Review of state of the art methods for measuring water in Landfills

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Flowchart of the presentation

- Introduction
- Background
- Water Balance Approach
- Liquid Measurement Methods in Solid Waste
- Summary
- Cost Analysis
- Discussion
- Conclusions
Introduction

- Moisture control - the most critical parameter for bioreactor operation.
  - Insufficient liquid limits biodegradation rate
  - Excess liquid results in side seeps, poor gas collection and geotechnical instability.
  - Sensors to assess moisture distribution within the landfill, controlled liquid addition

- Review of moisture sensor devices that have been tested in the field and hold promise for monitoring moisture within landfills.
Background

Liquid in bioreactor landfills
- While optimum moisture content for degradation is above 65%, typically it is between 15 and 40%.
- liquid and gas transport
- Geotechnical stability due to increase in unit weight

Sources of liquid
- Non-indigenous liquid required
- Fresh water (expensive); storm water; ground water; industrial wastewater;
- Additional gas potential for anaerobic bioreactors by using industrial wastewater
Background

Requirements of a liquid injection systems
- Distribute uniformly
- Minimal increase in pore water pressure
- Be easy and economical to install
- Types (horizontal trenches; high conductivity material blanket; vertical injection wells)

Type of liquid measurement
- Moisture content
- Water saturation and volumetric water content
Background

- Relationship between moisture content, water saturation and volumetric water content

\[ \theta_w = n \times S_w \]

\[ M_c = \frac{S_w \times n \times P_w}{P_{wb}} \]

Where

- \( \theta_w \) = volumetric water content;
- \( S_w \) = water saturation
- \( n \) = total porosity of refuse sample;
- \( M_c \) = moisture content;
- \( S_w \) = water saturation;
- \( P_w \) = density of water;
- \( P_{wb} \) = wet bulk density of waste
Moisture Content Calculation

\[
PMC = \left( \frac{L_o \times M}{M} \right) + P + LA - LCH \times 100
\]

- \( L_o \) = Moisture entering with waste mass (kg/kg of Waste Mass)
- \( M \) = Total waste mass in bioreactor cell (kg)
- \( P \) = Total precipitation infiltrating in bioreactor (kg)
- \( LA \) = Liquids added to waste mass including recirculation (kg)
- \( LCH \) = Total Leachate collected (kg)

Source: EPA-456/R-03-007
Moisture Content Calculation

- A typical value of $L_o$ in most MSW landfills in the United States is about 25% on wet basis (wt of water/(wt of water + dry solids))
- $M$: Waste mass is calculated from waste acceptance and waste placement data
- $P$: Total precipitation infiltrating in the cell can be calculated using a rigorous approach (HELP or EPA spreadsheet - Ifmassbalbxl.xls)
Moisture Content Calculation

- **LA**: Liquids added is the sum of leachate recirculated through Horizontal/Vertical wells, and/or horizontal trenches, and/or liquids introduced at the top via truck.

- **LCH**: Total amount of leachate as indicated by flow meter readings, and leachate, if any, collected and directly sent for treatment.
WS1.0: A Numerical Tool for Calculation of Moisture Balance in Landfill

- A FORTRAN program to calculate moisture balance for bioreactor landfill.
- Numerical tool that calculates liquids addition from different sources.
- The actual leachate generation of leachate may differ from the model results given the preferential flow of liquids.
- Based on EPA Moisture Content Calculation (EPA-456/R-03-007)
WS1.0 Input Data – Landfill Description

- Aerial spread (acres)
- One longitudinal dimension and the height
- Assumes a side slope of one vertical to two parts horizontal in order to calculate the top area of landfill.
- Number of lifts
- Total quantity of solid waste on as received basis (or specific weight)
- Cover is assumed to be ten percent of solid waste
- Initial moisture content value on wet weight basis and the moisture content at field capacity
WS1.0 Input Parameter - Time

- Time in years for running the simulation
- Time in years for the landfill to complete the waste placement
WS1.0 Input Parameter – Moisture Addition

- Volume of moisture addition due to precipitation infiltration
- Volume of liquids hauled to the top of the open landfill,
- Volume of liquids injected using vertical wells.
Method described by Jain et al. (2006) is the basis for calculating the maximum injection capacity of a vertical well.

