SOURCE ZONE REMOVAL USING PRESSURE PULSE TECHNOLOGY

Peter A. Gray, Wavefront Environmental Technologies, Kitchener, Ontario, Canada
Brett Davidson, Wavefront Environmental Technologies, Kitchener, Ontario, Canada
Angela MacDonald, Wavefront Environmental Technologies, Kitchener, Ontario, Canada

ABSTRACT

Source zone free product removal continues to be one of the primary limiting factors to a successful groundwater restoration program. Conventional pump and treat systems, although initially successful at recovering free product upon their commissioning, essentially become groundwater containment schemes over time. The challenges in recovering free phase product are due to a number of physical conditions, including the free product's specific gravity (or density), viscosity, interfacial tension and surficial tensional forces. Efforts to recover the free product give rise to long term dissolved phase restoration programs.

Pressure Pulse Technology (PPT) uses a process of periodic hydraulic excitations (eg. 15 pulses per minute) via pressure pulses of water to introduce hydraulic strain energy into the saturated formation. This energy is effective in geologic materials that exhibit elastic properties, such as unconsolidated sediments and sedimentary rocks. The strain energy dislodges blocked matter, opens perforations, increases pressure and re-establishes connectivity to reservoir pressures. Through these combined effects the PPT process enhances or restores the formation's permeability and a well's capacity to produce fluids.

This paper reports the results of a field testing program whereby PPT was applied as an add-on technology to enhance the effectiveness and operations of an existing pump-and-treat free product recovery system. PPT effects included increased LNAPL thickness and recovery rates in excess of 500% higher than non-pulsing conditions.

1. INTRODUCTION

Source zone free product removal continues to be one of the primary limiting factors to successful groundwater restoration programs. Conventional pump and treat systems often simply become groundwater containment schemes over time. The challenges in recovering free phase product, which give rise to long term dissolved phase restoration programs, are due to a number of physical conditions, including the free product's specific gravity (or density), viscosity, and interfacial tensional forces.

In order to reduce the free product's viscosity and tensional forces and thus aid in its recovery, solvents or other such compounds, including surfactants have been introduced to the subsurface through a process termed "flooding" (Holm and Csaszar 1962). Flooding is a well documented secondary or tertiary oil recovery scheme employed in the petroleum industry whereby a fluid is injected into the ground through a well to assist in the subsurface flow of liquids and thus to enhance the recovery of heavy oils from oil producing formations (Gatlin and Slobod 1960; Larson et al. 1982). Flooding effects are limited, however, due to the development of viscous fingering and permeability channeling which arise either due to permeability heterogeneities or the physical interaction of fluids of varying viscosities

(Davidson et al. 1999). In order to overcome the viscous fingering effects due to flooding, traditional flooding approaches have been enhanced, or augmented by PPT (Spanos et al. 1999).

2. PRESSURE PULSE TECHNOLOGY (PPT)

2.1 Background

About 15 years ago, Tim Spanos of the University of Alberta completed the initial development of a rigorous theory of porous media mechanics. Previous simplifications and assumptions were examined, found wanting, and corrected, resulting in a theory that is more thermodynamically sound than either Darcy theory for non-dynamic flow, or Biot-Gassmann theory for wave propagation. The phenomena of PPT and the benefits arising from its applications do not fall within the “conventional” view of porous media mechanics. The mechanics involved in the application of systematic PPT are not radical, yet currently accepted porous mechanics models cannot correctly account for the dynamic effects that have been demonstrated (Spanos et al. 1999).

Scientists and engineers working in fluid flow have been taught that the quasi-static Darcy flow paradigm ($q \propto \partial p/\partial \ell$), where gradient is a macroscopically defined quantity ($\partial p/\partial \ell = (p_1 - p_2)/\ell$), is a sufficient theory for porous media flow over a wide range of conditions. Perhaps some inability to correctly predict flow rates or dispersion behavior in clays, shales or fractured media is admitted, but otherwise Darcy theory is accepted uncritically.

Similarly, geophysicists working with porous media wave mechanics have been taught that Biot-Gassmann theory is sufficient to describe porous media wave propagation, given a wavelength much greater than the particle size. Neither of these “fundamental” theories is complete, although each may be sufficient for practical purposes under certain restrictive conditions.

