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The Landfill Whisperer
(Settlement as a Second Language)

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April 30, 2015
Why Does Landfill Settlement Matter?

• **Everything** we do is impacted by landfill settlement
  – Permitting, design, construction, closure/post-closure care, end-uses

• **Significant potential benefits** from understanding settlement
  – $K’s to $M’s
  – Environmental and regulatory
  – Operational (lifespan/airspace, maintenance, planning forward)
  – End use options

• **Landfills are not static**
  – Dimensionally
  – Temporally
  – Environmentally ("live and breath")
Landfill Settlement: downward movement of the landfill surface over time due to compaction, physical compression from loads, particle re-orientation, biological decomposition & chemical degradation of the waste mass, and underlying foundation materials.

- Waste interactions are complex
- Not random; difficult to predict
- Important to monitor, observe, and “listen”
Common ‘Soft Edge’ Settlement

Virginia

Maryland

California

Maryland
Paved Taxiway on Old Landfill
(8 feet of asphalt in places)

California
“Lake” Novo Gramacho
(>300 feet of waste below)

Rio de Janeiro
Health and Safety Challenges
(Rain, Soft Foundation and No Compaction)
Impact of Settlement on Gas Wells

Rio de Janeiro
Settlement Due to Elevated Temperatures

The “Smoking Sump”

Sink hole

Australia
Hard Edge Settlement
Mechanics of Waste Settlement
(Ref: G. F. Sowers, Moscow, 1973)

Physical/mechanical due to compaction and self-weight;
Compression, crushing, re-orientation, raveling, reduce voids, erode waste particles;
Aerobic + anaerobic decomposition
Mechanics of Waste Settlement
(Ref: G. F. Sowers, Moscow, 1973)

Closed Biological decomposition (anaerobic) + Mechanical compression

\[ \Delta H \]

Time, \( t_i \)

10 20 30 40 years

Secondary Phase(s)

\[ + C_xH_yO_z + H_2O = X(0.5 \text{ CH}_4 + 0.5 \text{ CO}_2) + \text{Trace Gases} \]

Gas => Mass (carbon) => Volume reduction => Settlement
Estimating Secondary Compression and Gas Generation

Sowers, 1973:

$$\Delta H_D = H \times \left( \frac{\alpha}{1 + e_0} \right) \times \log_{10} \left( \frac{t_2}{t_1} \right)$$

- $H$: Existing waste thickness
- $\Delta H_L$: Settlement ($S$)
- $e_0$: Original void ratio
- $\alpha$: Secondary compression factor (0.03 to 0.09 $e_0$ per Sowers)
- $t_1$: Start of time period
- $t_2$: End of time period

EPA LandGem Model for Gas

$$Q_M = \sum_{i=1}^{n} 2kL_0M_i(e^{-kt_i})$$

- $M$: Mass of solid waste
- $k$: Methane generation constant
- $L_0$: Methane generation potential
- $t_i$: Age of waste
Semi-log Plot of Secondary Compression (Why Sower’s Used Log$_{10}$)

End of Filling, $t_0$

Time, $t$ (log scale)

- 100 days
- 1000 days
- 10,000 days
- 100,000 days

$\Delta H$ Settlement

Primary “compression”

Secondary compression

$c_\alpha = \text{slope} = -\Delta e/\log_{10}(t_2/t_1)$
External Loading Settlement

- $H$ = Existing waste thickness
- $\Delta H_L$ = settlement (S)
- $e_0$ = original void ratio
- $C_c$ = compression index = 0.15 $e_0$ to 0.55 $e_0$
- $\Delta P$ = induced load at middle of layer...additional lift, road, cover
- $P_i$ = initial stress in middle of layer (geostatic)

From Soil Mechanics – One Dimensional Compression Theory:

$$\frac{\Delta H}{H} = \frac{\Delta e}{1+e_0}$$

$$\Delta H_L = \frac{(H)(C_c)}{(1+e_0)} \times \log_{10} \left(1 + \frac{\Delta P}{P_i}\right)$$

Fig. 5–1. One-dimensional compression of soil layer.
Settlement Monitoring: Case Studies

- Long term monitoring of a closed landfill
  - Future Energy Park Redevelopment
- Deformation of a Sloping Landfill
  - Is it stable?
- Correlating Gas Generation with Waste Settlement
  - Hiriya LF Rehabilitation, and others
  - Checking *LandGem*
- Settlement Accommodation Plan
  - How to Overfill in Pennsylvania
- Surcharging an Old Landfill
  - What and when can we build?

