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Modeling the Effect of Density Flow on Waste Spreading During and After Deep Well Injection

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Abstract

A computer program was developed based on superposition of elementary analytic solutions: the analytic element method. This preliminary study assumes a homogeneous aquifer and a sharp interface between the ambient brine and a less dense waste fluid. Viscosity differences are ignored. Simulations of the waste/brine interface movement over time indicate that aquifer permeability has a major influence on the range of waste spreading away from the injection well. Considering a relatively light waste and permeability data pertinent to the Mount Simon Sandstone (Cambrian) aquifer in northwestern Indiana, it is found that nearly cylindrical spreading of waste occurs about the well in regions of low permeability, whereas in regions of high permeability waste flows only out of the upper portion of the well bore and spreads rapidly underneath the upper aquifer boundary. Consequently, a light waste in combination with a high permeability poses an increased risk for waste movement through an imperfect upper aquiclude. Upon cessation of waste injection, density flow causes an upward movement of waste. This is particularly pronounced in the highly permeable aquifer, causing a further spreading of waste near the aquifer top.

KEYWORDS: Deep well waste injection, computer modeling, density flow.

INTRODUCTION

The United States Environmental Protection Agency is currently assessing the suitability of basal sandstone as a deep well injection reservoir in the north-central United States. As part of this four state study, the Indiana Geological Survey has examined aspects of the hydrogeology of the basal sandstone in Indiana, the Mount Simon Sandstone (Cambrian). Together with the School of Public and Environmental Affairs (SPEA) of Indiana

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University a computer modeling study has been conducted to improve our understanding of waste spreading in the Mount Simon due to density differences between aquifer brine and injected waste. Of primary concern is the extent of any lateral waste spreading just underneath the top of the Mount Simon, because spreading in this region would increase the risk of waste movement into overlying formations and useable aquifers.

This paper presents first, an outline of the modeling strategy, followed by a very brief description of the modeling technique used for the study. Next the data sources are discussed along with the rationale for the choice of modeling parameters obtained from these field data. The modeling results are discussed in conjunction with computer graphics depicting transient interface positions between waste and brine. The final section of this paper summarizes the modeling results and presents recommendations regarding both injection practices and further study.

MODELING APPROACH

Ideally, the problem of waste spreading in the Mount Simon Sandstone of northwestern Indiana should be studied by use of a comprehensive computer simulation. Such a study would include the real world complexities of varying fluid properties, varying geologic conditions, and all chemical processes which may affect the contaminant distribution in the Mount Simon Sandstone. Although sophisticated computer programs that incorporate many of these features do exist, the lack of detailed field data and sufficient quantitative knowledge about some of the processes seems to make their application here premature.

Modeling Strategy

The present modeling study is limited in scope. The modeling results presented in this paper are merely intended to provide insight into the role of density differences on the spreading of a relatively light waste fluid. Of particular interest are those conditions under which a relatively light waste may move upward and spread underneath the upper confining aquifer boundary. Also considered is how plugging of the well, after the injection period, would inhibit further upward flow of waste.

The objective of our study is not to predict the actual contaminant movement in northwestern Indiana, but rather to understand the consequences of two major aquifer and fluid properties: permeability and density. The results of this study may be used to influence operating practices of waste injection, as well as guide future more comprehensive modeling efforts.

Modeling Technique

The modeling study is based on a number of simplifying assumptions, among which:

- Injected waste and the Mount Simon brine each have a different but constant density.
- Viscosity differences between waste and brine are negligible.
- There are no physical and chemical reactions between the waste, the formation, and the ambient brine.
- Waste and brine are separated by an abrupt interface.
- The Mount Simon aquifer is bounded by two horizontal aquicludes and has an homogeneous and isotropic permeability and porosity.
- Both the aquifer and the pore fluids are incompressible.

- The well bore is open across the full thickness of the Mount Simon aquifer.
- There is at all times a hydrostatic pressure distribution inside the well.
- Regional flow is negligible, which leads to axi-symmetric flow conditions about the well.

