

9.0 SOIL WASHING, SOLVENT EXTRACTION, AND SOIL FLUSHING

9.1 Process Description

Three remediation technologies are described below: soil washing, solvent extraction, and soil flushing. These are all primarily separation processes designed to decrease the volume of contaminated soil, and further treatment of the collected contaminants typically will be required. While these separation processes may be more effective in treating soils contaminated with petroleum fuels, generally they are employed to treat soils containing metals or heavy organic compounds.

Additional information about each of these three remediation technologies is contained in the engineering bulletins contained in Appendix F.

9.1.1 Soil Washing

Soil washing is an *ex situ* process in which contaminated soil is excavated and fed through a water-based washing process. It operates on the principle that contaminants are associated with certain size fractions of soil particles and that these contaminants can be dissolved or suspended in an aqueous solution or removed by separating out clay and silt particles from the bulk soil. Additives such as surfactants or chelating agents sometimes are used to improve the separation efficiency (treatment using additives may be referred to as chemical extraction). The aqueous solution containing contaminants is treated by conventional wastewater treatment methods (U.S. EPA, 1990).

Most organic and inorganic contaminants bind chemically or physically to clay or silt soil particles, which in turn adhere to larger sand and gravel particles primarily by the relatively weak forces of compaction and adhesion. Typically, 99% of the contaminants in soil are associated with particles of less than 60 μm in diameter (Leggiere and Wehner, 1995). Particle-size separation by washing enables the contaminated clay and silt particles (and the bound contaminants) to be concentrated. Separating the sand and gravel from the small contaminated soil particles significantly reduces the volume of contaminated soil, making further treatment or disposal more economical. The larger particles may be returned to the site (U. S. EPA, 1990).

Soil washing is effective for a wide range of organic and inorganic contaminants, including petroleum and fuel residues (Anderson, 1993). Removal efficiencies range from 90-99% for volatile organic compounds (VOCs) and from 40-90% for semi-volatile compounds. Compounds with low water solubilities such as metals and pesticides sometimes require acids or chelating agents to assist in removal (U.S. EPA, 1990). If soil washing lowers contaminant concentrations in the soil to acceptable levels, the only additional treatments to be considered are emission controls for any water or air discharge. In many cases, however, further soil treatment is required and soil washing serves as a cost-effective pre-processing step.

Soil washing potentially can be effective for the remediation of soils with a small amount of clay and silt particles, but large amounts of clay and silt particles mitigate the effectiveness of soil washing. Soil washing is reported to be cost-effective

for soils containing up to 40% fines, but it is most applicable to soil with 20% or less fines (HWC, 1993). Particle size distribution is a key parameter in determining the feasibility of soil washing. The relative effectiveness of soil washing for various soil types is shown below.

Particle Size Distribution (mm)	Relative Effectiveness
>2	Requires pretreatment of oversized particles
0.25-2	Effective soil washing
0.063-0.25	Limit soil washing
<0.063	Clay and silt fraction: not amenable to soil washing

Bench-scale and pilot-scale treatability tests are recommended before undertaking full-scale operation. Further concerns about feasibility include the fraction of hydrophobic contaminants that require surfactants or organic solvents for effective removal, how the complexity and stability of the contamination affect washing-fluid formulation, and the effect of washwater additives on wastewater treatment (U.S. EPA, 1990).

Figure 9-1 shows a process diagram of a soil washing process. Excavation and removal of debris and large objects precedes the soil washing process. Sometimes water is added to the soil to form a slurry that can be pumped. After the soil is prepared for soil washing, it is mixed with washwater and extraction agents are sometimes added. At this point, three separation processes occur:

- 1) water-soluble contaminants are transferred to the washwater;
- 2) contaminants are suspended in the washwater; and
- 3) clay and silt particles to which contaminants are adhered are separated from larger soil particles.

After separation from the washwater, the soil is rinsed with clean water and may be returned to the site. The suspended soil particles are removed by gravity from the washwater as sludge. Sometimes flocculation is used to aid in sludge removal. This sludge is more highly contaminated than the original soil and undergoes further treatment or secure disposal. The spent washwater from which the sludge is removed is treated and recycled. Residual solids from the recycle process may require further treatment (U.S. EPA, 1990).