2.2 Current Flow and Wave Paradigms

Darcy theory is a quasi-static theory, and contains no inertial terms. Thus, when liquid or solid phase accelerations are important with respect to the system flow velocity, one may expect effects that cannot be quantitatively explained. This does not invalidate the Darcy paradigm within the restrictive conditions for which it was stipulated (ie. no inertial effects). However, it does mean that Darcy theory is incapable of predicting or quantifying the effects that we report in this article. This is an important point: because Darcy-based flow theories cannot explain our results, it proves that a more complete theory is required.

The Biot-Gassmann theory of wave propagation in porous media is to wave mechanics what Darcy theory is to flow mechanics, yet Biot-Gassmann theory is based on a set of assumptions that have recently been shown to be inadequate. The two most important flaws are the following:

- Porosity is assumed to be a constant scalar quantity; and,
- The energy in a porous medium can be described by a single-valued function.

Clearly, Darcy theory does not include inertial effects; for example, it is known to be inapplicable to flows involving turbulence (Barenblatt et al., 1992), where internal energy dissipation from inertial effects are important. During the large amplitude excitation applied to the cells in our experiments, inertial effects, sudden acceleration and deceleration of the pore fluid, dominate the flow regime. To overcome this limitation of Darcy flow theory, it is insufficient to introduce empirical factors: a new flow theory including inertial effects must be formulated at the correct scale from fundamental physical principles.

2.3 Development of a New Theory

A new model of wave propagation in porous media was developed to overcome limitations associated with the restrictive assumptions in the Biot-Gassmann theory. The de la Cruz and Spanos model (1989, 1993) utilizes volume averaging in conjunction with physical arguments to construct a set of macroscopic continuum equations that more completely describes wave propagation in a fluid-filled porous medium.

The resulting model consists of coupled, first order macroscopic equations which describe wave propagation in porous media saturated with a single viscous compressible fluid. These equations have been derived and published elsewhere (de la Cruz et al., 1989, 1993), and will not be repeated here. The basic characteristics of the model include inertial mass coupling between the phases, porosity as a variable, energy dissipation because of phase compression, and rigorous incorporation of the dilatational behavior of all phases.

3. PPT FIELD APPLICATION

3.1 Site Geology and Hydrogeology

The site geology includes from ground surface to approximately two metres below grade; granular fill, from 2-15 metres grade fractured and weathered dolostone with an average horizontal hydraulic conductivity of 2.5×10^{-5} m/s and a porosity ranging from 5 – 10 %; from 15-25 metres below grade a zone of low permeability dolostone which acts as an aquitard between the upper fractured and weathered dolostone bedrock, and an underlying fractured dolostone bedrock unit which extends from approximately 25 to 100 metres below grade. Shallow unconfined groundwater flow is in an easterly direction beneath the site at a depth of approximately 2.5 metres below grade, below the top of the bedrock.

3.2 Site Characterization

Site characterization activities at the site have identified a free phase zone and a dissolved phase zone of di-octyl phthalate (DOP), with a density of 0.9861 g/cm^3 ; viscosity of 150 cp and measured average thickness of 0.5 cm within the on-site plume, within the fractures in the bedrock located at a depth of approximately 2.5 metres below grade. Historic DOP free product recovery rates in the northeast corner of the site have ranged from 20-45 ml/week using a conventional pump and treat system augmented with manual free product recovery using a peristaltic pump. Pump and treat activities have included the continuous withdrawal of groundwater from three individual recovery wells which are steel cased, 0.1 m in diameter and continuously grouted from ground surface to a depth of 2.5 metres below grade. From 2.5 to approximately 8.5 metres depth, the well is completed as an open hole in the bedrock. The recovered LNAPL is shipped off-site for disposal at a licensed facility, while groundwater is treated through micronic and coalescing filters prior to polishing via activated carbon filters. Treated groundwater is either reused on-site as makeup water for industrial chilling purposes or discharged to the sanitary sewer.

3.3 Study Objective and Methodology

The overall objective of augmenting the current pump and treat system with PPT was to document and measure the effect of pressure pulsing on a shallow unconfined bedrock aquifer and the resulting increased free product levels and recovery rates of DOP LNAPL at the site.

