Veneer Stability Calculations

MSW, Mixed & Hazardous Waste Landfills
Superfund Sites (… that used to be Landfills)
Heap Leach Pads and Tailings Impoundments
Earthfill Dams

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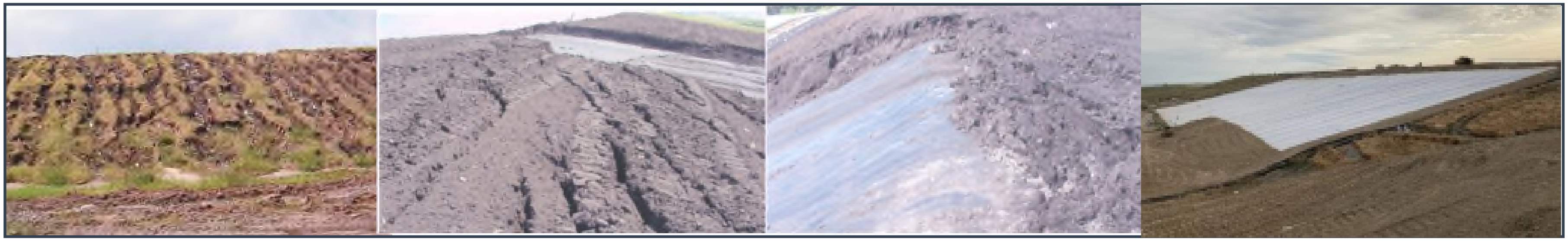
OUTLINE

1. Introduction
2. "Simplified" Analyses
3. Case Study (Composite Cover)
4. Special Cases
5. Advanced Analysis
6. Take-Aways ... and spreadsheets and papers to download

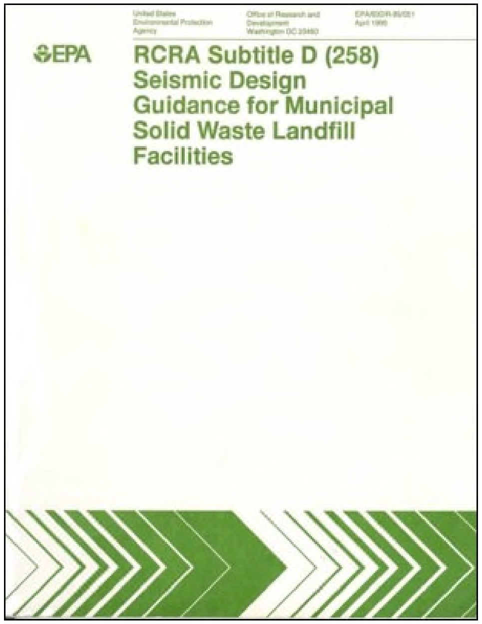
} State-of-the-Practice

← State-of-the-Art



INTRODUCTION

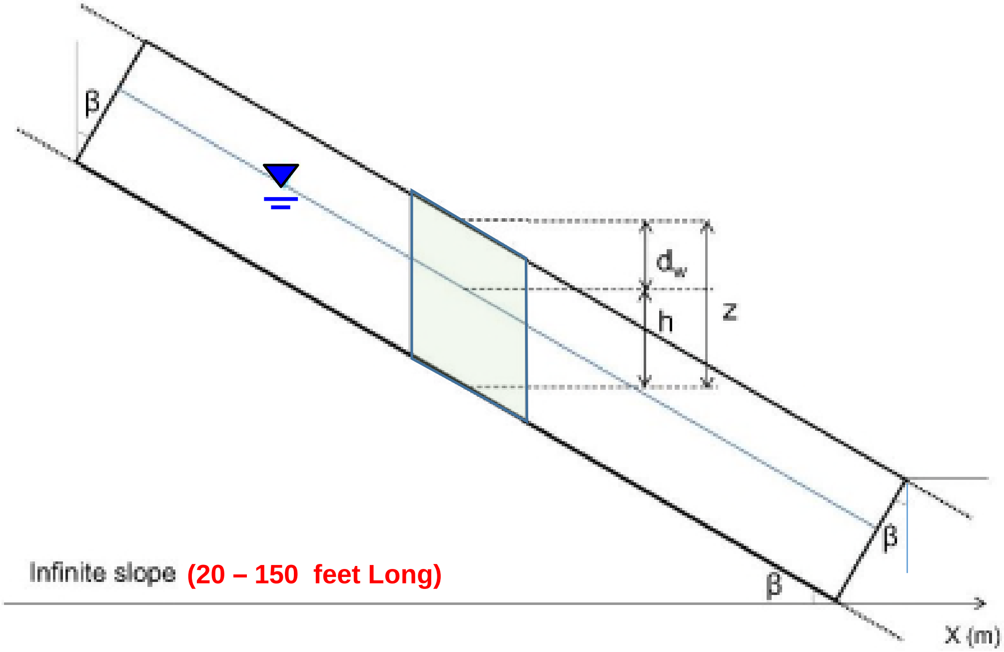
VENEER STABILITY ≈ INFINITE SLOPE (?)



EPA

RCRA Subtitle D (258)
Seismic Design
Guidance for Municipal
Solid Waste Landfill
Facilities

Richardson et al. (1995) or EPA (1995)



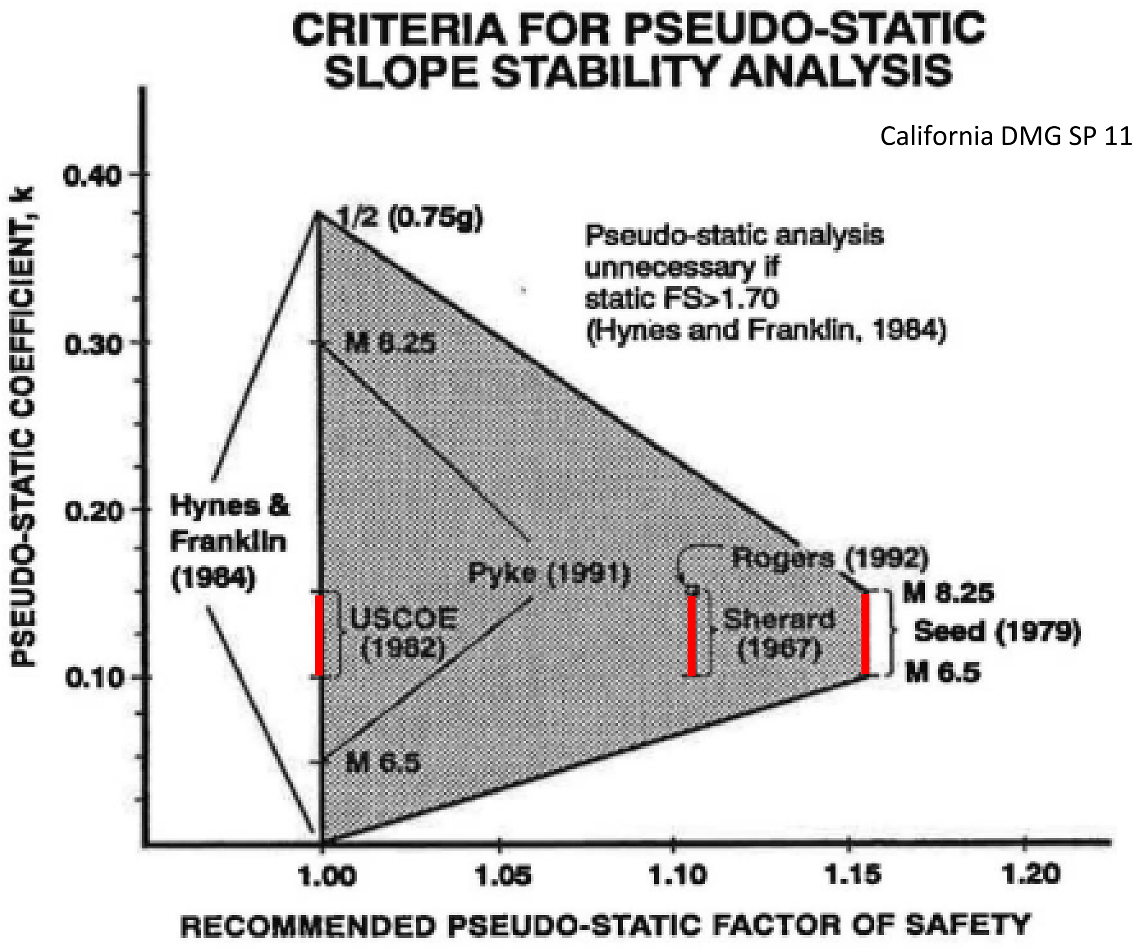
$$FS = \frac{\frac{c}{\gamma\, z\, \cos^2\beta} + \tan\phi\left[1 - \frac{\gamma_w\,(z - d_w)}{\gamma\, z}\right] - \boxed{k_s}\tan\beta\,\tan\phi}{\boxed{k_s} + \tan\beta}$$

Matasovic (1991)

k_s = Seismic coefficient (dimensionless constant; H = k_s x W)

FGI
Fabricated Geomembrane Institute

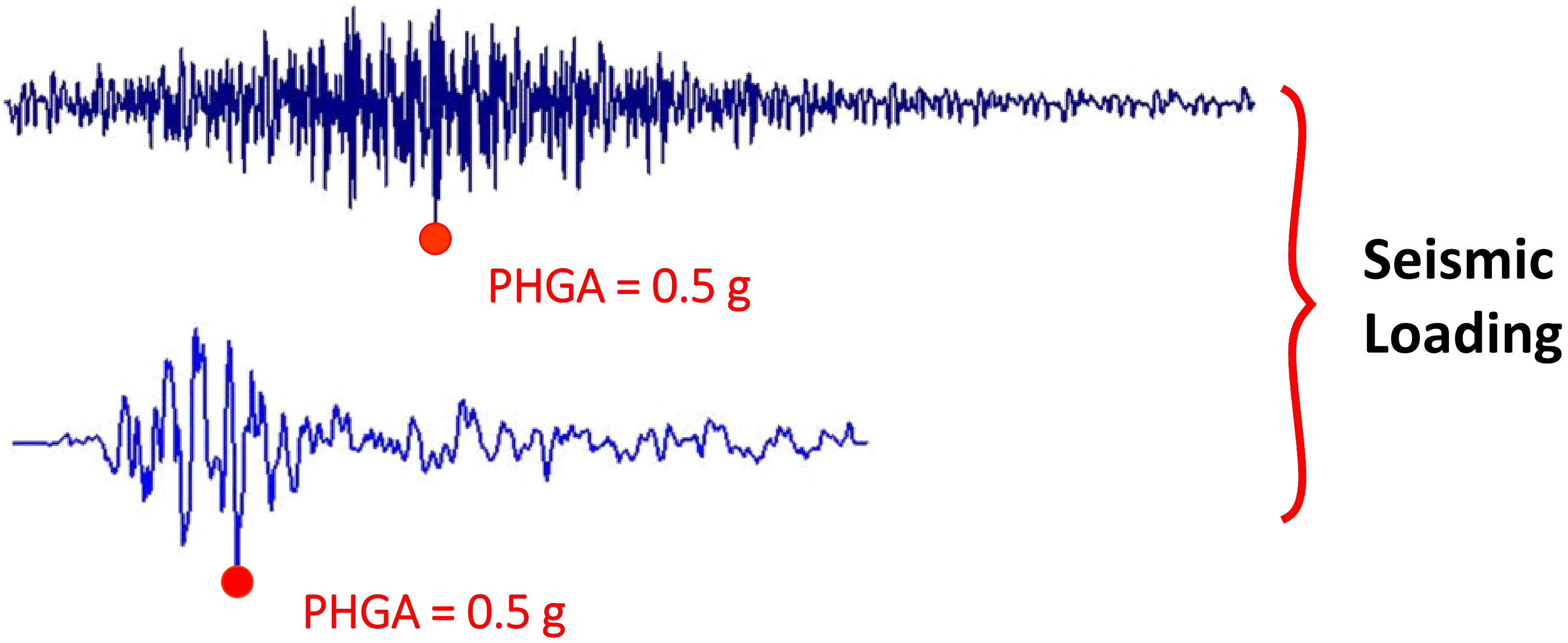
EVALUATION OF k_s



California DMG SP 117 (1997)