Soil washing generates four waste streams:

- 1) contaminated solids separated from the washwater;
- 2) wastewater;
- 3) wastewater treatment sludge and residual solids; and
- 4) air emissions.

There are a number of treatment options that may be feasible for the contaminated clay fines and solids: incineration, low-temperature thermal desorption, solidification and stabilization, and biological or chemical treatment. It is recommended that as much blowdown water

Figure 9-1. Schematic Diagram of Aqueous Soil Washing Process.

be recycled as possible. Blowdown water released to local wastewater treatment plants must meet local discharge standards. Sludge and solids from wastewater treatment require appropriate treatment and disposal. Collected air emissions from the waste site or soil-washing unit can be treated using carbon filters (Banerjee, et al., 1993).

Advantages of the soil washing process include:

- Applicability to a wide variety of organic and inorganic compounds;
- High removal efficiencies for certain soil types; and
- Minimal fire and explosion hazards.

Some disadvantages are that soil washing:

- Is only suitable for certain soil types;
- Does not destroy contaminants; and
- May require additives that improve removal but compromise treatment of the waste streams.

9.1.2 Solvent Extraction

Solvent extraction differs from soil washing in that it employs organic solvents rather than aqueous solutions to extract contaminants from the soil. Like soil washing, it is a separation process that does not destroy the contaminants. The contaminants will have greater solubility in the solvent than in the soil. The equilibrium concentration gradient drives the mass transport process such that the contaminant transfers from the soil to the solvent. When

the soil is separated from the solvent, the soil contaminant concentrations are presumably lower than before contact with the solvent. “Solvent extraction” treats organic compounds much more effectively than inorganic compounds and metals. It can be used in conjunction with other processes to reduce remediation costs (U.S. EPA, 1994).

Sediments, sludge, and soils contaminated with volatile organic compounds (VOCs), petroleum wastes, PCBs, and halogenated solvents can be effectively treated with solvent extraction. The removal of inorganic compounds such as acids, bases, salts, and heavy metals is limited, but these types of compounds usually do not hinder the remediation process. Metals may undergo a chemical change to a less toxic or leachable form but their presence in the waste streams may also restrict disposal and recycle options (U.S. EPA, 1994).

Figure 9-2 shows a process diagram of the solvent extraction process. The remediation process begins with excavating the contaminated soil and feeding it through a screen to remove large objects. In some cases, solvent or water is added to the waste in order to pump it to the extraction unit. In the extractor, solvent is added and mixed with the waste to promote dissolving of the contaminants into the solvent. Laboratory testing can determine which solvent adequately separates the contaminants from the soil (U.S. EPA, 1992). Generally, the solvent has a higher vapor pressure than the contaminants (i.e., it has a lower boiling point) so that with an appropriate pressure or temperature change, the solvent may be

Figure 9-2. Schematic Diagram of Solvent Extraction Process.

separated from the contaminants, compressed, and recycled to the extractor (U.S. EPA, 1994).

Up to five waste streams may result from the solvent extraction process:

- 1) Concentrated contaminants;
- 2) Solids;
- 3) Wastewater;
- 4) Oversized rejects; and
- 5) Treated air emissions.

The concentrated contaminants may be analyzed and subsequently designated for further treatment, recycle, or reuse before disposal. While solvent extraction presumably improves the condition of the solids, they often still need dewatering, treatment for residual organic compounds, additional separation, stabilization, or other treatment. The water from the dewatering process, the solids, and the water from the extractor will need to be analyzed to aid in the choice of the most appropriate treatment and disposal.

The solvent-extraction units are a closed-loop design in which the solvent is recycled and reused. Typically, solvent extraction units are designed to produce negligible air emissions, but solvents have been detected in the off-gas vent system (U.S. EPA, 1994). In addition, significant levels of emissions (both vapor-phase and particulate matter) may occur during waste preparation activities such as excavation and materials handling.

The primary advantage of solvent extraction is the treatability of a wide variety of media. This capability is in contrast to soil washing, the success of which is heavily dependent on the particle size distribution.

