Remote Sensing for Solid Waste Landfills and Hazardous Waste Sites

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Abstract

Geological remote sensing can be used to characterize solid waste landfills and hazardous waste sites in two ways: the use of digitized stereo photos to compute digital elevation models (DEM) of the landfill and the use of multispectral image data to map chemical compositional differences that are environmentally significant. The former can result in more accurate predictions of surface water run-off, measurement of the volume of water that can be stored in depressions in the landfill surface, and performance of volumetric measurements. The latter can likely be used to map clays, iron oxides associated with contaminated groundwater geochemical "cells," stressed vegetation, and even gaseous methane plumes escaping from the landfill.

Background

Since new solid waste landfill regulations (U.S. Environmental Protection Agency, 1991) came into effect on 9 October 1993, the need for technical information about landfills has increased. The great expense of acquiring point-measurement data, which often requires man-intensive, equipment-intensive, and laboratory-intensive methods for data collection, is an impediment toward denser areal coverage than the minimum requirements. For instance, one lab analysis of a single water sample can cost between $1,200 and $5,000, depending on the level of detail in the analysis. Field and lab methods usually require long response times, sometimes too long to permit the information obtained to be useful as a management planning tool.

Remote sensing from aerial and satellite image data is a mature technology with several benefits. Multispectral image processing of such data provides information (both visible and invisible to the human eye) about chemical composition of the Earth's surface with better spatial context than non-imaging sensors can generally provide. Digital photogrammetry, which involves spatial image processing of digitized stereo images, can yield elevation data (digital elevation models, or DEM) of higher spatial resolution than can be derived from non-digital DEM productions methods. In both cases, remote sensing image data offers opportunities for the areal extrapolation of point measurements made in the field, resulting in an increase in the area for which information can be gleaned from a given set of point measurements, or a decrease in the number of point measurements required to obtain a specified area of coverage. Once remote sensing images are collected, multispectral and spatial image processing can typically be completed on computers no larger than a work station in less time than field measurements and sample collections can be made and analyzed.

For example, soil coring and surface soil chemical analysis are point-measuring methods that can show the content of contaminants at the surface and in the shallow underground. However, both greatly under-sample the area of interest and tend to be slow and expensive if sampled over a large area. Remote sensing data and methods can be used to extrapolate a few point measurements over large areas whenever a remotely sensed surface property (such as a subtle topographic expression or a surface geochemical alteration) is found to be correlated with important lab-measured or field-measured surface or subsurface information at sites of point data collection. The resulting information contains much denser information (for every pixel in an image instead of for a few points on a map) than could be afforded, both in time and dollars, by point measurements alone.

What information can remote sensing images provide about subsurface conditions? This is the same question that faced remote sensing companies in the 70's and 80's concerning petroleum and mineral exploration. In that case, remote sensing geologists found that geochemical alteration of surface soils had been caused by ancient hydrocarbon seeps, which had risen to the surface from ruptured reservoirs thousands of feet deep (Vincent, 1977; Abrams *et al.*, 1984). It was also found that detailed observation of surface topography made it possible to detect and locate subtle topographic expressions of some of the fault traps that help define underground petroleum reservoirs (Abrams *et al.*, 1984). In summary, remote sensing geologists were able to infer what was beneath the surface by mapping compositional and topographic indicators that were present at the surface.

Remote sensing through photointerpretation of historical photos has already been found useful for studying landfills (Erb *et al.*, 1981; Stohr *et al.*, 1987; Stohr *et al.*, 1988) and water resource management (Salomonson, 1983.). There have also been some applications to landfill problems (Lyon, 1982; Stohr *et al.*, 1994) of remote sensing involving electronic imaging. This paper attempts to extend the conceptual horizons of remote sensing for landfill investigations beyond those pioneering efforts.

