

Soil Remediation in Coarse Gravelly Soils: Challenges and Lessons Learned

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Remediation of hydrocarbon contamination in coarse gravelly soils presents several unique challenges in terms of regulatory requirements, analytical procedures and the technical approach. This paper reviews how these challenges were addressed during the remediation of two former sour gas well sites in central Alberta.

The Alberta Soil and Water Quality Guidelines for Hydrocarbon at Upstream Oil and Gas Facilities (AENV, 2005) broadly divides soils into two textural categories based on the median grain size diameter (d_{50}). This division separates fine soils (silts and clays) from sands and coarser soils. However, the generic (Tier 1) guidelines also indicate that they may not apply for sites where the soils are predominantly coarse sands and gravels with bulk hydraulic conductivity greater than 1×10^{-5} m/s. As such, the application or modification of the guidelines and selection of appropriate exposure pathways requires careful consideration for such sites.

The existing laboratory analytical protocols, including the Canada Wide Standard for Petroleum Hydrocarbons, focus only on the coarse sand and finer textured fraction of the soils. Modern lab equipment (designed to maximize efficiency through minimization of solvent use and extraction times) can arbitrarily limit analyses to only the finer portion of the soil samples by physically restricting the particle sizes analysed. This can create a bias in the analysis as hydrocarbons are often more concentrated in the finer fraction of the soil, which may represent a small proportion of the overall soil mass. To address this problem a modified extraction procedure was developed in co-operation with EnviroTest Labs for gravelly soils to achieve a representative analysis of the whole sample.

The soils at the three sites comprise a mix of sands, gravels and cobbles with only minor amounts of silt and clay. Within such soils the hydrocarbon contamination is distributed in different manners. In the cobbles, gravel and sand grains the hydrocarbon contamination is distributed primarily as surface coatings with very little if any of the mass actually penetrating the grains. In contrast, for the finer particle sizes the hydrocarbons may be adsorbed onto organic carbon, diffused into the soil matrix and/or present as a surface coating. This bimodal distribution of hydrocarbon contamination was confirmed through bench scale separation of coarse soils (gravel plus) from finer soils. Once sorted, the gravel plus soils were generally found to meet remedial objectives (using the new extraction method), while the fine soils contained the majority of the contamination. Hence, a remedial program was designed using a mobile screener to

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separate soils into coarse (gravel plus) and fine fractions. The separated finer soils were addressed either through on-site biotreatment in engineered cells or off-site disposal.

The technical approaches and lessons learned from these sites have immediate practical applications for other hydrocarbon contaminates sites in gravelly soils.

Introduction

On behalf of Petro-Canada, Komex International Ltd (Komex) is currently managing the remediation of two former gas well sites in the Ricinus field. These are located approximately 50 km southwest of Caroline, Alberta on crown land.

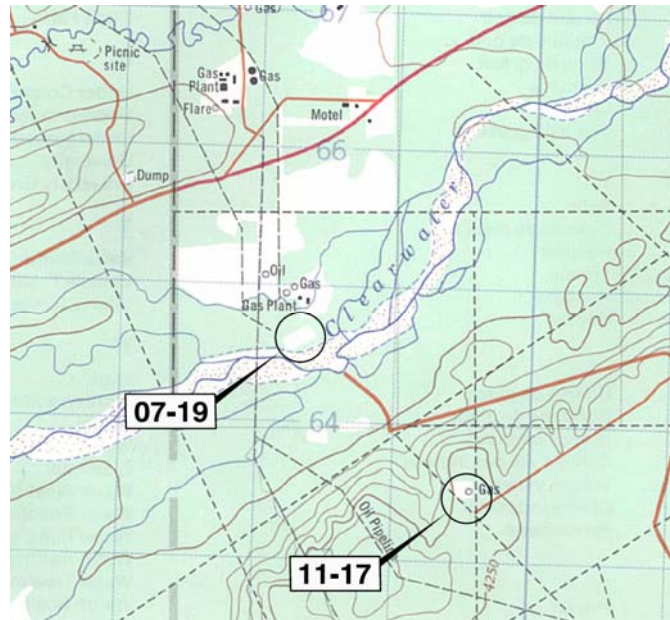


Figure 1: Relative Locations and Topography of the Two Ricinus Sites

Site conditions at these locations are atypical for Alberta in that they exist on the bank of the Clearwater River and on a former glacial river terrace of the Clearwater River, respectively. Consequently, they are underlain by coarse alluvial gravel deposits, which cannot be readily compared against Alberta Environment's upstream hydrocarbon guidelines (AENV, 2001) due to the low volume of fine or organic soil material and the high volume of cobbles and gravels. The gravelly soils at these locations presented unique challenges in terms of applicable regulatory guidelines, remedial approaches and analytical methodologies. This paper outlines how these challenges were addressed in the course of the remedial program.

