

In Situ Thermal and Subsidence

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In Situ Thermal and Subsidence – When is it a risk?

Organic contaminants are often released below or close to buildings and structures, and the source zones remain for decades. In situ thermal remediation (ISTR) has been proven effective for removal of the source material, typically by heating the subsurface to temperatures close to or above the boiling point of water. When considering ISTR below buildings, the question of subsidence and potential damage to the buildings is an important one. The US EPA reported on the issue as follows (US EPA, 2014):

“Subsidence occurs when drying of the subsurface results in desiccation and shrinkage. Subsidence can be of concern when ISTT occurs beneath structures and can also affect installed ISTT systems.

Subsidence has generally not been a problem for ISTT projects for a number of reasons including the fact that heating often occurs at depth and the degree of moisture reduction does not result in sufficient desiccation to cause subsidence.

Based on the Camelot Cleaners experience, subsidence may need to be considered at sites with significant clay content in near surface zones which will be subject to ISTT.”

In this memo, the causes of subsidence are discussed, and field evidence from approximately 220 completed ISTR projects are summarized. The intent is to outline site conditions leading to the potential for significant volume changes and damage to buildings and underground structures, and options for precautions.

What makes soils and sediments change volume?

Most sites have subsurface layers with sedimentary and bedrock deposits, with the solids made up of more than 99% quartz or clay minerals. Sediments based on quartz (SiO₂) grains have porosities in the 25-45% range and grain-to-grain contact of solid, non-compressible material. Near building such layers are well consolidated. These layers change very little, even when heated and dried out. The subsurface materials prone to volume change are (see Table 1 for more detail):

- Clays with swelling/shrinkage potential with varying water content, such as smectite, illite and montmorillonite, consisting of anionic aluminosilicate layers held together by ionic forces by inter-layer cations (Hensen and Smit, 2002).
- Organic materials, such as peat and humic and fulvic acids, where a reduction on the organic content is sufficient to change the grain-to-grain contact of the load-bearing particles.

Subsidence risks are associated with (1) moisture changes in swelling clays and (2) loss of mass due to oxidation or dewatering of organic-rich layers. The potential for volume change is highest when the layers are unconsolidated – e.g. in areas which have not been prepared for buildings.

Is there a difference between ERH and TCH in terms of the risk?

Two things contribute to volume changes: (1) removal of water from the formation and (2) oxidation and removal of organic matter. For volatile contaminants, both ERH and TCH targets temperatures near the boiling point of water for the bulk of the target treatment zone. However, due to the difference in heating mechanisms, small differences can be important.

ERH is based on current flow through the formation, and works best when the solids remain wet. Typically, relatively uniform heating is targeted, and between 10 and 50% of the pore water is removed as steam. Dry zones are rare and unwanted, as they cause the power delivery to drop off around the electrodes. As a result, complete drying of layers does not occur, and temperatures are restricted to the boiling point of water (100°C above the water table and slightly higher with depth below it).

TCH is based on heating of steel casings and transfer of heat by conduction. As a result, the zone immediately around the heaters can reach temperatures of 500°C or higher, with localized drying (Heron et al. 2013). At a site targeting 100°C for removal of PCE and TCE, an estimated 3% of the soil volume reached temperatures above boiling, indicating that they were dry. This was the cylindrical zone around each heater boring which extended 1-3 ft from the boring itself. The remaining 96% of the soil volume was still wet at the end of thermal treatment.

For organic-rich soils or soil layers, TCH has the potential to start subsurface oxidation reactions, also known as smoldering. Where the temperature and oxygen levels are sufficient to initiate smoldering, exothermic reactions have been observed to result in destruction of organic matter by either pyrolysis or oxidation (Baker et al. 2007). Such reactions require an organic matter content on the order of 3,000 mg/kg to sustain the reaction, and therefore are expected to occur only in soils and sediments with either high fraction of organic matter (more than 0.3%) or presence of hydrocarbon NAPL with soil concentrations above 3,000 mg/kg. When smoldering occurs, very little (less than 1%) of the original organic matter is left in the solids (Grant et al. 2016).