High Resolution Topographic Mapping

For over half a century, photogrammetry has been employed for the production of elevation contour maps from a pair of stereo photos, which are two downward-looking photos that

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overlap (usually around 60 percent) (Avery, 1977). One-foot contour maps take a long time to produce by traditional methods, which are mostly manual. Typically, it takes weeks or months to get a conventionally produced one-foot contour map delivered, once the aerial photos are available for stereo-plotting. Even then, only the contour maps are available, which are insufficient by themselves for measurement of temporal changes in landfill volume. If those maps are digitized and elevations are interpolated between the contour lines, then the resulting DEM of day one can be subtracted from a similarly created DEM for day two, and volume change of the landfill can be calculated (sum of the elevation changes for all elevation grid cells multiplied by the area of one grid cell). The image data from the photos, however, remain separate from the contour map and DEM, if traditional photogrammetric methods are employed.

Photogrammetric technology has been greatly changed, however, by developments over the last decade in the automation of photogrammetry. For example, a computer software package (Vincent *et al.*, 1984a) called ATOM (for Automatic Topographic Mapper), developed by GeoSpectra Corporation, is capable of automatically extracting elevation data for every pixel in the overlapped region of two digitized stereo images, while keeping this high-resolution elevation data in perfect co-registration with the image data from one of the two stereo images. In the case of SPOT data stereo images are originally collected as digital images. Stereo aerial or space photos are digitized by scanning them with a digital scanner, of which many types are available commercially, such as the line of scanners produced by Optronics, a subsidiary of Intergraph. What goes into ATOM are two digitized stereo images (the source images) and about a half-dozen ground control points for which *x*, *y*, and *z* locations are known. What comes out are two computer files, one a high-resolution DEM (with a measured elevation for every pixel, except for a few that must be interpolated) and the other a digital orthophoto (a digital image from which parallax has been removed), which perfectly overlay one another because they were both produced from the same source images. The resulting DEM and digital orthophoto have the same spatial resolution as the digitized stereo source images.

For instance, 1:4,000-scale photos that are scanned with a 25-micrometre spot size (1,000 dots per inch) yield an overlapped region (an area on the ground of about 3,000 ft by 1,500 ft) that contains about 41 million pixels per photo, with each pixel covering about 4 inches square on the ground. ATOM can extract an elevation for each of these 4-inch pixels with a root-mean-square error in elevation of about 5 or 6 inches (Vincent *et al.*, 1987) in about half a work day on a work station computer. Never before were such high-resolution DEM available, nor were they so perfectly overlayed with image data, primarily because processing times previously were far too slow to make high-resolution DEM practical and because digital orthophotos were commonly produced from an image and a DEM that came from different source images.

The resulting high-resolution DEM can be employed in several useful ways. First, it can be used as input to a surface runoff model for determining where rainfall or flood water runoff will transport surface waste fluids and gases from different parts of the landfill to outlying areas and where depressions in the landfill cover may collect and concentrate runoff (Vincent *et al.*, 1994). Second, the total volume of water that can be stored in those depressions can be calculated (Vincent *et al.*, 1994), which is the same as the volume of soil required to fill in the depressions. Third, by extraction of elevations from stereo images taken at two different times, it would be possible to calculate very accurately what volume change has been caused by subsidence or additional filling between the two data collection times over the solid waste landfill. Fourth, numerous computer programs are available which can transform the DEM and digital orthophoto into simulated perspective views, or even into a "fly-around," of an existing solid waste landfill or a potential new landfill site. Perspective views and "fly-arounds" could be useful in court proceedings or for briefing local and state officials about the true appearance of a landfill or other waste site.

