Experiences from applying thermally enhanced in-situ remediation methods beneath buildings

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Abstract
Thermally enhanced Soil Vapour Extraction (TSVE) had been applied more often in practise during the last years. The benefit of these methods is a rapid source removal of volatile and semi-volatile organic contaminants (e.g. VOC, BTEX, petroleum derived hydrocarbons) without excavation of the soil. Several physical and chemical processes interact to enable a remediation success within weeks. Among others, one major process is the vaporisation of Non-Aqueous Phase Liquids (NAPL) and the extraction of the soil vapour (SVE). Cause TSVE meet EURODEMO's sustainability demands for innovative technologies for the cleaning of soil and groundwater, TSVE have been selected by EURODEMO as "Feature Technologies" as being eco-efficient and a 'Factor-4-Technology' (a technology providing a double service and having half the impacts).

In combination with an advanced site management and a detailed engineering, TSVE had been applied as well for the removal of contaminant sources beneath buildings, even the usage of these buildings continued during the remediation. The rapid remediation processes allow asking for some confidence, to enable the installations below buildings. Nevertheless, a lot of interfaces between inhabitants, lodgers, owners, neighbourhood, administration and executing companies have to be managed in advance to avoid conflicts and to enable a project start.

Several projects had been finished during the last years and some of them will be presented within this paper. Restrictions to the usage of the buildings had been mainly made during the installation of wells, pipes and the treatment plant. The use of workshops above the remediation field and even housing in a floor above the remediation facility could be continued without any restrictions during the remediation.

Examples will be used to explain the remediation processes and remediation results as well as site management tools and engineering parts before and during the remediation. Comparisons with site specific ‘cold’ applications will be used to quantify the reduction of environmental impacts like energy consumption or CO_2-immissions from remediation activities. Due too the significantly shorter remediation time, LCA results for the innovative TSVE methods using steam-air-injection (TUBA method) or thermal wells (THERIS method) show advantages in terms of ecological aspects compared to the conventionally used ‘cold’ soil-vapour extraction.

The site management and engineering is more complex compared to conventional remediation methods like ‘cold’ SVE or excavation and disposal. Examples to overcome successfully administrative, interpersonal, technical and economical barriers will be presented. Site-specific needs of confidence-building measures e.g. indoor-air quality measurements and building-structure monitoring will be explained.

The opportunities of TSVE beneath buildings as well as in urban areas and their application in the context of brownfield redevelopment projects will be presented.

1 INTRODUCTION

The remediation of contaminant sources beneath buildings causes very often difficulties due to the impossibility of an excavation of the contaminated soil or a several years lasting conventional in-situ remediation like “cold” soil vapour extraction (SVE) or pump-and-treat (P&T) [KOSCHITZKY 2007]. However, the last years, thermally enhanced in-situ remediation methods like TUBA (steam- (air-) injection) or THERIS (thermal well application) (Fig. 1) have been successfully applied for field remediations even beneath buildings. Cause these methods meet EURODEMO's sustainability demands for innovative technologies for the cleaning of soil and groundwater, Thermally enhanced Soil Vapour Extractions (TSVE) using TUBA or THERIS have been selected by EURODEMO as "Feature Technologies" [EURODEMO 2008]. *VEGAS* (research facility for subsurface remediation, Universität Stuttgart) and reconsite – TTI GmbH (*VEGAS* spin-off) have successfully demonstrated in several pilot and field applications that soil remediation using TSVE is effective, energy efficient and fast [EURODEMO 2005]. Therefore, TSVE with TUBA or THERIS is promoted by EURODEMO as being eco-efficient and a 'Factor-4-Technology' (a technology providing a double service and having half the impacts) [EURODEMO 2008].
TSVE-applications for the cleanup of volatile and semi-volatile organic contaminants in the unsaturated and saturated zone are promising and reliable technologies for enhancing the remediation of source zones, because [EURODEMO 2008]:

- the physical principles and processes induced by the technology are understood,
- the set-up and the results of lab experiments and field studies are well documented and
- compared to a conventional reference technology (SVE: ‘cold’ Soil Vapour Extraction)
    - contaminant extraction rates are high and remedial targets are effectively achievable,
    - decontamination is considerably faster (up to factor 10) and
    - costs and wider environmental impacts are significantly less.

This paper focuses on TSVE-applications beneath buildings summarizing the specific boundary conditions and presents solutions to enable a continued usage of the buildings even during remediation.

