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Contaminant Mobilization Impacts of Hydraulic Fracturing for Groundwater Remediation

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# CONTAMINANT MOBILIZATION IMPACTS OF HYDRAULIC FRACTURING FOR GROUNDWATER REMEDIATION

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## ABSTRACT

Hydraulic fracturing has considerable potential when applied in conjunction with a variety of methods of groundwater remediation. However, the application of hydraulic fracturing in this context may result in detrimental mobilization of the target contaminants due to the fluid flow regime which is induced by processes that accompany fracture extension. A range of mathematical procedures for estimating the mobilization of aqueous and non-aqueous phase contaminants as the result of hydraulic fracturing are summarized, and issues associated these methods of analysis are identified. Selected results are presented for the PKN model of hydraulic fracture evolution subject to the limiting conditions of high and low fracturing fluid loss to the contaminated formation.

## RÉSUMÉ

La fracturation hydraulique a des possibilités intéressantes lorsqu'appliquée en conjonction avec une variété de méthodes d'assainissement des eaux souterraines. Pourtant, dans ce cas, l'application de la fracturation hydraulique peut causer une mobilisation dommageable de contaminants a cause du régime d'écoulement du fluide induit par l'extension d'une fracture. Un ensemble de techniques mathématiques pour estimer la mobilisation des contaminants aqueux et non-aqueux sont présentées et les paramètres critiques de ces méthodes sont identifiés. Quelques résultats typiques sont présentés pour le modèle PKN d'évolution de fracturation hydraulique, sujet aux conditions de hautes et basses pertes de fluide de fracturation à la formation contaminée.

## Management Perspective

Hydraulic fracturing is a standard method of hydrocarbon reservoir stimulation that has numerous applications in the remediation of contaminated groundwater. There is, however, concern that the application of hydraulic fracturing technology in this context may result in detrimental mobilization of the target contaminants, thus hindering, rather than expediting, the accompanying groundwater remediation program. This paper summaries a series of published studies which present various mathematical approaches to estimating the potential for contaminant mobilization as the result of hydraulic fracturing. Selected results are presented for aqueous and non-aqueous phase contaminants for the PKN model of hydraulic fracture evolution subject to the limiting conditions of high and low fracturing fluid loss to the adjacent formation. These conditions correspond to endpoint contributions of the two processes which typically accompany hydraulic fracture extension, and that are thought to be capable of mobilizing groundwater contaminants.

## INTRODUCTION

Hydraulic fracturing is a proven method of hydrocarbon reservoir stimulation that appears to have considerable potential when applied in conjunction with existing, and emerging, methods for the remediation of contaminated groundwater. Hydraulically fracturing a formation involves the injection of fracturing fluid at a rate that is sufficient to propagate a fracture in the plane of the minimum in situ stress. The geometry of the resulting hydraulic fracture is defined by the properties of the formation, the fracturing fluid, and the rate and duration of fluid injection. There are several ways in which hydraulic fracturing technology may be used to assist in groundwater remediation. For example, hydraulic fracturing might be used to place conductive drains to increase the efficiency of pump-and-treat approaches. Similarly, hydraulic fracturing might be used to place impermeable barriers to divert groundwater and contaminant migration. Hydraulic fracturing might also be used to distribute microorganisms within a contaminated formation to initiate biological remediation, and then to supply oxygen to the active microbial population. Finally, hydraulic fracturing might be used to place permeable, reactive barriers that degrade contaminants percolating through the barrier within flowing groundwater.

The mere mention of injecting fluid into a contaminated formation to create a hydraulic fracture often elicits concern regarding the mobilization of the contaminants. While the mechanisms that are suspected of causing contaminant mobilization are entirely plausible, it is not clear that the magnitude of the potential impacts is sufficient to preclude the application of hydraulic fracturing within contaminated formations. This paper summaries a series of studies which assess the mobilization of groundwater contaminants by hydraulic fracturing. The objective of these studies has been to provide a rational and quantitative basis for determining the feasibility of applying hydraulic fracturing technology in conjunction with groundwater remediation. The mathematical formalities of the studies are reported elsewhere in the literature; this presentation focuses on synthesis of the results that have been achieved to date.

