The transformation and migration of contaminants during the remediation process of heterogeneous strata by the in-situ thermal conductive heating (TCH) technology: A literature review

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Abstract: There are currently large quantities of heterogeneous contaminated sites and the in-situ thermal conductive heating (TCH) technology have been widely used in soil remediation. Some engineering cases have shown that when soil remediation of heterogeneous sites use TCH technology, the gases carrying contaminants migrate laterally and contaminate clean areas. However, there are relatively few domestic studies on this phenomenon. Some international scholars have confirmed the occurrence of this phenomenon on the laboratory scale, but have not proposed an effective solution to the above scientific question. This study first introduced the heating mechanism and heating process of TCH. Meanwhile, the forms and transformation mechanism of organic contaminants were fully expounded during soil remediation by TCH. In addition, the formation, migration, accumulation, and lateral diffusion of gaseous contaminants were comprehensively reviewed during the in-situ thermal desorption of heterogeneous strata. Finally, arrangement methods of extraction pipes to effectively capture gas are provided for the heterogeneous contaminated soils remediated by TCH. The results of this study will provide theoretical and technical support for in-depth understanding of steam movement in heterogeneous formations and the remediation of heterogeneous contaminated sites by TCH technology.

Introduction

With the acceleration of urbanization, soil and groundwater are facing serious environmental pollution. The soil environment is a gathering place for hydrophobic organic pollutants. Soil contamination caused by VOCs, SVOCs and DNAPLs has become a global environmental problem (Tang et al. 2015, Heron et al. 2016). At present, traditional in-situ remediation technology, such as in-situ chemical oxidation and soil vapor extraction, mainly rely on groundwater hydraulic gradients to either facilitate remediation agents or the spread of pollutants. When these technologies are applied to the heterogeneous subsurface, they can only effectively reduce the contaminant concentrations in the high permeability layer, while in medium and low permeability layers, their removal is limited by mass transfer (Heron et al. 2013). Compared with the above technologies, the in-situ thermal desorption technology utilizes thermal energy to heat the soils and change the thermodynamic state of contaminants to remove them from soils. It is not as sensitive to soil permeability, and even has good remediation effects for soils with the low and medium permeability layers (Zhao et al. 2014, Hiester et al. 2013).

The in-situ thermal desorption technology selectively promotes the gasification and volatilization of contaminants by controlling the system's temperature and heating time (Baker and Heron 2004, Biache et al. 2008). According to different heating methods, it is usually divided into electrical resistive heating (ERH), thermal conduction heating (TCH), and steam enhanced extraction (SEE) (Oberle et al. 2015). Among them, TCH can heat up to 800°C and can treat most organic pollutants, including LNAPLs and DNAPLs, such as BTEX, chloro-carbon solvent, TPH, PAHs, PCBs, etc. (He et al. 2021, Anna et al. 2006). In addition, TCH has the lower sensitivity to underground matter, whereas the heating effect of ERH will be affected by underground metal impurities; and the low soil permeability will interfere with SEE. The exhaust gases from TCH need to be treated before being discharged. The waste gas is concentrated into the concentration recovery

system through the extraction well, and after gradual condensation and gas-water separation, the waste gas enters the adsorption system and is discharged after treatment, the wastewater is discharged after being treated by the wastewater treatment system.

