Numerical simulation for saltwater-freshwater interface movement of sandbox experiments

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Indoor sandbox experiments and the responding numerical simulations have been carried out. The results show that, the longer time saltwater intrusion, the more differences between saltwater level and freshwater level, lower velocity of the saltwater moving. From the transport rates of saltwater-freshwater interface, it could be seen that, the smaller differences between saltwater level and freshwater level, the earlier equilibrium state reach. Moving rates are different ascribe to the different concentration of saltwater, and the differences of moving rates becoming smaller over time. Impact of saltwater concentration on moving rate becoming smaller over time. Numerical simulation results show that, the established models could simulate the sandbox under different saltwater concentrations. The established models could be used to study the saltwater intrusion processes.

[Key words: Saltwater-freshwater interface, sandbox experiment, numerical simulation, coastal management]

Introduction
Saltwater-freshwater interface controlling the saltwater intrusion processes in the coastal urban areas during urbanization.$^{1-4}$ As water demand increases due to increasing population levels and social and economical development, increasing amounts of groundwater are pumped out and the fresh groundwater levels decrease, while saltwater intrudes into freshwater systems, which can damage the local environment and ecosystem.$^{5-12}$ Accordingly, describing and predicting saltwater intrusion is becoming one of the main issues in coastal hydrogeology and groundwater management.$^{13-15}$ The saltwater-freshwater interface has been studied for more than 100 years, resulting in many publications, mathematical equations describing saltwater intrusion and numerical and experimental simulations, all of which have provided a solid foundation for studies of saline water intrusion.

Sandbox experiment simulation and numerical simulation are the two main research tools in groundwater solute transport processes studies.$^{16-20}$, also in the saltwater intrusion studies besides the field monitoring works$^{21-22}$, especially for the research on groundwater solute transport mechanism and impact factors, sandbox experiment simulation and numerical simulation are powerful tool to investigate the effects of factors.$^{23-28}$

Materials and Methods
According to the former study results, the main impact factors for saltwater intrusion are the difference of concentrations and water levels as well as density between saltwater and fresh groundwater.$^{13}$ The sandbox experiments have been used to simulate the intrusion velocity of saltwater-freshwater interface under the conditions of different hydraulic gradients and original salty water concentrations conditions.

The schematic system of sandbox model used in this study could be seen in figure 1, from the figure it can be seen that, the sandbox is constructed by Plexiglas, with the length, width and height of 180 cm, 10 cm and 60 cm respectively, there are two Mariotte Bottles on both sides of the sandbox for water supply. The sand grain diameters are from 0.6 mm to 0.9 mm, with the permeability of about $2.2\times10^{-3}$ m/d.

Several scenarios were designed in the sandbox experiments (table 1). From the table it can be seen that, the water level differences between saltwater and fresh water have been set as 0 mm, 20 mm and 30 mm,
the concentration of saltwater have been set as 15 g/L, 25 g/L and 40 g/L, respectively.

In order to display out the movement of saltwater-freshwater interface intuitively, a kind of dye named carminum has been used to fill in the Mariotte bottles to color the saltwater during the sandbox experiments, the concentrations of carminum have been set as 0.25 g/L, 0.5 g/L and 1.0 g/L when the concentrations of saltwater are 15 g/L, 25 g/L and 40 g/L respectively, in order to avoid the weak adsorption of the two kind of medium from each other, the movement of colored saltwater can be remarked by the imagining technology.

FEFLOW is an advanced finite-element subsurface flow and transport modeling system with an extensive list of functionalities, including variably saturated flow, variable fluid density mass and heat transport, and multi species reactive transport. As a typical density-dependent simulation model, the software code (version 6.2) has been used to model the indoor saltwater intrusion sandbox experiment under steady-state conditions. The finite element method was adopted for its flexibility and ability to simulate the geometric forms.

The length of the simulation area is 1600 mm, the height of the simulation area is 370 mm, the aquifer has been set as unconfined aquifer, the porosity of the sand is about 32.86 %, the horizontal permeability is about $1 \times 10^{-4}$ m/d, the vertical permeability is about $1 \times 10^{-5}$ m/d, the horizontal dispersion and vertical dispersion are $8.3 \times 10^{-3}$ m and $8.3 \times 10^{-4}$ m respectively. As an unconfined aquifer, the upper boundary is free water face, the bottom boundary is aquiclude, the left boundary is land boundary, and the freshwater level has been set as 340 mm, the concentration of NaCl has been set as 0 mg/L; the right boundary is sea boundary, the saltwater level has been set as 370 mm, the original concentration of saltwater has been set as 15 g/L, 25 g/L and 40 g/L. the grids and the boundary conditions could be seen in figure 2, from the figure it could be seen that, there are about 486 cells and 494 nodes.

