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Groundwater remediation engineering——Study on the flow distribution of air sparging using acetylene

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Abstract: Air sparging(AS) is an emerging method to remove VOCs from saturated soils and groundwater. Air sparging performance highly depends on the air distribution resulting in the aquifer. In order to study gas flow characterization, a two-dimensional experimental chamber was designed and installed. In addition, the method by using acetylene as the tracer to directly image the gas distribution results of AS process has been put forward. Experiments were performed with different injected gas flow rates. The gas flow patterns were found to depend significantly on the injected gas flow rate, and the characterization of gas flow distributions in porous media was very different from the acetylene tracing study. Lower and higher gas flow rates generally yield more irregular in shape and less effective gas distributions.

Keywords: air sparging; gas flow pattern; groundwater; radius of influence(ROI)

Introduction

Soil and groundwater contamination resulting from releases of anthropogenic chemicals has cost billions of dollars to locate and evaluate, and will cost more to clean up(EPA, 1996). There are number of techniques available to remediate contaminated soils and groundwater.

These include physical containment, *ex situ* treatment, and *in situ* treatment by various forms of physical, chemical and biological processes.

Air sparging is an *in situ* remedial technology that reduces concentrations of volatile constituents in petroleum products that are adsorbed to soils and dissolved in groundwater. This technology is considered a hybrid technology, because air can be used to physically strip the volatile and semi-volatile components out of contaminated soil and groundwater, and the oxygen in air is used to stimulate indigenous microorganisms to degrade organic compounds from contaminated soil and groundwater.

Even though air sparging has been successfully applied at many contaminated sites (Murray, 2000; Bass, 2000; Johnson, 2002; 1998), the demand for remediation technology for soil and groundwater has outstripped the development of these technologies. Results from field implementation studies are block box: they are known to work, but the actual removal mechanisms are not clearly understood. Because of this, no widely accepted rational approach to utilizing these technologies has emerged, and the approach used to clean up a contaminated site relies upon the professional judgement of the individual designer.

A working knowledge of the extent and nature of air movement through saturated soil is important in order to assist in the design of air sparging systems and the estimation of their field performance. The radius of influence(ROI) is a very important parameter to estimate the extension of treated region. The ROI is often defined as the radial distance from the well to the outer edge of the treatment zone by a given injection well(Semer, 1998).

The movement of air through a water saturated porous medium is a complex flow process, but flow visualization and flow characterization experiments can provide valuable insight into AS air distributions and how they are affected by geology and process conditions. Some flow visualization and flow characterization experiments were reported in the literature. Wei(Wei, 1993) used different sized glass beads to simulate air flow patterns under various soil conditions. Lundegard (Lundegard, 1995) used electrical resistance tomography (ERT) to estimate ROI at field site in Italia. Semer(Semer, 1998) performed laboratory air sparging experiment by using actual soils to investigate the injected air flow pattern.

This paper focuses on gas flow distributions during air sparging. The method by using acetylene as the tracer to directly image the gas distribution results of AS process has been put forward. Some of the other traces(Berkey, 2003) such as helium and sulfur hexafluoride(SF_6), were used to evaluate air distribution characterization during AS. Helium can be metered in with air injection stream to determine both the air distribution in the vadose zone and the recovery efficiency of the associated soil vapor extraction system, but its detectable levels were expected only in vadose samples not in saturation samples. SF_6 did not as handy as acetylene and its solubility only about half the solubility of oxygen was lower than acetylene's. The acetylene is chemically stable, nontoxic, and can be detected in extremely low concentrations in water samples, so it can be used to trace the appearance of injected air.

1 Experimental methodology

1.1 Experimental test setup

A two-dimensional aquifer simulation test setup(Fig.1) has been developed to study the air sparging system. In order to visualize airflow through the medium, the experiments were carried out in a plexiglas tank. The tank measures 100 cm in length, 80 cm in height, and 15 cm in width. The interior of the tank consists of three compartments; a soil chamber measuring 75 cm in length is centered within the tank and is flanked by two groundwater reservoirs, measuring 10 cm in length each. The tank reservoirs are separated from the soil chamber by a 150-mesh stainless steel screen.

On the front face of the soil chamber, twenty sampling ports are arranged in four rows of each five. Two effluent gas-sampling ports were installed into the tank cover. In the middle of tank's bottom, there were two ports. One is contaminant injection port using to inject contaminant solution into the sands prior to a test, another is gas entry port fitted with a three holes stainless steel column using as sparge point. There is one hole in the middle of column's top, and the other two arranged symmetrically at the side of column.