In practical engineering, heterogeneous sites are common, and homogeneous sites are almost non-existent. Some engineering cases have shown that when soil remediation of heterogeneous sites uses TCH technology, pollutants-carrying gases migrate laterally and move outside the target treatment area to contaminate the clean area. (Jennifer et al. 2010). Most current laboratory studies on in situ thermal remediation have focused on homogeneous, highly permeable materials (Hicknell et al. 2018, Hegele and Mumford 2014). Limited studies focusing on low-permeability materials are conducted in homogeneous systems (Martin and Kueper 2011, Munholland et al. 2016), and the removal of pollutants in heterogeneous media is less studied. Laboratory studies by some international scholars have confirmed that pollutants-carrying gases accumulate under low-permeability soil layers and migrate horizontally when using ERH technology remediation heterogeneous soil (Martin et al. 2016, Martin et al. 2017). However, to date, no reasonable solution has been proposed for this phenomenon. Therefore, it is urgent to understand how the site is heated, and how the steam generated in the heterogeneous system migrates during thermal remediation. Therefore, this review aims to cover the following aspects: (i) describe the heating mechanisms and process of soils remediated using TCH technology; (ii) expound on the forms and transformation mechanism of contaminants; (iii) comprehensively review the formation, migration, accumulation and lateral diffusion of gaseous contaminants during the in situ thermal desorption of heterogeneous strata; and (iv) propose laying methods of extraction wells for effective gas capture aiming at the inhomogeneous contaminated soil remediated by TCH. The results of this study will provide theoretical and technical support for in-depth understanding of steam movement in heterogeneous formations and the remediation of heterogeneous contaminated sites by TCH technology.

Mechanisms of heating process

The core of TCH remediation lies in the two processes: the heating temperature of soils and the generation and collection of pollution gases. More than 90% of contaminants in the treatment zone are removed in the gas phase (Vermeulen and McGee 2000). TCH can be divided into gas heating and electric heating. Gas heating, usually fueled by natural gas or liquefied petroleum gas, heats the surrounding soil in the form of thermal conduction. The electric heater used in electric heating is generally placed in a metal casing to heat the surrounding soils. The temperature gradient between the heating wells and the surrounding soil is considered to be the driving force behind the heat flow of each heating well. As the temperature increases up to the boiling or co-boiling point of the contaminant, the steam is generated in soil and finally captured in the extraction wells (Heron et al. 2013).

In heterogeneous sites, the heat transfer effect of TCH technique is almost the same, because the thermal conductivity of different types of soil has no great differences, i.e., the changes from sand to clay are no more than 4 times. The heat transfer effects of ERH technology on soils differs significantly, due to the fact that electrical conductivity of different soil types vary by 0–200 times. In general, clay has higher electrical conductivity than sand and heats up faster (Martin et al. 2016). SEE technology is inappropriate for the treatment of low permeability media or heterogeneous sites since the soil permeability varies by 10^2–10^4 times (Suthersan et al. 2016). The range of variation is much more extensive than the thermal and electrical conductivity (Nilsson et al. 2011, Janfada et al. 2020).

In the presence of DNAPLs, the heating process of TCH for soils in the target treatment areas is generally divided into the following stages (Jonah et al. 2016) (**Fig. 1**):

 (i) Stage of DNAPLs-water heating, where the soil ambient temperature continues to rise, DNAPLs and aqueous phase are heated to DNAPLs-water co-boiling point.

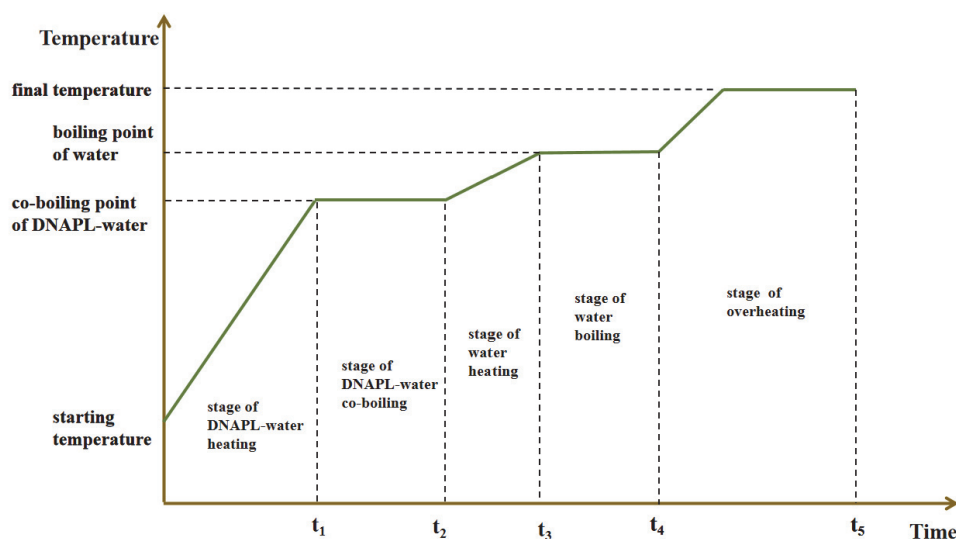 (ii) Stage of DNAPLs-water co-boiling, which is only appropriate for DNAPLs whose co-boiling point

