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Original Research

The Migration Mechanisms of Trichloroethylene (TCE) in Soil Structures During Thermal Conduction Heating

Jiabin Yao[1, 2], Wei Ji[1, 2], Dongdong Wen[1, 2], Zhigen Wu[1, 2], Rongbing Fu[1, 2, 3]°*

[1]State Key Laboratory of Pollution Control and Resource Reuse, College of Environmental Science and Engineering, Tongji University, Shanghai 200092, China
[2]Centre for Environmental Risk Management and Remediation of Soil and Groundwater, College of Environmental Science and Engineering, Tongji University, Shanghai 200092, China
[3]Shanghai Institute of Pollution Control and Ecological Security, Shanghai 200092, China

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Abstract

In this study, batch thermal conduction heating (TCH) experiments were performed in a TCH simulation device with trichloroethylene (TCE) as a typical contaminant to investigate the effects of temperature field distribution, soil water content, and heterogeneity on TCE transport in homogeneous and heterogeneous layers consisting of silt, medium sand, and coarse sand. The results showed that the temperature differences between the upper and lower layers of the heterogeneous fine and coarse-grained layers increased, while those in the heterogeneous coarse and fine-grained layers remained relatively stable, with the increase of water content. In addition, the TCE migration radius in homogeneous coarse sand exceeded that in heterogeneous systems by 18-23% under the same conditions. Stratigraphic heterogeneity dominated TCE distribution patterns, with pronounced gas accumulation (up to 37% higher vapor density) beneath fine-grained layers, compared to heterogeneous layers. In addition, the phenomenon of lateral migration of pollutant gases in heterogeneous soil layers is severe, providing a relevant basis for the application of gas extraction technology utilising differences in soil pore pressure. These findings would provide critical insights for optimizing in-situ thermal remediation in layered subsurface environments.

Keywords: *in-situ* thermal desorption, migration, temperature field, heterogeneous layer, soil moisture contents

*e-mails: furongbing@tongji.edu.cn
°ORCID iD: 0009-0001-0135-2003

Introduction

In recent years, soil pollution with organic contaminants has been an environmental concern. Organic contaminants are often present in the form of non-aqueous phase liquids (NAPLs) and dense non-aqueous phase liquids (DNAPLs), which can migrate downward into groundwater under gravity, subsequently forming contamination plumes upon infiltrating soil pores. The migration process of organic contaminants such as trichloroethylene (TCE) can lead to the enduring contamination of both soil and groundwater, which poses significant challenges to groundwater security globally [1]. To date, soil remediation strategies mainly include gas-phase extraction, thermal desorption, chemical redox, phytoremediation, and microbial remediation [2, 3]. In-situ thermal desorption technology is highly efficient in extracting target contaminants from soils through controlled heating temperature and time, thereby promoting their selective evaporation and gasification. In contrast, other methods have limited remediation efficiency in heterogeneous subsurface systems, where preferential flow paths and capillary barriers substantially affect contaminant transport dynamics [4, 5].

Thermal desorption technology is classified into 3 main types: electrical resistance heating (ERH), steam-enhanced extraction (SEE), and thermal conduction heating (TCH) [6]. In contrast, ERH has been extensively studied for heterogeneous soil layers [7-9], while TCH remains underexplored, despite its distinct advantages in low-permeability environments. Notably, in-situ thermal desorption remediation was significantly influenced by key factors such as heating temperature, moisture content, and soil texture [10-12]. In addition, the substantial heterogeneity of actual contaminated sites poses complexities in contaminant migration during TCH. Existing studies mainly focus on coarse-grained soil layers, while neglecting fine-grained soil layers. This knowledge gap motivates our systematic investigation of TCH-mediated TCE transport across varied stratigraphic configurations.

Materials and Methods

Experimental Setups

Generating System

TCH experiments were conducted in a self-constructed experimental setup, the schematic diagram of which is shown in Fig. 1. The custom-designed experimental setup includes 3 integrated systems: the thermal delivery system, the hydraulic control system, and the monitoring system.

(1) Thermal delivery system: A stainless-steel chamber (22×33×2 cm^3) with a 200 W cartridge heater and a PID temperature controller (±0.5ºC accuracy). Soils were filled in layers and compacted by vibration at 200 Hz.

(2) The heating rate of the heat source was set at 10ºC per min, with a target temperature of 100ºC. In the experimental setup, the heating durations for the coarse sand layer, medium sand layer, and silt layer were 180 min, 240 min, and 200 min, respectively.

(3) Hydraulic control system: Precision peristaltic pumps maintaining moisture content at 10%, 15%, 20% (±0.3% variance).

(4) Monitoring system: Distributed fiber-optic sensors (0.1ºC resolution) and time-lapse photography for migration tracking.

Heating and Temperature Control Systems

A single-ended rod with 200 W of power and uniform heat dissipation was used for heating. The heating rod was positioned on the left side of the device and connected to an intelligent digital temperature control device via a wire. The temperature control device monitored the instantaneous temperature of the heating rod in real time, ensuring that the heating temperature remained constant.

Data Collection System

The data collection system included multiplexed temperature rovers and power meters, which were employed to gather temperature data within the soil layers. The specific locations of temperature measurement points are illustrated in Fig. 1.

Experimental Materials

TCE and Oil Red O were purchased from Sinopharm Chemical Reagent Co. The initial concentration of TCE was approximately 1.46 g/kg. Oil Red O is a mixture of lipophilic azo dyes, primarily composed of 2-naphthylamine-4-azo-benzenesulfonium iodide. It readily dissolves in trichloroethylene to form a deep red solution, enabling the characterisation of TCE migration pathways within soil. The experimental setups used in the study included an infrared thermal imaging camera and an electronic analytical balance. Instruments for detection and analysis included the Tekmar Atomx blowing and trapping system (Tekmar, USA). Clean quartz sand with low organic carbon content was used as the soil medium. Quartz sand particles of 0.8-1.2 mm, 0.2-0.38 mm, and 0.045 mm were selected to simulate the coarse sand, medium sand, and silt layers, respectively.

Experimental Methodology

Simulation of Heat Transfer in Homogeneous Layers

Three gradients of water content (10%, 15%, 20%) were set for 3 homogeneous soils (i.e., coarse, medium

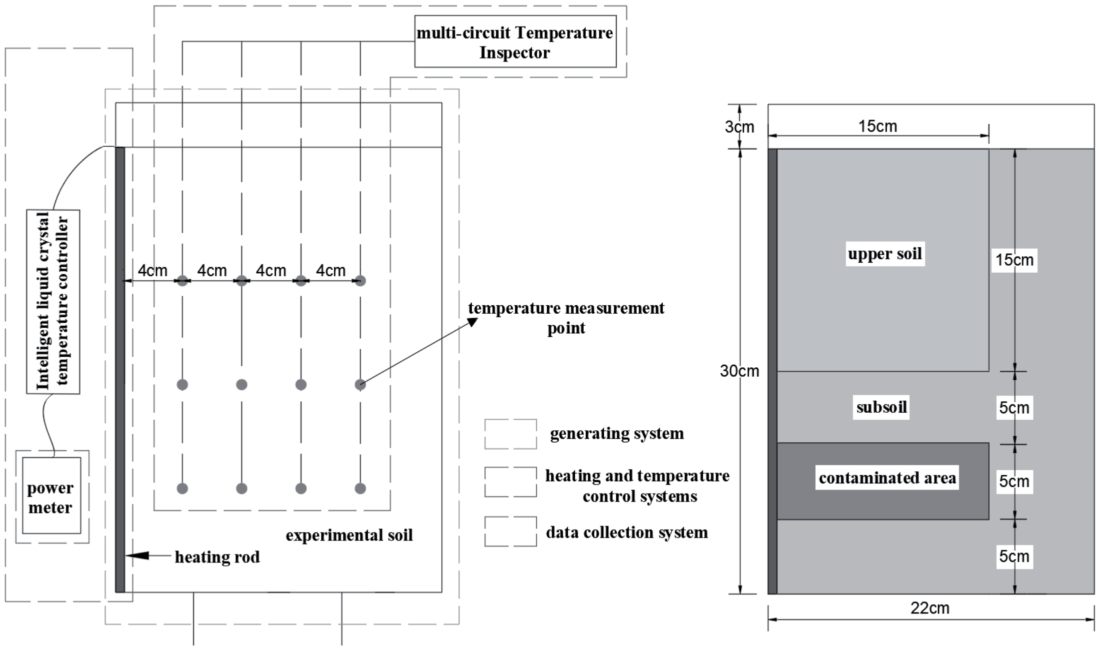

Fig. 1. Schematic diagram of the experimental setup and dimensional map of contaminated areas in a heterogeneous layer.

sand, and silt sand), resulting in 9 experimental groups. The heating temperature was set at 100ºC.

