Thousands of Waste Fills in the U.S., and Many Thousand More Around the World

- ~2,000 active municipal solid waste (MSW) landfills
- ~10,000 closed MSW landfills
- ~1,000s of:
  - Industrial waste impoundments and by-product landfills
  - Mine tailings impoundments
  - Coal combustion residual (CCR) impoundments and landfills
  - RCRA and TSCA hazardous waste (HW) landfills
  - Low-level radioactive waste and mixed waste (LLRW) facilities
- Globally, there are many times the number of waste fills as in the U.S. (but focus today is on the U.S.)

Unstable Waste Fills Pose Risks to Lives, Property, and the Environment
Typical Layout of Modern Lined Solid Waste Fill

- Composite Liner (Geomembrane (GMB)/Compacted Clay Liner (CCL))
- Intermediate Cover Soil Layer
- Gas Extraction Well
- Final Cover System
- Leachate Collection and Removal System (LCRS)
- Leachate Removal Piping/Pumps
Geotechnical design engineers must be cognizant of multiple potential static and seismic failure modes that can exist at each stage of waste fill development.
Organization of Lecture

1. Where Did We Start
   - (early 1980s to mid 1990s)
2. What Did We Learn
   - (by mid 1990s)
3. Continuing Challenges
   - (2010 to present)
4. Observations and Recommendations
Where We Started
(early 1980s to mid 1990s)
Where We Started (35 to 20 years ago)

Waste Fill Failures Drew the Scrutiny of Owners, Regulators, and Geotechnical Engineers

- Kettleman Hills HW Landfill, CA (1988)
- Crossroads MSW Landfill, ME (1989)
- Chiquita Canyon, CA (1994)
- Keller Canyon Landfill, CA (1994)
- Rumpke MSW Landfill, OH (1996)
- Mahoning MSW Landfill, PA (1996)
In early 1988, a year after filling began, and with the waste fill in an interim configuration with a height of 90 feet, 600,000 CY of waste moved ~ 35 feet laterally over several hours.

References: Mitchell et al. (1990, 1993); Seed et al. (1990); Geosyntec (1991); Byrne et al. (1992); Stark et al. (1994); Filz et al. (2001)
Forensic investigation revealed a translational sliding mechanism along liner-system interfaces.

Slippage was observed to be at the interface between the secondary HDPE GMB and underlying CCL; post-failure testing of this interface produced undrained residual interface strengths of about 500 psf.

Geosynthetic-geosynthetic interfaces were also found to be weak, with measured residual interface friction angles of less than 10°.

Analyses and physical modeling also showed that 3-D effects were important given the waste fill geometry, and that the failure mechanism involved progressive loss of interface strength (peak to residual).
Kettleman Hills HW Landfill Unit B-19, California (1988)
Waste Mass and Liner System Interface Failure
Lessons Learned

- Many liner system interfaces are weak and exhibit pronounced shear softening, with residual strengths much lower than peak strengths.
- Liner system construction and waste placement operations can induce movements that mobilize post-peak interface conditions within the liner system; the potential for progressive failure must be considered in design.
- Waste mass stability evaluations need to address all interim waste filling configurations (“all development phases”).
- GMB/CCL interface strengths are sensitive to their moisture, density, and shearing conditions.

Conundrum - CCL compaction conditions that favor low permeability and intimate GMB/CCL contact also favor low interface shear strength.
Crossroads MSW Landfill, Maine (1989)
Waste Mass and Foundation Soil Failure

- 8-acre landfill with foundation consisting of very sensitive ($S_t \sim 5$ to $10$) glaciomarine clay-silt layer
  - Overconsolidated (OC) crust
  - Normally consolidated (NC) at depth (20 feet)
- Clay-silt layer served as in-situ hydraulic barrier – there was no constructed liner or LCRS
- With the waste height at 70 feet, and after a period of heavy rain, a rapid (~ minute) retrogressive slide occurred involving 650,000 CY of MSW
- Sliding surface was found to be in the clay-silt layer below the OC crust
- Waste blocks “floated” up to 160 feet to the west on remolded foundation soil

References: Richardson and Reynolds (1991); Luettich et al. (2015); Reynolds (2015)
Several months prior to failure, engineers performed “updated” staged-construction stability analyses that produced $FS \approx 1.0$

Foundation movements from inclinometers of 1.5 mm/month were assessed as “high, but acceptable”

Site operations continued and stabilizing toe berms were constructed – but not on the west side

