(142) Evaluation of Sustainability on the Sustainable Thermal Accelerated Remediation (STAR) for Soil Remediation- A Pilot Case Study on Heavy End TPH

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1. Introduction

For contaminated soil, *ex-situ* remediation technologies are frequently applied compared to *in-situ* remediation technologies. The trend is rather opposite to groundwater remediation strategy that *in-situ* remediation technologies are used for most of contaminated sites in Taiwan. Partly, it is due to the limited availability of *in-situ* soil remedy options. Consequently, *ex-situ* soil remediation has been the main stream remedy for soil remediation in Taiwan. However, the usual outcomes of ex-situ soil remediation result in the question on the good use of soil resource, such as the damage to the nature resource and the appropriateness of treating soil as waste. Thus, seeking and establishing in-situ soil remediation technologies which are more sustainable compared to traditional approaches will be vital to long-term soil remediation strategy.

Among the in-situ soil remediation technologies, there are few widely applied ones including Soil Vapor Extraction (SVE), *in-situ* solidification, and thermal enhanced remediation. For volatile organic compound (VOC) contamination, SVE and thermal enhanced remediation are frequently employed due to the ease of implementation and effectiveness, in particular for VOCs of lower carbon number. However, there have been legacy sites contaminated with heavy end organic contaminants that are challenging to traditional remedies. Thus, a thermal based in-situ remediation technology, namely Sustainable Thermal Accelerated Remediation (STAR), was selected for pilot testing to assess the feasibility for remediation of heavy end organic contaminants. STAR is an energy-efficient self-sustaining combustion process that captures and recycles the energy released from hazardous materials to destroy them in an effective, controllable, and safe manner.1) The process is sustained by the addition of air through a well to the target treatment zone and is initiated through a short duration, low energy 'ignition event'. Once the process is initiated (ignited), the energy of the reacting contaminants is used to pre-heat and initiate combustion of contaminants in adjacent areas, propagating a combustion front through the contaminated zone in a self-sustaining manner *(i.e.*, no external energy or added fuel input following ignition) provided a sufficient flux of air is supplied. Active control of the combustion front is maintained by the air supply. This efficient recycling of energy is made possible by the presence of the porous matrix (i.e., contaminated aquifer) that is being remediated. STAR is a technology which employs thermal destruction of contaminant instead of thermally enhanced desorption. This characteristic enables STAR to be one of the better choices for in-situ remediation of organic contaminants, especially for heavy end petroleum contamination.

Taiwan Environmental Protection Administration (TWEPA) has initiated a pilot test work for evaluation and assessment of STAR technology at a legacy site located at southern Taiwan. The site was found contaminated with TPH of high carbon number in the early 90s and have not been able to conduct the remedy program due to numbers of reasons (e.g., the depth of source area, condition of vicinity, and potential high cost of *ex-situ* remediation, and potential ineffectiveness of SVE and thermal enhanced remedy). The pilot test site conditions are illustrated in Figure 1.

The complete report with respect to the pilot test results and analysis can be found elsewhere 2). The purpose of this study, on the other hand, is to further assess the sustainability of using STAR compared to in-situ and ex-situ technologies more generally applied (*i.e.*, ISCO and excavation) to understand and to evaluate the advantage/disadvantage in social, environment, and economic aspects. Also, this study assessed the potential of STAR technologies as a Green and Sustainable Remediation (GSR) option.