05/08/2014
City of Annapolis, MD Landfill

Operated 1959 - 1993
Closed 1997
20 to 30 feet of waste
6 passive flares

Future Energy Park Development?

Flare Settlement Trends

Average 0.2” to 2.6” per year over 10 years
Total ~4% to 8% of Thickness

y = -0.284Ln(x) + 154.66
y = -0.1419Ln(x) + 153.05
y = -0.2977Ln(x) + 147.96
y = -0.0465Ln(x) + 134.52
y = -0.1859Ln(x) + 132.52
y = -0.0199Ln(x) + 129.44
Unlined Hillside Landfill

• Cracks formed at top
• Depressions along slope
• Distortion at toe...

- Is it Stable?
- Cost to stabilize >$250K

18 years of data
**Settlement vs. Creep**

**Based on Monitoring & Analysis:**
1. LF is stable (FS>1.4 by modeling)
2. Settlement & Creeping ~0.5 to ~4 inches per year
3. Cracks filled and covered at low cost
4. Restabilization not justified….savings in the mid $100K’s

- Weather (rainfall & ground)

**Graph:**
- Vertical (settlement)
- Horizontal (slope creep)
- Max V 6.5 ft
- Max H 6.5 ft
Hiriya Landfill
Settlement, Redevelopment, Gas Generation

- Operated 1950 to 1998
- 100 acres x 200 feet deep
- Poorly vegetated, but stable
- Surrounding area undeveloped

H = 200 feet
Settlement Plates 2003-05:
- Settling ~1 to 2+ ft/yr
- Extrapolated 6 to 12 feet to 2020
- Total ~3% to ~6% of H

LandGem v3.02 model

Closed 1998

Filling

Gas Recovery
The Future “Ariel Sharon Park”
## Settlement and LFG

### Case 1: Hiriya Landfill (>15,000,000 tons in place; closed 1998)

Gas Generation over 15 years based on 2 years of settlement monitoring:
- **Volume reduction:** 100 acres x 43,560 x **10 feet** = 1.61 MCY  
  (organic MSW; ~60% of settlement from decomposition)
- **Mass reduction:** 0.60 x 1.61 MCY x 0.60 tcy = 580,800 tons
- **Gas volume** = (580,800x2000)/[(.067pcf)(365)(24)(60)(15)] = **2200 scfm**
- **Estimated per LandGem v3.02 model:** **2370 scfm** ---very close

### Case 2: City of Annapolis Landfill (<1,000,000 tons in place; closed 1997)

Gas Generation over 15 years based on 10 years of settlement monitoring:
- **Volume reduction:** 67 acres x 43,560 x **15 in/12** = 135,100 CY  
  (normal MSW; ~50% settlement from decomposition)
- **Mass reduction:** 0.50 x 135,100 x 0.50 tcy = 33,775 tons
- **Gas volume** = (33,775x2000)/[(.067pcf)(365)(24)(60)(15)] = **128 scfm**
- **Estimated per LandGem v3.02 model:** **404 scfm** ---close
**Case 3: PA Landfill (still active; preliminary estimate)**

Gas Generation estimated for 25M tons over 230 acres from 2005 to 2103 (waste dates back to pre 1993)

- Volume reduction: \( \sim 6.0 \text{ feet} \times 230 \text{ acres} = 2.22 \text{ MCY} \)
  (organic MSW; \( \sim 50\% \) of settlement from decomposition)
- Mass reduction: \( 0.50 \times 2.22 \text{ MCY} \times 1.00 \text{ tcy} = 1,111,000 \text{ tons} \)
- Gas volume: \( (1,111,000 \times 2000)/[(.067 \text{pcf})(365)(24)(60)(8.5)] = 7423 \text{ scfm} \)

- Estimated per *LandGem v3.02* model: \( \sim 7000 \text{ scfm} \) OK---close

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**Figure 1. LFG Generation Projection**

8.5 years of settlement data
“Lost” Airspace Example with Proposed Overfill

Potential Lost Airspace Due to Settlement ~1.3 MCY over a 20 acre segment

Proposed Overfill to recover airspace in 5 years, based on observed and estimated settlement

Lower slopes capped & settled 5 to 15 ft.
Settlement Accommodation Plan (SAP)  
Pennsylvania DEP SOP (2014)  

• **Issue:** PA landfills losing significant airspace as regulations required capping commence after reaching final grade. Caps were exhibiting depressions; couldn’t recover airspace.

