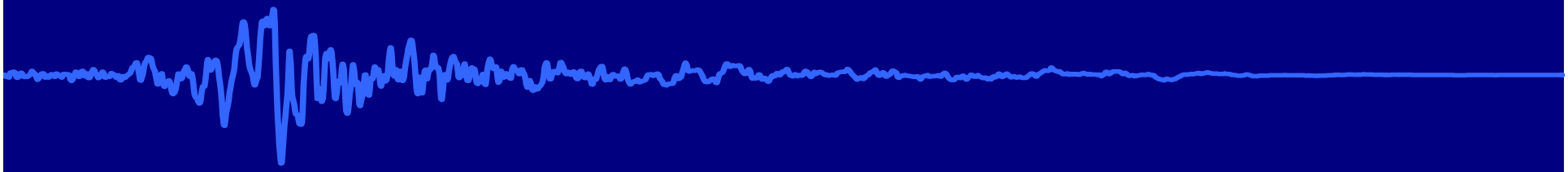
Validity of the pseudostatic surface assumption for evaluating seismically-induced deformation in slopes



Patrick M. Strenk
Joseph Wartman

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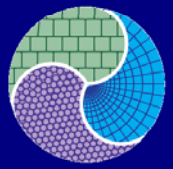
Philadelphia, PA, USA

August 27, 2008



First International
***FLAC/DEM* Symposium on Numerical Modeling**

Introduction

"Serviceability" governed by deformation (δ) not FS!

Deformation-Based Procedures:

"Rigid- Block" Method
Newmark (1965)

"Decoupled" Method
Makdisi & Seed (1978)

Assumes deformations occur on the *critical "pseudostatic" surface* (by limit-equilibrium)

Questionable assumption since…

Objective!

Quantify how dynamic response affects the failure mechanism geometry

Ground Motion Database

124 earthquake recordings from 24 events

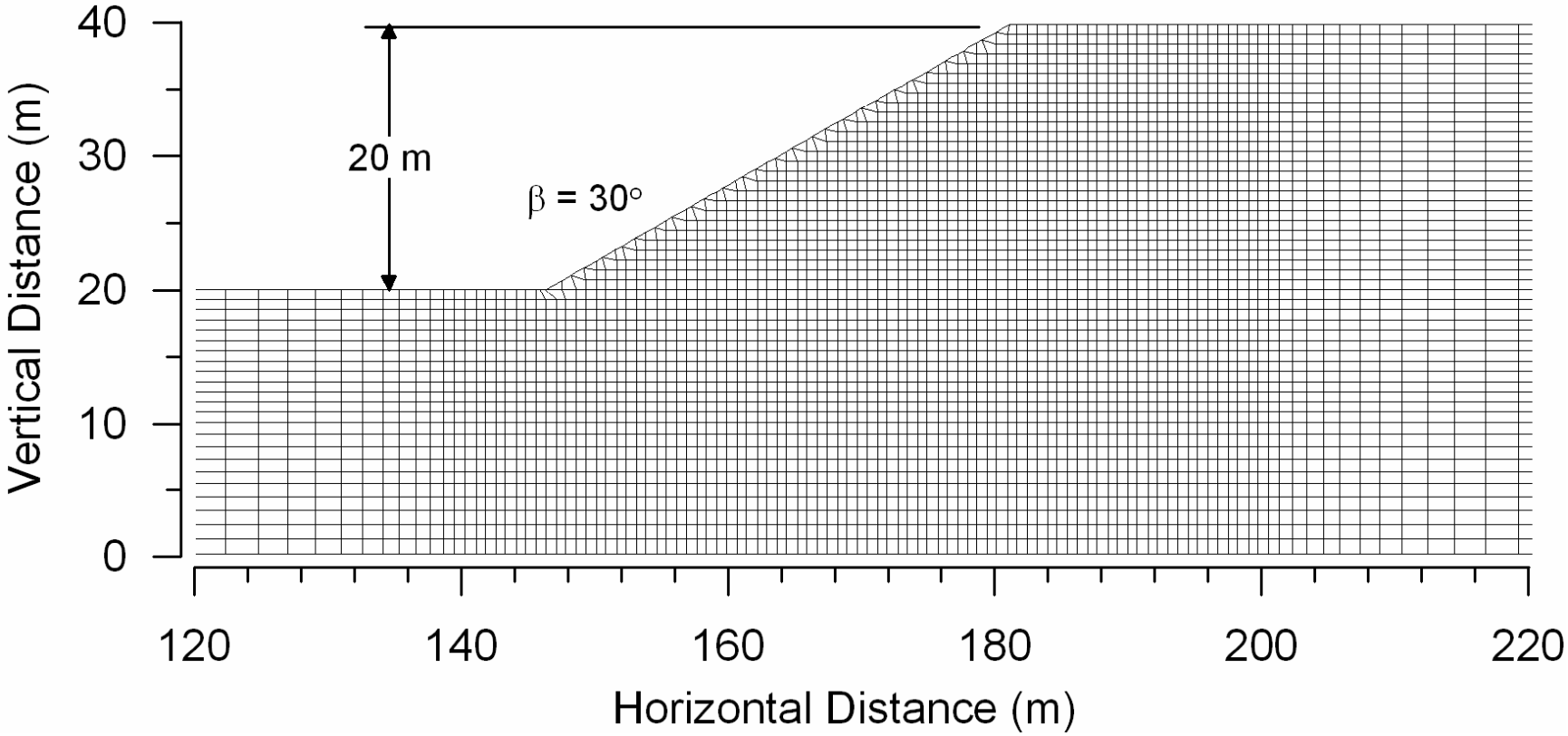
- Mean-square frequency (f_m) ranges from 0.85 to 8.1 Hz

