FINITE ELEMENT MODELLING OF DENSITY-DEPENDENT GROUNDWATER FLOW AND SOLUTE TRANSPORT IN THE UNSATURATED LAYERED COASTAL AQUIFER SYSTEM

Byeongju JUNG, **Jun-Mo KIM**, and **Ho-Wan CHANG**

School of Earth and Environmental Sciences, Seoul National University,
Seoul 151-742, REPUBLIC OF KOREA

Increasing withdrawals of groundwater from coastal aquifers during periods and temporary increasing population can induce seawater intrusion in the aquifers, which consequently results in a decline in water quality. Therefore the knowledge of the location of the freshwater-seawater interface and the pattern how the solute is transported are important for efficient use of groundwater in the coastal area and to reduce problems of salinization.

Layered heterogeneity, one of the natural factors affecting seawater intrusion in coastal aquifer has influence on both groundwater and solute transport. And artificial groundwater withdrawal in layered aquifer may cause different distribution of concentrations in layers having different material properties depending on pumping scenarios applied.

To investigate density-dependent groundwater flow and solute transport in the unsaturated layered coastal aquifer, a three-dimensional numerical model is presented. This numerical model is developed based on the fully coupled governing equations for density-dependent groundwater flow, solute transport and the Galerkin finite element method. Two different cases of unsaturated aquifers are simulated for the purpose of comparison: a layered aquifer system composed of lower sand and upper clay layer, and a corresponding single-layer aquifer system composed of an equivalent lumped material. Also two different pumping scenarios are applied on same aquifer condition to compare variations of concentrations and degrees of salinization in clay and sand layers.

Figure 1 shows a three-dimensional finite element grid used for modelling. The model domain has 4581 nodes and 4000 elements covering 500m×500m×50m of domain. The size of each element is 25m×25m×5m. Specific-head boundaries are applied along the freshwater side and seawater side, and no-flow boundaries are applied upside, bottom side, light and left side. The basement rocks probably act as a no-flow boundary at the bottom. The hydraulic head of freshwater side is set higher than seawater side by 2m representing natural groundwater flow at the coastal area. Depth of upper clay and lower sand layers are same as 20m. To simulate intrusion of seawater, the boundary condition of seawater side is set constant and continuous solute concentration. The pumping well to observe the effect of artificial withdrawal near the beach is located in centre of right side. The same scenario of pumping is applied to both layered and lumped aquifer. Pumping persists during 6 years from initial state, and after that 8.6 years recovery using natural gradient from freshwater side. The steady-state simulation was performed for initial state. Material properties of the layered aquifer and lumped aquifer are presented in Table 1.