- 50-ft spacing is assumed
- The model checks that the maximum injection capacity of a vertical well is not exceeded.
- The maximum head is kept such that it does not exceed a level of five feet from the top of landfill.
WS 1.0 Input Parameter – Liquid Injection

- Number of wells,
- Depth of well
- Screen length,
- Diameter of well,
- Total flow rate for all wells together.
- Start and stop time

In its present form the model is unable to handle wells of different depths and intermittent injection of liquids.
Output

- Indication of operation outside flow capacity of wells
- Average MC within each lift as a function of time
- Liquids balance as a function of time
  - Leachate production once field capacity is exceeded
  - Contribution from infiltrating precipitation
  - Contribution from injection wells
  - Net change in liquid content
Liquid measurement methods

- Neutron probe
- Electrical resistance sensors (ERS)
- Electromagnetic techniques
  - Time domain reflectometry (TDR)
  - Time domain transmissivity (TDT)
- Electrical resistivity tomography (ERT)
- Partitioning gas tracers test (PGTT)
- Fiber optic sensors
Neutron probe

Principle
- Emitted neutrons thermalized by hydrogen atoms provided by water molecules
- Calibration curve between volumetric water content and thermalized neutrons

Limitations
- Hydrogen atoms may originate from wood and plastic materials
- Neutrons may also be captured by elements like iron, potassium and chloride.
- Can not be used to measure absolute values but may assess changes in moisture conditions.
Neutron probe

- Field applications
  - Requires installation of aluminum access tubes in the field which ultimately requires a relatively large hole
  - Regulatory safety standards may be hindrance
  - Storage of equipment and disposal of probe
Electrical resistance sensors

**Principle**
- Relates electrical resistance to a current passing through the sensor to the matric potential of surrounding media.
- Composed of gypsum, fiberglass, nylon or PVC tubes
- Readings are affected by temperature and conductivity

\[
C_{25} = \frac{C_m}{1 + 0.02(t_m - 25)}
\]

Where
- \(C_{25}\) = corrected conductivity value adjusted to 25°C
- \(C_m\) = actual conductivity measured
- \(t_m\) = water temperature at time of \(C_m\) measurement in °C
Electrical resistance sensors

Limitations

- Cannot work reliably above the entry air pressure or below the field capacity
- Other sources of error include sensor hysteresis, dependence on waste porosity and density, poor contact with the media, and deterioration of sensor over time

Yolo County Sensor
Resistivity Probe For Moisture Measurements
### Field applications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>New River Regional Landfill</th>
<th>Anaerobic and Aerobic Test Cells at Yolo County, CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between sensors (m)</td>
<td>15</td>
<td>3-5 (horizontally), 15-20 (vertically)</td>
</tr>
<tr>
<td>Number of sensors</td>
<td>134</td>
<td>161</td>
</tr>
<tr>
<td>Approximate measurement volume (m³)</td>
<td>914,400</td>
<td>410,884</td>
</tr>
<tr>
<td>Data collection mode</td>
<td>Automatic, every 12 hours</td>
<td>Automatic, every 6 minutes</td>
</tr>
<tr>
<td>Comparison of $M_c$ with gravimetric measurements</td>
<td>MTG Sensors $M_c=0.48$; Gravimetric $M_c=0.28$</td>
<td>See Figure</td>
</tr>
<tr>
<td>Duration of data collection period (years)</td>
<td>4</td>
<td>3 to 4 (depending on landfill cell)</td>
</tr>
<tr>
<td>Sensor costs</td>
<td>US$10,000</td>
<td>US$2,400</td>
</tr>
<tr>
<td>Installation equipment costs</td>
<td>US$30,000</td>
<td>US$48,000</td>
</tr>
<tr>
<td>Installation labor costs</td>
<td>US$10,000</td>
<td>US$11,000</td>
</tr>
</tbody>
</table>
Electrical resistance sensors

- Relationship between sensor resistance readings and $M_c$ is shown in Fig. 1 for three specific conductivity values 4, 8, and 16 mS/cm at room temperature.

Fig. 1 Calibration curve for electrical resistance sensors developed at the University of Central Florida for varying moisture conductivities.
Electrical resistance sensors

- 134 sensors installed at New River regional landfill (NRRL)
- 161 sensors installed at Yolo county
- Distances shown are between sensors and refuse samples.