• **Resolution:** PADEP (2014) developed SAP approach that allows sites to “overfill”.

• **Key Provisions:**
  – Allows 5 years for overfill to settle; calculations required at 1, 3, 5 yrs
  – Maximum overfill slope 2.5:1; final slopes at 3.0:1. Check stability
  – Limiting overfill = 10% of underlying waste thickness
  – Remove all waste over permitted grades
  – Settlement analysis, monitoring, reporting required
Settlement problems after initial ballfields constructed (no engineering). Ponding, differential settlement, cracks, gas/odor, erosion, etc..

Football and LaCrosse Athletic Fields
“Ballfield Landfill”
Prince William County, Virginia
Stabilized & Monitored Area With Soil Surcharge
>12 months

8’ TO 10’ SURCHAGE DIRT
ΔP ~900 TO 1100 PSF

15 Settlement Plates & Risers

Remove Surcharge
Settlement Monitoring Data
Phase 2 Eastern Portion

- Max. total settlement = 1.5 feet
- Rate < 1.7 inches/year (with surcharge in place)
- Goal < Total 1 inch/year (no surcharge)
Phase 2 (Eastern) Surcharge Area Final Turf Section

- Athletic field type sod
- 12” Premium topsoil
- 12” Drainage Layer
- Automatic irrigation system and piping
- Biaxial Geogrid
- Soil Cushion
- Waste (includes active gas wells)
# Potential Benefits

| Planning & Operations | • Maximize airspace & revenues  
• Recover airspace on slopes & top deck  
• Compaction (density) evaluation  
• Avoid running out of airspace  
• Validate gas generation modeling |
|-----------------------|-----------------------------------------------------------------|
| Closure and Closure Planning | • Fine tune closure scheduling (R.C.Method)  
• Capture settled areas before closure (Settlement Accommodation Plan) |
| Post Closure | • Monitoring and maintenance  
• Check for liner elongation & integrity |
| End Use Development | • Foundation support and utility design  
• Settlement estimation  
• Early identification & resolution of problems (instability, fire, drainage, ponding, etc....) |
## Show Me The Money

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>APPROXIMATE RANGE OF COSTS/REVENUE /SAVINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confirming/validation of gas modeling</td>
<td>$&gt;10K to $&gt;50K</td>
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<tr>
<td>Predicting settlement from gas generation:</td>
<td></td>
</tr>
<tr>
<td>End Use Planning and Development:</td>
<td>$&gt;$50K to $&gt;$250K + Cost of Real Estate + Lease Fees</td>
</tr>
<tr>
<td>• Athletic fields, parking &amp; storage areas</td>
<td></td>
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<tr>
<td>• Composting, transfer stations, etc…</td>
<td></td>
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<tr>
<td>• Commercial development</td>
<td></td>
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<tr>
<td>• Limiting maintenance</td>
<td></td>
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<tr>
<td>Identify potential liner or stability problems:</td>
<td></td>
</tr>
<tr>
<td>• Avoiding liner rupture &amp; repair</td>
<td>$&gt;$20K to $&gt;$100K</td>
</tr>
<tr>
<td>• Identification of other problems (e.g., combustion, instability, settlement, slope creep, etc…)</td>
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**Show Me The Money**

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<tr>
<td>Running short of airspace:</td>
<td>&gt;20% to new cell construction</td>
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<tr>
<td>• Accelerated cell construction &amp; permitting</td>
<td>&gt;$1M (flow and tipping fee dependent)</td>
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<tr>
<td>• Off-site hauling &amp; disposal (6 months)</td>
<td></td>
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<tr>
<td>Revenue Loss by not considering settlement and closing prematurely:</td>
<td>&gt;$1.8M in lost airspace</td>
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<tr>
<td>• Closing 6 months early</td>
<td>&gt;$3.6M in lost airspace</td>
</tr>
<tr>
<td>• Closing 12 months early</td>
<td>(based on 200 tpd; 25 acre cell, 0.6 tcy density; $50/ton tip fee)</td>
</tr>
<tr>
<td>Unrecoverable Airspace (delay in capping):</td>
<td>&gt;$600K</td>
</tr>
<tr>
<td>• 6 months delay (avg. 6” settlement)</td>
<td>&gt;$1.2M</td>
</tr>
<tr>
<td>• 12 months delay (avg. 12” settlement)</td>
<td>(25 acre site; assuming 100 ft deep with 1% settlement per year)</td>
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**Costs could be high, or could be low, or just right.**
Are You Listening?