7 single-frequency sine motions (f = 1.25 to 5 Hz)

Motions scaled to uniform peak acceleration

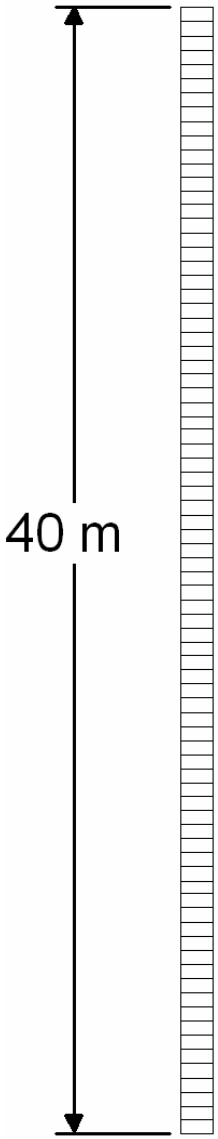
FLAC Models

Simple, homogeneous slope

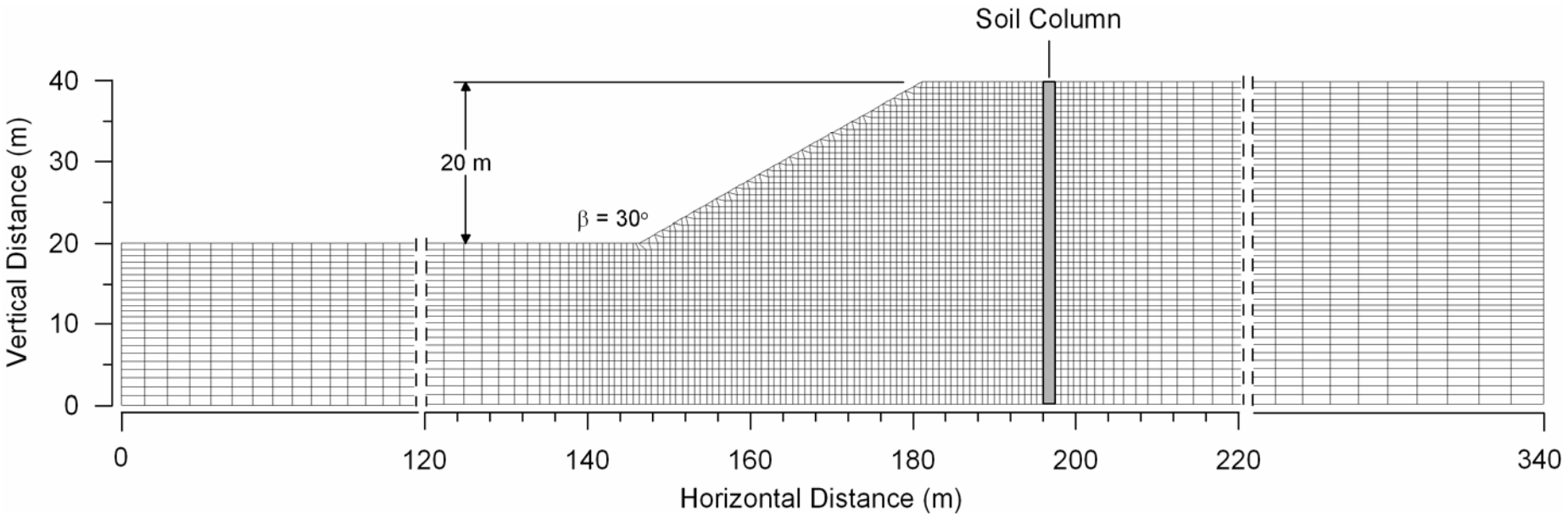


FLAC Models

Soil Column



FLAC Models


Soil Column
20 m
β = 30°
Vertical Distance (m)
40
30
20
10
0
0
120
140
160
180
200
220
340
Horizontal Distance (m)

