# 行政院國家科學委員會專題研究計畫成果報告

蒸汽注入法去除地下水中含氯有機物之研究(II)

The removal of chlorinated organic compounds in groundwater by steam injection system (II)

計畫編號：NSC 89-2621-Z-002-068

執行期限：89 年 8 月 1 日至 90 年 7 月 31 日

主持人：駱尚廉 教授　　　　國立台灣大學環境工程學研究所

**中文摘要**

本計畫所執行之現場蒸汽注入系統證明比傳統之抽水處理有效，低壓蒸汽注入含水層中 10m，在三個月的現場試驗中，使地下水溫度最高達到 118ºC。計畫執行期間，共進行了五次採樣，採樣結果顯示含水層深層之五氯酚濃度明顯降低，且淺層之五氯酚濃度則升高。可歸納出升高之地下水溫度使得土壤內被吸附之五氯酚得以釋放至水中，且深層之高溫地下水又將這些溶解於水中之五氯酚帶至淺層，因此可解決過去傳統抽水處理時無法抽出被土壤吸附之有機物的困難。藉著蒸汽注入，可大幅增加抽水處理之效果，使得整治期程縮短，且達到較佳之整治效果。

## Abstract

A pilot study of a steam injection method for the treatment of pentachlorophenol (PCP)-contaminated soil and groundwater has shown potential advantages over the traditional pump-and-treatment method. Low-pressure steam was injected 10 m below the groundwater surface. The groundwater temperature was raised to 110ºC over a period of three months. Five soil and groundwater sampling events were performed during the pilot test. Results of sample analysis showed that the PCP contamination plume moved up to the groundwater surface due to the temperature gradient in the groundwater. The concentrations of PCP in the groundwater did not vary significantly during the test. PCP concentrations in deep aquifer soil decreased dramatically whereas those in shallow aquifer soil increased. It was concluded that the raise in groundwater temperature desorbed PCP in the deep aquifer soil. The hot, deep groundwater moved upward and also brought the desorbed PCP to the shallow aquifer. By using steam injection, PCP can be desorbed from soil and be moved upward to the ground surface so that it can be removed more easily through pump and treatment.

## Introduction

There are several methods of remediating PCP-contaminated soil and groundwater. Soil washing with ethanol / water mixtures to extract PCP in soil has been studied. The results of batch tests showed that the PCP concentration in the soil was reduced from 785 mg/kg to 7.9 mg/kg (Khodadoust et al., 1999), but application of this technique in-situ does not seem very promising because of the large amount of groundwater in aquifers. Bioremediation of PCP has also been studied widely (Davis, et al 1993; Cole, et al. 1996; Tumeo and Guinn, 1997). Davis et al. (1993) showed that only 8% of PCP could be dechlorinated when the initial concentration was 2 mg/L and suggested that an initial concentration of 20 mg/L was the upper limit for in-situ microbial reductive dechlorination.

Thermal treatment technologies have also been studied extensively (Hadim et al., 1993; Keyes and Silcox, 1994; Udell, et al., 1996; Heron, et al., 1998). Heron et al. (1998) performed a laboratory study of soil heating to remove trichloroethylene (TCE); the soil TCE concentration was reduced from 273 mg/kg to 0.6 mg/kg within 36 days. Hadim et al. (1993) conducted experiments on steam stripping and reported that 86% of No.2 heating oil was removed from contaminated soil after injecting one pore volume of steam at 12.4 kPa. Other methods of raising groundwater temperature, such as electrode soil heating, hot water injection, and hot air injection, should help to enhance remedial pump-and-treatment work. Carrigan and Nitao (2000) simulated in-situ electrical heating and showed it to be a promising technology for removing dissolved solvents in aquifers. A one-dimensional study by Udell et al. (1996) showed that more than 80% of PCP in soil was removed after being subjected to 9000 pore volumes of steam.

