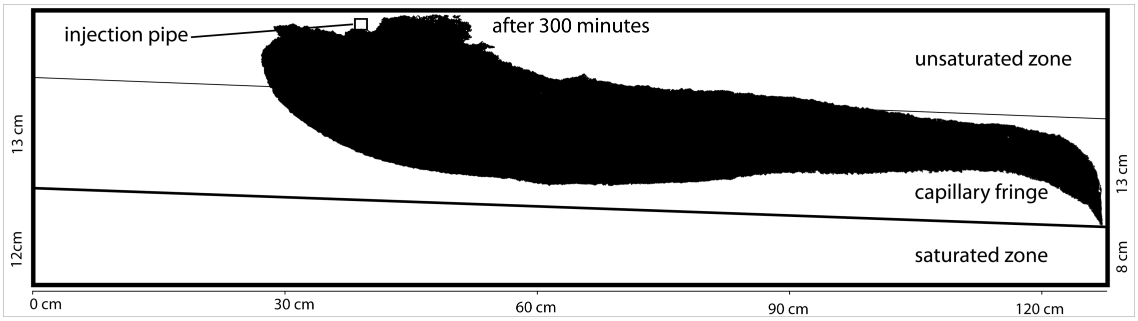

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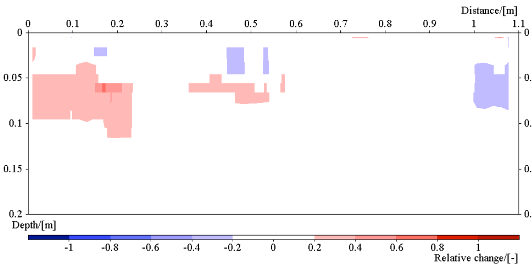

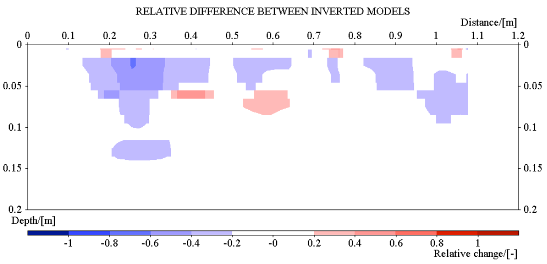

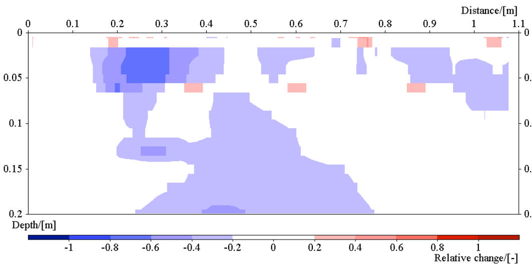

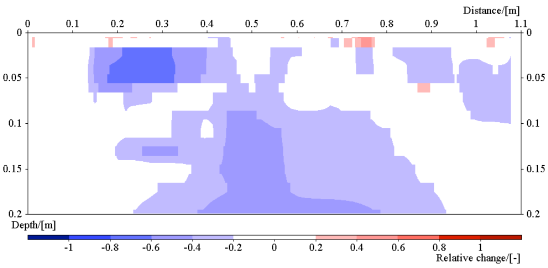

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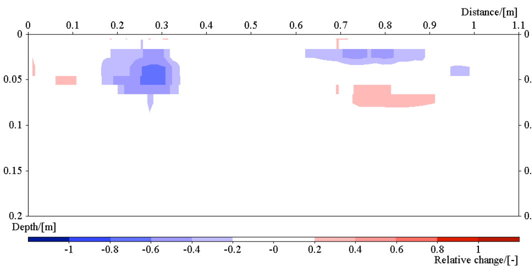
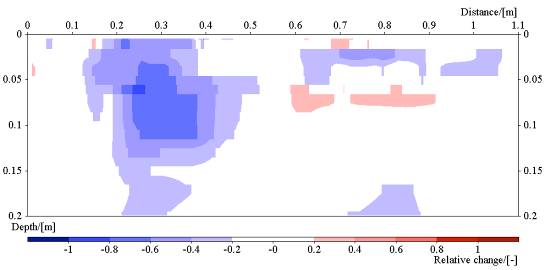
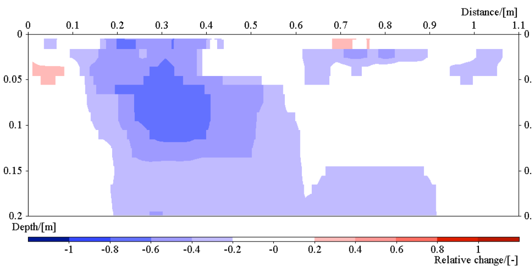
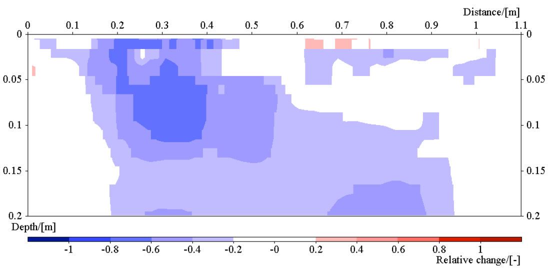
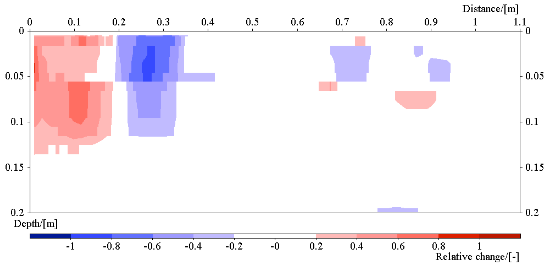