Background

11-17 Site Background

The project area is situated in the Rocky Mountain Foothills, near the western boundary of the Alberta Plains (Bostock, 1967). The regional topography generally slopes to the

northeast and consists of rolling hills. The 11-17 well site is situated on a high glacial river terrace approximately 1.25 km southeast of the Clearwater River. Surface drainage is likely to the west and north.

The facilities on the 11-17 site included a sour gas well, a buried flare pit and drilling sump (which appear to have coalesced), a bermed tank farm, and several small buildings. The well has been abandoned and all facilities have been removed. The surrounding land is forested.

According to the surficial geology map (Bydell, Bayrock and Reimchen, 1971) the 11-17 site is situated on glacio-fluvial valley train deposits of gravel with minor sand that are generally thick and form broad terraces.

Overburden comprises 0 to 1.5 m of sandy clay fill, overlying sand and gravel with cobbles to at least 25 m (the maximum depth investigated). Bedrock has not been encountered beneath this site. The groundwater table occurs at a depth of 22 to 24 m below grade. Thus, the 11-17 site is underlain by a thick unsaturated zone.

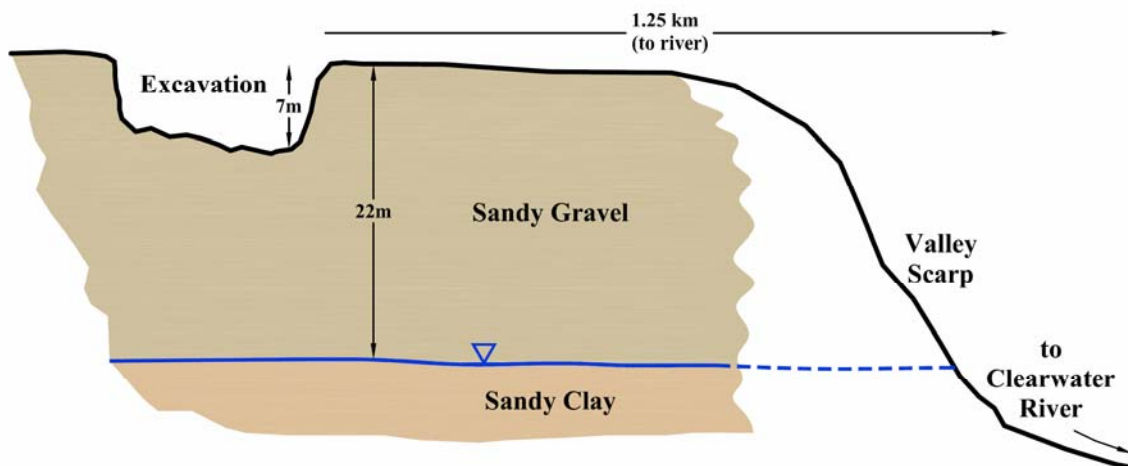


Figure 2: Cross-Sectional Diagram of Ricinus 11-17 Site

Impacted areas were defined, during the soils investigation, which included the former drilling sump and flare pit. Elevated barium, zinc, EC and SAR were identified in the buried drilling mud. Field observations and laboratory results indicated the presence of extractable and purgeable hydrocarbons as well as PAHs in the soils associated with the buried drilling sump.

Contaminants encountered during the remedial excavation include: barium, PHC F₂ and F₃, benzene, toluene and ethylene (Komex, 2005b). One large excavation was created, extending approximately 45m in width, 65m in length, and 4 to 7m in depth. Approximately 7,750 m³ of soil have been excavated to date.

7-19 Site Background

The 7-19 site is located on the north bank of the Clearwater River. The site is relatively flat with a slight slope towards the river. The elevation of the site is only 1.5 to 2 m above the non-flood river level and the site is clearly located within the river floodway. The land to the north is forested. Approximately 500 m to the north, a parcel of land has been developed by an outfitter and includes a cabin and storage for various types of outdoor equipment.