California Title 27 requires "Dynamic FS ≥ 1.5" (… but offers no further guidance)

SEISMIC COEFFICIENT (k_s)

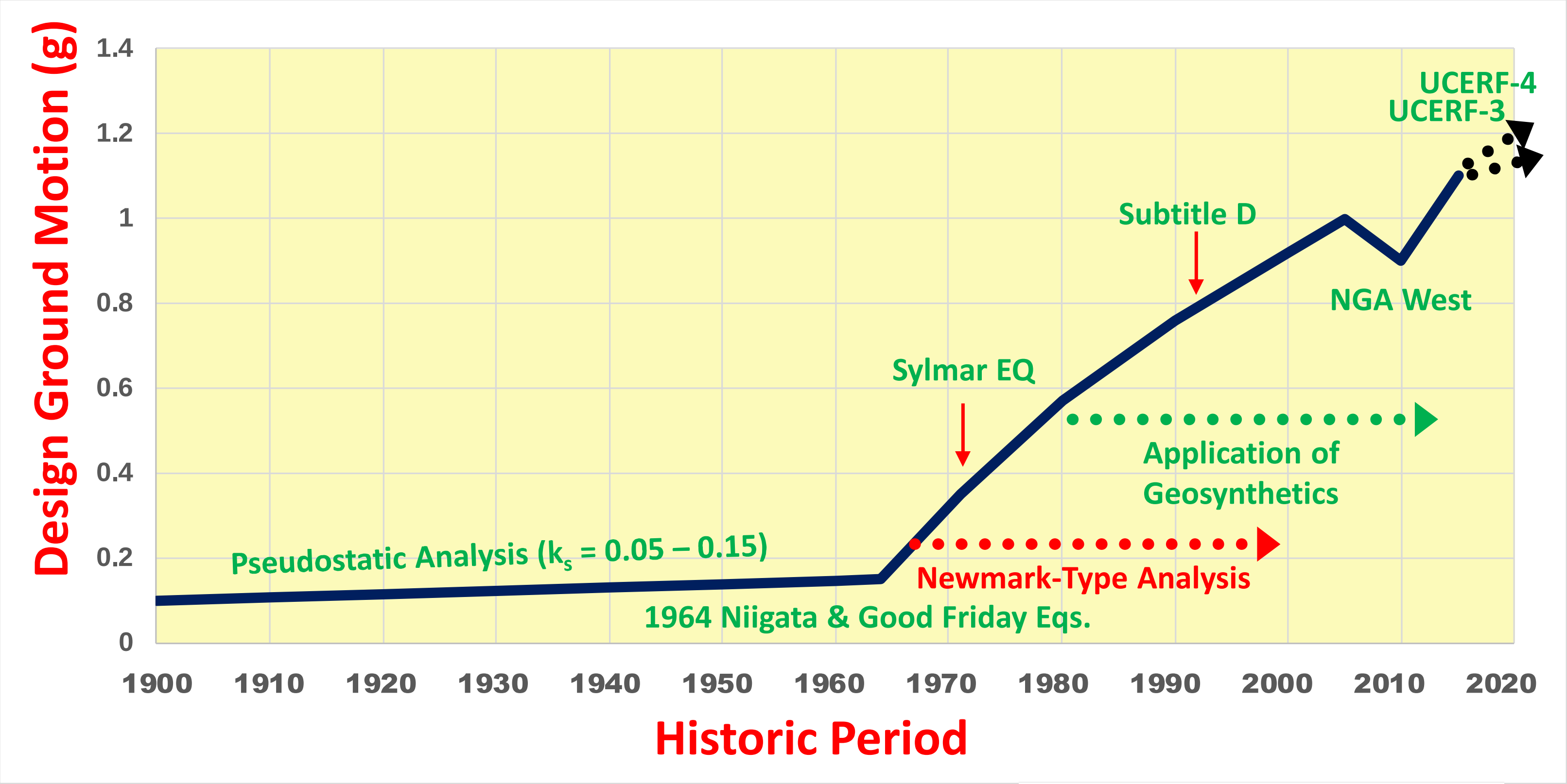


Can one evaluate k_s from PHGA?
Is damage potential induced by these two motions the same?

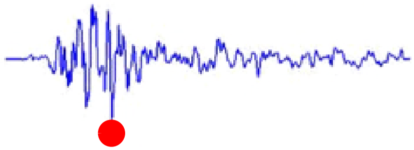
SEISMIC COEFFICIENT (CONT.)

Conceptual Trend of Ever-increasing Design Ground Motion

PHGA



2014 M 6.0 South Napa (California) Eq. – Recorded PHGA = 1.0 g!



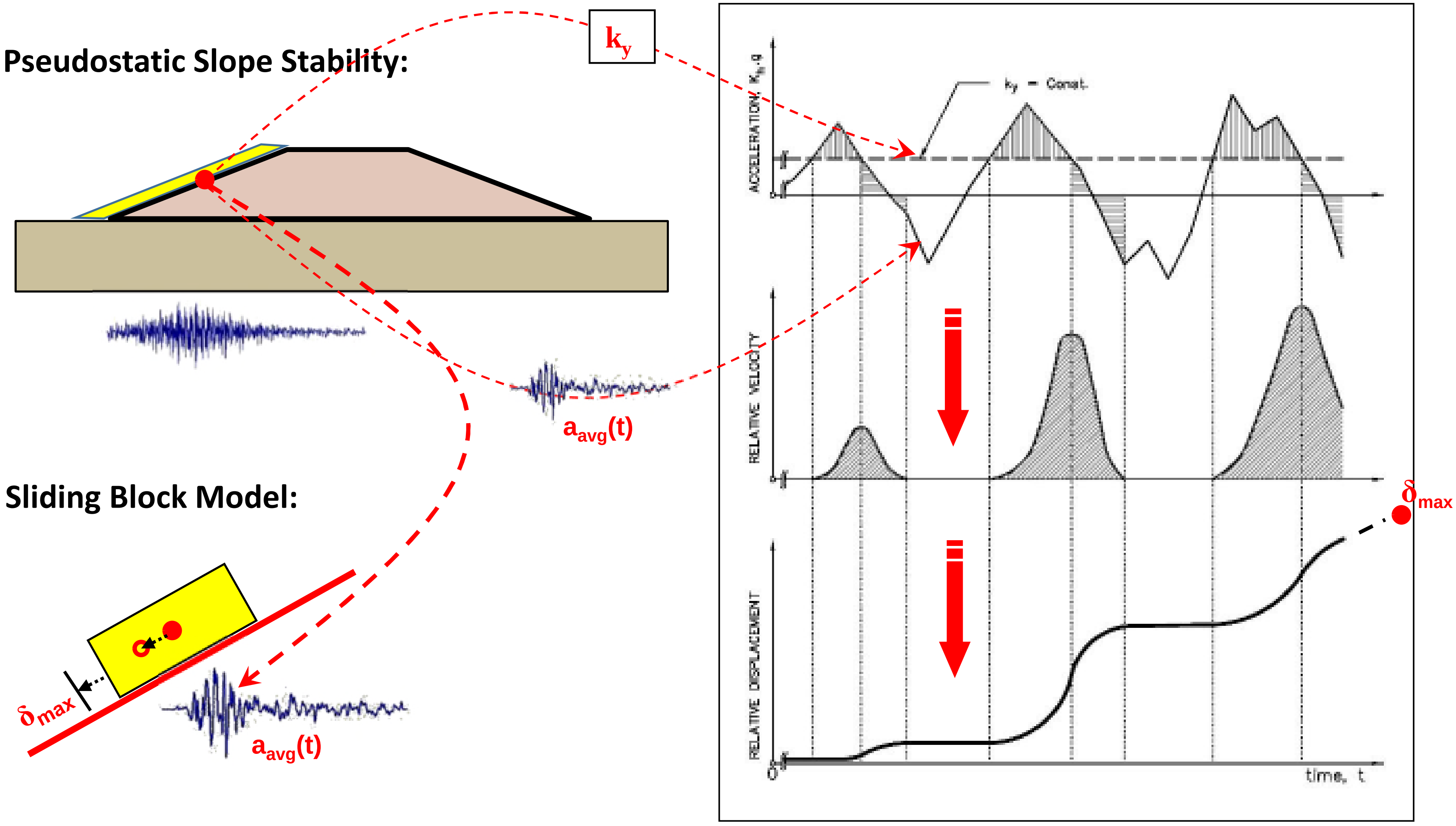
CA (MPE): Design event must be ≥ than the largest historic event …

NEWMARK-TYPE ANALYSIS

(Sliding Block Analysis)

- FS = 1.0 does not necessarily mean a failure! It means "block starts to move …"
- Performance-Based Design – The intensity of calculated displacement controls the design

NEWMARK-TYPE ANALYSIS (CONT.)



Pseudostatic Slope Stability:

Sliding Block Model:

After Newmark (1965)

NEWMARK-TYPE ANALYSIS

(Simplified Approach / "Spreadsheet")

Input (“Simplified” Analyses Only):

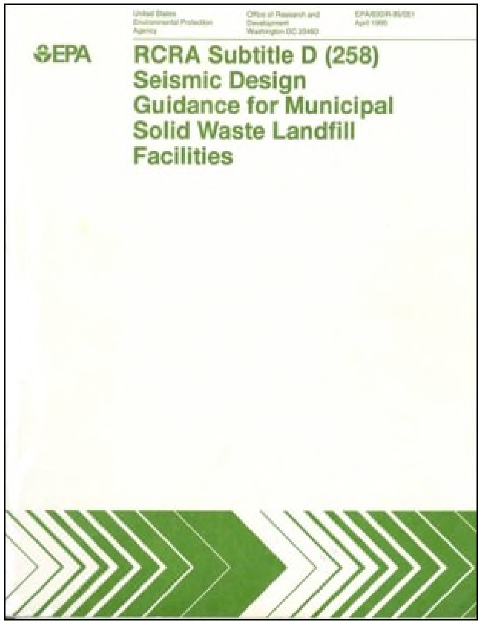
1. Yield acceleration of sliding mass (k_y) (accel. for FS = 1.0)
2. Initial Fundamental period of sliding mass (T_s)
3. (Design) ground motion (M, S_a, and PGV, …)

Output:

- Maximum calculated permanent seismic displacement (δ_{max})

Note: M = Moment Magnitude; S_a = Spectral acceleration at the base of the sliding mass …; PGV = Peak Ground Velocity at the base of the sliding mass …

INP. 1. YIELD ACCELERATION (k_y)



