

Experimental Investigation of Transient Saltwater Intrusion in Heterogeneous Porous Media

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ABSTRACT

A 2D sandbox style experiment was developed to compare the results of numerical modelling to physical testing for saltwater intrusion in homogeneous and heterogeneous aquifers. The sandbox consisted of a thin central viewing chamber filled with glass beads of varying diameters (780 μ m, 1090 μ m and 1325 μ m) under fully saturated conditions. Dyed saltwater (SW) was introduced at the side boundary and a head difference imposed across the porous media. Images of the SW wedge were recorded at intervals in order to assess the suitability of the numerical models predictions of transient SW intrusion. Numerical modelling of the experimental cases were simulated using SUTRA. Two main parameters were chosen to express the condition of the intruding SW wedge at each recorded time step; the toe penetration length (TL) and the width of the mixing zone (WMZ). The WMZ was larger under transient conditions in the heterogeneous case, while the TL was longer for the homogeneous case. The increased variability in the flow field for the heterogeneous case resulted in increased dispersion, and thus, increased WMZ.

INTRODUCTION

Image analysis has been widely used to track the migration of contaminants in groundwater flow using sandbox style experiments (Schincariol & Schwartz, 1990; Goswami & Clement, 2007; Chang & Clement, 2013). Laboratory scale saltwater (SW) intrusion may not be capable of reproducing exactly the conditions found in real world aquifers, but the increased level of control does allow for validation of numerical methods. This paper briefly outlines the implementation of image analysis techniques to heterogeneous aquifers and presents a comparison of TL and WMZ from the physical tests with numerical simulations using SUTRA (Voss & Provost, 2010).

METHODS

Sandbox Experimental Setup

The sandbox (0.38m x 0.128m x 0.01m) consisted of a narrow viewing chamber filled with glass beads packed in a variety of arrangements. Two tanks were located at either side of the viewing chamber and were separated from the chamber by a fine screen. One of the side tanks was filled with clear deionised fresh water (FW) while the other contained a SW solution (density = 1025kg/m³) dyed with food colouring. The water levels in these tanks provided constant head FW and SW boundaries using a variable overflow system similar to Goswami & Clement (2007). By imposing a difference in water level (dH) between the side tanks a hydraulic gradient was created across the porous media and a SW wedge intruded into the central viewing chamber. Ultrasonic sensors, with an accuracy of 0.1mm, were used to measure the water level in both side tanks. Two LED lights provided transmissive illumination of the SW wedge progression through the clear porous media. Initially, the aquifer was totally flushed with FW and $dH=6$ mm was imposed. Images of the dyed SW wedge were recorded every 5 minutes until a steady state condition was reached (50 minutes). The head difference was then decreased to $dH=4$ mm and the advancing

movements of the wedge were captured. After a steady state condition was achieved, the receding SW wedge dynamics were analysed by finally increasing $dH=5\text{mm}$. An 8-bit 1280 x 1024 resolution high speed IDT Vision camera was used to capture the images. Initially, 3 diameters of beads ($780\mu\text{m}$, $1090\mu\text{m}$ and $1325\mu\text{m}$) were tested under homogeneous conditions. A series of tests using horizontal layered and hand packed block-wise bead arrangements followed the homogeneous experiments. The results from the homogeneous $1090\mu\text{m}$ tests and hand packed block-wise experiment, which included all 3 bead diameters, are discussed further in this paper. An intrinsic test based on Darcy's law was conducted to determine the permeability for each bead arrangement and was used in the numerical model.

Calibration

In order to calculate the salt concentration field from the light intensities captured in the images a calibration was required. The calibration involved flushing the aquifer with known concentrations of dyed SW solution and recording the change in light intensity. For this experiment 8 concentrations were used: 0, 0.05, 0.10, 0.20, 0.30, 0.50, 0.70, 1.00, where 0 equates to undyed FW and 1.00 equates to fully dyed 1025kg/m^3 SW. A power curve was chosen to describe the relationship between concentration and light intensity, and a least squares regression analysis was used to determine suitable values for the curve coefficients.