In order to accomplish this, water and free product levels were measured prior to, during, and post pressure pulsing activities in 15 wells (recovery and/or monitoring) in the area of the PPT activities. During and after pressure pulsing activities, level monitoring and free product pumping events were maintained to document changes in production rates from existing product recovery wells. Monitoring of free product in all monitoring wells was also completed to determine if free product levels became measurable in wells where it had not previously been documented.

3.4 PPT Instrumentation and Operation

The PPT application at the site was affected by installing one tooling assembly in one of the on-site 0.10 metre ID, 8.5 metre depth, steel cased recovery wells (see Figure 4). Prior to pulsing activities, the static water level (water table) was measured at 2.5 metres below grade. Prior to, during and subsequent to the pulsing activities, water levels and LNAPL thicknesses were measured in 15 separate monitoring wells, up to 100 metres from the pulsing well.

From June 5, 2000 to August 25, 2000, pressure pulsing was applied at the site in one well, at a depth of 2.5 metres below grade; at a frequency of 15 pulses per minute and a continuous water injection rate of 27 L/min. Electricity to operate the pulsing unit was obtained on-site. The delivery of the pressure pulses of water was through the patented pressure pulsing device, whereby water was instantaneously injected into the well bore through the open bottom of the PPT tool. Compressed air was obtained from the facility on-site to activate the pulsing device at a pressure of 80 psi; and water used for pulsing was initially obtained from the on-site municipal system, and later switched over to utilize the groundwater being pumped from the three on-site recovery wells. During the pulsing period, the pulsing injection rate of 27 L/min was balanced by a combined removal rate of 27 L/min from three recovery wells situated around the pulsing well.