United States
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EPA

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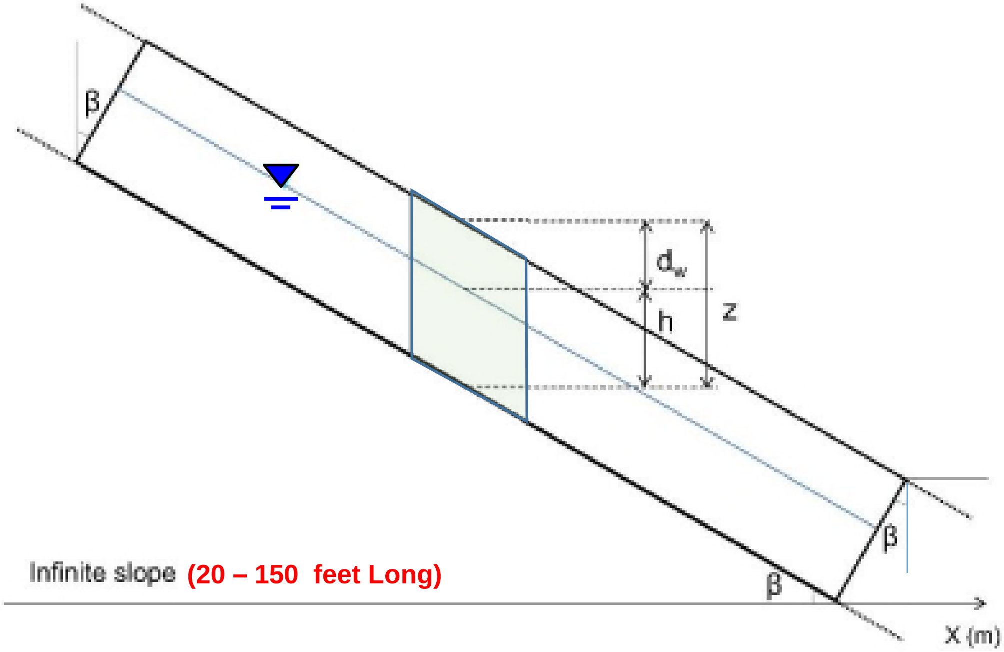
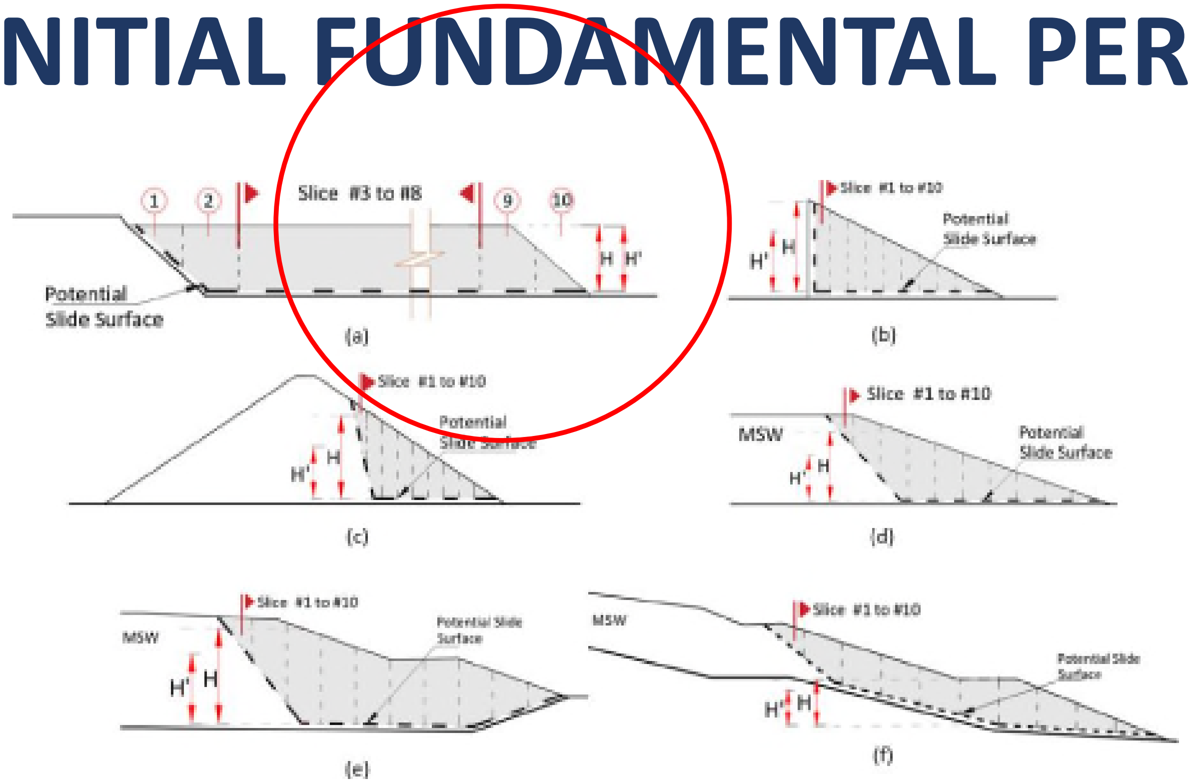


Infinite slope **(20 – 150 feet Long)**

$$k_y = \frac{\frac{c}{\gamma\, z\, \cos^2\beta} + \tan\phi\left[1 - \frac{\gamma_w\,(z - d_w)}{\gamma\, z}\right] - \tan\beta}{1 + \tan\beta\tan\phi}$$

Matasovic (1991)

INP. 2. INITIAL FUNDAMENTAL PERIOD



Bray and Macedo (2021)
Matasovic and Thiel (2021)

$$T_s = 4\,H'/V_s$$

T_s = initial fundamental period of the potential sliding mass

H' = the effective height of an equivalent one-dimensional sliding mass

V_s = (average) shear wave velocity

INP. 3. DESIGN GROUND MOTION

Input: **("Simplified" Analyses Only; USGS web page):**

A. Latitude and Longitude & "Applicable Code"

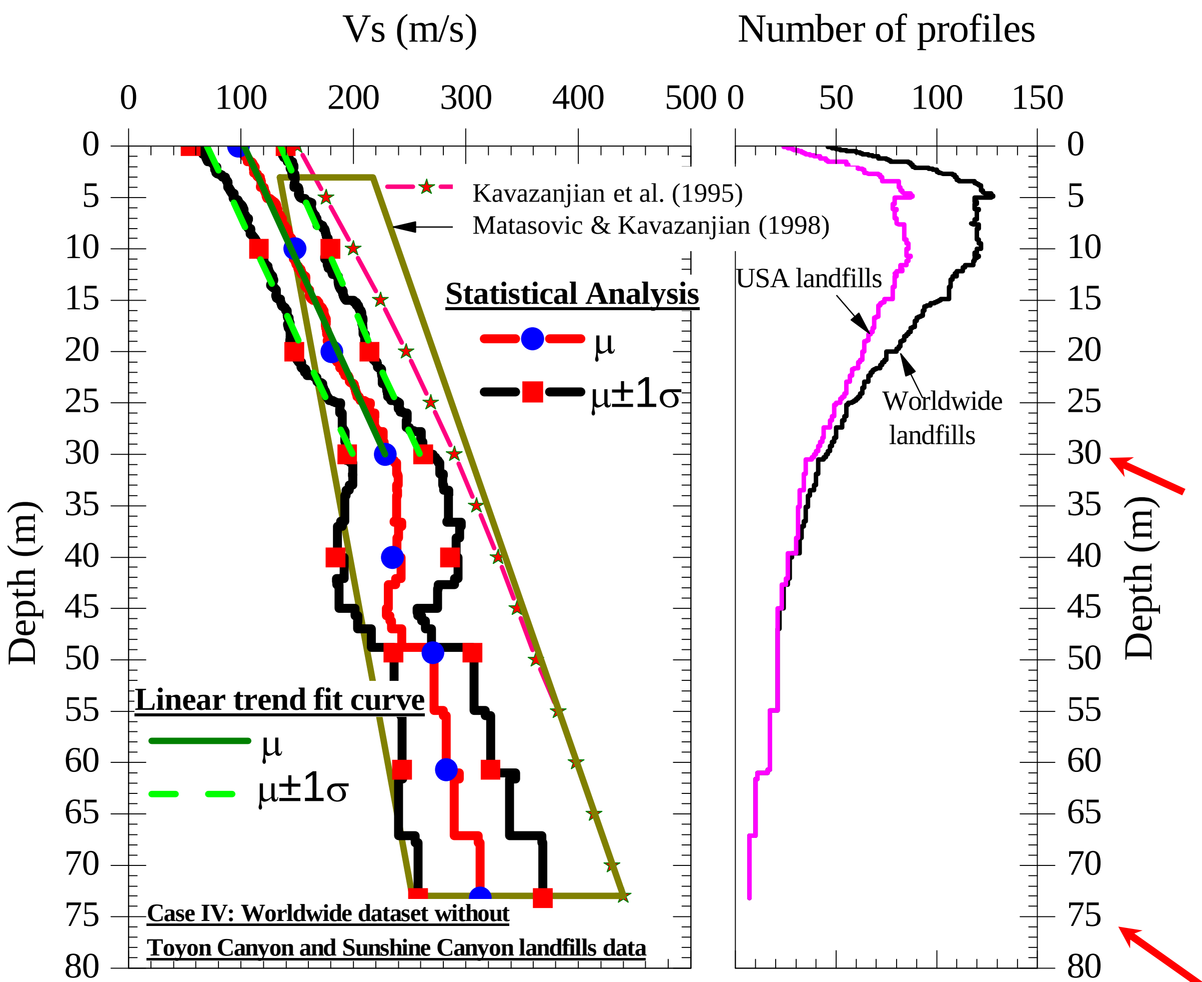
B. $V_{s\text{-}30}$ (NEHRP Site Class)

Output:

- M, S_a (PHGA), and PGV, …
- Other

Note: For landfill cover, Spectral Acceleration Ordinate, $S_a \approx$ PHGA at the landfill surface

INP. B. SHEAR WAVE VELOCITY PROFILE



Ramaiah et al. (2015)

V_{s-30}

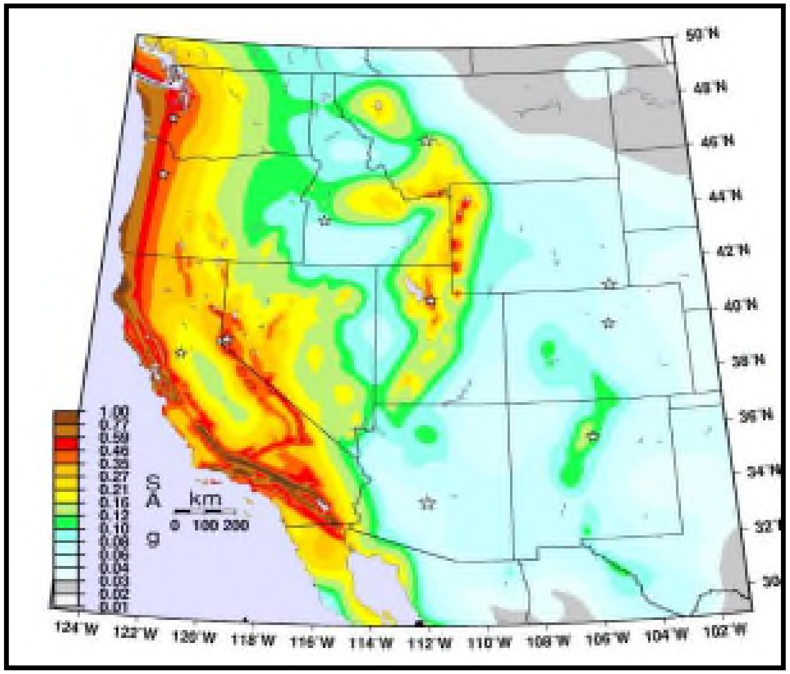
75 m = 250 ft

Digitized average V_s profile from Matasovic and Kavazanjian (1998)

Depth (ft)	V_s (ft/s)
-5	820.2
-10	569.6
-20	593.2
-30	616.8
-40	640.4
-50	664.0
-60	687.7
-70	711.3
-80	734.9
-90	758.5
-100	782.2
-110	805.8
-120	829.4
-130	853.0
-140	876.6
-150	900.3
-160	923.9
-170	947.5
-180	971.1
-190	994.8
-200	1018.4
-210	1042.3
-220	1065.6
-230	1089.2
-240	1112.9
-250	1136.5