FLAC Analyses

Simple, homogeneous slope

- **"Pseudostatic-stepping" method**

  Compare FLAC to the LEM "pseudostatic" surface

- **Fully-coupled non-linear dynamic analysis**

(Rayleigh, ξ = 2.5%)

Compare the fully-coupled surfaces to the FLAC "pseudostatic" surface ("pseudostatic-stepping")

Soil column

- **Linear, elastic dynamic analysis** **(Rayleigh, ξ = 2.5%)**

  Determine how dynamic response affects the depth of the "critical surface"

Simple, Homogeneous Slope

Frictional-cohesive material

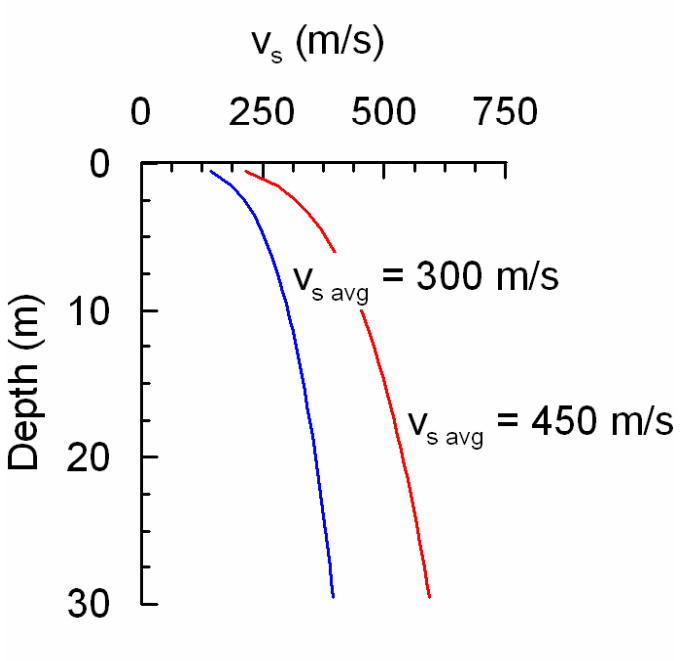
- Strain-softening model
- $\phi = 30^o$, $c \approx 210$ psf with SI = 1.05
- Non-associated flow rule ($\psi = 0^o$)

Purely-cohesive material

- Mohr-Coulomb model
- $\phi = 0^o$, $s_u/p = 0.33$

2 shear wave velocity profiles

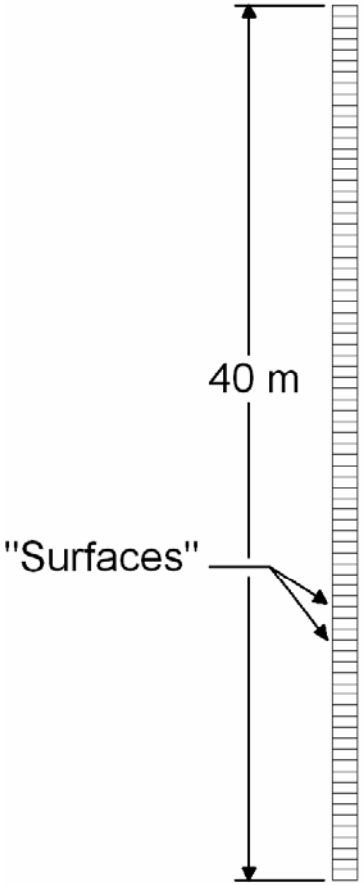
- Increasing with depth
- v_s = 300 and 450 m/s



$$G_{max} = 21.7\, p_a\, K \left(\frac{\sigma'}{p_a} \right)^{0.5}$$

Seed & Idriss (1970)

