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EPA Project Summary

A Study to Determine the Feasibility of Using a Ground-Penetrating Radar for More Effective Remediation of Subsurface Contamination

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A study was conducted (1) to assess the capability of ground-penetrating radar (GPR) to identify natural subsurface features, detect man-made objects buried in the soil, and both detect and define the extent of contaminated soil or ground water due to a toxic spill, and (2) to determine the minimum performance specification (in terms of hardware, data collection, and signal processing) necessary for a GPR to achieve these goals. As a means of addressing both aspects of the study, several models were developed to quantify the response of different GPR systems to these subsurface environments. A number of conclusions emerged from this study. The technology for making all of the above measurements already exists, but the systems most commonly found in commercial use today either are not adequately designed to detect and define subsurface soil and ground-water contamination or are not operated in such a way as to make this possible. In terms of hardware, it was found that, to operate effectively in all three generic subsurface environments investigated in this study, a radar system must have a very high figure of merit. In terms of signal processing, it was found that for typical GPR systems synthetic-aperture-radar (SAR) processing is required; this conclusion was based on three reasons: (1) better horizontal resolution is achieved with SAR processing; (2) SAR processing allows the system to operate at lower frequencies and thus achieve deeper penetration; and (3) SAR processing reduces ambient noise, which improves the detection and identification capabilities of GPR. It is recommended that simple proof-of-principle experiments be undertaken to validate the models developed in this study. To the extent that the experiments prove successful, GPR may become a significant tool in rapidly identifying and cost-effectively remediating subsurface contamination.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Remediation of toxic spills is often costly and entails cumbersome procedures to determine the horizontal and vertical extent of the contaminated soil or ground water. The traditional method is to drill core samples in the area where the contaminant is thought to be present and then analyze these in a laboratory. The denser the sampling grid, the more effective it is; unfortunately, it is also more expensive to implement and more damaging to the environment. Even with very dense sampling grids, serious interpretation mistakes can be made if a fluvial pathway is not detected by monitoring wells. A nonintrusive method of detecting subsurface contamination, therefore, would be highly desirable. Toward this end, the use of ground-penetrating radar (GPR) to locate and map subsurface contamination was investigated. If GPR proves effective, it can be combined with conventional methods to ensure better placement of drilling sites and to reduce the number of samples necessary.

GPRs have been proposed repeatedly for applications involving sensing or mapping the location of underground contaminants. Some experimental evidence of the successful use of GPR for this purpose has been presented in a number of publications and technical presentations. However, this evidence is largely anecdotal and lacks quantitative support. Thus, those positive results appear as special cases that cannot be extrapolated to general situations. This deficiency arises from the lack of a quantitative model for the effect of contaminants on those properties of soils that affect GPR performance and, hence, GPR performance specifications. The work described in the full report shows that the lack of success in these earlier programs can be largely ascribed to use (or considerations) of radars whose performance levels are insufficient for the task and to a need for much more intensive data processing.

While the literature indicates that radar measurement systems may have the potential to improve remediation efforts, such potential has yet to be realized. Three key elements are lacking in the radar studies: (1) a quantitative model of the effect of contaminants on the radar-relevant properties of soils, (2) understanding and "matching" the radar characteristics to the environment and the target(s) to be detected so as to get the best possible signals, and (3) the development of signal-processing methods best suited to take advantage of the signals returned from subsurface scatterers.

Objectives

One objective of this work was to assess the capability of GPR to identify natural subsurface features, detect man-made objects buried in the soil, and both detect and define the extent of contaminated soil or ground water. The second objective was to determine the minimum GPR performance specification required to accomplish the first objective.

Report Organization

The work done in fulfilling these objectives is presented in the final report, "A Study to Determine the Feasibility of Using a Ground-Penetrating Radar for More Effective Remediation of Subsurface Contamination."

Conclusions

The consideration of alternative designs for the radar system required the elucidation of a "figure of merit" for the system that included hardware and data collection considerations. This work considered the relative performance of several existing radar designs: a typical short-pulse radar, a short-pulse radar with higher transmitter power, and a synthetic-pulse radar. The results of this work showed that, although the short-pulse and synthetic-pulse radars were mathematically equivalent, the synthetic-pulse radar offered performance that was potentially 40 to 60 dB better than the short-pulse radar because it could transmit far greater power per spectral line. Furthermore, while the improved performance offered by the synthetic-pulse system was not often needed for the usual "hard-target" GPR applications, this improved performance was essential for the detection of small changes in dielectric constant such as would be expected in a situation where a small region (or thin layer) of contamination was encountered.

Two signal-processing methods were included in this stage of the work: real-aperture and synthetic-aperture (SAR) processing. The results showed that synthetic-aperture (coherent) processing had a significant advantage in remediation applications over the typically used incoherent processing. Although it is computation-intensive, SAR processing afforded a higher signal-to-noise ratio and effectively suppressed the clutter from adjacent reflections. To detect modest levels of most common contaminants at depths of 10 to 15 m and in moderately conducting soils, it was estimated that a combined radar-processing figure of merit of 200 to 220 dB is necessary. Considering the current radar technology, it was determined that this level of figure of merit could best be achieved by combining a synthetic-pulse radar with synthetic-aperture processing. It was also determined that one can obtain an additional processing gain of 35 dB by using a 3000-s observation time to collect data from a three-dimensional volume and then SAR-processing these data; the figure of merit could thus be effectively increased by 35 dB, which would mean better performance of the GPR in detecting the desired target.

