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A field study of the vertical immiscible displacement of LNAPL associated with a fluctuating water table

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Abstract A variety of field techniques were utilized to study the immiscible displacement of LNAPL (gasoline) above a fluctuating shallow water table. Hydrophobic and hydrophillic tensiometer measurements were compared to a dual-well monitoring system that measured the potentiometric head of groundwater and the LNAPL-water interface in a fully screened well. This combination of techniques successfully monitored the changing water and LNAPL heads as the potentiometric surface fluctuated. Tensiometric measurements revealed that as the potentiometric surface fluctuated, there were proportional changes in water pressures, whereas the LNAPL pressures responded to its changing saturation and redistribution due to the release and entrapment of LNAPL. The strongly seasonal water table fluctuation caused a temporal forcing whereby the thickness of LNAPL in a well was not always in equilibrium with the difference in LNAPL and water heads. Therefore, theories for predicting the amount of mobile LNAPL in an aquifer based on static conditions and the measured LNAPL thickness in a well will not necessarily be valid. Cores revealed that the LNAPL distribution above a falling potentiometric surface increased with depth and reached a maximum saturation of 20% at the level of the air-LNAPL interface in an observation well. In contrast, the LNAPL distribution above a rising surface was uniform at a saturation of 6-8%.

INTRODUCTION

A light (less dense than water) non-aqueous phase liquid (LNAPL) such as gasoline trapped in the subsurface constitutes a major long-term contamination source to a groundwater system. Although the constituents of gasoline have a low solubility, they are toxic at low concentrations.

The form in which LNAPL is held in the soil changes vertically in the profile ranging from films and individual ganglia, to full saturation. The form in which LNAPL occurs is dependent upon total available LNAPL, pore size distribution, and water saturation. LNAPL ganglia trapped in the saturated zone may become mobile when the potentiometric surface falls and allows the LNAPL to become part of the continuum in the unsaturated zone. Lowering, followed by a subsequent rise in a potentiometric surface will retrap LNAPL by either a snap-off or bypassing mechanism (Chatzis *et al.*, 1983). Estimates of retrapped LNAPL saturation below the potentiometric surface can be made by an empirical equation (Land, 1968). A modified version that includes hysteretical effects is given by Kaluarachchi & Parker (1992).

In addition to displacement, depletion of the LNAPL mass by volatilization, biodegradation and mass transfer to the aqueous phase will also cause a change in the distribution of LNAPL with time. However, the subject of this study is to measure the redistribution attributed to immiscible displacement. The study is aimed at developing an understanding of how displacement of LNAPL by a seasonally fluctuating water table affects the availability to these depletion processes. Observations from the field study will also provide information on the relationship between the distribution of LNAPL in the profile, quantity of mobile LNAPL and the thickness of LNAPL seen in fully-screened boreholes.

Site description

The field study area is an industrial site located approximately 40 km south of Perth, Western Australia. The potentiometric surface varies from 0.86 to 1.36 m AHD (Australian Height Datum) during the 1993-1994 season. The ground surface is at 3.46 m AHD. Seasonal and possible tidal effects influence the potentiometric surface. The aquifer is composed of an unconsolidated Pleistocene sand known as the Safety Bay Sand. This dune sand is comprised of a uniform fine-grained (d_{50} = 150 μm) carbonate material. Stringers of partially cemented carbonate sand occurs as a laterally continuous

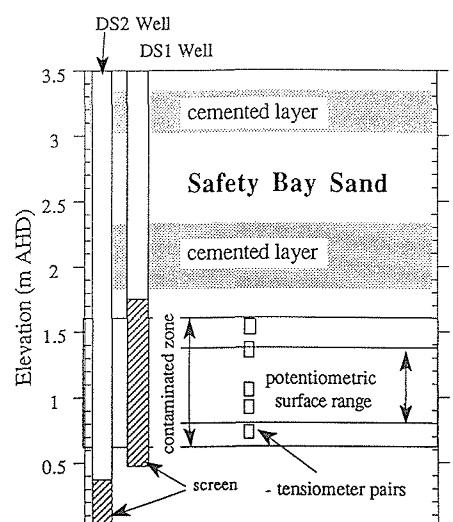

Fig. 1 Vertical profile of the study area depicting tensiometer locations, range of water table fluctuation, zone of LNAPL contamination, and location of screens in DS1 and DS2.

layers of up to 62 cm thick. Figure 1 depicts the location of the zone of contamination, the range of potentiometric surface fluctuation in relation to instrumentation.