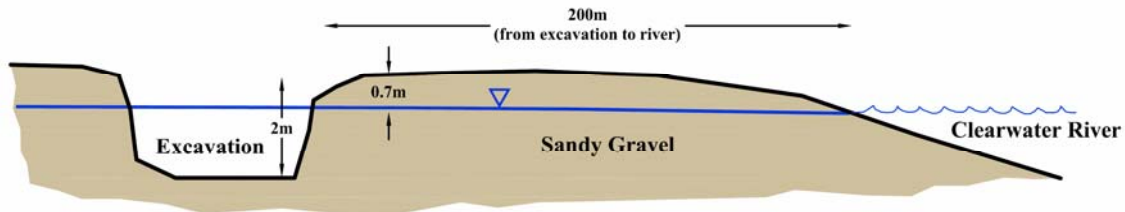


Figure 3: Cross-Sectional Diagram of 07-19 Site

According to the surficial geology map (Bydell, Bayrock and Reimchen, 1971) the 7-19 site is located on recent alluvial gravel deposits. The Quaternary deposits at the site consist primarily of sands and gravels associated with the Clearwater River terraces. Area soils are mapped as recently deposited coarse outwash material (Peters and Bowser, 1957). There is very little fine textured material overlying the gravel, and soils are typically Regosolic.

The Ricinus area is underlain by deposits of the Paskapoo Formation (Upper Cretaceous Paleocene). The Paskapoo formation comprises interbedded sandstones, siltstones and shales, and is considered an important regional aquifer (Tokarsky, 1971). Bedrock was encountered at 6.9 mbgs (maximum depth of investigation).

The 7-19 site was referred to by Petro-Canada as a sour water plant. The on-site facilities consisted of an inlet separator, a produced sour water tank, a producing sour gas well and a flare stack. The wellhead has been abandoned and all surface and subsurface facilities have been removed.

The potential sources of environmental issues on site were identified as: buried flare pit, buried drilling sump, and surface impact from former above ground facilities and storage tanks. Hydrocarbon and salinity impacted soil in this area was confirmed in the soil investigation. Elevated levels of barium and phenanthrene were also found in this area. A second hydrocarbon-contaminated area was found on the west lease south of pipeline repair excavation (due to a backfilled pit or sump). Free phase hydrocarbons were present in the saturated zone at this location. There was no evidence of off-site soil impacts.

Groundwater analyses indicated only trace amounts of hydrocarbons, and salts close to anticipated background conditions. The shallow (1.5 to 2.5 mbgs) groundwater flow is to the east and upwards.

Contaminants identified during the remedial excavations include: benzene, toluene, ethylbenzene, PHC F1, F2 and F3, pH, SAR, arsenic, boron, lead (Komex, 2005a). The excavation in the former buildings, flare pit and drilling sump was approximately 115 m long, 50 m wide and 2 m deep. Approximately 10,135 m³ of impacted soil were removed. In the area of the former tanks, an excavation approximately 30 m long, 25 m wide and 2 m deep was created. Approximately 1,320 m³ of soil was removed from that area.

Regulatory Guidelines

The primary contaminant at both sites are petroleum hydrocarbons, thus the “Alberta Soil and Water Quality Guidelines for Hydrocarbons Upstream Oil and Gas Facilities” were consulted. The two Ricinus sites are located within the Green Zone and the primary land use in the area is forestry with oil and gas exploration secondary. The area also receives relatively frequent use from recreation outdoor enthusiasts particularly hunters and fishers, more so at the 7-19 site, due to its locations along the bank of the Clearwater River. However, there is no permanent human habitation. The two Ricinus sites are therefore consistent with the Natural Area land use as described in the upstream hydrocarbon guidelines (AENV, 2001).

This document indicate that Tier 1 the coarse soil guidelines only apply to soils with a hydraulic conductivity of $< 1 \times 10^{-5}$ m/s, which is typical of silty sands. Given this limitation, it was necessary to develop Tier 2 guides for the gravelly soils beneath both the 11-17 and 7-19 sites.

For a Natural Area land use, hydrocarbon guidelines must address each of the following pathways:

1. soil contact (plants and invertebrates);
2. soil ingestion (wildlife);
3. protection of potable groundwater;
4. protection of groundwater for aquatic life; and,
5. protection of groundwater for wildlife.

The soil contact pathway guidelines can only be re-assessed by conducting detailing bioassays on the soils in question. This work is normally considered as part of a Tier 3 risk assessment and was beyond the scope of the current project. Additionally, it is not clear how this type of testing should be done on a gravel soil. The Environment Canada (2005) bioassay test protocols call for removal of rocks (*i.e.*, gravel plus fractions) as part of the sample preparation, which would exclude the majority of the Site soils. Therefore the approach adopted for the Ricinus sites was to apply the existing coarse soil eco-contact guidelines only to the “finer” fraction (sand minus fraction) of soils that could act as potential growth medium for plants and invertebrates.

The soil ingestion by wildlife pathway was not re-evaluated as the existing Tier 1 guidelines are independent of soil texture. Additionally, the existing guidelines are sufficiently high that this would not be a limiting pathway in any case.