2 SHORT DESCRIPTION OF THE REMEDIATION METHODS

The principle of TSVE-remediation is based on the heat-up of the subsurface to increase the volatilisation of organic solvents, to vaporize organic contaminants like Non-Aqueous Phase Liquids (NAPL) and to reduce the interfacial tension, therewith extraction rates increase significantly [DAVIS 1997]. As the remediation processes induced by the heating are similar for different kinds of contaminants, TSVE have been successfully applied mainly for efficient source removal of VOC, BTEX, petroleum derived hydrocarbons and similar components. Usually, the main mass recovery of contaminants at a successful TSVE-application is done by a SVE (Figure 1). Nevertheless, site-specific an additional groundwater extraction may be recommended.

TSVE can be applied in the unsaturated zone as well as in the saturated zone over a wide range of contaminants and soil permeability (sand to clay). Compared to other in-situ remediation technologies TSVE have the big advantage that soil heterogeneities have minor to little effects on heat propagation [EURODEMO 2008]. Efficient treatment of soil layers with high to moderate permeability within one remediation zone can be achieved by TUBA (steam-(air-) injection) through convective heating. In layers of low permeability THERIS (thermal wells) can be applied by using mainly a conductive heat transfer. In some specific cases both methods, TUBA and THERIS, can be combined to optimise the heating of stratified layers. Applied for source removal, TUBA and THERIS are cost efficient alternatives to conventional methods like excavation and disposal (dig and dump).

During the past years several projects have been successfully finished in urban areas and beneath buildings without any restriction to their use or to the use of adjacent buildings. To finish a remediation within some weeks or a few months, a detailed engineering for the design and the application is needed. The impacts on the surroundings could be limited temporarily on the installation of the treatment system and maintenance intervals.

Widely independent of site-specific boundary conditions, all conducted life cycle assessment analyses (LCA) of successfully completed TSVE field projects have shown for TSVE lower natural resource consumptions (e.g. fossil resources) as well as lower environmental impacts (e.g. CO_2-immissions, global warming potential, acidification) compared with conventional remediation methods [HIESTER & SCHRENK 2005].

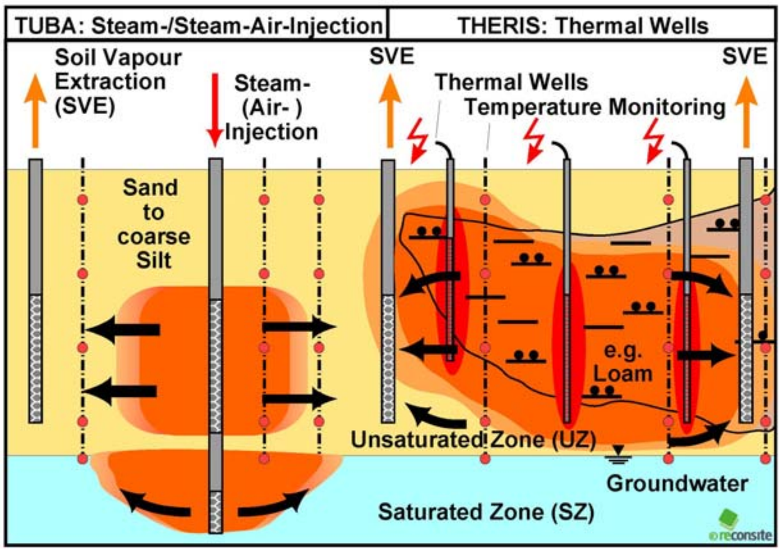

FIGURE 1: Principle of the thermally enhanced in-situ-remediation methods TUBA and THERIS.

3 SPECIFIC CONDITIONS BENEATH BUILDINGS

3.1 GENERAL LIMITATIONS

Usually, buildings or parts of a building are used before the remediation and continuous usage has to be considered within the remediation concept and must be guarantied by the executive companies. Depending on the site, a continuous usage must be enabled in the rooms directly above the contaminated source or in neighbouring rooms or floors. A detriment of the indoor-air has to be prevented. This necessitates a continuous monitoring of the indoor-air including informing the building users about the ongoing results.

Damages on the building structure by the TSVE-remediation, e.g. at the building foundation, have to be prevented. This requires a detailed knowledge about foundation and building static during the design phase. These information are difficult to obtain for many older houses or buildings, especially in case of extensions of older buildings by younger parts. Anyway, an independent building structure monitoring, e.g. by surveyors or specific skilled engineers, during the remediation is recommended.

