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DYNAMIC PROPERTIES OF MUNICIPAL SOLID WASTE IN A BIOREACTOR CELL AT ORCHARD HILLS LANDFILL, ILLINOIS, USA

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ABSTRACT

Bioreactor landfills enhance municipal solid waste (MSW) degradation through recirculation of leachate inside the waste mass. In-situ monitoring of moisture distribution and changes in mechanical properties (stiffness) of MSW is needed to optimize the safe and effective operation of bioreactor landfills. Geophysical methods, such as electrical resistivity tomography, are shown to have great potential to monitor the moisture distribution. This study is aimed at investigating seismic surveys to characterize changes in dynamic properties (e.g., shear wave velocity and Poisson's ratio) of MSW to infer the extent of degradation and provide the input needed for seismic stability evaluation. To achieve this goal, a seismic survey was performed in a bioreactor cell, within a MSW landfill (Orchard Hills Landfill, 15 km south of Rockford, Illinois, USA), to image seismic velocity structure and the Poisson's ratio of MSW. Seismic data were collected through the cell using "fan shot" direct P- (compressional) and S- (shear) wave surveys. The fan shot surveys employed a sledgehammer source on one side of the landfill and geophones on the opposite side, thus exploiting the landfill's topography and geometry to image MSW to a depth of at least 10 m. P- and S- wave velocity tomographic models from these direct-wave (through-pile) raypaths indicated a dramatic velocity increase below 5 m depth, perhaps indicating consolidation and compaction of MSW. Shear-wave velocity ranged from 150 m/s to 170 m/s. The P/S ratio ranged from 1.8 to 3.7, with an average of about 2.7 and Poisson ratios ranged from 0.29 to 0.46, with an average value of 0.42 (standard deviation 0.024). Below 4-5 m depth, compressional-wave seismic refraction profiling also indicates a subtle change in velocity. Repeated electromagnetic (EM) conductivity measurements with maximum sensitivity at 10 m depth show conductivity increased in the MSW approximately 20-40 mS/m over a 14 month period. Conditions appear to be more uniform at depth as well, after this 14-month interval. Overall, this study showed that seismic and EM surveys have potential to monitor spatial and temporal variation of dynamic properties of MSW and infer the extent of degradation.

INTRODUCTION

Currently, "bioreactor" landfills are being designed on the premise that leachate recirculation provides an enhanced environment for faster anaerobic degradation of municipal solid waste (MSW), shorter duration of post-closure management and more rapid land reuse (Sharma and Reddy, 2004). Different methods used at bioreactor landfills include spray irrigation, infiltration ponds, subsurface trenches or wells, drainage blankets, and direct application to the working face (Reddy, 2006). One of the greatest challenges is to monitor moisture distribution in a landfill during leachate recirculation, and also monitor the effects of degradation on the strength properties of MSW. The non-uniform moisture distribution or excessive leachate injection and reduction in strength of MSW due to biodegradation can endanger the

stability of the bioreactor landfill; hence both require careful monitoring (Reddy, 2006).

Various field techniques are used to monitor the leachate distribution in the landfill. These methods generally require installation of sensors (e.g. time-domain reflectance [TDR] cables) at discrete locations and depths to monitor changes in moisture content. Unfortunately, such techniques are expensive and only provide the information at a few specific locations. As the moisture increases, the organic fraction of MSW degrades and the strength (stiffness) of the MSW changes. Currently, the monitoring of strength (stiffness) requires drilling, sampling and testing or in-situ strength testing (Reddy et al., 2009a,b). Again, such testing is expensive and does not provide information on spatial variations in the strength of MSW.

