In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes

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Vertical Circulation Flows for Vadose and Groundwater Zone In Situ (Bio-)Remediation

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ABSTRACT

Vertical circulation flows have been established under in situ remediation techniques. Their hydraulic flow field permits physical and biological remediation of the saturated, as well as the unsaturated subsoil. A special advantage is that these techniques can be combined with any appropriate in-well or on-site technique. Even addition of nutrients and/or electron acceptors for stimulating biological degradation processes are possible. This paper discusses the different remediation techniques and the numerical results associated with the influence of hydrogeologic conditions on the system's radius of influence and time behavior.

INTRODUCTION

Because of the risk of groundwater and soil contaminants to humans and the environment, a strong effort has been made over the last decade to find innovative in situ remediation techniques and to improve existing methods to remove the contaminants. In situ techniques are less threatening to the environment and can be cost-effective systems. Furthermore, alternatives to pump-and-treat techniques, which have been proven inadequate in many cases, are needed (U.S. EPA 1989a, 1989b). Various existing methods are convenient for handling saturated or unsaturated soil. In the unsaturated zone, soil air is used as a solvent and transport medium for contaminants, and analogous free groundwater is used in the saturated zone. Whereas some treatment methods are based only on physical cleaning, others are supported by biological degradation processes (Hinchee 1994).

Vertical circulation flows around wells with at least two screen sections are universally applicable remediation tools. They are employed in several techniques, e.g., the groundwater circulation wells (German: Grundwasser-Zirkulations-Brunnen [GZB]), the vacuum vaporizer well (Unterdruck-Verdampfer-Brunnen [UVB]), and the groundwater flushing circulation well (SZB). Within the well, the groundwater moves vertically. The contaminated groundwater enters the well at the bottom, and stripped or treated water leaves at the top or vice versa. In the vicinity of the well, an area of vertical flow circulation is created. One well should be used to remediate only one aquifer (confined or phreatic) and should not connect different aquifers.

VERTICAL CIRCULATION FLOWS FOR PHYSICAL IN SITU REMEDIATION

At numerous sites in Germany and more recently in the United States, the UVB technique has been used for in situ groundwater remediation where the underground is contaminated by strippable substances such as the volatile chlorinated hydrocarbons benzene, toluene, ethylbenzene, and xylenes (BTEX). As an alternative to conventional hydraulic redevelopment measures (pumping, off-site cleaning, and reinfiltration), the contaminated groundwater is stripped by air in a below-atmospheric pressure field in the UVB. In the case of contamination heavier than water (DNAPL) an upward operating UVB (Figure 1) is used, whereas for lighter compounds (LNAPL) the well works downward. Often the well is used for vapor extraction at the same time to support the remediation of the vadose zone as demonstrated in Figure 1. The contaminated air is cleaned by using activated carbon or, in the case of suitable contaminants, by using biofilters.

Through this technique, groundwater is pumped/injected along one screen in a well and withdrawn at another screen at another location in the same well to induce circulation. No water comes out of the soil, thus reducing the risk of further pollution. The well casing is divided by a separating plate into a lower and an upper part. A pump transports the water from the lower section to the stripping area (Figure 1). This causes a potential gradient between the two screen sections, which induces the circulation flow in the aquifer. Additionally, soil air is drawn from the surrounding contaminated unsaturated zone at many sites. Stripped air and soil air are transported through the ventilator and across activated carbon, onto which the contamination is adsorbed. Thus, only clean air escapes into the atmosphere. The cleaning effect of the well is based on (1) the high concentration gradient between water and clean air; (2) the considerable surface area of the air bubbles as a result of the air intermixing; and (3) the reduced pressure, which reinforces the escape of volatile contamination out of the water.

The cleaned groundwater leaves the well casing through the upper screen section in the reach of the groundwater surface, which is lifted in a phreatic aquifer by the previously explained pump processes and the below-atmospheric pressure (Figure 1). The groundwater then returns in an extensive circulation to the well bottom or the upper screen, respectively. In this way, the aquifer material surrounding the well also is remediated. The artificial groundwater circulation determines the sphere of influence of a well and overlaps the natural groundwater flow.