The computer modeling technique used for this study is based on superposition of many elementary analytic functions: the Analytic Element Method (AEM) (Strack,1989). Approximate analytic solutions to flow near a partially penetrating well (Haitjema and Kraemer,1988) and the condition of an abrupt interface between two fluids of different density (De Josselin de Jong,1979) are combined into a comprehensive solution to the flow problem of waste spreading about an injection well. The computer program developed for this study, MUFLO6 (*MU*ltiple fluid *FLO*w), is an improved version of an earlier axi-symmetric interface flow simulator MUFLO4 (Haitjema,1980). In both these programs the contribution to the flow field, from the interface, is introduced by use of a vortex distribution along the interface. The vorticity is proportional to the density difference, the aquifer permeability, and the slope of the interface (De Josselin de Jong,1979). The resulting vortex distribution is approximated by a series of vortex rings which coincide with the axi-symmetric interface (Haitjema,1980).

The computer program MUFLO6(Haitjema and Kraemer,1988) features an interactive input command structure, giving the user full control over the modeling process. For instance, the user may make graphical output at desired times during the modeling, or may change the time step during the course of the modeling in accordance with the pace of observed interface movements. Input data are limited to basic aquifer and fluid parameters, and to a series of points defining the initial interface. These interface points, input with a data tablet, serve as 'control points' at which the fluid velocities are calculated. The interface is displaced in time using an explicit time-marching scheme. Because the description of the flow problem is analytic, no numerical dispersion occurs that may otherwise obscure the proper interface location. If desired, the definition of the interface, that is the distribution of control points, may be changed during the course of the modeling. This feature of the model is useful to maintain computational efficiency and a proper definition of the deformed interface.

DATA SET DEVELOPMENT

Deep-well waste injection is presently practiced in northwestern Indiana and the geology and injection practices of the area were used as a guide in determining ranges for model parameters.

In northwestern Indiana the Mount Simon Sandstone, a fine to coarse-grained, well-sorted quartz sandstone with minor amounts of interbedded shale,ranges from 900 to 2200 feet in thickness. The sandstone is underlain by the Precambrian basement complex composed of igneous rock and is overlain by a fine-grained silty shale: the Eau Claire Formation (Cambrian). Both the Precambrian rock and the Eau Claire shale are considered aquicludes. The interstitial spaces of the Mount Simon are filled with a brine which is characterized by total dissolved solids in the range of 30,000 mg/l along the upper section to 200,000 mg/l in the lower section.

The predominant types of waste injected in the area are acidic and alkaline industrial wastes and pickle liquor. Of particular interest to this study are those wastes with a low specific gravity, because the wastes lighter than the aquifer brine will tend to rise and therefore present a potentially greater environmental hazard to shallower potable water aquifers. Wastes heavier than the aquifer brine will tend to sink and therefore pose little risk to overlying aquifers. Ranges for field data, pertinent to the study, are summarized

Table 1: Relationship Between Field Data and Study Parameters.

	Field Data		Study Parameters	
	Min.	Max.	Low	High
Mt. Simon Thick. (ft)	900	2200	2000	
Effect. Porosity (%)	8	18	13	
Permeability ($10^{-12} ft^2$)	0.22893	41.547	0.22893	41.547
Brine Sp. Gr. (-)	1.02	1.14	1.08	
Waste Sp. Gr. (-)	0.99	1.28	1.00	
Pumping Rate (ft^3/day)	12,964	42,864	12,964	42,864

in Table 1. The data in Table 1 have been derived from records kept at the Indiana Geological Survey and the Indiana Department of Environmental Management. For the purposes of the modeling, the extremes of the permeability and injection rate were used. Other parameters were set at 'average' values while the waste and brine viscosities were set to 1 Centipoise, which is the viscosity of pure water.

MODELING RESULTS

Because we were particularly interested in studying the effects on waste spreading of the waste injection rate, the aquifer permeability, and well plugging after injection was completed, the modeling of waste spreading during injection was conducted for four different cases:

- Case 1. Low injection rate and low aquifer permeability
- Case 2. High injection rate and low aquifer permeability
- Case 3. Low injection rate and high aquifer permeability
- Case 4. High injection rate and high aquifer permeability.

