

Combining electrical resistance heating and steam enhanced extraction for sustainable remediation of heterogeneous organic-contaminated media

Rui Yue

1174093876@qq.com

Chongqing Bureau of Geological and Mineral Resource Exploration and Development

Likun Zhao

WISDRI Engineering & Research Incorporation Limited, WISDRI Water Resources Branch

Tao Xu

PipeChina Institute of Science and Technology

Zhengkai Jing

Chongqing Bureau of Geological and Mineral Resource Exploration and Development

Jinmei Wen

Chongqing Bureau of Geological and Mineral Resource Exploration and Development

Yuxiang Lv

Chongqing Bureau of Geological and Mineral Resource Exploration and Development

Xuhui Mao

Hubei International Scientific and Technological Cooperation Base of Sustainable Resource and Energy,
Wuhan University

Research Article

Keywords: Soil remediation, Electrical resistance heating (ERH), Steam enhanced extraction (SEE), Heterogeneous media, Thermal remediation, Phenanthrene

Posted Date: September 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10649733/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Combining electrical resistance heating and steam enhanced extraction for sustainable remediation of heterogeneous organic-contaminated media

Rui Yue^{1,2,3*}, Likun Zhao⁴, Tao Xu⁵, Zhengkai Jing¹, Jinmei Wen¹, Yuxiang Lv¹, Xuhui Mao^{2*}

1. No. 208 Hydrogeological and Engineering Geological Team, Chongqing Bureau of Geological and Mineral Resource Exploration and Development, Chongqing, 400700, China

2. School of Resource and Environmental Sciences, Hubei International Scientific and Technological Cooperation Base of Sustainable Resource and Energy, Wuhan University, Wuhan 430079, China

3. Chongqing Bureau of Geological and Mineral Resource Exploration and Development, Chongqing, 400700, China

4. WISDRI Engineering & Research Incorporation Limited, WISDRI Water Resources Branch, Wuhan, 430223, China

5. PipeChina Institute of Science and Technology, Tianjin, 00450, China

Corresponding author: Rui Yue (1174093876@qq.com), Xuhui Mao (clab@whu.edu.cn)

Abstract

This study evaluates the sustainability of electrical resistance heating–steam enhanced extraction (ERH–SEE) for remediation of heterogeneous organic-contaminated media, in terms of temperature distribution, remediation efficiency, and energy consumption. Laboratory soil box experiments were conducted on three typical heterogeneous media: layered media, media with heterogeneous moisture content, and media containing a low-permeability lens. Single ERH and SEE both suffered from severe uneven heating caused by heterogeneity. ERH–SEE exhibited strong synergistic effects, delivering faster and more uniform heating in layered and moisture-heterogeneous media, significantly improving phenanthrene removal and reducing energy consumption by 49.17% and 40.21% compared with

ERH and SEE alone. However, ERH–SEE failed to heat lens-bearing media uniformly due to low conductivity of river sand. Injecting 0.5% NaCl solution to increase sand conductivity effectively solved this problem, achieving uniform heating and further cutting energy consumption by 57%. ERH–SEE combined with conductivity enhancement is a highly efficient and energy-saving thermal remediation method for heterogeneous sites, especially those containing low-permeability lenses.

Keywords: Soil remediation, Electrical resistance heating (ERH), Steam enhanced extraction (SEE), Heterogeneous media, Thermal remediation, Phenanthrene

1. Introduction

The contaminated sites resulting from global industrialization and evolving industrial patterns pose great threat to human health, environmental ecology and urban sustainable development(Zhao *et al.*, 2024; Somadas and Sarvade, 2025). It is estimated that the number of contaminated sites worldwide exceeds 5 million(Hou *et al.*, 2023). Among them, there are more than 45,000 in the United States and over 1 million in China. Toxic organic compounds (Polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons and dense nonaqueous phase liquids (DNAPLs), etc.) are the most common contaminants in contaminated sites(Samborska-Goik and Pogrzeba, 2024; Tiwari and Tripathy, 2023). Thus, efficient and sustainable remediation of organic contaminated sites is crucial for human development.

A variety of remediation technologies are available for organic contaminated sites, such as chemical oxidation, bioremediation and flushing remediation. However, the heterogeneity of subsurface and mass transfer resistances limit the effectiveness of these remediation technologies, as organic pollutants can persist for a long time in low-permeability zones(Triplett Kingston *et al.*, 2010; Horst *et al.*, 2021; Bolhari and Sale, 2023; Zhang *et al.*, 2019). In situ thermal treatment (ISTT) involves heating contaminated soil in situ to a sufficiently high temperature to volatilize organic pollutants from the soil into the gas phase or dissolve them into the liquid phase, which are then separated from the soil via an extraction system(Ding *et al.*, 2019; Triplett Kingston *et al.*, 2010). Compared with other in situ remediation technologies,

it features a shorter remediation period and higher pollutant removal efficiency(Horst et al., 2021). However, the prominent drawback of ISTT is high energy consumption. Therefore, there is an urgent need to develop energy-saving and efficient ISTT.

Depending on the heating mechanism, ISTT encompass a variety of types. Electrical resistance heating (ERH) and steam enhanced extraction (SEE), are the two most commonly used heating methods for ISTT(Triplett Kingston et al., 2010; Xu et al., 2022; Vidonish et al., 2016). SEE is an effective remediation method when steam can penetrate into soil pores(Ye et al., 2023). However, SEE is not applicable to low-permeability media (e.g., clay), as steam penetration is severely impeded, leading to unsatisfactory remediation efficiency(Trine et al., 2019). Consequently, heterogeneous subsurface exhibit uneven heating as injected steam preferentially heats the more permeable media, leading to high energy consumption and the risk of incomplete remediation(Liu et al., 2022; Peng et al., 2013). ERH, delivering electric current to subsurface and heating the entire treatment area based on Joule's Law, can effectively heat low-permeability clay, but it also suffers from non-uniform heating(Han et al., 2020; Beyke and Fleming, 2005; Carrigan and Nitao, 2000). There exists a significant difference in heating rates between the vicinity of electrodes and the center of the electrode array, causing uneven subsurface heating(Li et al., 2020). Soil heterogeneity further exacerbates this non-uniformity: zones with higher electrical conductivity (e.g., low-permeability clay) are heated first, while zones with lower conductivity (e.g., high-permeability gravel and sand) are heated subsequently(Martin et al., 2016).

To improve the energy efficiency of ERH and SEE, researchers had carried out a series of studies. One way is to improve the efficiency of single ERH or SEE. For example, Geng et al. reported that energy consumption of ERH using pulsed direct current (PDC) was 27.8% lower compared to that with conventional alternating current (AC) at the same voltage gradient, as PDC showed higher current and faster temperature increase with electroosmosis driven migration(Geng et al., 2021; Zheng et al., 2024; Zheng et al., 2025). Our previous study developed propylene glycol (PG)-mixed SEE for sustainable remediation of PAHs-contaminated soil, the energy

consumption of PG-mixed SEE decreased 78.9% compared to SEE, as PG vapor preferentially condensed to form a hot liquid with concentrated PG to significantly solubilize PAHs(Yue *et al.*, 2023). Besides, Coupling ISTT with chemical oxidation remediation and bioremediation to lower the thermal treatment temperature is also an effective approach to reduce energy consumption of thermal treatment technologies(Wen *et al.*, 2023; Geng *et al.*, 2024; Han *et al.*, 2023; Li *et al.*, 2025; Wang *et al.*, 2022). Yet, this way cannot effectively alleviate the problem of non-uniform heating in SEE and ERH caused by subsurface heterogeneity.

Another way is to combine ERH and SEE (ERH-SEE) to achieve the goal of energy consumption reduction. Heron G et al. had proved the success of ERH-SEE strategy in remediation of DNAPL-contaminated sites(Heron *et al.*, 2005). Our previous research had studied the mechanism of ERH-SEE strategy in remediation of perchloroethylene-contaminated homogeneous soil. Preheating soil by ERH could increase soil permeability, effectively alleviating the problem of preferential flow of steam(Yue *et al.*, 2022). Meanwhile, steam injection heated the soil and provided moisture for maintaining soil electrical conductivity, thereby ensuring power stability in the ERH process. Yang et al. developed a quantitative assessment framework, a model based on the life cycle assessment, to evaluate the environmental, economic, and social sustainability of ERH-SEE, results indicated that ERH-SEE offered better environmental sustainability performance compared to ERH only, with a reduction in carbon emissions by 52.6%(Yang *et al.*, 2024).