3.2 PROJECT EXAMPLES

In the following three TSVE-remediations beneath buildings are presented (Table 1). All projects have been completed within the last four years in Germany. The wide variety of boundary conditions for a successful application of TUBA- and THERIS-remediations allows to serve even complex conditions.

3.2.1 SITE DESCRIPTION AND SPECIFIC REQUIREMENTS

Example 1: Due to industrial activities in a former production facilities of a metal working enterprise, the unsaturated zone and the groundwater was contaminated by chlorinated hydrocarbons (PCE). A soil volume of 250 m³ (approx. 50 m²) underneath a four-floor building (established after World War II) was affected [SMARTE.ORG 2008]. The soil was characterized as "difficult for clean-up" due to a heterogeneous structure consisting of small strata of clay, clay stone, marl and limestone with low permeability and confined aquifer conditions. Several in-situ remediation technologies such as P&T, SVE and in-well stripping were installed and operated for 7 years. After this period the total costs were approximately € 600,000 [STEIDINGER 2004]. The low contaminant removal rates and the very slow decrease of PCE-concentrations did not meet expectations to complete the clean-up within the next decade. Nevertheless, the local authorities insisted on continuing the remediation process since PCE-concentrations in the groundwater still exceeded the threshold values (10 µg/L) by a factor of 800.

A basic requirement for potential remediation methods was that the new user of the building would maintain regular production processes in the building during the clean-up [SMARTE.ORG 2008]. Vibrations of the floor and settlements in a range of more than 2 mm had to be avoided to prevent damages within the very sensitive production process.

TABLE 1: Summarised data of the exemplarily sites [sources: □□ STEIDINGER 2004; □: FÄRBER ET AL. 2004; □□ EURODEMO 2005; □□ SMARTE.ORG 2008]**.**

	Example 1	Example 2	Example 3
Site Location	Baden-Württemberg	North of Germany	Bavaria
Contaminants	PCE	PCE	PCE, TCE, cis-DCE
Base Area of thermal treatment	~ 50 m² (□)	~ 120 m²	~ 45 m²
Unsaturated / saturated zone	both (□)	unsaturated zone	unsaturated zone
Layer to be remediated [m bgs]	2 m unsaturated, 2 m saturated zone (mainly 2 – 6 m bgs)	mainly 4 – 7 m bgs	primer 2 – 4 m bgs
Soil within the **target treatment zone (TTZ)**	silt, clay marl, lime stone (□)	loam, marl, silt	clay
Building usage during TSVE	production	workshop business	housing
"historical" remediation: - method(s) - removed contaminant mass - remediation time	P&T, SVE, inwell- stripping (□) ~ 36 kg (□) ~ 7 years (□)	 "cold" SVE unknown 4 years	 Excavation + P&T < 2 kg + ~ 20 kg 1 month + 6 years
pre-thermal treatment: - method(s) - removed contaminant mass - remediation time	 Air Sparging (□) < 0.3 kg 5 days	 "cold" SVE ~ 1 kg 1 week	 P&T, "cold" SVE ~ 1.5 kg 1 month
thermal treatment: - method(s) - removed contaminant mass - remediation time	 TUBA (□) ~ 11 kg 3 month	 THERIS ~ 1 600 kg ~ 9.5 month	 THERIS ~ 5.5 kg 3 month
post-thermal treatment in the saturated zone: - method(s) - removed contaminant mass - remediation time	 Air Sparging (□) < 0.3 kg 25 days	 non non non	 P&T ~ 1 kg > 1 year

Example 2: A former dry cleaner contaminated the unsaturated zone and the groundwater with PCE. A "cold" SVE had been operated for four years without a realistic chance to reach the remediation goals in a sufficient time frame. Maximum values from soil exploration after finishing the "cold" SVE and before starting the TSVE-remediation have been > 5,000 mg/kg. The remediation goal of values < 5 mg/kg has been fixed before the remediation started. The TSVE-remediation focused only on the source in the unsaturated zone, cause the plume is remediated separately.

The building of the former dry cleaner had been replaced by workshops in the 1960ies. Parts of the source (approx. 120 m²) had been located beneath the workshops, used by SMBs (small and medium-sized businesses). Because the TSVE-remediation time had been estimated to take several months, a part time closure of the workshops would have caused the risk of insolvency of the SMB. So a continuous business of the workshop during the remediation had to be enabled.