Each experimental group used the same temperature measurement points, as shown in Fig. 1. The temperature was recorded at one-minute intervals. The experimental soils were soaked to the corresponding moisture contents before initiating the heating process. Regular observations of the instruments during the experiment were conducted to ensure that the heating process proceeded normally. Once the thermocouple probes indicated that the temperature at each point changed little (with a temperature change not exceeding 1ºC within one hour), the heating was terminated, and the experimental data were recorded.

Simulation of Heat Transfer in Heterogeneous Layers

Four heterogeneous horizons were established using coarse, medium, and silt sands, with each heterogeneous horizon consisting of 2 different soil textures. The soil compositions for the four heterogeneous horizons are described, and their dimensions and compositions are illustrated in Fig. 1. For 4 groups of heterogeneous layers, 12 groups of experiments were conducted with 3 gradients of water content. The locations of the temperature measurement points are shown in Fig. 1.

Simulation of Contamination Transport in Homogeneous and Heterogeneous Layers

The experiments were designed to investigate 3 types of stratum: (1) a homogeneous coarse sand stratum, (2) a heterogeneous fine-grained–coarse-grained stratum, which was characterized by a pulverized upper layer and a coarse sand lower layer, and (3) a heterogeneous coarse-grained–fine-grained stratum, which was characterized by a coarse sand upper layer and a pulverized lower layer. Contaminated areas were designated for each group of experiments, and the dimensions of the contaminated areas are depicted in Fig. 1.

For the 3 horizons, 3 gradients of water content were implemented, resulting in 9 groups of experiments. TCE was selected as a representative contaminant to infiltrate and contaminate clean soils. To facilitate the observation and recording of TCE migration during the heating process, the hydrophobic dye Oil Red O was used to dye the TCE. After filling, the soils were tapped and compacted, and the power was activated to heat the soils. The front-side stainless steel plate was dismantled every hour. The soils were photographed to record TCE migration.

Results and Discussion

Influence of Water Content and Soil Types on Homogeneous Horizon Temperature

The temperature variations at each temperature measurement point in the 3 homogeneous layers are depicted in Fig. 2. The horizontal coordinates represent time, and the vertical coordinates represent temperature. The grey line (T1), light grey line (T2), and dark grey line (T3) represent soil temperatures at the same distance from the heat source and the same column, extending from the top of the temperature measurement points to the bottom, respectively.

As observed in Fig. 2, Fig. 3, and Fig. 4, the temperatures in 3 homogeneous soils exhibited increasing trends with the increase in water content. This phenomenon can be attributed to heat transfer from the soil and its pore fluids [13]. In addition, the presence of vapor was possibly a key factor influencing the observed temperature increase [14].

Prior to saturating the soils with water, the primary constituents of the soils included soil skeleton, water, and air. Considering that the thermal conductivity of water (0.56 $W\cdot m^{-1}\cdot K^{-1}$) was higher than that of air (0.026 $W\cdot m^{-1}\cdot K^{-1}$) under a certain percentage of soil solids, an increase in water content leads to the displacement of the original air in pore spaces by water. Consequently, the overall thermal conductivity of the soils increased, resulting in a relatively higher temperature of the soils. As the soils reached a water-saturated state, their thermal conductivity showed a stable trend. The heat conduction effects further showed minimal enhancement. As the soil particle sizes decreased, the temperature at each temperature point within the 3 homogeneous soils also decreased. The results were mainly attributed to the fact that once the soils reached saturated water states,

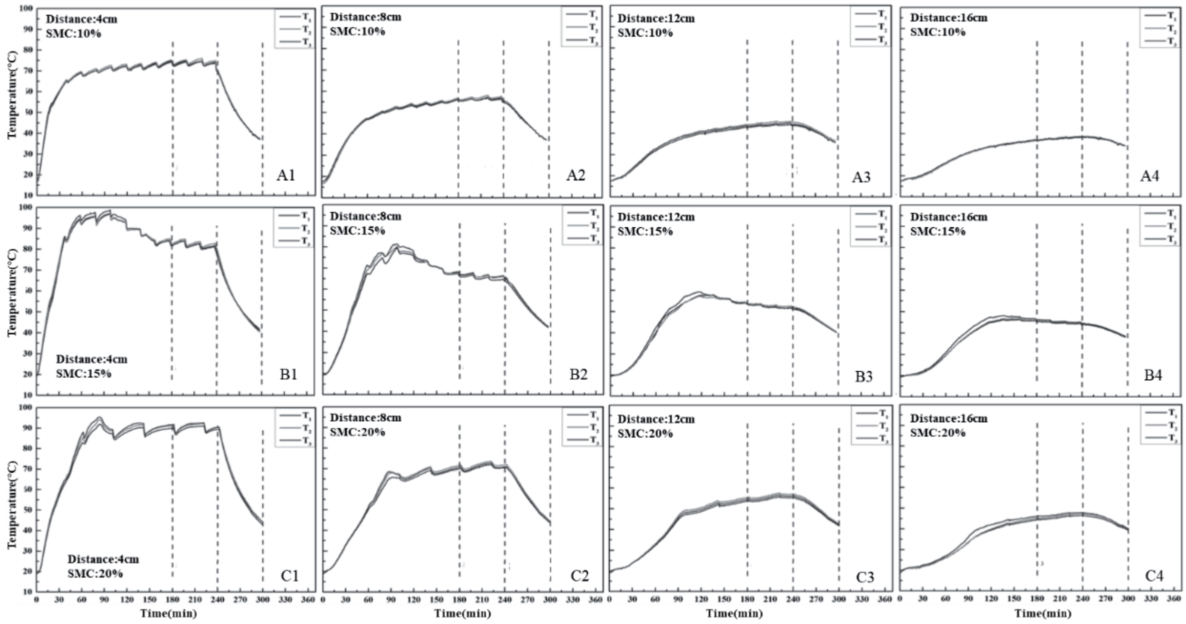

Fig. 2. Temperature variation in homogeneous coarse sand layer.