However, the synergistic effect of ERH-SEE strategy in remediation of heterogeneous organic contaminated sites remains unclear. Furthermore, given the complex stratigraphic structure, further research is needed to determine whether the SEE-ERH strategy can achieve satisfactory heating performance for different heterogeneous media. In this paper, a laboratory-scale soil box system was established to evaluate the performance of SEE-ERH. Heterogeneous media are constructed using river sand and soil as high-permeability and low-permeability media, respectively. The temporal and spatial distribution of the temperature, organic pollutant removal efficiency, and energy consumption under SEE, ERH, and ERH-SEE treatments are

systematically investigated. The adaptability of the SEE-ERH heating method for heterogeneous media include layered media, lenticular media is explored, and approaches for improving the heating efficiency of heterogeneous media are sought.

2. Methods and materials

2.1 Chemicals and materials

Phenanthrene (Phe, analytical grade), acetone (analytical grade), *n*-hexane (GC grade) and dichloromethane (GC grade) were purchased from the Aladdin Chemical Reagent, China. River sand samples and soil samples were provided by Songyu company in Suzhou, China. Soil were ground into small particles and sieved through 100-mesh screens. The physical properties of river sand samples and soil samples is shown in Table S1 in the Supplementary materials. The components of soil samples is shown in Table S2 in the Supplementary materials.

Preparation of Phe-spiked soil. A given amount of Phe was dissolved in 1000 ml acetone, then 1.5 kg clean soil samples was added into the solution. The resulting mixture was stirred intensely by glass rod for 10 min, then dried in fume hood for 24 hours while stirring multiple times during drying. The prepared Phe-spiked soil samples were sealed in the refrigerator and aged for 21 days.

2.2. Experimental setup and procedures

The schematic of the ERH-SEE laboratory-scale setup is shown in Fig.1. The setup is composed of soil box, steam injection unit, electrical resistance heating unit and temperature monitoring unit. The soil box was made of polytetrafluoroethylene. The wall thickness is 2 cm, the inner wall length is 20 cm, the width is 2 cm, and the height is 15cm. Twelve thermocouples (T1-T12) were installed on the side of soil box, and the thermocouples are all 5 cm apart. The left and right bottoms of the soil box are respectively provided with a 0.5 cm diameter outlet. The steam injection well is made of stainless steel, with an inner diameter of 1 cm, an outer diameter of 0.5 cm, and a length of 13 cm. The injection well is a perforated stainless-steel pipe with holes of 2 mm diameter. The steam injection well was placed in the middle of soil box. A schematic of the actual soil box is shown in Fig.S1 in the Supplementary materials.

For the steam injection part, a metering pump delivers water at desired flow rate to the steam generator. Steam from the generator is injected from the top of the soil box to produce a vertical downward flow through the soil box. A voltage-adjustable transformer is used to provide AC electrical power for ERH. The transformer is connected to a standard power grid (AC phase voltage, 220 V, and 60 Hz). An electricity meter is connected to the transformer to monitor AC voltage, power, and electrical current. The electrodes are 1.8 cm wide and 15 cm high stainless steel sheets arranged on both sides of the soil box.

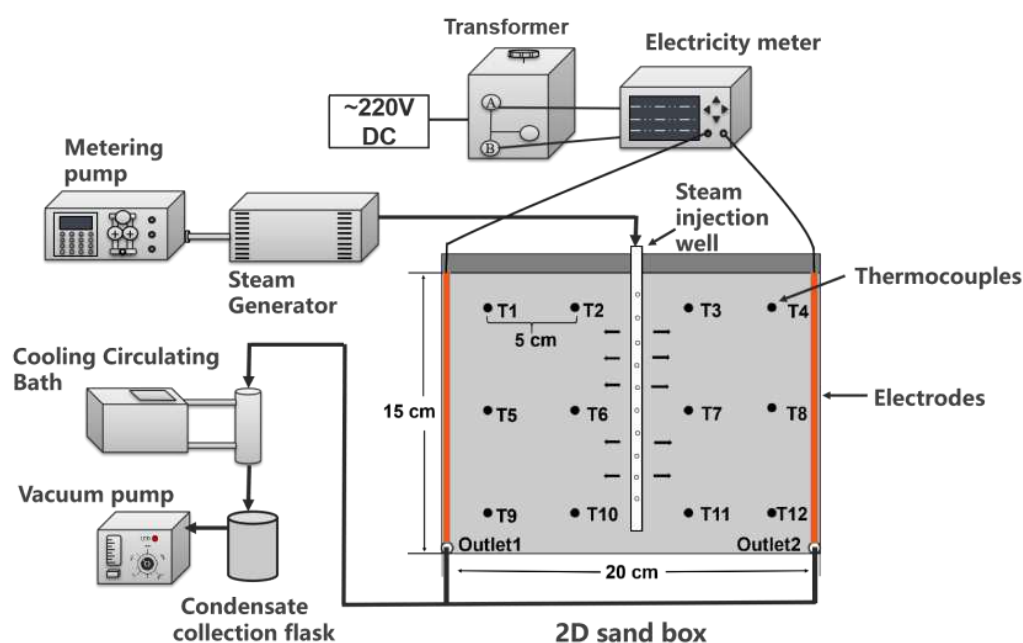


Fig. 1 Schematic of the ERH-SEE laboratory-scale setup

The soil box can be filled with about 900 g of soil or sand samples. The soil samples with a certain moisture content was filled into the soil box several times, and the soil layer was compacted while filling to ensure the soil layer is uniform.

For the Phe removal experiments, a certain amount of Phe-spiked soil samples (or river sand) were filled according to the target heterogeneous media. After ERH, SEE, SEE-ERH experiments, the soil samples around the thermocouples and the outlets were taken for analysis.

2.3 Construction of heterogeneous media

Three types of heterogeneous media are investigated in this study. The first type

is media with heterogeneous water content, which considers that water content of subsurface is typically heterogeneous, with deeper soil having a higher water content than shallow soil. Moreover, water content affects soil permeability and electrical conductivity. As shown in Fig. 2(a), the media with heterogeneous water content was constructed by filling the lower half of the soil box with soil (450g in dry weigh) at 40% water content and the upper half with soil (450g in dry weigh) at 10% water content. The second type is stratified heterogeneous media which is typically heterogeneous media in subsurface. As shown in Fig. 2(b-c), stratified heterogeneous media are constructed by filling soil box with river sand and soil samples, these two media exhibit significant differences in permeability and electrical conductivity. Each medium layer has an identical dry weigh in the soil box, and the water content of all media is uniformly 20%. The third type is heterogeneous media with a low-permeability lens (Fig. 2(d)). A lens refers to a local heterogeneous body (e.g., clay lens) embedded within the primary medium (e.g., sand layer). Such lenses form heterogeneous media and significantly affect the migration behavior of water and solutes. Back-diffusion of contaminants within lens poses the greatest challenge in soil and groundwater remediation(Ding *et al.*, 2022). As shown in Fig. 2(d), heterogeneous media with a lens were artificially constructed, in which the background medium is river sand and the lens is soil. The river sand (600 g in dry weight, the moisture content was 20% (w/w)) was filled surrounding a square lens of soil (approximately 10 cm × 7.5 cm, ~300g in dry weight, the moisture content was 40% (w/w)) in the center of the soil box as a low permeability zone.

