BENCH-SCALE INVESTIGATIONS ON VIBRATORY MOBILIZATION OF IMMISCIBLE LIQUID GANGLIA

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ABSTRACT Prior investigations by the principal author evaluated the feasibility of mobilizing non-aqueous phase liquid (NAPL) ganglia by inducing vibrations in a soil-NAPL-water medium. In this paper, results from bench-scale experiments are reported to provide a practical understanding of the impact of vibrations (induced with a probe-type vibrator) on relative density of the medium and on the ganglia concentrations. It is shown that the variation of ganglia concentrations in the vibrated zone are governed not only by the relative density variation but also by the uniformity of flow gradients. Non-uniform flow rates in the zone around the vibrator may result in clean-up of some areas and in accumulation of ganglia (exceeding initial residual volumes) in other areas. The results from the experiments support an integrated approach where the vibrator is augmented with a pumping mechanism yielding uniform and predictable flow gradients in the vibrated zone.

KEYWORDS: relative density, vibrations, NAPL ganglia

INTRODUCTION

Pump-and-treat processes implemented at sites contaminated with non-aqueous phase liquids (NAPLs) often leave behind discrete ganglia which are entrapped by strong capillary forces. As summarized in Mercer and Cohen [1], residual saturations of these ganglia vary within a broad range of 18 to 52 percent depending on soil, NAPL, and ground water flow conditions. It is well recognized that hydraulic gradients provided by typical pumping velocities are insufficient to dislodge these ganglia [2]. Development of innovative remedial technologies involving physical, chemical, and biological processes, to remediate NAPL-contaminated sites, is an area of active research over the recent years.

In prior studies by the principal author [3, 4], the effects of vibrations induced in a soil-NAPL-water medium were investigated in an attempt to evaluate the feasibility of vibratory remediation of NAPL-contaminated sites. Reddi [3] reported results from an exploratory study dealing with practical issues related to the implementation of vibrations at NAPL-contaminated sites. The analogy of vibratory mobilization of ganglia to an *in situ* process known as vibroflotation is brought out in this study. Reddi and Challa [4] conducted shaking table experiments to identify the fundamental effects of changes in density of soil (as a result of vibrations) on the recoveries of residual NAPL ganglia. Results from these experiments revealed that initial soil density, vibration amplitude, and flow rates in the column during vibrations govern the ganglia recovery. Recoveries of up to 88% (of the trapped NAPL ganglia) observed in these experiments encouraged further studies to conduct bench-scale experiments and to study the variation of ganglia concentrations in the vibrated zone.

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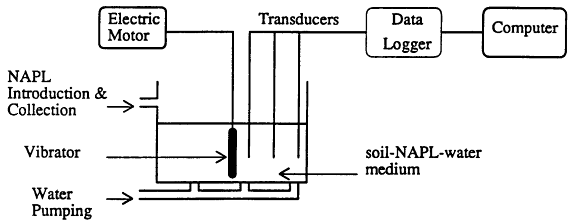

FIGURE 1. SCHEME OF EXPERIMENTS.

EXPERIMENTAL PROGRAM

The scheme of bench-scale experiments is shown in Figure 1. The experiments were conducted using a PVC circular tank of 2-ft (61 cm) height and 3.5-ft (107 cm) diameter. A commercially-available concrete vibrator with frequency control, regulated by a variable speed motor, was used as the source of vibrations. Pre-sieved Kansas river sand with a relatively uniform grain size distribution (particle size ranging from 0.05 to 0.5 mm) was used in the experiments. Soltrol-130, a colorless liquid mixture of C_{10} and C_{13} isoparaffins provided by Phillips 66 Co., was chosen as the NAPL because of its mild odor, negligible solubility in water, and relatively low volatility. The tank was instrumented with three semi-conductor transducers (GEOKON, Model:4879), which are capable of measuring pore pressures up to 15 psi (103 kN/m^2). These were placed at various radial distances from the probe and were located at the same depth (15 cm above the bottom of the tank). The purpose of these transducers was to assess the attenuation of cyclic pore pressures in the soil as a result of vibrations. A data logger, capable of recording data at the rate of 4 measurements per second, and a digital computer installed with PRONTO software, were used to store and analyze the pore pressure data. A rotary vane pump with a flow rate control was used in the experiments to pump water into the column.