Fig. 1. The process of soil heating

with water is smaller than the boiling point of water. In this process, when the temperature rises to the co-boiling point, the co-boiling phenomenon occurs at the interface between the DNAPLs and the aqueous phase, and DNAPLs can be steamed into action. The evaporation of liquid water can be negligible. If multiple DNAPLs were present in soils, multiple DNAPLs-water co-boiling stages would be created. The DNAPLs evaporation depends on their co-boiling points with water. Using the ideal gas law, the volume of gas produced can be estimated during the co-boiling process (Burghardt and Kueper 2008):

$$V_g = \frac{n_n R T_{cb}}{P_n^v} \qquad (1)$$

Where V_g is the volume of gas produced (m³), n_n is the molar number of DNAPLs, R is gas constant (m³·atm/°C·mol), T_{cb} is the co–boiling point (°C).

(iii) Stage of water heating. DNAPLs-water co-boiling stage is complete. Moreover, DNAPLs has been boiled and evaporated, and aqueous phase continues to be heated.

(iv) Stage of water boiling. As the ambient temperature reaches the boiling point of water and soil-water, the soil temperature remains at the water boiling point, until the pore water completely evaporates. The content of pore water determines duration.

(v) Stage of overheating. The soils continue to be heated to the targeted temperature, then remain for a certain period. Other contaminants are evaporated or decomposed due to high temperature, the contaminated soil is remediated by TCH.

TCH increases soil temperature and affects the structure of soil microbial communities and organic matter to a certain extent. When the heating temperature is above 300°C and the heating time exceeds 100 days, the soil microbial mass may not recover by itself (Menno et al. 2016). A study (Bonnard et al. 2010) on the bioefficiency of soil contaminated with PAHs and metals found that thermal desorption did not reduce the genotoxicity of earthworms. The damaged body cavity cells of earthworm in the soil after thermal desorption were significantly higher than those before treatment, because thermal desorption increased the bioavailability of metal pollutants. Organic matter will undergo volatilization, carbonization or oxidation reactions, and the total content and structure will change accordingly. When the treatment temperature is 100–300°C, the volatile components volatilize, lignin and hemicellulose are degraded. At 300–500°C, humic acid and fulvic acid will be decarboxylated into light hydrocarbons. At temperatures above 500°C, all alkyl aromatics, lipids and sterols volatilize and cause carbonization (Aurelie et al. 2011).

Mechanisms of contaminants transformation

In the unsaturated zone, organic contaminants are presented as four forms: adsorbed in soil particles, dissolved in aqueous phase, DNAPLs, and gaseous in soil pores (**Fig. 2**). In the process of TCH, the primary mechanism of the pollutants' removal is steam generation at the porosity scale. The increase in soil temperature enhances the evaporation, volatilization, dissolution and desorption of organic pollutants in the soil environment, which is controlled by vapor pressure, Henry's law constant, soil–water partition coefficient and octanol--water partition coefficient, as well as the solubility of solid and subcooled liquids, respectively (Baker et al. 2006, Hegele and Mumford 2014). Evaporation of DNAPLs dominates first, and the contaminants that dissolved in the pore water and adsorbed on the soil particles are then treated. The transformation of each phase state of pollutants is described in **Fig. 3**.