The transient positions of the interface between the waste and Mount Simon brine, during a 25 year (24 hr/day) injection period, are depicted in Figure 1. The computer plots (a) through (d) in Figure 1 show cross-sections through the Mount Simon aquifer with the injection well at the left hand boundary. The interface surfaces are obtained by rotating the interface lines in Figure 1 about the well axis. Inspection of Figures 1(a) through (d) indicates that changes in the injection rate does not significantly affect the spreading pattern of the waste. However, aquifer permeability does have a major effect on the waste spreading pattern. For the case of a low aquifer permeability, Figure 1(a) and (b), the spreading pattern is nearly cylindrical over the full thickness of the Mount Simon. For the case of a high aquifer permeability, Figure 1(c) and (d), the waste spreads predominantly near the top of the Mount Simon, leaving most of the well unused for injection. The spreading pattern seen in Figures 1(c) and (d) is much less desirable than that in Figures 1.(a) and (b). As more waste moves underneath the top of the Mount Simon, the risk that the waste may find pathways into the overlying formations increases.

The transient positions of the waste/brine interface, after injection has stopped, are depicted in Figure 2(a) for Case 2. and Figure 2(b) for Case 4. In Figure 2(a) the interface is plotted at times 0 and 50 years after injection has stopped. The solid lines represent the interface positions when the well bore is completely plugged, and the dotted line represents the interface position when the well bore is left open. The difference in this case appears insignificant. In Figure 2(b) no run is presented with the well unplugged because the differences are indistinguishable on the scale of the figure. The density difference between

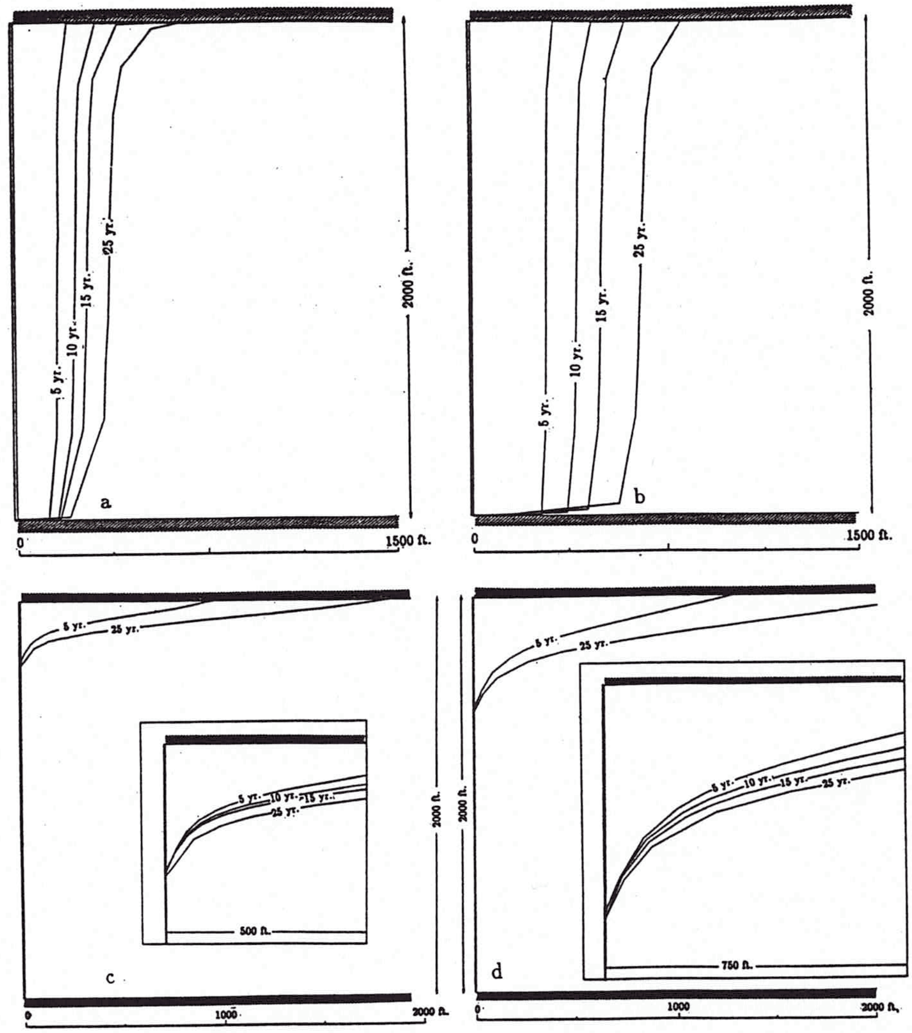

Figure 1: Positions of Waste/Brine Interface for (a) Case 1. Low injection rate and low aquifer permeability, (b) Case 2. High injection rate and low aquifer permeability, (c) Case 3. Low injection rate and high aquifer permeability, and (d) Case 4. High injection rate and high aquifer permeability.