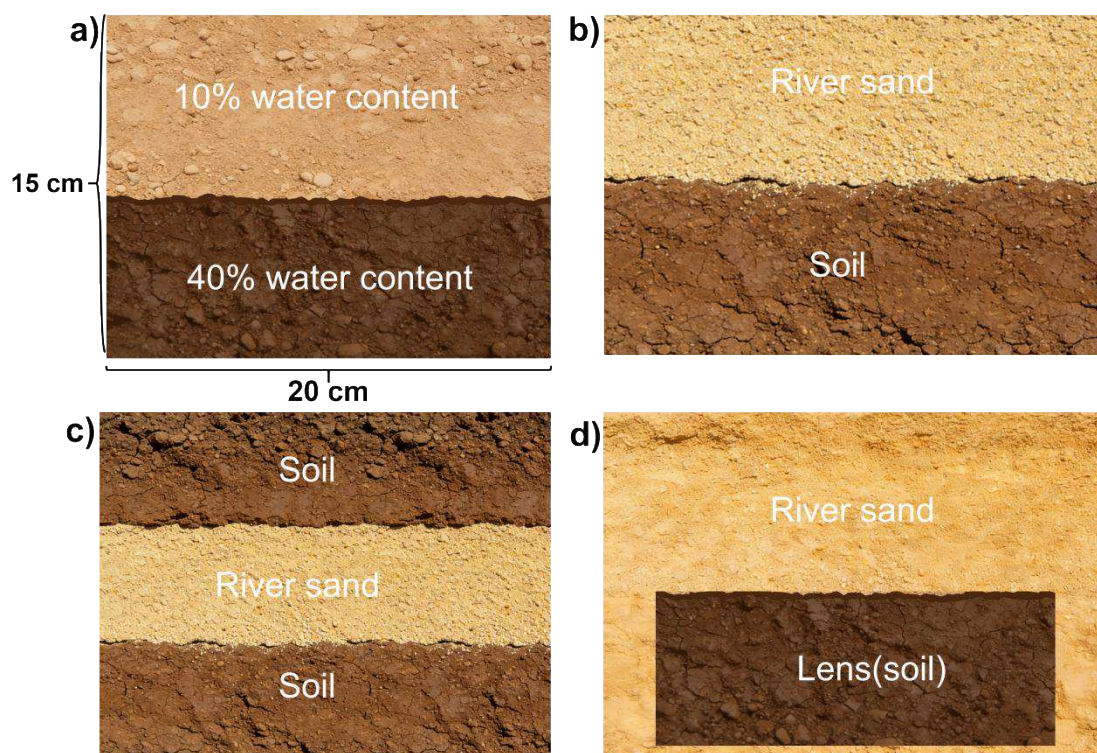


Fig. 2 Diagram of the profiles of heterogeneous media for experiment. (a) media with heterogeneous moisture content with the upper half having a water content of 10% and the lower half 40%, (b) stratified heterogeneous media with a river sand layer in the upper and a soil layer in the bottom, (c) stratified heterogeneous media with a river sand layer in the middle and soil layers in the upper and bottom, (d) heterogeneous media with a lens.

2.4 Analytical methods

Determination of Phe in Phe-spiked soil. The soil samples were placed in a freeze dryer for 2 days until completely dry. In a mortar, the dry soil samples were ground to a fine powder. 2 g of soil samples and 10 ml of dichloromethane were added to a 15 ml centrifuge tube; then the centrifuge tubes were shaken on a vortexer for 15 min, sonicated for 1h, centrifuged at 5000 rpm for 10 minutes. Use a syringe to take the supernatant from the centrifuge tube and filtered it through a filter. Then the supernatant was analyzed by high-performance liquid chromatography (HPLC) (SPD-15 C, Shimadzu) according to the national standard of China (HJ 784–2016). The parameters for HPLC system running include: C18 analytical column, 35 °C column temperature, UV detector at 254 nm wavelength, water/ methanol (1:9 (v/v))

mobile phase at 1 ml/min rate. The residual Phe mass in the soil box at the end of the experiment was calculated according to Eq.1

$$m_t(g) = \frac{m_{media} \times \sum_{i=1}^{i=14} c_i}{14} \quad (\text{Eq.1})$$

Where m_t is the Phe (g) mass remained in soil and sand; $m_{media}(g)$ is mass of media(900g) ; c_i (mg/kg) is the concentration of Phe in the media.

Energy consumption of SEE only considers the energy input for heating, namely, the energy for steam generation (Q_s) which was calculated using the following Eq.2:

$$Q_s = mc(T_1 - T_2) + m\Delta h x \quad (\text{Eq.2})$$

In the equation, m represents the amount of water required to produce steam; c denotes the specific heat capacity of water; t_2 denotes the steam temperature; t_1 is the initial water temperature (25°C in this study); Δh refers to the latent heat of vaporization; and x is the steam dryness fraction, which is set to 90% in this study. Notably, small amounts of energy for injecting steam were excluded when calculating Q_s . In other words, the energy required for the metering pump was not considered. The energy consumption of ERH (Q_e) is directly read from the electricity meter. Energy utilization efficiency (kW·h/g) for Phe removal was calculated by energy consumption (Q) divided by the mass of removed Phe.

The temperature field was obtained via the interpolation analysis method in the numerical simulation software COMSOL. First, a numerical model of the soil box was established to determine the coordinates of the 12 thermocouple monitoring points. Subsequently, the temperature data measured by the thermocouples and the corresponding coordinate information were imported into COMSOL, and the interpolation analysis was adopted to acquire the temperature field distribution within the soil box.

3. Results and discussion

3.1 Temporal and spatial distribution of temperature in media with heterogeneous moisture content

The temperature in media with heterogeneous moisture content showed an uneven distribution during both in single ERH and SEE treatment with significant temporal and spatial variations (Fig. 3). For ERH treatment, the heating rate of the bottom soil layer with higher moisture content is significantly higher than that of the upper soil layer with lower moisture content (Fig. 3(a)). After 60 min, the temperatures at the bottom soil layer (T9–T12) were 66°C, 33.6°C, 33°C, and 55°C, respectively; meanwhile, those at the upper soil layer (T1–T4) were 33.1°C, 28°C, 30°C, and 32°C, respectively (Fig.S2a). With continuous ERH treatment, the soil layer temperature increased gradually. After 180 min, the temperatures at the bottom layer (T9–T12) rose to 70°C, 57°C, 50°C, and 65°C, respectively, while those at the upper layer (T1–T4) were 47°C, 42°C, 39°C, and 40°C, respectively (Fig. S2(a)). The average temperature difference between the bottom soil and the topsoil reaches 20°C.

Soil moisture content is positively correlated with its electrical conductivity. The electrical conductivity of soil determines its resistance. According to the formula ($P=U^2/R$), a higher soil electrical conductivity corresponds to lower resistance, which yields greater heating power of ERH and a faster soil temperature rise rate. Soil electrical conductivity (σ_s) is affected by multiple factors including soil porosity, water content, pore fluid conductivity, and temperature (Arps, 1953, Archie and G., 1942). The influence of the above factors on electrical conductivity can be expressed by the following equation:

$$\sigma_s = \theta^m S_w^n \sigma_w \quad (\text{Eq.3})$$

$$\sigma_{w2} = \sigma_{w1} \frac{T_2 + 21.5}{T_1 + 21.5} \quad (\text{Eq.4})$$

Where σ_s and σ_w represent the bulk electrical conductivity of the porous medium and the electrical conductivity of pore fluid, respectively; θ denotes porosity; S_w is the water saturation of the medium; m and n are the cementation exponent and saturation exponent, correspondingly; σ_{w1} denotes the electrical conductivity of water at the reference temperature T_1 , while σ_{w2} represents the water electrical conductivity when

the temperature rises to T_2 . It can be inferred from the Eq.3 that higher soil water content leads to elevated soil electrical conductivity, thereby increasing the heating power of ERH. Furthermore, the heating rate of soil near the electrodes (T_9 , T_{12}) is significantly higher than that far from the electrodes(T_{10} , T_{11}), which is consistent with previous studies(Yue et al., 2022).