Example 3: A former dry cleaner (building established after World War II, Fig. 2) contaminated the unsaturated zone and the groundwater. PCE, TCE and cis-DCE had to be remediated. An old waste dump had been excavated in the year 2000 and P&T has been started in the same year. Nevertheless, contaminants in the unsaturated zone had been still present in a clay layer between 2 – 4 m beneath ground surface (bgs). The TSVE-remediation focused on the removal of this source in the unsaturated zone. P&T continued and is expected to be shut down within the next months due to the minor amount of remaining contaminants in the aquifer. A significant plume could not be observed at that site. The closest monitoring well 35 m downstream the source is almost without any contaminants.

The challenge at this site was to enable a continued housing during the TSVE-remediation one floor above the remediation plant (Figure 2). Furthermore, neighbours had to be protected against any impacts from the remediation including noise from the pumps and blowers. A dewatering of the aquifer had to be prevented due to static reasons of the older building including the later attached part of the building.

3.2.2 SITE-SPECIFIC SOLUTIONS

The "historical" remediations in Table 1 focus on the time frame before TSVE had been discussed. A pre-thermal treatment is done usually with the TSVE-remediation system, but without a heat-up of the subsurface. This reduces the system often to a conventional SVE or P&T-system. Nevertheless, this phase is important and often used as a check-up of the remediation plant. A post-thermal treatment might be conducted at some sites. The post-thermal treatments in this paper focused on the groundwater.

Example 1: To remediate the unsaturated and the saturated zone, a steam-air injection was conducted as the first application worldwide of this technology in the saturated zone [SMARTE.ORG, 2008]. *VEGAS,* Universität Stuttgart, designed, installed and operated the process engineering. The cleanup success with steam-air injection was achieved within 3 months, while the target zone was heated up > 90°C [STEIDINGER 2004]. To avoid vibrations of the floor, all drilling works have been conducted during shut down of the building users production nearby. The treatment facility itself did not limit the production process and was installed in the building. A surveyor monitored settlement and building structure every two weeks.

Example 2: The unsaturated zone had been remediated by using thermal wells. Reconsite designed and monitored the THERIS-remediation conducted by Bauer + Mourik Umwelttechnik GmbH, part of the BAUER Umweltgruppe [HIESTER ET AL. 2006]. A cleanup success was achieved within 9 months, but took longer than expected. The total mass of extracted contaminant reached 1,600 kg PCE and exceeded the expected mass (about 200 kg PCE) from pre-treatment soil samples by a factor of 8.

The workshop must be temporarily cleared for the THERIS installation. Clearing of the workshop equipment, drilling works and installation of a temporal intermediate floor took all in all two weeks. A temporal intermediate floor during the remediation enabled a continuous business of the workshop during the whole remediation period. The installation of the intermediate floor was more cost efficient than a subsurface installation of cables, SVE-pipelines and monitoring systems.

Example 3: Even the remediation focussed on the unsaturated zone, thermal wells had been extended as well into the contaminated aquifer. Reconsite designed and monitored the THERIS-remediation conducted by Bauer + Mourik Umwelttechnik GmbH. A cleanup success was achieved within 3 months, and matched time frames well. The total mass of extracted contaminant with the pre-thermal and the TSVE-treatment reached 7 kg and was in the range of expected mass (about 5 kg).

To enable this THERIS-remediation within a residential area (Figure 2), a very good sealing of the bore holes between well pipelines and floor as well as a continuous monitoring of the indoor air have been essential for a acceptance of the remediation concept. During the whole remediation no increasing indoor-air concentration in the treatment room or in the neighbouring basements could be detected.

