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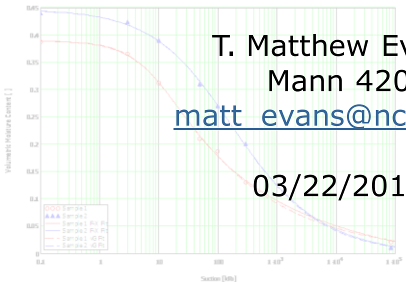
Stability of Slopes in Landfills

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03/22/2010

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Overview

- Shear Strength
- Modes of Slope Failure
- Slope Failure in Landfills
- Details, Details…
  - Infinite slopes
  - Rotational failure
  - Anchor trench pullout failure
- Case Histories

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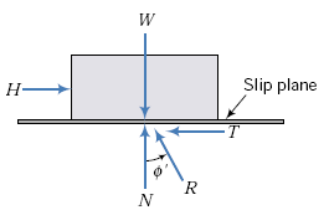
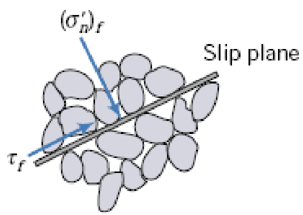
Shear Strength (1)





$$T = \mu N \rightarrow \frac{T}{A} = \mu \frac{N}{A} \rightarrow \tau = \mu\sigma \rightarrow \tau = \sigma \tan\phi'$$

This shear strength formulation applies to long-term loading of soils and for shear along interfaces.

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Shear Strength (2)

- Short-term loading (e.g., that experienced during rapid slope failures with curved failure surfaces) requires a different expression for shear strength that incorporates the effects of water.
- We refer to this as *undrained* shear strength (s_u) or sometimes (incorrectly) cohesion
- The distinction is necessary because during rapid loading, there is no time for water to escape from the soil pores, resulting in constant volume deformation (i.e., because fluid is incompressible)
- Undrained shear strength increases with increased confinement (e.g., at greater depth), so it may vary along the failure surface

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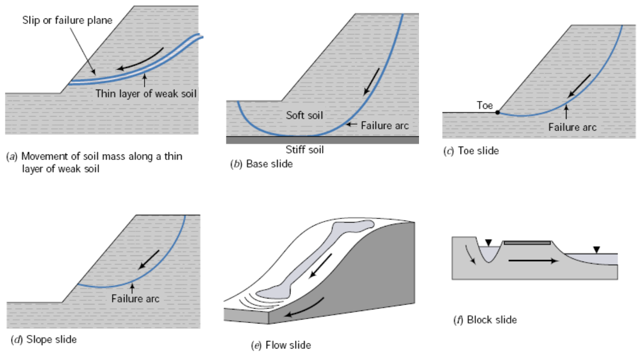
Modes of Slope Failure



(after Budhu, 2000)

Infinite slope failure in Seattle, WA, USA. Sheets of soil slide off the hillside.

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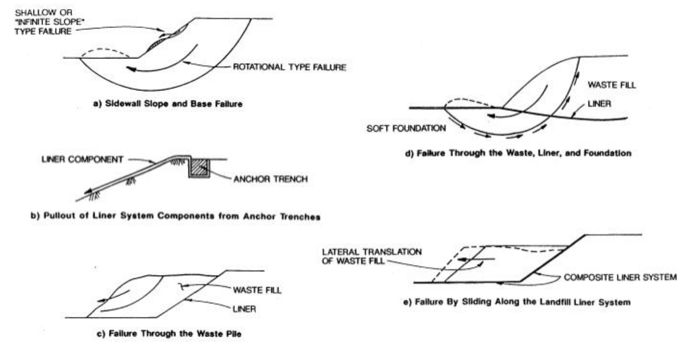
Landfill Slope Failure Modes



(from Mitchell and Mitchell, 1992)

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What is slope instability and what causes it?