According to studies by Achard et al. (1996), the solubility of PCP in water is 21.4 ± 1 mg/L at 25.1°C and 86.2 ± 2 mg/L at 46.8°C, revealing that PCP tends to show preference for the aqueous phase than the soil matrix when the temperature is raised.

Our laboratory studies (Tse and Lo, 2000) on the kinetics and isotherm of PCP desorption from field soil also showed that thermal treatment can enhance the desorption rate and increase the water equilibrium concentration. The adsorption isotherm of PCP on field soil for various temperatures was found to fit the Freundlich isotherm:

$$q_e = (18.8 - 0.05T)C_e^{1/(0.016T-3)} \qquad (1)$$

where T, $q_e$, and $C_e$ are the temperature (K), soil, and water concentration at equilibrium, respectively.

**Results and Discussion**

The soil concentration data of each sampling event at GW1, 5m from the steam injection well, was drawn in Figure 1. The initial hot spot was located at 7 m BGS; most of the PCP was distributed between 5~10 m. After a two-month steam injection period, the PCP plume moved upward to between 2~5m, shown as the first sampling results. After each injection period, the PCP seemed to continue traveling upward. The highest PCP concentration by the second sampling occurred at 2 m

BGS. The highest PCP concentration by the third and fourth samplings occurred at 1 m BGS where the soil was unsaturated. But, the concentration variations from the first sampling event to the fourth sampling event were not as great as the change from the initial values to the first sampling event. The same phenomenon occurred at GW2, 12.5m from the steam injection well (Figure 2). In actuality, the PCP plume at GW2 did not move after the first injection period. The PCP mass reduction at GW1 and GW2 was 76.9% and 65.4%, respectively.

Figure 3 shows the groundwater PCP concentrations in GW1. Initial concentrations at 4 m deep and 9 m deep were 25.7 mg/L and 2.98 mg/L, respectively. The fourth sampling results revealed that the PCP concentration had been reduced to 18.2 mg/L at 4 m and 0.33 mg/L at 9 m. In total, the groundwater PCP concentration in GW1 was reduced by 34.1%, which was much less than the amount reduced in soil. In GW2, the PCP concentration in the groundwater increased from and initial concentration of 20.2 mg/L to 26.5 mg/L by the end of the fourth injection period (Figure 4); the PCP mass in the groundwater increased by 34.7%. The percent reduction in PCP concentration in GW1 was almost equal to the percent increase in GW2. The concentration variations in the groundwater showed that PCP in groundwater tended to move outward as temperature increased. When the groundwater temperature increased, water flowed toward and brought dissolved PCP to the cooler zone, thereby decreasing the groundwater PCP concentration in GW1 and increasing it in GW2.

The PCP vapor concentration in the horizontal SVE pipe ranged from 1.3~24.4 $mg/m^3$ and showed no particular trend. During the test period, 576000 $m^3$ of soil vapor was extracted. Roughly 5.8 kg of PCP was extracted by the SVE system, which calculates to about a 7% removal efficiency (initial PCP mass in the test area estimated to be 81.3 kg).

As steam injection began, the scenario in the aquifer can be described as follows: PCP in the soil was desorbed to the groundwater as the temperature was raised. Hot water moved upward and laterally to the cooler zone. Heat was transported through heat convection and conduction within the steam front. Where steam disappeared, heat conduction was the main mechanism of heat transfer. Hot water also brought dissolved PCP upward and laterally to the cooler zone. Dissolved PCP was readsorbed by soil in the cooler zone, which increased the soil concentration at the upper aquifer. Once PCP arrived in the cooler zone, it ceased to move upward, because the temperature gradient of the water was not enough to drive the water upward.

**Suggestions on Implementation of the Steam Injection System**

The PCP vapor extracted from the unsaturated zone is only a small portion of the total PCP mass in the aquifer. Removal of PCP should be performed by pumping hot water from the aquifer. Since the PCP plume moves upward as soil and water temperatures increase, the steam injection point should also be adjusted to the upper position. In other words, the steam injection point should always be right under the hot spot zone to give the most effective stripping. Moreover, the openings of the pumping wells should also be placed in the hot spot zone. A slurry wall should be placed outside the remediation area to prevent PCP from travelling outward.