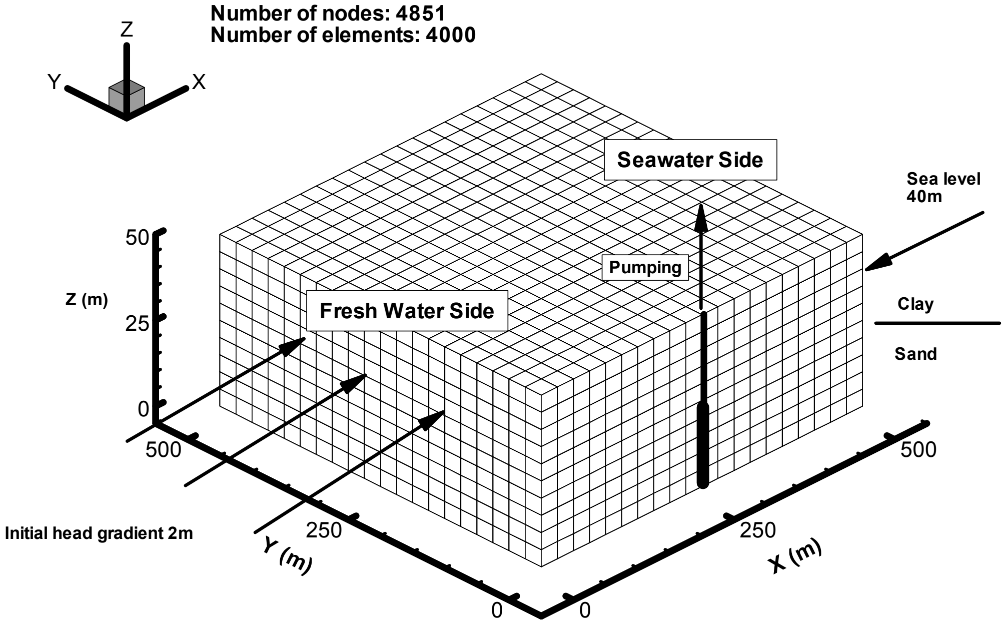

Figure 1 *Finite element mesh used in the numerical simulation and boundary conditions*

This study is performed using a numerical code made by Yeh (Yeh et al., 1995). The 3DFEMFAT code is based on a Galerkin finite element discretization of the variably saturated flow equations and a hybrid Eulerian-Lagrangian finite-element discretization of the advective-dispersive or pure advective solute-transport equation. The code is applicable to either three- or two-dimensional systems. The use of a hybrid Eulerian-Lagrangian discretization scheme allows for coarser time and grid discretization.

Property	Layered aquifer		Lumped aquifer
	Sand	Clay	
Porosity[a], n	0.41	0.45	0.43
Saturated hydraulic conductivity[a], K_{sat} ($mday^{-1}$)	50	0.001	25
Solid density, ρ_s (kgm^{-3})	2.65×10^3	2.80×10^3	2.68×10^3
Irreducible water content[a], θ_r	0.065	0.068	0.067
Unsaturated hydraulic parameters			
α_v[a] (m^{-1})	3.6	0.8	2.2
n_v[a](dimensionless)	1.56	1.09	1.325
Longitudinal dispersivity, α_L (m)	25	28	26.5
Transversal dispersivity, α_T (m)	2.5	2.8	2.65
Tortuosity, τ (dimensionless)	0.4	0.4	0.4
Modified compressibility of medium, α' (m^{-1})	1.618×10^{-4}	1.912×10^{-3}	1.040×10^{-3}
Modified compressibility of water, β' (m^{-1})	4.900×10^{-6}		
Density difference ratio, ε (dimensionless)	0.035		

[a]The values are adopted from Guymon (1994).

Table 1 *Material properties of the layered aquifer and lumped aquifer*

As shown in Figure 2, during 6 years pumping in the layered aquifer, seawater intrusion through lower sand layer is intensified further inland near the pumping well (a2). Seawater intrusion in the layered aquifer occurred significantly through lower sand layer due to relatively high hydraulic conductivity compared to clay layer. After 8.5 years recovery following pumping, the spatial distributions of concentrations of each aquifer are quite different. The layered aquifer still has a large amount of salt in upper clay layer compared to lower sand layer. And comparing to the lumped aquifer, which has average hydraulic conductivity of clay and sand layer, the resident salt in clay layer is noticeable. This phenomenon is thought to be caused by different groundwater velocity of two layers. During the pumping period, solute from seawater is transported mainly through the sand layer, relatively mobile, in which transport is dominated by advection, and groundwater velocity by artificial pumping is faster than by natural gradient from freshwater side. But, the clay layer, relatively immobile, has low concentration of solute due to low hydraulic conductivity.