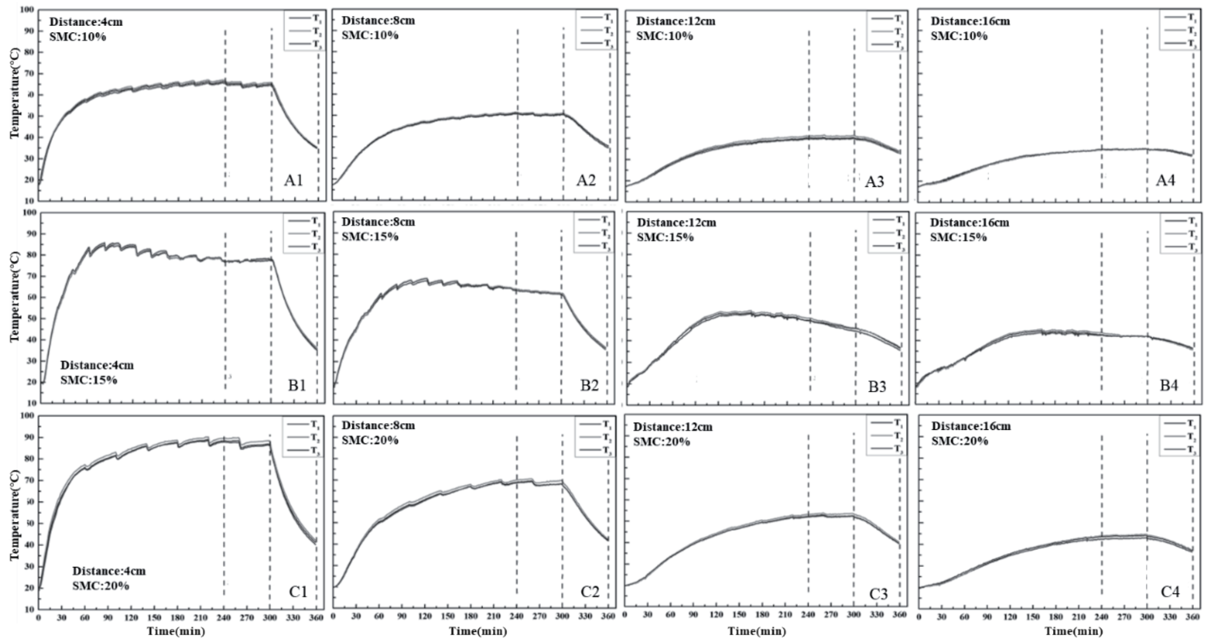

Fig. 3. Temperature variation in homogeneous medium sand layer.

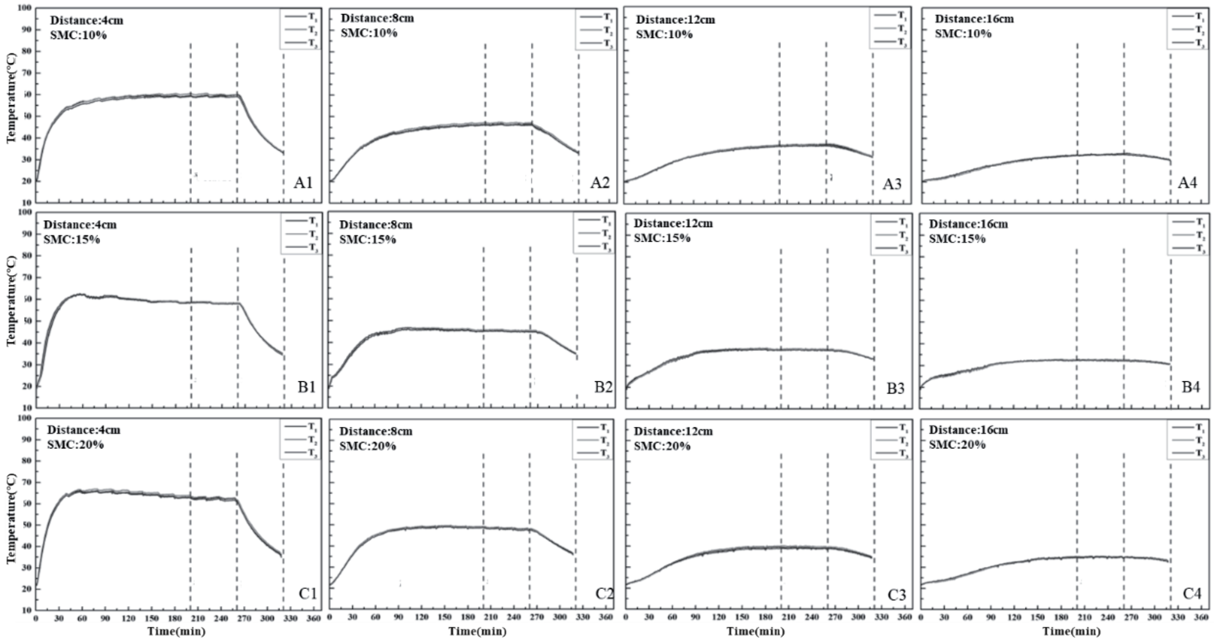

Fig. 4. Temperature variation in homogeneous silt layer.

smaller soil particle sizes had greater total porosity, due to the larger thermal conductivity coefficient of the air occupying the smaller spaces. Conversely, an increase in the particle sizes of the soils reduced their porosity, as the same volume of solids proportionally increased [15]. The larger air spaces with a coefficient of thermal conductivity of solid particles resulted in an overall increase in the thermal conductivity of the soil medium. Consequently, the temperature at each temperature measurement point within the soils also increased accordingly.

Furthermore, larger soil porosity corresponded to smaller particle sizes. Under the same water contents, more water was connected to soil particles with larger porosity. Since the thermal conductivity coefficient of water was significantly higher than that of air, the soil medium with more water connected to the solid particles exhibited increased overall thermal conductivity. Under similar heating conditions, the higher thermal conductivity coefficient showed relatively higher temperatures [16].

Effect of Water Content and Heterogeneity on Temperature in Heterogeneous Layers

The temperature variations at each measurement point within 4 groups of heterogeneous horizons are illustrated in Fig. 5, Fig. 6, Fig. 7, and Fig. 8, respectively. The horizontal coordinates represent time, and the vertical coordinates represent temperature. The grey line (T1), light grey line (T2), and dark grey line (T3) represent the temperatures measured by the same column of temperature probes. These measurements span from the top to the bottom at the same distance from the heat source.

Fig. 5, Fig. 6, Fig. 7, and Fig. 8 revealed that the average temperature during the heating process increased, with the increase in water contents for the heterogeneous medium sand and coarse sand layer, silt and coarse sand layer, and coarse sand and silt layer. The results were mainly due to the gradual replacement of air spaces in the soil pores by water, as water content increased. The thermal conductivity of water was higher than that of air, leading to an overall increase in soil thermal conductivity and higher temperatures [12, 17].

Regarding temperature differences between upper and lower layers, the temperature difference increased with the increase in the water content of the heterogeneous medium with coarse sand layer and heterogeneous medium with silt and coarse sand layer. However, for the heterogeneous medium with coarse and medium silt sand layer and heterogeneous medium with coarse and silt sand layer, water contents did not significantly affect temperature variation between different soils. The results were mainly because, for the former layers, although water potential difference increased with water contents, the upward migration of water by capillary action was small, which was insufficient to equalize water used for evapotranspiration among the layers. For the heterogeneous medium with sand and silt layer and the heterogeneous medium with coarse sand and silt layer, the silt layer was below with larger saturated water contents, water from the layers above was driven by water potential difference to the silt layers, which also moved to the silt layer under gravity effects [18, 19]. There were few changes in water saturation between the layers, due to dominant gravity effects, resulting in small differences between the upper and lower soil layers in the overall soils [20].