The study area is subject to a Mediterranean climate with a mean annual rainfall of approximately 800 mm. A 7-month dry season from October to April, and a 5-month wet season from May to September generates a well defined seasonal water table fluctuation in the shallow sand aquifer.

The study site lies 100 m north of a large gasoline storage facility. Unknown quantities of the LNAPL have been leaking from the storage facility for at least 5 years. LNAPL contamination has moved northward and the seasonal water table fluctuations have smeared the LNAPL across a 1-m vertical interval in the vicinity of the current water table. Several years ago, recovery wells and trenches were installed to stop the progression of the plume. Leakage of LNAPL has now been stopped. The LNAPL recovery operation ceased prior to the commencement of the field work.

METHODS

The components of the field work include (a) characterizing the LNAPL composition, (b) coring and measuring the distribution of LNAPL and water saturations, (c) measuring the hydraulic conductivities, grain size distribution, and lithology, (d) monitoring the vertical movement of LNAPL, (e) monitoring potentiometric surface and rainfall events, and (f) monitoring water and LNAPL fluid pressures. The initial stage of the field work was to locate a suitable site for installation of the tensiometer nest and monitoring wells which will be referred to as the installation site. Figure 2 shows the layout of instrumentation at the installation site.

Coring

The cores were collected to provided an instantaneous profile of the LNAPL and water saturations. From May 1993 to July 1994, 12 cores were taken across the contamination

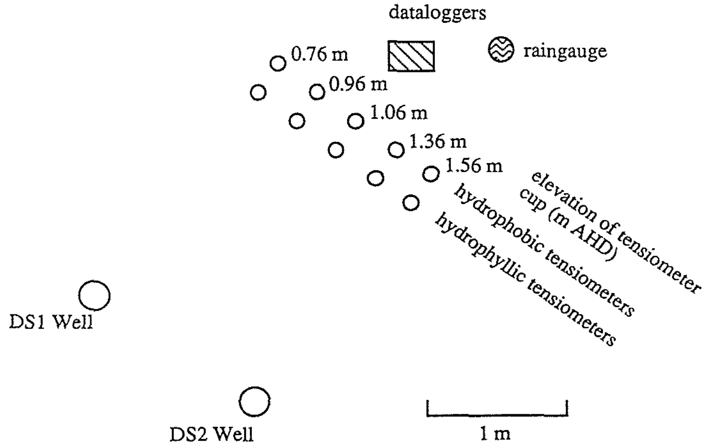

Fig. 2 Plan view of installation site.

zone, each 1.5-1.8 m in length. Seven of these 12 cores were retrieved from the installation site. All cores were cut into 0.05-m lengths which were subsampled for total hydrocarbon content and water saturation.

Monitoring wells

Thirteen observation wells are monitored manually with an interface probe every week for the water and LNAPL table levels. The wells are scattered over the 30 m by 200 m study area. All but one of the wells were screened across the water table. Two of the 13 wells form a dual-well monitoring system to record LNAPL and water tables on a semi-continuous basis. Well DS2 is screened in the water-saturated zone below the water table and LNAPL-contaminated zone. The other well (DS1) is screened across the contaminated zone and water table. These wells are monitored by capacitance probes and recorded hourly by data loggers. The capacitance probe recorded potentiometric head in the well screened below the water table and the level of the water-LNAPL interface (when LNAPL was present) in the well screened across the water table. The LNAPL table (air-LNAPL interface) was deduced from the potentiometric head and the water-LNAPL table.