Recently, various geophysical techniques have been investigated as a means to non-invasively monitor moisture distribution in landfills, particularly bioreactor landfills (Carpenter et al., 2008; Carpenter and Reddy, 2011). Most MSW leachate is electrically conductive, so typically electrical geophysical methods are used to map moisture distribution. Resistivity imaging (ERT), frequency-domain electromagnetics (EM), ground-penetrating radar (GPR), and well logging (electrical resistivity) have also been used to monitor moisture distribution (Carpenter et al., 2008). Grellier et al. (2003, 2005, 2006, 2007) mapped temporal resistivity changes within bioreactor landfills following leachate injection. Zones of decreased resistivity appeared near the leachate injection points in these landfills. Though some success has been shown using ERT to monitor moisture distribution, the studies on changes in mechanical properties of MSW due to degradation of organic fraction are scarce.

Seismic reflection and refraction methods have great potential to monitor spatial and temporal changes in stiffness of the MSW (Zekkos, 2011). These methods rarely been utilized in landfill investigations due to high absorption of seismic wave energy and velocity inversions within the MSW (Carpenter et al., 1991). In this study, seismic surveys were conducted using direct P- and S-waves passing through the MSW. Complementary electromagnetic surveys were performed in the same location as seismic surveys to assess the extent of MSW affected by the leachate recirculation. These surveys provided the in-situ Poisson's ratio and conductivity of MSW in a bioreactor landfill cell subjected to leachate recirculation.

PROJECT SITE

The seismic and electromagnetic surveys were conducted at a MSW landfill, known as the Orchard Hills Landfill, located approximately 14 km south of Rockford, IL, along and immediately west of State Highway 251. Data were collected at a location where MSW is undergoing enhanced decomposition through leachate recirculation.

MSW was placed in the bioreactor cell from September 2004 to October 2005 at the rate of about 3200 tons per day. The MSW consisted of approximately 70 % municipal solid waste, 17 % construction and demolition debris, 11% soils and 2% special and other waste. More details on the MSW composition are presented by Grellier et al. (2007b).

Leachate recirculation was initiated in the cell during filling by spraying on the working face. In addition, horizontal leachate recirculation lines were installed in the cell during filling; these consisted of 15 cm diameter perforated HDPE pipes in gravel-filled trenches spaced 15-20 m between centers. Leachate was recirculated intermittently through the LRLs, depending on the availability of leachate (Grellier et al. 2006, 2007a).

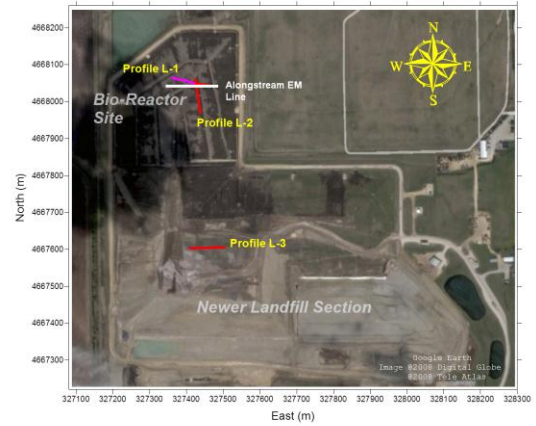


Fig. 1. Site map showing seismic and EM profile locations at the Orchard Hills Landfill. Lines L-2 and L-3 are not discussed in this paper.

SEISMIC SURVEYS

Background

Seismic waves propagate at a rate governed by material properties such as rigidity (shear strength), compressibility (bulk modulus) and density. Seismic wave propagation is governed by the rigidity, compressibility, and density of the propagating medium. Equations (1) and (2) describe the relationships between compressional-wave (V_p) and shear-wave (V_s) velocity and these material parameters for a linear elastic isotropic substance:

$$V_p = \{(K + 4/3G)/\rho\}^{1/2} \quad (1)$$

$$V_s = \{G/\rho\}^{1/2} \quad (2)$$

where K is the bulk modulus (incompressibility), G is the rigidity modulus (shear modulus) and ρ the density.