Fig. 5, Fig. 6, Fig. 7, and Fig. 8 also showed a crossover in equilibrium temperatures during the heating of the 4 heterogeneous layers under a water content of 10%. The average temperature of the heterogeneous medium with a coarse sand layer was the highest, while the temperature of the heterogeneous medium with a silt and coarse sand layer was the lowest. The average temperatures of the heterogeneous medium with coarse sand and silt and coarse sand layers were generally higher than the other 2 layers under a water content of 15% and 20%. The results were due to the thermal conductivity relationships of the 3 soils, i.e., silt < medium sand < coarse sand. The overall thermal conductivity of the heterogeneous medium with coarse and sand layers and the heterogeneous medium with silt and coarse sand layers was greater than that of the heterogeneous medium with sand and silt layers and the heterogeneous medium with coarse sand and silt layers. Additionally, under the effects of water potential differences, part of the water in coarse sand layers below the heterogeneous medium with fine- and coarse-grained layers would enter the upper medium

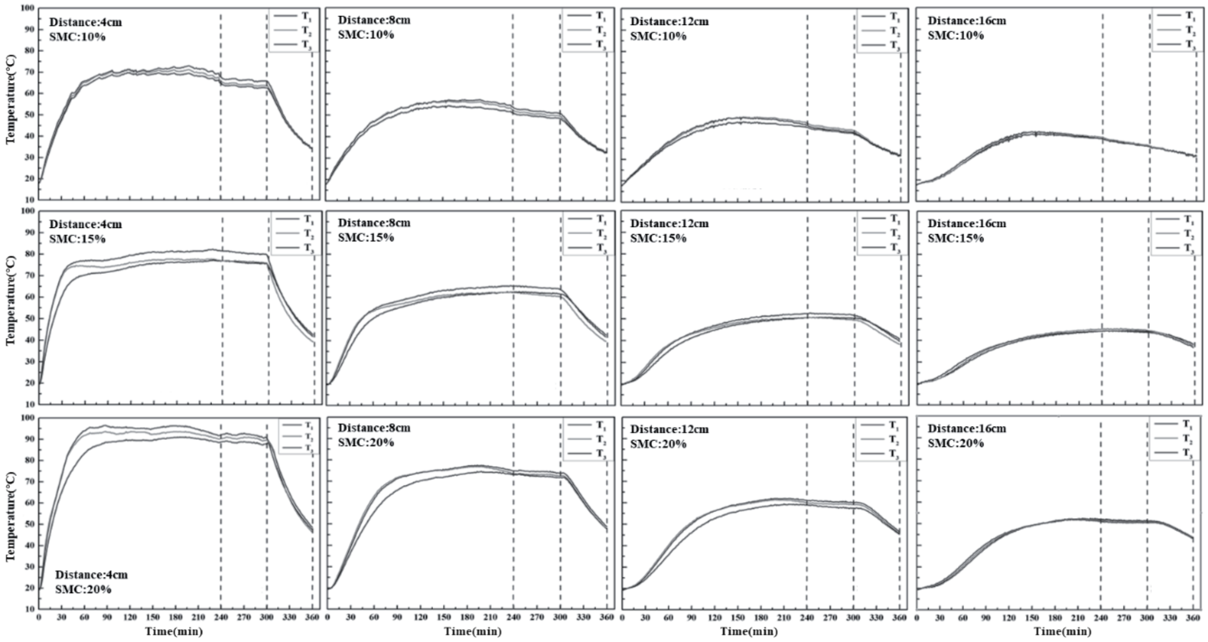

Fig. 5. Temperature variations in heterogeneous medium sand-coarse sand layer.

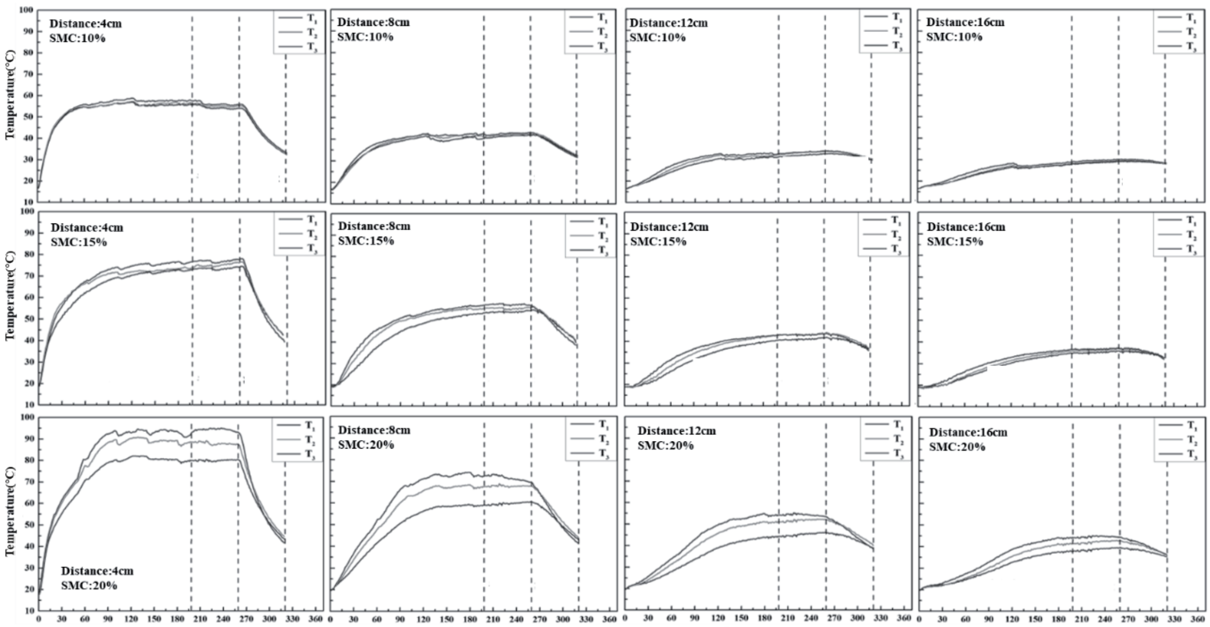

Fig. 6. Temperature variations in heterogeneous silt-coarse sand layer.

with sand silt layer by capillary action under a water potential gradient. The result might lead to an increase in the water contents of the upper soil layers, and the coefficient of thermal conductivity. For heterogeneous medium coarse- and fine-grained layers, the silt layers with the largest saturated water contents were located in the lower parts [21]. The moisture in the upper coarse sand layer or medium with sand layer moved downward under the dual effects of water potential difference and gravity, causing a significant reduction in the thermal conductivity of the upper layer and a smaller increase in the thermal conductivity of the lower silt layer. The overall thermal conductivity of the heterogeneous medium with coarse- and fine-grained layer was smaller than that of the heterogeneous fine- and coarse-grained layer.

Concerning the impact of layer heterogeneity on the temperature difference between the upper and lower soil layers, layer heterogeneity had no significant effects on heat transfer at 10% soil moisture content. The temperature difference between the upper and lower soil layers was larger for the heterogeneous

