DRAMATIC INCREASED LNAPL RECOVERY USING PRESSURE PULSE TECHNOLOGY

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INTRODUCTION

A state-of-the-art Light Non-Aqueous Phase Liquid (LNAPL) recovery field study has been performed at a large manufacturing facility in Cambridge, Ontario, Canada (the "Site"). The Site is directly underlain by fractured dolostone bedrock (approximately two metres below grade), and the water table is encountered beneath the bedrock surface, approximately 2 – 3 metres below grade, flowing in an easterly direction towards a river located along the Site's eastern boundary.

Environmental studies conducted at the Site have delineated a zone of LNAPL floating on the water table in the fractures and weathered bedding planes within the dolostone bedrock. The LNAPL, composed of bis (2-ethylhexyl) phthalate – also referred to as di-octyl phthalate (DOP), has a density of 0.9861 g/cm^3 and viscosity of 150 cp. The LNAPL layer has a measured average thickness of 0.5 cm within the on-site plume, and the historical recovery rate using conventional pump-and-treat technology has been approximately 14 litres/year.

The objective of this study was to modify a technology termed Pressure Pulse Technology (PPT) (Spanos et al., 1999) which has been proven and commercialized in the petroleum industry, and adapt the technology for application in the environmental industry to enhance the recovery of the LNAPL from the fractured dolostone at the Site.

At the Site PPT was used to produce pulses of pressure at the water table (approximately 2.5 metres depth), and was shown to have the positive effects of increasing aquifer water levels, and LNAPL free product thickness and recovery rates in monitoring and recovery wells.

THEORY REVIEW

About 15 years ago, Tim Spanos at the University of Alberta finished 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. As stated, The phenomena of PPT and the benefits arising from its applications do not fall within the "conventional" view of porous media mechanics. What is being done during systematic PPT is not radical, but currently accepted porous mechanics models cannot correctly account for such dynamic effects.

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.

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 (no inertial effects). However, it does mean that Darcy theory is incapable of predicting or quantifying the effects that we will 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. 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 a constant scalar quantity; and,
- The energy in a porous medium can be described by a single-valued function.

It has recently been demonstrated that porosity plays a fundamental thermodynamic role in porous media and must be treated as a thermodynamic state variable. As an example, in attempts to develop physically consistent models of sand production, porosity plays a role similar to that of temperature in metals (Geilikman et al., 1993). In sand production, the formation goes from a porosity of 29-32% to a condition of complete liquefaction at porosities >50%, under the influence of gravitational forces and seepage forces. The liquefaction phase transition is akin to temperature-induced melting of metals.

In the Biot-Gassmann development of wave propagation models for porous media, it was assumed that, for a representative elementary volume, a single functional could express the energy state. This leads to a conundrum that can be demonstrated by a simple example. If a single energy functional is sufficient, there can be only one value and direction of maximum gradient, and if the energy is solely a function of pressure, this means that there can only be one flow direction. However, for decades people have conducted flow experiments where two continuous immiscible fluid phases (e.g. oil and gas) are induced to flow in opposite directions or at 90º. This implies that a single energy functional is insufficient. Indeed, recent work has shown that if N continuous phases exist, N energy functionals (linked together by the laws of physics and properly scaled) are required (de la Cruz and Spanos, 1989). For example, in a sand-oil-water system, it is theoretically possible that the three phases can be moving relative to one another in three different directions.

Clearly, Darcy theory does not include inertial effects; for example, it is known to be inapplicable at 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.

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. This model includes porosity as a dynamic variable that plays a fundamental role in both the thermomechanics and thermodynamics of the porous medium. Also, the model includes explicit thermomechanical coupling; that is, first-order heat generation from compression and expansion of the phases due to external heating and cooling or due to pressure changes. Incidentally, this latter aspect also accounts for well-known wave attenuation behavior in a natural way, without empirical attenuation relationships for which parameters must be evaluated for each specific case.

Imposing the microscopic boundary conditions of no slip, continuity of stress, conservation of momentum transfer and continuity of heat flux to the following equations develops this theory:

- Equations of motion for a fluid;
- Equation of motion for an elastic solid;
- Continuity equation for a fluid;
- Continuity equation for a solid;
- The solid heat equation; and,

- The fluid heat equation.

It is assumed that the porous medium is composed of pores of random size and orientation, but macroscopically homogeneous and isotropic, enabling the use of volume averaging principles for specific parameters. As a preliminary solution, assuming a plane-wave, new dispersion relations for S and P waves have been constructed. This resulted in four P waves and two S waves, whose phase velocities and attenuation are frequency dependent.

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 dilational behavior of all phases.

One important aspect of the new wave propagation theory is that it predicts the existence of a non-seismic porosity-pressure diffusional wave that is symbiotically coupled to a quasi-static porosity diffusion process (Geilikman et al., 1993), and travels at velocities on the order of 5-150 m/s in porous media. This wave is not predicted by Biot-Gassmann theory. The role of the porosity diffusion wave in the mechanics of pressure pulsing in the laboratory and the field is paramount: it is the porosity-pressure diffusion wave that leads to the flow enhancement.