Tier 2 guidelines were calculated for the three primary groundwater pathways (3, 4 and 5 listed above) using Site-specific properties. This was performed using the models of the AENV Upstream guidelines, with modification to the following key variables as summarized below.

Table 1: Site-specific properties used in guideline calculation				
Parameter	Tier 1 Coarse Value	11-17 Value	7-19 Value	Comments
fraction of organic carbon	0.005	0.0022	0.0034	measured, corrected for “whole sample”
source length (m)	30 m	55 m	115 m	as delineated
source width (m)	10 m	40 m	55 m	as delineated
source thickness (vertical) (m)	3 m	7 m	2 m	as delineated
distance to downgradient receptor (water body) (m)	10 m	300 + m	200 m	measured
distance from base of contamination to watertable	0 m	15 m	0 m	measured
saturated hydraulic conductivity (m/s)	1×10^{-5}	1×10^{-3}	1×10^{-3}	measured ¹ / Domenico and Schwartz, 1990
lateral hydraulic gradient	0.01	0.02	0.01	measured/calculated
days with surface temp < 0 °C	0	150	150	ENV Canada, average of days with min and max temp < < 0 °C
infiltration (mm/year)	60	480	480	conservatively assumed 90% of annual precip (535 mm) – Env Canada

¹Field measurements from single well response tests were recorded as “recovery too fast to measure”, therefore a reference value for sandy gravel was selected.

The following tables summarize the calculated Tier 2 guidelines with Tier 1 coarse soil guidelines for comparison.

Table 2: Calculated Tier 2 Guidelines for Protection of Potable Groundwater Pathway

Site	B (mg/kg)	T (mg/kg)	E (mg/kg)	X (mg/kg)	F1 (mg/kg)	F2 (mg/kg)
Tier 1 Coarse Soil	0.13	1.6	0.36	49	3,700	5,100
11-17	0.21	380	2700	RES	RES	RES
7-19	0.02	0.3	0.06	8	590	810

RES = concentration > 20,000 mg/kg

Table 3: Calculated Tier 2 Guidelines for Protection of Groundwater for Aquatic Life Pathway

Site	B (mg/kg)	T (mg/kg)	E (mg/kg)	X (mg/kg)	F1 (mg/kg)	F2 (mg/kg)
Tier 1 Coarse Soil	1.6	0.16	79	59	360	230
11-17	17	43	RES	RES	19,000	8,300
7-19	4.2	0.14	30	27	410	293

RES = concentration > 20,000 mg/kg

Table 4: Calculated Guidelines for Protection of Groundwater for Wildlife Pathway

Site	B (mg/kg)	T (mg/kg)	E (mg/kg)	X (mg/kg)	F1 (mg/kg)	F2 (mg/kg)
Tier 1 Coarse Soil	5.3	5,400	RES	RES	16,000	15,000
11-17	RES	RES	RES	RES	RES	RES
7-19	13.9	4,800	15,000	RES	17,000	16,000

RES = concentration > 20,000 mg/kg

For the 11-17 site, calculated Tier 2 guidelines for all groundwater protection pathways were higher than the Tier 1 coarse soil guidelines. This is primarily due to the significant attenuation that is predicted to occur within the 15 m thick unsaturated zone between the base of the contaminated zone and the water table. The least attenuated compound is benzene, which due to its relatively high solubility and low octanol-water partitioning coefficient (Koc), is predicted to migrate relatively quickly through the unsaturated zone. Tier 2 benzene guideline for protection of freshwater aquatic life is slightly more than 10 times the Tier 1 guideline (17 mg/kg vs. 1.6 mg/kg). In contrast, the Tier 2 guideline for PHC F1 is more than 50 times the Tier 1 guideline (19,000 mg/kg versus 360 mg/kg). The PHC F1 components have lower solubilities and higher Koc values than benzene.

Tier 2 guidelines calculated for the 7-19 site were either more stringent or comparable to the Tier 1 guidelines. Unlike the 11-17 site, contaminants at 7-19 are in contact with the water table; hence there is no predicted attenuation in the unsaturated zone. The effect of

other site-specific parameters was mixed, with some increasing the sensitivity of the site (leading to more stringent guidelines), while others decreased the sensitivity.

Factors or parameters which increase the sensitivity of the site relative to the Tier 1 model are:

- higher assumed infiltration rate;
- lower fraction of organic carbon; and,
- greater source dimensions.

Factors which tend to decrease the sensitivity of the site are:

- higher groundwater flow velocity; and,
- greater distance to receptors.