V_{s-30} is required to evaluate the design ground motion

NOTE ON DESIGN GROUND MOTION



RP = Return Period

PE = Probability of Exceedance

MPE = Maximum Probable Earthquake

MCE = Maximum Credible Earthquake

California mandates deterministic seismic hazard analysis (MPE & MCE); Everybody else mandates probabilistic (2% PE in 50 years or 2,475-yr RP)*

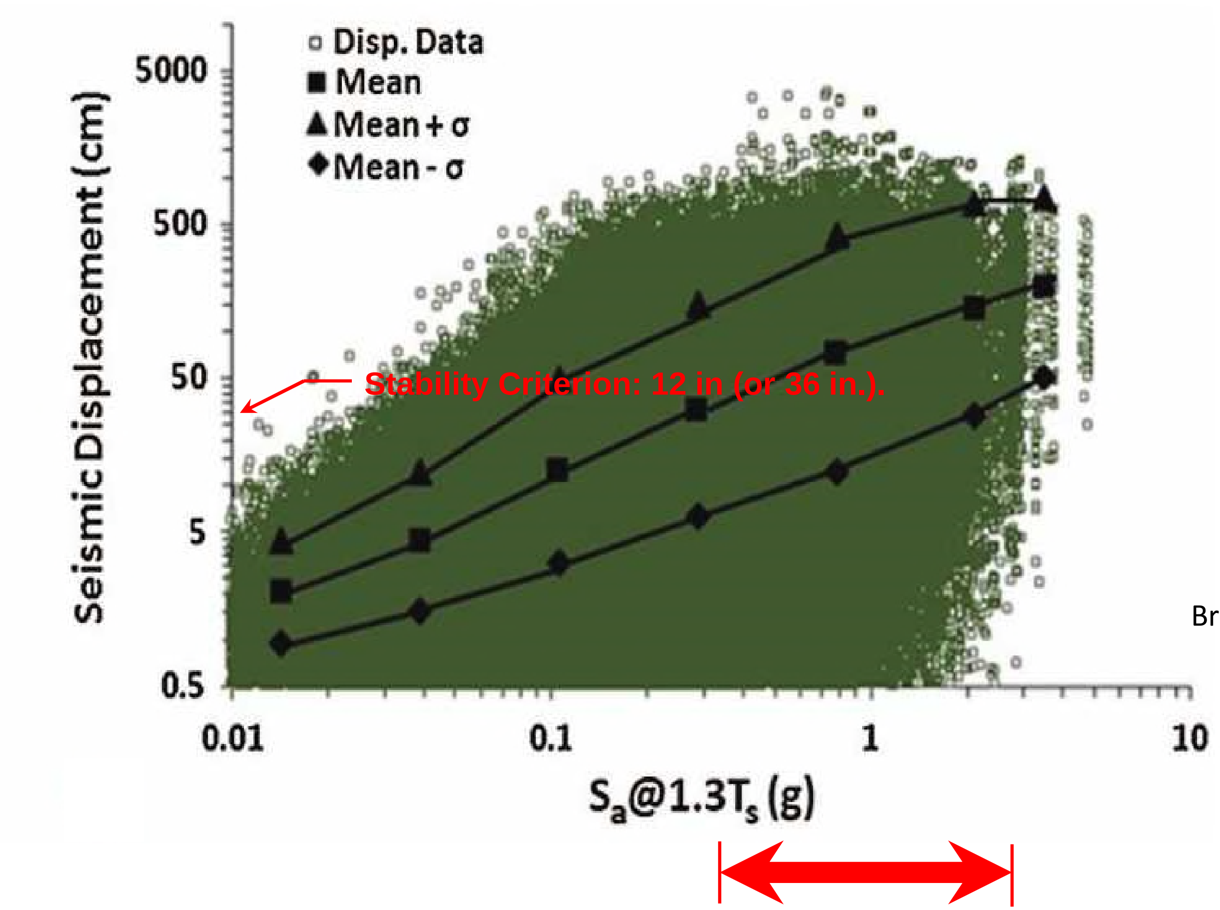
Building code allows for a 2/3 Reduction of design ground motion; US Subtitles D & C do not. So, buildings in US are designed for approx. 500-yr RP, while landfills outside of CA are designed for a 2,475-yr RP

2,475-yr RP motion is typically much higher than its deterministic (MPE and MCE) counterparts

Site specific analysis is required to obtain PGV

STATE OF PRACTICE* – BRAY & TRAVASAROU

(Latest Update: Bray and Macedo, 2019; 2021)



Stability Criterion: 12 in (or 36 in.).

Bray and Macedo (2019)

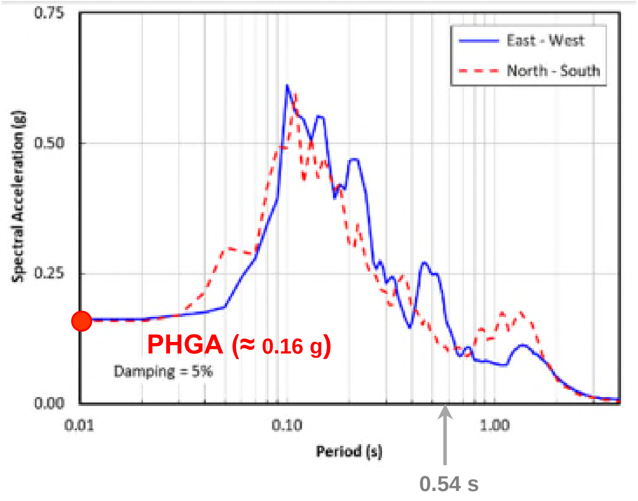
Landfills

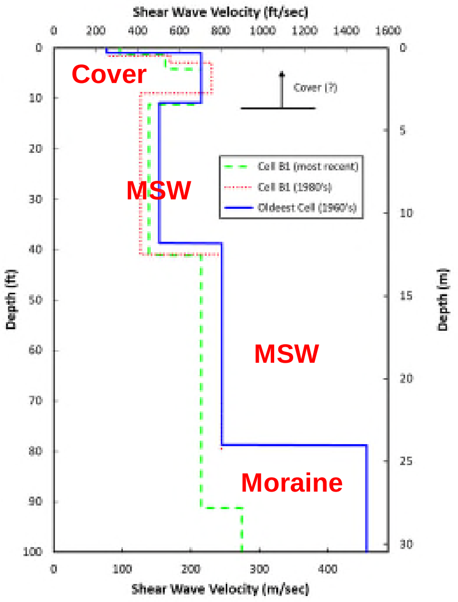
(T_s ≈ 0.3 – 3.0 s)

OLYMPIC VIEW SANITARY LANDFILL

(Composite Landfill Cover Seismic Case History)

- MSW Landfill in WA; Founded in Moraine (Weak Rock)
- 2001 M 6.8 Nisqually Eq.
  - SM: Recorded in Moraine ≈ 1 km from the Site
  - Weak Rock PHGA ≈ 0.16 g
  - Site-Specific Measurements (V_s and in-plane strength)
  - Post-EQ Observation: δ_{max}= 0 (no cracks in cover observed)



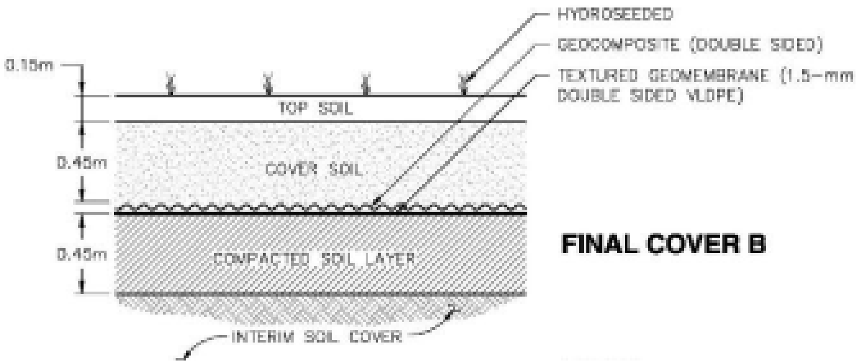


Matasovic and Kavazanjian (2006)

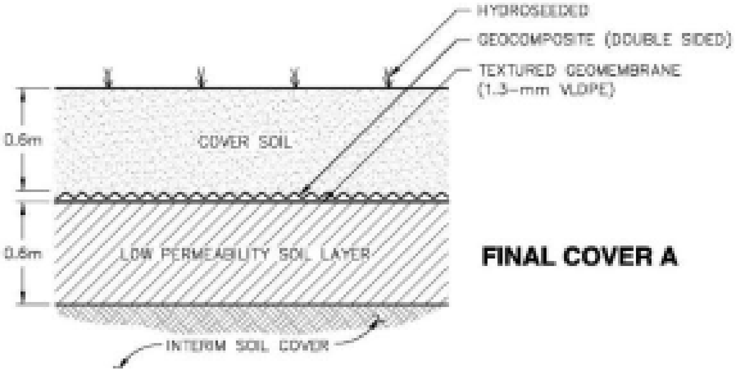
OLYMPIC VIEW SANITARY LANDFILL – AERIAL VIEW IN 2001

Matasovic and Kavazanjian (2006)

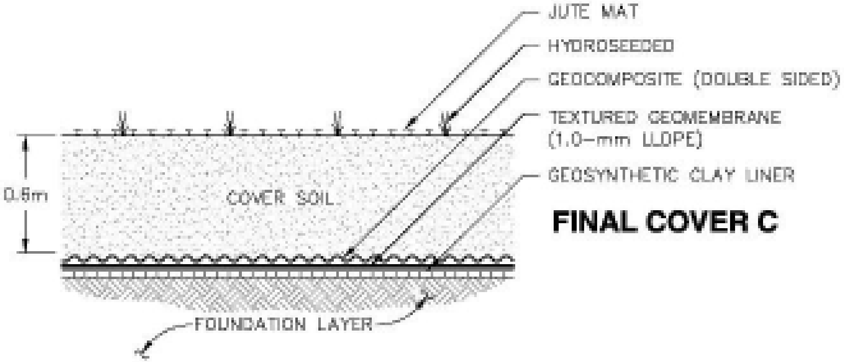
OLYMPIC VIEW
SANITARY LANDFILL



FINAL COVER B

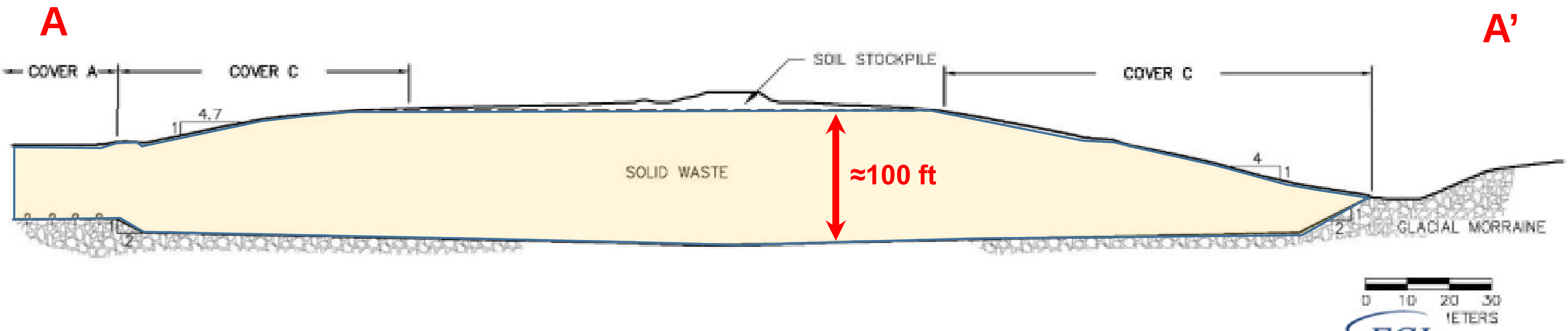


FINAL COVER A



FINAL COVER C

Matasovic and Kavazanjian (2006)