- "Slope stability" means a slope moves downhill. A more descriptive term might be "slope instability", since this is the problem.
- The general population calls this a landslide, or mudslide, or a rockslide, depending on the material in the slope.
- Usually the slope moves quickly downhill. However, slow movements occur, and these can be just as dangerous and costly.
- Gravity pulls the soil down with more force that the strength of the soil holding the soil in place. The soil strength can be reduced by water in the slope from rainfall, leaking pipes, infiltration from runoff and other sources. The presence of water reduces the effective stresses between soils particles reducing the strength, as well as increasing the weight of the slope.

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Where are the slope stability problems in landfills?

- Slope failures may occur in the soil, in the waste, at the geosynthetic/waste interface, or in the combinations of the soil and waste and geosynthetic.
- The slopes that must be checked are:
  - bare soil slopes, after excavation (or berm construction)
  - soil slope with lining system in place
  - soil slope with lining system in place and some waste in place
  - waste slope stability, inside the landfill, when waste is being placed below grade
  - waste slope stability when the waste is being placed above grade
  - cover slope stability when the waste is being placed above grade
  - waste and cover slope stability when the waste is being placed above grade

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Examples of Possible Landfill Slope Failures

- When under construction, the soil on the sides of the landfill may fail before waste is placed. These failures may be quick, since the soil was unloaded quickly.
- When the lining system is placed on the side slopes of the landfill, the lining system may fail. Any of the several components – liner, drainage layer, filter layer, or filter protection layer may fail. There must be adequate friction/cohesion/anchorage of the lining components to keep them in place.
- The waste may fail when placed in the landfill. The failure plane may be at, or within, the lining system, or in the soil underneath. The weight of the waste may cause any of these failures.

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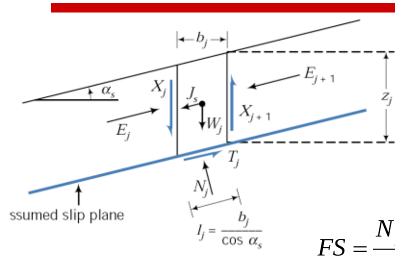
Infinite Slope Failure



$$FS = \frac{\text{soil shear strength}}{\text{minimum strength required for stability}}$$

$$N_j = W_j \cos\alpha_s$$

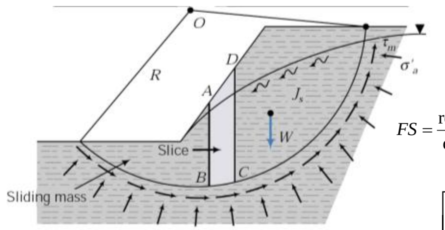
$$T_j = W_j \sin\alpha_s$$

$$FS = \frac{N_j \tan\phi'}{T_j} = \frac{W_j \cos\alpha_s \tan\phi'}{W_j \sin\alpha_s} = \frac{\tan\phi'}{\tan\alpha_s}$$

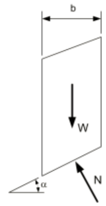
For short-term stability, we use the undrained shear strength and perform a similar analysis

(after Budhu, 2000)

Rotational Slope Failures



$$FS = \frac{\text{resisting forces}}{\text{driving forces}}$$



Back-of-the-envelope solutions:

$$FS = \frac{R\theta s_u}{Wx}$$

$$FS = \frac{\sum_{slices}\left[\frac{(W - u\Delta x \sec\alpha)\tan\phi'}{\cos\alpha + \frac{\sin\alpha \tan\phi'}{FS}}\right]}{\sum_{slices} W \sin\alpha}$$

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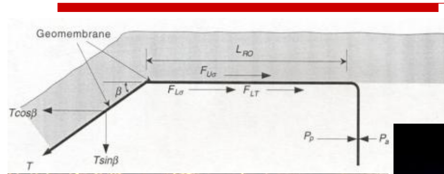
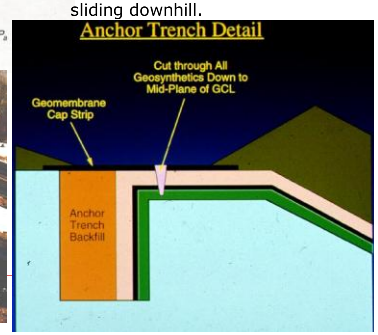
Anchor Trench Pullout Failures

The geosynthetic lining system components (geomembrane, geonet, geogrid, GCL) are placed in *anchor trenches* at the top of the slope to resist geosynthetic sliding downhill.