For the 7-19 site, the Tier 2 protection of drinking water guidelines are more stringent than Tier 1 by a factor of approximately 6 for all compounds. The same adjustment applies to all of the hydrocarbon parameters because the Tier 2 modification change only the predicted dilution of soil pore water as it enters the saturated zone which is not chemical specific. The goal of the protection of potable groundwater guideline is to ensure that drinking water standards are met everywhere within a domestically useable aquifer. Hence the AENV model conservatively does not include attenuation during lateral transport through the saturated zone.

Calculated Tier 2 soil guidelines for the protection of ecological groundwater pathways were more stringent for some compounds and less stringent for others, relative to Tier 1. The higher groundwater flow velocity through the gravels produces contrary effects. The high groundwater flow velocity increases the predicted dilution of infiltration through the contaminated zone. However, it also reduced the travel time available for biodegradation relative to the Tier 1 calculation. The net results of the Tier 2 modifications are more stringent guidelines for the more degradable hydrocarbons (toluene, ethylbenzene and xylenes) and less stringent guidelines for the less degradable hydrocarbons (benzene, PHC F1 and F2).

Remediation Program Approach

The soils at the two Ricinus sites comprise a mix of sands, gravels and cobbles with only minor amounts of fines. Within such soils the hydrocarbon contamination is distributed in different manners. In the cobbles, gravel and sand grains, the hydrocarbon contamination is distributed primarily as surface coatings with very little if any of the mass actually penetrating the grains. In contrast, for the finer particle sizes the hydrocarbons may be adsorbed onto organic carbon, diffused into the soil matrix and/or present as a surface coating.



Figure 4: In-Situ Soil at 11-17 (Note the Size of the Pen and Coarse Material)

To address the bimodal distribution of hydrocarbons, the selected remedial approach involved mechanical separation the ‘fine’ (sand minus) particles from the ‘coarse’ (gravel plus) particles. The fine particles could then be addressed either through on-site biotreatment in engineered cells or off-site disposal, and the coarse particles would likely be suitable for use as backfill material. By removing the gravel plus fraction, the volumes to be treated and the landfilled could be greatly reduced.

Pilot Test Program

A pilot test was conducted to study the distribution of the hydrocarbon contamination between the sand minus and gravel plus fractions of soil at the 11-17 site. The test involved mechanically separating a representative contaminated soil sample from each of the well sites into gravel plus and sand minus fractions using a shaker screener. For this study the gravel plus fractions was defined as any material greater than 3/8”. This grain size threshold was selected based on practical limitations. Large scale separation of material to finer than 3/8”, is problematic and thus likely to be cost prohibitive. Note, this division differs substantially from the Alberta Environment (AENV, 2001) fine/coarse threshold, which is based on the sand/silt textural boundary ($\pm 75 \mu\text{m}$)

The mechanical separation results are summarized below:

Table 5: Weight percent of each particle size fraction

Well Site	Gravel Plus Fraction (> 3/8”)	Sand minus Fraction (< 3/8”)
11-17	78 %	22 %
7-19	57%	43%

The coarse and fine fractions were submitted separately for laboratory analysis of semi-volatile petroleum hydrocarbon fractions (PHC F1 to F4 and F4G). Analytical results are summarized and compared against Alberta Environment’s “Natural Area” coarse surface soil guidelines (AENV, 2001) for the most conservative pathway, in the following summary tables. Both the gravel plus and the sand minus fractions are compared against guidelines for coarse surface soils.

Table 6: Hydrocarbon Concentrations By Size Fraction

Hydrocarbon Fraction	Gravel Plus Fraction (>3/8") (mg/kg)		Sand Minus Fraction (<3/8") (mg/kg)	
	Result	Guideline	Result	Guideline
F2 (C _{>10} to C ₁₆)	220	230	3,300	230
F3 (C _{>16} to C ₃₄)	190	400	4,500	400
F4 (C _{>34})	41	2,800	990	2,800
F4 grav. (C _{>34})	700	2,800	5,800	2,800
Baseline at C ₅₀ ?	No		No	

Bold = analytical result exceeds guideline for Natural Area land use, most conservative pathway.

The bimodal distribution of the hydrocarbon contamination was confirmed; the gravel plus soils were found to meet the criteria, while the fine soils contained the majority of the contamination. Hence, a remedial program was designed using a mobile screener to separate soils into gravel plus and sand minus fractions on site.

Full Scale Program

Because of the similarity of the contaminant situations and the sediments encountered at the two Ricinus sites a common remediation process was developed. The excavation programs were guided by initial delineation information gathered through borehole drilling combined with verification sampling around the excavation limits. The process for determining the destination for the soil removed from the excavations based on the analytical results of the samples is shown in Figure 5.