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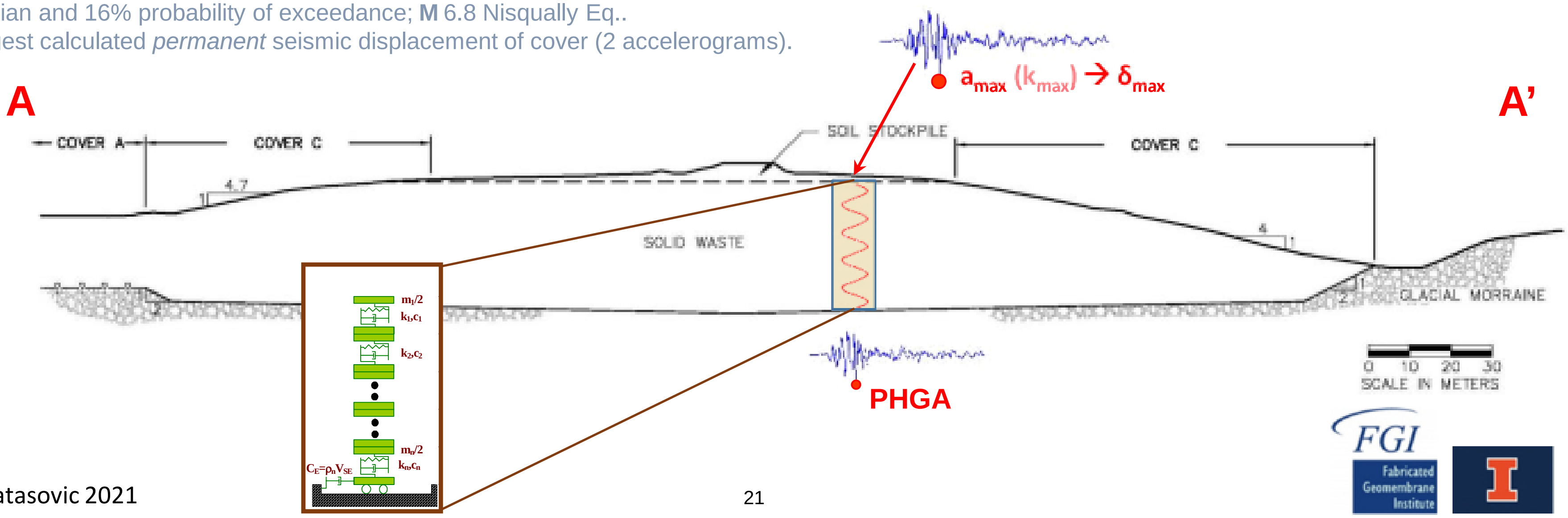
SITE RESPONSE & SEISMIC DEFORMATION ANALYSIS

Method	Bedrock PHGA (Input)	a_{max}	k_{max}	δ_{max} (k_y = 0.17 g)	δ_{max} (k_y = 0.22 g)
1 EPA (1995) / H & F Charts 	0.16 g	0.47 g	0.47 g	100 mm[A]	< 100 mm[A]
2 EPA (1995) / M & S Charts 	0.16 g	0.47 g	0.47 g	100 - 230 mm[B]	50 - 130 mm[B]
3 Bray et al. (1998)	0.16 g	0.28 – 0.34 g	0.28 - 0.34 g	30–130 mm[C]	6 – 40 mm[C]
4 De-Coupled Analysis (D-MOD2000)	0.15 g (NS); 0.16 g (EW)	0.18 - 0.19 g	0.18 - 0.19 g	< 1 mm[D]	0

Matasovic and Kavazanjian (2006)

H & F = Hynes and Franklin (1984).
M & S = Makdisi and Seed (1978).
[A] Mean plus one standard deviation curve.
[B] Mean and upper bound for the **M** 6.5 chart.
[C] Median and 16% probability of exceedance; **M** 6.8 Nisqually Eq..
[D] Largest calculated *permanent* seismic displacement of cover (2 accelerograms).



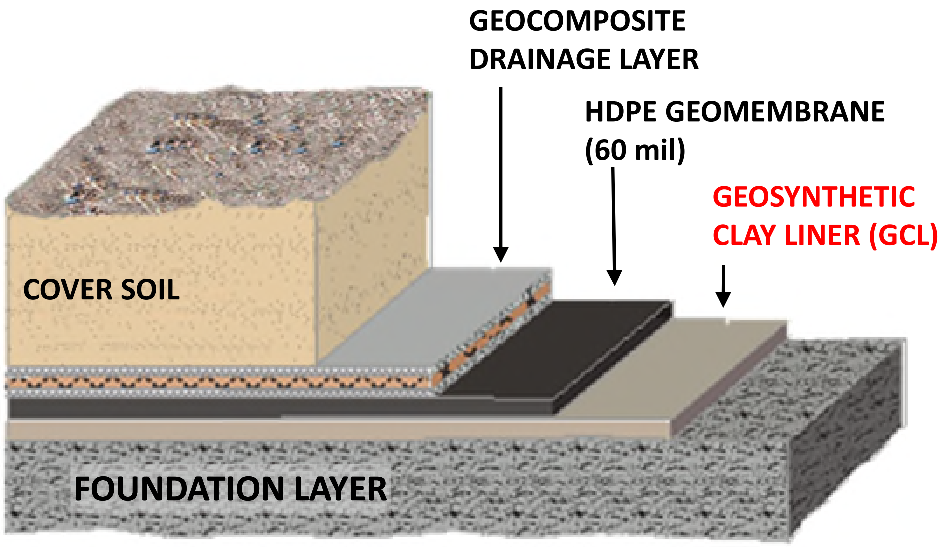
STATE-OF-PRACTICE - DISCUSSION

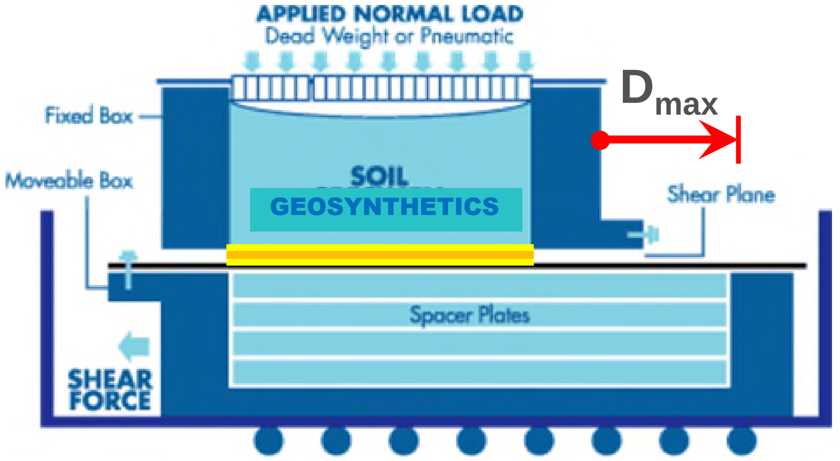
- Is SOP Conservative (?)
- Is SOP Economical (?)
- Limitations of the SOP?
  - Very High Design Ground Motions
  - Complex Geometry
  - Thick Fills (350^+ ft or 100^+ m)
- Perf.-Based Stability Criteria (12 – 36 in.)
- Other …

ET Cover

Composite Cover

LAB MEASUREMENT OF IN-PLANE STRENGTH





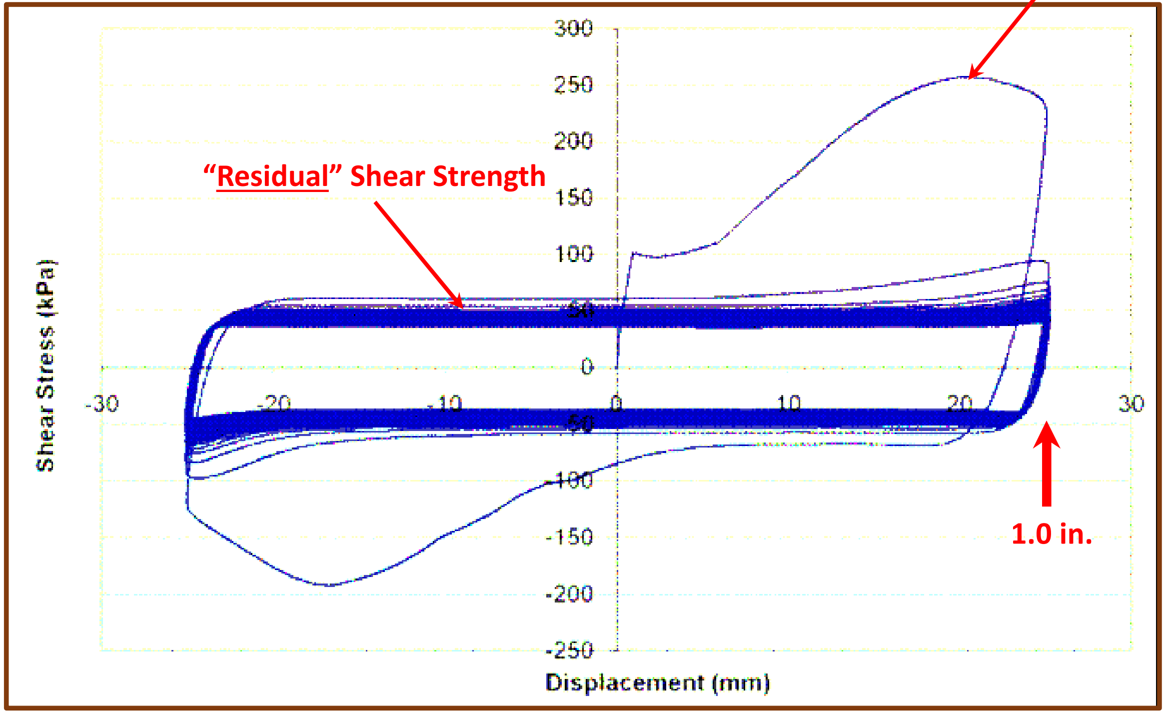
Conventional Shear Box:

- Box: 305×305 mm (12×12 in.)
- D_{max} = 90 mm (3.5 in.)
- 1 mm/min (0.04 in./min) or
- 0.1 mm/min (0.004 in./min) GCL internal
- Static Only!

LAB MEASUREMENT OF IN-PLANE STRENGTH

“**Peak**” Shear Strength

Stress-Strain Loops (Cyclic Test):



“**Residual**” Shear Strength

1.0 in.

Nye and Fox (2007)

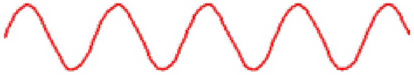
GCL (Bentomat ST)

σ_n = 141 kPa (30 ft of MSW)

D_{Static} = 0.9 m (36 in.