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Case Study: Kettleman Hills

- Hazwaste landfill
- 15 acre failure
- Slope Height = 90 ft
- Bowl-shaped volume
- Side slopes – 2H:1V to 3H:1V
- Waste placement began in 1987
- Failure occurred on March 1988
- Leachate pumping ~ 4,500 gal/month
- 20-inch avg. leachate level in LCS

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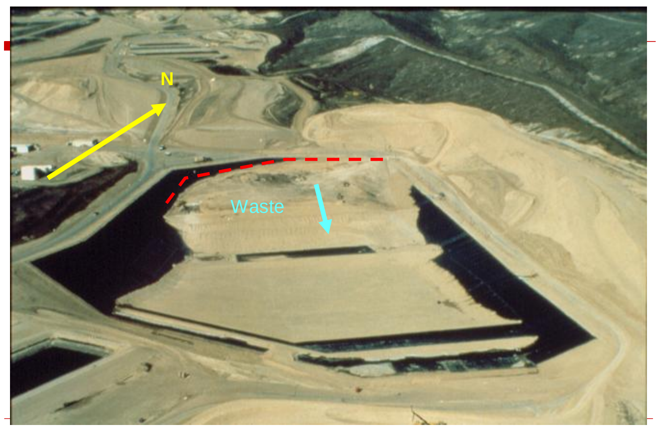
Kettleman Hills Landfill



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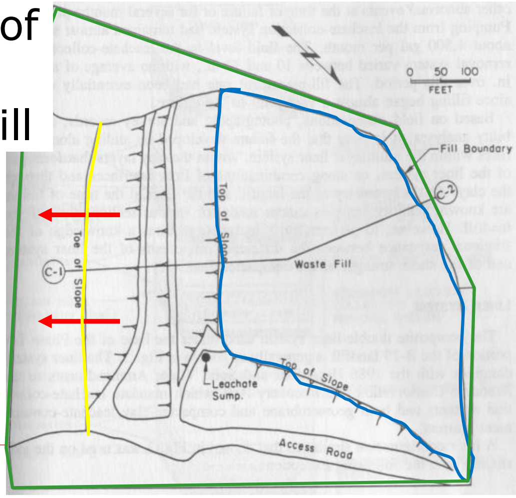
Plan View of Kettleman Hills Landfill



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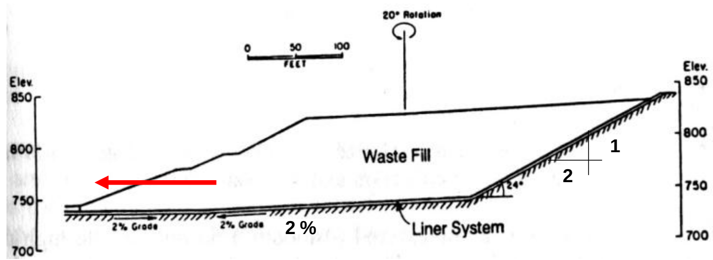
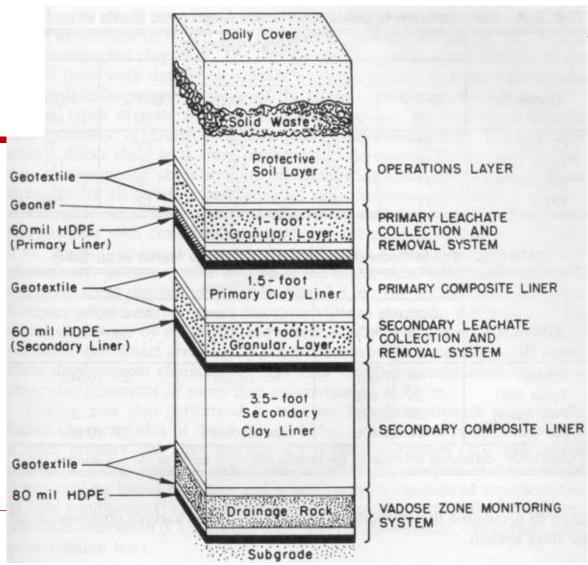
Elevation View