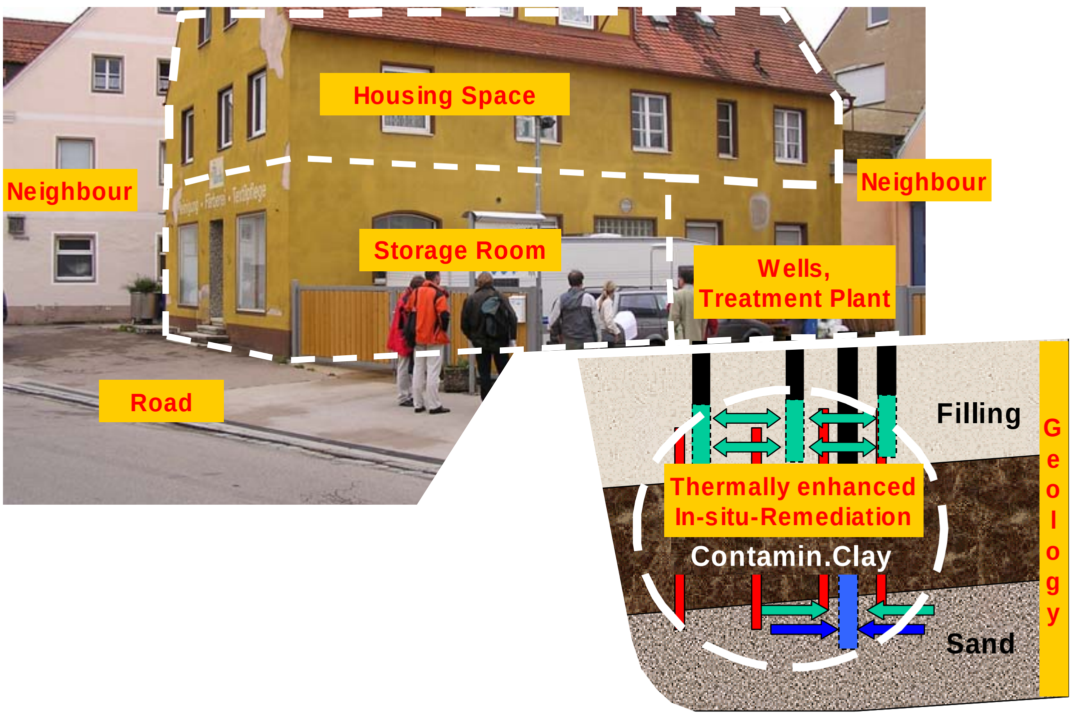

FIGURE 2: Sketch of a thermally enhanced In-situ-Remediation beneath a building (Example 3).

3.2.3 GENERAL ARRANGEMENTS FOR TSVE-REMEDIATIONS BENEATH BUILDINGS

A good estimation of the remediation time is essential for the acceptance of the remediation (Table 2). The remediation time depends on the achieved temperatures in the subsurface as well as on the stored contaminant mass. In all examples, sufficient temperatures had been achieved within four to six weeks. An efficient and well maintained SVE-system is one of the key jobs enabling a soon remediation success by an efficient mass recovery from the subsurface. As shown in Figure 3a, the contaminant mass of the different sites varied by more than two orders of magnitude, but the remediation volume varied only by a factor of ± 2 between the different sites. Nevertheless, the principle characteristics during the remediation are almost similar (Figure 3b) [HIESTER ET AL. 2004]. Due to the high mass recovery during TSVE, the recovery during a post-thermal treatment in the saturated zone is low to very low (Table 1, Figure 3).