Mapping Chemical Composition Indicators

The applications of multispectral remote sensing for exploration geology offer many opportunities to engineering geology for mapping exposed soils and geochemical alterations caused by elevated concentrations of wastes interacting with surface soils. First, clays have been distinguished (e.g., Abrams *et al.*, 1977) with multispectral scanners, and clays are an important constituent of solid waste liners and caps. It would be possible, for instance, to use multispectral data from the 1.55 to 1.75-micrometre and the 2.08- to 2.35-micrometre region (bands 5 and 7, respectively, on Landsat Thematic Mapper satellite, which are duplicated in the Daedalus Enterprise's DS-1268 Airborne Thematic Mapper) to produce a spectral ratio image (Vincent *et al.*, 1984b) that shows clays in sharp contrast to other materials (except, perhaps, for carbonates and sulfates). It is likely that soil consisting of at least one-third clay could be recognized as clay-rich by having a band 5 to band 7 spectral ratio above an emperically determined threshold ratio value. Large percentages of landfill surface area covered by recognized clay-rich soil would indicate effective cover of the landfill by a clay cap.

Ferric oxides and hydroxides (such as hematite, limonite, and goethite) can also be mapped with multispectral scanners (e.g., Rowan *et al.*, 1983; Vincent, 1983), especially with spectral ratios of visible red to visible green bands (like the 0.6- to 0.7- and 0.5- to 0.6-micrometre wavelength coverage, respectively, of Landsat MSS bands 5 and 4), and they are often found where ground water has discharged through gravel and sand. Under some circumstances the oxidation-reduction phenomena associated with contaminant leakage into ground water will deposit iron oxides in a manner similar to ferric and ferrous oxide exposures related to geochemical cells used for mineral exploration. When this happens, it is often a by-product of oxidation-reduction phenomena, rather than the compound of principal interest itself, that produces a tell-tale sign that such chemical reactions have occurred. This is an indirect approach similar to that used by exploration geologists, who map clay and sulfate exposures when looking for gold deposits (Abrams *et al.*, 1977) that contain gold in far too small a quantity to detect directly.

It is also likely that surface exposures of exotic compounds with unique spectral features, such as cyanide and chromium compounds, will result from some leachate or contaminant interactions with surface soils and water. An example would be "blue soil," a cyanide compound that this author has observed to be associated with coal gas production wastes. Many of these exotic compounds will be more easily observed in the reflective infrared and thermal infrared wavelength regions than in the visible region detectable in

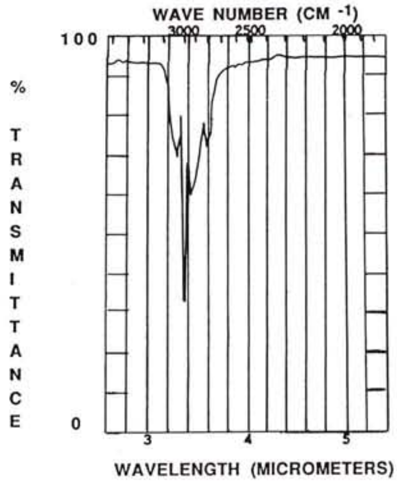

Figure 1. Percent transmittance spectrum of methane (gas cell of 10 cm length at 190 mm of mercury pressure) in the 3.0 to 5.0 micrometre thermal infrared wavelength region (Sadtler Research Laboratories, Inc., 1976).

the human eye. Just as in mineral exploration, the properly filtered multispectral sensor can map some chemical composition differences that a human can walk across, but overlook. Multispectral remote sensing is literally a matter of looking at the Earth in a new light.

Remote sensing data can also be useful for monitoring solid waste landfills and toxic waste sites by mapping vegetative stress in the vicinity of waste leakage. Herman *et al.* (1994) reports in this issue on the extension of a GeoSpectra study of a waste site in Michigan where escaping toxic liquids has actually killed trees that were part of a nearby swamp. Vegetation stress that ranges from chlorosis to death can be mapped from multispectral data that are sensitive to relative amounts of chlorophyll in vegetation.