For SEE treatment, in contrast to ERH, the upper soil layer with a low moisture content (10%) was heated preferentially and exhibited a relatively rapid heating rate (Fig.3 b). After 90 min of heating, the soil temperatures at monitoring points T_1 – T_4 reached 73 °C, 89 °C, 82 °C, and 72 °C, respectively; while the soil temperatures at monitoring points T_9 – T_{12} were 38 °C, 58 °C, 54 °C, and 32 °C, respectively (Fig. S 2(b)). A pronounced temperature difference exceeding 30°C was observed between the upper and bottom soil layers. After 180 min, the temperatures at T_9 – T_{12} were 50 °C, 62 °C, 59 °C, and 41 °C, respectively, indicating no significant temperature increase in the bottom soil (Fig. S 2(b)).This observation suggests that when steam is injected into soil layers with heterogeneous moisture content, the steam cannot be effectively transported into the soil layers with higher moisture content.

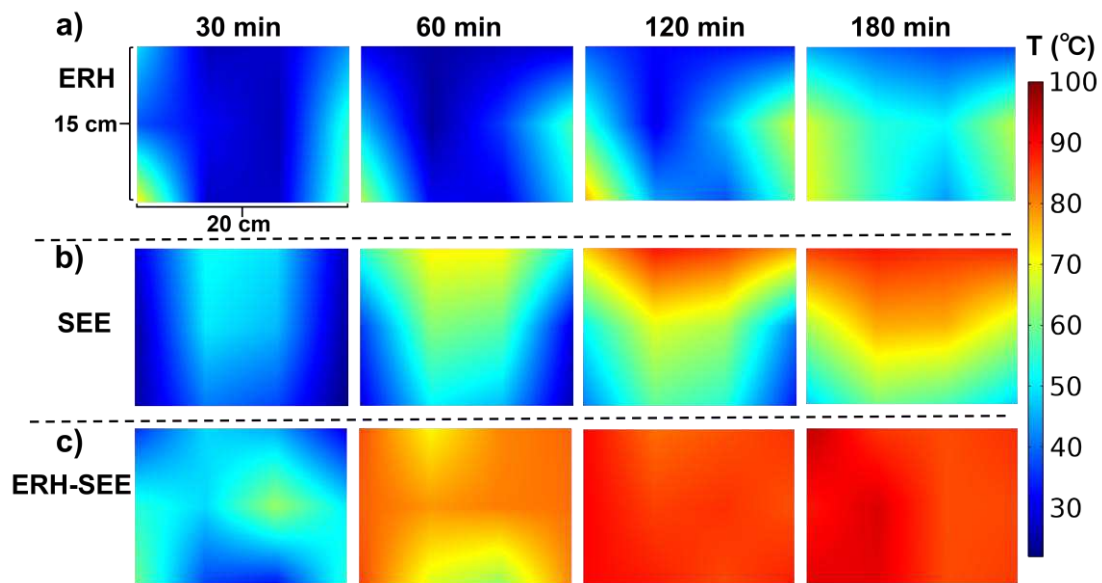


Fig. 3 Two dimensional spatial variations of temperature in media with heterogeneous moisture content. (a) ERH treatment, (b) SEE treatment, (c)ERH-SEE treatment. The steam injection was operated at 1.5 g/min. Electric field strength was 8 V/cm.

The observed heterogeneous heating behavior can be primarily attributed to the significant influence of soil moisture content on steam migration and heat transfer. As described by the Corey correlation(Piquemal, 1994), soil permeability (K_G) is governed by water saturation S :

$$K_G=(1-S_e^2)(1-S_e)^2 \quad (\text{Eq.5})$$

The effective saturation of the wetting liquid (S_e) is defined as:

$$S_e=(S-S_i)/(1-S_i) \quad (\text{Eq.6})$$

where (S_i) denotes the irreducible saturation of the wetting liquid. It can be deduced from the above equations that an increase in water saturation S raises the effective saturation (S_e), which in turn reduces soil permeability and increases the flow resistance of vapor. In the upper soil with low moisture content (10%), the relatively high porosity and low water saturation provide favorable pathways for steam flow, allowing rapid heat propagation and fast temperature elevation. In contrast, the higher moisture content (30%) in the bottom soil leads to increased water saturation and reduced effective porosity, which impedes the penetration and diffusion of steam. The high water content not only consumes considerable latent heat for vaporization but also blocks the preferential flow channels for steam transport.

Compared with single ERH and SEE treatment, ERH-SEE treatment resulted in a more uniform temperature distribution and a faster heating rate in the soil layers (Fig. 3(c)). After 60 min, the soil temperatures at monitoring points T1–T8 in the upper and middle layers all exceeded 72 °C; the soil temperatures at T9–T12 in the bottom layer were 80 °C, 65 °C, 62 °C, and 73 °C, respectively; after 90 min, the overall temperature of the soil layers exceeded 80 °C (Fig. S2(c)). The results demonstrate that for soil layers with heterogeneous moisture content, ERH-SEE treatment can significantly overcome the problem of uneven temperature distribution associated with single ERH or SEE,.

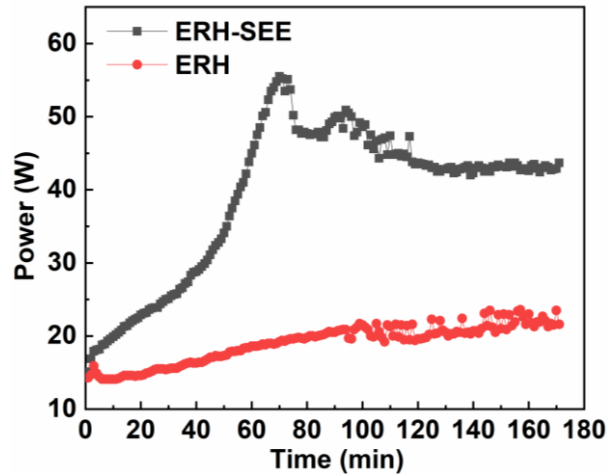


Fig. 4 Profiles of input heating power of ERH in media with heterogeneous moisture content.

The excellent performance of ERH-SEE system can be explained by the synergistic mechanism between ERH and SEE. The complementary effects of these two approaches optimize heat propagation within heterogeneous soil layers: ERH mitigates the uneven temperature distribution caused by preferential steam flow, while SEE compensates for the relatively low heating efficiency of ERH alone. Besides, Fig. 4 shows the variation in the input heating power of ERH. During ERH-SEE treatment, the input heating power of ERH rose rapidly, reaching a maximum of 55 W at 63 min. In contrast, under single ERH treatment, the heating power increased slowly to 18 W at the same moment. Subsequently, the input heating power of ERH-SEE began to decrease and stabilized at 45 W after 120 min, while that of single ERH remained steady at 20 W.

A higher input heating power of ERH corresponds to faster soil heating, indicating that SEE significantly enhanced the heating efficiency of ERH. According to the power formula $P=U^2/R$, the input heating power increases with decreasing resistance. Steam injection increases soil water content and elevates soil temperature simultaneously, both of which contribute to the reduction in soil electrical resistance according to Eq.3 and Eq.4. Consequently, the ERH-SEE system effectively alleviates heating limitations induced by heterogeneous moisture content, achieving both rapid temperature elevation and uniform thermal distribution. This synergistic effect confirms that the combined heating strategy is highly favorable for the remediation of

soils with variable moisture conditions.

3.2 Temporal and spatial distribution of temperature in stratified heterogeneous media

Similar to the heating of soil layers with heterogeneous moisture content, during the treatment with single ERH and single SEE, the temperature in the stratified heterogeneous media also showed an uneven distribution and exhibited significant spatiotemporal variations. For ERH treatment, the heating rate of the soil layer was significantly higher than that of the river sand layer (Fig. 5(a)). After 180 min, the temperatures of the soil at monitoring points T9–T12 rose to 79 °C, 39 °C, 40 °C, and 73 °C, respectively (Fig. S3(a)). In contrast, the temperatures of the river sand at T1–T4 were 33 °C, 31 °C, 32 °C, and 34 °C, respectively (Fig. S3(a)). The phenomenon of non-uniform soil temperature distribution became more pronounced, compared with soil layers with heterogeneous moisture content. The temperature difference between the soil layer and the river sand layer could be more than 40°C. The distinct heating behavior can be mainly attributed to the differences in their physical properties. As shown in table S1, soil generally has higher electrical conductivity and stronger effective thermal conductivity than river sand, which facilitates more efficient heat accumulation and temperature elevation.