For thick peat layers, the sole effect of lowering the water table can lead to oxidation and shrinkage, as peat exposed to oxygen tends to lose weight by slowly being oxidized. If a site is dewatered and then heated under constant vapor extraction (which pulls in atmospheric air rich in oxygen), oxidation and loss of peat mass has been observed, even when targeting 90-100°C for removal of volatiles (Nielsen et al. 2010).

In summary, the risks are similar between ERH and TCH, except when TCH is used for highly organic soils or sediments, where in situ smoldering can be initiated by the elevated casing temperatures. Smoldering can occur at sites which contain peat or other organic-rich layers, or high soil concentrations and NAPL. It is also possible that the drying which occurs around TCH borings can lead to very localized shrinkage of swelling clays such as smectite. These effects are expected to be less pronounced during ERH treatment, as water is added around the electrodes in order to keep the soils wet.

Of 220 ISTR sites, which ones showed sign of subsidence?

Few of the completed sites had real issues with subsidence. However, some did, as presented in Table 2 and shown in Figure 1. Most of these sites were not close to buildings, and the observed subsidence either expected or accepted as part of the remedy.

As Table 2 shows, the causes of subsidence were:

- Desiccation of clays around heater borings.
- Removal of large quantities of mass from waste disposal areas such as gas holders.
- Exposure of peat and other organic-rich layers to oxygen and heat.
- Desiccation of unconsolidated fill or excavated soils during thermal treatment.

Notable projects where subsidence had to be avoided are listed in Table 2, along with details of monitoring conducted to ensure protection of the sensitive structures (buildings, railroad tracks, roads). An example of thermal treatment next to a house sitting on 9 meters of clay is shown in Figure 2. This site was heated to boiling for removal of PCE, and no evidence of subsidence was seen (Nielsen et al. 2010). The same group monitored very carefully for subsidence below an active dry cleaner treated to boiling temperatures using TCH and steam (Nielsen et al. 2008). Figure 3 shows an ERH system operating on both sides of, and underneath an active railroad, without adverse impacts on any signs of subsidence. This site was heated to boiling temperatures from 5 to 30 ft below grade.

Overall, less than 10% of the completed sites showed significant subsidence. And in all cases, the subsidence was either expected or explained by the site conditions.

How to prevent subsidence, and when you cannot

The main precautions for lowering the risk of subsidence are:

- Peat sites: Avoid dewatering and exposure to oxygen, limit temperatures to near boiling.
- High organic matter sites: Either use ERH or limit TCH heater temperatures below ignition points for smoldering.
- Sites with swelling clays: Minimize changes in clay water content, where possible, by heating gently and replacing moisture as it is removed (such as water drip during ERH heating).

For some sites, subsidence cannot be prevented if the contaminants require heating to temperatures of 100°C or higher. The high-risk sites have the following characteristics:

- SVOC target contaminants which require heating to temperatures of 200-400°C, hot enough to remove the SVOCs and also reduce the fraction of natural organic matter.
- Sites with peat, meadow-mat or other high organic matter layers (more than 0.3% f_{oc}).
- Wet swelling clays with substantial contamination requiring removal of a significant fraction of the pore water to reach remedial goals (for example smectite clay with PCE requiring 99% mass reduction).

Whenever treatment is required under or close to structures, these factors should be considered.

Testing Options – to evaluate the risk of shrinkage and subsidence

During the selection and design of an ISTR system, the following data is important for evaluating the risks of volume change and subsidence:

- Degree of consolidation of the subsurface materials below and near buildings and structures.
- Content of natural organic matter in the layers (f_{oc}).
- Thickness and water content of organic rich layers (peat, meadow-mat, organic clays, etc.).
- NAPL saturation and total soil concentration of combustible organics (when high soil concentrations are suspected).

- Clay mineralogy with focus on presence of swelling clays.
- Water table depth and fluctuations.

These parameters can be determined using relatively simple analytical methods.