Vapor pressure

The volatilization of contaminants dissolved in water is controlled by vapor pressure. Under certain conditions, the contaminants will evaporate from boiling water, when the vapor pressure of contaminant is equal to the system pressure. The higher is the vapor pressure, the lower is the boiling point. When evaporation occurs in a one-component system, in the absence of dissolved or non-condensable gases, the vapor pressure of the liquid is defined as the sum of the hydrostatic
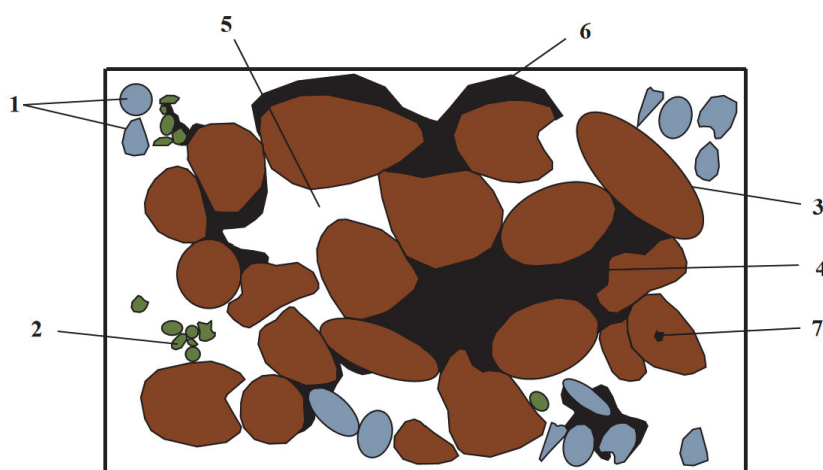

Fig. 1. The form of contaminants in the soil environment

1– silt, 2 – clay, 3 – sand, 4 – DNAPL, 5 – pore space/contaminants vapors, 6 – contaminants adsorbed in the soil particles, including a percentage of DNAPL, 7 – contaminants dissolved in the soil moisture, including a small percentage of DNAPL

water pressure and the capillary pressure (Carey 2007, Triplett et al. 2014):

$$P_v = P_w + P_c \qquad (2)$$

Where P_v is the vapor pressure of the liquid (Pa), P_w is the hydrostatic water pressure (Pa), and P_c is the capillary pressure required for nucleation (Pa).

P_w and P_c have impacts on the vapor pressure of the substance. When P_w or P_c increases, the substance needs a greater temperature to increase the vapor pressure. Meanwhile, the boiling or co-boiling point of substance also increases. In general, the hydrostatic water pressure increases linearly below the water table. The larger is the burial depth, the higher is the hydrostatic water pressure. For example, the boiling point at a certain groundwater level at 1 atmosphere is 100°C, and can reach 118°C at further 30 feet down.

When evaporation occurs in a miscible fluid, the vapor pressure of the substance can be expressed as follows (Smith and Van 1987):

$$X_1 P_1 + H_2 P_2 + ... X_n P_n = P_w + P_c \qquad (3)$$

Where X_n is the molar fraction of the pure liquid component at a specific temperature, and P_n is the vapor pressure of the pure liquid component (Pa).

When evaporation occurs at the interface of incompatible liquids, such as groundwater and DNAPLs, the vapor pressure of the substance can be expressed as follows (Hegele and Mumford 2014):

$$\sum_i^n X_i P_i^v + P_{v,w} = P_w + P_c \qquad (4)$$

Where P_i^v is the vapor pressure of the DNAPLs component i (Pa). $P_{v,w}$ is the vapor pressure of water (Pa).

Based on the above formulas, the vapor pressure of the miscible liquids is additive at its interface, which is greater than the vapor pressure of any liquids. Therefore, the boiling point of a miscible liquid is lower than that of any pure solution that composes it. For example, at normal temperature and pressure,

the boiling point of pure TCE is 100°C, while the co-boiling points of TCE-water is only 73°C.

By increasing the temperature, the vapor pressure of the contaminants can be changed to allow for better evaporation. The change in vapor pressure of water and DNAPLs with increasing temperature can be estimated using Anthony's equation:

$$\mathrm{Log} P_i^v = A_i - \frac{B_i}{T + C_i} \qquad (5)$$

Where A_i, B_i and C_i are compound – specific empirical constants, respectively (Sinnott 2005). Previous studies have shown that when the underground surface is heated from 20°C to 100°C, the vapor pressure of pollutants will increase by 10–30 times (Udell 1996).