VERTICAL CIRCULATION FLOWS FOR IN SITU BIORESTORATION

When the groundwater is contaminated by other than strippable substances, which are suitable for bioreclamation, the extensive circulation flow around the UVB can be used to bring nutrients and/or electron acceptors to all places within the circulation cell, where they are needed. Any appropriate gaseous or liquid substance that is soluble in water can be added in measured quantities while the groundwater passes the well casing. In this case the aquifer itself is used as a bioreactor. For in situ bioremediation of many contaminants, oxygen is essentially needed. The in situ stripping process with air of a UVB provides oxygen saturation. While the quantity of groundwater captured by a well remains

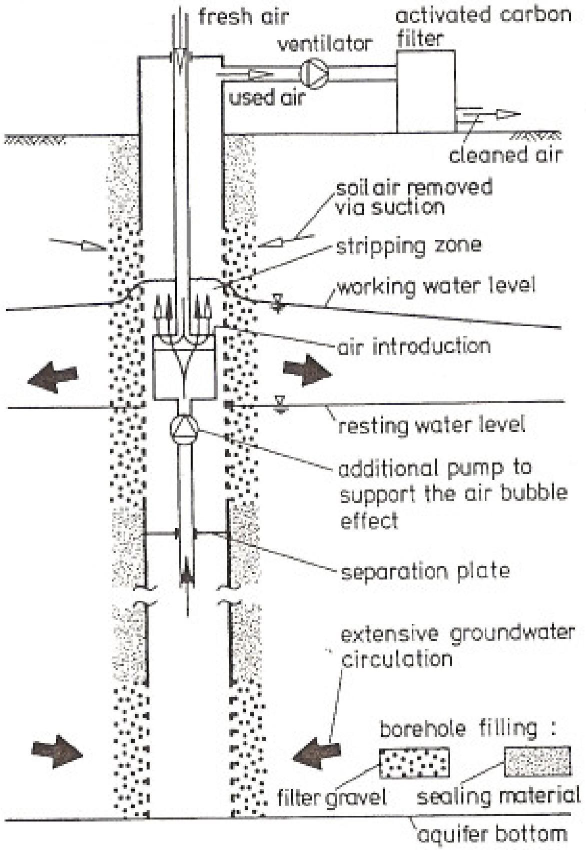

FIGURE 1. In situ stripping by a UVB operating upward for DNAPL (e.g., PCE, TCE).

relatively constant, the quantity of circulating water around the UVB can be extremely enhanced by a stronger pump in the well casing which results in a faster rotation velocity of the circulation flow. Thus, the amount of oxygen supplied for in situ bioremediation can be considerably increased. Carbon dioxide as a by-product is removed from the groundwater by the same stripping process, so new problems don't arise due to a drop in pH value. The contaminated air is cleaned by using activated carbon or biofilters. A UVB technique that combines vapor extraction with the stripping process is generally used for those sites. It supplies oxygen to the vapor zone and capillary fringe for biodegrading processes.

On the other hand, a special bioreactor has been installed within the well casing between the lower and upper screen in the case of a triazine contamination (Buermann et al. 1992). The vertical circulation delivers the hydraulic flow field which transports the contamination from the surrounding aquifer into the well. Here the pesticide is adsorbed within the in-well bioreactor and, after reaching the bioavailable concentration, is biodegraded.

An analogous treatment of groundwater contaminated by nitrate is possible. The use of in-well containers, in which a catalytic reduction of nitrate to N_2 by immobilized enzymes occurs, enabling the elimination of nitrate from the groundwater. The dissolved N_2 is finally removed via in situ stripping using the UVB technique. The technique has been developed at the laboratory scale and is being prepared for field applications (Mellor et al. 1992).