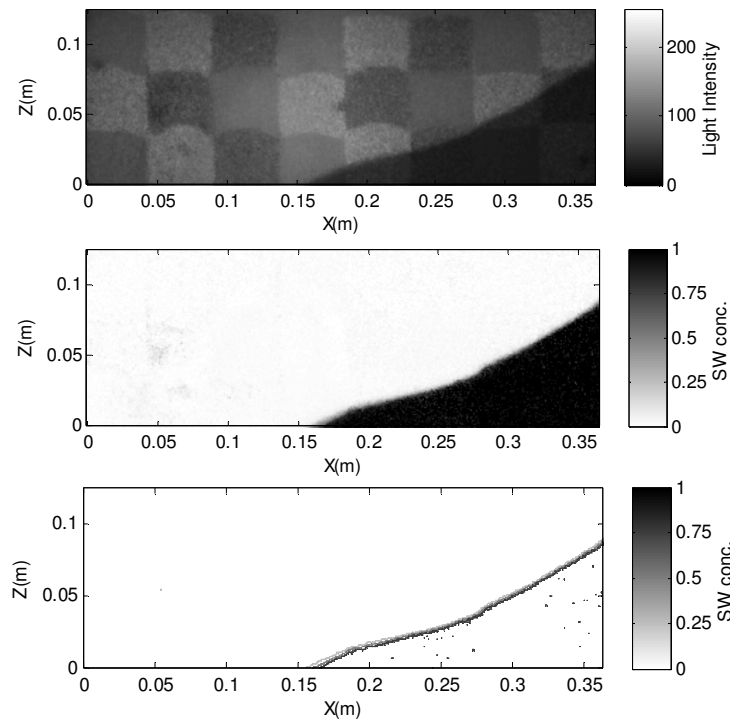


Figure 1. Analysis area of image (top), colour map of SW concentration (middle) and contour plot of concentration isolines [0.25 0.50 0.75] (bottom)

Figure 1 shows an image of the block-wise aquifer and a contour plot of the 0.25, 0.50 and 0.75 concentration isolines. The top plot in Figure 1 shows large discrepancies in lighting uniformity, which complicates the calibration step as average image light intensity is no longer a suitable parameter to use in the regression analysis. This prompted the use of a pixel-wise calibration method, where a least squares regression analysis was carried out for every pixel in the image. Each individual pixel locations calibration relationship was then applied to the test data, with the results shown in the middle and bottom plots of Figure 1. The pixel-wise calibration method is capable of producing concentration fields in highly non-uniform lighting conditions with small error.

RESULTS

Transient toe length (TL)

The transient experimental and numerical TL for the blocked heterogeneous case is shown in Figure 2 (top left). Generally the numerical results compare fairly well to the physical tests, as shown in the steady state 0.5 concentration isolines in Figure 2 (bottom left). However, the numerical model over predicts the steady state TL at $dH=6\text{mm}$, but under predicts the TL at $dH=4\text{mm}$. This change from over prediction to under prediction is hypothesized as being due to packing issues, where the porous media at the bottom is being compressed more due to the load of the media situated above it. The homogeneous TL results (not shown) have very similar trends to the blocked heterogeneous but are slightly larger at steady state conditions. The range of bead size did not provide a large enough permeability variation for a significant change in the steady state TL. Figure 2 shows a lag in TL movement when the head difference increases from $dH=4\text{mm}$ to $dH=5\text{mm}$. The SW wedge should be receding under these conditions but has been delayed. After it begins to move the receding TL reaches a steady state condition quicker than the advancing wedge. This is in agreement with Chang & Clement (2013) who reasoned that the flow field changes from the SW opposing the FW while the SW wedge is advancing, to a unidirectional flow field while the SW wedge is receding. This would also explain the delay in wedge movement when dH is increased as the flow field has to reorientate.