Henry's law constant

Henry's law constant determines the tendency of distribution of certain contaminants between the aqueous and gaseous phases in an equilibrium state and controls volatilization of contaminants. For organic contaminants, the Henry's law constant is affected by temperature, which can be expressed as follows (Chen et al. 2012):

$$\ln H_i = A_i - \frac{B_i}{T} + C_i \ln T \qquad (6)$$

Where H_i is Henry's law constant (atm·m^3/mol), T is the temperature (K).

Previous studies have shown that when temperature increases by 10°C, the Henry's law constant of contaminants can increase by 1.6 times (Suthersan et al. 2016). In the process of TCH, when the soil temperature and the Henry's constant of contaminants increase, the slightly soluble or immiscible organic contaminants in water are more likely to enter the gas phase from the water phase and are then removed.

Solubility

Solubility of a contaminant indicates the degree to which a contaminant dissolves in pore water at a specific temperature.
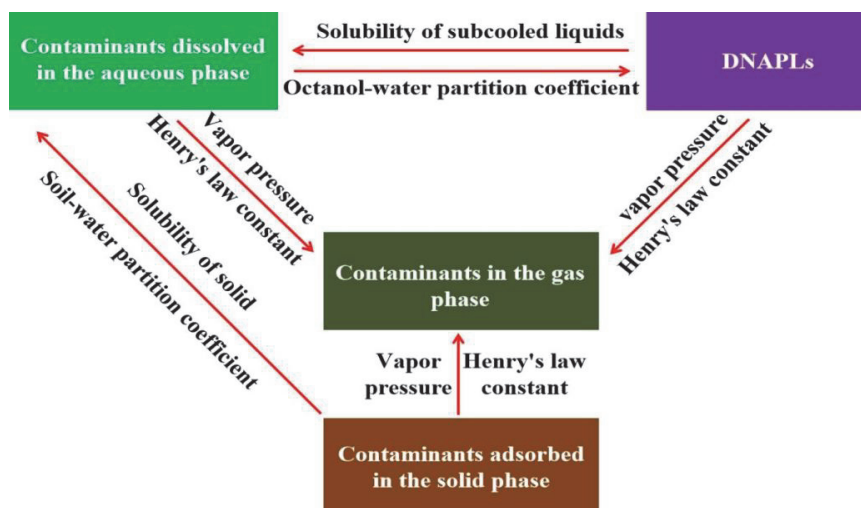

Fig. 3. Phase conversion of contaminants

Solubility in the traditional sense refers to the solid-state solubility of the substance, whose dissolution process refers to the change of a substance from solid to liquid, followed by diffusion into an aqueous solution. For DNAPLs, the dissolution is only the process of liquid diffusion to aqueous solution. So, the concept of subcooled liquid solubility is introduced, which means the water solubility of substances that remain liquid below the freezing point under atmospheric pressure (Schwarzenbach et al. 2003).

As soil temperature increases, the solid-state solubility and the subcooled liquid solubility of substance increase. Thus, the substance more easily diffuses from the solid or non-aqueous liquid to the aqueous solution. However, the high solubility can limit the process of the substance entering the gas phase from the aqueous phase. Previous studies have shown that for organic pollutants that are easily soluble in water, such as acetone and alcohols, it is not easy to enter the gas phase from the water phase, due to their high solubility in water, and even high temperatures. Therefore, it is usually necessary to boil all pore water, when TCH is applied to remove such contaminants.

Partition coefficient

The distribution and transformation of contaminants in the soil are also affected by soil-water partition coefficient and the octanol-water partition coefficient of contaminants. The former represents the ratio of the concentration of contaminants in the solid and aqueous phases of the soil under certain conditions. The latter reflects the migration capacity of contaminants between aqueous and organic phases, which is closely related to the water solubility and soil adsorption constants (Netzeva et al. 2003). In addition, the entry of organic pollutants into soil organic matter is controlled by distribution, not adsorption (Chiou et al. 1983).

The soil-water partition coefficient of the contaminants is affected by the water solubility of the contaminants and can be expressed as follows:

$$\text{Log}K_{om} = -0.729 lgS + 0.001 \tag{7}$$

Where K_{om} is the soil-water partition coefficient of the contaminant, S is the water solubility of the contaminant.