GROUNDWATER FLUSHING IN THE UNSATURATED ZONE

In the unsaturated zone, bioremediation is influenced by the soil moisture content. For most biological degradation processes, the optimal water content is in a range between 50% and 80%. When the vadose zone is contaminated with light, nonaqueous-phase liquids (LNAPLs; e.g., diesel, BTEX, mineral oil), the groundwater flushing circulation well (SZB) makes it possible to establish an adjustable, vertical, unsaturated multiphase flow in the contaminated region (see Figure 2). The flushing water is pumped from the upper saturated groundwater zone and/or the capillary fringe to a reactor situated at the upper end of the well casing near the ground surface. The water enters the otherwise closed casing through a local screen at that height. At the reactor, the water is (optionally) stripped with air in a vacuum. Before stripping, nutrients can be added for bioremediation processes or tensides for an enhanced flushing process. The stripping with air leads to oxygen saturation of the water.

Before the water leaves the reactor zone, it flows through a zone with a special granulated material separating the LNAPL from the water; LNAPL remains on top of the granulated material and can be recovered as free product from time to time. The vacuum in the reactor leads to a vacuum pressure distribution under the filter material, which dictates the unsaturated inflow conditions. Therefore, a vertical, circular, unsaturated multiphase flow occurs. A "dynamic water mound" with adjustable flushing water saturation is produced around the well, and leads to the uniform distribution of nutrients and oxygen within its sphere of influence.

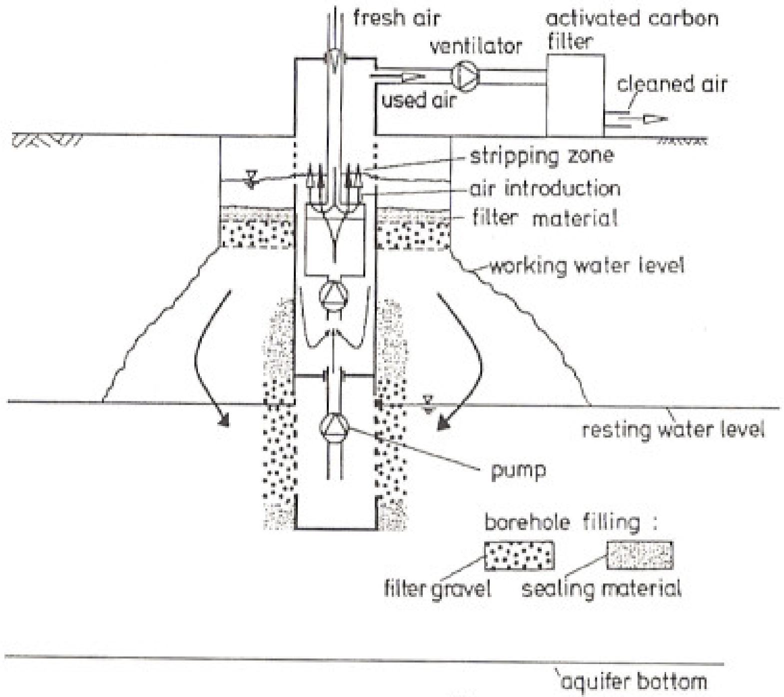

FIGURE 2. Groundwater flushing circulation well (SZB) for remediation of the vadose zone and capillary fringe. Various circulation flow patterns are possible.

Table 1 shows an overview of possible applications of vertical circulation flows in the vadose and groundwater zone for different contaminants. It does not claim completeness. All UVB and GZB systems can be employed for source as well as for plume restoration. The SZB-technique focuses on point-source treatment in the vadose zone and the capillary fringe.

NUMERICAL INVESTIGATIONS

In this paper, only flow for confined aquifer conditions is demonstrated. In the computations the local below-atmospheric-pressure field (in case of a UVB) was neglected. Further, density effects were ignored; only steady-state conditions were taken into account, and, to estimate the capture zone, only convective

TABLE 1. Overview of vertical circulation flow applications.