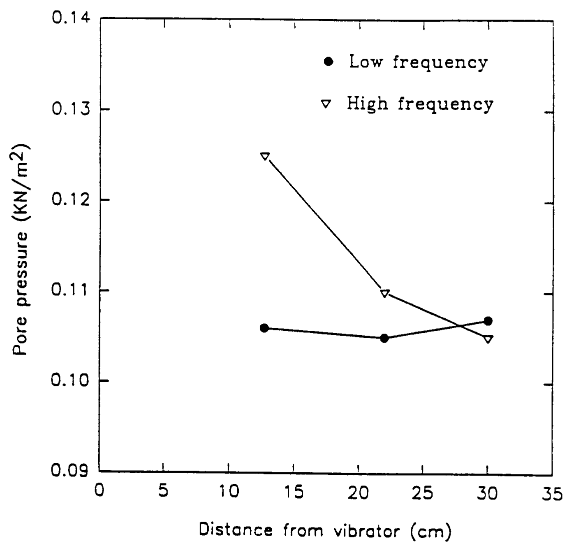

FIGURE 2. ATTENUATION OF CYCLIC PORE PRESSURES FOR TWO FREQUENCIES OF VIBRATIONS.

Trial experiments were conducted to study the attenuation of vibrations in soil-water medium and to identify a range of suitable frequencies of vibrations. The cyclic pore pressures monitored at the three radial locations are shown in Figure 2 for high and low frequencies of vibrations. The exact numbers for the two frequencies are not known; however, it is estimated from the manufacturer's literature that the eccentric weight inside the vibrator rotates at about 8,000 rpm and 3,000 rpm for the two frequencies. No attenuation of pore pressures was apparent at low frequencies, and wave reflection from the tank wall was suspected. At high frequencies, on the other hand, attenuation of pore pressures was contained entirely within the tank; therefore, these frequencies were used in the experiments on soil-NAPL-water medium.

The experimental procedure began with positioning the transducers in standing water in the tank. Two inches (5 cm) of filter material (gravel) was placed to prevent soil from clogging the ports at the bottom of the

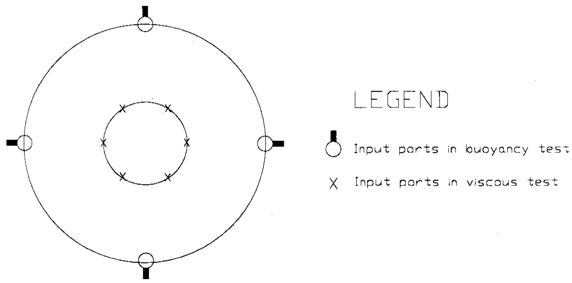

FIGURE 3. INLET PORT LOCATIONS FOR BUOYANCY AND VISCOUS TESTS.

tank, prior to pouring the sand from a constant height to a height of 1 ft. (30 cm) above the filter. One pore volume of Soltrol was then introduced at the top of standing water. The water in the tank was pumped out through the bottom ports at a relatively low flow rate (500 ml/minute) until the Soltrol front was observed in the transparent tubes connected to the ports. The tank was then backflooded at a flow rate of 1,000 ml/minute to create residual entrapment of Soltrol ganglia. The free Soltrol recovered over the standing water was collected by siphoning and its volume was measured. The volume of entrapped Soltrol was estimated by mass balance. The vibrator was then introduced at the center of the tank and the soil was vibrated at the highest frequency while maintaining the flow rate of 1,000 ml/minute. The recovered Soltrol on the top of standing water was constantly siphoned and its volume was measured. The vibrator was turned off after 20 minutes when no more Soltrol recovery was visually noticed.

After the experiment was completed, water was drained from the tank, and samples were taken at three radial distances from the center of the tank. A tube-shaped sampler, 7.5 cm in diameter, with a thin steel wall was used to obtain the samples. The soil around the tube was excavated and the tube containing soil sample was carefully removed. For each radial location, four sample slices, 5 cm in thickness, were taken at different depths to determine their relative densities. Relative densities are indicative of the void ratios, e, relative to the loosest (e_{max}) and densest states (e_{min}) and are computed as $(e_{max} - e)/(e_{max} - e_{min})$; e_{max} and e_{min} for the Kansas river sand were determined *a priori* to be 0.681 and 0.447, respectively. Three subsamples were taken from each sample slice to conduct GC analysis for Soltrol content. Hexane was used to extract Soltrol in these analyses.

In the first experiment, water was introduced through four ports located on the wall at the bottom of the tank (Figure 3). Due to compaction of the vibrated soil in the middle of the tank, which reduced permeability in that zone, the flow short-circuited along the interfacial region between soil and the wall. As a result, flow rate in this region was high enough to cause localized liquefaction of sand; on the other hand, negligible flow occurred in the compacted zone around the vibrator. This experiment will be referred to as the “buoyancy” test to imply absence of viscous forces in the compacted zone of the soil-NAPL-water medium. In the next experiment, six ports were created at the bottom of the tank on the circumference of a 1.5-ft (46 cm) concentric circle (Figure 3). Since the flow was directed into the compacted zone, this experiment will be referred to as the “viscous” test.