As part of the radar design assessment task, a numerical model was developed that could illustrate the nature of radar returns from various modeled soils and geometries and show the processing gains obtained by different signal-processing methods. The model described the electrical characteristics of soils and of various potential contaminant materials at radar frequencies from about 20 MHz to about 200 MHz. This work showed that, for the radar frequencies considered, the dielectric constant and attenuation coefficient associated with these soils (with the exception of wet clays and ionic (salt-laden) silts and sands) were not fundamental obstacles to the propagation of radar energy through the medium. The work further showed that, for the range of radar frequencies most suitable to radar energy penetration to a working-goal-depth of about 10 m (in *nominal soil conditions*), consistent with the bandwidth necessary for adequate resolution, the dielectric constants and attenuation coefficients were nearly constant over the spectral range.

The second stage of the work entailed developing geological and contamination geometries that could describe various contamination layers and plumes. These geometries were needed so that the performance of the radar designs could be tested against the modeled electrical characteristics of the bulk materials. This work led to the development of three essential geometries that represented seven of the ten "common cases" of remediation configurations described by the EPA.

It is difficult to define a "typical" remediation site suitable for a baseline test, because soil properties, moisture content, and contamination environment differed dramatically from site to site. An almost limitless combination of factors could be ascribed; this made the radar design assessment difficult because not every combination could be addressed. To deal with this lack of a "typical site," a generic soil condition (comprised of a sand-clay mixture) was selected. The assessment work entailed adding various moisture and contaminant contributions to this soil mix, appropriate to the geometry considered. This "soil" is roughly equivalent to the "synthetic soil matrix" (SSM) developed by the EPA as representative of Superfund sites.

The numerical model allowed the effects of various spatial sampling schemes to be examined. This model showed that, with the incoherent signal processing usually applied to GPR data, the wide beamwidths associated with GPRs created a confusing display of the subsurface environment; these results were consistent with the images usually created by commercial GPRs. The numerical model also showed that when synthetic-aperture processing was used, the background noise in the radar images was reduced and discrete scatterers in the radar field of view were tightly localized.

A significant portion of the design assessment task addressed various detection strategies. That is, given a radar and a geometry, this work sought to identify key strategies that could be used to deduce the presence (or lack) of contamination in the subsurface returns from the processed data. This was a central effort in the work (after the basic feasibility of using synthetic-pulse radar and SAR processing for remediation support had been established). This work resulted in two novel findings. First, it appears that for contaminants with low dielectric constants (which include most non-ionic materials), there can be large contrasts in volumetric scattering (up to 7 dB) between contaminated and uncontaminated regions. Such contrast ratios are well within the detection range of a system with a high figure of merit, such as the synthetic-pulse radar with SAR processing designed in this work assignment. Second, it was determined that a thin layer of contaminant "floating" on the water table will produce a measurable signal if the layer is more than a few centimeters thick; the appearance of such a signal at some point in a survey would indicate the presence of contaminant there. However, the nature of this signal is such that it might be difficult to distinguish it from a local change in the depth of the water table, so its overall utility is questionable, even though it is surprisingly strong. On the other hand, thicker layers will produce a strong and distinctive signal. Strong signals will also be produced if abrupt transitions are induced at the boundaries between a lighter, immiscible contaminant and a water table with gradually increasing saturation. It was shown that volumes of pure fine and very fine soil particles (such as are found in silts and clays) can greatly degrade the performance of a GPR. Some fraction of these soils is usually composed of larger imbedded particles, such as sand grains. The analytical model has determined that the presence of these larger particles facilitates the detection of contaminated regions.

Recommendations

This work assignment showed that, for the environments and contamination geometries modeled here, a radar with a high figure of merit combined with coherent signal processing can detect contamination under a wide range of conditions. Such a radar can be achieved with existing technology.

The results of this work showed that two-dimensional coherent processing (surface distance, depth) was necessary to detect deep, low-contrast targets. Important performance gains, however, could be achieved with the use of three-dimensional techniques (surface area, depth). This type of data collection (and processing) will be necessary in order to enhance weak targets in a cluttered environment, and it is essential for providing a vehicle for "intelligent," understandable displays.

The models developed in this work represented an idealized soil environment and did not address an inhomogeneous propagation medium. In an extreme case, an inhomogeneous medium can lead to poor estimates of the radar propagation velocity, which limits the ability of the coherent processing to properly "register" the scatterers. It can also lead to an increase in the radar clutter field, which decreases the otherwise achievable high signal-to-noise ratio. On the other hand, the detection of contaminants is facilitated by the presence of small irregularities in an otherwise "pure" soil as a result of the increased volume scattering that occurs. While modeling of more complex environments is possible in principle, such work would not (because of the clutter) realistically or economically model any particular environment. Therefore, unless an experiment is performed to test and validate the models and the findings resulting from this work, the use of GPR for remediation purposes will remain an unanswered question.

It is recommended that simple proof-of-principle experiments be undertaken to validate the models and findings developed in this study. The purpose of the initial experiments would be to calibrate a GPR in terms of figure of merit and other needed parameters. Once the figure of merit of the radar has been estimated, additional experiments would be conducted at a quantified site. The purpose of this second set of experiments would be to collect a limited set of subsurface data with which to validate the models and better understand in real environments the use of high-figure-of-merit radars with synthetic-aperture signal processing. It is further recommended that in the initial experiments data be collected and coherently processed three-dimensionally. With theoretically attainable improvements in the performance figure of merit, GPR may become a significant tool in rapidly identifying and cost effectively remediating subsurface contamination.

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The complete report, entitled "A Study to Determine the Feasibility of Using a Ground-Penetrating Radar for More Effective Remediation of Subsurface Contamination," (Order No. PB92-169 382/AS; Cost: $26.00, subject to change) will be available only from:

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