Contaminants	Technique	Method	Special Features	Zone of Applicability
VOCs				
DNAPLs (e.g., PCE, TCE, VC)	upward operating UVB(a)	physical in situ stripping plus aeration/biodegradation	vapor extraction soil-air treatment	groundwater and vadose zone
LNAPLs (e.g., BTEX, kerosene, phenol)	downward operating UVB	physical in situ stripping plus aeration/biodegradation	vapor extraction soil-air treatment	groundwater and vadose zone
Nonvolatiles				
NAPLs	UVB/GZB(b)	aeration/biodegradation	addition of nutrients (gaseous or liquid)	support of biological degradation within the aquifer
DNAPLs (e.g., creosote, PCP)	UVB/GZB	biodegradation with in situ bioreactor	second pump system	free product recovery
Other biodegradable substances	SZB(c)	air-water flushing in the vadose zone	addition of nutrients	biostimulation and degradation of residual contaminants
	SZB		combination with UVB possible	treatment of water-saturated zone
Pesticides, nitrate	UVB/GZB	bioreactor (e.g., activated carbon, enzymatic biodegradation)	in-well bioreactors	water-saturated zone
				anaerobic degradation

(a) UVB: vacuum vaporizer well.
(b) GZB: groundwater circulation well.
(c) SZB: groundwater flushing circulation well.

transport was considered. All necessary diagrams for sizing a vertical circulation flow system, even for partial extraction or infiltration, are published by (Herrling & Stamm 1992).

The general character of vertical circulation flow is shown in Figure 3. In a vertical longitudinal section parallel to natural groundwater flow, streamlines and isopotential lines mark the flow around one (Figure 3a) and two (Figure 3b) upward-pumping UVBs or GZBs, which are separated by the distance S between the stagnation point and the well axis. The shape of the isopotentials (dashed lines in Figure 3a) indicates the reach of hydraulic influence of the circulation system. In a distance of approximately 4H (H = aquifer thickness), the isopotential lines are rather vertical, i.e., they are unaffected by the well. The strong vertical circulation flow, which is extremely beneficial in a highly polluted area near the contamination source, is evident even between the two wells (Figure 3b). Two wells aligned in the flow direction can be used to generate an anaerobic biodegradation zone around the first circulation well (GZB without air stripping, but with carbon source added within the well casing) and an aerobic zone with an UVB around the second well. Figure 3c demonstrates the flow pattern in a stratified aquifer with three layers, where the anisotropy K_H/K_V of each layer is equal to five (ratio between horizontal and vertical permeability) and the middle layer is ten times less permeable than the upper and lower one. It is obvious that stratification enlarges the circulation flow zone.

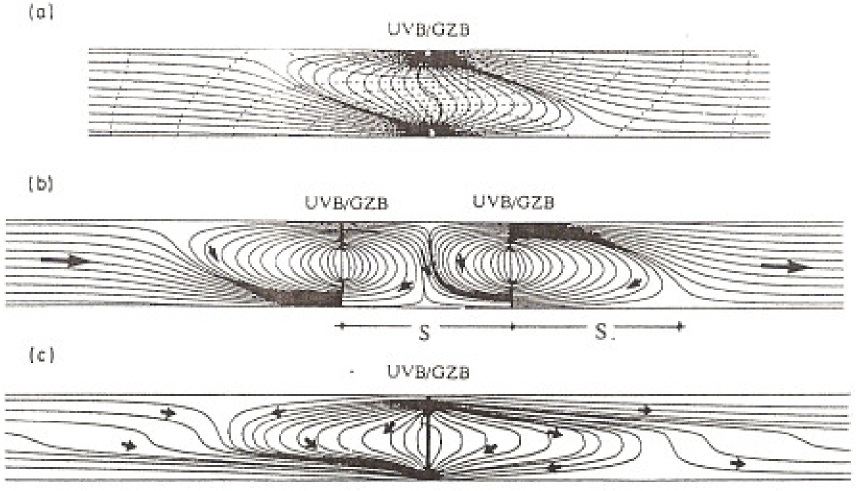

FIGURE 3. Streamlines and isopotential lines around (a) one UVB or GZB and (b) two UVBs or GZBs in a homogeneous aquifer, and (c) in a layered aquifer, shown in a vertical longitudinal section parallel to the natural groundwater flow.