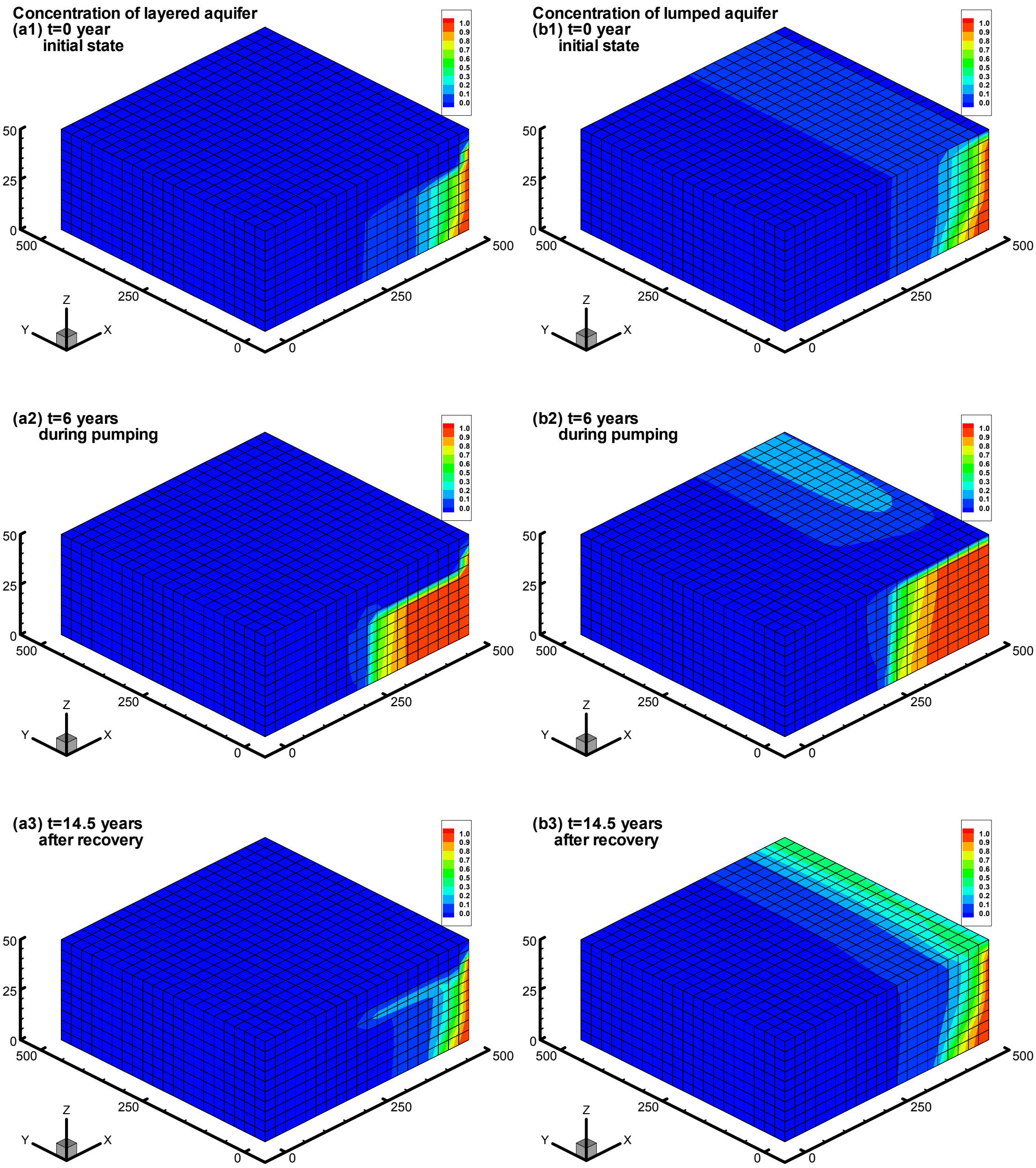

Figure 2 *Temporal variations of distributions of concentrations in layered aquifer and lumped aquifer. (a1)-(b1): t=0 year; initial state, (a2)-(b2): t=6 years; during pumping, (a3)-(b3): t=14.5 years; after recovery*

When pumping is stopped, and it comes to recovery period, the strong groundwater movement from seawater side by pumping suddenly changes to weak natural flow form freshwater side. Then solute near the interface of two layers is transported to upper clay layer, which has relatively low concentration by molecular diffusion. The solute in the clay layer, transported from sand layer is hardly flushed during recovery time due to low conductivity of clay layer. Figure 3-(a) shows temporal variation of concentration at selected nodes, which are located in clay and sand layers (x=375m, y=250m, z=10m for sand layer; x=375m, y=250m, z=35m for clay layer). If pumping is repeated in this situation, the concentration of resident salt in clay layer probably increases more higher.