RESULTS AND DISCUSSION

Mass balance estimates of ganglia recovery in the buoyancy and viscous tests were 52% and 45%, respectively. These estimates do not agree with the earlier studies [4] which indicate that viscous conditions generally yield higher recoveries than buoyancy conditions. However, consideration of the flow conditions in the two tests explains this discrepancy, as discussed following.

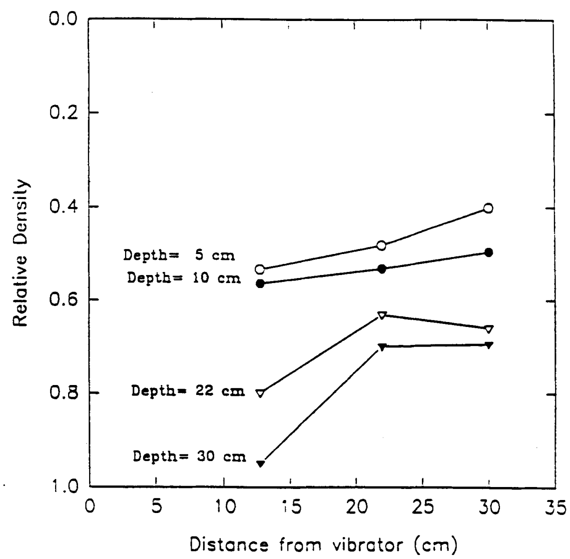

FIGURE 4. RELATIVE DENSITY VARIATION AT VARIOUS DEPTHS IN THE BUOYANCY TEST.

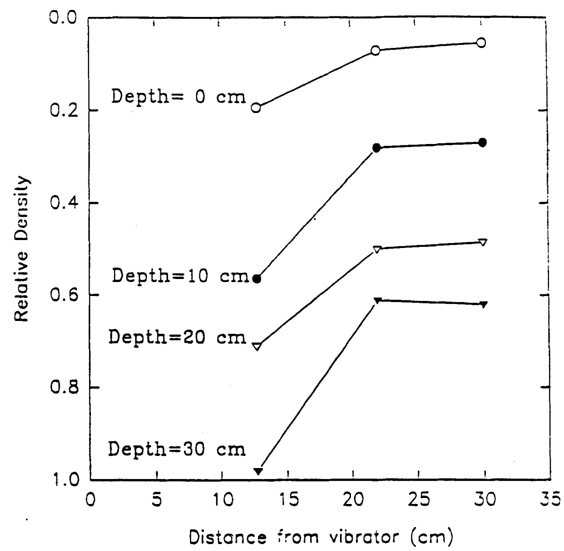

FIGURE 5. RELATIVE DENSITY VARIATION AT VARIOUS DEPTHS IN THE VISCOUS TEST.

The relative density variations for the two tests are shown in Figures 4 and 5. As seen in the figures, relative density increase is prominent within a radius of about 20 cm from the vibrator in both cases. Because the eccentric weight (source of vibrations) was located at the bottom of the probe, the deep layers were densified more than the shallow layers. In general, the overall densification was higher in the buoyancy test than in the viscous test. This might be due to the flow rates created in the compacted zone in the viscous test, which provided an upward seepage force resisting densification.

The lateral variation of Soltrol concentrations in the two tests are shown in Figures 6 and 7. The data plotted in the figures were obtained by averaging the three Soltrol concentrations measured at each location. The three values showed negligible differences for all the locations plotted in the figures. The initial concentrations shown as horizontal lines in the two figures were estimated using mass balance estimates of Soltrol entrapped in the soil prior to vibrations and assuming that the entrapped Soltrol was uniformly distributed in the soil. As seen in Figure 6, lack of viscous forces around the vibrator probe caused the residual Soltrol concentrations in that region to be higher than those near the edge of the wall. The remarkably low Soltrol concentrations near the edge of the wall were attributed to the localized liquefaction of sand, which was visually noticed during the experiments in the regions of ports through which water entered. The liquefaction of sand nullifies the capillary forces involved in ganglia entrapment and instantaneously causes the lighter ganglia to float in the liquefied sand.

