Beneficial Use of the Upwelling Phenomenon in Coal-tar Remediation Efforts

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INTRODUCTION

Manufactured gas plants (MGPs) were in operation in the State of New Jersey from about 1850 until the early 1930s. Manufactured gas or 'coal gas' was extensively used for cooking, lighting and heating and was produced by blowing air and steam through a coal bed at high temperature. Large gas holders constructed of steel, commonly emplaced deep in the subsurface, were used to produce and store the gas.

One by-product of coal gasification is a dense, viscous substance known as coal-tar which is commonly the source of many environmental problems in New Jersey. Coal-tar was often disposed of haphazardly and due to its high density, migrated downward causing significant contamination of groundwater supplies. Coal-tar is a dense, non-aqueous phase liquid (DNAPL) which, when released into an aquifer, can migrate downward until a low-permeability layer is encountered. Pools of coal-tar may be encountered at the bottom of an aquifer, becoming a continuous source of groundwater contamination.

The purpose of this paper is to show that the physical phenomena observed during the upwelling of saline water, such as in coastal aquifers, can be applied in coal-tar recovery operations. Field data of coal-tar upwelling from an MGP site in New Jersey are applied to the salt water upwelling methodologies used in coastal aquifers.

SITE CHARACTERIZATION

Site history

Between 1870 and 1930, an MGP site existed along the Hudson River in northern New Jersey. Coal gas was produced in four underground, steel tanks which extended to a depth of approximately 8 m below ground surface (bgs). The gas was piped to residences, industries and utilities through suburban New York City.

Environmental investigations

Between 1980 and 1995, environmental investigations were conducted at a manufactured gas plant in northern New Jersey. Forty-eight monitoring wells were installed and up to 5 m of coal-tar were detected at the bottom of a glacially-derived aquifer. Liquid-phase coal-tar had migrated approximately 100 m from the former gas holders, towards the Hudson River. Based on the thickness and horizontal extent of the coal-tar, it was estimated that up to 650 000 litres of liquid phase coal-tar were present in the subsurface at a depth of over 12 m bgs. Pilot tests were conducted in 1991 and 1994 to evaluate the pumping rate of the coal-tar saturated zone.

Environmental setting

There are four distinct geologic units beneath the MGP site. In descending stratigraphic order, the units are: fill, alluvial sand and clay, glacial till and bedrock.

The fill overlies the entire MGP site and consists of a heterogeneous mixture of sand, silt, clay and gravel with coal, ash, cinders, glass, asphalt, wood, concrete and brick with an average thickness of 5 m. The alluvial sand and clays are also continuous across the MGP site and are likely a remnant of streams and wetlands located along the Hudson River. The thickness of the alluvial layer is 2 to 4 m.

Glacial till, ranging in thickness from 3.5 to 10 m, underlies the entire MGP site and is composed of poorly-sorted silt, clay and sand with varying amounts of gravel and boulders. The till layer is believed to be composed of two units: an upper, ablation till with a higher relative permeability; and a lower, dense lodgement till with a very low permeability. Bedrock consists of a thin bed of arkosic sandstone and conglomerate which overlies serpentinite and schist.

Based on water level measurements collected from on-site monitoring wells, groundwater occurs at a depth of 3 to 4 m bgs. The groundwater flow direction is east, towards the Hudson River. Pumping tests completed with the monitoring wells indicated that the hydraulic conductivity (K) of the till zone was approximately 4 m per day.

Contaminant characteristics

Laboratory analysis of the liquid-phase coal-tar indicated that benzene, toluene, xylenes and napthalene were the predominant volatile components, while phenanthrene, acenaphthylene and fluorene were the predominant semi-volatile components. The density of the coal-tar (ρ_{CT}) was 1.06 grams per cubic centimetre (gm/cm^3), while the viscosity (μ_{CT}) ranged from 25 centistokes (cS) at 0°C to 5.7 cS at 22°C.

PILOT TESTING

In 1991, single-phase and double-phase pumping tests were conducted on the two monitoring wells which exhibited the largest quantities of liquid-phase coal-tar. In 1994, the double-phase test was repeated using a wider diameter recovery well. During the single-phase tests, only coal-tar was pumped, while during the double-phase tests, both coal-tar and ground water were removed using two pumping systems. The purposes of the tests were to determine:

- if coal-tar could be recovered without the pumping of groundwater;
- if coal-tar could be recovered using the double-phase method; and
- if coal-tar could be upwelled by the pumping of groundwater, thereby increasing the coal-tar recovery rate.