4. RESULTS AND DISCUSSION

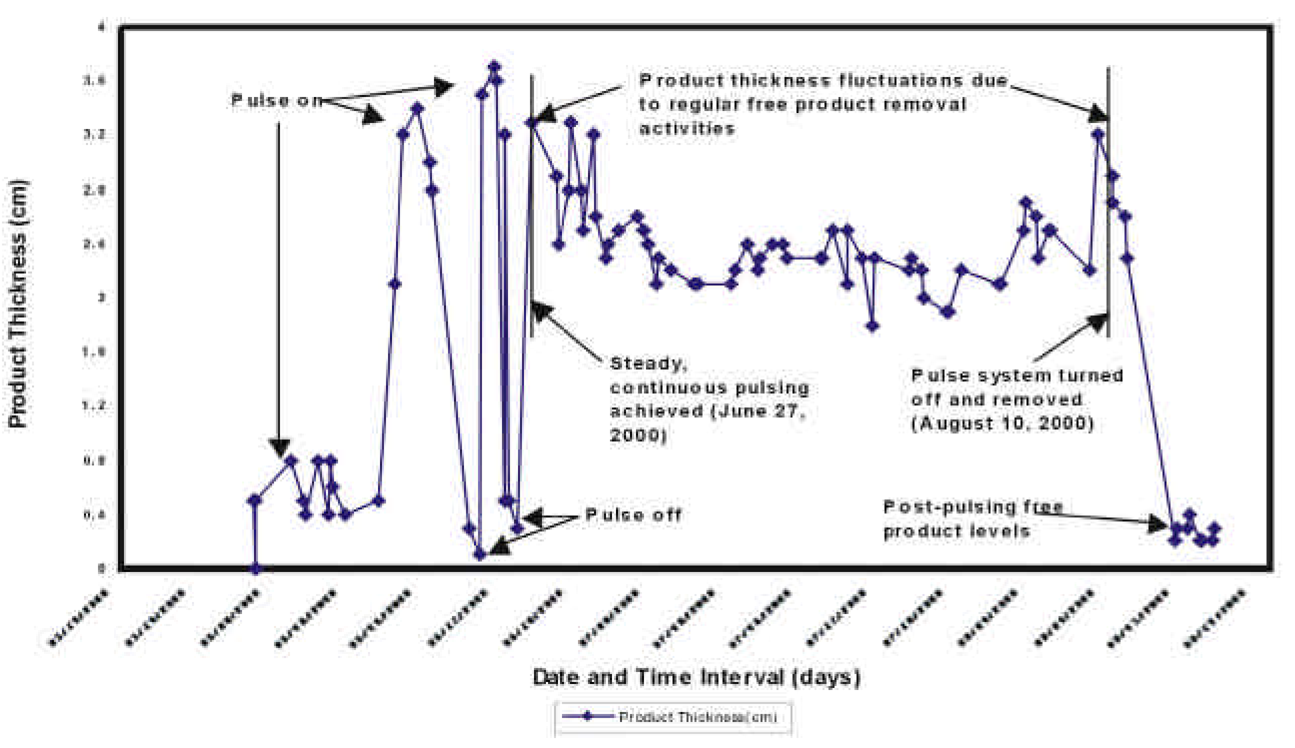
4.1 PPT Effects on Water Levels

The increased water levels measured during the pulsing period are as a direct result of the pulsing activities, and the trend evident through the first several weeks of pulsing coincide with the on/off cycling of the pulsing tool. From June 27/00 to the end of the pulsing period on August 10/00, the water levels remained relatively stable at a elevated height of approximately one metre higher than non pulsing conditions at OWC and the other monitoring locations, while the pulsing tool was operated on a continual injection basis of 15 pulses/min and a total injection rate of 27 L/min.

4.2 PPT Effects on Free Product Thickness

The hydrograph presented below presents the changes in free product thickness at the OWC location during the testing period. As shown, several days of pulsing had passed until the effects of pressure pulsing on the free product thickness were evident at this monitoring well located approximately 10 metres upgradient of the pulsing well. However, after approximately one week of pulsing, the free product thickness measured in OWC increased from approximately 0.5 to 3.5 cm, an increase of 800%. From the period of June 16 to June 27 the pulsing tool was turned off and on several times to document the effect on free product thickness. Each time the pulsing was

suspended, the free product thickness responded by dropping to pre-pulsing levels, and when pulsing was reinitiated, product thicknesses increased in the order of 800%. During the period of June 27 to August 10/00, while continuous pulsing rates were maintained, regular free product pumping events were initiated. Under these conditions, a consistent product thickness of approximately 2.5 cm was maintained, an increase of 500% from non pulsing thicknesses.



4.3 PPT Effects on Free Product Recovery Rates

As noted above, free product pumping events were initiated on June 27/00 and continued on a regular (daily to every two days) basis. In comparison, free product pumping events have occurred approximately once per month over the last several years, as it took approximately one month for free product levels to recharge to a comparable thickness to the month prior. During the pulsing period the frequency of free product pumping were able to be increased with an overall increase of recovery rates by 500% as a result of pressure pulsing.

5. CONCLUSIONS

In summary, PPT has had a direct impact at the site, including an increased water level in the vicinity of the pulsing well by as much as 1.5 metres, an increased LNAPL thickness increase of up to 800%, and increased LNAPL recovery rates up to 5 times faster (or 500% greater) than non-pressure pulsing rates. These increased free product thicknesses and recovery rates will result in a significantly shortened groundwater restoration program.

6. REFERENCES

Barenblatt, G.I., V.M. Entov, and V.M. Ryzhik 1992. Theory of fluid flows through natural rock, *Kluwer Academic Publishers*, Netherlands.

Davidson, B., T.J.T. Spanos, and M.B. Dusseault. 1999. Laboratory experiments of pressure pulse flow enhancement in porous media. *Proc. CIM Regina*, Oct. Tech Mtg., Calgary, Alberta.

de la Cruz, V., and T.J.T Spanos 1989. Thermomechanical coupling during seismic events, *Jour. Geophy. Res*., 94, B1, 637-642

de la Cruz, V., P.N. Sahay, and T.J.T. Spanos 1993. Thermodynamics of porous media. *Proc. R. Soc. London*, A 443, 247-255.

Gatlin, C. and R. L. Slobod. 1960. The alcohol slug process for increasing oil recovery. *Transactions AIME* 219, 46-53.

Holm, L.W., and A.K. Csaszar. 1962. Oil recovery by solvents mutually soluble in oil and water. *Society of Petroleum Engineers Journal 2*, no. 2: 129-144.

Larson, R.G., H.T. Davis, and L.E. Scriven. 1982. Elementary mechanisms of oil recovery by chemical methods. *Journal of Petroleum Technology* 34, no. 2: 243-258.

Spanos, T.J.T., B. Davidson, M.B. Dusseault, and M. Samaroo. 1999. Pressure pulsing at the reservoir scale; a new EOR approach. *Proc. 50th CIM Conference*, June 1999, Calgary, Alberta