## MECHANISMS OF CONTAMINANT MOBILIZATION

Contaminant mobilization may result from two related processes that typically accompany hydraulic fracture extension. The first of these processes is fracturing fluid loss to the formation due to the difference between the fluid pressures within the fracture and formation. The second process is the poroelastic response of the formation to dilation of the fracture, a process which has only recently been assessed mathematically (Ouyang 1994). Both of these processes establish a transient fluid flow regime within the contaminated formation. The simplest approach to characterizing the potential for contaminant mobilization as the result of this flow regime is to calculate the displacement of the fluid saturating the formation in response to the induced flow. This approach is most applicable to aqueous phase contaminants. Non-aqueous phase contaminants, particularly dense non-aqueous phase liquids (DNAPL), are another important group of groundwater contaminants. DNAPL contaminants occur simultaneously as continuous, residual, and dissolved phases. While the mobilization of the dissolved phase may be addressed by the calculation of fluid displacement, a significantly different approach is required to assess the mobilization of the continuous and residual phases. A candidate approach that is currently being developed is to calculate the peak hydraulic gradient induced by hydraulic fracturing and then compare this value to a critical magnitude required for motion of the DNAPL. This critical hydraulic gradient might be estimated from the dimensions and geometry of the porosity of the contaminated formation and from the capillary properties of the contaminants.

Both the terminal geometry of a hydraulic fracture, and the evolution of the fracture toward this geometry, regulate the potential for contaminant mobilization. This paper summarizes results derived using limiting analytical solutions for the PKN model of hydraulic fracture evolution, which is illustrated in Figure 1. These solutions correspond to high fracturing fluid loss, where evolution is regulated entirely by fluid loss considerations, and to low fracturing fluid loss, where evolution is regulated entirely by viscous flow and elasticity considerations. High fluid loss translates to nominal poroelasticity effects. Low fluid loss translates to minimal fluid loss effects. The PKN model assumes a constant height, H, and a length, L, which increases during fluid injection and remains constant during closure. Fluid loss is uniform over the height of the fracture and varies along the length of the fracture. Fracture width, or dilation, varies over both the height and length of the fracture. Figure 1 also illustrates the mobilization of a contaminant plume. If the plume is displaced over a significant distance, the intended benefit of hydraulically fracturing the formation may be lost to the increased distribution of the contaminant.

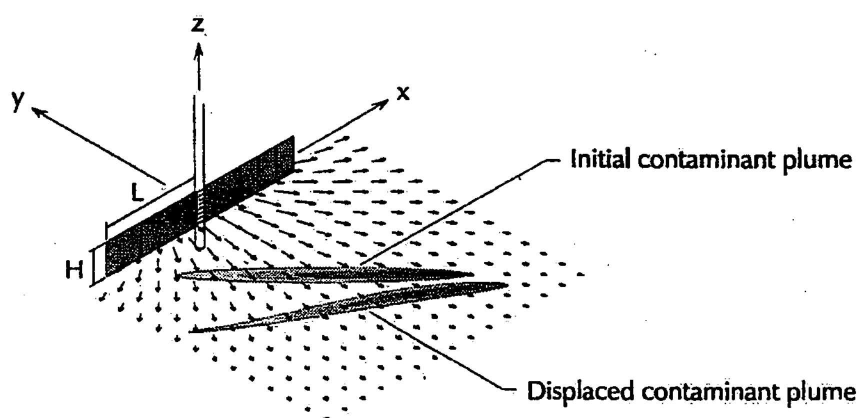


FIGURE 1. Illustration of a PKN hydraulic fracture.