On the west side, a 6-foot deep excavation was being made along the entire toe of the landfill for construction of a new lined landfill cell

This excavation led to foundation over-stressing at the toe, an initial localized toe failure, and then the rapid retrogressive slide

The forensic investigation showed that the degree of consolidation of the foundation soil under the staged waste loading was poorly estimated, soil strengths and waste unit weights were significantly underestimated (25-30% each), and liquid levels in the fill were not
Crossroads MSW Landfill, Maine (1989)

**Lessons Learned**

- Both waste and foundation unit weights and shear strengths must be adequately characterized; waste self weight is by far the largest contributor to foundation loading, hence the importance of proper characterization.
- A clear understanding of the liquid levels and pore pressure conditions in the waste fill are critical to the satisfactory assessment of waste fill stability.
- Each significant construction and/or operational change in the field should be evaluated prior to implementing the change (in this case, excavation at toe triggered the slide).

For soft soil sites, the rate of waste filling may need to be limited by the rate of foundation soil consolidation and strength gain – this is a classical staged geotechnical construction condition that must be thoroughly understood.
Starting in 1940s, waste was placed in ravines on the Rumpke property, directly onto **clayey, colluvial/residual soils that formed a mantle over bedrock** – landfilling continued until 1996, to **grades exceeding permitted design grades**.

- A week prior to failure tension cracks were observed at the top of the landfill.
- The morning of the slide, the toe of the landfill began to move and the tension cracks at the crest were observed to be growing wider.
- After several hours of gradually increasing creep rates, the slope failed, starting at the toe, and retrogressing to the headscarp location.
- In only 5 minutes, 1.5-million CY of material slid hundreds of feet into a deep adjacent excavation.

References: Geosyntec (1996,1997), Hendron and Schmucker (1997); Evans and Stark (1997); Stark et al. (2000a,b); Chug et al. (2007)
Due to delays in opening the lateral expansion, the landfill top deck had been overfilled by 30-40 feet in the 18 months prior to failure; and the average slope was steepened from 3H:1V to 2.6H:1V; prior to the failure, a stability analysis of the overfill was not conducted.

Forensic investigation showed that the slip surface extended at a near vertical angle from the landfill crest, through the waste, to the native soil, where it followed the bedding of the soil layer.

The investigation determined that leachate levels in the waste mass at failure were substantial (up to 30-40 feet).

Post-failure shear testing of the native soil produced fully-softened and residual friction angles in the range of 20° and 8°, respectively; mobilized average friction angle at failure based on back-analysis is about 12°.

An excavation at the toe for an access road and freezing conditions that impeded leachate toe drainage (by creating an ice dam) may have contributed to initial triggering of the slide.
Lessons Learned

- Foundation conditions for old-unlined waste fills must be thoroughly understood if additional filling, excavation, or expansion of the fill is planned.

- Strain incompatibility between MSW (ductile) and colluvial soil (brittle) can lead to uneven development of shear resistances, localized shear softening, and progressive failure.

- Leachate buildup in old unlined waste fills can reduce slope stability factors of safety and contribute to the development of unstable slope conditions; they need to be monitored.

- Operational activities (e.g., filling above the permitted heights and slopes) may reduce slope stability.
What Did We Learn
(by mid 1990s)
**Lessons Learned** by the Mid 1990s (nearly 25 years ago)

1. Don’t forget fundamental soil mechanics
2. Waste materials have geotechnical properties that must be characterized
3. Liquid and gas conditions in the fill are important – they can create elevated pore pressures
4. Soil and geosynthetic interface strengths must be characterized (both peak and residual)
5. Mobilized strength compatibility is often an issue
   - waste *(often ductile)*
   - geosynthetic interfaces *(often brittle and strain softening)*
   - foundations *(sensitive, brittle, strain softening, undrained, and/or liquefiable)*
6. Progressive failure mechanisms must often be considered
7. Time-dependent staged loading response must be addressed at soft soil sites
8. Numerous interim waste configurations often require assessment
9. Operating conditions in the field often deviate from the original design
10. Approach expansions on top of old unlined fills with caution
11. Surface cracking and toe bulging may be signs of incipient failure
12. Communications between engineers and operators are critical
Continuing Challenges
(fast forward to 2010 to present)

“So, Why do We Keep Having These Waste Fill Failures?”
U.S. Waste Fill Stability Failures Have Continued to Occur on a Regular Basis *(more than one per year on average)*

- Matlock Bend MSW Landfill, TN (2010)
- Confidential MSW Landfill, Eastern U.S. (2011)
- Big Run MSW Landfill, KY (2013)
- Chrin Brothers MSW Landfill, PA (2013)
- Tri-Cities MSW Landfill, VA (2015)
- Confidential MSW Landfill, GA (2018)
- Confidential MSW Landfill, SC (2018)
- Confidential MSW Landfill, GA (2019)
At the time of the failure in September 2011, waste filling had recently been completed in a landfill expansion being built over the 190-foot tall slope of a previously filled landfill cell (veneer geometry).