Some disadvantages of the process are that solvent extraction:

- Does not destroy the contaminants;
- May not be appropriate for contaminants with high vapor pressures because these compounds may be removed with the solvent in the separation process instead of remaining with the concentrated contaminant stream;
- Is compromised by the presence of detergents and emulsifiers which compete with the solvent in dissolving the contaminants;
- May leave residual solvent and contaminant concentrations in the treated waste;
- Is not effective for high molecular weight or hydrophilic compounds; and
- May use flammable or mildly toxic solvents.

A variety of solvent extraction systems have been developed to treat several types of contamination (see Appendix F for further information). Four systems where full-scale or pilot-scale performance data are available are described below.

CF Systems

Probably the most widely used solvent extraction system is the CF Systems, which uses liquified hydrocarbons such as propane and butane as the solvent to treat soil and sludge, and carbon dioxide to treat wastewater. Water is added to the waste to enable pumping of the material through the extraction process. Particles greater than 1/8

inch in diameter are removed. In some cases, oversized particles are reduced in size for subsequent processing. The pH is adjusted in the feed to minimize corrosion of metallic components of the treatment system. CF Systems has used a 25-tons/day-capacity unit to remediate refinery sludge and achieved extraction efficiencies greater than 99% for benzene, toluene, and xylenes (BTX) and PAH compounds (U.S. EPA, 1994).

RCC B.E.S.T.™

RCC's B.E.S.T.™ system does not need a pumpable waste and uses aliphatic amines (often triethylamine) as the solvent. Feed pH is adjusted to alkaline conditions, and objects over one inch in size are removed. The process operates at near ambient temperature and pressure. Due to its high vapor pressure and low boiling point azeotrope formation, triethylamine is removed with steam stripping. The full-scale system has treated refinery waste streams, heavy metals, PAHs, and PCBs.

Terra-Kleen

The Terra-Kleen solvent extraction system has been used at three Superfund sites to remediate soils containing PCBs. Removal efficiencies of 90% or better were achieved.

Dehydro-Tech

The Carver-Greenfield (C-G) Process®, developed by Dehydro-Tech Corporation, was evaluated in a pilot-scale test to remediate 640 pounds of contaminated drilling mud. About 90% of the oil and essentially 100% of the total petroleum hydrocarbons were removed from the material.

Soil flushing differs from soil washing and solvent extraction in that it is an *in-situ* process in which the solvent is injected into or sprayed over the contaminated area, percolates through the soil and dissolves the contaminants (it is sometimes referred to as *in-situ* soil washing). A process diagram for soil flushing is shown in Figure 9-3. Water is introduced and allowed to percolate down into the soil. The applied solution may contain fertilizer or other additives designed to promote microbiological activity in the subsurface. Elutriate is collected in a series of wells and drains. If possible, the collected liquid is recycled. Standard pump-and-treat methods are employed to remove and treat the ground water.

Flushing solutions may include the following:

- 1) Water for water-soluble contaminants;
- 2) Acidic aqueous solutions for metals and basic organic contaminants;
- 3) Basic aqueous solutions for some phenols, complexing and chelating agents for metals such as zinc, tin, and lead; and
- 4) Surfactants.

Soil flushing is generally used in conjunction with other treatment technologies such as activated carbon, *in-situ* biodegradation, or chemical precipitation to treat the contaminated ground water that is collected (U.S. EPA, 1991). The method is theoretically suitable

9.1.3 Soil Flushing

Figure 9-3. Generalized Soil Flushing Process Flow Diagram.

for a wide range of contaminants. Soil flushing is most effective for permeable soils ($K > 1.0 \times 10^{-3}$ cm/sec).

The advantages of soil flushing (Rizvi and Nayyar, 1995) are that it:

- Can be used to remove contamination from areas inaccessible to excavation or other treatment;
- Can be used to provide oxygen and nutrients to enhance natural biodegradation; and
- Entails minimal disturbance to any on-going operations at the site.

The disadvantages of the method include:

- Soil flushing is limited to medium-to-coarse grained soils so that the reinjected water can readily flow through the soil;
- The depth to groundwater must not be too shallow (or surface flooding may occur) nor too deep (or recovery will be affected); and
- Solvents and contaminants may migrate into uncontaminated areas and also be resistant to removal due to soil heterogeneity (Chambers, C.D., et al., 1990).