INFLUENCE OF HYDROGEOLOGY

In a simulated test aquifer with seven equidistant horizontal layers, the influence of layering was investigated. Each layer has a thickness, d, and has a realistic anisotropy of $K_H/K_V = 5$ (Figure 4). The model was used to determine the influence of a single layer in various positions and with various permeabilities. The parameter α is introduced to define the decadal logarithmic ratio between the hydraulic permeability of the layer and of the entire aquifer ($\alpha = 1$ means the permeability of the layer is ten times higher than the permeability of the aquifer).

Figure 5 demonstrates the effect of layer position and ratio of permeability, α, on the effective anisotropy of the whole system. In the absence of natural groundwater flow, for example, the sphere of influence of a GZB with a central layer ($d = H/7$) that is 100 times less permeable than the ambient aquifer ($\alpha = -2$) is identical to the radius of influence in a homogeneous aquifer with an anisotropy of $K_H/K_V = 140$ and the same overall thickness H (Figure 5). As the anisotropy increases, the radius of influence of a GZB also increases. The case $\alpha < 0$ leads to a rapid increase in effective anisotropy, whereas for $\alpha > 0$ the changes are negligible. Furthermore, it is obvious that the closer the layer is to the middle of the aquifer (pos. 0), the higher its influence on the circulation flow regime.

One consequence of increasing effective anisotropy, accompanied by enlarging circulation cell diameters, is a decrease in circulation velocity. Figure 6a shows, in a dimensionless form, the dependence of the effective anisotropy (K_H/K_V) on the relative circulation quantity (Q_{Tzirk}/Q) within a certain travel time T_{Zirk}. This diagram permits determining the percentage of circulating water Q_{Tzirk} within a definite time from the total well discharge Q. Qualitatively with increasing anisotropy the quota Q_{Tzirk}/Q decreases for a fixed time.

The knowledge of Q_{Tzirk}/Q, or in a more common form Q_r/Q (defines the portion of Q that circulates within a radius r around the well), allows a determination of corresponding radius r (see Figure 6b), over which this percentage of Q circulates during the time T_{Zirk}. From these data it is possible to determine the supply of nutrients over time and location. For the case where natural groundwater flow is present, several diagrams are available.

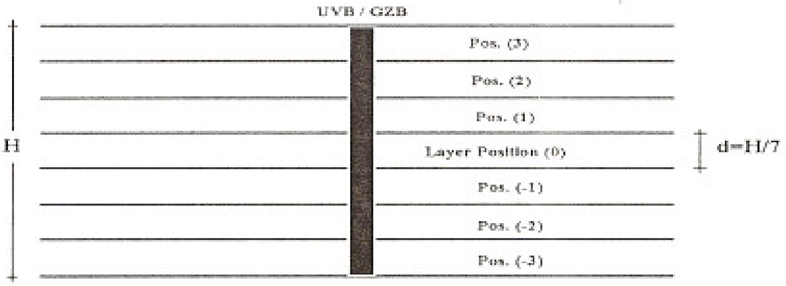

FIGURE 4. Test aquifer for numerical simulations with seven layers.

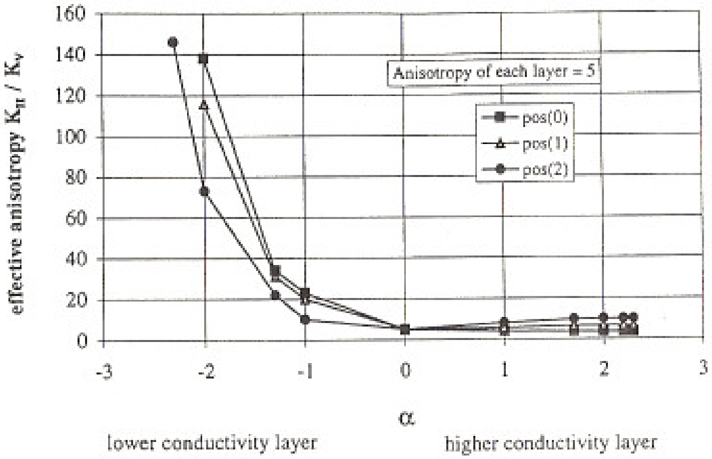

FIGURE 5. Effective anisotropy of an aquifer as a function of the position and permeability ratio of an intermediate layer vs. overall homogeneous medium.