It is not wise to restrict multispectral efforts to the mapping of solids or liquids associated with landfills, because gases can be a problem, too. When solid waste decomposes, gases are given off as products of decomposition, with the most prevalent one being methane. Municipal solid waste landfill emissions consist primarily of methane and carbon dioxide, with trace amounts of more than 100 different non-methane organic compounds (NMOC's) such as ethane, toluene, and benzene (U.S. Environmental Protection Agency, 1991). Methane in landfills acts as a stripping (or transport) gas, moving the NMOC's present in the landfill through the landfill to the atmosphere. These landfill gas emissions have adverse health and welfare effects resulting from NMOC's, some of which are known or suspected carcinogens or cause other noncancer health effects (U.S. Environmental Protection Agency, 1991). NMOC's also contribute to ozone formation at low altitudes, which can cause lung irritations. Besides adverse health effects, the NMOC's in landfill gas emissions can cause odor nuisances, and methane itself has caused explosions and fires resulting from its migration to on- and off-site structures or enclosures (U.S. Environmental Protection Agency, 1991).

It should be possible to use remote sensing methods to image differences in the chemical composition of gases, if the instruments used are properly filtered and the gas concentrations are sufficiently high. Figure 1 shows a spectral transmittance spectrum (Sadtler Research Laboratories, 1976) of a 10-cm-length gas cell of methane gas at a pressure of 190 mm of mercury in the 3.0 to 5.0-micrometre wavelength region, within an atmospheric window. The 3.1 to 3.9-micrometre absorption band could be exploited by a down-looking, two-channel infrared imaging device that compared the radiance in this region to radiance in the 4.3 to 5.0-micrometre region by means of spectral ratio imaging. Such imaging would permit easier location of methane plume exit sites than would be afforded by non-imaging detection methods and would help separate landfill methane from other sources of methane, such as natural gas wells or swamps, but virtue of the plume location. Because methane is the most common landfill gas, it is the primary indicator of where landfill gas is escaping to the atmosphere. It is also possible that groundwater contamination from the landfill could be traced by the imaging of methane escape from contaminated near-surface aquifers, because methane is dissolved in leachate-contaminated springs. Existing multispectral sensors might also be modified to image other landfill gases with thermal infrared absorption bands, such as ozone, ethane, toluene, and benzene, from airborne (aircraft or tethered balloon) multispectral platforms.

Experimentation is needed to determine how much concentration of a landfill gas is required before it can be imaged. However, if methane, the most prevalent landfill gas, can be imaged, an important new tool will be available for verifying the presence or absence of landfill gases.

Summary and Conclusions

Geological remote sensing, which has been useful to exploration geologists for over two decades, can be equally helpful to engineering and environmental geologists for landfill monitoring in two technically different ways. One is the use of high-resolution digital photogrammetry to perform detailed topographic mapping, and the other is the use of multispectral image data to map chemical compositional differences on and around a landfill.

Detailed topographic mapping by high-resolution (every-pixel elevation extraction) digital photogrammetric methods can be used to yield high resolution elevation data sets that have at least four applications. High-resolution DEM can first be used as input to surface water run-off models to predict where contamination from solid waste and toxic landfills is most likely to occur and where depressions on the landfill may collect and concentrate runoff. Second, the same DEM can be used to calculate total volume of depressions in the landfill cover, which is the same as the volume of soil required to fill in those depressions. Third, DEM produced from stereo images taken at two different times can be used as input to cut-and-fill estimate software for the accurate calculation of volumetric changes in landfills due to continued in-filling or to later subsidence. Fourth, high-resolution DEM and digital orthophotos can be used with visible simulation software to produce simulated perspective views of the landfill from any user-selected position of the observer, with the same resolution as the source stereo photos.

Image processing of multispectral data can be used to map chemical composition differences in both solids and gases. Mappable solids of significance to landfills include clays in liners and caps, ferric and ferrous oxides that are byproducts of low-temperature geochemical "cells" caused by contaminants in wastes, and possibly some unique compounds (such as cyanides and chromates) that indicate the presence of specific wastes. Mappable vegetation stress, such as chlorosis, can be indirect indicators of liquid and gaseous waste leaks. Multispectral imaging of gases is probably possible with properly filtered multispectral imaging sensors, especially for methane, which is the most common gas escaping from landfills.

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