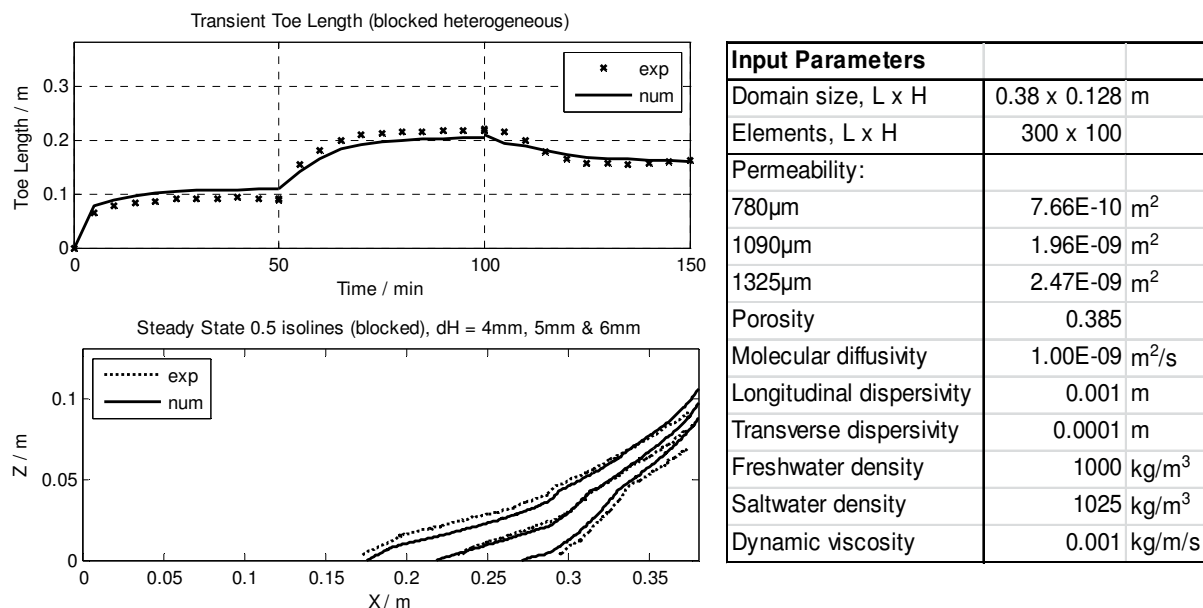


Figure 2. Transient TL, 0-50min $dH=6\text{mm}$, 50-100min $dH=4\text{mm}$, 100-150min $dH=5\text{mm}$ (top left), steady state 0.5 conc. isolines (bottom left) and numerical model input parameters (right)

Transient width of mixing zone (WMZ)

The transient experimental and numerical WMZ for the homogeneous and blocked heterogeneous case is shown in Figure 3. The size of the mixing zone in both the homogeneous and heterogeneous case is very small, around 5mm. The experimental results show much greater variation in WMZ to the numerical, particularly when the head difference across the aquifer is changed. This is attributed to small scale heterogeneities induced in the packing process and from slight variations in bead size. The WMZ shows a similar response to the TL when increasing from $dH=4\text{mm}$ to $dH=5\text{mm}$. However, the lag response and

magnitude of WMZ increase are smaller for the homogeneous case because the higher uniformity of the permeability field allows the switch in flow field to establish faster. The size of the WMZ change is much greater when the wedge is receding. This can be explained by the increased velocities the unidirectional flow field creates which increases dispersion.

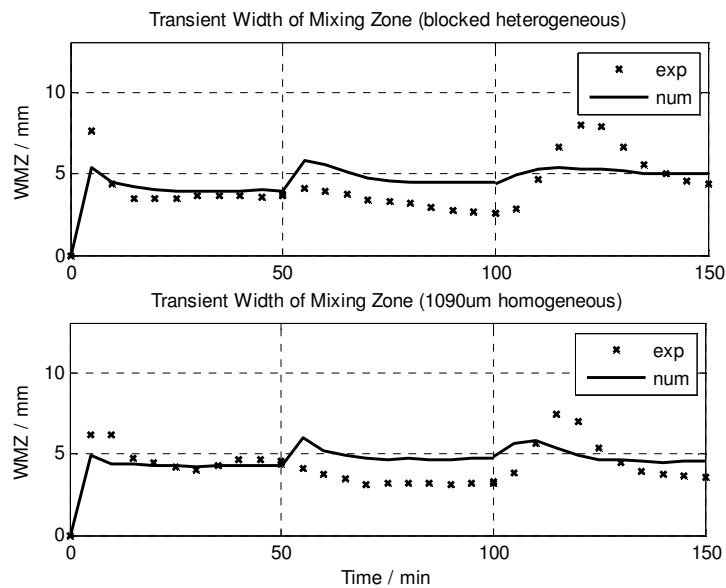


Figure 3. Transient WMZ, heterogeneous (top) and homogeneous (bot)

CONCLUSION

An experimental system was developed and calibrated, and a study conducted to determine the effects of heterogeneity on a transient SW wedge, in terms of toe length (TL) and width of mixing zone (WMZ), for a homogeneous and block-wise heterogeneous case. The homogeneous results were similar to the heterogeneous cases in terms of TL and WMZ. Larger WMZs were observed in the heterogeneous case under transient conditions while the TLs were slightly longer in the homogeneous case. There was an increase in WMZ when the head difference was changed, but the response was greater for receding wedges when compared to advancing wedges. The WMZ response was in agreement with the hypothesis of changing flow field direction within the SW wedge discussed in Chang & Clement (2013) for receding TL.

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