This was a very wet landfill:
- leachate recirculation at the site had been in the range of 5 to 10 million gallons per year for many years
- high levels of stormwater infiltration occurred (flat top deck, permeable daily cover)
- dewatered sewage sludge was being accepted for disposal

Failure occurred in the expansion area (waste veneer) in a matter of minutes and involved ~ 160,000 CY of waste that flowed ~ 500 feet beyond the limit of liner system and retrogressed more than 100 feet behind the crest.
Confidential MSW Landfill Failure, Eastern U.S. (2011)
Waste Mass and Intermediate Cover Soil Interface Failure

- Post-failure investigation showed that the slip surface was at the interface between the expansion area waste and underlying intermediate cover soil layer.
- CPT_U testing (20 soundings) around the perimeter of the failed area showed high piezometric levels in the expansion waste mass.
- On-site observations the day after the slide revealed leachate pools and gas vents within the failure area, clear evidence of a wet “pressurized” fill.

Intact intermediate cover exposed after failed waste removal
Confidential MSW Landfill Failure, Eastern U.S. (2011)
Waste Mass and Intermediate Cover Soil Interface Failure
Slope stability analyses were conducted using the $CPT_U$-derived piezometric levels and the observed failure surface.

Back-analyses of the failure resulted in a drained waste friction angle of 26° for FS=1.0 ($c = 100$ psf).

Direct shear tests on an MSW/sludge (75%/25%) sample from the site, performed at Arizona State University, resulted in drained secant friction angles of 24° and 20°, respectively, at 10 and 20 psi normal stresses.

These calculated and measured MSW strengths are lower than those for “typical” MSW (e.g., Kavazanjian et al., 1995) revealing the effects of the sludge and possibly decomposition on waste strength.
Confidential MSW Landfill Failure, Eastern U.S. (2011)

Lessons Learned

- Excessive leachate recirculation and stormwater infiltration can lead to the buildup of elevated liquid levels and pore pressures in the waste.

- **Vertical expansions** that involve the placement of new waste over old need to account for the interface conditions:
  - In this case, a low-permeability intermediate cover impeded leachate percolation from the expansion area to the LCRS, contributing to leachate buildup.
  - Either the cover needed to be removed, or a new LCRS placed on top of it.

- **Gas collection efficiency** can be greatly reduced in excessively wet landfills, both through operational problems such as the flooding or of gas wells, and by the reduction of gas permeability at increasing levels of waste saturation.

- **The effects of sludge** on the strength (↓), permeability (↓), and degree of saturation (↑) of the waste mass must be accounted for in design.
Landfill cell was constructed in a deep excavation (45-60 feet) into over-consolidated native fat clay (CH)

Excavation:
- occurred in 1996 to obtain borrow soil for ongoing site operations
- liner system construction did not begin until 2007
- for a decade, stormwater ponded in the cell bottom

Liner system:
- CCL overlain by sand LCRS
- not a factor in the failure

Waste filling occurred from mid 2007 to early 2009, creating a slope 95 feet high inclined at 4H:1V

Translational movement occurred in February 2012 over a several day period ~ three years after filling was substantially complete and after 3.5 inches of rain fell in the preceding 48 hours
Waste Mass and Foundation Failure

- The first signs of a problem occurred three months prior to the failure when north-south oriented cracks developed at the eventual location of the slide head scarp.
- Owner/operator filled the cracks, but they reopened with time, typically after rain events.
- The slide involved translational movement of ~ 700,000 CY of waste and soil a distance of 25 feet.
- Forensic investigation concluded that failure mechanism involved shallow translational movement in the native clay beneath the bottom of the liner.
Decade-long open excavation allowed ponded water to infiltrate the native clay through desiccation cracks, slickensides, and soil suction – this led to swelling and softening of the clay and fully-softened shear strength conditions.