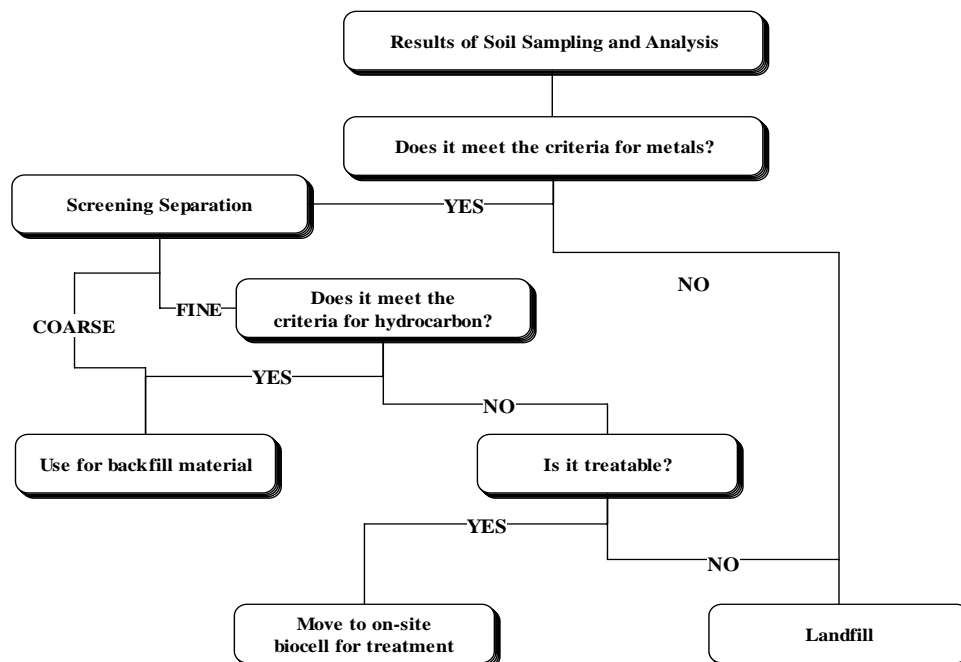


Figure 5: Remedial Process Based on Sample Results

At the 7-19 site, excavated soils were screened to $\pm 3/8''$ (10 mm) using a mobile shaker screener (approximately $3/8''$). The gravel plus fraction was sampled and used for backfill. The sand-minus fraction has been transferred to an on-site one-time use biotreatment cell and are undergoing bio-treatment until lab results indicate that applicable soil quality guidelines have been met.

At the 11-17 site, the majority of contaminated soils were relatively fine-grained drilling muds, and screening of this material was not considered practical. This material exceeded the applicable criteria and was landfilled. More moderately hydrocarbon contaminated (un-screened) soils from 11-17 have been placed in an on-site one-time biotreatment cell and are undergoing bio-treatment.

Analytical Procedure

The coarse nature of the soils at the Ricinus sites also presented a challenge when analyzing soil samples for hydrocarbons. The existing laboratory analytical protocols, including the Canada Wide Standard for Petroleum Hydrocarbons, extract only from the soils fractions with coarse sand and finer grain sizes. Modern lab equipment, designed to maximize efficiency through minimization of solvent use and extraction times, arbitrarily limit analyses to only the finer portion of the soil samples by physically restricting the particle sizes analysed. This arbitrarily biases the results towards the finer fraction of the soil in a given sample. This can create a bias in the analysis as hydrocarbons are often more concentrated in the finer fraction of the soil, which in the case of the Ricinus soils, represents a only small proportion of the overall mass.

The current standard hydrocarbon extraction method used by Enviro-Test Laboratories (and other commercial labs) employees a automated Soxhlet apparatus for solvent extraction (USEPA 35.41). The Soxtec is a relatively new extraction apparatus that has been shown to be equivalent to the older Soxhlet process by the [US Environmental Protection Agency 35.40](#). The Soxtec provides more cost and time efficient extraction method by performing the solvent extraction at a higher temperature. It also minimizes the amount of solvent used thereby limiting vapour emissions to the atmosphere. However, the Soxtec is very restrictive in the size of particles from a sample that can be used in the extraction.

The current procedure involves collecting a small core from the sample and placing it in a standard extraction thimble. The size of the thimble limits the maximum grain size of the soil sample to 6.35 mm (the inner diameter of the thimble). This is an arbitrary grain-size cut-off that does not align with any formal classification such as the [Unified Soil Classification System \(ASTM International, 2000\)](#). Figure 2 compares the particles sizes and soil types defined by the USCS, the AENV coarse/fine soil classification, the separation of particles on-site using the shaker screener, and the Soxtec particle size limitation.

