PROTECTION OF COASTAL AQUIFER FROM SALTWATER INTRUSION BY ARTIFICIAL RECHARGE

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ABSTRACT

This paper deals with the effectiveness of artificial groundwater recharge to protect freshwater aquifer from saltwater intrusion. A numerical model employed abrupt interface approximation is applied to the three dimensional aquifer. To validate the numerical model, the experimental work is carried out by means of a three dimensional sand box model. The computed results of moving interface show good agreement to the experimental results under both no rainfall condition and rainfall condition. The numerical model is applied to the simulation of groundwater flow with artificial recharge by a ditch or the wells. From the results, it is obviously seen that the increase of recharge rate has significant effect to retard saltwater intrusion, but there is little effect of the difference of recharging location.

1. INTRODUCTION

An aquifer is an important source of fresh water for oceanic island where soil condition does not permit surface water storage due to high permeability of the soil. An excessive pump up, however, makes an intrusion of salt water into the aquifer occur. There are various method to protect the freshwater aquifer from saltwater intrusion, including construction of subsurface barriers
[1] and artificial recharge facilities, modification of pumping pattern, etc. [2]. This paper deals with an effectiveness of artificial recharge by the numerical simulation.

The analyses of saltwater intrusion in the coastal aquifer can be classified into two mathematical models. One model take into account the transition zone between fresh water and intruded salt water in its mathematical formulation [3,4,5]. The other assumes an abrupt interface between fresh water and salt water [6,7,8]. Fresh water and salt water are actually miscible fluids and there exist a transition zone caused by hydrodynamic dispersion. Several observations, however, show that the thickness of the transition zone is relatively narrow in comparison with the depth of the aquifer, when salt water ascends. Thus, the assumption of abrupt interface can be applied to the analysis in the intruding process with sufficient accuracy. In this paper, the numerical analysis is based on the abrupt interface approximation. The other assumption is the Dupuit's approximation.

A numerical model [1] constructed to simulate saltwater intrusion into the vertically two dimensional unconfined aquifer is applied to the three dimensional aquifer. The computed results are validated with the observations obtained from a three dimensional sand box model. The response of the interface is then numerically simulated in the various boundary conditions with artificial recharge.

2. MATHEMATICAL FORMULATION AND COMPUTATION

![Figure 1 Schematic diagram of vertical cross section](image-url)
A flow domain in the coastal aquifer is divided into two regions. One is the region where only fresh water flows in the vertical cross section of the aquifer, termed a freshwater region. The other is the freshwater/saltwater region, where fresh water flows in the upper part of a vertical section and salt water flows in the lower part, separated by a freshwater/saltwater interface as shown in Figure 1. Combining Darcy's law with the continuity equation, the governing equations for the analysis of unsteady groundwater flow in the unconfined aquifer are expressed as follows:

About the freshwater region

\[
\frac{n}{\partial t} + \sum_{i} \frac{1}{\partial x_i} \left[ k(h_f-z) \frac{\partial h_f}{\partial x_i} \right] + q = 0
\]

(1)

and about the freshwater/saltwater region

\[
\frac{n}{\partial t} - \frac{n}{\partial t} \sum_{i} \frac{1}{\partial x_i} \left[ k(h_f-h_s) \frac{\partial h_f}{\partial x_i} \right] + q = 0
\]

(2)

\[
\frac{n}{\partial t} + \sum_{i} \frac{1}{\partial x_i} \left[ k(h_f-z) \left( \frac{\rho_f \frac{\partial h_f}{\partial x_i} - \rho_s \frac{\partial h_s}{\partial x_i}}{\rho_f} \right) \right] = 0
\]

(3)

where \( n \) is effective porosity, \( k \) is hydraulic conductivity, \( q \) is groundwater recharge intensity, \( \rho \) is fluid density with subscripts \( f \) and \( s \) denoting fresh water and salt water, respectively. The other terms are as shown in Figure 1.

The finite difference method is applied to obtain the numerical solution of the governing equations. The equations are discretized by the central scheme in space and the explicit scheme in time. In the calculation for the progressive position of the interface, we applied the simple technique that includes both the imaginary interface to calculate the toe of interface and the quadratic equation to extrapolate the position of interface on the coastline [9,10].

3. EXPERIMENTAL SIMULATION OF SALTWATER INTRUSION

3.1 Apparatus

An apparatus used is a three dimensional sand box model shown in Figure
2. The sand box is made of the acrylic plates. The modelling part of the aquifer is 165.8 cm long and 47.5 cm high. The width of the model has two values; from upstream side until to the length 83.5 cm the width is 30 cm and from the length 83.5 cm onward to the downstream side the width is 63.2 cm. Salt is added to freshwater and thoroughly mixed up to the density of 1.030 to
model salt water and then the modelled salt water is colored by dye in order to observe the position of freshwater/saltwater interface. The density of fresh water is measured and equal to 1.001. The porous medium of the coastal aquifer is modelled by using sand of which the mean diameter is equal to 0.76 mm. A rainfall model box is made of the acrylic plates and the injection needles. The rainfall coverage surface area is 50 cm long and 30 cm wide. The modeled rainfall is partially applied on the upstream portion of the sand model.

3.2 Experiment

A preliminary experiment is carried out under the condition where only fresh water flows in the model in steady condition. The hydraulic conductivity \((k=1.293 \text{ cm/s})\) is then determined from the comparison of measured discharge rate of water and one calculated by Eq. 1. The effective porosity \((\theta=0.40)\) is also determined from the comparison of the measured velocity and the calculated Darcy velocity. The measured velocity is observed by trace of dye in the sand box model. The measured rainfall intensity is equal to \(1.438 \times 10^{-3} \text{ cm/s}\).