Liner System
(Base liner)



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Comments on Stability Analyses

- Wet vs. Dry Base: Changes FS ~ 10%
  - Failure would have occurred wet or dry.
- 3-D FS ~ 10 to 15% less than 2-D FS.
- 3-D FS ~ 1.01 to 1.08
- Uncertainties:
  - Interface Friction Angles - ± 10%
  - 3-D Analysis - ± 10%
  - GM/Clay Interface Strength - ± 25%

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Summary of Stability Analyses

Base Liner Conditions	2-D Analyses	3-D Analyses	Overall Best Estimate
Probable Wetted Base	1.2 to 1.25	1.08	~0.95 to 1.25
Full-base Wetting	1.1 to 1.15	1.01	~0.85 to 1.15

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Practical Implications

- Large variability in measured interface-strengths:
  - Perform tests for proposed facilities.
- Special consideration in design process for low strength liner systems:
  - Consider 3-D effects on stability.
- Major outcome:
  - Development of *textured* geomembranes.

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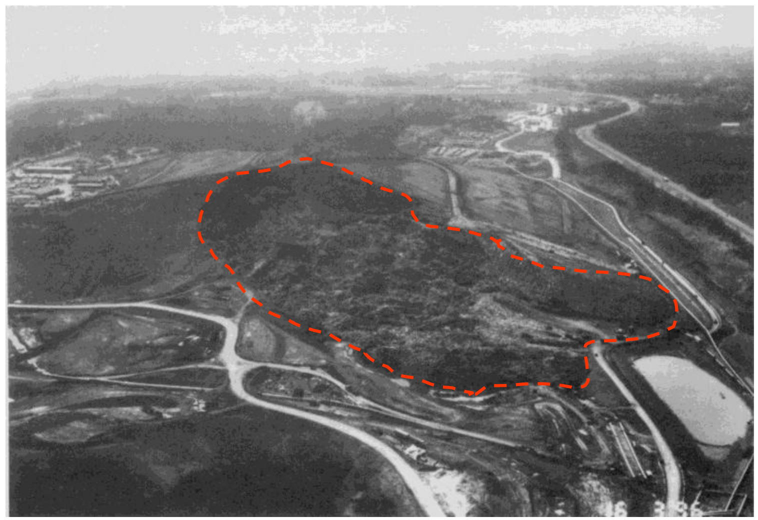
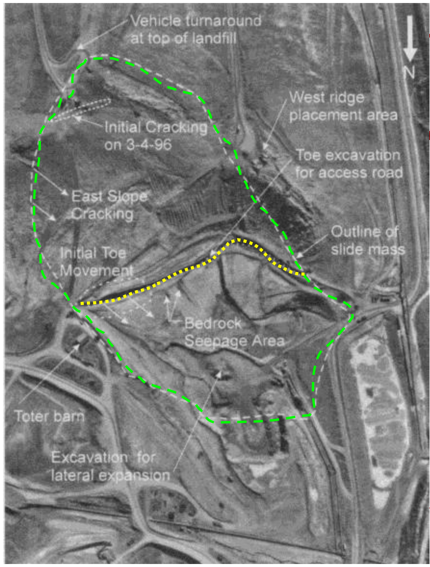
Case Study: Rumpke Landfill