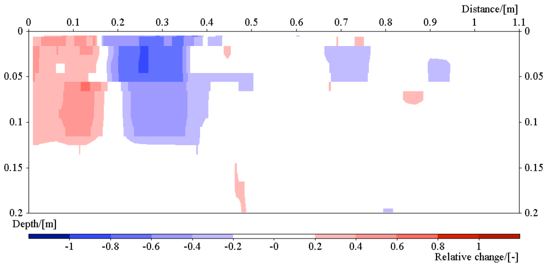




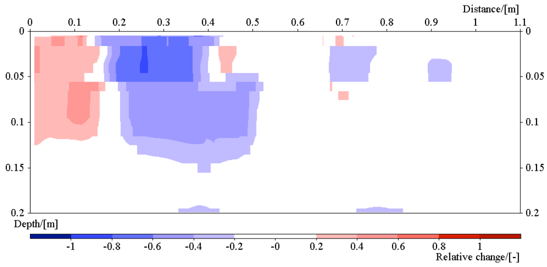
Line 3:



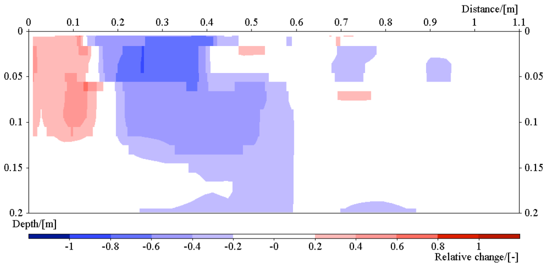
Distance/[m]
Depth/[m]
Relative change/[-]



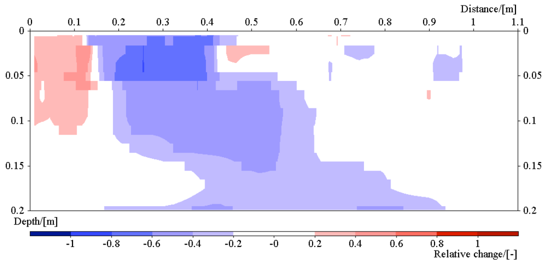
Distance/[m]
Depth/[m]
Relative change/[-]



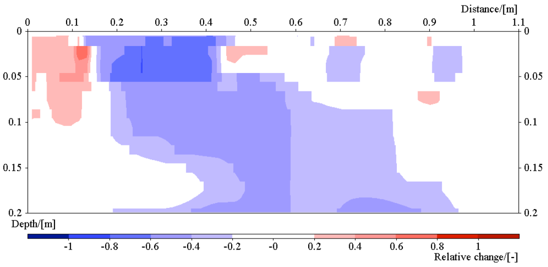
Distance/[m]
Depth/[m]
Relative change/[-]



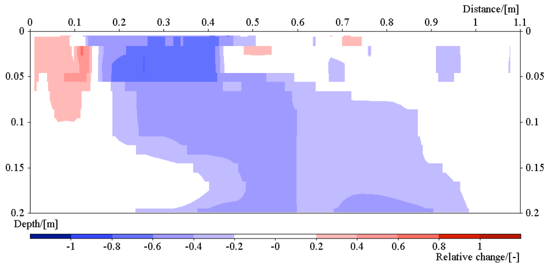
Distance/[m]
Depth/[m]
Relative change/[-]



Distance/[m]
Depth/[m]
Relative change/[-]

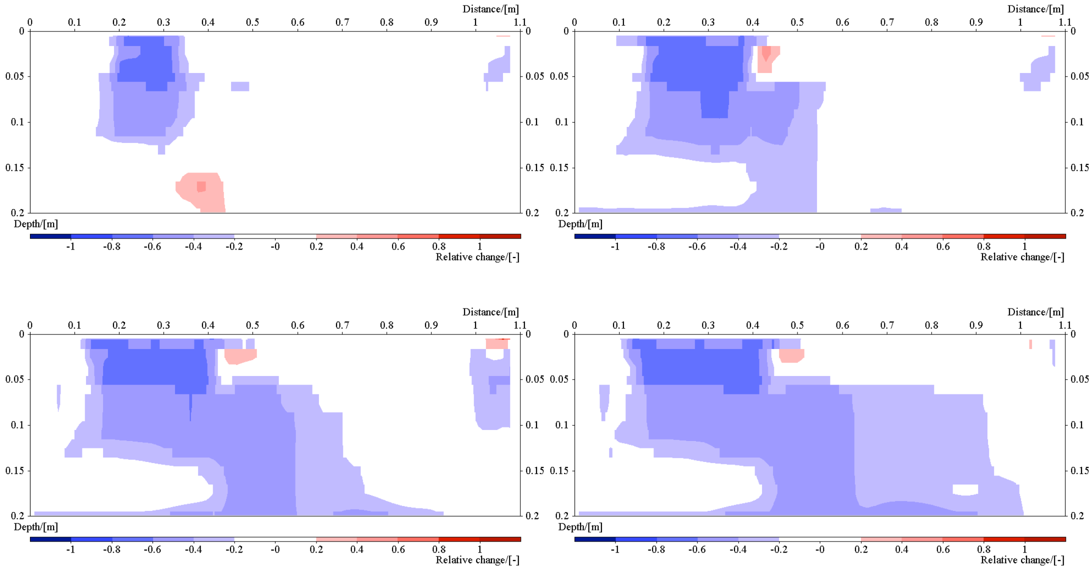


Distance/[m]
Depth/[m]
Relative change/[-]

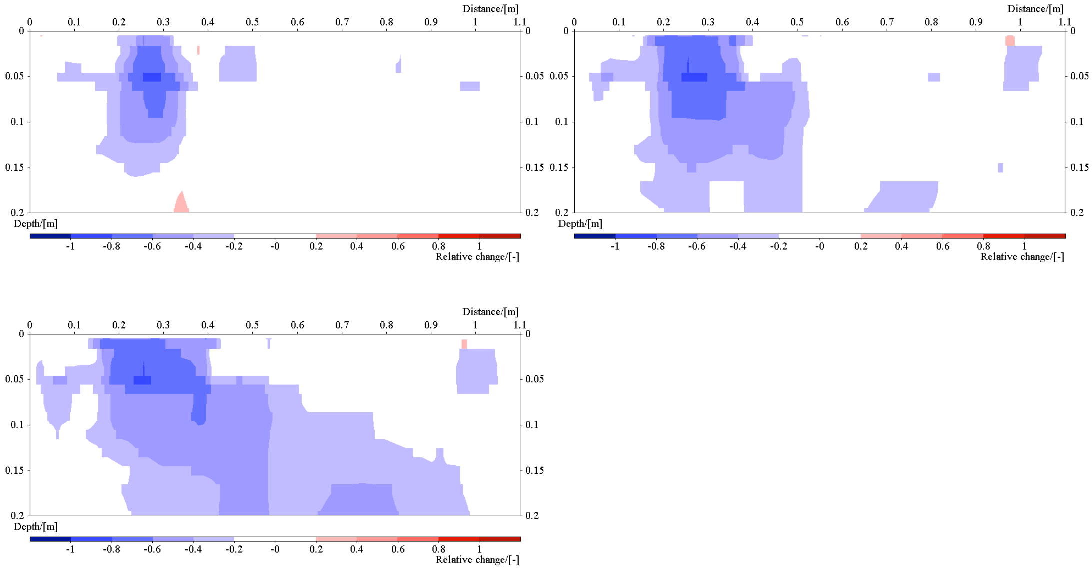


Distance/[m]
Depth/[m]
Relative change/[-]