Saltwater intrusion is simulated experimentally under no rainfall condition and rainfall condition, respectively. At the first stage, the hydraulic heads in both sides of the model are fixed in about three hours to achieve initial steady state. The upstream head \((H_2)\) is then reduced at every 30 minutes time interval by the change of over flow height as shown in Figure 3. This reduction simulates drawdown of groundwater table caused by pumping or drought. The freshwater/saltwater interface is measured at time step of 30 minutes on both sides and bottom of the model.

In the experiment a distinct freshwater/saltwater interface is observed as

![Figure 5: Equipotential lines of flow](image)

Figure 5  Equipotential lines of flow
Figure 6 Comparison of experimental and calculated results for no rainfall condition

shown in Figure 4. The experimental results also show some characteristics of the moving interface as follows; saltwater intrusion in a recess area of the aquifer is faster than one in a main flow area. The overall response of the interface under the rainfall condition is slower than the no rainfall condition; that is, rainfall has the effect on retardation of saltwater intrusion. The isochronous arrival lines of the toe of interface are similar to the equipotential lines of the flow in this model shown in Figure 5.
4. NUMERICAL SIMULATION OF SALTWATER INTRUSION

By using the finite difference method, we attempt to compute saltwater intrusion in the three dimensional sand box model. The initial position of the freshwater/saltwater interface is selected to be that measured in the experiment at time equal to zero. The initial free surface elevation is calculated iteratively by Eq. 1 or Eq. 2 with fixing the position of freshwater/saltwater interface.
Time step $dt$ is calculated to satisfy the following stability condition of explicit scheme and is taken to be equal to 0.03 sec.

$$\frac{h}{n} \left( \frac{k}{\partial x^2} + \frac{k}{\partial y^2} \right) dt \leq \frac{1}{2}$$

(4)

The results of the numerical computation are compared to the experimental results. Figures 6 and 7 show the interface response under no rainfall condition and rainfall condition, respectively. It can be noted that a shape of the freshwater/saltwater interface is convex when the interface advances in a right-angled direction to the main flow as shown between two corners in the figures of bended side. These figures show that the computed response of the interface well agrees with the experimental result outside around the outflow face. From these results, we can confirm the validity of the numerical model.

5. PROTECTION OF SALTWATER INTRUSION BY ARTIFICIAL RECHARGE

There are various method to protect freshwater aquifer from saltwater intrusion. By the numerical simulation, we attempt to examine the method that the flow rate of fresh water is increased by the artificial groundwater recharge. The artificial recharge can be categorized into two method. The first method uses a line recharge facility such as a ditch on the ground surface and a horizontal pipe in the ground. The other is a point recharge from the wells. The boundary shape of the aquifer in the numerical simulation is selected to be the same with the experiment.

5.1 Line recharge

At first, we investigate the response of the interface under the artificial recharge from a linear facility, such as a ditch and a horizontal pipe. The simulated results with various recharge rates are examined to compare the arrival position of the toe of interface at the same elapsed time. Figure 8 shows the relation between the intruded length of the interface toe ($L$) and recharge rate from a linear facility ($Q$). Here, the intruded length on the bended side is measured in total length along the boundary. $Lo$ is the length...
of recess area as shown in Figure 9. It can be obviously seen as recharge rate increases the freshwater/saltwater interface is pushed back towards the sea, especially in the recess area. This result indicate the effectiveness of artificial recharge to retard saltwater intrusion.

Secondly, we investigate under the condition where the facility is located
nearer and further from the seaside. The locations in the three kinds of simulation are shown in Figure 9. Here, $D$ is the distance from the seaside to the facility. Figure 10 shows the relation between the intruded length and the distance from the seaside. It can be observed that there is very little effect of the recharging location on the retardation of saltwater intrusion.
5.2 Point recharge

Another method of artificial recharge is examined on the point recharge from the wells. This method is suitable where the facility space is restricted, such as in urban areas. We investigate the response of the interface position caused by the point recharge under the same condition with the line recharge case. A pair of wells is located in parallel to the seaside as shown in Figure 11. The result on the change of the intruded length caused by the difference of recharge rate is shown in Figure 12. It can be obviously seen as recharge increases the freshwater/saltwater interface is pushed back towards the sea. The effect of seawater retardation is almost the same with the line recharge case. Next we study the position of the interface toe as we changed the location of the wells. The relation between the intruded length and the location of the well is shown in Figure 13. Figure 14 shows the results under the condition where a pair of wells is located in perpendicular to the seaside. The arrival positions of the interface only show little shift for two kinds of well location. It can be concluded that there is little effect of the location of the well on the retardation of saltwater intrusion.

6. CONCLUSION

The numerical model based on the abrupt interface approximation is quite effective in simulating the movement of the intruded saltwater region under
unsteady condition. The simulated moving interface should be a good approximation of the actual groundwater management in coastal aquifer. It is obvious artificial recharge have a significant effect on the retardation of saltwater intrusion. It observed from the simulated results with same amount of recharge that the effect of saltwater retardation is almost the same for line and point recharge. In the areas where the space is costly the point recharge method is preferred. It is also obvious that there is little effect of the location of the well on the retardation of saltwater intrusion.

Finally, this paper dealt with the effectiveness of artificial recharge on the saltwater intrusion in mathematical view. In the actual field, there is several problems such as clogging of the aquifer on the management and the cost over benefit analysis on the construction. We should also look at the management of groundwater discharge due to heavy pumping in coastal areas by limiting the number of pumps in the area and rate of pumping allowed.

REFERENCES

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