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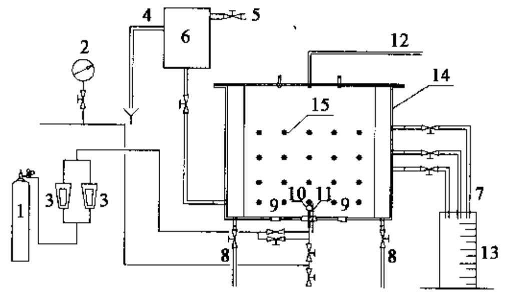

Fig.1 Acetylene experimental apparatus of air sparging
1. acetylene steel bottle; 2. pressure gauge; 3. flow meter; 4. overfall pipe; 5. water inlet pipe; 6. clean water reservoir; 7. water outlet pipe; 8. reservior drain; 9. sand removal port; 10. sparge point; 11. contaminant injection port; 12. effluent gas port; 13. measuring cylinder; 14. plexiglas tank; 15. sampling port

The diameters of holes were all 2.5 mm. Air was injected into the soil profile from the sparge point, and the effluent gas emanated into atmosphere.

1.2 Materials

The porous media used in all the experiments were 20—40 mesh quartzose sands that were sterilized by high temperature for eliminating the effect of the biodegradation and the soil adsorption. The sand characterization is given in Table 1. Acetylene was used as tracer to track the gas distribution.

Table 1 Properties of experimental soil

Parameters	Notation	Units	Values
Grain size	d	mm	0.420—0.841
Sand bulk density	ρ	g/cm^3	1.605
Porosity	Φ	-	0.336
Hydraulic conductivity	K	m/s	1.63×10^3
Permeability	k	m^2	1.95×10^{-10}

1.3 Chemical analysis

During air sparging, gastight syringe was used to extract pore water from the various ports. Port water was sampled at different time intervals to monitor the concentration profiles and analyzed using gas chromatography (GC). A Perkin-Elmer AutoSystem GC model equipped with flame ionization detector(FID, 200℃) and a PE-WAX capillary column (30 m × 0.53 mm × 1.0 μm) was employed in this work. Nitrogen was used as carrier gas at a flow rate of 3 ml/min and the oven temperature was set constant at 110℃. Split injection(split ratio 10:1; 150℃) was applied to analysis.

1.4 Testing procedure

To conduct an experiment, sands were loaded into the tank through its top using a consistent drop height and temped in order to avoid forming large interspaces and faultages. After the height of loaded sands was up to 58 cm away from the bottom of tank, the clean water infiltrated from the water reservoirs until the height of water lever reached 54 cm. Once the sands were saturated, the acetylene was continuously injected with a specified flow rate. After some times, the acetylene concentration distribution in aquifer was determined from sampling ports by gas chromatographs. In addition, a digital camera was used to record the appearance of bubbles at ground surface. After that, clean water was used to wash the sands until the acetylene concentration in the aquifer was zero. Then another injection was started at different flow rate.

2 Results and analysis

2.1 Observed air flow pattern

Acetylene was injected into the sands at flow rate ranged from 0.05 m^3/h to 0.3 m^3/h. During sparging, the height of the water level rose continuously at each flow rate. After a few seconds, new water level was established and steady state was achieved. Small bubbles were seen in the middle zone at the level of the water table. When the injection gas flow rates was increased, the bubbles appeared to be larger in size and bubbling activity region was greater, it is to say the radius of influence(ROI) was increased.

The results of the ROI measured from these bubbles at different gas flow rates are illustrated in Fig.2. The ROI was increased with increasing of flow rate, which was from 0.10 m^3/h to 0.30 m^3/h. When gas flow rate was 0.10 m^3/h, the ROI was measured 15 cm. Increasing the flow rate to 0.15 m^3/h the ROI reached to 18 cm. When the flow rate was further increased to 0.30 m^3/h, the ROI measured 37 cm. In this test, the ROI was difficult to be measured when flow rate was lower than 0.15 m^3/h, while the size of ROI exceeded the dimensionality of experimental zone of sands if flow rate was larger than 0.30 m^3/h. During field applications, such ROI increase indicated that the treatment zone of a sparging well might increase. As a result, fewer injection wells would be required for the remediation of contaminants, and the cost of remedial project would decrease.

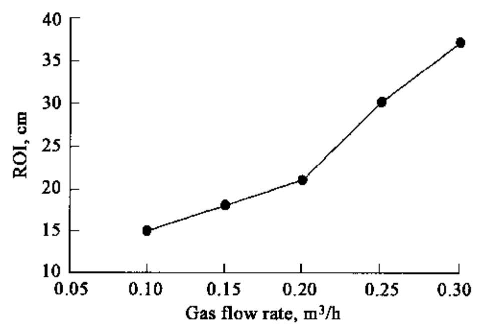

Fig.2 Radius of influence vs. gas flow rate

2.2 Gas flow distribution traced by acetylene

Fig.3, 4 and 5 show the acetylene distributions within the sands after 60 min sparging time at flow rate of 0.05, 0.15, 0.30 m^3/h, respectively. The acetylene concentrations of 20 sampling ports were measured using GC analysis, and the concentration contours were constructed by those results data using 2D cubic interposal method.