Line 4:

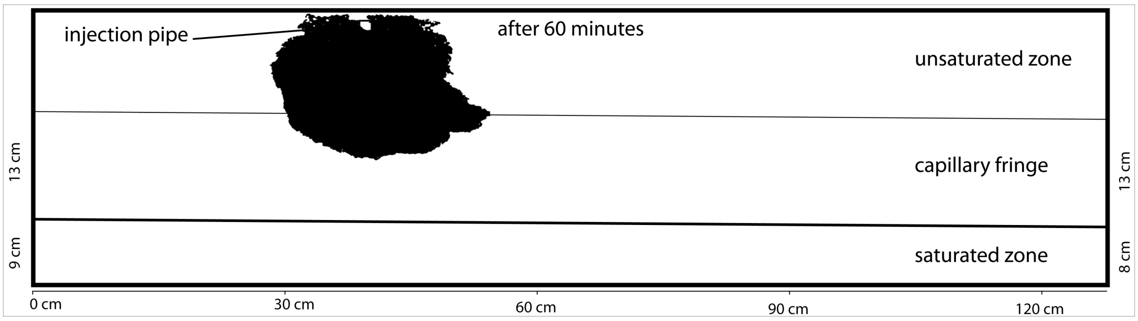

Distance/[m]
Depth/[m]
Relative change/[-]

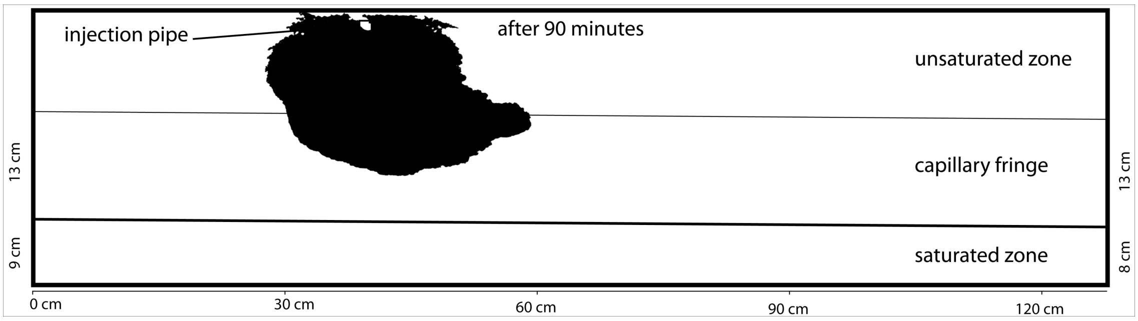
Line 5:

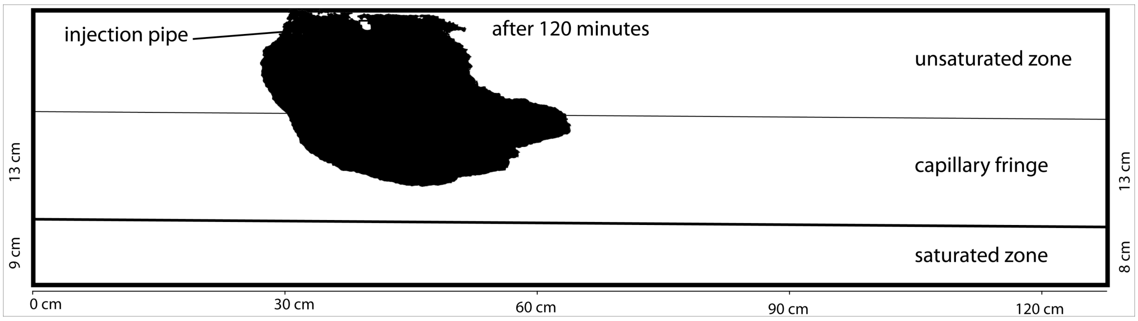

Distance/[m]
Depth/[m]
Relative change/[-]