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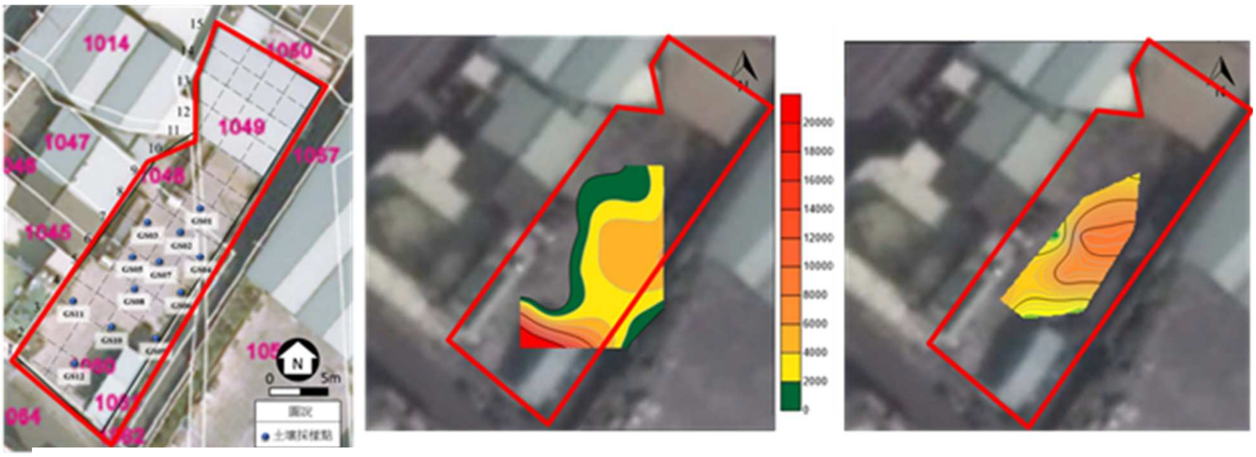

Figure 1 The TPH Concentrations at two different depths ranges

Table 1 The TPH Concentrations at Different Depth

Sampling Points	Depth (m bgs)	TPH C6-C9 (mg/kg)	TPH C10-C40 (mg/kg)	TPH C6-C40 (mg/kg)
GS01	0.5-1.0	ND	ND	ND
	3.0-3.5	<10(4.10)	634	638
GS02	2.5-3.0	45.1	986	1,030
	4.5-5.0	31.6	1,590	1,620
GS03	3.0-3.5	26.7	1,270	1,300
	6.5-7.0	181.0	2,120	2,300
GS04	2.5-3.0	99.9	4,150	4,250
	4.0-4.5	46.8	3,040	3,080
GS05	2.5-3.0	11.5	<150(123)	<160(135)
	4.5-5.0	527	7,730	8,260
GS06	4.5-5.0	<10(4.23)	<150(71.6)	<160(75.8)
	8.0-8.5	ND	<150(140)	<160(144)
GS07	2.5-3.0	<10(7.62)	4,570	4,580
	6.5-7.0	ND	ND	ND
GS08	2.5-3.0	175	2,520	2,690
	5.0-5.5	412	7,850	8,260
GS09	2.5-3.0	28.2	3,210	3,240
	4.0-4.5	46.8	6,260	6,300
GS10	2.5-3.0	63.6	1,990	2,050
	5.0-5.5	<10(7.98)	<150(141)	<160(149)
GS11	4.5-5.0	41.9	432	474
	6.5-7.0	<10(5.65)	436	442
GS12	1.5-2.0	352	18,500	18,900
	4.0-4.5	198	4,380	4,570

2. Method

2.1 Pilot Test Setup

The pilot test area was setup as a 15 m by 15 m where high TPH concentrations were found at 4.0~5.5 m bgs. Although there was high TPH concentrations found in shallow range, the advantage of STAR can be demonstrated for deeper soil contamination. Thus, a deeper contamination area was selected for the pilot test. Within the area, ignition points, vapor extraction point, and vapor monitoring points were implemented. To monitor the temperature profile in the subsurface, 20 sets of thermal couples (TC) were assembled to monitor 6 different depths at each location. Supporting systems include control system, which control the air flow and pressure based on the temperature profile, monitoring system, and aire extraction system. The layout and is shown in Figure 2.

2.2 Data Compilation

For assessing the effectiveness and the consequent GSR related characteristics, various data needed were collected and compiled. The testing data sets used include:

- ○ Continuous monitoring of CO_2, CO, and VOC concentrations in extracted air before and after the SVE system;
- ○ Continuous monitoring of temperature at all TCs and the corresponding injection air pressure and flow;
- ○ Periodically monitoring of diesel fuel consumed during the test period;
- ○ TPH concentrations in the soil at the influenced area before and after the pilot test.