Laboratory tests are recommended to determine the best flushing solution for the types of soil and contaminants present. The flushing solution may affect the soil such that removal is hindered and it may also alter the soil's physical and chemical properties after remediation. The suitability of the site

to soil flushing should be determined by a groundwater injection test and/or a ground water pumping test.

9.2 Identification of Air Emission Points

In the soil-washing process, the greatest potential for emissions of volatile contaminants occurs in the excavation, materials handling, feed preparation, and extraction processes. Air emissions from the excavation and pretreatment steps typically are uncontrolled. Air emissions from the batch soil-washing process may be collected and, if so, typically are treated by carbon adsorption or incineration (U.S. EPA, 1990). The waste streams also have the potential to be sources of VOC emissions.

Solvent extraction may also produce emissions during excavation and soil transport and from contaminated oversize rejects (U.S. EPA, 1994). The solvent recovery process involves vaporization of the solvent, so fugitive emissions are possible from this as well as other stages of the solvent process. The waste streams also have the potential to be sources of VOC emissions to the extent that any VOCs are present.

Emissions from soil flushing may emanate from the soil surface, solvent storage vessels and spray system, and from locations where the contaminant-laden flushing solution is recovered and treated.

9.3 Typical Air Emission Species of Concern

For petroleum-contaminated soils, the primary air emission species of concern are volatile and semi-volatile organic

compounds. For solvent extraction processes, emissions of the solvent itself also may be cause for concern. For soil flushing, products of aerobic and anaerobic decomposition are possible, but these tend to be predominantly carbon dioxide and methane.

9.4 Summary of Air Emissions Data

No data were identified for the air emissions from soil washing, solvent extraction, and soil flushing. Information on emissions from excavation may be found in Section 3.

9.5 Identification of Applicable Control Technologies

Carbon adsorption and incineration are typical controls used to treat collected emissions. In solvent extraction, volatile solvents are recovered and recycled. These control technologies are described in Section 5.5.

9.6 Capital and Operating Costs for Remediation

Recent data on operating costs for specific soil washing and solvent extraction processes are summarized in Table 9-1. Capital cost data generally are very limited, though some data may be found in the SITE program reports given in the references.

Cost for remediating contaminated soil by soil washing range from \$53 to \$215 per ton of feed soil, according to information from vendors of the equipment. The more expensive processes included in the cost range cover disposal of soil residue (U.S. EPA, 1990).

Solvent extraction costs are most influenced by waste volume, number of extraction stages, operating parameters, and lost time resulting from delays in equipment operation. Operating parameters include labor, maintenance, setup, decontamination, and demobilization. The choice of solvent, solvent/waste ratio, feed rate, extractor residence time, and number of passes through the extractor determine the efficiency of the process. Estimated costs range from \$50 to \$900 (U.S. EPA, 1994).

No cost data are available on soil flushing, although costs are expected to be moderate if inexpensive flushing solutions are used and the network of extraction wells is relatively simple.

9.7 Capital and Operating Costs for Emission Controls

No cost data for emission controls for these treatment processes were found. General costs for controlling point source emissions are given in Section 5.7.

9.8 Equations/Models for Estimating Emissions

No equations or models for predicting the air emissions from these processes were identified.

9.9 Case Studies of Remediation and Air Emissions

Given the lack of air emissions data, no suitable case studies showing emissions were found for these processes.

Table 9-1
Summary of Costs for Soil Washing and Solvent Extraction

Treatment Method	Type of Contamination^a	Process Rate, Mg/hr (tons/hr)	Operating Cost, \$/Mg (\$/ton)^b	Reference
Soil Washing	--	--	68-113 (75-125)	HWC, 1994
Soil Washing	TPH, metals, etc.	5-91 (5-100)	24-120 (27-132)	HWC, 1994
Soil Washing	Fuel oil	53 Mg/day (58 tons/day)	109 (120)	Leggiere and Wehner, 1995
Soil Washing	TPH, metals, etc.	68 Mg/day (75 tons/day)	181 (200)	Leggiere and Wehner, 1995
Soil Washing	Crude oil	454-1,814 total Mg (500-2,000 total tons)	67-145 (74-160)	Banerjee, et al., 1993
Soil Washing	Lead	2-4	150 (165)	Gaire, 1995
Solvent Extraction	TPH	1.4	200 (221)	Raptis, et al., 1992
Solvent Extraction	PCBs	50 tons/day	136-408 (150-450)	Valentinetti, 1990a and 1990b