The octanol-water partition coefficient of the contaminants is expressed as follows:

$$K_{ow} = \frac{C_o}{C_w} \tag{8}$$

Where K_{ow} is the octanol-water partition coefficient; C_o is the concentration in the n-octanol phase in an equilibrium state (μL/L); C_w is the concentration in the aqueous phase in equilibrium state (μL/L). The greater is the water solubility of a contaminant, the smaller is the soil-water partition coefficient and octanol-water partition coefficient, and the easier it is for the substance to be distributed to the aqueous phase.

The migration process of contaminants

Gas formation

There are gas cavities (cracks, pits, etc.) on the surface of the soil particles, and the gas nucleates here first due to the

geometry of the gas cavities, local wetting characteristics, capillary pressure and priority contact angles. Experimental results have shown that when the sites are heterogeneous, the generation of bubble begins with nucleation in the gas cavities on the surface of soil particles at the high-low permeability interface and then extends outward (Martin et al. 2017, Martin et al. 2016). Contaminants are preferentially removed in areas with high permeability, whereas the areas with low permeability may maintain high pollutant concentrations (Martin et al. 2017, Kevin et al. 2021).

Gas expansion

After nucleating, the bubbles begin to grow and expand. The growth rate and volume of bubbles are affected by various factors, including liquid viscosity, surface tension, ambient temperature, etc. The higher temperature increases higher gas pressure, resulting in more considerable bubble expansion. Soil temperature is the most critical factor affecting the growth of bubbles, and the volume of the bubble can be expressed as follows (Scriven 1959):

$$R = 2\beta\sqrt{kt} \tag{9}$$

Where R is radius of bubble, t is time, β is dimensionless growth parameters, k is diffusion terms, which is the coefficient of thermal diffusion of soil in cases where heat conduction controls bubble growth.

Bubble growth is accompanied by bubble merger, which can form a discontinuous gas phase. Soil pores are gradually occupied by the discontinuous gas phases, which will cause drainage inside the pores and introduce gases in a dispersed manner (Jones et al. 1999). The above process continues until the gas clusters encounter adjacent pore throats and are resisted by capillary forces. Taking the removal of DNAPLs by TCH as an example, the bubbles are distributed to the upper surface of the DNAPLs phase after forming the gas cavities on the soil surface at the high-low permeability interface. Then the new bubbles generated by other dissolved gases are continuously expanded, burst, mobilize and fuse to form a discontinuous gas phase, which expands to a certain extent to move up under buoyancy or pressure gradients (Brooks et al. 1999, Mumford et al. 2008).

Gas migration

Two flow regimes were determined from studies by Brooks et al. (1999), i.e., discontinuous (or bubble) flow and continuous (or channel) flow. Discontinuous flow refers to gas clusters distributed discontinuously, some of which may be trapped in soil pores. In contrast, others may move up or down under the competitive action of buoyancy and capillary forces. Continuous flow refers to a continuous flow along the path of least resistance, i.e., the pore with the largest radius, driven by pressure gradient, which was consistent with Darcy's law or Hagen-Poiseuille's law (Geistlinger et al. 2006).

Highly permeable media with particle sizes greater than 1 to 2 mm typically undergo bubble transport during TCH. Buoyancy is a large contributor to the movement of bubbles towards low water pressure, whose size depends on soil permeability, soil temperature and groundwater velocity. The capillary force of the soil pore throat prevents the expansion and

migration of the discontinuous gas phase in the soil pores. Only when the buoyancy of the discontinuous gas phase is greater than the capillary force of the pore throat, the discontinuous gas phase migrates vertically to the adjacent pore bodies (Munholland 2015). The magnitude of the capillary pressure is expressed using the Laplace equation:

$$P = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \qquad (10)$$

Where P is the surface pressure at the curvature of the curved surface (Pa); σ is the air–water surface tension (N/m); R_1 and R_2 are the two main radii of curvature of the surface (m). When the surface is spherical, $R_1=R_2$, the above equation can be simplified to:

$$P = \frac{2\sigma}{R} \qquad (11)$$

The relationship between the radius of curvature of the surface and the radius of the capillary can be expressed as follows:

$$R = \frac{r}{cos\theta} \qquad (12)$$

Where r is the radius of the capillary, which is effective aperture of soil; θ is the angle between surface curvature radius and capillary radius.