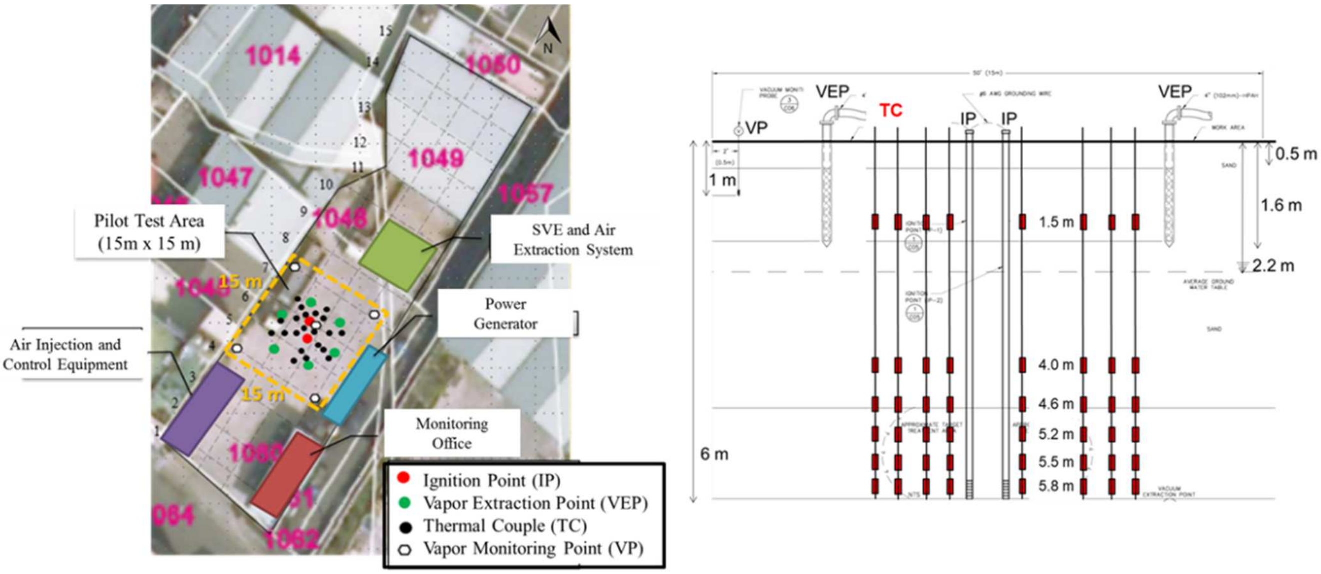

Figure 2 The Layout of the Pilot Test Site

2.3 GSR Assessing Protocol and Tool

The remediation environmental footprint was assessed with the GSR protocol developed by TWEPA. The protocol define the assessment methodology for energy, water, and carbon dioxide footprints. The formulas used in the protocol are listed as in Table 2. A web-based GSR assessment platform implemented by TWEPA was used for the calculation.