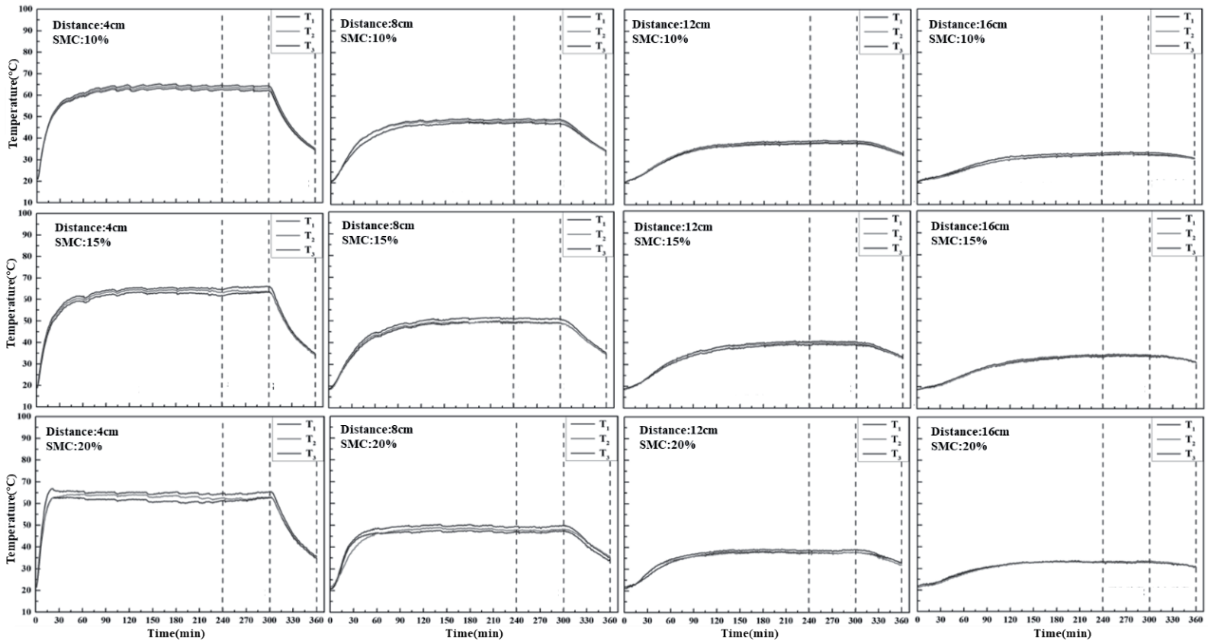

Fig. 7. Temperature variations in heterogeneous medium sand-silt layer.

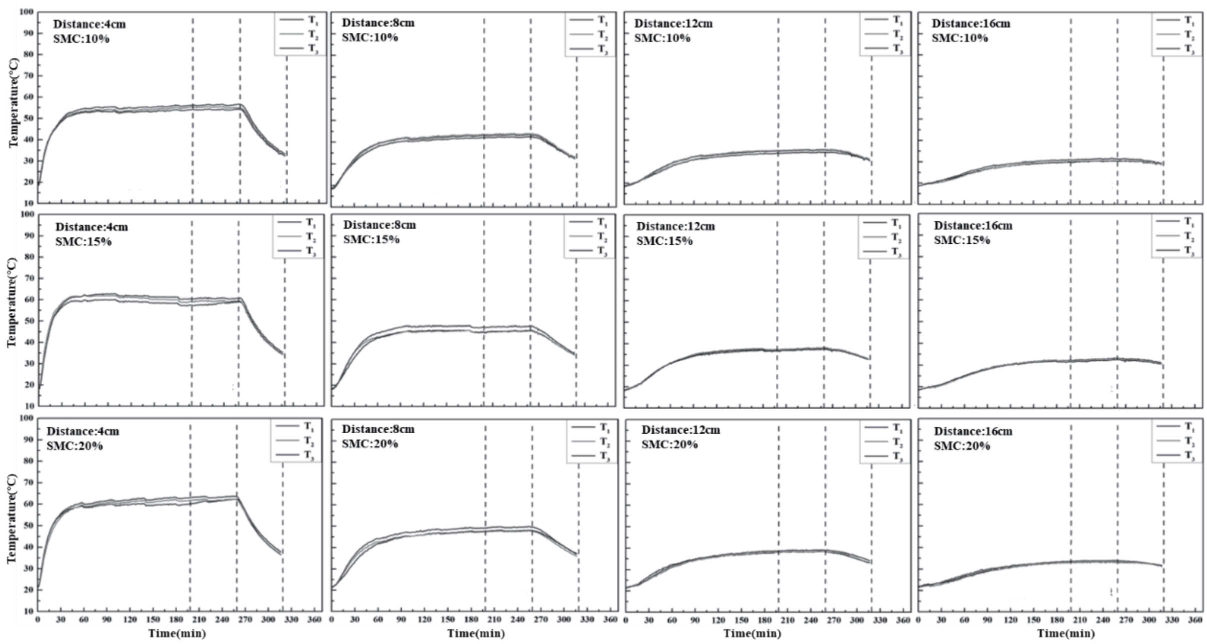

Fig. 8. Temperature variations in heterogeneous coarse sand-silt layer.

fine- and coarse-grained layer under water contents of 15% and 20%. This was mainly because the saturated water contents were greater for the fine sand layers, followed by the medium sand and the coarse sand. For the heterogeneous coarse- and fine-grained layer, the heterogeneity of the stratum had smaller impacts on its internal heat transfer. This was mainly because the largest saturated water contents of the fine layers were located in the lower part of the layer. Above the coarse sand layer or the middle sand layer, water moved to the fine layers due to the difference in water potential and gravity [22]. The results led to an increase in the overall thermal conductivity of the lower silt layer, and the overall thermal conductivity of the upper coarse-grained layer decreased due to the decrease in moisture. The decreased difference in thermal conductivity between the upper and lower soil layers resulted in small differences between the upper and lower layers of the overall soil interior.

TCE Transport Processes in Homogeneous and Heterogeneous Layers

TCE Migration in Homogeneous Coarse Sand Layers

Fig. 9 illustrates TCE migration within the homogeneous coarse sand layer under an initial water content of 10%, 15%, and 20%. Contaminated areas expanded with increasing heating time. In addition to TCE moving downward vertically under gravity and upward vertically due to heating-induced evaporation, there was an observable horizontal movement of TCE away from the heat source. The lateral movement could be attributed to the composition of the homogeneous coarse sand layer, primarily including solid skeleton and moisture [23]. As heating initiated, energy was continuously released from the heat source, forming temperature front that progressed to the right with time. Evaporation, volatilization, and diffusion were most pronounced near the heat source. Vapor generated in this region exhibited a strong tendency to carry TCE away from the heat source area. The rapid evaporation near the heat source created a humidity difference with other regions, leading to water diffusion toward this area; the diffusion rates were significantly lower than the evaporation rates. As a result, TCE was observed to migrate in 3 directions within homogeneous soil layers.

During the heating process, the internal particles of homogeneous coarse sand resulted in minimal temperature differences in the vertical direction at each temperature measurement point. As depicted in Fig. 9, TCE movement in the vertical direction remained unhindered with prolonged heating, and the migration radius gradually expanded. Notably, experimental groups with higher internal temperatures concurrently exhibited larger TCE migration radii. The impact of