Measurement of seismic wave velocity, along with information on MSW density, allows investigation of these material properties without having to conduct excavations or emplace borings or wells. Of particular interest here is whether the seismic character and elastic properties of MSW undergoing leachate circulation differs significantly from MSW impounded in a conventional manner. Waste decomposition should be accelerated in the recirculation cell, thus changing its elastic properties and seismic velocity.

Even without density information, a comparison of V_p and V_s demonstrate, to a first approximation, how MSW compressibility and shear-strength varies in space. Also, the V_p/V_s ratio can be converted to a Poisson's ratio. Given an independent measure of density, estimates of the bulk and

rigidity moduli can be determined from V_p and V_s data.

Seismic Surveys

Seismic surveys were conducted during November, 2007, and consisted of direct (“through-pile”) measurements of compressional (P) and horizontally-polarized shear (SH) waves. Profile L-1 tests the ability of tomographic methods to image the interior of the bioreactor cell.

Direct-wave measurements were only collected along Profile L-1 located on the northeast corner of the leachate-recirculation bioreactor cell, as shown in Figure 1. Two additional surveys employing different methods, lines L-2 and L-3, were also collected, but are not discussed here. Survey geometry consisted of a 24-channel geophone string located on the east-facing slope (about midway up the cell) with shot points located on the landfill top and the northwest-facing side. Receivers were spaced at 2 m intervals and shots were spaced 10 m apart. The shot-receiver geometries and resulting (approximate) raypaths, are shown in Figure 2. These raypaths suggest a maximum depth of penetration of about 10 m. The P-wave surveys utilized a 7.3 kg sledgehammer vertically hitting a metal plate, with vertical receivers. SH-wave surveys used horizontally oriented receivers (positive polarity towards the north) and both northward and southward directed impacts on a steel plate (~45° to horizontal) to generate polarized SH waves.

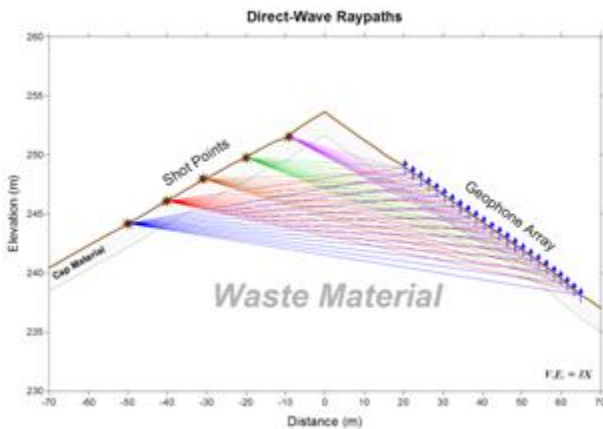


Fig. 2. Cross-section of the bioreactor cell showing approximate direct-wave geometry and coverage.

These data were recorded without analog filters using a sampling interval of 0.25 milliseconds (ms), and 512 ms record length (2048 samples). Signal enhancement employed stacked shots (multiple repeat impacts per shot-point), with a range of 3-25 stacks (higher stack counts were required at further distances from the receiver string and were required to obtain clear SH waves).

The processing sequence for the direct-wave data consisted of

picking first arrival times from receiver records (traces) for each shot, assigning the array-geometry to the first arrival data, and inverting the first-arrival information for velocity and depth using a tomographic inversion algorithm.

Processing the SH data required collating the data and plotting the alternate polarity signals side-by-side on a trace-by-trace basis (resulting in 48-channels per shot location, 24-channels for each polarity). The first-arrival of the SH wave was determined based on changes in polarity and amplitude for the polarity-trace pairs. Figures 3 and 4 show examples of P- and SH-wave data.