Results from Yolo County compared with gravimetric measurements

Fig. 2
Electromagnetic Techniques

Principle

- Relates the time of travel of EM waves to the dielectric constant of the waste which in turn can be correlated to $\theta_w$.
- While TDR looks at time of travel of waves reflected back to the pulse generator, TDT measures the total time of travel through media and connecting cables.
- Affected by changes in liquid electrical conductivity and temperature.
TDR Device Used in Florida
Electromagnetic Techniques

Field applications

- used at NRRL site, permeable blanket test in Michigan (Khire and Haydar, 2005) and San Sophie landfill in Quebec, Canada
- 25% failed after two years at NRRL
- Reported the passage of leachate front, but showed moisture contents above actual levels
Electrical resistivity tomography

- **Principle**
  - Based on measurement of the potential distribution arising when electrical current is injected into the underground via galvanic or capacitive contact.
  - Resistivity variations that occur during leachate injection trials indicate changes in the waste moisture content.
# Field application of ERT

<table>
<thead>
<tr>
<th>Parameters</th>
<th>La Vergne bioreactor (ONYX), Vendée (France)</th>
<th>Sydom bioreactor, Jura (France)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection system</td>
<td>Vertical wells</td>
<td>Horizontal trenches</td>
</tr>
<tr>
<td>Distance between injection wells/trenches (m)</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>Leachate injection flow (m³ h⁻¹)</td>
<td>5 to 30</td>
<td>5 to 10</td>
</tr>
<tr>
<td>Number of electrical lines</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Number of electrodes</td>
<td>176</td>
<td>48</td>
</tr>
<tr>
<td>Distance between electrodes along electrical line (m)</td>
<td>1</td>
<td>2.25</td>
</tr>
<tr>
<td>Interval between ERT on each electrical line</td>
<td>large time: ~2 months; short time (during leachate injection): 30 minutes</td>
<td>large time: 1 week; short time (during leachate injection): 15 minutes</td>
</tr>
<tr>
<td>Number of ERT</td>
<td>~700</td>
<td>~500</td>
</tr>
<tr>
<td>Number of measurements per ERT</td>
<td>360 to 1374</td>
<td>84</td>
</tr>
<tr>
<td>Range of volumetric water content deduced from ERT (%)</td>
<td>15 to 25</td>
<td>not available because of insufficient temperature sensors</td>
</tr>
<tr>
<td>Man hours per ERT (data processing, report, not including field measurements)</td>
<td>~1</td>
<td>~1</td>
</tr>
<tr>
<td>Man hours to install all electrodes and electrical lines</td>
<td>56</td>
<td>24</td>
</tr>
<tr>
<td>Capital costs for one electrical line embedded in the waste</td>
<td>US$3,750</td>
<td>US$2,500</td>
</tr>
</tbody>
</table>
Variations of electrical resistivity during an injection on the middle horizontal trench at the Sydom (Jura, France) test site during a short-time study. Gray-scale images show measured electrical resistivity, while color images indicate changes in resistivity during and after leachate injection. Axis scales are in meters.
Partitioning Gas tracers Technique (PGTT)

**Principle**

- The partitioning gas tracer test (PGTT) involves the injection and extraction of two tracers under steady gas flow within solid waste.
- Because the tracers are separated “chromatographically” in time due to the influence of water, the difference in mean arrival times is a measure of the fraction of the pore space occupied by water, i.e. $S_w$.
- Key thermodynamic parameter is Henry’s law constant, $K_H$ which in turn depends on temperature and dissolved solutes.
Instrumentation shed where all field analyses were conducted (Yolo County). Anaerobic bioreactor test cell is in background.