**Conclusions**

Steam injection was shown to increase the groundwater temperature very effectively. Aquifers were proven to be good heat reservoirs. Heat convection was important when steam existed in the aquifer, and heat conduction dominated when the temperature was lower than the boiling point. As the soil and water temperatures were raised, PCP in the soil was desorbed to water. Hot water moved upward by the density-driven gradient and also brought PCP upward to the upper aquifer. A small amount of PCP was extracted by the SVE system from the unsaturated zone, but most of the PCP was dissolved in the water and may have been readsorbed into the soil if the soil temperature was reduced. Total PCP mass in the groundwater did not change much because PCP was continuously desorbed from the soil. PCP in soil, on the other hand, was reduced significantly by thermal desorption. Thermally enhanced pump and treatment is suggested as the most effective in-situ remediation method for this site.

**計畫成果自評**

本計畫針對蒸汽注入法在實場之應用進行研究，且結果顯示可有效增加抽水處理之效果，本研究已投稿國際期刊，目前正於審核中。所獲得之實驗數據，包括水溫變化、濃度變化等資料，亦可提供下階段之電腦模式模擬之用。

**References**

[1] Achard, C., M. Jaoui, M. Schwing, and M. Rogalski, *J. Chem. Eng. Data*, Vol. 41, No. 3, pp. 504-507, 1996.

[2] Carrigan, C. R., and J. J. Nitao, *Environmental Science & Technology*, Vol. 34, No. 22, pp. 4835 – 4841, 2000.

[3] Cole, J. D., S. L. Woods, and T. R. Bricker, *Ground Water*, Vol. 34, No. 5, pp. 784-790, 1996.

[4] Davis, A., J. Campbell, C. Gilbert, M. V. Ruby, M. Bennett, and S. Tobin, *Ground Water*, Vol. 32, No. 2, pp. 248 – 257, 1994.

[5] Hadim, A., F. H. Shah, and G. P. Korfiatis, *Journal of Soil Contamination*, Vol. 2, No. 1, pp. 37-58, 1993.

[6] Khodadoust, A. P., M. T. Suidan, G. A. Sorial, and D. D. Dionysiou, *Environmental Science & Technology*, Vol. 33, No. 24, pp. 4483 – 4491, 1999.

[7] Tanjore, A., and T. Viraraghavan, *Int. J. Environ. Studies*, Vol. 45, No. 2, pp. 155-164, 1994.

[8] Tse, K. K. C., and S. L. Lo, *Water Research*, (accepted), 2000.

[9] Tumeo, M., and D. A. Guinn, *Journal of Cold Regions Engineering*, Vol. 11, No. 3, pp. 221 – 231, 1997.