Profile 1: Example Direct P-Wave Records

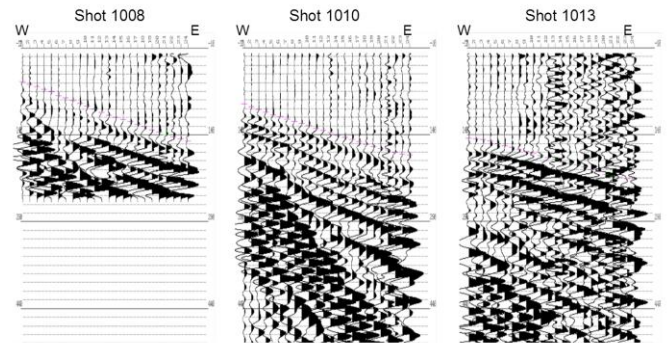


Fig. 3. Examples of P-wave direct-wave data.

Profile 1: Example Direct Sh-Wave Records

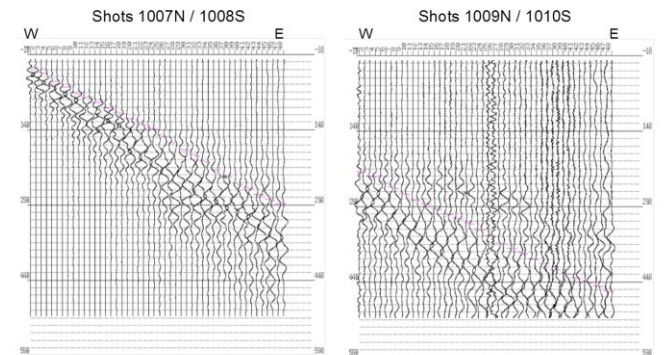


Fig. 4. Examples of SH-wave data.

The GeoTomCG software package (GeoTom LLC, 2008) was used to perform the tomographic inversion. GeoTomCG uses the simultaneous iterative reconstruction technique, or SIRT (Peterson et al., 1985; Tweeton et al., 1992) to perform the inversion. SIRT calculations modify an initial velocity model by iterating three steps: forward computation of model travel times, calculation of residuals, and application of velocity corrections, until the desired root-mean-square (RMS) error in residuals is achieved.

Seismic Survey Results

First-arrivals associated with the P-wave are clearly discernable across the shot-records shown in Figure 3, and surveying using repeat shots (stacking) was able to overcome non-static noise associated with the movement of heavy trucks and equipment for both P- and SH-wave records. SH-wave first-arrival times are interpreted based on both an amplitude increase and a marked change in polarity on adjacent traces. The SH-wave data are also clearly visible across the receiver spread, as shown in Figure 4.

The tomographic velocity-model constructed from the P-wave arrival times is shown in Figure 5. Cells in the final tomographic model range in P-wave velocity from 350 to 643 m/s, with an average value of 484 m/s (standard deviation 53 m/s). The velocity model suggests 2 separate regions, a lower velocity (380-460 m/s) upper zone 3-to-6 m in thickness, and a deeper region of dominantly higher velocity (505-560 m/s). The interface between these regions exhibits a pronounced eastward dip, but this dip is possibly a model artifact due to the limited shot-receiver coverage.

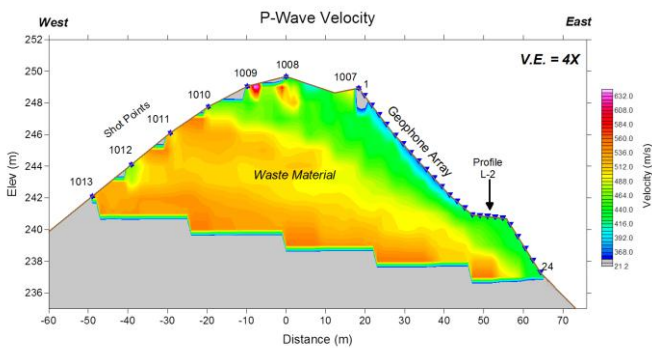


Fig. 5. P-wave velocity tomogram of the bioreactor cell.