Photos courtesy of Paul Imhoff
Gas cylinders containing helium and difluoromethane for injection in tracer tests.
Adjustment of tracer gas flows from gas cylinders outside of shed.
Injection of tracer gases into desire tubes that terminate at different locations in bioreactor test cells.
Collection of tracer gases from the aerobic bioreactor in horizontal gas collection well.
Header pipe carrying landfill gas (and tracers) from landfill back to blower. Samples extracted from piping and directed into instrument shed.
A subset of samples analyzed in the field with field-portable gas chromatograph.
A subset of samples transported back to the lab to “check” field analysis of samples.
Field applications of PGTT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aerobic Bioreactor, Yolo County, California</th>
<th>Sandtown Landfill, Delaware Solid Waste Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between injection/extraction wells (m)</td>
<td>3.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Approximate measurement volume (per test) (m³)</td>
<td>20</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of tests</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Range of Sₜ measured</td>
<td>0.082 – 0.30</td>
<td>~0.0 – 0.32</td>
</tr>
<tr>
<td>Range of Mₜ measured</td>
<td>0.086 – 0.29</td>
<td>~0.0 – 0.245</td>
</tr>
<tr>
<td>Comparison of Mₜ with gravimetric measurements</td>
<td>PGTT: $M_c = 0.29 \pm 0.03$</td>
<td>PGTT: $M_c = 0.245 \pm 0.02$</td>
</tr>
<tr>
<td></td>
<td>Gravimetric $M_c = 0.24$</td>
<td>Gravimetric $M_c = 0.26 \pm 0.06$</td>
</tr>
<tr>
<td>Duration of each test (h)</td>
<td>22.7 and 43.9</td>
<td>6.2 - 12</td>
</tr>
<tr>
<td>Expendable costs per test</td>
<td>US$550</td>
<td>US$250</td>
</tr>
<tr>
<td>Capital costs</td>
<td>US$2,500</td>
<td>US$4,000</td>
</tr>
<tr>
<td>Man hours per test (h)</td>
<td>35 and 60</td>
<td>8-15</td>
</tr>
</tbody>
</table>
Field applications of PGTT

Tracer gas concentrations (He = Helium, DFM = difluoromethane) measured at the gas extraction well for Test #6 at the Sandtown Landfill (Delaware Solid Waste Authority). Gas concentrations are normalized with the maximum influent concentration of each tracer. Lines indicate exponential extrapolations of the data.
Fiber Optic Sensors

- **Principle**
  - Distributed temperature sensing method based on Raman scattering
  - Equipment sends a short laser pulse into the sensing fiber.
  - Local reflections are received along the fiber length.
  - Measuring the optical signal received at different times can give temperature readings.
  - Changes in volumetric water content can be detected directly or by combining temperature measurements with heat pulses.
## Field application of Fiber Optic Sensors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ämmässuo landfill site</th>
<th>Mustankorkea landfill site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality of surface-sealing layer</td>
<td>Effects of leachate recirculation (municipal solid waste and two different ashes)</td>
<td></td>
</tr>
<tr>
<td>Installation year</td>
<td>2001</td>
<td>2003</td>
</tr>
<tr>
<td>Installation geometry</td>
<td>one horizontal layer</td>
<td>two horizontal layers</td>
</tr>
<tr>
<td>Length of monitoring cable (m)/test location</td>
<td>3800</td>
<td>90</td>
</tr>
<tr>
<td>Number of test target</td>
<td>1</td>
<td>4 (four test cells)</td>
</tr>
<tr>
<td>Number of sensor points</td>
<td>7,600 – 15,200</td>
<td>4 x 180-360</td>
</tr>
<tr>
<td>Approximate measurement area (m²) or volume (m³)</td>
<td>20,000 m²</td>
<td>112 m³</td>
</tr>
<tr>
<td>Spatial resolution (m)</td>
<td>0.25-5</td>
<td>0.25-0.5</td>
</tr>
<tr>
<td>Number of data collection periods</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Duration of each data collection period (h)</td>
<td>1-72</td>
<td>Jan-72</td>
</tr>
<tr>
<td>Main results and observed events</td>
<td>Effects of gas flow, possible leakage through the sealing materials, possible seepage paths in sides, temperatures below 0°C indicating possibility for frost and functioning problems in the mineral sealing</td>
<td>One corner of one cell was wet, otherwise small temperature differences throughout waste, low ambient temperatures kept the test cells cool</td>
</tr>
<tr>
<td>Capital costs of sensor system with installation costs</td>
<td>US$35,000</td>
<td>US$3,500</td>
</tr>
<tr>
<td>Man hours per test/ data collection periods</td>
<td>4-21</td>
<td>4-10</td>
</tr>
</tbody>
</table>
An example of **temperature surface maps** (about 200m x 100m area) measured by the fiber optic sensor cable network installed in the surface-sealing layer at the Ämmässuo landfill site. The locations of the fiber optic sensor cables (thin black lines) and gas collection pipes (blue lines) are also seen in the maps.
## Summary