Tensiometer nest

Pairs of hydrophobic and hydrophillic tensiometers that allowed both LNAPL and water pore pressures to be monitored were used to monitor changes in the vicinity of the water table. The hydrophobic tensiometer is an adaptation of a laboratory technique (Lenhard & Parker, 1990; Wilson *et al.*, 1990) where the ceramic cup of a tensiometer is treated with chlorotrimethylsilane to render it hydrophobic. This field study represents a new application of the technique.

A nest of 10 tensiometers (five hydrophobic and five hydrophillic) were installed to monitor the LNAPL and water pore pressures in the contamination zone (Fig. 2). Pairs of hydrophobic and hydrophillic tensiometers are installed at 10-30 cm intervals across the contamination zone (Fig. 1). Each individual tensiometer is measured by a gauge pressure transducer that is recorded hourly by a data logger. The pressure transducers were affected by temperature variations and results presented here have not completely eliminated the effect. In addition, an air-filled carbon filter was present to protect the sensing membrane in the pressure transducers monitoring the hydrophobic tensiometers. Changes in the air bubble volume affected the measured pressure. To reduce some of these diurnal variations the data have been smoothed by taking a moving average.

RESULTS AND DISCUSSION

Vertical movement of LNAPL with a falling potentiometric surface

Figure 3 depicts LNAPL and water saturations from five cores (00794/1, 05494/1, 13194/1, 15994/1, 20294/1) retrieved from within 2 m of the tensiometer nest, and fluid