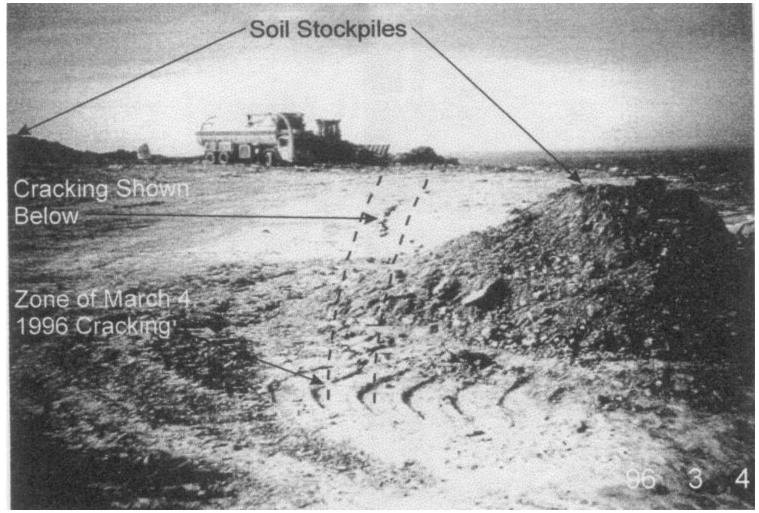
- MSW landfill
- Farm waste storage 1945
- Failure, March 9, 1996
- 1,100,000 m^3 of MSW
- No liner most of site
- 1988 clay liner, ~ 5.7 ha
- 1994 composite liner proposed ~1.5 ha
- Natural soil – low k, *colluvium*
- Interbedded shales and limestone
- Mass waste movement
- Translation of 50 to 60 m (in 5 minutes)
- Observed failure surface: steep angle through waste to underlying colluvium



Rumpke Landfill

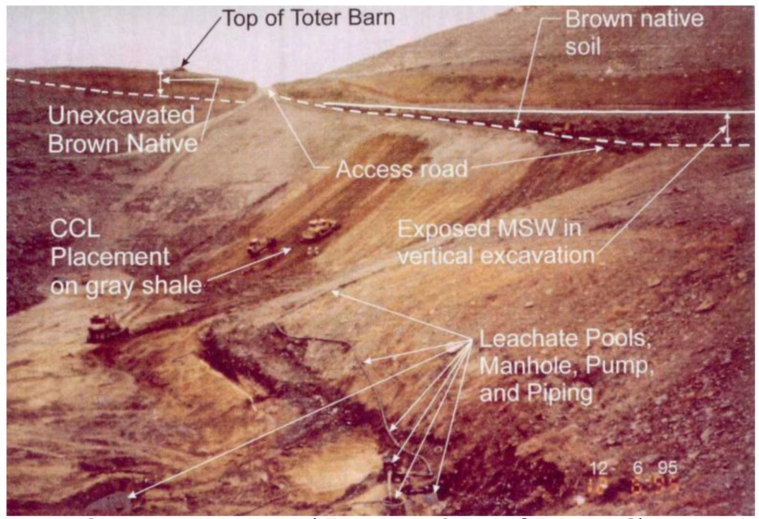


Landfill 32 days prior to slide.