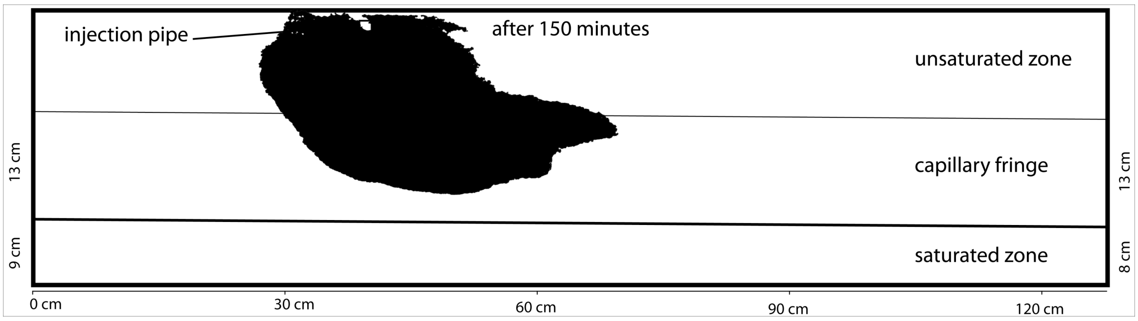
C: Experiment 3

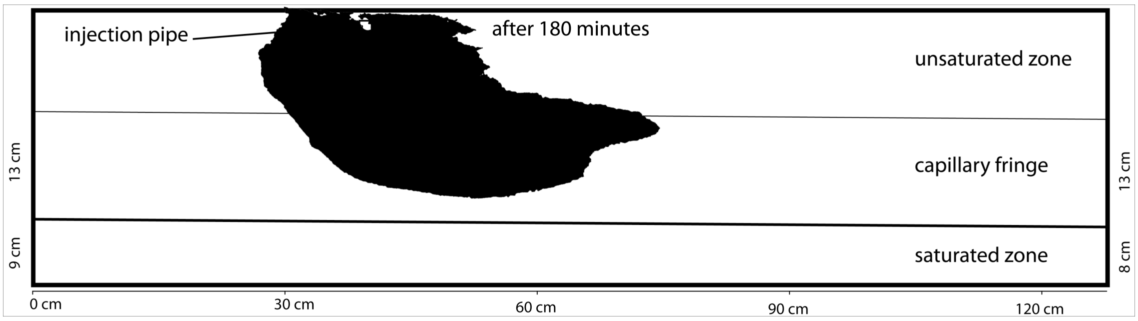
Image analysis:

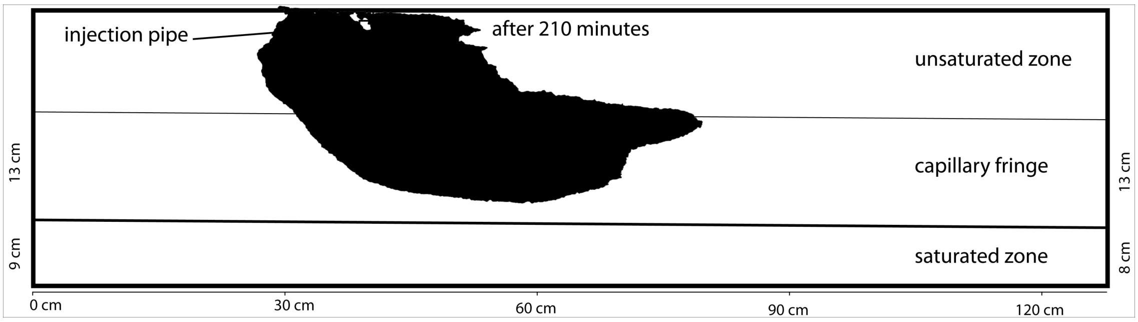


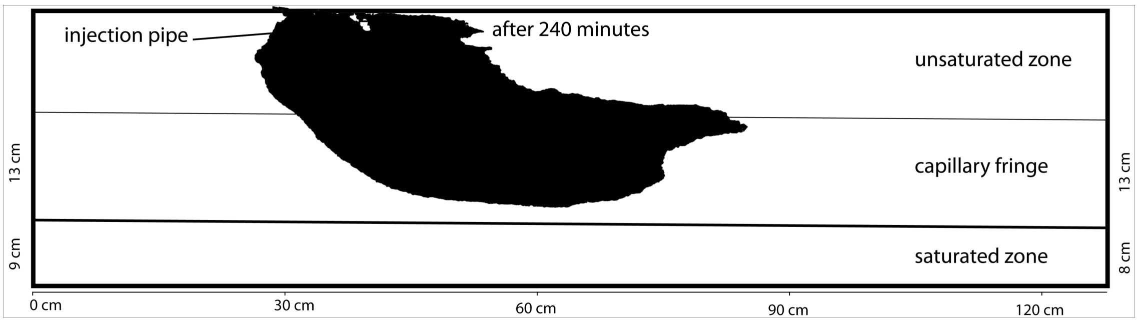


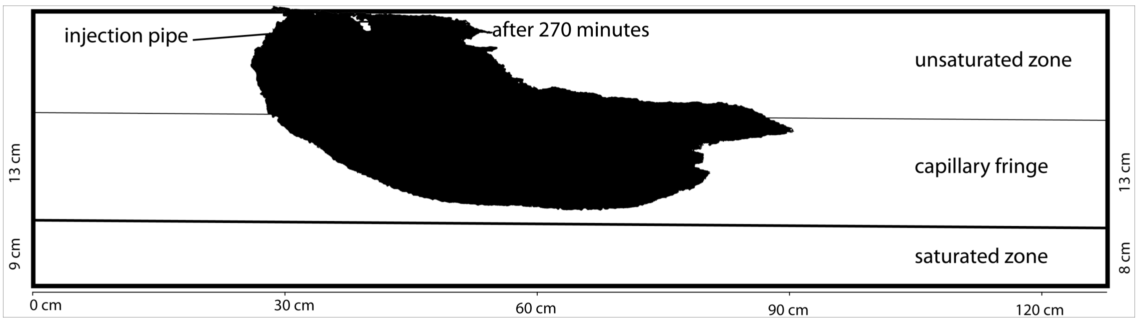


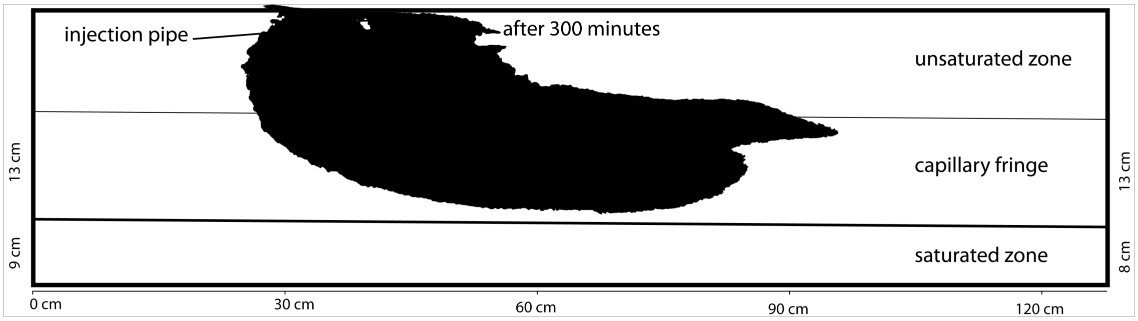

injection pipe
after 150 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm

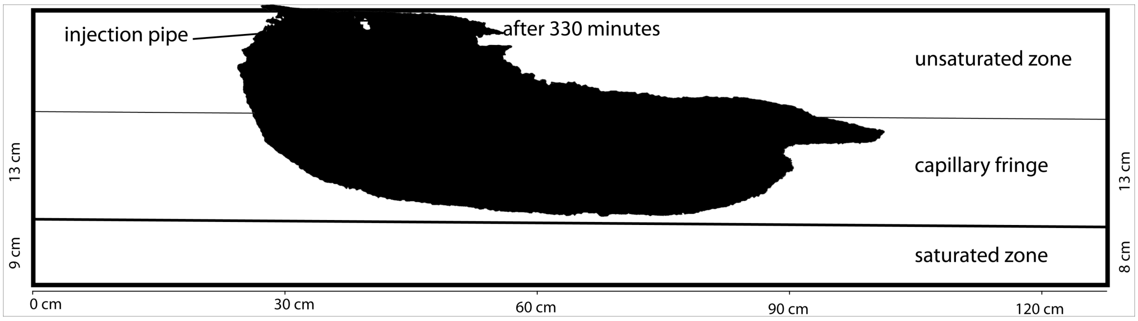

injection pipe
after 180 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm

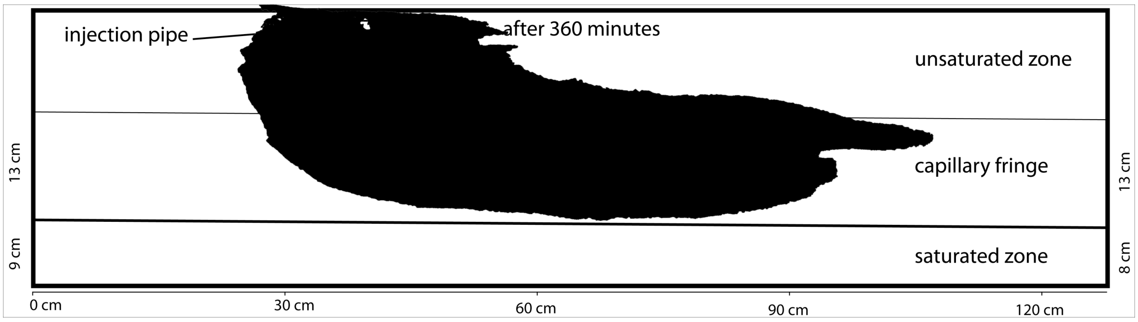

injection pipe
after 210 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm

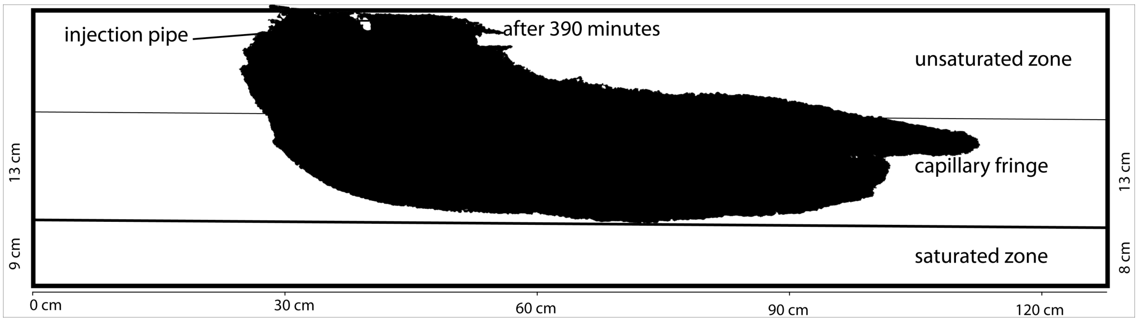

injection pipe
after 240 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm


injection pipe
after 270 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm


injection pipe
after 300 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm


injection pipe
after 330 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm

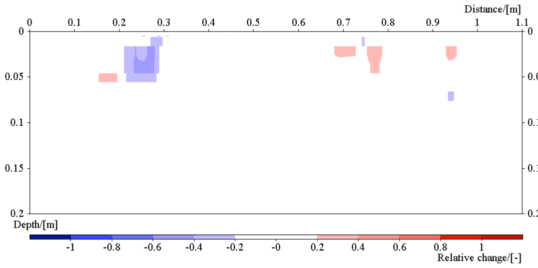

injection pipe
after 360 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm

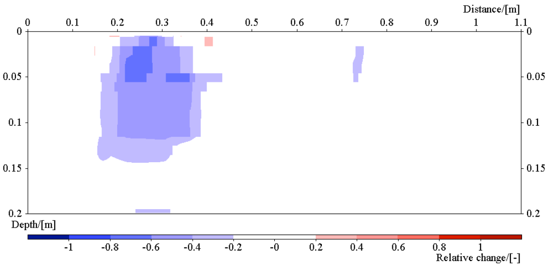

injection pipe
after 390 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm

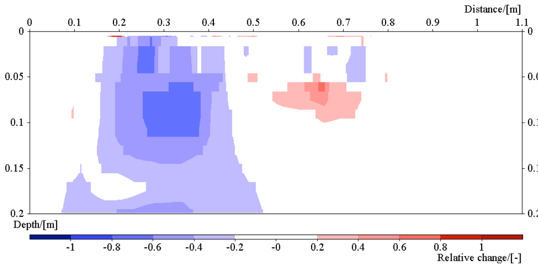

injection pipe
after 420 minutes
unsaturated zone
capillary fringe
saturated zone
13 cm
9 cm
13 cm
8 cm
0 cm
30 cm
60 cm
90 cm
120 cm

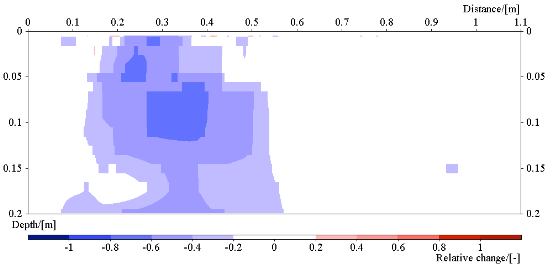
Resistivity images:

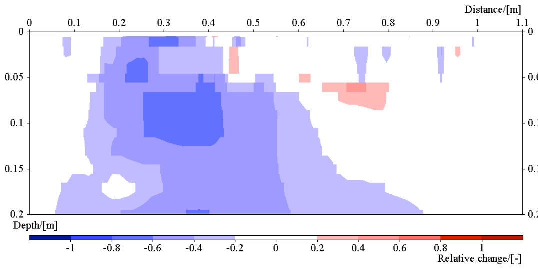
Line 1:

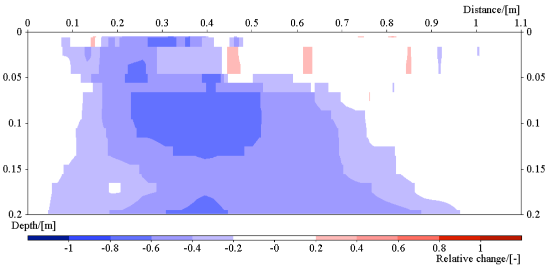




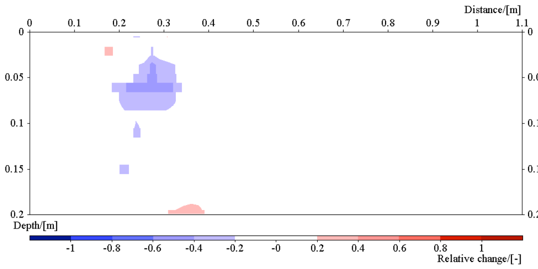


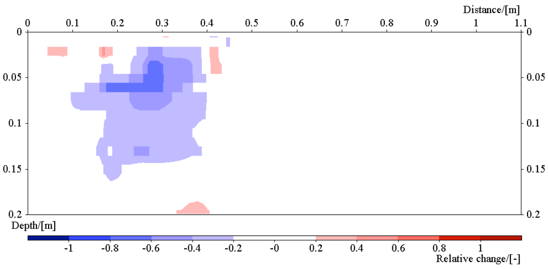


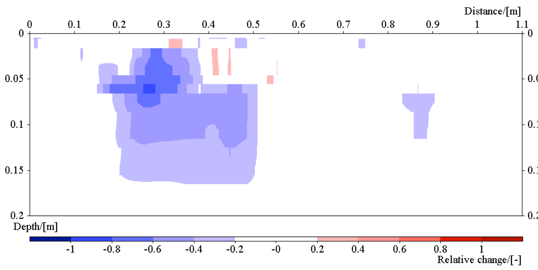


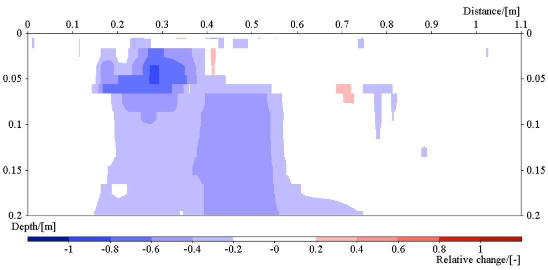


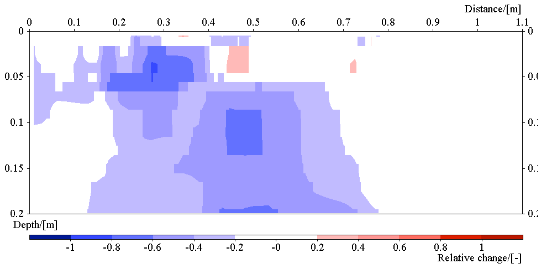
Line 2:







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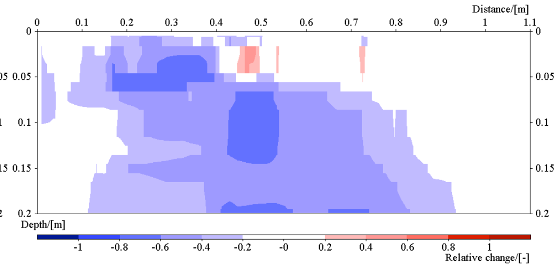
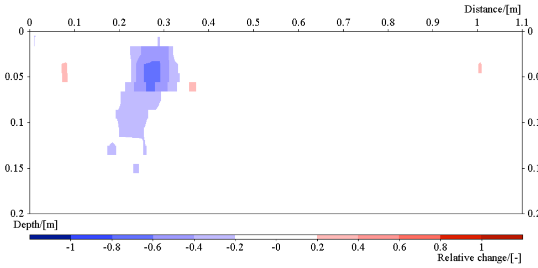
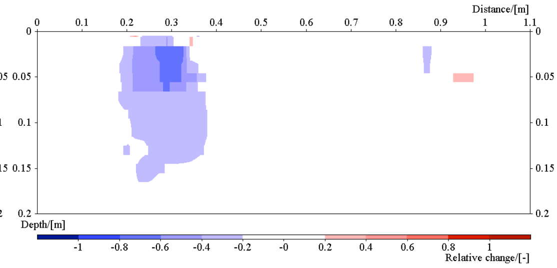
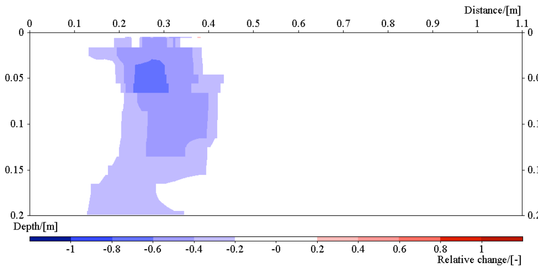
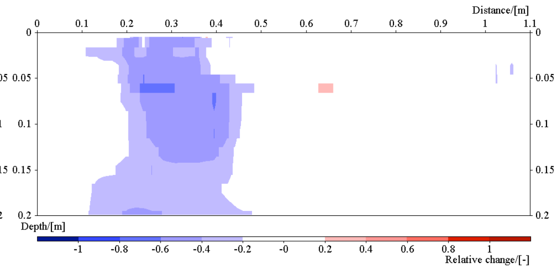
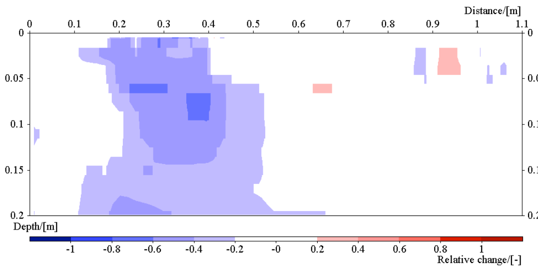
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Line 3:


Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Distance/[m]
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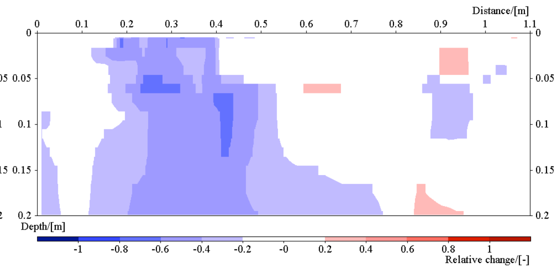
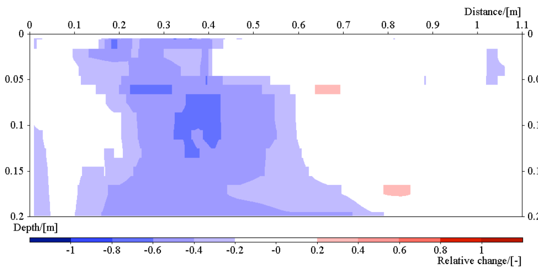
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Distance/[m]
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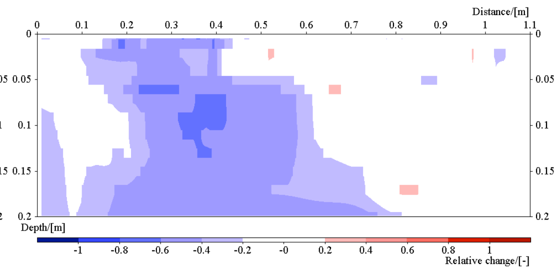
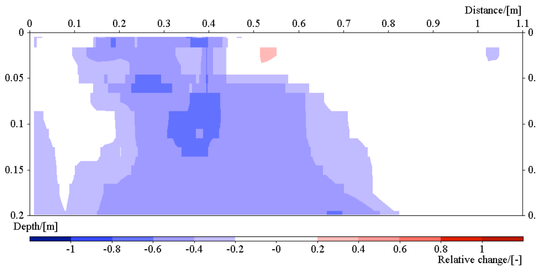
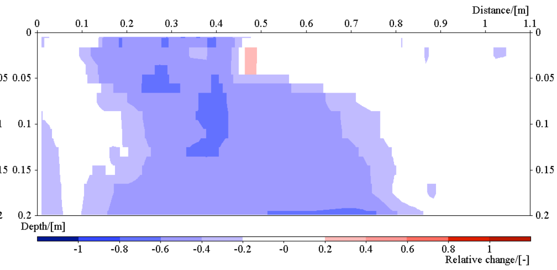
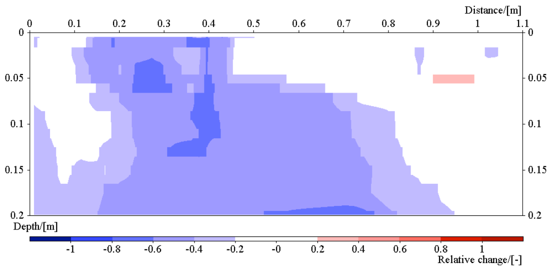
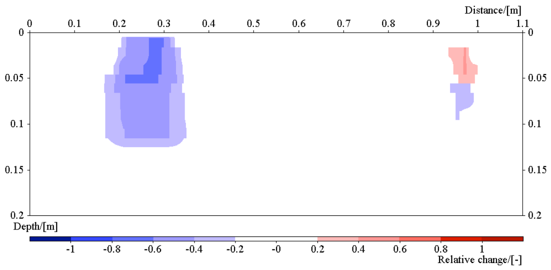
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

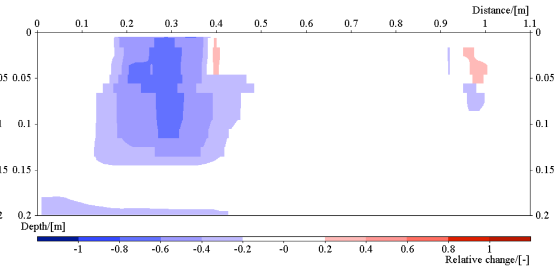

Distance/[m]
Depth/[m]
Relative change/[-]

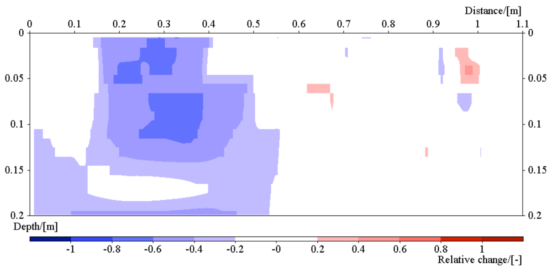

Distance/[m]
Depth/[m]
Relative change/[-]

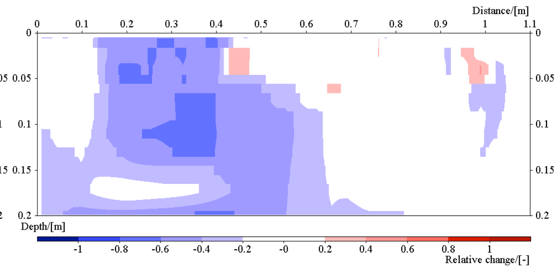

Distance/[m]
Depth/[m]
Relative change/[-]

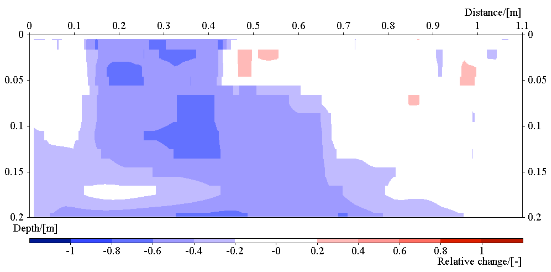
Line 4:


Distance/[m]
Depth/[m]
Relative change/[-]