## ESTIMATION OF CONTAMINANT MOBILIZATION

Three studies addressing contaminant mobilization by hydraulic fracturing have been completed to date, and a fourth is ongoing. The first study (Piggott and Elsworth 1994a) produced a solution for the fluid displacement induced by the extension of a PKN hydraulic fracture subject to high fracturing fluid loss. The second study (Piggott and Elsworth 1994b) extended this to include both fluid loss and poroelasticity effects; the KGD, PKN, and radial models of hydraulic fracture evolution; and the representation of hydraulic boundary conditions. The accuracy of the solution procedure invoked in the first two studies was assessed in the third study (Piggott 1995). The fourth study, which is ongoing, involves calculating the potential for the mobilization of non-aqueous phase contaminants. The following paragraphs briefly summarize these results.

Fluid Displacement Due to Fluid Loss and Poroelasticity Effects

The fluid displacement induced by fluid loss or dilation at a particular location along a hydraulic fracture, and at a particular time, may be computed using the fundamental solutions for instantaneous, point fluid injection and dilation. The response due to fluid loss or dilation over the length of the fracture, and duration of fluid injection, may be determined through the superposition of these solutions. Here, the spatial and temporal distributions of fluid loss and dilation are determined from analytical relations for fracture evolution. To facilitate these calculations, geometry may be expressed in the dimensionless form

$$x_d = \frac{x}{L_p},\ y_d = \frac{y}{L_p},\ \text{and}\ z_d = \frac{z}{L_p} \qquad [1]$$

where $L_p$ is the length of the fracture at the end of fluid injection. Computed fluid displacements may also expressed in a dimensionless form, $\Delta_{T,d}$, where the actual displacement magnitudes, $\Delta_T$, are related to the dimensionless results using

$$\Delta_T = \frac{Qt_p}{2HL_p n}\Delta_{T,d} \qquad [2]$$

where Q and $t_p$ are the rate and duration of fluid injection and n is the porosity of the contaminated formation. Figure 2 shows the distributions of fluid displacement in the planes of the x and y and y and z axes (see Figure 1). The solid and dashed lines represent fluid displacement due to fluid loss and poroelasticity effects, respectively. Both distributions are shown in enlarged detail in the vicinity of the fracture surface. The distributions corresponding to fluid loss and poroelasticity effects differ at less than one fracture length from the fracture surface, and converge with increasing distance from the fracture. This reflects the fact that the total volume of fluid loss to the formation is equal to the total dilation of the fracture. These quantities are distributed differently over the height and length of the fracture, and this produces the discrepancy between the distributions in the vicinity of the fracture. The impact of the differing distributions of fluid loss and dilation becomes less significant with increasing distance from the fracture and therefore the corresponding fluid displacements tend to converge. Fluid displacement is constant over the height of the fracture for the case of fluid loss effects as fluid loss to the formation is uniform over the height of the fracture. Fluid displacement due to poroelasticity effects varies over the height of the fracture, in the immediate vicinity of the fracture, due to the variable width of the fracture, and converges toward the displacement due to fluid loss effects at greater than one fracture length from the fracture surface. Again, the impact of the variation of dilation over the height of the fracture diminishes with increasing distance from the fracture. The contours of dimensionless displacement listed in Figure 2 vary from 0.1 to 0.55. For a typical reservoir stimulation scale hydraulic fracture treatment, which would likely be extreme in a groundwater remediation context, these values translate to fluid displacements on the order of 0.1 m. This magnitude is a small fraction of the dimensions of the hydraulic fracture that would be created under these conditions.