As shown in Fig.3, the zone of gas influence in sands was small, the acetylene concentrations only in two of twenty sampling ports were higher. It can be concluded that the acetylene traveled through only these two ports while other ports did not experienced gas pass. When low flow rate(0.05 m^3/h) was used, a few thin and disperse gas channels formed inside the sands. This behavior is consistent with that reported by Wei(Wei, 1993), which used beads to simulated soil.

When the sands were subjected to 0.15 m^3/h flow rate, the acetylene traveled through the voluminous regions of sands except the left and right of lower regions as shown in Fig.4. It can be seen that the gas equably distributed and the whole gas plume formed a roughly symmetrical parabolic structure. The gas was denser and the concentration gradients were

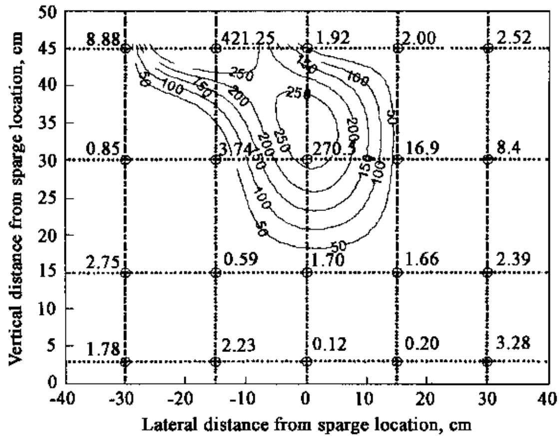

Fig.3 Acetylene concentration profiles; flow rate = 0.05 m^3/h

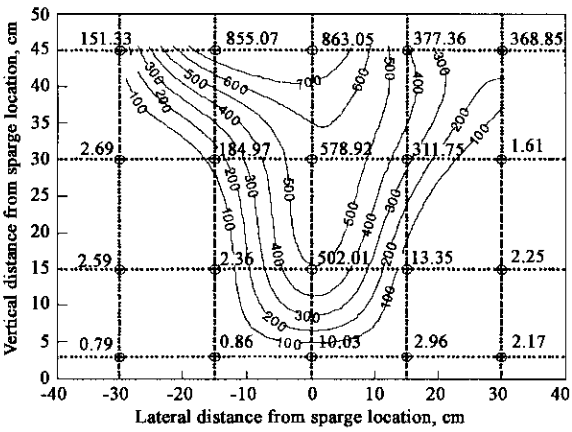

Fig.4 Acetylene concentration profiles; flow rate = 0.15 m^3/h

lower in the middle of parabolic plume at 0.15 m^3/h flow rate, while it was reverse at the edge of the plume. In addition, Fig.4 depicts the size of ROI increased much at flow rate of 0.15 m^3/h than that at 0.05 m^3/h in contrast with Fig.3 as mentioned above.

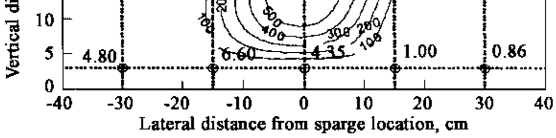

Fig.5 Acetylene concentration profiles; flow rate = 0.30 m^3/h

In Fig.5, it is appeared that when 0.30 m^3/h flow rate was used, the acetylene plume in middle and lower region of sands traveled slowly forward right region, while that in upper region leaned to left. So the gas distribution was very asymmetrical and easily traveled along a path of least resistance if higher gas flow rate was used. From these results, it can be concluded that increasing gas flow rate will increase the gas-phase saturation and the size of the ROI, eventually increase contaminant removal efficiency. On the other hand, airflow distributions may be irregular in shape and there may be preferred directions of flow at higher flow rate. Moreover, high gas flow rate do not serve to remove the contaminant more efficiently and may be unnecessary.

3 Conclusions

Gas flow distributions in porous media were studied experimentally using acetylene tracer. The experimental results showed that the ROI of air sparging was increased with the increasing of gas flow rate. When low flow rate(0.05 m^3/h) was used, a few thin and disperse gas channels formed inside the sands. When gas was injected at 0.15 m^3/h, the gas equably distributed and the whole gas plume formed a roughly symmetrical parabolic structure. The gas was denser and the concentration gradients were lower in the middle of parabolic plume at that flow rate, while the things were reverse at the edge of the plume. When added to the flow rate to 0.30 m^3/h, the gas plume was very asymmetrical and easily traveled along a path of least resistance.

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