When the buoyancy is more than the capillary pressure generated by the soil pore, the discontinuous gas phase enters the pores and leads to internal drainage. When the pore fluid is emptied, if a stable gas flow can be provided, the pore can transmit gas at a specific rate.

Porous media with particle sizes equal to or less than 1 to 2 mm typically undergo channel transport during TCH. Evaporated contaminants and water as a separate gas phase migrate upwards in channel flow, which is controlled by local entry pressures with capillary pressure dominating. Previous studies have shown that an increase in the temperature can reduce the interfacial tension of the DNAPLs-water system and the entry pressure, and also increase the contact angle (Sleep and Ma 1997, O'Carroll and Sleep 2007).

In addition to the vertical movement demonstrated in the laboratory, there are studies indicating that pollutants also move horizontally. In a project to remediate a brownfield site near San Francisco, California (Heron et al. 2013, Jennifer et al. 2010), it was found that once heating begins, the soil in the area closer to the heater is first heated to dryness and serves as a preferential flow path for the generated steam. As the heating progresses, the area farther away from the heater becomes the evaporation zone, and the water in the farthest wet zone that does not reach the boiling point migrates to the evaporation zone in the form of liquid water, and the steam generated by the evaporation zone enters the drying zone closer to the heater in a diffusive manner and moves up along this drying zone.

Gas accumulation

In heterogeneous site, the radius of capillaries formed in highly permeable soils is larger than that formed in low permeability

soils, and the capillary pressure generated is relatively small. In the transition process from coarse grain soil to fine-grained soil, the bottom of the fine-grained soil will pose a potential obstacle to the upward migration of gas, due to the increase of the entry pressure of the capillary barrier (Kueper and McWhorter 1991).

When treating TCE contaminated soil with ERH, Martin et al. (2016) found that under the fine-grained capillary barrier, high capillary entry pressure prevents upward migration of gases and forms gas accumulation. Jonah et al. (2016) found that during DNAPLs-water co-boiling process, gases generated at the DNAPLs pool interface accumulate in the coarse sand layer, due to higher entry pressure in the upper part of the coarse sand layer, and the lower part of the soils with low-permeability. When gas is accumulated under the capillary barrier and reaches the critical thickness, it can enter the fine-grained porous medium driven by the pressure gradient. The maximum gas accumulation height H_{max} before the gas break via the capillary barrier can be expressed by:

$$H_{max} = \frac{P'' - P'}{(\rho_w - \rho_g)g} \qquad (13)$$

Where H_{max} is the maximum thickness that a gas can accumulate under the capillary barrier (cm), P'' is the entry pressure of the capillary barrier (Pa), P' is the pressure produced by the accumulated gas (Pa), $(\rho_w-\rho_g)$ is the density difference between water and gas (kg/m³), and gas, g is the acceleration of gravity (m²/s).

Gas lateral diffusion

Continuous gas accumulation leads to lateral migration of gases, before the accumulated gases below the low–permeability areas reach critical thickness of gas, which is a potential mechanism for the lateral diffusion of contaminants (Martin and Kueper 2011). Heron et al. (2005) observed the co-boiling process of DNAPLs-water in heterogeneous structures, and observed that there is gas generation and accumulation under the fine sand layer. When gas is not sufficiently captured, lateral migration occurs, and the polluted gas is transported outside the treatment area (Martin and Kueper 2011, Heron et al. 2009). Jonah et al. (2016) also found in the studies on TCE-water co-boiling that the lateral migration of gas to the edges of the coarse layer leads to the gas migration outside the treatment zone, and the gas migration radius is much larger than the heating radius of the targeted treatment zone. When gas migrates laterally to a lower temperature area or the heating of the soils does not continue, the gaseous contaminants collapse and rapidly condense into DNAPLs, and transfer the gas phase mass back into the aqueous phase. If not addressed, it can increase the contaminant concentrations in previously clean groundwater and expand the contaminated areas (Magdalena et al. 2011).