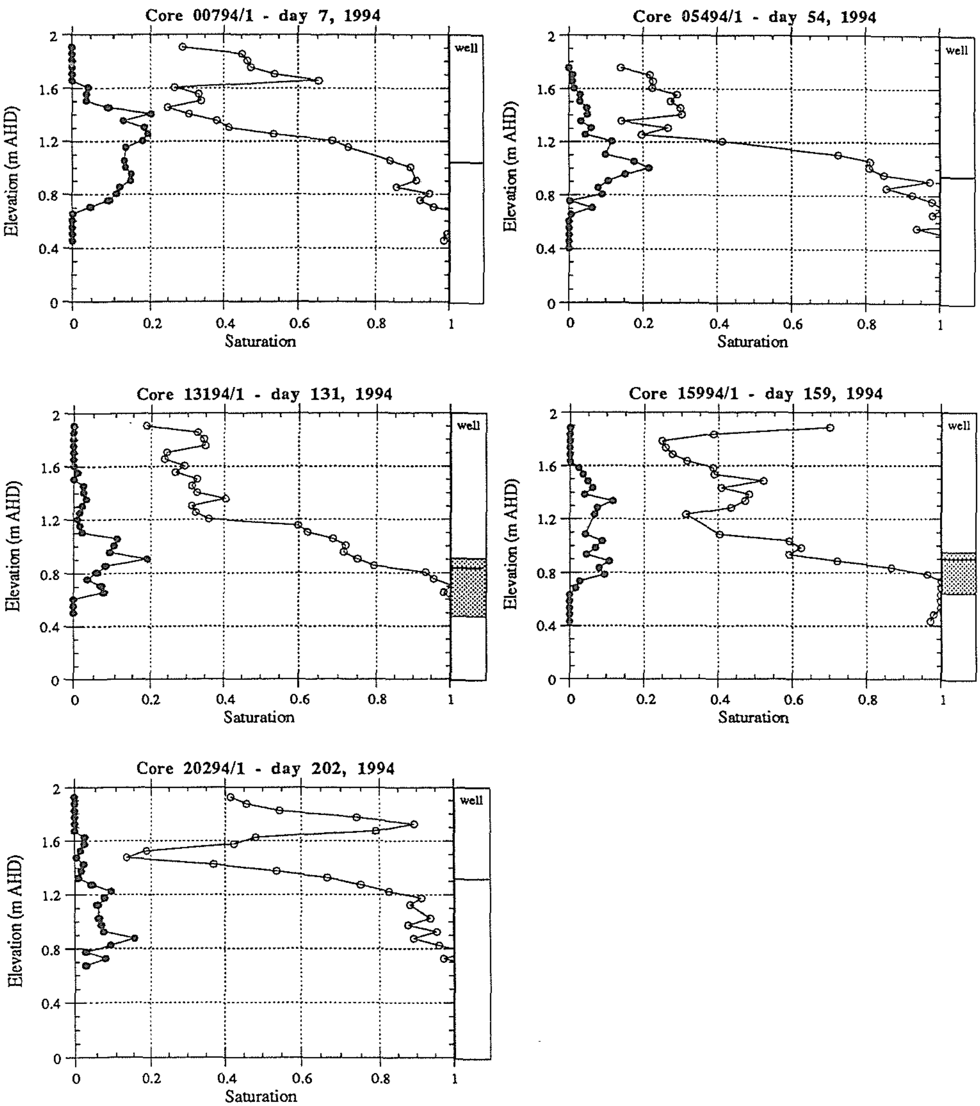

Fig. 3 LNAPL (solid circles) and water (open circles) saturations obtained from cores retrieved at the installation site and the corresponding product thickness (shaded) and potentiometric surface (line).

levels within the DS1 well at the time of coring. The soil core data indicates that the LNAPL has been vertically redistributed by the 0.32 m seasonal fluctuation of the water table, capillarity, and gravity. Contamination appears to be restricted between 0.66 and 1.66 m AHD. Cores 00794/1, 05494/1, 13194/1, 15994/1, and 20294/1 have a total LNAPL mass of 37, 30, 21, 19, and 19 kg m^{-2} of surface area, respectively. An apparent 51% depletion in the vertical LNAPL mass has occurred over the sampling period. The depletion may be attributed to dissolution, volatization, biodegradation, or local variability in LNAPL content. This depletion would explain the saturation decreases seen both above and below the potentiometric surface. This, however, has not interfered with the detection of LNAPL displacement.

The potentiometric surface declined up to a maximum rate of 1.5 mm day^{-1} over the 7-month dry season which commenced in October 1993. Figure 4 shows results from the capacitance probes in the DS1 and DS2 wells as well as the manual measurement of the air-LNAPL interface using the interface probe.

During the fall of the potentiometric surface, LNAPL movement detected by cores 00794/1, 05494/1, and 13194/1 closely followed the falling potentiometric surface. The maximum LNAPL saturations below the potentiometric surface are 15%. Above the potentiometric surface, a maximum saturation of 20% is found at the elevation of the air-LNAPL interface in well DS1. An LNAPL saturation of 7-9% is found approximately 0.40 m above the potentiometric surface. These saturation values are typical of published data (Wilson *et al.*, 1990; Ryan & Dhir, 1993) and agree with laboratory long-column and retention cell studies performed as part of this investigation (not presented).

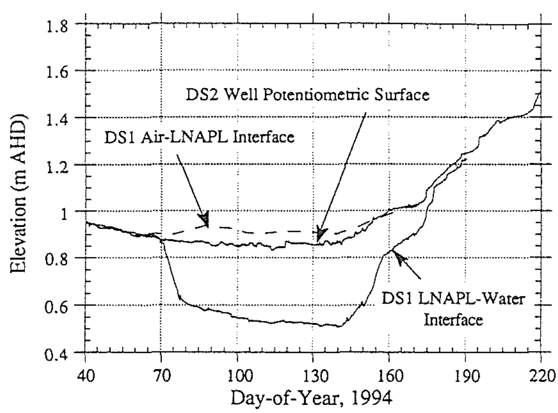

Fig. 4 Dual-well monitoring results during the appearance of LNAPL in DS1 well.