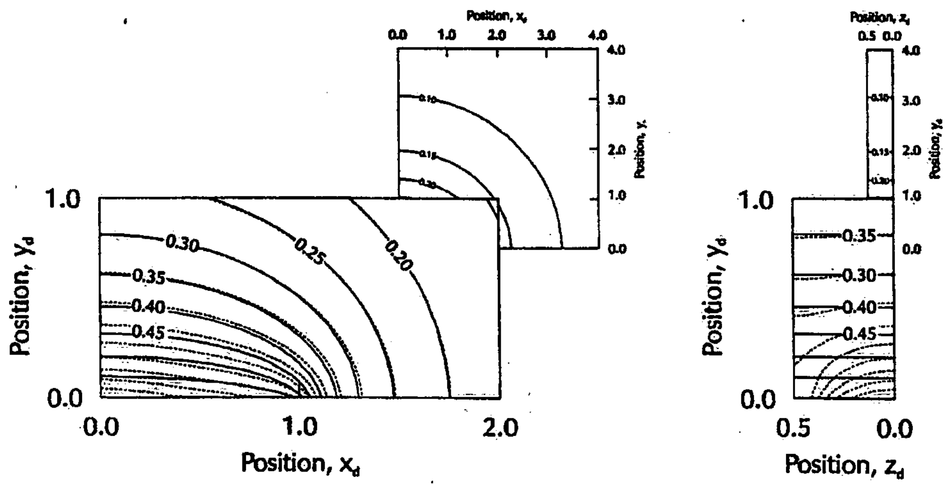


FIGURE 2. Fluid displacement corresponding to fluid loss and poroelasticity effects.

Axisymmetric Approximation of Fluid Displacement

The relations used to construct Figure 2 rigorously represent the influence of fracture geometry, and the spatial variation of fluid loss and dilation, on the distribution of fluid displacement. Considerably simpler solutions can be obtained by assuming fluid loss and dilation at the wellbore, rather than along the length of the fracture. Figure 3 compares the distributions of fluid displacement corresponding to fluid loss effects (solid lines) and poroelasticity effects (dashed lines) to this axisymmetric approximation. Results are shown along the x and y axes and are expressed as a function of distance from the wellbore, $r_d$. Both sets of results converge toward the axisymmetric solution at greater than two fracture lengths from the wellbore. Thus, at remote locations, fluid displacement can be accurately predicted using the axisymmetric solution. The solution representing distributed fluid loss and dilation is required closer to the wellbore as the axisymmetric solution greatly overestimates the distributed results in this region.

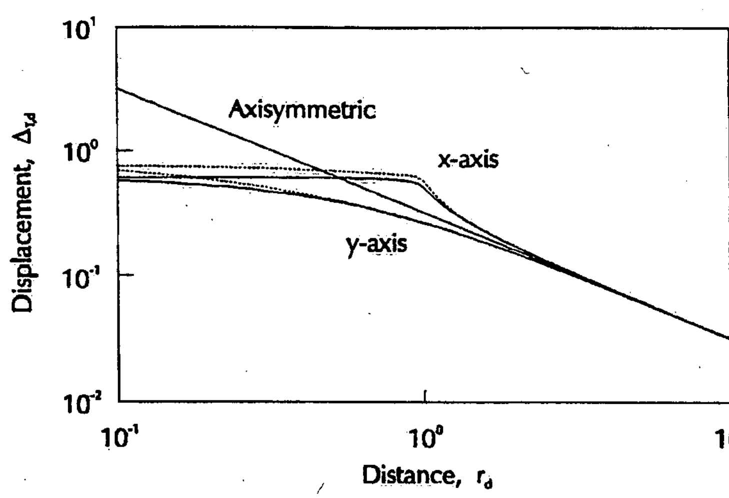


FIGURE 3. Fluid displacement predicted by the distributed and axisymmetric solutions.