The porosity diffusion wave disperses geometrically just as any other wave, therefore, as it propagates from the source, its magnitude drops. However, in many cases, particularly those involving irreversible deformations such as compaction (overburden downward movement), energy can be systematically extracted from the gravitational stress field. This is an important aspect: suitable high-amplitude pressure pulsing can trigger dilation and liquefaction; this process is dominated by the overburden stresses and yield (shearing) processes arising from gravitational and flow forces that also feed energy into the porosity diffusion wave propagation process. Indeed, if the wave can continue to extract energy from the surroundings, it can propagate with far less attenuation than expected from geometrical spreading.

The existence and characteristics of the porosity diffusion wave has been demonstrated, measured in the laboratory (velocity ~ 8.0 m/s in a 36% porosity oil saturated sand pack at <0.5 MPa confining stress), and is considered to be critical to the flow enhancement phenomena we observe. The porosity diffusion wave also appears to be important in earthquake mechanics as a mechanism for the triggering of more remote earthquakes in critically stressed regions through an increase in pore pressure arising from a large perturbation (Geilikman et al., 1993).

The PPT described above has been patented by PE-TECH of Cambridge, On. / Edmonton Ab., and licensed to Wavefront Environmental Technologies of Kitchener, On. / Edmonton, Ab. for application in the environmental industry.

FIELD APPLICATION – RESULTS AND DISCUSSION

As noted above, environmental studies conducted at the Site identified a zone of DOP LNAPL floating on the water table in the fractures and weathered bedding planes within the bedrock at an area on the Site. Historic hydrogeologic studies characterized the dolostone bedrock to have an average hydraulic conductivity of 2.5×10^{-5} m/s and a porosity of 5 – 10 % and a transmissivity of approximately 6×10^{-2} m^2/s. The uppermost weathered bedrock zone extends to a depth of 15 metres below grade, and is underlain by a zone of lower permeability dolostone extending from 15 to 25 metres below grade. Historic remedial activities undertaken at the Site to remove the LNAPL, and the associated dissolved phase plume include the installation of groundwater / free product extraction wells along with monthly manual pumping of the LNAPL with a peristaltic pump. Average LNAPL recovery based on conventional removal technologies are approximately 14 L/yr. The recovered LNAPL is shipped off-site for disposal at a licensed facility.

The PPT application at the site was affected by installing the tooling assembly in one of the on-site 0.10 metre ID, 8.5 metre depth, steel cased recovery wells. The casing had been grouted from ground surface to 2.8 metres below grade, with an open 0.10 metre OD hole in the bedrock extending to the completion depth of 8.5 metres. The static water level (water table) was 2.5 metres below grade. Water levels and LNAPL thicknesses were measured in 15 separate monitoring wells, up to 100 metres from the pulsing well, prior to, during, and after the pressure pulsing period.

From June 5, 2000 to August 25, 2000, continuous pressure pulsing was applied at the Site at a depth of 2.5 metres below grade; at a frequency of 15 pulses per minute and a water injection rate of 27 L/min. Electricity was obtained on-site to power the tooling device; 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 the three recovery wells.

The effects of PPT at the Site include an average water level increase of up to 1.0 metre, and an increased LNAPL thickness of 0.5 cm to an average thickness of 2.5 cm in those wells with a measurable thickness. In one monitoring well (located 20 metres from the pulsing well), the thickness of LNAPL increased to 50.0 cm. Recovery rates of LNAPL also increased from 20 – 45 ml/week (or 14 L/yr) to in excess of 200 ml/week (or 100 L/yr).

There remain a number of areas outside the oil sector where PPT can, and is being applied to yield significant results. In fact, the types of problems incurred in the environmental industry are physically quite similar to those encountered in the petroleum industry except for two major factors; the pressures are much lower because of the shallow burial and there is often a phreatic interface close to or within the aquifer. Applications of PPT in the environmental industry include:

1. Mobilizing and enhanced recovery of LNAPL'S and DNAPL's.
2. Introduction of bioactive agents and nutrients in a well-dispersed manner.
3. Stabilizing viscous fingering or permeability channeling.
4. Increasing the basic flow rate so as to shorten any clean-up activity.
5. Unplugging blocked water wells through mechanical perturbation effects of PPT.
6. Purge aquifers of saline water encroachment through excessive pumping.
7. Reduce the blockage rate of filtration beds (i.e. iron walls).
8. Deep well disposal of liquid dominated slurries such as feedlot wastes.

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 1.0 metre, an increased LNAPL thickness ranging from 300 to more than 1000%, and increased LNAPL recovery rates up to 7.5 times faster than non-pulsing recovery rates.

REFERENCES

Barenblatt, G.I., Entov, V.M., and Ryzhik, V.M., 1992. "*Theory of Fluid Flows Through Natural Rock*", Kluwer Academic Publishers, Netherlands.

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

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

Geilikman, M.B., Spanos, T.J.T., and Nyland, E., 1993. "Porosity diffusion in fluid-saturated media",*Tectonoph.*,217, 11-113.

Spanos, T.J.T., Davidson, B.C., Dusseault, M.B., and Samaroo, M., 1999. "Pressure pulsing at the reservoir scale: a new IOR approach". Proc. 50th CIM Annual Tech. Mtg., Calgary, Alberta.