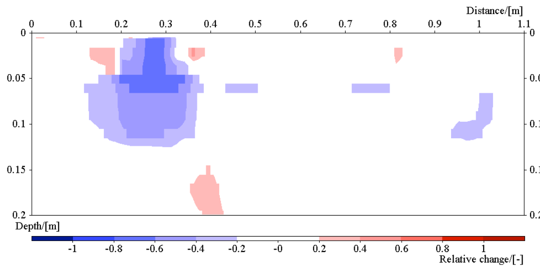

Distance/[m]
Depth/[m]
Relative change/[-]


Distance/[m]
Depth/[m]
Relative change/[-]


Distance/[m]
Depth/[m]
Relative change/[-]


Distance/[m]
Depth/[m]
Relative change/[-]

Line 5:



Distance/[m]
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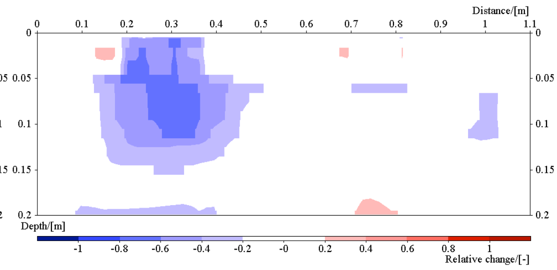
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]



Distance/[m]
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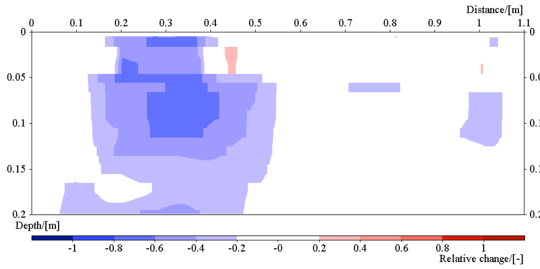
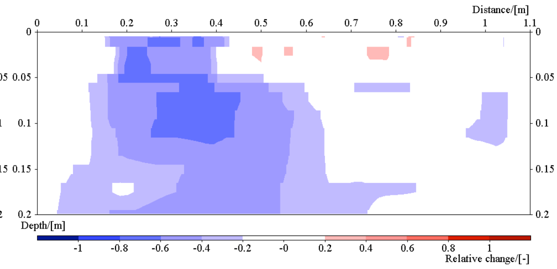
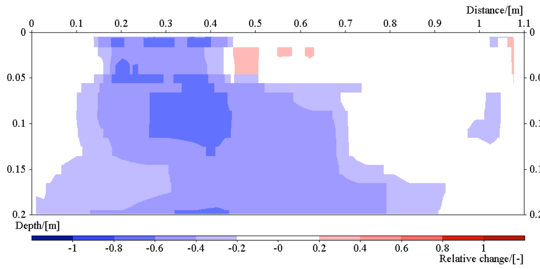
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]



Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]



Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]



Distance/[m]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
0 0.05 0.1 0.15 0.2
Depth/[m]
-1 -0.8 -0.6 -0.4 -0.2 -0 0.2 0.4 0.6 0.8 1
Relative change/[-]

D: Calculations

Density quartz = $\delta_p = 2{,}65 g/cm^3$

Bulk density sand = $\delta_b = 1{,}5 g/cm^3$

Experiment one:

Dye tracer speed measured in image = $V_m = 6{,}72 cm/h$

Water flow circulating in aquarium = 3,6 l/h = $0{,}0036 m^3/h$

Dye tracer insertion speed = 2 l/h = $0{,}002 m^3/h$

Total fluids transported in the sand = $0{,}0036 + 0{,}002 = 0{,}0056 m^3/h$

Movement area in sand including capillary fringe = $0{,}0955 m^2$

Speed of total fluids in the sand = $V_{cr} = \dfrac{0{,}0056}{0{,}0955} \bullet 100 = 5{,}86 cm/h$

Speed in the sand calibrated for porosity =

$$V_c = \frac{V_{cr}}{1 - \frac{\delta_b}{\delta_p}} = \frac{5{,}86}{1 - \frac{1{,}5}{2{,}65}} = 13{,}51 cm/h$$

Measured speed divided by calculated speed in percentage

$$\frac{V_m}{V_c} = \frac{6{,}72}{13{,}51} \bullet 100 = 49{,}7\%$$

Experiment two:

Dye tracer speed measured in image = $V_m = 9{,}12 cm/h$

Water flow circulating in aquarium = 8 l/h = $0{,}008 m^3/h$

Dye tracer insertion speed = 2 l/h = $0{,}002 m^3/h$

Total fluids transported in the sand = $0{,}008 + 0{,}002 = 0{,}01 m^3/h$

Movement area in sand including capillary fringe = $0{,}1045 m^2$

Speed of total fluids in the sand = $V_{cr} = \dfrac{0{,}01}{0{,}1045} \bullet 100 = 9{,}57 cm/h$

Speed in the sand calibrated for porosity =
$$V_c = \frac{V_{cr}}{1-\frac{\delta_b}{\delta_p}} = \frac{9,57}{1-\frac{1,5}{2,65}} = 22,05 cm/h$$

Measured speed divided by calculated speed in percentage
$$\frac{V_m}{V_c} = \frac{9,12}{22,05} \bullet 100 = 41,36\%$$

Experiment three:

Dye tracer speed measured in image = $V_m = 5,28 cm/h$

Water flow circulating in aquarium = 1,7 l/h = $0,0017 m^3/h$

Dye tracer insertion speed = 2 l/h = $0,002 m^3/h$

Total fluids transported in the sand = $0,0017 + 0,002 = 0,0037 m^3/h$

Movement area in sand including capillary fringe = $0,097 m^2$

Speed of total fluids in the sand = $V_{cr} = \frac{0,0037}{0,097} \bullet 100 = 3,81 cm/h$

Speed in the sand calibrated for porosity =
$$V_c = \frac{V_{cr}}{1-\frac{\delta_b}{\delta_p}} = \frac{3,81}{1-\frac{1,5}{2,65}} = 8,79 cm/h$$

Measured speed divided by calculated speed in percentage
$$\frac{V_m}{V_c} = \frac{5,28}{8,79} \bullet 100 = 60,07\%$$