Figure 6 is the velocity model constructed from the SH-wave arrival data. SH-wave velocities in the model range from 90 to 210 m/s, averaging 171 m/s (standard deviation 9 m/s). Haker et al (1997) report similar shear-velocities for landfills in Australia and the U.S. An approximately 2-to-3 m thick zone of relatively higher SH-velocity dips eastward from the locus of shot pairs 1108N/1109S and 1110N/1111S. It is not clear at this stage whether this is a modeling artifact, a result of incorrect SH arrival picks, or an actual feature. This mimics the eastward dipping structure observed on the P-velocity plot (Figure 5).

The P to SH velocity ratio and estimated Poisson ratio (or Poisson number) is shown in Figure 7, with the resulting structure dominated by the two velocity regions modeled from the P- and SH-wave data. Valid ratios are limited to regions where both the P and SH velocity models produced reliable data. The V_p/V_s ratio ranges from 1.8 to 3.7, averaging 2.7. This gives a Poisson ratio range of 0.29- 0.46, averaging 0.42 (standard deviation 0.024).

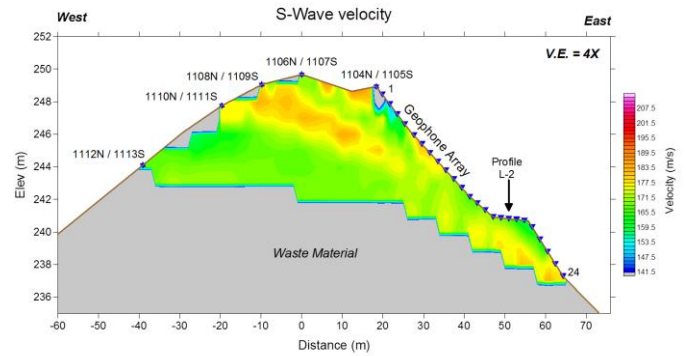


Fig. 6. SH-wave velocity tomogram of the bioreactor landfill cell.

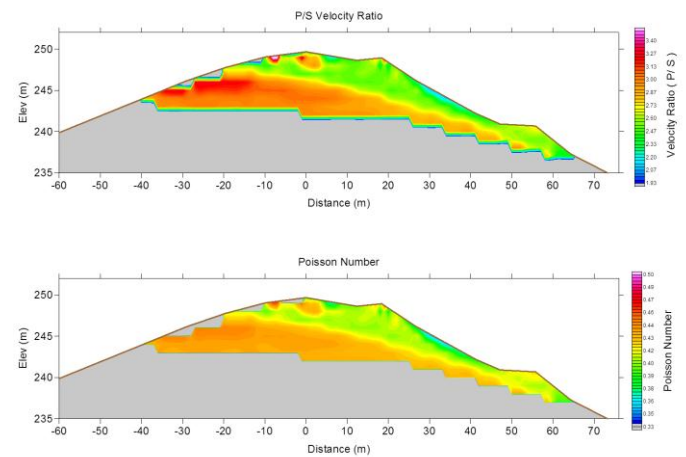


Fig. 7. VP/VSH and the Poisson's ratio (Poisson number) for the bioreactor cell.

ELECTRICAL CONDUCTIVITY SURVEYS

Figures 8 and 9 show changes over a one-year period along a profile directly over a leachate recirculation line (LRL) that is essentially coincident with seismic line L-1. The profile is here referred to as the "Alongstream Line," as shown in Figure 1. Apparent conductivity data were recorded with the Geonics EM34 conductivity meter at dipole spacings of 10 m and 20 m, respectively, which correspond to maximum response depths of 5 m and 10 m, respectively, in the vertical dipole (VD) loop orientation. Maximum response is near the surface for the horizontal dipole (HD) loop orientation. Higher apparent conductivities are recorded in 2007 in the VD orientation. In the case of the 20 m (deeper) dipole data, the VD apparent conductivities are generally 20-40 mS/m higher than those measured in 2006. The horizontal dipole (HD) conductivities are either unchanged or about 10-20 mS/m higher than those collected in 2006. The greater increase in VD conductivity, however, suggests the deeper MSW is more conductive, perhaps as a result of the repeated leachate injections (Carpenter et al., 2008).