Table 2 The Formulas for GSR Assessment by TWEPA

Item	Formula
Raw Material	weight of the raw material (kg) × emission coefficient per unit weight($\frac{\text{kg emission}}{\text{kg}}$) =environmental footprint emission (kg)
Equipment	A. Fuel consumption (1) Drilling Operating time (hours)×fuel used per hour ×emission coefficient per unit volume ($\frac{\text{kg}}{\text{Liter}}$)=environmental footprint emission (kg) (2) Other equipment Horse power (HP) × operating time (hours) × BSFC ($\frac{\text{Liters}}{\text{HP-hour}}$) × partial load factor (%) ×emission coefficient unit fuel used($\frac{\text{kg}}{\text{Liter}}$)=environmental footprint emission (kg)
	B. Electricity Power consumed (kWh)= $\frac{\text{HP} \times \text{full load}}{\text{Efficiency}}$ Power consumed (kWh)× electricity coefficeint($\frac{\text{kg}}{\text{kWh}}$)= environmental footprint emission (kg)
Transportation	A. Ground Distance (km)×kpl($\frac{\text{kilometers}}{\text{Liter}}$) × emission coefficient unit fuel used($\frac{\text{kg}}{\text{Liter}}$)=environmental footprint emission (kg) Distance (kilometer) × number of persons (passenger) × pkpl($\frac{\text{passenger}-\text{kilometers}}{\text{Liter}}$) ×emission coefficient unit fuel used ($\frac{\text{kg}}{\text{Liter}}$)=environmental footprint emission (kg)
	B. Air, Sea, and Railway Person mile traveled (passenger- kilometer) × emission per person mile traveled ($\frac{\text{kg}}{\text{passenger}-\text{kilometer}}$)=environmental footprint emission (kg) Weight mile traveled(ton- kilometers) × emission per weight mile traveled ($\frac{\text{kg}}{\text{ton}-\text{kilometers}}$)=environmental footprint emission (kg)
Waste Disposal	Weight of waste (ton)×emission coefficient per unit weight ($\frac{\text{kg}}{\text{ton}}$) = environmental footprint emission (kg)
Water Used and Wastewater Treatment	Weight of waste water(ton)×emission coefficient per unit weight ($\frac{\text{kg}}{\text{ton}}$) = environmental footprint emission (kg)
Laboratory Analysis	Lab operation cost(\$)×emission per dollar of lab analysis($\frac{\text{kg}}{\$}$)× market price correction factor =environmental footprint emission (kg)

3. Results and Discussion

3.1 Effectiveness Assessment

The TPH concentrations at the test area are compiled and listed in Table 3. The sampling point within the radius of influence of the smoldering mechanism suggested the TPH removal can be ranged from 58.4% to near 100% where most of the removal can reach >95%. The discrepancy among the removal could be due to the heterogeneous setting of the geology. Since the travel distance of the heating front depends on the transportation of the injected air, the less permeable geological condition (e.g., clay lens) can reduce the travel distance within a time period. Nevertheless, the smoldering mechanism can general remove heavy end TPH once the heat front can pass through or reach the targeted area. Also, the targeted depth was designed for 4.0 to 5.5 m bgs and the removal was to a satisfactory at the particular target range. The results indicated the influence depth or thickness can be around 4.0~5.75 m. That is, the heat front can be vertically transported with additional 10 to 15% in terms of influenced thickness. Therefore, the test results showed the good control of smoldering and the STAR can remove over 90% of heavy end TPH in general. It is worth to note that the operation of the system was less than 72 hours. This demonstrated the short remediation time cost benefit of STAR technology in remediation of contaminated soil.

Table 3 The TPH Concentrations Before and After the Pilot Test

ROI	Before Test			After Test			Removal (%)
	Sample Point	Depth (m)	TPH C6-C40 (mg/kg)	Sample Point	Depth (m)	TPH C6-C40 (mg/kg)	
≈1ft (East)	IP-1	-	-	S11	1.0-1.5	12,600	-
		4.8-5.0	ND		4.5-5.0	2,370	0%
		-	-		5.0-5.25	ND	-
		5.3-5.5	21,566		5.25-5.5	333	98.4%
		5.5-5.75	3,221		5.5-6.0	ND	100%
≈1ft (South)	IP-1	-	-	SP01	4.0-4.5	700	-
		4.8-5.0	ND		-	-	-
		-	-		-	-	-
		5.3-5.5	21,566		5.0-5.5	198	99.1%
		5.5-5.75	3,221		-	-	-
≈1ft (West)	IP-1	-	-	S12	1.0-1.5	9,970	-
		4.8-5.0	ND		4.5-5.0	ND	-
		-	-		5.0-5.25	ND	-
		5.3-5.5	21,566		5.25-5.5	553	97.4%
		5.5-5.75	3,221		5.5-6.0	ND	100%
≈1ft (North)	IP-1	-	-	SP02	4.0-4.5	267	-
		4.8-5.0	ND		-	-	-
		-	-		-	-	-
		5.3-5.5	21,566		5.0-5.5	ND	100%
		5.5-5.75	3,221		-	-	-
≈4ft (South)	TC-5	-	-	S07	0.5-1.0	10,100	-
		4.55-4.75	31,427		-	-	-
		5.20-5.40	24,939		5.0-5.5	896	94.2%
≈4ft (West)	TC-6	-	-	S10	1.0-1.5	31,600	-
		5.25-5.40	28,373		5.0-5.5	11,800	58.4%
		5.60-5.80	1,185		-	-	-