Gas capture

Li et al. (2002) found that when heating is carried out to a certain extent, although large amounts of gas are continuously produced due to DNAPLs and water co-boiling, the gas accumulation observed under the upper capillary barrier is highly consistent, which is the result of repeated upward discharge of gas via the delivery well. Delivery wells, the only way for gas transferring

from the capillary barrier, provide a pathway for the gas transfer from the capillary barrier. In the TCH remediation process of heterogeneous sites, it is crucial to establish a connecting gas phase path from the gas accumulation zone to the gas phase extraction point, which is the essential to maximize the mass removal of contaminants.

Suggestions and summary

TCH technology causes pollutants to evaporate, volatilize and be removed. During in situ thermal desorption in heterogeneous strata, different forms of organic pollutants are converted into each other and eventually converted into gaseous pollutants that are removed. Gaseous contaminants form as bubbles in the surface gas cavities of soil particles subsequently growing and expanding, then are transported through the soil environment in the form of a continuous or discontinuous flow. In heterogeneous site, when the permeability of the upper soil is less than that of the lower soil, the pollutants-carrying gases will accumulate in the heterogeneous boundary area. If the gas is not sufficiently trapped, lateral gas migration will contaminate clean areas.

Through the above analysis of the migration process of pollutant gases in the underground, methods of extraction pipes to effectively capture gas are provided for the heterogeneous contaminated soils remediated by TCH.

  (i) Since gases accumulate under the capillary barrier, it is important to establish a connected gas phase path from the gas accumulation zone to the gas phase extraction point. If the heterogeneous interface (the upper layer is a low permeability layer and the lower layer is a high permeability layer) is close to the ground and has a large range, the horizontal extraction tube with sieve holes can be installed at the interface of the high and low permeation layers to maximize the capture of polluting gases accumulated here. If the heterogeneous interface is far from the ground, or there is a local non-uniform interface caused by fractures and large pores, a vertical extraction well with sieve holes can be set up in the heterogeneous area, and the depth of the well reaches the heterogeneous interface.

 (ii) When there is soil with a higher permeability rate around the heater than in the treatment area, the dry soil around the heater will become the priority path for pollutants to pass through, and vertical extraction wells with sieve holes can be laid around the heater to extract contaminants as soon as possible, reducing pressure and making it easier for contaminants to move.

(iii) The pollutants in the low permeability area move slowly, and in the high permeability area move relatively quickly. The number of extraction wells can be appropriately increased in the low permeability area according to the actual situation of the project to ensure the capture and removal of pollutants.

To determine whether the methods presented in this article are effective in capturing vapors or preventing lateral migration, vapor pressure data in treatment areas, pollutants concentration of gas collection system and pollutants concentration at specific sampling points should be collected and analyzed during remediation. We can set up a pressure monitoring column to monitor the vapor pressure throughout the entire treatment area during the thermal repair process, focusing on the pressure at the heterogeneous interface and the pressure around the heater. If the pressure monitoring system shows that the pressure in the treatment area has not increased significantly and close to ambient conditions, it means that the gas collection system has effectively captured the gas. If the pressure monitoring system shows that the pressure in a certain place has increased significantly, and the difference from the ambient conditions is large, it means that steam has accumulated here and the gas collection system has not effectively captured the gas. In addition, the remediated soil should be sampled. Sampling points are evenly laid near the heating well and in the treatment area, and the sampling depth reach the heterogeneous interface. If the concentration of pollutants at the soil heterogeneous interface is much higher than the concentration monitored by the gas collection system, the pollutant accumulates at the heterogeneous interface. If the opposite is true, the pollutant does not accumulate at the heterogeneous interface. If the concentration of pollutants at each sampling point away from the heating well in turn is not much different, it indicates that the pollutant has not undergone lateral migration, and if the situation is reversed, the concentration of pollutants at the sampling point far from the heating well is high, indicating that the pollutants have undergone lateral migration.

Acknowledgement

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