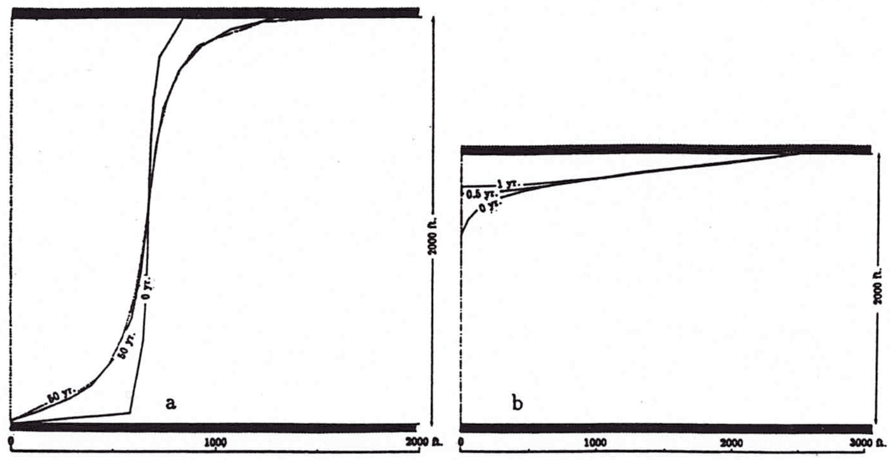

Figure 2: Interface Position after Injection Cessation for (a) Low aquifer permeability and (b) High aquifer permeability.

the waste and brine cause waste spreading to continue after injection has been completed. At depths where the Mount Simon has a low permeability, a nearly cylindrical inclusion of waste transforms slowly into the shape of an inverted bell (see Fig.2(a)), slowly increasing the spreading of waste underneath the aquifer top. In regions where the Mount Simon has a high aquifer permeability, a significant spreading underneath the aquifer top, which has started already during injection, continues after injection has stopped.

Effects of Aquifer Stratification

It is important to keep in mind that these results have been obtained assuming a homogeneous aquifer. In reality, however, the aquifer is known to be stratified vertically, with alternating layers of higher and lower permeability. When the contrasts in permeability are large enough, the spreading patterns observed in Figures 1 and 2 may be envisioned in every permeable layer. However, the assumption of a homogeneous aquifer is conservative from an environmental point of view, in that it predicts more spreading of waste directly underneath the upper aquifer boundary, thus predicting more risk of contamination to overlying aquifers.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been drawn from the modeling results:

- Injection of low density waste into regions of the Mount Simon Sandstone with a relatively *low permeability* exhibits nearly cylindrical waste movement.
- Injection of low density waste into regions of the Mount Simon with a relatively *high permeability* exhibits extended waste spreading underneath the aquifer top, and waste outflow occurs only over the upper portion of the well bore.
- Cessation of waste injection allows a dominance of density flow with a continued upward movement of lighter waste toward the aquifer top.

- Well plugging, after injection, has little effect on waste spreading, at least not in regions where the Mount Simon Sandstone is rather homogeneous.

When dealing with a relatively light waste and injecting into a relatively permeable region of the Mount Simon Sandstone, it seems advisable to case the upper 75% of the well bore so that waste will be injected in the lower part of the aquifer only. Lower permeable aquifer layers may then significantly retard the upward movement of the waste and prevent a rapid spreading underneath the upper aquifer boundary. A quantitative assessment of this phenomenon is desirable and may be obtained by including aquifer stratification in the modeling. Another improvement of the modeling may come from including viscosity differences which become important when they are an order of magnitude larger than the density differences. The program MUFLO6 may be adapted to include these features.

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References

De Josselin de Jong, G. Vortex theory for multiple fluid in three dimensions. *Delft Progress Report 4*, 87–102, 1979.

Haitjema, H.M. and S.R.Kraemer. A new analytic function for modeling partially penetrating wells. *Water Resources Research*, 24(5):683–690pp., 1988.

Haitjema, H.M. The use of vortex rings for modeling salt water upconing. *LGM Mededelingen*, 139–146, 1980.

Strack, O.D.L. *Groundwater Mechanics*. Prentice-Hall, Englewood Cliffs, NJ, 1989.