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Neutron Probe         | - Moisture content can be measured regardless of its physical state in soils or waste  
- Offers large radius of influence, between 150 mm in wet soil and 700 mm in dry soil | - Moisture Measurement of absolute moisture content is difficult  
- Presence of non-water bound hydrogen interferes with the measurement  
- Some elements other than hydrogen have a propensity to absorb high-energy neutrons  
- Changes in density affect the results  
- The radioactive source of neutron probe is a highly regulated material  
- Automation is not possible |
## Summary

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<thead>
<tr>
<th>Measurement Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| **Electrical Resistance/Impedance Sensors** | - Sensors are relatively inexpensive  
- Sensor installation is easy  
- Automated measurement is possible  
- Can be produced inexpensively  
- Density does not affect readings  
- Fast response to leachate front arrival | - Sensors suffer from hysteresis at low moisture contents  
- Results affected by changes in electrical conductivity and temperature  
- Once wet the sensors do not drain quickly  
- Sensor must be calibrated using extracted waste |
## Summary

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic Techniques (Time Domain Reflectometry/</td>
<td>- Sensors are relatively inexpensive</td>
<td>- Results affected by changes in electrical conductivity</td>
</tr>
<tr>
<td>Transmissometry)</td>
<td>- Results are reproducible</td>
<td>- Local heterogeneity of material properties affects the results</td>
</tr>
<tr>
<td></td>
<td>- Automated measurement is possible</td>
<td>- Sensor must be calibrated using extracted waste</td>
</tr>
<tr>
<td></td>
<td>- Fast response to leachate front arrival</td>
<td></td>
</tr>
<tr>
<td>Measurement Technique</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Electrical Resistivity Tomography | - Non-intrusive technique  
- A two-dimensional evolution of a leachate injection plume can be obtained  
- Fast response to leachate front arrival | - Requires the knowledge of leachate electrical conductivity  
- Needs measurement of in situ temperatures from additional temperature sensors  
- Expensive instrumentation costs  
- Technique not evaluated for moisture content measurement |
## Summary

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGTT</td>
<td>- Provides reasonably accurate assessment of moisture content</td>
<td>- Gas sample collection and laboratory analysis pose difficulty for automation</td>
</tr>
<tr>
<td></td>
<td>- Measurement accuracy is unaffected by the measurement volume</td>
<td>- Needs measurement of in situ temperatures from additional temperature sensors</td>
</tr>
<tr>
<td></td>
<td>- Relatively inexpensive field setup is required</td>
<td>- On larger scale provides assessment of average conditions and may not identify relatively wet spots</td>
</tr>
<tr>
<td></td>
<td>- Tracer gases can be injected through existing injection wells of a landfill</td>
<td></td>
</tr>
</tbody>
</table>
## Summary

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Optical Fiber         | ▪ Provides data measurements at high spatial resolution  
                        ▪ Ease of installation and automation  
                        ▪ Fast response to leachate front arrival | ▪ Technique not evaluated for moisture content measurement  
                        ▪ Interference from preferential high gas flows in measurements |
Cost Analysis

Sampling Volume = 200 m³

Sampling Volume = 20 m³

- Electrical Resistance
- Partitioning Gas Tracers
- Time Domain Reflectometry
- Neutron Probe
- Electrical Resistivity Tomography
- Fiber Optic

Total Sampling Cost - US Dollars

Frequency of Measurement
Discussion

Several criteria to evaluate the methods
- Accuracy of measurement
- Water saturation or volumetric water content; ability to track infiltration fronts in refuse; reliability in the landfill environment; and cost (covered earlier)
- Accuracy of measurement
- PGTTT successful but at low to intermediate moisture contents
- Electric resistance and TDR sensors resulted in biased estimates
- Neutron probe helpful in determining volumetric water content
- Results from ERT and fiber optic sensors not compared with field data.
Discussion

- Tracking infiltration fronts
  - Electric resistance, TDR and ERT successful
  - PGTT method not appropriate because of long time duration involved.
  - Neutron probe and fiber optics not tested in field

- Instrument reliability
  - ERS gave the best results
  - Sufficient record not available for other methods
Conclusions

- For accurate measurement of moisture content in refuse, PGTT method should be preferred.
- To track infiltration fronts:
  - Electrical Resistance Sensors
  - Time Domain reflectometry
  - Electrical Resistivity Tomography
- For frequent measurements:
  - An automated method would be best
  - Still to be researched
thank you!