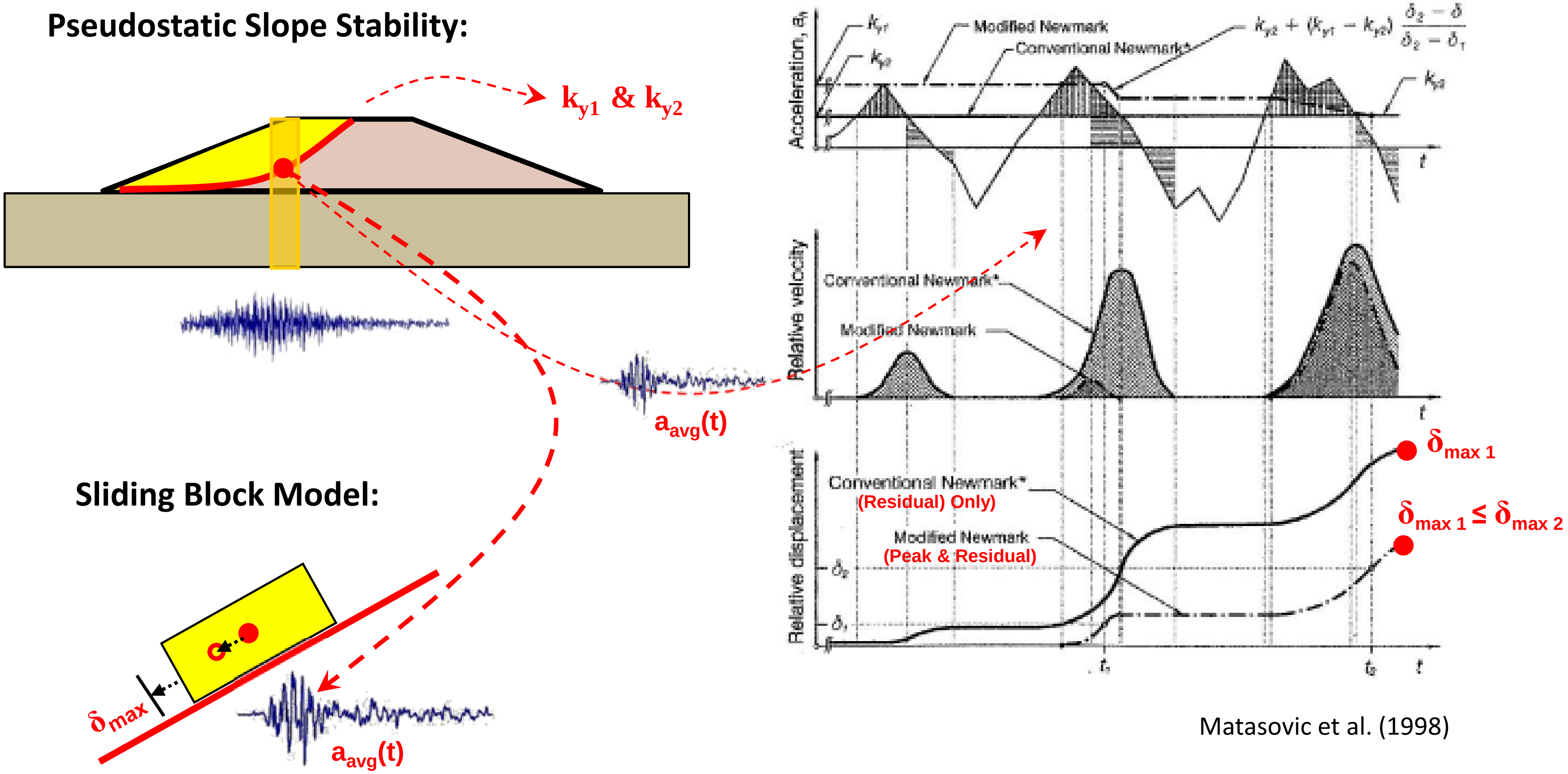
D_{Cyclic} = ± 25 mm (±1 in.)

f = 1 Hz



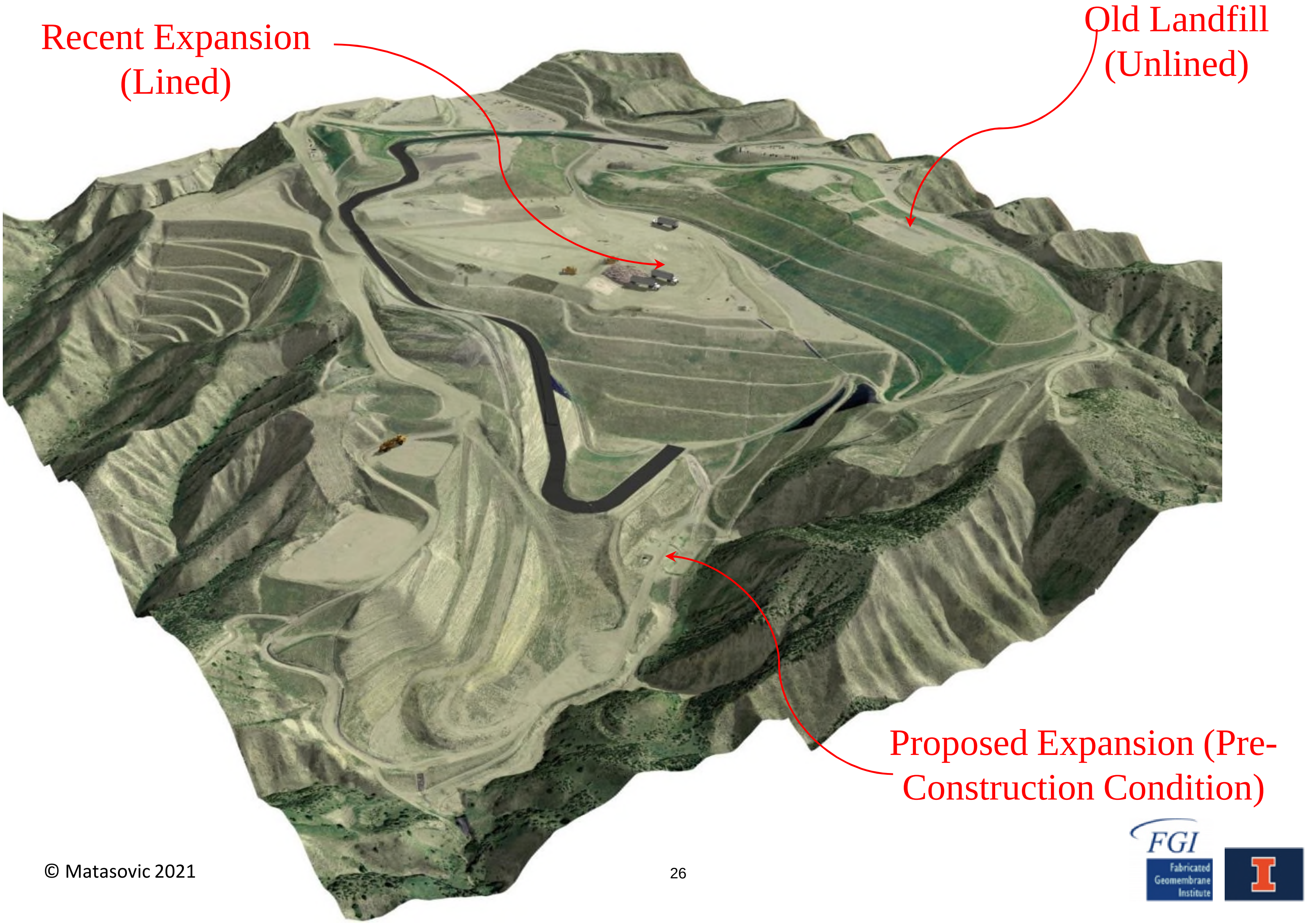
MODIFIED NEWMARK-TYPE ANALYSIS

(Newmark-Type analysis w/ Degrading Yield Acceleration)

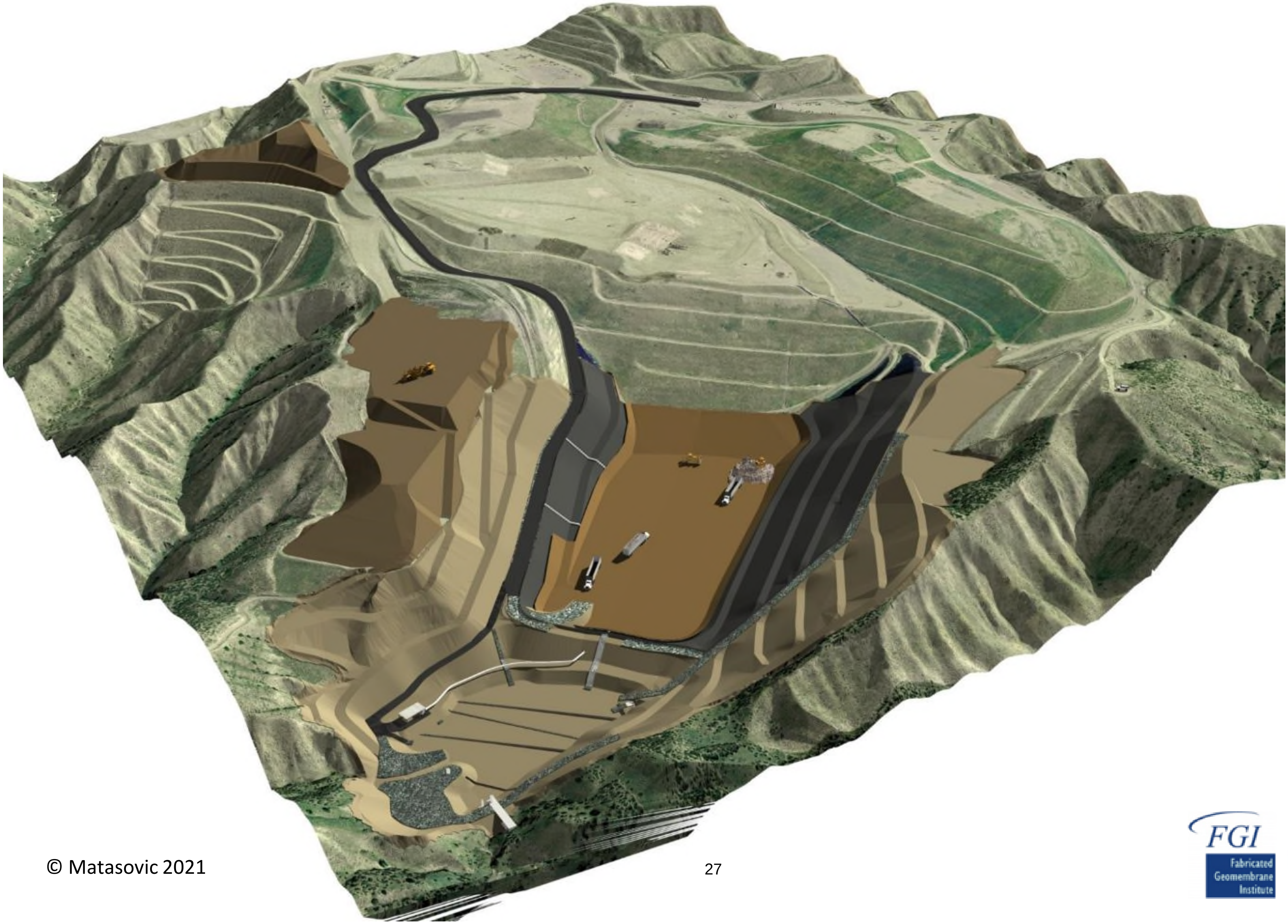


Matasovic et al. (1998)