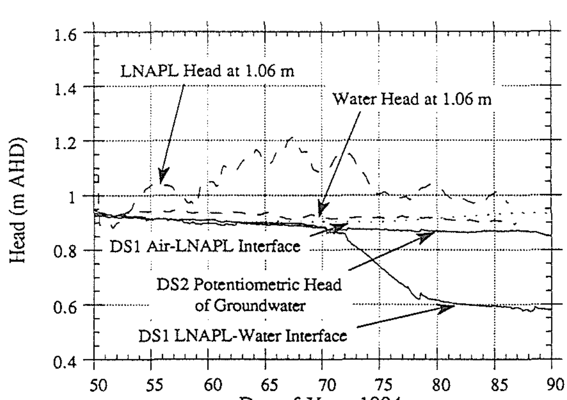

Fig. 5 Total pressure head of LNAPL and water, water level and product thickness in DS1 well, and potentiometric surface measurement in DS2 well during a falling water table.

LNAPL pore pressures at 1.06 m AHD increased to +30 cm of pressure head over a 2-week period prior to inflow of LNAPL into the DS1 well (Fig. 5). There are two proposed reasons for this elevated LNAPL pore pressure prior to the well inflow. First, as residual LNAPL ganglia are released and become part of the LNAPL continuum above the potentiometric surface, the LNAPL pore pressure increases accordingly. However, the relative hydraulic conductivity of LNAPL at <20% saturation is extremely low and any movement induced by the resulting LNAPL head gradient will be slow. Therefore there may be a significant time lag between the increase of a pressure gradient, the resulting movement, and readjustment of fluid pressure. An increase of LNAPL pore pressure due to additional LNAPL inflow to the field site. This appears unlikely because of the observed depletion of LNAPL mass with time. Alternatively, the lag between the development of LNAPL positive pressure head and inflow of LNAPL into the well may have been a result of LNAPL displacing the water-filled pores that surrounded the monitoring well. This annulus of disturbed fine-grained sand may have been produced during installation of the well.

Once inflow commenced, the LNAPL accumulation was detected in DS1 through the depressed LNAPL-water interface. Figure 5 depicts the LNAPL-water interface once LNAPL product enters the DS1 well, the potentiometric surface in DS2 well, and the LNAPL and water heads as recorded by the tensiometer pair at 1.06 m AHD. The water head decline corresponded directly to the potentiometric surface decline, whereas the LNAPL head was independently controlled by the changing LNAPL continuum above the potentiometric surface.

Once LNAPL inflow started, the LNAPL head declined at a rate similar to the fall of the LNAPL-water interface in DS1 (Fig. 5). The rate was constant at 33 mm day^{-1} at a LNAPL saturation of <20% within the aquifer. After a balance of the weight of the LNAPL mass and the weight of the displaced water was achieved, the LNAPL reached a new quasi-steady-state inflow that corresponded to the potentiometric surface decline of 4 mm day^{-1} between day 78 and 134, 1994. This phenomenon has been observed in pumping-induced water table declines (Sullivan *et al.*, 1988). Equilibrium between the LNAPL and water heads was only sensed between days 134-139, 1994 (Fig. 6). This implies that methods based on the pore pressure equilibrium assumption to estimate the

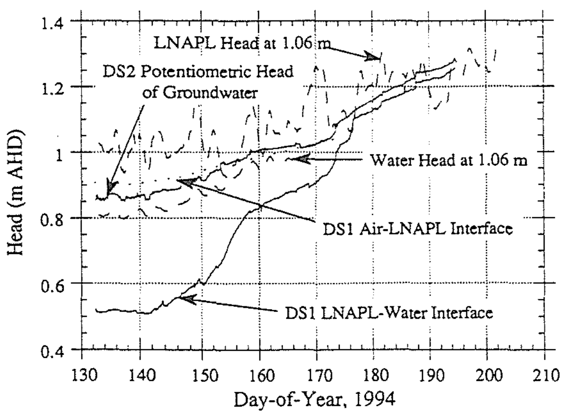

Fig. 6 Total pressure head of LNAPL and water, water level and product thickness in DS1 well, and potentiometric surface measurement in DS2 well during a rising water table.

amount of mobile LNAPL free-phase from product thickness in a well are relevant only for a limited time (4-5 days). At equilibrium, field measurements of product thickness in DS1 and thickness of mobile LNAPL in the aquifer are 0.46 and 0.25 m, respectively. Various estimates of thickness of mobile LNAPL based on product thickness in a well are 0.39 m (Lenhard & Parker, 1990), 0.37 m (Kemblowski & Chiang, 1990), 0.25 m (Sullivan *et al.*, 1988), and 0.31 m (Schiegg, 1985).