Soil Column



Linear-elastic model

- 4 shear wave velocity profiles
- v_s = 150, 300, 450 and 600 m/s
- Seed & Idriss (1970)

$$HEA(t) = \frac{\tau(t)}{\sigma_v} g$$

$$k_{max} = \max[HEA(t)]$$

"Seismic Demand"

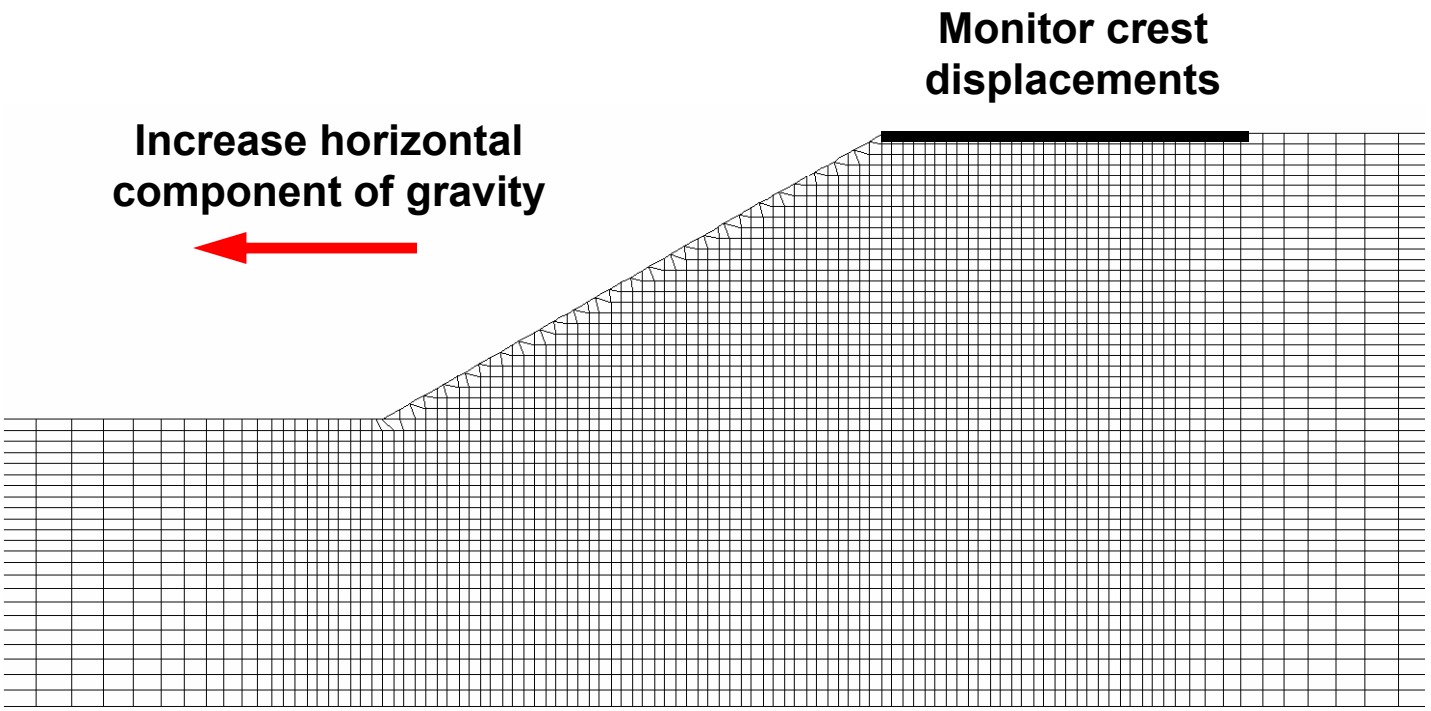
$$k_y = \frac{\tau_{max}(z)}{\sigma_v} g$$

"Seismic Resistance"