Stresses generated by the waste fill induced shear deformations in the native clay leading to progressive strength loss and ultimately failure.
Lessons Learned

Geotechnical fundamentals matter: in this case, the OC plastic clay swelled and softened due to unloading and access to water, resulting in fully-softened shear strength conditions, followed by progressive failure due to the shear stresses imposed by the waste fill.
In February 2017, a 15+ acre waste slope failure occurred, resulting in a worker fatality.

In the weeks leading up to the failure, surface cracking, slope bulging, leachate seeps, and gas venting were all observed; at the time of the failure, the owner was attempting to install gas wells in the area to relieve pressure.

The failure occurred over about 10 minutes, starting with the bursting of the bulging landfill face which triggered a larger slide, releasing 220,000 CY of waste that flowed several hundred feet beyond the limit of the liner system.
The area where the failure occurred involved an expansion of a new waste cell against the intermediate slope cover of an older portion of the landfill (again, veneer configuration).

Intermediate cover for the original landfill consisted of cuttings from O&G drilling operations blended with lime, resulting in a relatively hard, smooth, and impermeable layer upon which waste was placed (again, no removal of the layer or installation of a new LCRS on top).

In addition to MSW, the landfill accepted a variety of special wastes, including sludge described as low shear strength waste (LSSW).
The operations plan for the landfill required LSSW to be placed 100 feet back from the landfill edge of slope, to prevent leachate seeps and to maintain stability (a good idea).

The setback limited the cell area in which LSSW could be placed and the amount of MSW available for mixing with the LSSW, because:

- the cell had a 90° wedge front face
- the MSW was being used up to form the setback zones so it wasn’t available for mixing with the LSSW

This resulted in interior zones in the cell (brown) with high proportions of LSSW (an unintended consequence) and ultimately a weak zone through which shearing occurred.

While the landfill only accepted about 20% LSSW by total tonnage, these operational factors resulted in a zone estimated to have >40% LSSW.
Representative samples of MSW and LSSW were obtained from bucket augering and sonic coring in the slide area.

Direct shear testing was conducted at CSU on test specimens of MSW, LSSW, and mixtures of MSW + LSSW.

Test results showed that MSW/LSSW mixtures became substantially weaker at LSSW mass fractions above about 40%.

Lessons Learned

- Special (non-MSW) wastes can create operational problems - procedures developed to mitigate the problems can have unintended consequences.

- Special wastes if placed at too high a mass fraction, and if not thoroughly mixed with MSW or other stronger waste, will create weak zones that adversely affect waste fill stability.

- Low permeability zones in the waste (e.g., from special wastes or intermediate cover soil layers) trap liquids and gases in the waste fill causing fluid pressures to become elevated.
Observations and Recommendations in Light of Continuing Challenges
We are Re-learning Many of the Lessons First Learned 25 Years Ago – Why?

1. Don’t forget fundamental soil mechanics
2. Waste materials have geotechnical properties that must be characterized
3. Liquid and gas conditions in the fill are important – they can create elevated pore pressures
4. Soil and geosynthetic interface strengths must be characterized (both peak and residual)
5. Mobilized strength compatibility is often an issue
   - waste (often ductile)
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   - foundations (sensitive, brittle, strain softening, undrained, and/or liquefiable)
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8. Numerous interim waste configurations often require assessment
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Recent Lessons Learned and Recommendations

1. Aggressive leachate recirculation can saturate waste and cause high piezometric levels
2. Gas well collection efficiency is substantially diminished in very wet landfills
3. High moisture content landfills can lead to elevated temperatures in some cases
4. Co-disposal of sludges and special wastes can lead to stability and other problems
5. Vertical expansion configurations and materials have contributed to waste fill failures

Leachate Recirculation:
• Recirculation rates may need to be moderated to avoid saturating the fill
• A proper water balance should be maintained in the waste fill (requires monitoring)
• Additional internal drainage features (e.g., chimney and trench drains) may be needed to drain fill

Sludges and Special Wastes:
• Detailed special waste acceptance plans (SWAPs) should be developed for each special waste stream
• SWAPs should address potential impacts to leachate and gas generation rates, waste properties, slope stability, and operations
• Unintended consequences of special operating procedures must be carefully considered
• A higher level of operating vigilance is needed - observational approach

Vertical Expansions:
• The intermediate cover interface must be carefully engineered for stability and permeability
  • in some cases, the cover should be removed
  • in others, a new LCRS should be installed on top of the cover
• The effects of the vertical expansion on leachate and gas movements in the waste fill should be carefully assessed
Thank You

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