Vertical movement of LNAPL with a rising potentiometric surface

As the potentiometric surface rose during the remaining 5 months of the year, the amount of LNAPL product in DS1 decreased while the LNAPL head increased in the aquifer (Fig. 6). The subsequent potentiometric surface rise, which commenced around day 140, 1994, has resulted in a noticeable change in the LNAPL distribution. There is an absence of the 20% LNAPL saturation peak immediately above the potentiometric surface and is replaced by a more evenly distributed LNAPL saturation of 6-8% (cores 15994/1, 20294/1). After LNAPL had completely disappeared from the DS1 well, the distribution of the LNAPL is distributed evenly above the potentiometric surface at saturations of 2%, and below the potentiometric surface ranging up to 16% and averaging 7% (core 20294/1 – Fig. 3).

The rising potentiometric surface can push the LNAPL product in the well upward as a plug. It then flows back into the soil at a relatively constant rate (Kemblowski & Chiang, 1990). The rate of flow into the aquifer was being controlled by the relative hydraulic conductivity of the LNAPL at a saturation of 20% or lower. LNAPL head at 1.06 m AHD increased at a rate less than both the rate of increase of the air-LNAPL and LNAPL-water interfaces in DS1 (Fig. 6). The water head increased at a rate slightly faster than the potentiometric surface.

As the potentiometric surface rose past a hydrophobic tensiometer, the tensiometer continued to sense the pore pressure of the LNAPL. This indicates that the continuum of the LNAPL phase will exist below the potentiometric surface until the displacement pressure of water into LNAPL (0.08 m) is exceeded and the water phase traps the LNAPL phase. Once the LNAPL is trapped, the hydrophobic tensiometer will sense a pressure which is a combination of hydrostatic water pressure and a capillary pressure between trapped air-LNAPL or trapped LNAPL-water. In either case, the hydrophobic tensiometer measures a value less than true LNAPL head.

SUMMARY AND CONCLUSIONS

A hydrophobic and hydrophillic tensiometer nest has successfully monitored LNAPL and water pore pressures above a dynamic water table. Field tests showed the hydrophobicity of ceramic material lasts thousands of hours, an order of magnitude larger than in laboratory applications.

LNAPL inflow to a monitoring well commenced during a long period of seasonal water level decline. The LNAPL pressure head in the soil profile decreased at a rate corresponding to the LNAPL-water interface drop in a nearby monitoring well, i.e., faster than the potentiometric head of the groundwater. This decrease continued until a critical product thickness accumulated in the monitoring well, at which time the LNAPL head decreased at a rate proportional to the potentiometric head decline.

Subsequently, the water head at a given depth in the soil increased following the potentiometric surface rise. The LNAPL head increased at a slower rate corresponding to the rise in the air-LNAPL interface in the well. Individual tensiometers continued to sense LNAPL pore pressure until the LNAPL surrounding the tensiometer cup was displaced by water. At the time of LNAPL disappearance from the well, the hydrophobic tensiometers indicated no LNAPL at greater than atmospheric pressure above the potentiometric surface.

Cores revealed a significant difference in the saturation distribution of the LNAPL above the water table between a falling and rising potentiometric surface. The distribution above a falling potentiometric surface increased with depth and reached a maximum saturation of 20% at the elevation corresponding to the air-LNAPL interface in an observation well. The LNAPL distribution above a rising surface was a uniform saturation of 6-8%.

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