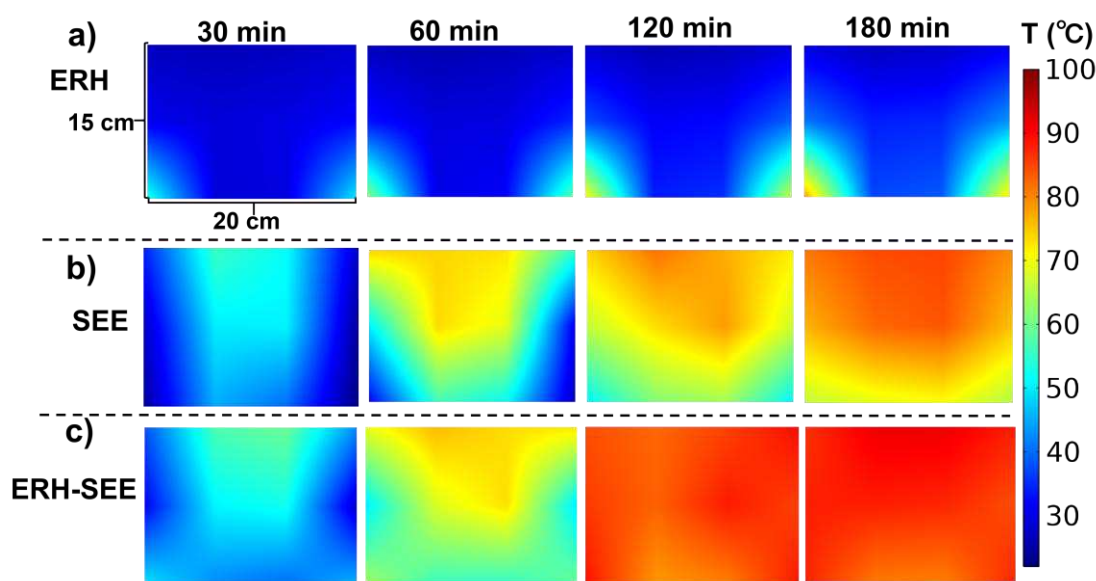


Fig. 5 Two dimensional spatial variations of temperature in stratified heterogeneous media with a river sand layer in the upper and a soil layer in the bottom. (a) ERH

treatment, (b) SEE treatment, (c) ERH-SEE treatment. The steam injection was operated at 1.5 g/min. Electric field strength was 8 V/cm.

For SEE treatment, the upper river sand layer exhibited a faster heating rate (Fig. 5(b)). After 60 min, the temperatures of the river sand at monitoring points T1–T4 reached 60 °C, 70°C, 73°C, and 65°C, respectively; while the bottom soil layer at T9–T12 reached 35 °C, 55 °C, 53 °C, and 30°C, respectively (Fig. S3(b)). After 180 min, the temperature of the upper river sand layer exceeded 80°C, while the bottom soil layer remained below 70 °C, resulting in a considerable temperature difference between the river sand and soil layers (Fig. S3(b)). This results indicates that steam preferentially migrates in the river sand layer. As shown in table S1, river sand is characterized by bigger permeability coefficient, higher porosity and larger particle size, which provide favorable flow channels for steam migration and heat transfer, leading to rapid temperature rise. In comparison, the soil layer has finer particles, and lower permeability, which hinder steam penetration and diffusion. These results further confirm that media texture and pore structure play a dominant role in steam transport efficiency during thermal remediation.

During ERH-SEE heating, the temperature distribution was more uniform and the heating rate was faster (Fig. 5(c)). After 60 min, the temperatures at monitoring points T1–T8 all exceeded 70°C, and those at T9–T12 exceeded 60°C (Fig. S3(c)). After 120 min, the overall temperature of the media exceeded 80°C (Fig. S3(c)). The results demonstrate that for stratified heterogeneous soil, ERH-SEE treatment can significantly overcome the problem of non-uniform heating associated with single ERH or SEE. ERH-SEE exhibits an excellent synergistic heating effect for stratified heterogeneous media

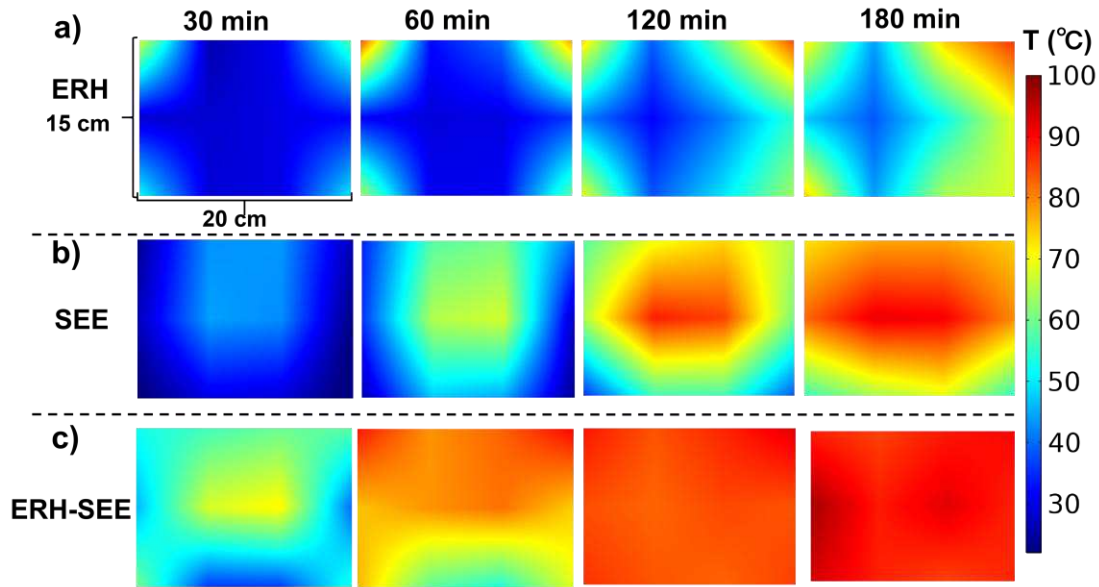


Fig. 6 Two dimensional spatial variations of temperature in stratified heterogeneous media with a river sand layer in the middle and soil layers in the upper and bottom. (a)ERH treatment, (b)SEE treatment, (c)ERH-SEE treatment. The steam injection was operated at 1.5 g/min. Electric field strength was 8 V/cm.

To further verify the synergistic effect of ERH-SEE, a more complex stratified heterogeneous media, consisting of a river sand layer in the middle and soil layers in the upper and bottom, was also investigated. Consistent with the previous results, obvious spatiotemporal heterogeneity in temperature distribution was observed under single ERH and single SEE treatment. Under ERH treatment, the upper and bottom soil layers were effectively heated, whereas the temperature of the middle river sand layer increased very slowly (Fig. 6(a)). Under SEE treatment, the middle river sand layer was heated preferentially (Fig. 6(b)). In contrast, during ERH-SEE treatment, the temperature distribution was more uniform and the heating rate was faster. After 120 min, the temperature of all media layers exceeded 80°C.

For stratified heterogeneous media, the ERH-SEE treatment optimizes heating efficiency and overcomes the limitations of single heating technologies. The efficient steam migration in river sand and the stable thermal conduction in soil layers to enhance ERH. Meanwhile, ERH provides stable and continuous thermal energy throughout the soil layers, effectively improving the uniformity of the temperature distribution and compensating for the uneven heating caused by preferential steam

flow. These results confirm that the ERH-SEE system can effectively alleviate the problem of uneven heating of single heating technologies in stratified heterogeneous media, thereby providing a more reliable and efficient heating strategy for the thermal remediation of stratified heterogeneous media.