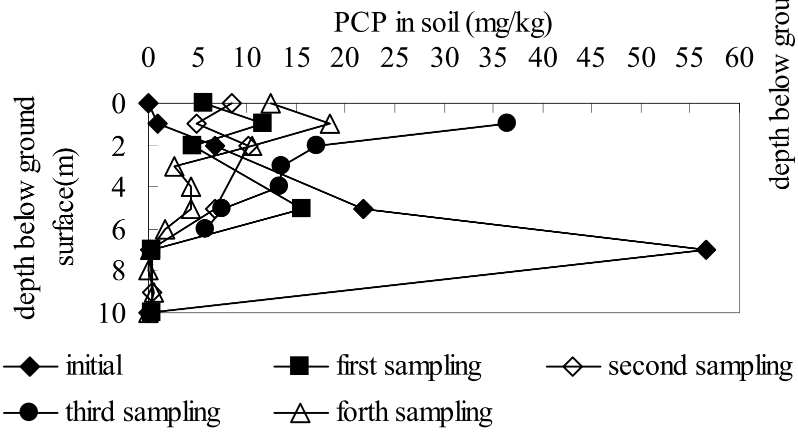


Figure 1 Soil concentrations at GM1 in each sampling

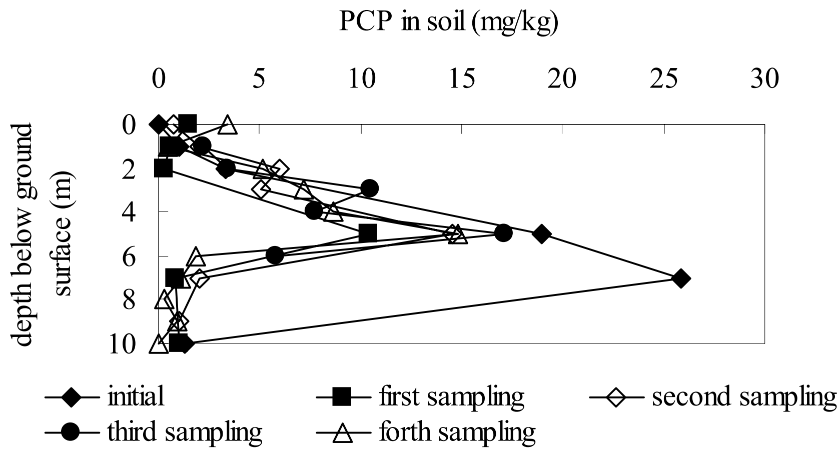


Figure 2 PCP concentrations at GM2 in each sampling

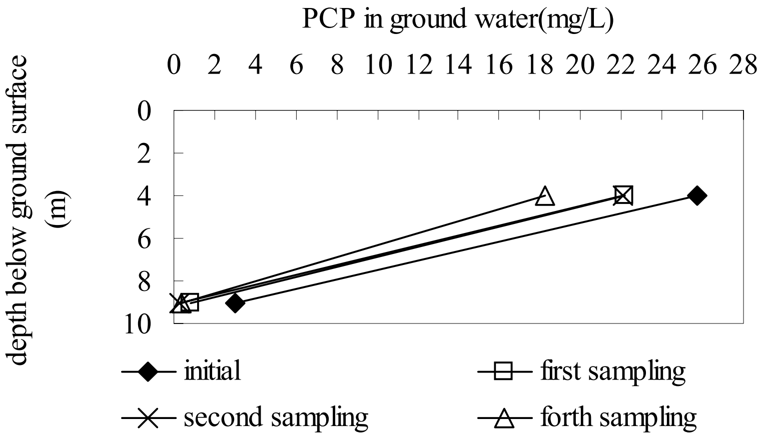


Figure 3 Ground water concentration at GM1

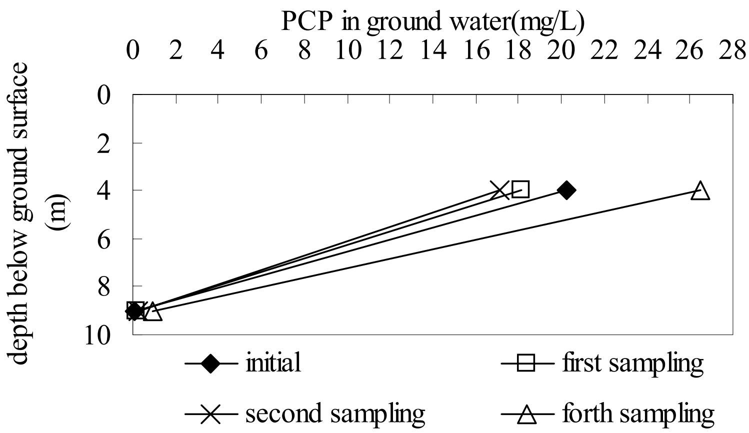


Figure 4 Ground water concentration at GM2