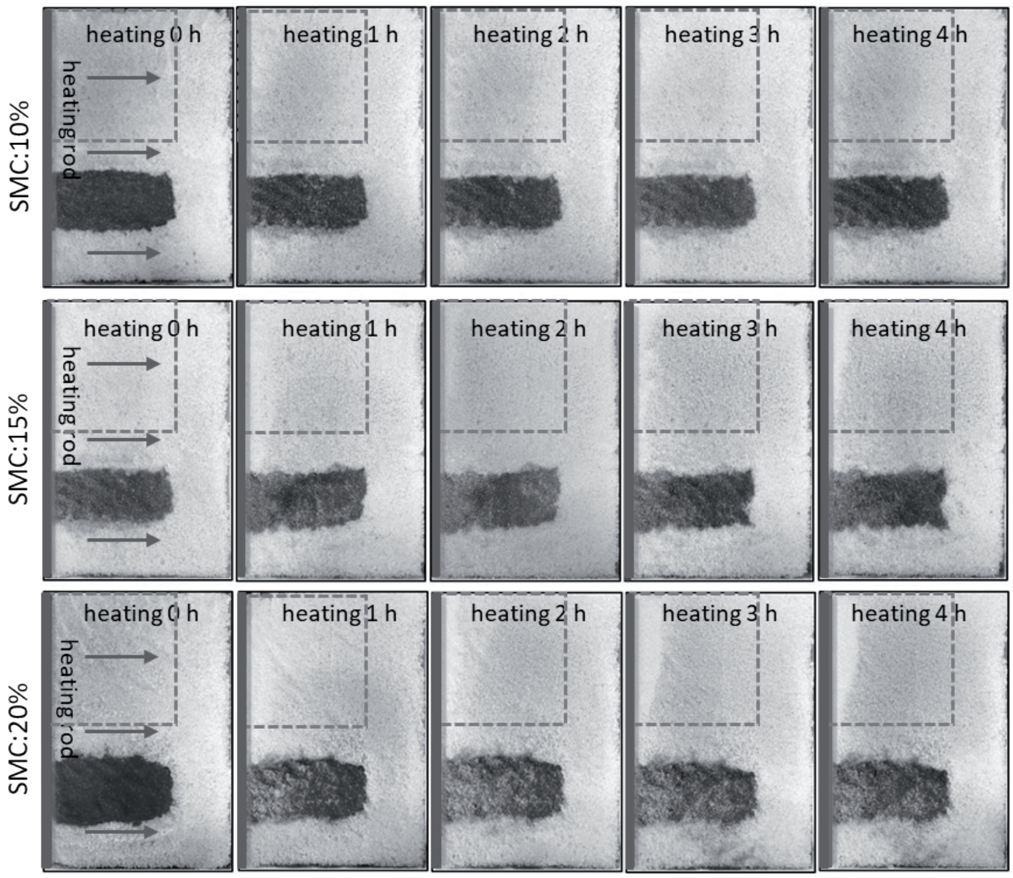

Fig. 9. Contaminant migration in heterogeneous coarse sand layer.

water contents on site remediation through in-situ heat transfer technology was twofold. On one hand, water contents influenced the overall thermal conductivity of the soils, subsequently affecting the heating temperature of contaminated sites. On the other hand, water contents led to the generation of water vapor through evaporation, facilitating TCE escape from the soils [17, 24].

In the case of the homogeneous coarse sand layer, as illustrated in Fig. 9, TCE migration under 3 water contents, was primarily characterized by upward movement in the vertical direction and accompanied by a minor degree of lateral migration away from the heat source. With increasing water contents, the contaminated area expanded for the same heating duration, enhancing TCE migration.

TCE Migration in Heterogeneous Coarse Sand and Silt Layers

Fig. 10 depicts TCE migration within the heterogeneous coarse sand and fine silt layer under the water contents of 10%, 15%, and 20%. After heating begins, TCE within the fine and silt layer exhibited downward movement along the vertical axis due to gravity, and simultaneously moved upward in the vertical direction due to heating-induced evaporation. The migration region of TCE expanded with increasing heating time. However, when the heating temperature reached 150ºC, the temperature of the sands at 4 cm was higher than the boiling point of TCE. It was challenging for TCE to migrate from the lower layer of fine silt grains under all 3 water content conditions. Through the experimental process, TCE did not migrate from the fine silt grains to the coarse sand layer.

As depicted in Fig. 10, the area of TCE migration and diffusion increased with the overall soil temperature, although the effect was not highly significant. Under the same heat source temperature, the heat transfer efficiency of the heterogeneous coarse sand and fine silt layer was relatively lower. Consequently, the overall internal temperature of the soils remained lower. However, the upper and lower soil temperatures exhibited minimal differences during the heating process, with no significant temperature variance between the upper and lower layers. The temperature differences had little impact on TCE migration.

As depicted in Fig. 10, the area of TCE migration and diffusion showed a slight increase with increasing water content. This phenomenon is attributed to the marginal elevation in the overall temperature of the heterogeneous coarse sand-fine stratum as water content increased. However, this temperature increment was relatively modest. The water contents were ineffective at influencing the overall thermal conductivity of the soils, thus having little impact on heating temperature. Furthermore, in the heterogeneous coarse sand-fine

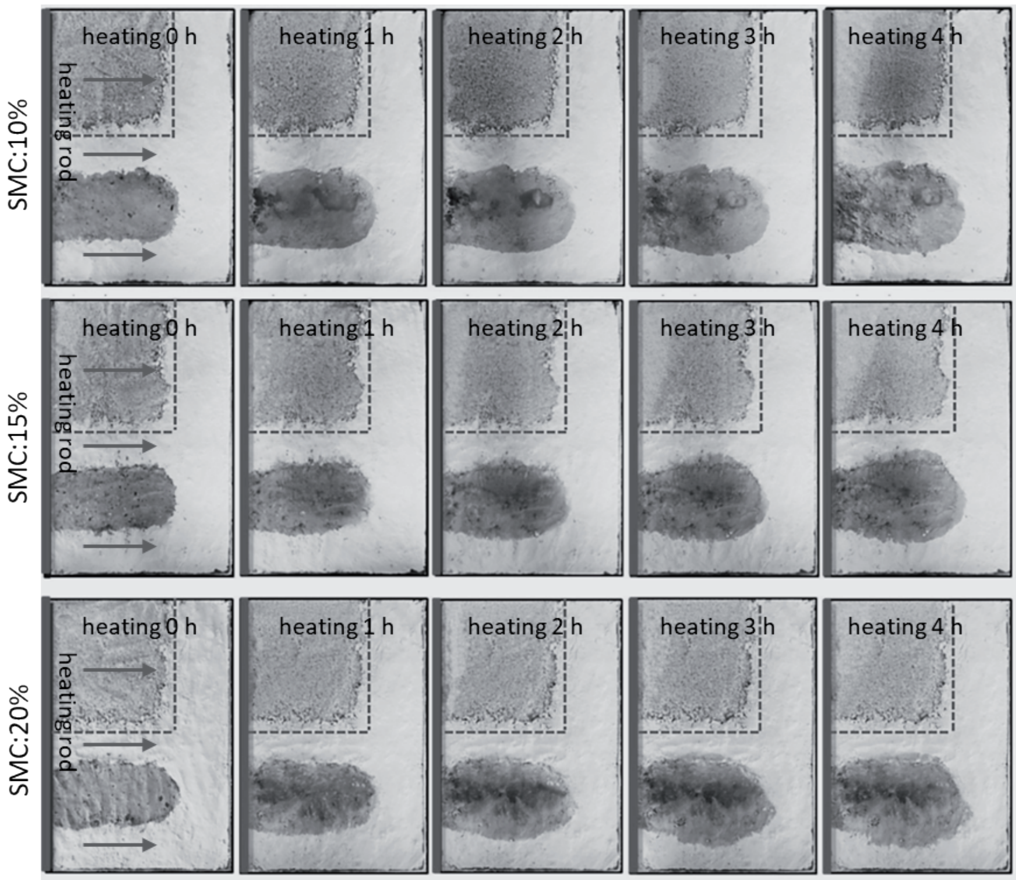

Fig. 10. Contaminant migration in heterogeneous coarse sand-silt layer.

stratum, the fine layers with higher saturated water contents were positioned below. The water from the coarse sand layer above infiltrated the fine layers, due to the combined effects of water potential difference and gravity. This infiltration reduced the amount of water readily available for evaporation and the consequent formation of water vapor, thereby impeding TCE migration [20, 25].

TCE migration in the homogeneous coarse sand layer was more efficient than in the fine layer of the heterogeneous coarse sand-pulverized stratum. TCE exhibited rapid migration rates in the coarse sand layer, covering a substantial radius and a broad range under the same heating time. Conversely, TCE migration in the pulverized stratum from the lower pulverized layer to the upper coarse sand stratum was not observed during the entire experimental process. This observation indicated that evaporated TCE moved upward with water vapor as a whole gas phase after it reached its boiling point. The TCE moving process was influenced by both gas pressure (Pg) and pore pressure (Pe). When gas pressure (Pg) > pore pressure (Pe), the gas could migrate to neighboring pore spaces. The pore pressure (Pe) was determined by the radius of the pore throat using the following Equation:

$$Pe = \frac{2\sigma \cos\theta}{R}$$

Where σ represents air-water surface tension (N/m), θ represents the contact angle (°), and R represents the pore throat radius (m), which is proportionate to the soil grain sizes.