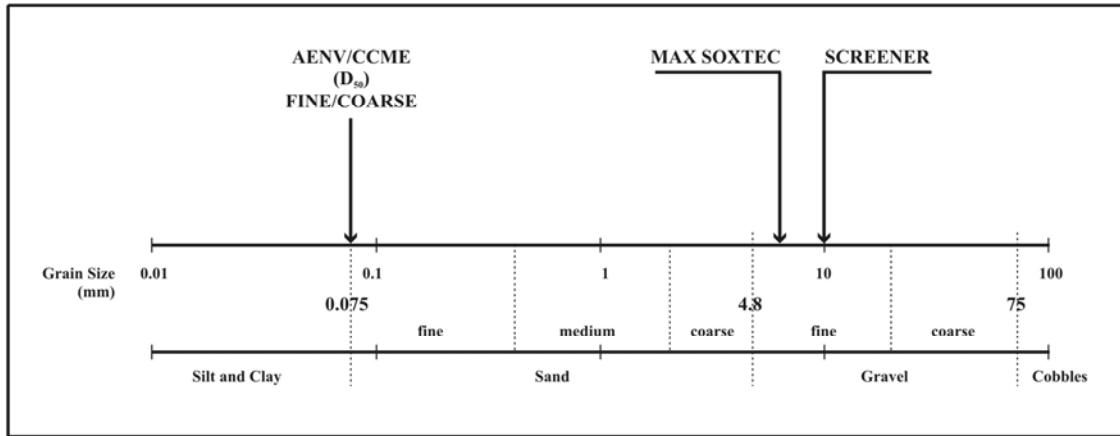


Figure 6: USCS Textural Division and Important Reference Points

Due to the coarse nature of the material, this size restriction severely biases the analytical results for the Ricinus sites. The following table summarizes the grain size division from sieve analysis of samples from each site:

Table 7: Weight Percent by Size Fraction

Site/Material	Weight Percent >6.3 mm	Weight Percent <6.3 mm
7-19 sediments (in situ)	71%	29%
7-19 screened gravel plus fraction	85%	15%
11-17 sediments (in situ)	63%	37%

Thus the size of the Soxtec thimble arbitrarily excludes more than 63% of the unscreened material and more than 85% of the screened material, resulting in unrepresentative analyses.

Several options were considered for obtaining a representative analysis of the coarse soil: gravel crushing, constructing a large Soxtec thimble or a two-stage extraction process. Crushing the gravel to fit into the Soxtec with the finer material was dismissed due to possibility of losing volatile hydrocarbon matter. A “whole sample” extraction involving all grain sizes could be performed by constructing a large Soxtec/Soxhlet apparatus with an opening sufficiently large to accommodate the maximum grain size (Lloyd Hodgins, EnviroTest Labs, 2005). This option was dismissed because the timeline and cost for construction and testing of the thimble would delay the project, and require excessive solvent use. Therefore, a modified two-stage extraction procedure was developed in conjunction with EnviroTest Laboratories that provided a more representative analysis of the hydrocarbon concentration across the complete distribution of grain sizes.