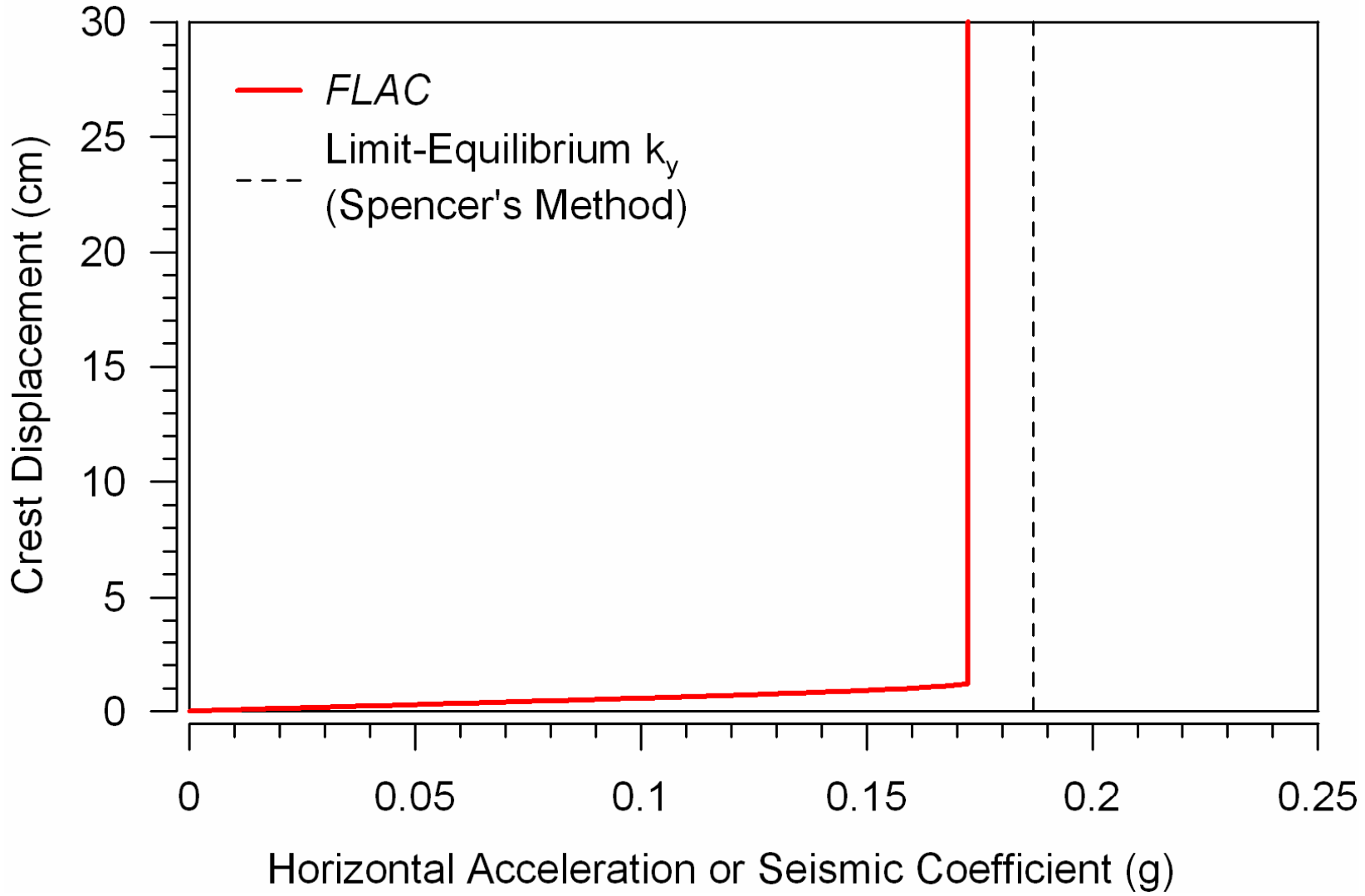
Stability ratio: k_y/k_{max}

Depth at *minimum* k_y/k_{max} is *most unstable (critical)!*

“Pseudostatic-Stepping” Analysis

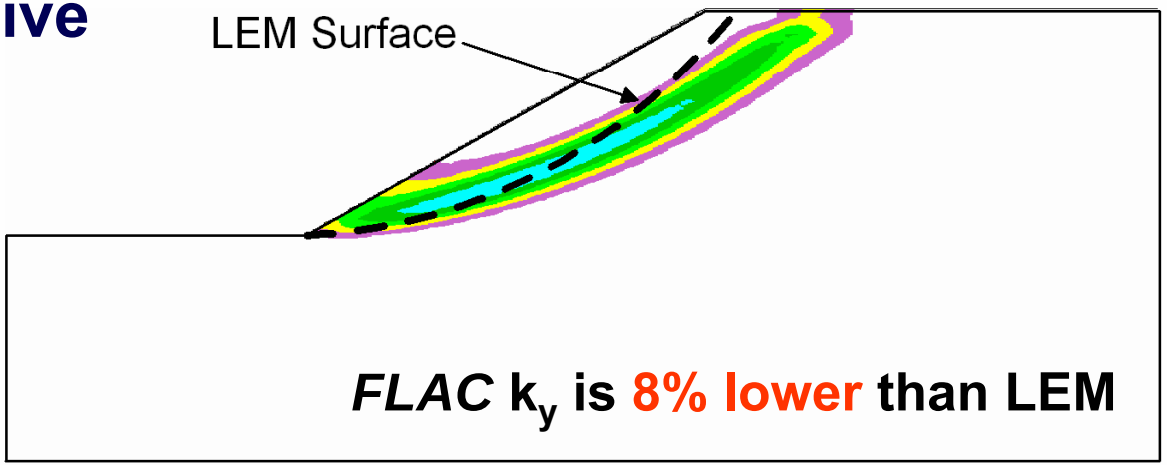


“Pseudostatic-Stepping” Analysis

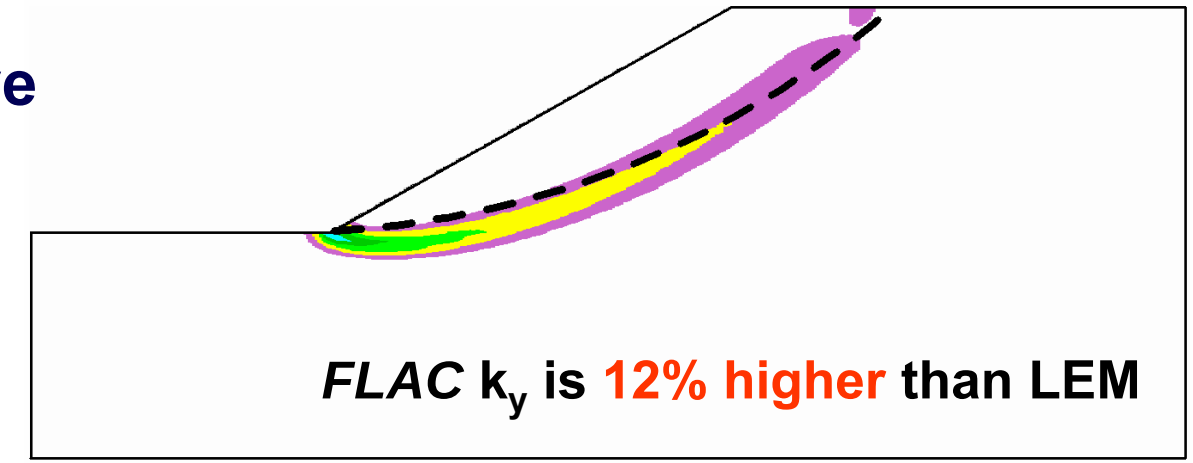