CONCLUSION

The broad applicability of vertical circulation flow systems around groundwater circulation wells (GZB) has been summarized for various in situ and remediation techniques. The modular concept of the presented technique allows many system variations and their respective adaptations to specific site requirements. By means of numerical computations, diagrams based upon dimensionless parameters have been created that enable the sizing of vertical circulation flow remediation measures in a layered aquifer. It has been shown that the effect of a layer is equivalent to an increasing effective anisotropy for a homogeneous medium.

ACKNOWLEDGMENTS

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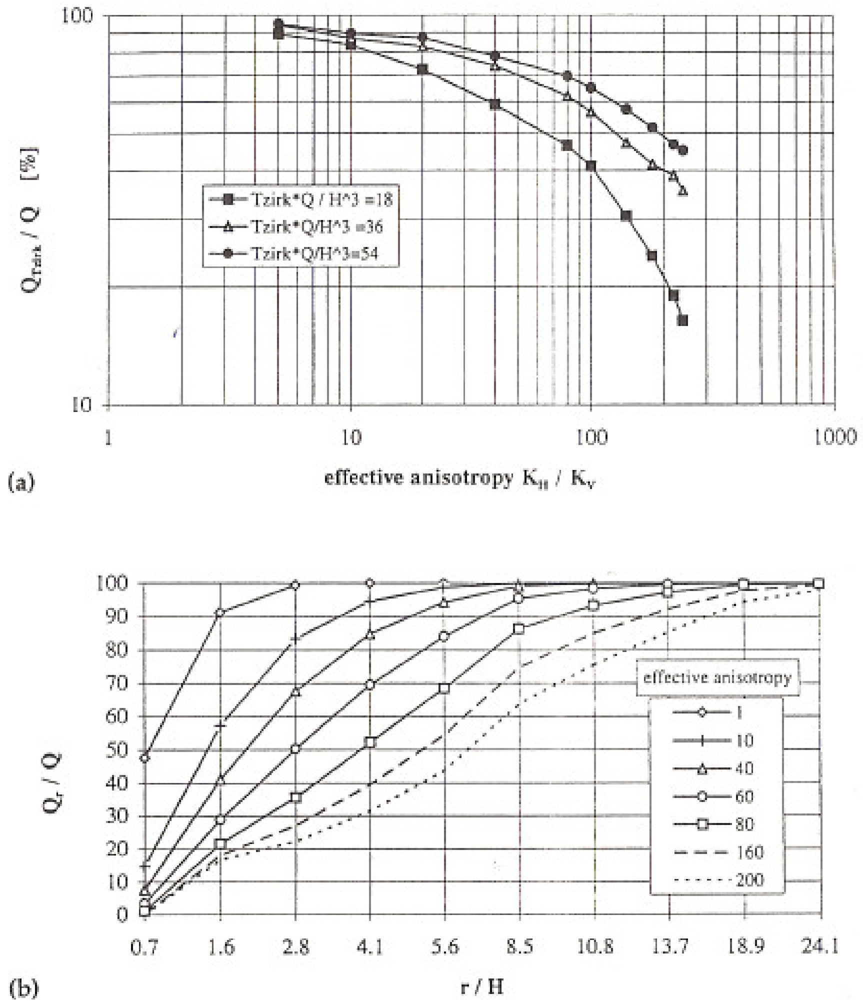

FIGURE 6. **(a) Ratio of circulation quantity (Q_{Tzirk}) within a definite time to total well discharge (Q) vs. effective anisotropy (K_H/K_V). (b) Ratio of circulation quantity within a definite radius (Q_r) to total well discharge (Q) vs. relative well distance (r/H) for several effective anisotropies.**

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