3.2 GSR Assessment for STAR Pilot Test

The GSR assessment of the STAR pilot test was conducted using the GSR platform implemented by TWEPA[3]. The assessment was divided into three phases: (1) site investigation, (2) remediation, and (3) verification. The results with respect to environmental aspect are shown as in Figures 3. In the site investigation phase, the laboratory analysis is the main footprint contributor in environmental footprint. The transportation comes next due to the sampling action. In the remediation phase, the main contributor is the equipment followed by raw material. Thus, the operation of the remediation system (e.g., air compressor, SVE system, heater) is the most significant footprint contributor and it should be considered as the place of priority to implement better practice and management measure. On the other hand, the raw material footprint was a result of using special materials (e.g., stainless steel and cast iron) for ignition point (IP) and vapor extraction point (VEP). The usual material for air extraction in a SVE system is PVC while the STAR setup required materials that can sustain high temperature. Therefore, high environmental foot print in raw material category was found. Finally, the verification phase is similar to site investigation that laboratory analysis is the main environmental footprint contributor. It is not surprised since site investigation and verification are both related to sampling and monitoring. The result suggests the potential improvement of best management practice cab focus on the remediation phase.

3.3 The Comparison with Alternative Remediation Technologies

With the similar scale of test area, the alternative remediation technologies were evaluated for their sustainability using the GSR platform. The alternative remediation technologies were in-situ chemical oxidation and excavation-and-disposal. The evaluation included environmental, economical, and social aspects that are normalized to a ranking system in the GSR platform. The result is shown in Figure 4. The STAR has the highest total score among the technologies evaluated while ISCO has the lowest. However, excavation/disposal has advantage over STAR and ISCO in social aspect. Part of the reason is that area was adjusted to the actual radius of influence in the pilot test and the much smaller area leaded to shorter remediation time and less influence on the vicinity resident. The main causes for STAR to stood out in the environment and economical aspects might be less energy (or fuel) used and the collateral benefit in the social aspect (*e.g,* job creation)

From the outcomes of the comparison, the best management practices (BMPs) for STAR technology application were proposed as follows:

○ Raw material: use of regenerated activated carbon for SVE off-gas treatment;

○ Project management: reuse of ignition wells, thermal couples, equipment, and various wells as well as implement noise reduction measures;

○ Energy and power: use land line power in place of diesel generator;