The results of the single-phase pilot tests indicated that coal-tar could not be recovered. Under these pumping conditions, the coal-tar recharge rate was very small, less than 0.01 litres per minute. The double-phase tests indicated that coal-tar could be upwelled at a groundwater pumping rate of 1.5 litres per minute, coal-tar upwelled approximately 2 m and the coal-tar recovery rate was approximately 0.6 litres per minute.

ANALYTICAL METHOD FOR PREDICTING COAL-TAR UPWELLING

In the 1950s and 1960s, several Israeli researchers devised analytical methods for predicting the magnitude of salt water upwelling. Along coastal areas, overpumping of water supply wells caused upwelling of deeper salt water. The researchers determined that to properly manage the water supplies, the optimum pumping rates must be known in order to maximize the quantity of water removed and prevent excess upwelling of salt water. The purpose of these activities was to prevent upwelling, however, this upwelling phenomenon can be used to facilitate the removal of coal-tar impacted sites.

At coal-tar impacted sites, a layer of liquid phase coal-tar typically exists on top of a low-permeability layer which is overlain by water. When water is pumped above a pool of coal-tar, the weight of the water column decreases, thereby producing a pressure gradient. As a result, the coal-tar moves upward and rises to an equilibrium point.

Schmorak and Mercado (1969) determined that upwelling of the salt-water interface could be predicted with the following equation:

$$Z\,(r = 0;\, t \to \infty) = \frac{Q}{2\pi d\,(\Delta p/p)\,K_x} \qquad (1)$$

where Z is the ultimate rise of salt-water interface, r is the distance from the pumping well, t is time, Q is the groundwater pumping rate, d is the distance between the well's bottom and the interface at t = 0, $\Delta p/p$ is the dimensionless density difference between the two fluids and K_x is the horizontal hydraulic conductivity.

The following assumptions were used to to predict the magnitude of coal-tar upwelling:

1. K_x can be converted to a coal-tar conductivity (K_{CT}) using known values for p_{CT} and μ_{CT} and the following equation:

   $$K_{CT} = kp_{CT}g/\mu_{CT} = K_x\mu_w p_{CT}/\mu_{CT}p_w \qquad (2)$$

   where g is the gravitational constant and k is the intrinsic permeability (Freeze and Cherry 1979). Equation (2) can be solved using known values for K_x, water density (p_w), water viscosity (μ_w) and k. Assuming a K_x of 4 m per day, K_{CT} is estimated at 0.33 m per day.
2. The coal-tar is not compressible and upwelling is caused solely by pressure gradients.
3. Coal-tar physical characteristics, such as p_{CT} and μ_{CT} are constant and do not fluctuate based on pressure and temperature changes.
4. The coal-tar chemical characteristics, which will influence the physical characteristics, are also constant.
5. d is the distance between the water pump and the coal-tar interface. d was 4.3 m during the 1991 test and 2 m during the 1994 test.
6. The recovery well is 100% efficient and, therefore, drawdown values obtained from the well reflect actual conditions in the aquifer.

During the 1991 double-phase test, groundwater was pumped at a rate of 2.6 litres per minute and the coal-tar interface was upwelled approximately 2.5 m. Based on known values for d, Q, p_w and p_{CT} and the estimated value for K_{CT}, the magnitude of upwelling predicted by equation (2) is 2.2 m.

During the 1994 double-phase test, groundwater was pumped at a rate of 1.5 litres per minute and the coal-tar interface was upwelled approximately 2 m. The magnitude of upwelling predicted by equation (2) is 2.8 m.

CONCLUSIONS

- The pumping of groundwater over a pool of liquid-phase coal-tar causes pressure gradients to develop. The pressure difference induces coal-tar to upwell, thereby increasing the coal-tar recovery rate.
- The upwelling of a pool of liquid-phase coal-tar is comparable to the salt water upwelling phenomenon observed in coastal aquifers. The analytical methods developed to manage salt water upwelling have been applied to predict the feasibility and potential efficiency of coal-tar remediation efforts.

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