^aTPH = total petroleum hydrocarbons

^bDoes not include cost of excavation

Table 9-2a.
Summary of Performance Data on Soil Washing

Process	Contaminants	Range of Removal Efficiencies	Residual Concentrations, ppm
Soil Cleaning of America	oil and grease	50 - 83%	250 - 600
Biotrol Soil Treatment System	Pentachlorophenol	90 - 95%	<115
	other organics	85 - 95%	<1
EPA's First Generation Pilot	oil and grease	90 - 99%	<5 - 2400
MTA Remedial Resources	volatile organics	98 - 99+%	<50
	semi-volatile organics	98 - 99+%	<250
	most fuel products	98 - 99+%	<2200
Bodemsandering Nederland BV	aromatics	>81%	>45
	crude oil	97%	2300
Harbauer of America	total organics	96%	159 - 201
	PAH	86 - 90%	91.4 - 97.5
Heidemij Froth Flotation	oil	>99%	20
Klockner Umweltechnik	hydrocarbons	96.3%	82.05
	chlorinated hydrocarbons	>75%	<0.01
	aromatics	99.8%	<0.02
	PAHs	95.4%	15.48

Source: U.S. EPA, 1990.

Table 9-2b.
Results of Remediation of Soil Containing Fuel Oil Using Soil Washing

Test Run	TPH in Untreated Soil (mg/Kg)	TPH in Treated Soil (mg/Kg)	Removal Efficiency
#1	7,666	2,650	65%
#2	7,567	2,033	73%
#3	9,933	2,833	72%

Source: Banerjee, et al., 1993.

Table 9-3a.
Results of Remediation of API Separator Sludge by Solvent Extraction

Compound	Initial Concentration ($\mu\text{g/g}$)	Final Concentration ($\mu\text{g/g}$)	Percent Removal
Benzene	30.2	0.18	99%
Toluene	16.6	0.18	99%
Ethylbenzene	30.4	0.23	99%
Total Xylenes	13.2	0.98	93%
Anthracene	28.3	0.12	99%
Benzo(a)pyrene	1.9	0.33	83%
Bis-(2-ethylhexyl)phthalate	4.1	1.04	75%
Chrysene	6.3	0.69	89%
Naphthalene	42.2	0.66	98%
Phenanthrene	28.6	1.01	96%
Pyrene	7.7	1.08	86%

Source: Valentinetti, 1990b.

Table 9-3b.
Results of Remediation of Drilling Mud Waste Using Solvent Extraction

Test Run	Removal Efficiency of Indigenous Oil	Removal Efficiency of Indigenous TPH
#1	92.1%	100%
#2	88.3%	100%

Source: Raptis, et al., 1992.

Table 9-4
Results of Remediation Using Soil Flushing

Site	Compound	Peak Ground Water Concentration (µg/L)	Ending Ground Water Concentration (µg/L)	Reduction
Gasoline station Well #1 ¹	Benzene	7	ND	100%
	Toluene	76	ND	100%
	Ethylbenzene	140	ND	100%
	Xylenes	1,300	5	99.6%
	Naphthalene	81	ND	100%
Bus garage Well #4 ²	Benzene	1,800	690	62%
	Toluene	9,000	1,400	84%
	Ethylbenzene	2,300	1,500	35%
	Xylenes	10,000	5,600	44%
	Naphthalene	270	369	-37%

Source: Rizvi and Nayyar, 1995.

Notes:

1. Data for gasoline station are from June 1992 to February 1995
2. Data for bus garage are from June 1993 to February 1995

Remediation performance data, however, were available and Tables 9-2 through 9-4 show selected results of treatments at several sites. Further information may be obtained from the relevant documents listed below.

9.10 References

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