The particle sizes of fine silt particles were smaller than those of coarse sand, resulting in greater pore pressure compared to coarse sand. Consequently, TCE migration within the fine and silt particle layers became more challenging. This phenomenon underscored the key roles of extraction wells in VOCs removal from fine-grained soils. TCE gases in fine-grained low-permeability soils exhibited sluggish movement due to the necessity of overcoming significant pore pressures [26]. Extraction wells served as conduits for contaminant gases in fine-grained soils to move with reduced resistance, thereby facilitating TCE migration from the soil.

TCE Migration in Heterogeneous Silt-Coarse Sand Layers

Fig. 11 illustrates TCE migration within the heterogeneous chalk–coarse sand layer under an initial water content of 10%, 15%, and 20%. After heating begins, TCE moved upward, driven by evaporation.

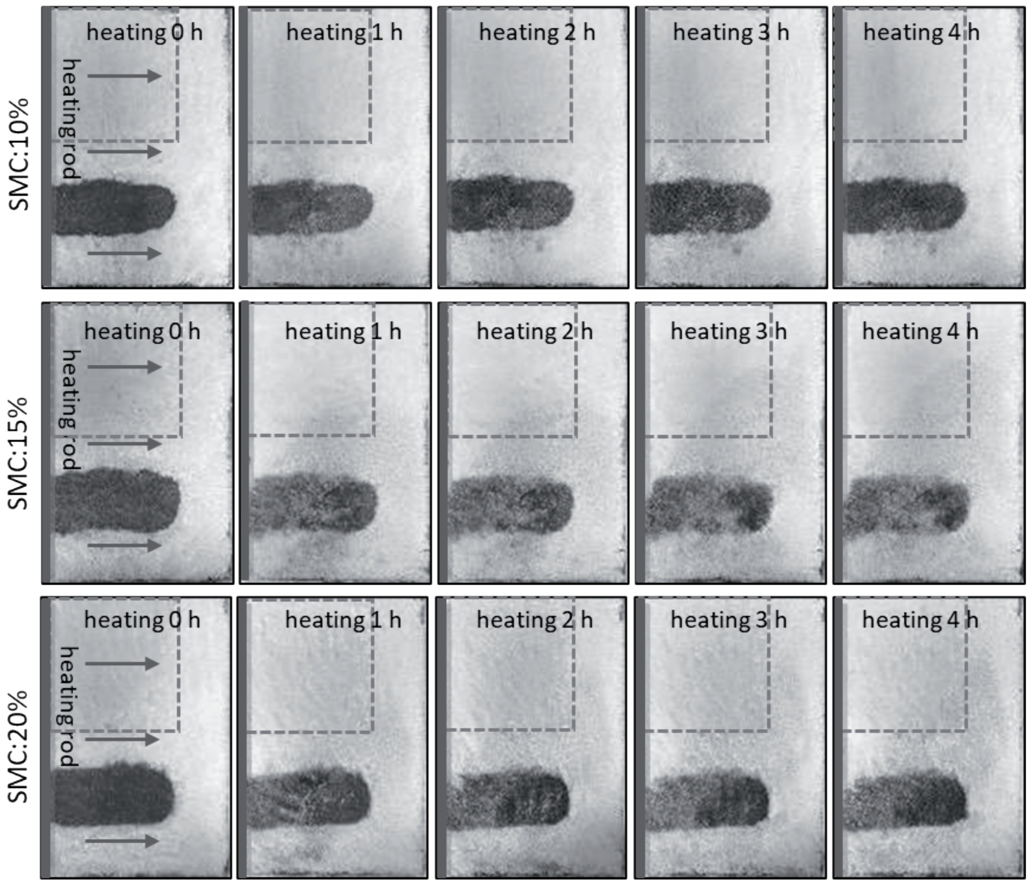

Fig. 11. Contaminant migration in heterogeneous silt-coarse sand layers.

Upon reaching the upper chalk layer, vertical upward migration of TCE was impeded, preventing TCE from moving from the lower coarse sand layer to the upper chalk layer. Instead, TCE moved laterally along the junction of the coarse sand and chalk away from the direction of the heat source. With increasing heating time, TCE migrated laterally to the area without the fine layer above and then continued to migrate upward in the vertical direction.

In the heterogeneous silt and coarse sand layer, a temperature difference existed between the upper and lower soil layers, with the upper chalk layer exhibiting a lower temperature than the lower coarse sand layer. Fig. 11 depicts the upward movement of TCE around the upper layer of fine grains. However, it was determined that the temperature difference between the upper and lower soil layers was not the sole cause of TCE migration. The result was supported by 2 observations: (1) under a water content of 10% in the heterogeneous silt and coarse sand layer, the temperature differences between the upper layer of fine grains and the lower layer of coarse sand were small, with nearly identical temperatures in the upper and lower soil layers. Nevertheless, TCE did not ascend vertically and instead migrated laterally. (2) Under conditions of equilibrium relative humidity, TCE gases tended to accumulate beneath the clay and migrate laterally. Despite the theoretically higher temperature of clay, it had 200 times greater electrical conductivity than that of coarse sand and produced a larger amount of water vapor in the water-saturated state, and TCE gases persistently accumulated and migrated horizontally beneath the fine-grained clay [27]. Therefore, temperature alone was not a key factor influencing TCE accumulation beneath fine-grained layers and their lateral migration.

As observed in Fig. 11, the migration radius of TCE increased with an increase in water contents under the same heating time. Lateral migration was enhanced, and TCE exhibited a tendency to migrate upward by passing the fine grain area. During the heating process in the heterogeneous silt and coarse sand layer, TCE evaporated and migrated upward through channel transport, which was influenced by gas pressure and adjacent pore pressure. In the heterogeneous silt and coarse sand layer, the particle sizes of the lower coarse sand were larger than those of the upper chalk [28]. Consequently, the pore pressure in the lower coarse sand layer was smaller than that in the upper chalk layer. TCE evaporated in the coarse sand layer could overcome pore pressure by gas pressure, migrating upward within the coarse sand layer.

However, during migration from the coarse sand layer to the fine layer, as pore pressure increased, the pressure generated by TCE gas might not breach the upper fine layer. TCE gas accumulated at the bottom of the fine layer, leading to lateral migration. The pore pressure in the lateral coarse sand layer remained unchanged. The contamination continued lateral migration until the gas accumulated at the bottom of the fine layer reached a key level. Gas pressure could overcome the pore pressure of the upper fine-grained layer, enhancing TCE migration. The process repeated until TCE reached the upper layer [29, 30].

TCE Migration in a Heterogeneous Medium with Coarse Sand Layers

At the interface between the coarse sand layer and the pulverized sand layer during the heating process of the heterogeneous pulverized-grained-coarse sand stratum, another experiment was conducted to better understand the effects of heterogeneous layers and heterogeneity on TCE migration. TCE migration in the heterogeneous medium with sand and coarse-sand stratum under in-situ heat transfer heating was included in the experiment.

Fig. 12 illustrates TCE migration in the heterogeneous medium with sand and coarse-sand formation from the bottom to the top under the water contents of 10%, 15%, and 20%. The TCE migration range gradually expanded with increasing heating time. TCE migration occurred in both vertical and horizontal directions. In the vertical direction, the upward movement of TCE driven by evaporation was restricted, but some TCE contamination was observed to migrate to the middle sand layer above. Under the same heating time conditions, the migration ranges of TCE through the medium sand layer were smaller than those through the adjacent coarse sand layers. In the horizontal direction, TCE still moved away from the heat source.