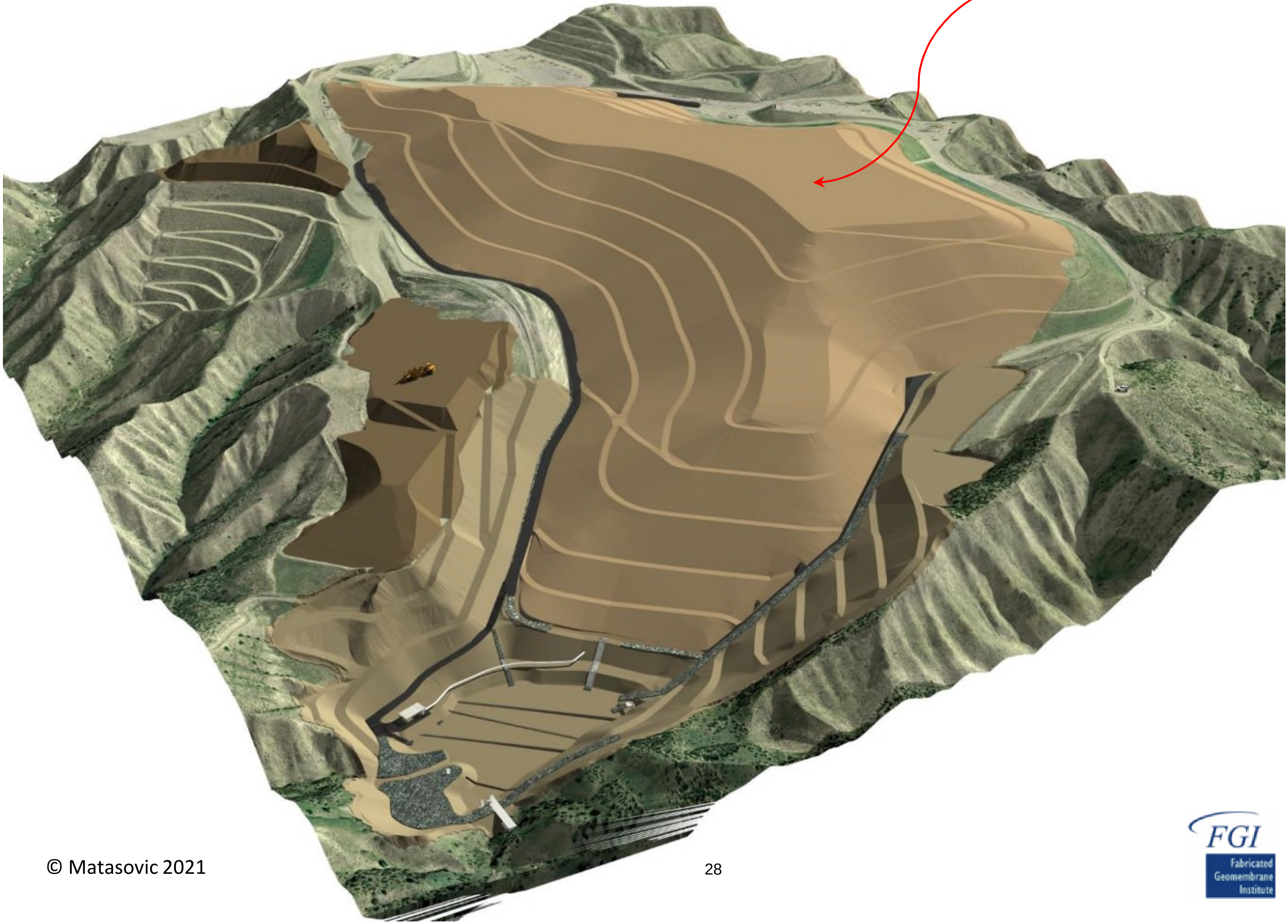
COMPLEX GEOMETRY / THICK FILL …



COMPLEX GEOMETRY / THICK FILL …



COMPLEX GEOMETRY / THICK FILL …



500^{+} ft Thick Fills

500-ft Thick Fill

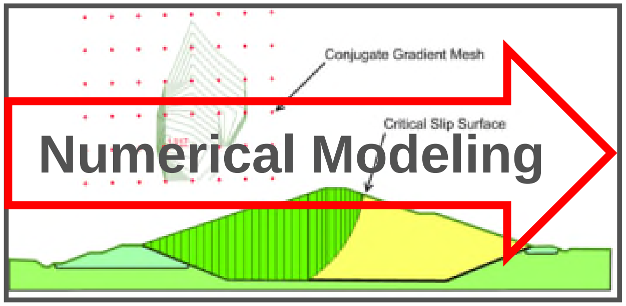
500-ft Thick Fill

Landfills do not respond to strong shaking like this structure (even though …)

Landfills respond to strong shaking like these structures … were not designed using charts …

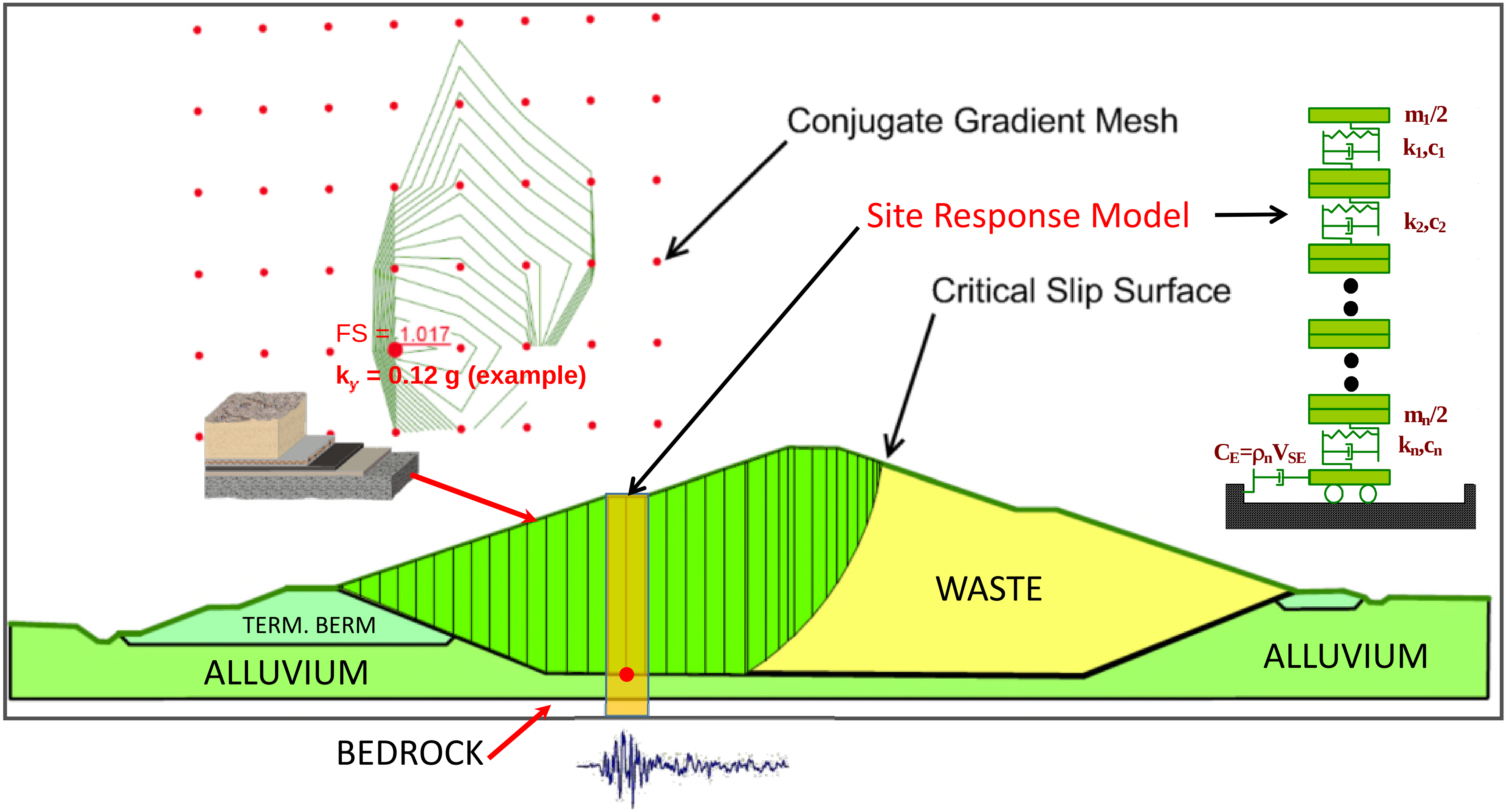
CAN WE DO “BETTER” THAN SOP?

1. Des. Ground Motions
2. Properties of MSW
    - Static
    - Dynamic
3. In-Plane Properties
    - Static (incl. creep)
    - Dynamic
4. Other (Bedrock Prop., …)

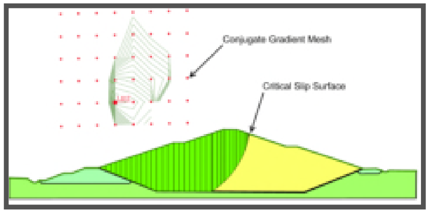


Numerical Modeling

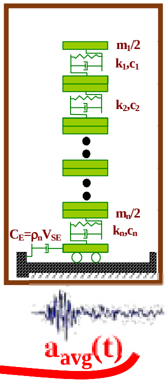
STATE OF PRACTICE - DECOUPLED ANALYSIS



STATE OF PRACTICE - DECOUPLED ANALYSIS

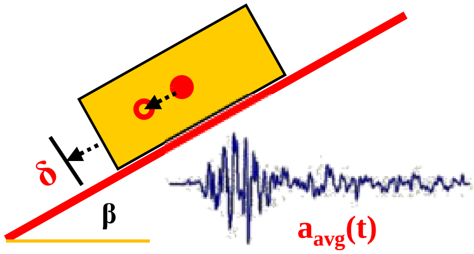


k_y = 0.12 g (example)

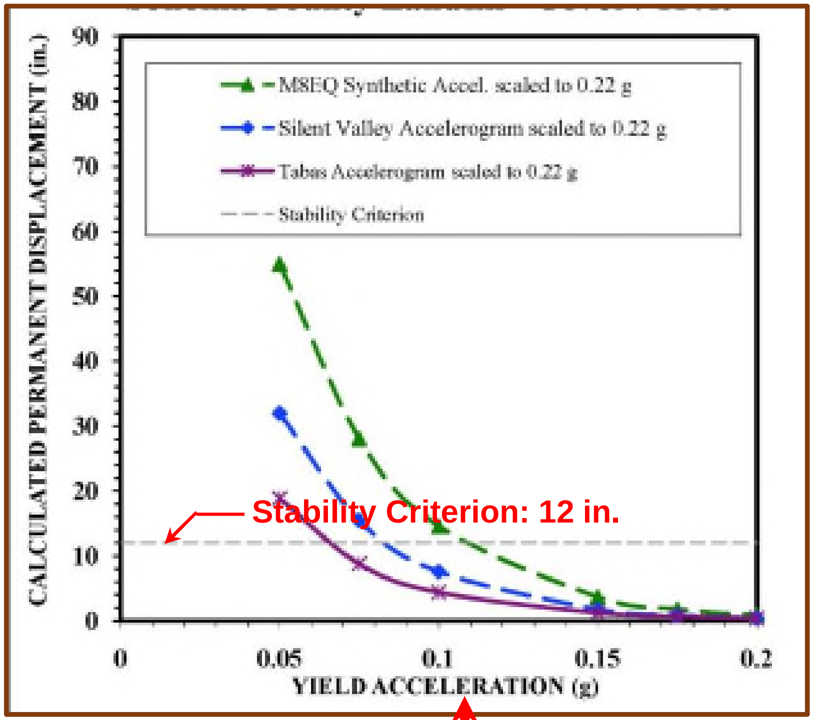


Sliding Block Model:

(Classical Newmark Analysis)