3.3 Temporal and spatial distribution of temperature in heterogeneous media with a low-permeability lens

As shown in Fig. 7(a-c), none of the ERH, SEE, and ERH-SEE, can effectively heat heterogeneous media with a lens. Under ERH treatment, the media temperatures showed no further increase after 180 min (Fig. 7(a)). Although soil lens exhibits relatively high electrical conductivity, it is surrounded by low-conductivity river sand, making the overall media difficult to heat by ERH. During SEE treatment, the upper river sand layer heated up rapidly, and its temperature exceeded 80 °C after 180 min(Fig. 7(b)). However, the temperature of the soil lens increased slowly. In particular, the river sand on both sides of the lens exhibited extremely slow heating, with the temperature remaining below 60 °C after 180 min, due to the steam is blocked by the lens and cannot be effectively transported to the river sand on both sides. During ERH-SEE treatment, the overall temperature rise trend of the media was nearly identical to that under SEE treatment, as the low electrical conductivity of river sand limited the heating efficiency of ERH, demonstrating that ERH-SEE also suffers from non-uniform heating when treating low-conductivity media containing low-permeability lenses(Fig. 7(c)).

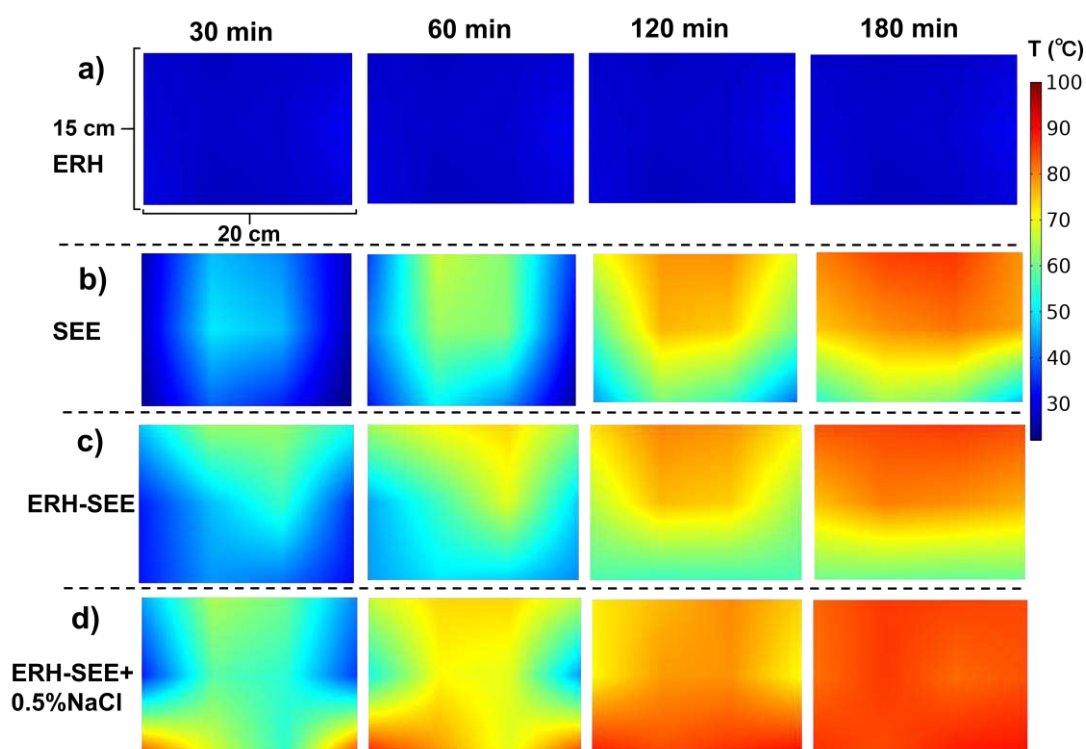


Fig. 7 Two dimensional spatial variations of temperature in heterogeneous media with lens under (a) ERH treatment, (b) SEE treatment, (c) ERH-SEE treatment, (d) 0.5% NaCl+ERH-SEE treatment. The steam injection was operated at 1.5 g/min. Electric field strength was 8 V/cm.

Increasing the electrical conductivity of river sand is an effective approach to solving the problem of low heating efficiency for lenses. As shown in Figure S4, to investigate the effect of salt content in river sand on ERH heating, water with different salt concentrations was added separately to the 5 cm-thick river sand layer at the bottom. As illustrated in Figure S5, when the NaCl concentration in the pore water of river sand was 0.2 wt%, the ERH heating efficiency improved significantly. The temperature of river sand near the electrodes reached 80°C after 30 min of heating, and stabilized at approximately 90°C after 90min. When the NaCl concentration was increased to 0.5 wt%, the ERH heating efficiency was further enhanced, and the temperature of river sand near the electrodes reached 90°C after only 30 min of heating (Figure S6).

To achieve uniform and efficient heating of the heterogeneous media with a low-permeability lens, a 0.5% NaCl aqueous solution was injected into the bottom

river sand before heating. After the injection of the NaCl solution, the ERH-SEE treatment achieved uniform and rapid temperature rise of media, and the heating rate of the bottom lens was faster (Fig.7(d)). After 150 min, the overall temperature of the media exceeded 85°C. The above experimental results indicate that, to address the problem of low heating efficiency in heterogeneous media containing lens, the SEE-ERH treatment can achieve efficient heating of entire media by injecting salt water into the river sand around the lens to increase the electrical conductivity of the media.

3.4 Evaluation of remediation efficiency and energy consumption

The Phe removal effects under ERH, SEE, and ERH-SEE treatments were systematically compared to clarify the remediation performance of different thermal treatment methods for Phe-contaminated heterogeneous media. For stratified heterogeneous media with soil layers in the upper and bottom parts and a river sand layer in the middle, ERH treatment showed poor phenanthrene removal efficiency ((Fig.8(a)). The Phe removal rate in the soil near the electrodes was 8%, while the Phe content in the soil far from the electrodes and the river sand showed almost no reduction ((Fig.8(a)). It can be found that there is a correlation between the Phe removal effect and the temperature distribution characteristics: the higher the medium temperature, the better the phenanthrene removal effect. Under SEE treatment, the Phe removal effect in the river sand layer was the best, with a removal rate of 15%–25%; followed by the upper soil layer, with a Phe removal rate of 10%–18%; the Phe removal effect in the bottom soil layer was the worst, and the content increased to 110%–118% compared with the initial concentration((Fig.8(b)). This may be due to the low temperature of the bottom soil layer, and the Phe removed from the upper layer may accumulate in the bottom layer.

During ERH-SEE treatment, Phe in both the soil and river sand layers was effectively removed. Among them, the phenanthrene removal effect in the upper soil and river sand layers was the best, with a removal rate of 30%–40%; the Phe removal rate in the bottom soil layer was 5%–15%, and the Phe concentration in the bottom

soil near the two outlets was the highest, which was caused by the accumulation of Phe removed from the upper layer here ((Fig.8(c)).The energy consumption calculation results showed that the ERH-SEE treatment is significantly more energy-efficient than single ERH treatment and SEE treatment: the energy consumption of ERH, SEE, and ERH-SEE was 17.49 kWh/g, 14.87 kWh/g, and 8.89 kWh/g, respectively ((Fig.8(d)). Compared with single ERH and SEE, the energy consumption of ERH-SEE was reduced by 49.17% and 40.21%, respectively.