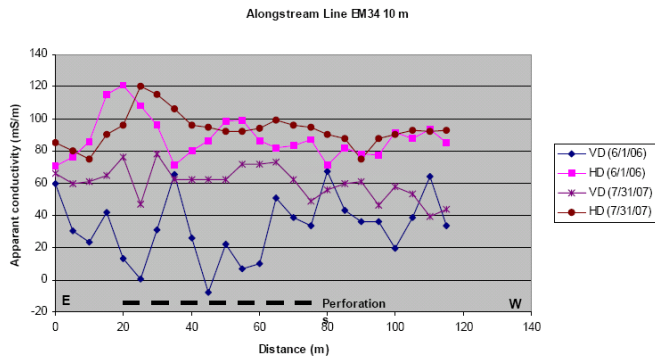


Fig. 8. Long-term apparent conductivity changes over a LRL in the bioreactor cell, as measured with an EM34 at a loop spacing (dipole spacing) of 10 m.

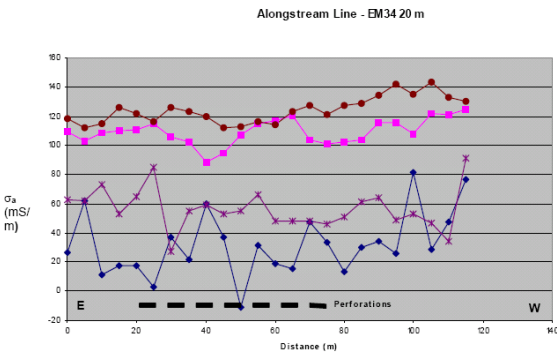


Fig. 9. Long-term apparent conductivity changes over a LRL in the bioreactor cell, as measured with an EM34 at a loop spacing (dipole spacing) of 20 m.

Surveys made during the summer of 2007, about 14 months after an earlier conductivity survey, suggest near-surface conductivity has basically remained the same, whereas conductivity of the deeper MSW has increased. The higher conductivity of the lower MSW over time suggests permeation by leachate or changes in MSW/leachate quality due to MSW biodegradation (higher conductivity due to higher total-dissolved-solids). Apparent conductivity values obtained in 2007 also showed much less fluctuation along the profile lines than those obtained during 2006. This may reflect more uniform conditions evolving deeper within the bioreactor cell.

SUMMARY

This study included performing various seismic surveys to compute the Poisson's ratio of MSW in a bioreactor landfill cell. It provided dynamic (or low-strain) dynamic properties of MSW which can be used for seismic stability analysis of bioreactor landfills. The seismic surveys also have great potential to monitor spatial and temporal variations in physical characteristics of MSW in bioreactor landfills.

The P to SH velocity ratio and estimated Poisson values are shown in Figure 7, with the resulting structure dominated by

the two velocity regions modeled from the P-wave data. Interestingly, the Poisson's ratio suggests decreasing rigidity with depth, primarily reflecting the decrease in shear-wave velocity with depth.

Though this study provided very useful information on the effects of leachate recirculation on shear modulus and Poisson's ratio of MSW, additional work is needed on several fronts. For example, seismic surveys need to characterize the MSW of significantly different ages. It is also recommended that an independent and auxiliary measure of material density and velocity be obtained to verify the seismic survey data. Additional direct-wave measurements can be acquired by placing the geophones and shot-points along the entire height of the landfill side with a denser spacing than the nominal 10 m spacing used.

Electromagnetic conductivity measurements indicate significant increases in MSW conductivity with depth, as well as more uniformity deeper in the MSW over time, perhaps reflecting MSW decomposition. Additional repeated EM measurements over different lines would help to verify these observations.

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