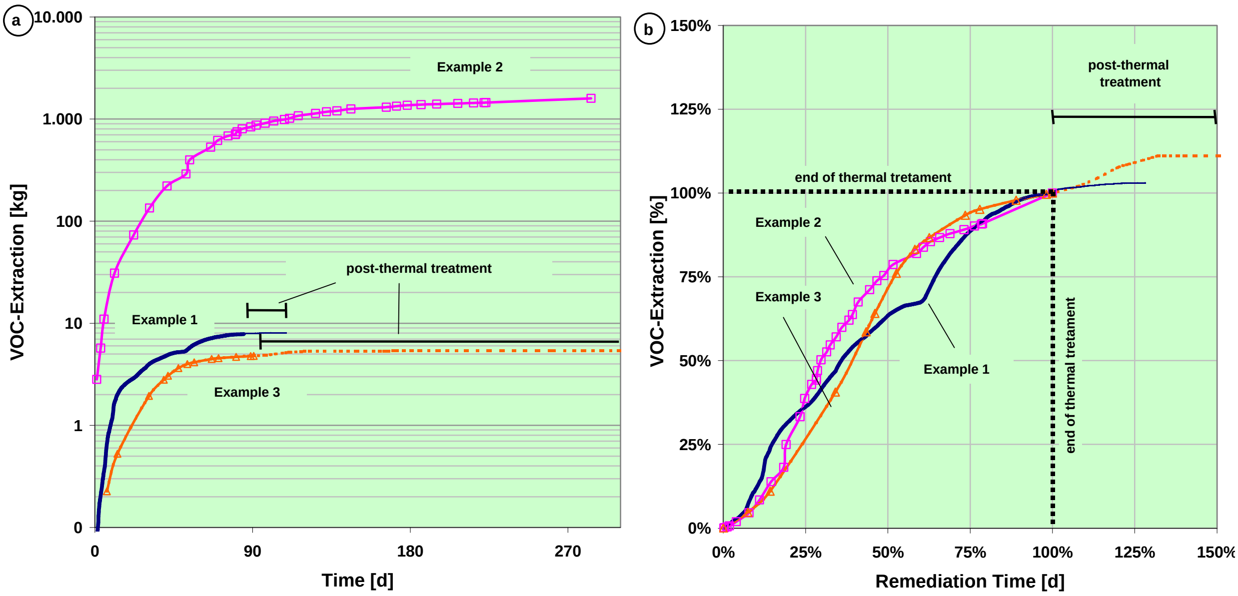

FIGURE 3: Comparison of the TSVE remediation progress from different sites: a) contaminant recovery versus time, b) normalised contaminant recovery versus normalised thermal remediation time (base: 100% = end of thermal treatment per site)

TABLE 2: Overview of important concerns, their risks and the needed action for a successful TSVE-remediation beneath buildings

Concern	Risk	Action
▪ inaccurate estimation of the remediation time	▪ impairment of acceptance of the remediation concept	▪ detailed site evaluation ▪ good evaluation of contaminated source zone
▪ gas migration into the building	▪ potential risk of impairment of health ▪ no licence for remediation plant operation	▪ preventing gas migration by a well maintained SVE-system and by sealing the boreholes round the well heads ▪ continuous measurements of the indoor-air ▪ continuous information of residents and building users
▪ settlements and / or damage of the building	▪ potential risk of impairment of health ▪ potential risk of high amount of loss	▪ detailed examination of soil, foundation, buildings structure ▪ evaluating the influence of a changing water content on soil stability (optional monitoring of the water content) ▪ monitoring of the building structure
▪ noise from the treatment plant	▪ impairment of living quality (e.g. noise during the night) ▪ no licence for remediation plant operation	▪ acoustic insulation of pumps / blower / container ▪ regular control of the treatment plant
▪ no or insufficient utilisation of the facility during TSVE	▪ no acceptance of the remediation concept	▪ individual concepts and / or temporary change of utilisation

In all cases the design of the TSVE-remediation based on a detailed evaluation of the building structure, the foundation as well as the soil. Because water and NAPL are vaporized together at any TSVE-remediation, the influence of changing water content on the soil stability has to be evaluated carefully. Nevertheless, a TSVE-remediation is usually finished by achieving steam distillation. So, the water content will be decreased during the remediation, but the soil will remain wet at their end [HIESTER ET AL. 2004, HIESTER 2009]. Anyway, a detailed monitoring of the building structure during the remediation is a must. In some cases, the measurement of the water content might be helpful as an additional information. At none of the described sites, even a partial damage of the building had been observed.

Health protection of residents during TSVE is an important factor. Noise can be avoided by a good acoustic insulation of the plant and by storing pumps and blower apart from noise sensitive rooms and areas. Gas migration from the subsurface can be avoided by a well maintained SVE-system, by a surface sealing and a good sealing of the boreholes for wells and monitoring devices. Thus, up to now, noise as well as indoor-air quality became no difficulty during TSVE beneath buildings.

Finally, individual, site-specific concepts are the major key for a successful TSVE-application beneath buildings and in urban areas. Getting residents and house users involved in the decision making process is important for the acceptance of the remediation concept. Key concerns, risks and needed actions are summarized in Table 2.

CONCLUSIONS AND OUTLOOK

During the last years the number of successful TSVE-applications for field applications increased due to the transfer of new research results to remediation practice as well as the application of TSVE-remediation at sites with complex boundary conditions. The application in residential areas and beneath buildings including a continuous usage of the buildings is a new field with interesting options for successful and efficient source removal.

TSVE has been evaluated as cost and eco-efficient in the past. The application beneath buildings offers a complete new field for fast and efficient in-situ-remediation. Even under difficult conditions like heterogeneous subsurface or low permeability layers, TSVE enables a source zone removal beneath buildings in the unsaturated as well as in the saturated zone in moderate to short-terms. The presented examples show, that damages at the building structure as well as change in indoor-air quality could not be observed.

In the context of brownfield redevelopment, TSVE-applications can open new options for the removal of demands from contaminated soil and groundwater including preservation of the building structure. Compared to the TSVE-application next to buildings, the additional concerns and risks for an application beneath buildings can be limited or even neglected by a moderate additional engineering and monitoring.

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