Static and Dynamic Calculation of Fluid Displacement

The results shown in Figures 2 and 3 are based on the assumption that fluid displacement is relatively small and is independent of the motion of the fluid. The accuracy of this assumption has been tested by comparing the resulting, static solution to a dynamic, particle tracking solution. The dynamic solution is much more computationally demanding than the static solution and therefore it is desirable to use the static solution where appropriate. Figure 4 illustrates this comparison for a PKN hydraulic fracture subject to high fracturing fluid loss. Fluid displacements computed using the static solution (lines) and dynamic solution (points) are shown for a range of porosities for the 5 observation locations indicated in the figure. The two solutions compare favourably for porosities greater than $10^{-3}$ but diverge at smaller values of porosity, with the onset of the discrepancy apparent first for larger displacement magnitudes. The static solution overestimates displacement in cases where the static and dynamic solutions differ. Thus, the static solution is a conservative approach to the estimation of contaminant mobilization as it results in an overestimate of fluid displacement in cases where it is not valid.

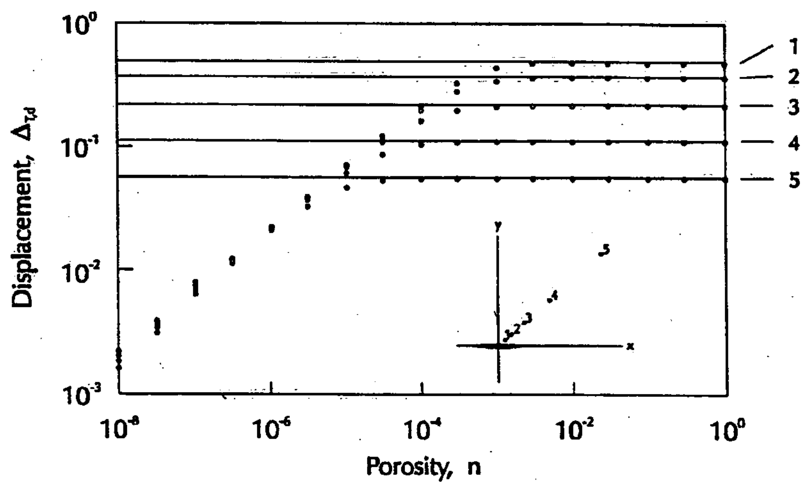


FIGURE 4. Fluid displacement predicted by the static and dynamic solutions.

Mobilization of Non-aqueous Phase Contaminants

The dynamic solution procedure described in the previous paragraph is based on the integration of advective flow velocities measured in the directions of the x and y axes. These velocities may be readily transformed into hydraulic gradients measured in the directions of the x and y axes, which may then be combined to obtain the total hydraulic gradient, $i_T$, as a function of location, time, and the diffusivity of the formation, D. The peak hydraulic gradient, $i_{T,peak}$, for a given location and diffusivity may be obtained by the optimization of $i_T$ with respect to time. Again, it is convenient to state the computed results in a dimensionless form. In this case, the dimensionless peak hydraulic gradient, $i_{T,peak,d}$, is related to the actual magnitude via

$$i_{T,\,peak} = \frac{Q}{2L_pHK} i_{T,\,peak,\,d} \qquad [3]$$

where K is the hydraulic conductivity of the formation. The diffusivity of the formation may also be expressed in a dimensionless form, $D_d$, relative to the duration of fluid injection and the length of the fracture. Figure 5 shows the variation of the peak hydraulic gradient with respect to diffusivity for the observation locations introduced in Figure 4. The computed peak hydraulic gradients, which are shown as points, initially increase with increasing diffusivity, and then approach an asymptotic value. This suggests two distinct behaviours. The first behaviour applies for small values of diffusivity when the rate of fracture extension is effectively instantaneous with respect to the rate of fluid diffusion. The second behaviour applies for larger values of diffusivity when diffusion is instantaneous with respect to fracture extension. These limiting behaviours may be used to form simplified expressions for the hydraulic gradients induced by fracture extension. These simplified expressions are less burdensome to compute and therefore may be useful in more detailed calculations involving, for example, multiple hydraulic boundary conditions. The variation of the peak hydraulic gradient with respect to diffusivity for diffusion and fracture extension limited behaviours are shown in Figure 5 as solid lines. The bilinear relations defined by these behaviours are conservative in that, during the transition between the behaviours, the relations overestimate the peak hydraulic gradients returned by the full solution. In the absence of a reliable estimate of diffusivity, it is reasonable to predict the peak hydraulic gradient according to fracture extension limited behaviour. This will, however, greatly overestimate the actual peak hydraulic gradient if diffusion limited conditions prevail.