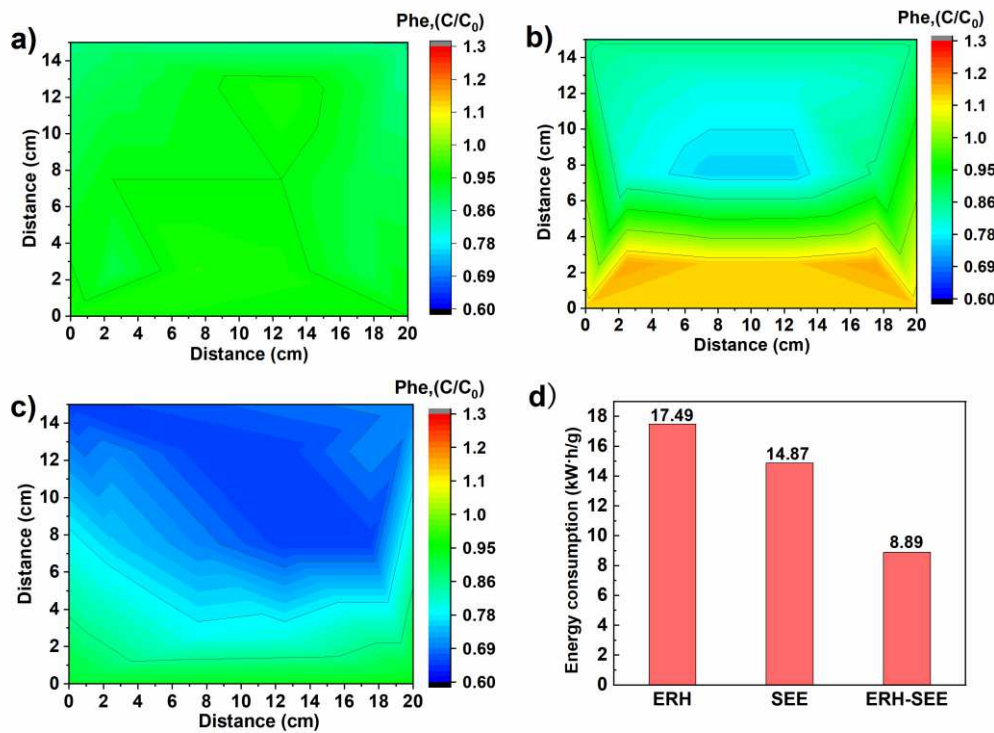
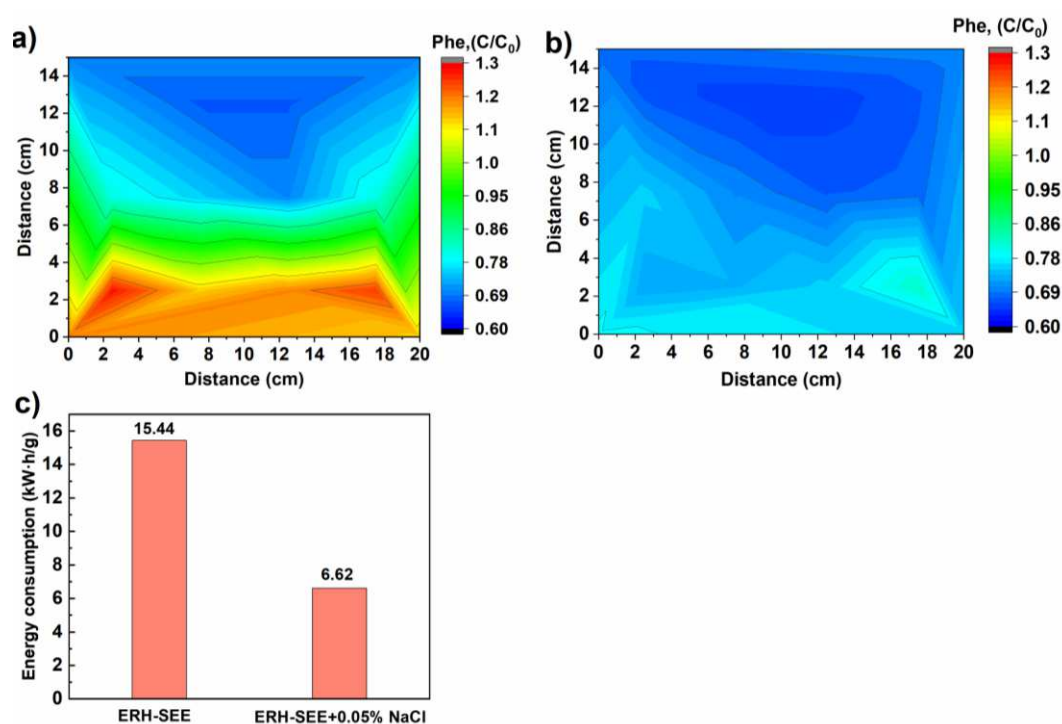


Fig. 8 The remediation performance of Phe-contaminated stratified heterogeneous medium. (a) ERH treatment, (b)SEE treatment, (c) ERH-SEE treatment. (c) Energy consumption calculation. The steam injection was operated at 1.5 g/min. Electric field strength was 8 V/cm. Initial concentration of Phe was 200 mg/kg.

From the above results, it can be concluded that for the removal of Phe in heterogeneous media, due to uneven temperature distribution of the media, single ERH or SEE remediation has the problems of low removal efficiency and Phe accumulation in low-temperature soil layers, resulting in high energy consumption. In contrast, during SEE-ERH treatment, the media temperature rises uniformly and reaches a higher level, resulting in a significant improvement in Phe removal

493 efficiency and a remarkable energy-saving effect.



494

495 Fig. 9 The remediation performance of Phe-contaminated in heterogeneous media
496 with a low-permeability lens. (a) ERH-SEE treatment, (b) 0.5% NaCl+ERH-SEE
497 treatment. (c) Energy consumption calculation. The steam injection was operated at
498 1.5 g/min. Electric field strength was 8 V/cm. Initial concentration of Phe was 200
499 mg/kg.

500 For heterogeneous media with a low-permeability lens, during ERH-SEE
501 treatment, the Phe removal rate in river sand layer was 15%–30%, while the Phe
502 concentration in the bottom lens increased to 110%–124% of the initial
503 concentration((Fig. 9(a)). Since the river sand could be heated to a relatively high
504 temperature, phenanthrene in the river sand was easily removed. However, the bottom
505 lens had a low temperature and poor permeability, so the Phe desorbed from the upper
506 river sand accumulated here when migrating to the lens.

507 After injecting NaCl solution into the bottom river sand, the ERH-SEE
508 treatment achieved high Phe removal efficiency in different media: the Phe removal
509 rate in the upper river sand layer was 20%–35%, and the Phe removal rate in the
510 bottom lens was 15%–20%((Fig. 9(b)). For the experimental group without NaCl
511 solution injection, the failure to heat the bottom lens led to extremely high energy

consumption for Phe removal, reaching 15.44 kW·h/g; the energy consumption of the experimental group with NaCl solution injection decreased to 6.62 kW·h/g, which was 57% lower than the former ((Fig. 9(c)).

4. Conclusion

This work systematically investigates heating behavior, remediation efficiency, and energy consumption of ERH, SEE, and ERH–SEE in heterogeneous media. Single ERH and SEE show obvious uneven heating: ERH preferentially heats high-conductivity zones, while SEE migrates along high-permeability layers, leading to low removal efficiency and high energy consumption. ERH–SEE presents remarkable synergistic effects, which optimize heat propagation, improve temperature uniformity, enhance Phe removal, and lower energy consumption in layered and moisture-heterogeneous media. For lens-bearing media, low sand conductivity limits heating performance of ERH–SEE. Increasing sand conductivity by NaCl injection greatly accelerates heating rate and improves uniformity across the entire medium, significantly enhancing lens remediation and energy efficiency. Overall, ERH–SEE is an efficient and sustainable thermal remediation technology for heterogeneous organic-contaminated sites. With conductivity enhancement, it can overcome heating bottlenecks caused by low-permeability lenses and provide a reliable technical basis for field applications.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgements

This study was supported by the National Key R&D Program of China (No. 2019YFC1805700) and Chongqing Natural Science Foundation General Project (CSTB2024NSCQ-MSX1077).

Electronic Supplementary Material

Supplementary material is available in the online version of this article at

<https://dx.doi.org/> and is accessible for authorized users.