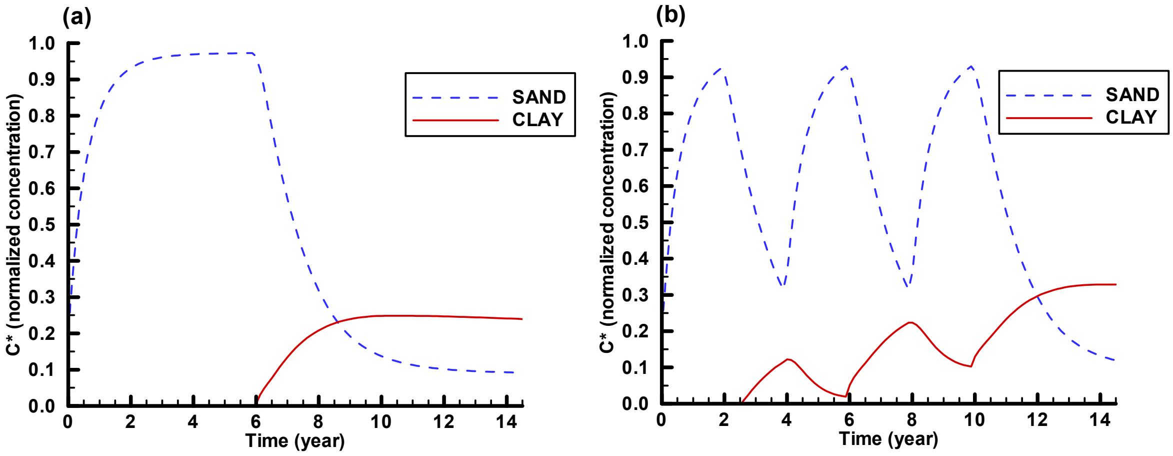

Figure 3 *Temporal distributions of concentrations at selected nodes at the layered aquifer applied two different pumping schemes. (a) 6 years pumping, 8.5 years recovery; (b) three cycles of 2 years pumping and 2 years recovery*

Figure 3-(b) shows the other result of a numerical experiment, which applies modified pumping scenarios with a higher frequency but shorter duration of pumping and recovery period to the same layered aquifer. The modified scenario has three cycles consisted of pumping and recovery period. All period of each cycle except last recovery period which persist 4 years, have duration of 2 years.

In Figure 3-(b), the concentration of solute in clay layer increase stepwise corresponding to recovery cycle, and compared to Figure 3-1, those concentration which has pumped more frequently in shorter time is more enriched than the previous case that has one long pumping period and following long recovery, even if total pumping time are same.

The numerical simulation results show that the layered heterogeneity has a significant effect on the patterns of groundwater flow and solute transport. Such an effect of layered heterogeneity is caused by hydrological and hydrodynamical differences between the sand and clay layers. Therefore, it may be concluded that the layered heterogeneity inherent to the coastal aquifer system should be properly considered when more reasonable and rigorous prediction of the seawater intrusion is required. And the numerical results also show that the degree and pattern of the seawater intrusion may depend upon the pumping scheme applied.

REFERENCES

Guymon, G.L., Unsaturated Zone Hydrology, Prentice-Hall Inc., pp. 210, New Jersey, 1994.

Yeh, G. T., 3DFEMFAT: Users Manual of a 3-Dimensional Finite Element Model of Density-Dependent Flow And Transport through Saturated-Unsaturated Media, The Pennsylvania State University, University Park, PA 16802, 1995.