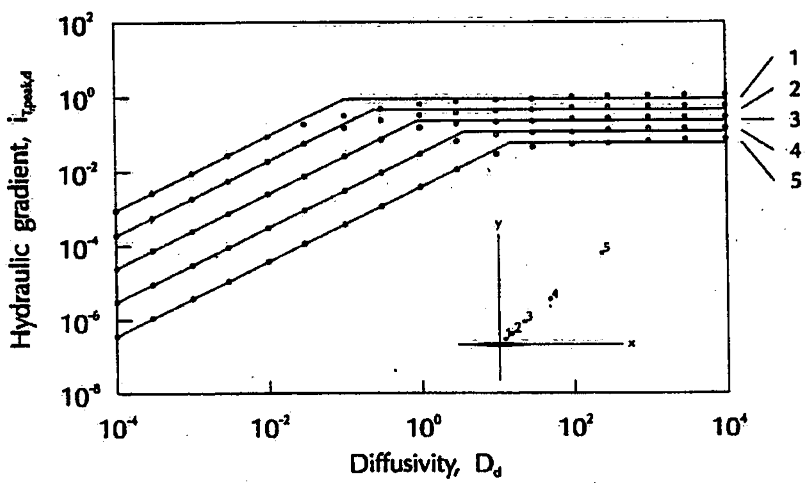


FIGURE 5. Peak hydraulic gradient as a function of diffusivity.

## DISCUSSION AND CONCLUSIONS

The analyses summarized in this paper invoke a number of simplifying assumptions which reduce the results to an analytic, dimensionless form that is suitable for practical application. In terms of hydrogeology, the analyses assume a homogeneous, isotropic, saturated formation and no difference between the properties of the fracturing fluid and groundwater. The analyses also disregard meaningful details of the solute transport process such as dispersion and retardation of the contaminants. In terms of the mechanics of hydraulic fracturing, very simple modes of fracture evolution are considered and only endpoint behaviours of fluid loss and poroelasticity effects are addressed. Typically, fluid loss and poroelasticity effects contribute to contaminant mobilization both simultaneously and cumulatively. It may be reasonable to interpolate between the endpoint behaviours, based on the relative extents of fluid loss and dilation, in order to represent the combined contributions of these two processes. More detailed representations of contaminant mobilization may be assembled by integrating advanced numerical models of hydraulic fracture evolution and groundwater transport, but this would result in a computationally demanding outcome that would be difficult to apply in a practical setting. In light of these limitations, it may be most appropriate to accept the results summarized in this paper as a quantitative but approximate index of the potential for contaminant mobilization by hydraulic fracturing. The results are quite adequate to differentiate displacement magnitudes measured in millimetres from magnitudes measured in metres. This sort of discerning capacity is likely to be sufficient for most practical applications, particularly when the results indicate either a minimal or obvious risk of contaminant mobilization.

In conclusion, the potential for the mobilization of groundwater contaminants as the result of hydraulic fracturing may be estimated as a function of the properties of the contaminated formation and the details of the proposed fracture treatment. While this potential should be determined on a case by case basis, the analyses that have been completed to date indicate a relatively small potential for the mobilization of aqueous phase contaminants. Naturally fractured formations characterized by very small effective porosities are an example of a plausible hydrogeologic setting where this observation may be suspect. Investigation of the impacts of hydraulic fracturing on the mobilization of non-aqueous phase contaminants is ongoing, and further results are required before a similar set of observations can be established for this important group of groundwater contaminants.

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