<table>
<thead>
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<th>Experiments ID</th>
<th>Water head difference (mm)</th>
<th>Concentrations of Cl$^-$ (g/L)</th>
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</tr>
<tr>
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<td>25.0</td>
</tr>
<tr>
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<tr>
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<td>30.0</td>
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</tr>
</tbody>
</table>
Results and Discussion

In order to study the water level differences impact on the saltwater intrusion, the water level difference between saltwater level and fresh groundwater level have been set as 0 mm, 20 mm and 30 mm, and the typical saltwater intrusion photos could be seen in figure 3.

From the figure, it can be seen that, when the water level difference is 0 mm, the saltwater intrusion occurred ascribe to the density driving force, and the bottom intrusion distance is longer than that of upper water; when the water level difference is 30 mm, the upper boundary is occupied by saltwater, and the saltwater intrusion occurred from the upper face and bottom.

The moving rate of the saltwater-freshwater interface under different water level differences could be seen measured and mapped in figure 4, from the figure it can be seen that, the moving rates decreased over time, and the bigger water level differences are, the bigger moving rates are, and the smaller water level differences, the earlier equilibrium state reached.

Also, the intruded saltwater area could also be measured to evaluate the saltwater intrusion rates according to the different location of the saltwater-freshwater interface, which is shown in figure 5. From the figure, it can be seen that, the area changes are similar between different concentrations, and the increasing rate reach zero point earlier when the water level difference is 0 mm, which means that, desalination of saltwater occurred, although the saltwater intrusion distance increasing at the bottom, the upper saltwater intrusion interface has been drawn back.

In order to study the saltwater concentrations impact on the saltwater intrusion, the saltwater concentrations been set as 15 g/L, 25 g/L and 40 g/L respectively, and the moving rate of the saltwater-freshwater interface under different saltwater concentration could be seen in figure 6, from the figure it can be seen that, the moving rates decreased over time, and the bigger saltwater concentrations are, the bigger moving rates are, the differences of saltwater-freshwater interface moving rates decreased over time.

The intruded area could also be measured to evaluate the saltwater intrusion rates according to the different locations of the saltwater-freshwater
interface under different saltwater concentrations, which are shown in figure 7. From the figure, it can be seen that, the saltwater intrusion areas are controlled by the saltwater-freshwater interface, and the changes are similar.

Comparison between the impact of water level differences and concentration differences, it could be seen that, the saltwater-freshwater interface moving rates increased with water level differences and concentration differences, and the increasing degrees of moving rates is proportional to the water level differences and concentration differences.

In order to compare the simulate the saltwater intrusion processes in sandbox experiments, numerical modeling has been done by using Finite Element Method, the water level difference between saltwater levels and fresh groundwater level has been set as 3 cm, and the concentrations of saltwater have been set as 15 g/L, 25 g/L and 40 g/L, respectively. Time intervals have been selected at 10 min, 20 min and 40 min during the saltwater intrusion processes both in sandbox experiment and numerical simulation, which are shown in figure 8 to figure 10.

From the figures, it can be seen that, when the concentration of saltwater is about 15 g/L, the numerical simulation results is similar to the sandbox experiment photos with carminum, the saltwater-freshwater interface moving distances are 13 cm, 27 cm and 51 cm at 10 min, 20 min and 40 min under the water level difference is 30 mm, respectively. The comparison results between simulation results and sandbox results under the concentration of 25 g/L and 40 g/L are similar to that under the concentration of 15 g/L. The numerical simulated saltwater-freshwater interface moving distances under concentration of 25 g/L are 18 cm, 55 cm and 63 cm at 10 min, 20 min and 40 min, respectively, the distances are 20 cm, 35 cm and 64 cm at 10 min, 20 min and 40 min, respectively.

The moving distance from the right boundary to toe at the saltwater-freshwater interface under the salty

![Graphs showing intrusion rates under different conditions](image)

Fig. 5 — Saltwater intrusion area increasing rates under different water level conditions

Fig. 6 — Saltwater intrusion interface moving rates under different concentration conditions
water concentration of 40 g/L are 23 cm, 40 cm and 72 cm at 10 min, 20 min and 40 min, respectively, the distances are 26 cm, 44 cm and 64 cm at 10 min, 20 min and 40 min, respectively; the numerical simulation models could be used to simulate the sandbox experiments. From these comparison, it could be concluded that the numerical simulation models can be used to simulate the sandbox experiments.

**Conclusions**

Indoor sandbox experiments and the responding numerical simulations have been carried out, and the results show that, the smaller differences between saltwater level and freshwater level, the earlier equilibrium state reach; the moving rates are different ascribe to the different concentration of saltwater, and the differences of moving rates becoming smaller over time, which means that, the impact of saltwater
concentration on moving rate becoming smaller over time; the numerical simulation results show that, the established models could simulate the sandbox under different saltwater concentrations, which mean that, the established models could be used to study the saltwater intrusion processes.

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References