References

- Archie, G E (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the Aime*, 146(01), 54-62
- Arps J J (1953). The effect of temperature on the density and electrical resistivity of sodium chloride solutions. *Journal of Petroleum Technology*, 5(10), 17-20
- Beyke G, Fleming D (2005). In situ thermal remediation of DNAPL and LNAPL using electrical resistance heating. *Remediation Journal: The Journal of Environmental Cleanup Costs, Technologies & Techniques*, 15(3), 5-22
- Bolhari A, Sale T (2023). Processes governing treatment of contaminants in low permeability zones. *Science of The Total Environment*, 879, 163010
- Carrigan C R, Nitao J J (2000). Predictive and diagnostic simulation of in situ electrical heating in contaminated, low-permeability soils. *Environmental science & technology*, 34(22), 4835-4841
- Ding D, Song X, Wei C, LaChance, J (2019). A review on the sustainability of thermal treatment for contaminated soils. *Environmental Pollution*, 253, 449-463
- Ding X, Feng S, Zheng Q (2022). Forward and back diffusion of reactive contaminants through multi-layer low permeability sediments. *Water research*, 222, 118925
- Geng Z, Liu B, Li G, Zhang F (2021). Enhancing DNAPL removal from low permeability zone using electrical resistance heating with pulsed direct current. *Journal of hazardous materials*, 413, 125455
- Geng Z, Zheng D, Qi Z, Xie Q, Li G, Zhang F (2024). Direct current driven persulfate delivery and activation for heterogeneous porous media remediation: Coupling effects of electric-thermal-chemical-flow fields. *Journal of Hazardous Materials*, 479, 135743
- Han C, Zhu X, Xiong G, Gao J, Wu J, Wang D, Wu J (2023). Quantitative study of in situ chemical oxidation remediation with coupled thermal desorption. *Water Research*, 239, 120035
- Han Z, Jiao W, Tian Y, Hu J, Han D (2020). Lab-scale removal of PAHs in contaminated soil using electrical resistance heating: Removal efficiency and

572 alteration of soil properties. Chemosphere, 239, 124496

573 Heron G, Carroll S, Nielsen S G (2005). Full - scale removal of DNAPL constituents
574 using steam - enhanced extraction and electrical resistance heating. Groundwater
575 Monitoring & Remediation, 25(4), 92-107

576 Horst J, Munholland J, Hegele P, Klemmer M, Gattenby J (2021). In Situ Thermal
577 Remediation for Source Areas: Technology Advances and a Review of the Market
578 From 1988 - 2020. Ground Water Monitoring & Remediation, 41(1)

579 Hou D Y, Al-Tabbaa A, O Connor D, Hu Q, Zhu Y, Wang L, Bolan N S (2023).
580 Sustainable remediation and redevelopment of brownfield sites. Nature Reviews
581 Earth & Environment, 4(4), 271-286

582 Li J, Wang L, Peng L, Deng Y, Deng D (2020). A combo system consisting of
583 simultaneous persulfate recirculation and alternating current
584 electrical resistance heating for the implementation of heat activated persulfate
585 ISCO. Chemical Engineering Journal, 385, 123803

586 Li Z, Liang J, Li J, Ma X, Lang Y, Li H, Zhao L (2025). Thermal desorption coupled
587 with persulfate oxidation for removing soil organic pollutants: Key role of soil
588 organic matter passivation. Journal of Hazardous Materials, 140382

589 Liu R, Yang X, Xie J, Li X, Zhao Y (2022). Steam migration and temperature
590 distribution in aquifers during remediation using steam injection. Journal of
591 contaminant hydrology, 245, 103942

592 Martin E J, Mumford K G, Kueper B H (2016). Electrical resistance heating of clay
593 layers in water - saturated sand. Groundwater Monitoring & Remediation, 36(1),
594 54-61

595 Peng S, Wang N, Chen J (2013). Steam and air co-injection in removing residual TCE
596 in unsaturated layered sandy porous media. Journal of contaminant hydrology, 153,
597 24-36

598 Piquemal J (1994). Saturated steam relative permeabilities of unconsolidated porous
599 media. Transport in Porous Media, 17(2), 105-120

600 Samborska-Goik K, Pogrzeba M (2024). A Critical Review of the Modelling Tools for
601 the Reactive Transport of Organic Contaminants. Applied Sciences, 14(9), 3675

602 Somadas P, Sarvade P G (2025). An overview of the impacts of various industrial and

603 urban wastes on soil properties: contamination and remediation strategies.
 604 Environmental Research Communications, 7(3), 32002
 605 Tiwari M, Tripathy D B (2023). Soil contaminants and their removal through
 606 surfactant-enhanced soil remediation: a comprehensive review. Sustainability,
 607 15(17), 13161
 608 Trine L S D, Davis E L, Roper C, Truong L, Tanguay R L, Simonich S L M (2019).
 609 Formation of PAH derivatives and increased developmental toxicity during steam
 610 enhanced extraction remediation of creosote contaminated superfund soil.
 611 Environmental science & technology, 53(8), 4460-4469
 612 Triplett Kingston J L, Dahlen P R, Johnson P C (2010). State - of - the - practice
 613 review of in situ thermal technologies. Groundwater Monitoring & Remediation,
 614 30(4), 64-72
 615 Vidonish J E, Zygourakis K, Masiello C A, Sabadell G, Alvarez P J (2016). Thermal
 616 treatment of hydrocarbon-impacted soils: a review of technology innovation for
 617 sustainable remediation. Engineering, 2(4), 426-437
 618 Wang Q, Guo S, Ali M, Song X, Tang Z, Zhang Z, Luo Y (2022). Thermally enhanced
 619 bioremediation:
 620 A review of the fundamentals and applications in soil and groundwater remediation.
 621 Journal of Hazardous Materials, 433, 128749
 622 Wen D, Liu H, Zhang Y, Fu R (2023). Electrokinetically-delivered persulfate and
 623 pulsed direct current electric field induced transport, mixing and thermally
 624 activated in situ for remediation of PAHs contaminated soil. Journal of Hazardous
 625 Materials, 444, 130414
 626 Xu X, Hu N, Wang Q, Fan L, Song X (2022). A numerical study of optimizing the well
 627 spacing and heating power for in situ thermal remediation of
 628 organic-contaminated soil. Case studies in thermal engineering, 33, 101941
 629 Yang Z, Wei C, Sima J, Yan S, Yin L, Xian A, Song X (2024). Quantitative
 630 sustainability assessment for in-situ electrical resistance heating coupled with
 631 steam enhanced extraction: An effective approach for the development of green
 632 remediation technologies. Water Research, 267, 122450

Ye C, Sima J, Zhou D, Chen Y, Yang J, Yan Y (2023). A coupled thermal desorption process for decontamination of polycyclic aromatic hydrocarbon from soil: important role of the steam injection. *Water, Air, & Soil Pollution*, 234(10), 642

Yue R, Chen Z, Liu L, Yin L, Qiu Y, Wang X, Mao X (2022). Combination of steam-enhanced extraction and electrical resistance heating for efficient remediation of perchloroethylene-contaminated soil: Coupling merits and energy consumption. *Frontiers of Environmental Science & Engineering*, 16(11), 147

Yue R, Chen Z, Zhao L, Song X, Chen C, Qi J, Mao X (2023). Propylene glycol-mixed steam enhanced extraction for an efficient and sustainable remediation of PAHs-contaminated soil. *Journal of Hazardous Materials*, 459, 132029

Zhang T, Lowry G V, Capiro N L, Chen J, Chen W, Chen Y, Hofmann T (2019). In situ remediation of subsurface contamination: opportunities and challenges for nanotechnology and advanced materials. *Environmental Science: Nano*, 6(5), 1283-1302

Zhao Y, Song J, Cheng K, Liu Z, Yang F (2024). Migration and remediation of typical contaminants in soil and groundwater: A state of art review. *Land degradation & development*, 35(8), 2700-2715

Zheng D, Geng Z, Ge R, Dong J, Li G, Zhang F (2024). Enhanced migration and degradation of nitrobenzene in heterogeneous porous media using pulsed direct current electrical resistance heating with hydraulic circulation. *Journal of Hazardous Materials Letters*, 5, 100113

Zheng D, Qi Z, Geng Z, Huang W, Li G, Zhang F (2025). Regulating the ion migration pathways to enhance Joule heating effect and dense nonaqueous phase liquid removal using pulsed direct current. *Journal of Cleaner Production*, 508, 145586

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementarymaterials.docx](#)