Keeping it real – sometimes we cannot both heat and keep buildings unaffected

Some sites have conflicting demands. If CVOCs are present in the upper 5-10 ft, effective removal requires heating to temperatures of 90-100°C. As a result, the soil immediately below the building foundation will be hot enough to facilitate conductive heat transfer to the floors, and the building will heat up significantly. The effects can be reduced by aggressive vapor extraction under the building, and by additional cooling and ventilation measures in the building. But sometimes heating to near boiling temperatures to remove the COC is at odds with keeping building temperatures low enough to allow for continued occupation/operation.

Similarly, rare cases involve having to remove mass near the buildings from swelling clays or organic-rich layers, and the subsidence cannot be prevented. In such cases ISTR may be eliminated as an option, or the building must be vacated and later repaired if the subsidence causes damage.

It is recommended to carefully evaluate the risk of subsidence for each site with sensitive structures near the ISTR target area.

References

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Table 1. Naturally occurring materials with the potential for volume change during ISTR.

Material	Volume change mechanisms	ISTR design consideration
Humic and fulvic acids – high f_{oc} soils and sediments	Partial mineralization when exposed to oxygen and elevated temperatures – loss of mass and load bearing capacity Smoldering if heated to 400°C or higher and exposed to oxygen	Avoid heating to over 300°C Minimize dewatering where possible
Peat and other organic material such as wood fragments	Partial mineralization when exposed to oxygen and elevated temperatures Smoldering at high temperatures	Minimize dewatering during thermal, avoid elevated temperatures
Swelling clays such as smectite	Changes in water content (typically lowering of the water content by boiling of pore water and removal of steam)	Minimize changes in saturation by gentle heating, water addition to electrodes and heaters

Table 2. Selected ISTR sites where subsidence was observed (from a database of 220 completed ISTR remedies).

Site	Observation	Proposed mechanism
Richmond, CA	Minor subsidence and cracking of the vapor cover above a 15-ft thick clay zone heated to 100°C using TCH	Limited desiccation of small zones around heater borings, potentially minor shrinkage of the underlying Bay Mud
North Adams, MA	Subsidence of materials in a gas holder heated to 325°C for removal of coal tar MGP waste	Physical removal of 16,000 gallons of DNAPL and potential oxidation or organics at 300-500°C
Skuldelev, Denmark	Subsidence in an area heated to 100°C using TCH to remove PCE	Partial oxidation of a 2 meter thick peat layer caused by dewatering, heating and vapor extraction
NASA Michoud, LA (1)	Subsidence in a parking lot area heated to 100°C using TCH for TCE removal from an organic-rich clay	Partial oxidation of the organic clay by heating and exposure to oxygen
NASA Michoud, LA (2)	Subsidence in an area heated to 90-100°C using ERH for TCE removal from an organic-rich clay	Partial oxidation of the organic clay by heating and exposure to oxygen
Hoboken, NJ	Subsidence of a zone heated to 100°C using TCH for removal of volatiles	Partial dewatering and oxidation of organic matter from a thick layer of meadow-mat
Da Nang, Vietnam	Shrinkage of soils and sediments heated to 300-400°C using TCH for removal of dioxins and herbicides	Settlement of unconsolidated material during dewatering and partial oxidation of naturally occurring organics

Table 3. Selected ISTR sites with heating near sensitive structures where detailed subsidence monitoring was performed.

Site	Observation	Comments
Knullen, Odense, Denmark	Site heated to 100°C using TCH and SEE. Minor lifting of the foundation during heating (a few mm) due to thermal expansion, return to original level during cooling. No negative impacts on building or chimney	Detailed levelling of multiple points in building and along a chimney located above the heated area (Nielsen et al. 2008)
Brandywine, MD	Site heated to 100°C next to and under active rail lines and a road. No negative impacts recorded.	Custom elevation monitoring of railroad tracks



Figure 1. Subsidence observed at a PCE site with a thick peat layer heated to 100°C and dewatered (Skuldelev, Denmark; Nielsen et al. 2010).



Figure 2. TCH remediation of a 9 meter deep clay layer heated to 100°C next to a building – no subsidence observed (Reerslev, Denmark; Kruger and TerraTherm, unpublished).



Figure 3. ERH operation under an active railroad – electrodes were placed under the railroad, and the subsurface was heated to boiling temperatures without any adverse impacts (Brandywine, MD; TRS Group, unpublished).