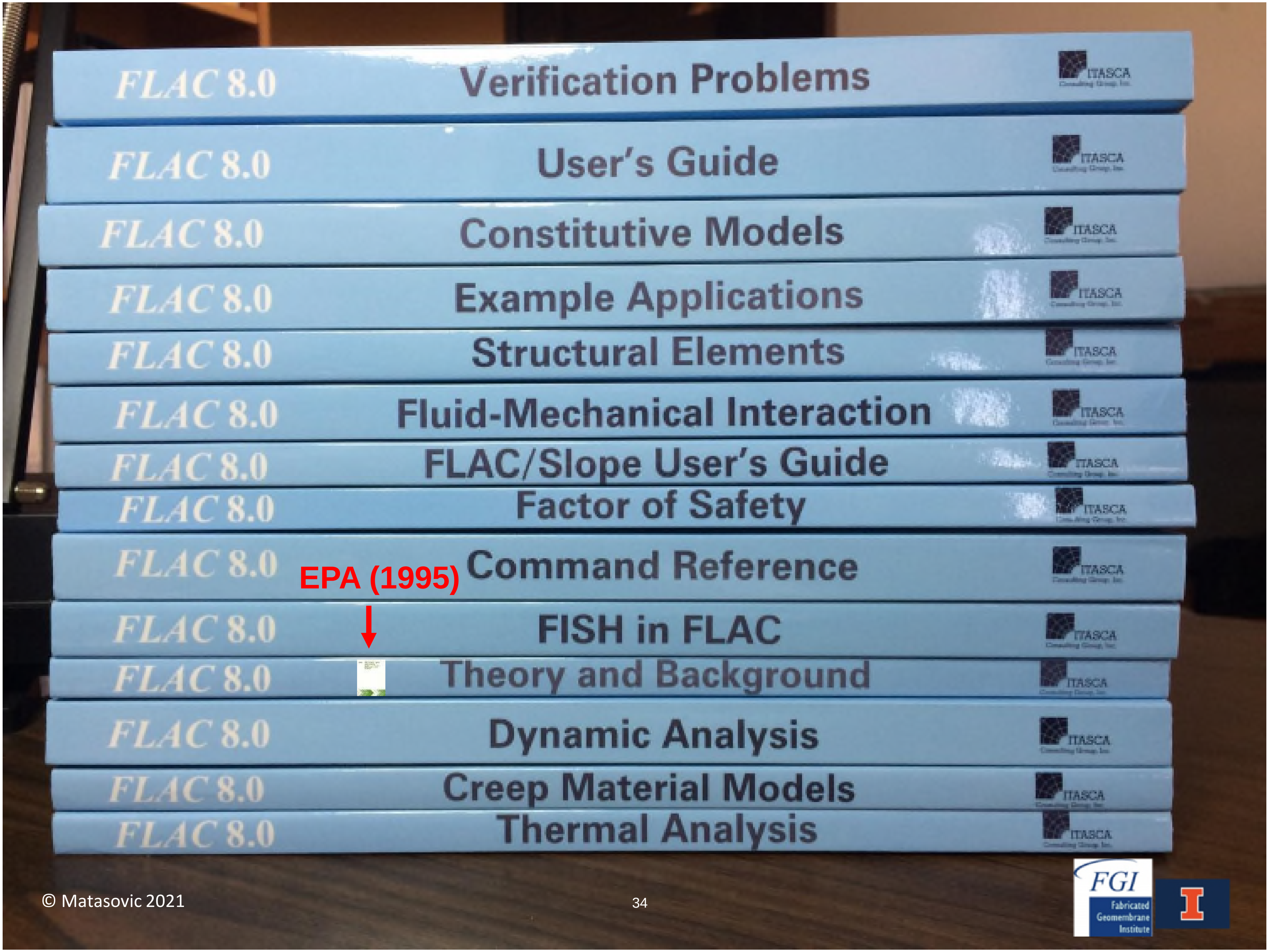
Presentation of the Results & Seismic Stability Criteria:



k_y = 0.12 g (example)

Decoupled Analysis is conservative …

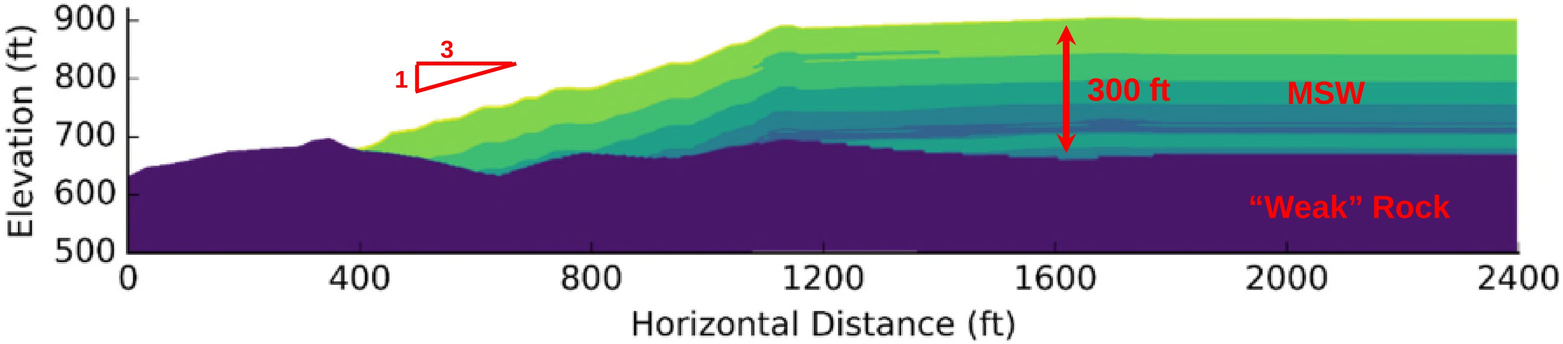
Lin and Whitman [1983], Gazetas and Uddin [1994], Matasovic et al. [1997; 1998], Kramer and Smith [1997], Rathje and Bray [1999], Wartman et al. [2003; 2005], …


FLAC 8.0 Verification Problems ITASCA
FLAC 8.0 User's Guide ITASCA
FLAC 8.0 Constitutive Models ITASCA
FLAC 8.0 Example Applications ITASCA
FLAC 8.0 Structural Elements ITASCA
FLAC 8.0 Fluid-Mechanical Interaction ITASCA
FLAC 8.0 FLAC/Slope User's Guide ITASCA
FLAC 8.0 Factor of Safety ITASCA
FLAC 8.0 Command Reference ITASCA
FLAC 8.0 FISH in FLAC ITASCA
FLAC 8.0 Theory and Background ITASCA
FLAC 8.0 Dynamic Analysis ITASCA
FLAC 8.0 Creep Material Models ITASCA
FLAC 8.0 Thermal Analysis ITASCA

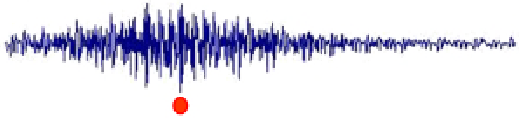
EPA (1995)

ADVANCED ANALYSIS

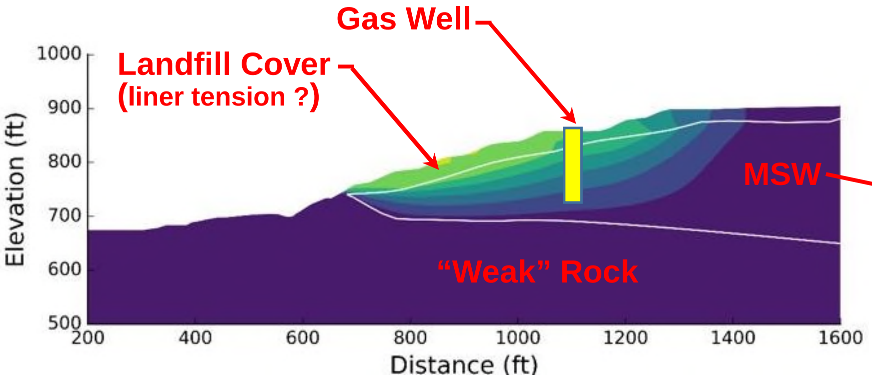
(Hazardous Waste Landfill in CA – Cover Design)



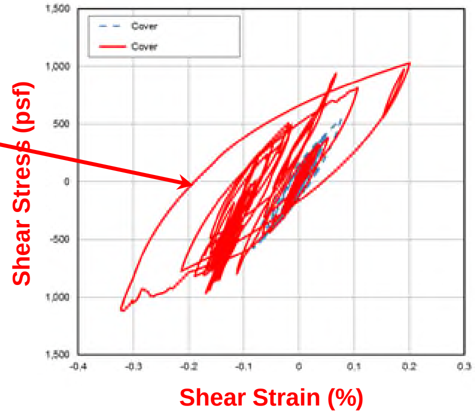
Shear Wave Velocity (ft/s)



PHGA = 0.8 g (M 7.8 – 8.5)



Calculated Horizontal Displacement (ft)



TAKE-AWAYS

- Don’t get deceived w/ the “infinite slope” equation - Composite landfill cover slope length should not exceed 150 ft.
- Landfill cover gas drainage layer: should be constructed from coarse sand (Coarse sand prevents capillary suction which, in turn, prevents gas migration).
- There are generic sets of material parameters of MSW and interfaces, but design ground motions and interface strength must be evaluated on a site-by-site basis, …

TAKE-AWAYS (CONT. 1)

- Always start with “simple” analysis first …
- Pseudostatic method with k_s is O.K. when cover PGA ≤ 0.2 g; Performance-based design (Newmark-type analysis) should be used for PHGA ≥ 0.2 g.
- State-of-the-Practice (seismic) is generally conservative, … (“cumulative” FS may be high!)
- Advanced analysis is less conservative, it is suitable for high ground motions, “thick fills,” complex geometry …

TAKE-AWAYS (CONT. 2)

- Nonlinear and/or 2-D site response analysis is recommended when bedrock PHGA ≥ 0.4 g. “Model calibration” may be required.
- The only proper way to check the results of advanced seismic stability analysis is to repeat it (for critical section …).
- Stability criteria – ever-evolving (12 ET; 36 in. composite; … consider release/no release of contaminants; ease of cover repair …).
- Remember video shown at the beginning of this presentation?

* * * * *

SELECT REFERENCES (posted @ www.geomotions.com)

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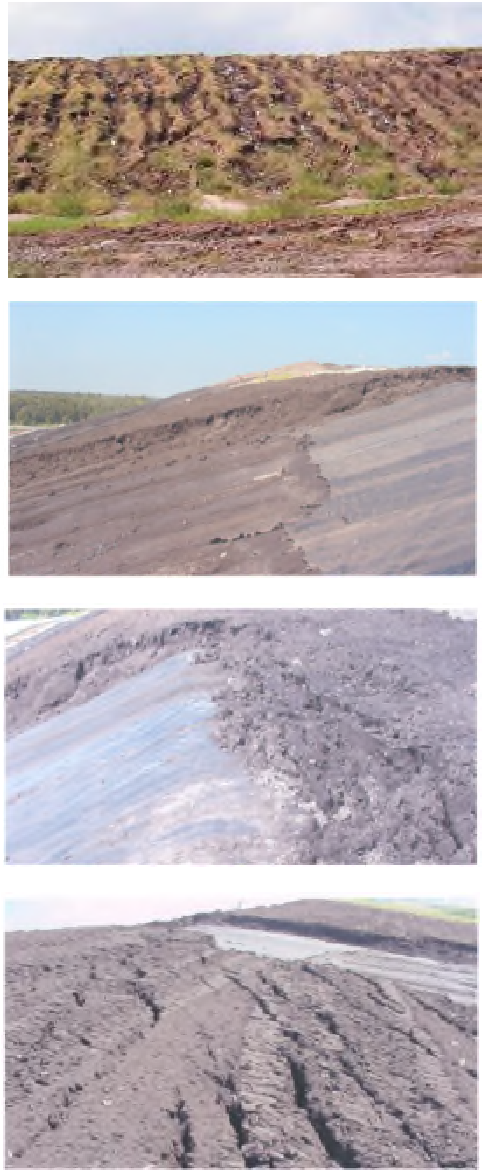

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