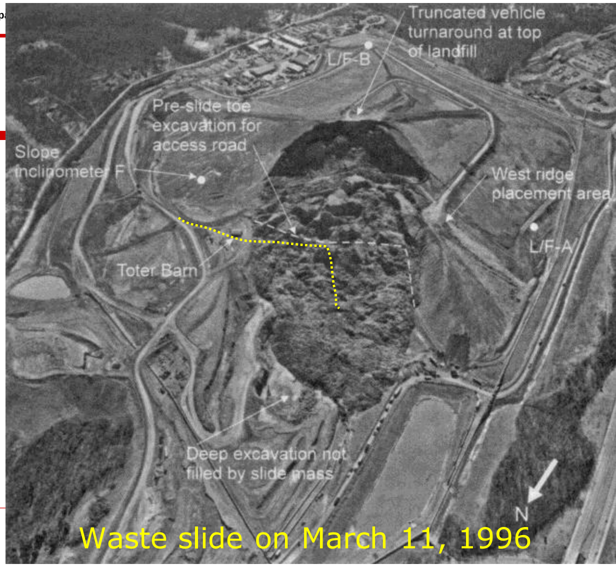


Waste placement and cracking at top of landfill, March 4, 1996

Cracking at top of landfill, March 4, 1996



Construction in Lateral Expansion & Toe of Existing Slope
December 6, 1995



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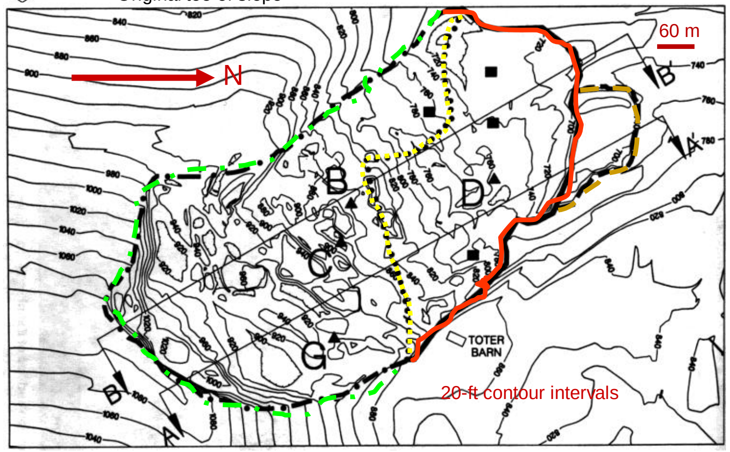
Original toe of slope

Extent of slide mass in excavation



Existing LF impacted area

30

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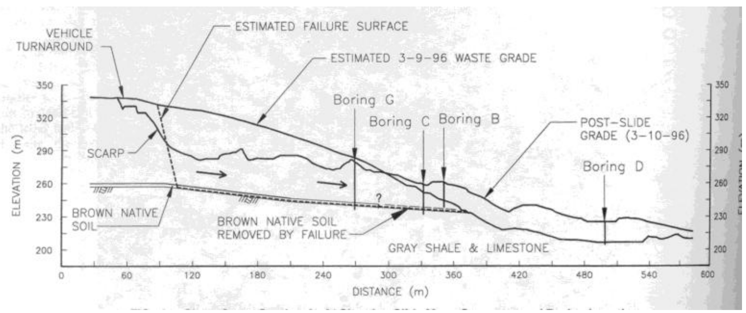
Cross-Section A-A': Slide Mass Geometry and Boring Locations



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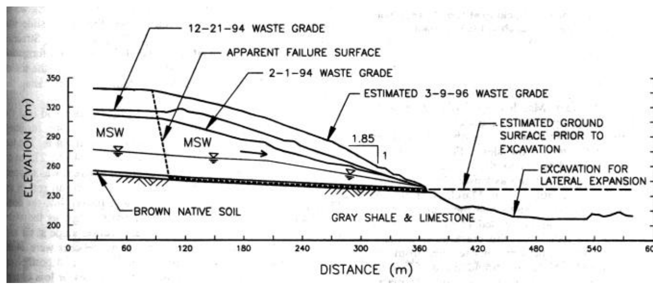
Cross section B-B'



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Summary

- Convergence of multiple unfavorable conditions:
  - Topography
  - Strain-softening soil
  - Toe excavation
  - North facing slope
  - Temps colder than normal
  - Pore pressure build up
- Lessons Learned
  - MSW Strength
    - High for static conditions
    - Low for dynamic conditions
  - Observations – look at the BIG picture
  - Post-peak strengths for soils
  - Strain incompatibility among materials
  - Blasting effects
  - Leachate collection & removal is critical.
  - Evaluate stability of INTERIM slopes

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Acknowledgements

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