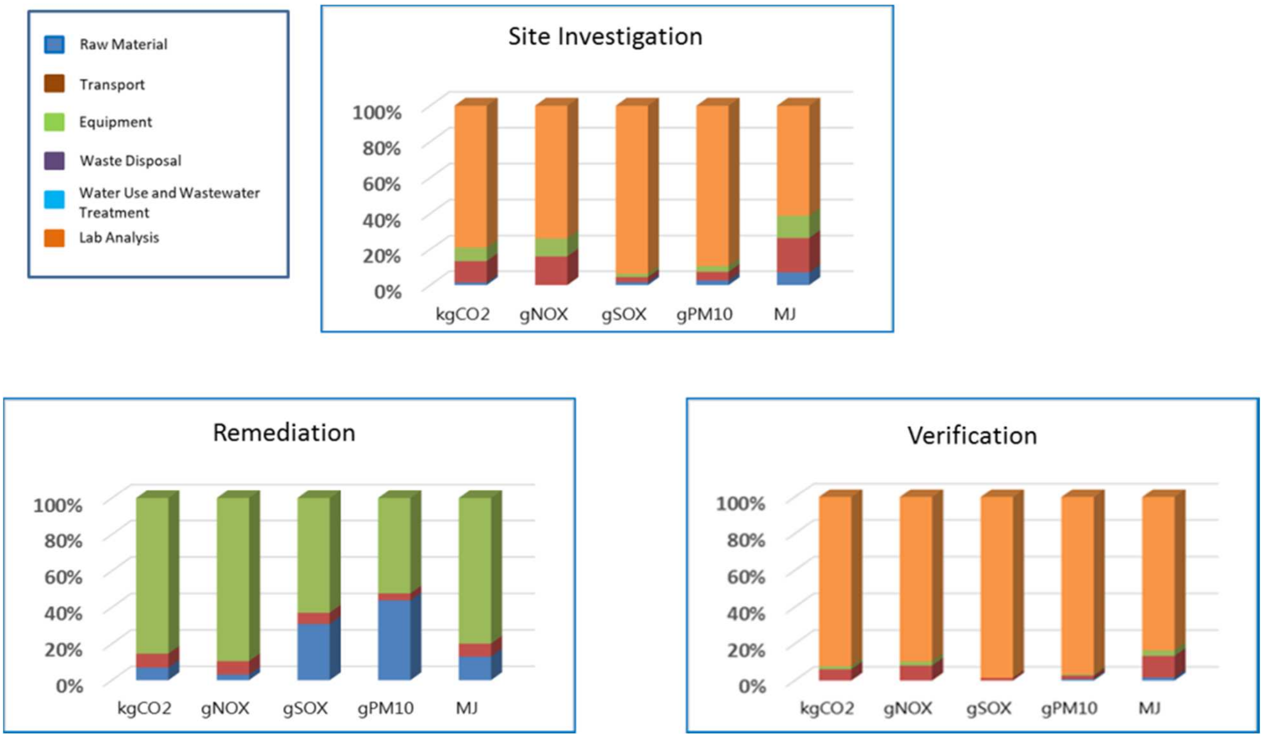

Figure 3 GSR Assessment for STAR (smoldering)

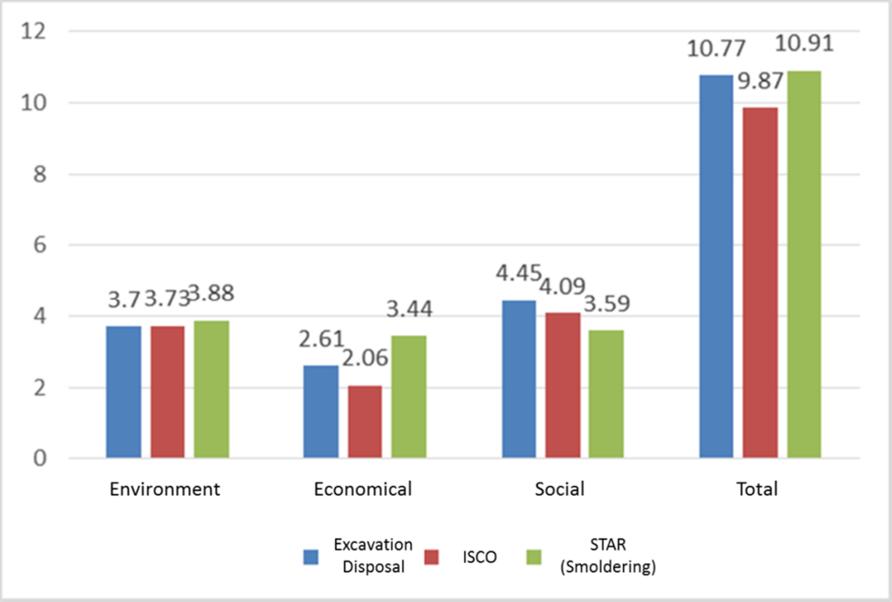

Figure 4 Comparison of Sustainability Scores among STAR and Alternative Remediation Technologies

4. Conclusions

Based on the result of this study, following conclusions can be made:

1. STAR technology or smoldering based thermal remediation technology can effectively clean up the heavy end TPH in soil and the removal can be > 90% within the radius of influence of smoldering reaction;
2. The STAR technology exhibits a competitive sustainability characteristic compared to ISCO and excavation. However, the improvement in social aspect should be considered as the main target in elevating the sustainability of STAR remediation implementation;
3. The remediation area and depth could be the major factors when selecting the applicable remedy. If the size of the treatment area or the depth are small or shallow, the alternative approaches might be worth evaluated in detail for clarification of the best options for heavy end TPH remediation..

Acknowledgements

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