In the case of the viscous test, flow through the ports created viscous forces in the middle region of the tank, and as a result, a reverse variation of Soltrol concentrations was observed (Figure 7). Soltrol concentrations in the edge region were not only greater than those near the vibrator, but were also greater than the initial concentrations. One possible explanation for

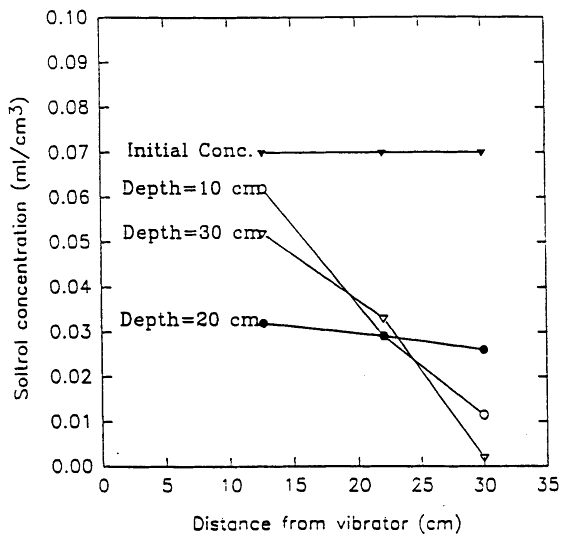

FIGURE 6. VARIATION OF SOLTROL CONCENTRATIONS IN THE BUOYANCY TEST.

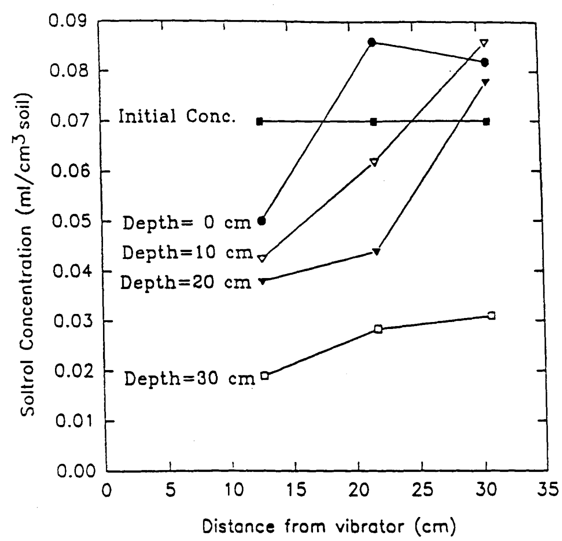

FIGURE 7. VARIATION OF SOLTROL CONCENTRATIONS IN THE VISCOUS TEST.

this behavior is as follows. The compaction of soil near the vibrator resulted in high relative densities and reduced the permeability of the medium. The reduction of permeability in turn increased the flow gradients in the zone, since the flow rate was kept constant at 1,000 ml/minute. The direction of the flow gradients, although upwards in general, was toward the uncompacted region near the edge of the wall. The ganglia dislodged in the vibrated zone were therefore mobilized to this area near the upper edge of the wall. They were subsequently stranded and accumulated because of lack of viscous forces in this area necessary to mobilize the ganglia into the standing water. Another possibility for this behavior is that the initial entrapment of Soltrol was not uniform in the tank and, therefore, Soltrol concentrations in the upper edge region of the tank might be higher than the mass balance estimates.

An important difference between the two tests lies in the relationship between the relative density and Soltrol concentration variations in the tank. The Soltrol concentration variation in the case of the viscous test was consistent with the relative density variation. Concentrations were in general lower in the deeper layers where the relative densities were high. In the case of the buoyancy test, however, no relationship was exhibited between the relative density variation and the Soltrol concentration variation. This indicates that although relative density is an important parameter representing the physical effect of vibrations, it may not always imply the zone of influence of vibratory mobilization. The uniformity of flow gradients in the vibrated zone seems to have a domination influence on the variation of ganglia concentration. These results emphasize the need for a controlled manipulation of flow gradients in the vibrated zone and justify the approach taken by Reddi [3] where the vibrator was augmented with a pumping mechanism which yielded predictable and uniform flow gradients from bottom to top of the vibrator probe. A quantitative basis to predict variation of ganglia concentrations as functions of relative densities and flow gradients is possible only when pore-scale processes involved in ganglia mobilization, such as break-up and coalescence, are considered in a theoretical framework. Ongoing network modeling studies are oriented in this direction.

SUMMARY AND CONCLUSIONS

Bench-scale experiments involving vibratory mobilization of NAPL ganglia were conducted to address practical aspects on variations of relative density and Soltrol ganglia concentrations in the vibrated zone. Higher recovery was observed in the buoyancy test than in the viscous test due to the different flow conditions in the tank. The variation of Soltrol ganglia concentrations was found to be consistent with relative density variations in the case of the viscous test; however, no relationship was exhibited in the case of the buoyancy test between the two variations. Flow gradients seem to be playing a key role in governing the variation of Soltrol concentrations in the tank. The results show that nonuniform flow gradients may result in clean-up of one area around the vibrator and accumulation in the other area. It is concluded that controlled manipulation of flow gradients is essential for success of vibratory mobilization.

ACKNOWLEDGMENTS

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