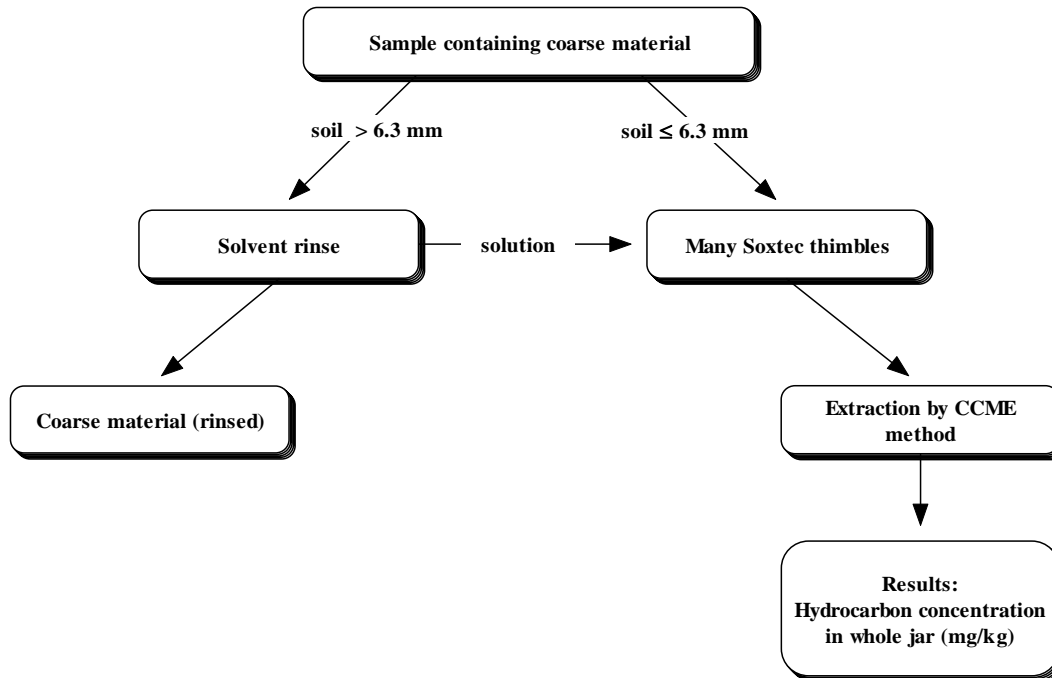


Figure 7: Two-Stage Hydrocarbon Extraction Procedure

In the modified extraction process, a solvent wash is used to extract hydrocarbons from the coarse fraction. This involves physical agitation of the samples until all visible hydrocarbon coatings are dissolved into the solvent. This solution is then used in the standard Soxhlet or Soxtec extraction process to extract hydrocarbons from the sand minus fraction. While the solvent wash process is not as aggressive as the Soxhlet/Soxtec extraction, it was rationalized that the coarse fraction does not require as vigorous of an extraction method to dissolve the hydrocarbon. It should be noted that this procedure applies only to the semi-volatile and non-volatile F2, F3 and F4 hydrocarbon fractions and does not include BTEX or F1.

Discussion

Three main challenges were explored with coarse soils; the applicable guidelines, remedial approach, and analytical method were all modified to compensate for the atypical grain sizes encountered. Not all of these modifications were endorsed by Alberta Environment. Specifically, they felt that because the plants and soil invertebrates grow in the sand minus fraction of the soils, that the standard CCME extraction method was preferred. However, clearly this is problematic especially for soils that were screened to removed fines. Additionally, it is debatable that the eco-contact pathway applies to the base of the excavation which is below the water table. Therefore, modified analytical method was used for the screened grave- plus material, while the standard CCME method was applied to the separated sand-minus material.

The following figure summarizes how the remedial approach, analytical technique and guidelines were combined to address the coarse and fine portions of the soil on the Ricinus sites.

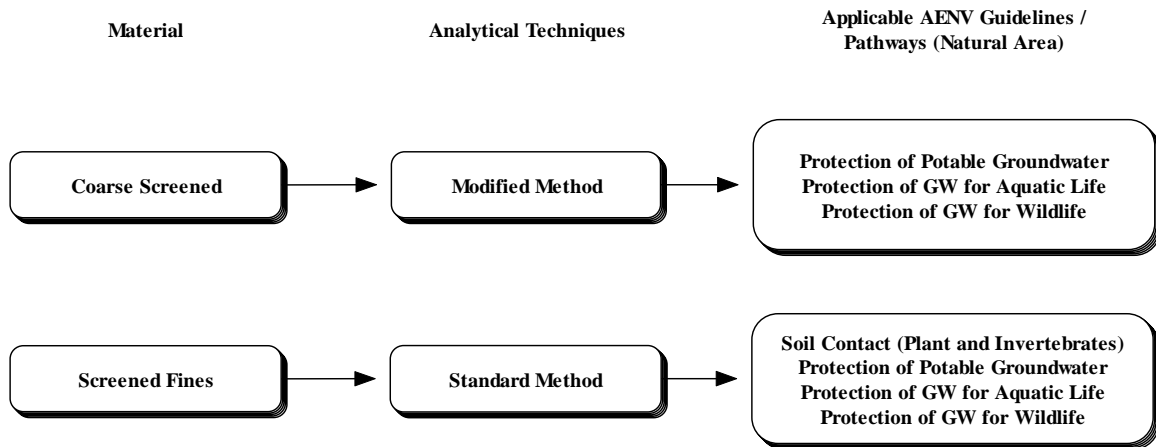


Figure 8: Application of the Screening, Analytical Method and Criteria

Conclusions

The remediation of hydrocarbon contaminated sites with gravelly soils currently is not well addressed existing regulatory frameworks or remediation technologies. The Ricinus projects have highlighted the many challenges of working with such material. Some aspects of our coarse soil remediation program, such as the generation of Tier II guidelines are highly site specific, as demonstrated by the two very different sites that we studied. Other aspects, such as the remedial approach and modified analytical techniques may be more widely applied.

Remediation of gravelly sites is an area that requires further attention from the environmental services industry and regulators to develop technical approaches and establish appropriate remediation goals. We believe our work at the Ricinus Sites provides some practical options and important lessons in this direction.

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