In the heterogeneous medium with a sand and coarse sand layer, temperature differences exist between the upper and lower soil layers, with the temperature of the upper medium sand layer being lower than that of the lower coarse sand layer. Like the heterogeneous chalk with a coarse sand layer, temperature differences between the upper and lower soil layers did not affect TCE accumulation at the bottom of the medium sand layer or their lateral migration. Instead, TCE contamination in the heterogeneous medium sand with a coarse sand layer continued to migrate along the path with lower temperatures.

As depicted in Fig. 12, the vertical upward movement of TCE in the heterogeneous medium with sand and coarse sand layers was impeded under a water content of 10%. Small amounts of TCE could be observed entering the heterogeneous medium with a sand layer above. However, both vertical and horizontal movement of TCE persisted under the water contents of 15% and 20%. Comparatively, under higher water contents, more TCE entered the heterogeneous medium with the sand layer under the same heating time, leading to a larger area of TCE migration and diffusion, with the horizontal migration being more obvious.

Collectively, under heterogeneous fine- and coarse-grained horizons, the heterogeneity of soils was the most key factor governing TCE migration during in-situ thermal conduction heating [31]. Within the

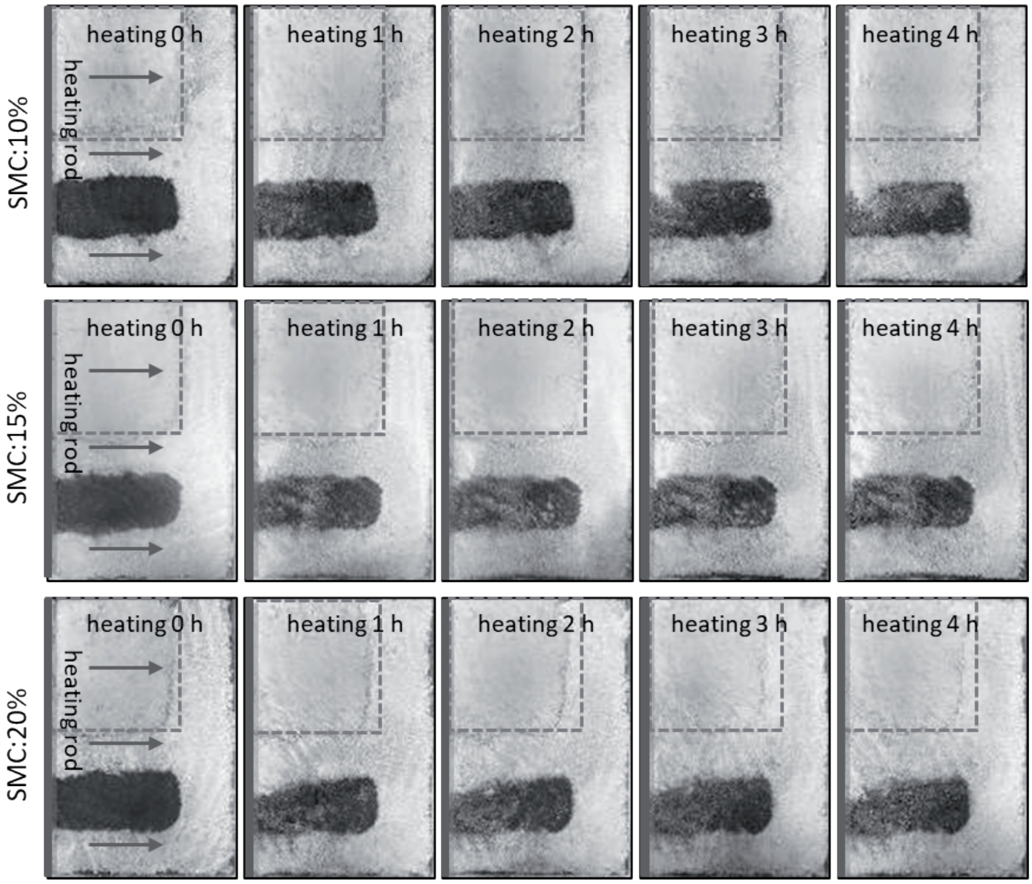

Fig. 12. Contaminant migration in heterogeneous medium-coarse sand formation.

heterogeneous medium with a coarse sand stratum, both vertical and lateral TCE migration coexisted, as they traversed small portions of the medium sand layer above. Conversely, in the heterogeneous medium with a fine-grained and coarse sand stratum, vertical TCE migration faced greater hindrance due to a substantial obstacle, while lateral TCE migration mainly occurred horizontally. Subsequently, TCE contamination moved vertically upon reaching areas with or without a fine-grained soil layer above. As the heterogeneity between the upper and lower soil layers increased, vertical TCE migration weakened, and lateral TCE migration strengthened. In addition, TCE contamination circumvented the upper fine-grained layer before migrating upward. The results became more obvious as the grain sizes of the upper soil layer decreased.

The smaller radius of the soil pore throats generated greater pore pressure, showing higher gas pressure for the migration of TCE gases. The results indicated that small amounts of TCE in the heterogeneous medium with sand and coarse-sand layer migrated through the heterogeneous medium with sand layers. In the heterogeneous chalk with a coarse sand layer, TCE did not traverse the chalk layer but migrated horizontally to areas with or without the chalk layer before proceeding vertically. The result could be attributed to the fact that gas pressure to breach the heterogeneous medium with sand layer was smaller compared to the chalk layer.

Conclusions

This study systematically investigated TCE migration in heterogeneous subsurface systems through controlled thermal conduction heating (TCH) experiments. The results indicated that with the increase in water contents and soil particle sizes, the internal temperature of the homogeneous stratum exhibited an increasing trend. The increase in soil temperature displayed spatial hysteresis concerning the distance from the heat source. Concurrently, as water content increased, the temperature difference between the upper and lower layers in the heterogeneous medium with fine- and coarse-grained stratum also increased. In contrast, minimal changes were found in the temperature difference between the upper and lower layers of the heterogeneous coarse and fine-grained stratum. Notably, heterogeneity during TCH was the key factor influencing TCE migration and distribution. The greater the heterogeneity, the more pronounced the lateral migration of TCE gases became.

Under the same heating durations, TCE in the homogeneous coarse sand layer exhibited a larger migration radius compared to the heterogeneous coarse sand and chalk stratum. The pore pressure generated by the chalk layer was higher than that of the coarse sand layer, which prevented TCE migration. These results underscored the significance of extraction wells, which provided a less resistant pathway for TCE gases in low-permeability soils and enhanced their migration from the soils.

In the remediation of a heterogeneous medium with fine- and coarse-grained stratum using TCH, the higher heating temperature was more favorable for the upper fine- and coarse-grained soil layers, which could achieve uniformity and effectiveness in the heating process. Similarly, for the remediation of a heterogeneous fine- and coarse-grained stratum using TCH, the higher heating temperature should be applied to the upper fine-grained soil layers to achieve uniformity and effectiveness. Additionally, the higher heating temperature could be adopted for both the upper and lower layers of the heterogeneous coarse- and fine-grained sites. Finally, although this study has revealed patterns in pollutant and soil property variations within TCH under different geological conditions, its conclusions are subject to certain limitations due to the significant disparity in scale between the heating duration (24 hours) and the actual engineering application cycle. Subsequent research is recommended to extend heating durations and increase apparatus scale, progressively aligning with practical engineering dimensions. This will further investigate relevant patterns to guide on-site remediation implementation.

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Conflict of Interest

The authors declare no conflict of interest.

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