"Pseudostatic-Stepping" Analysis

Frictional-cohesive



Purely-cohesive



Quantifying the Results

Dynamic response conditions:

Wavelength ratio $\frac{\lambda}{H} = \frac{V_{s\ avg}}{f_m H}$

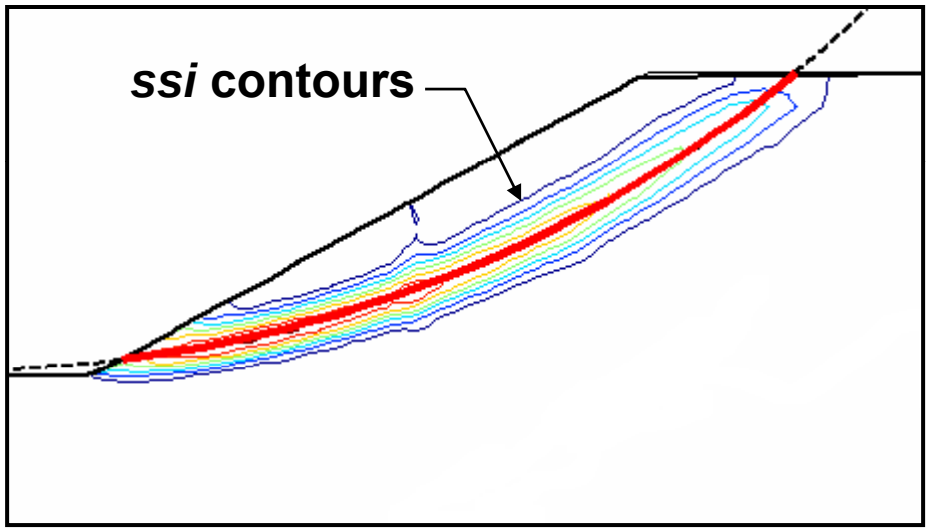
Simple relationship…

Low λ/H *means* High freq. motions

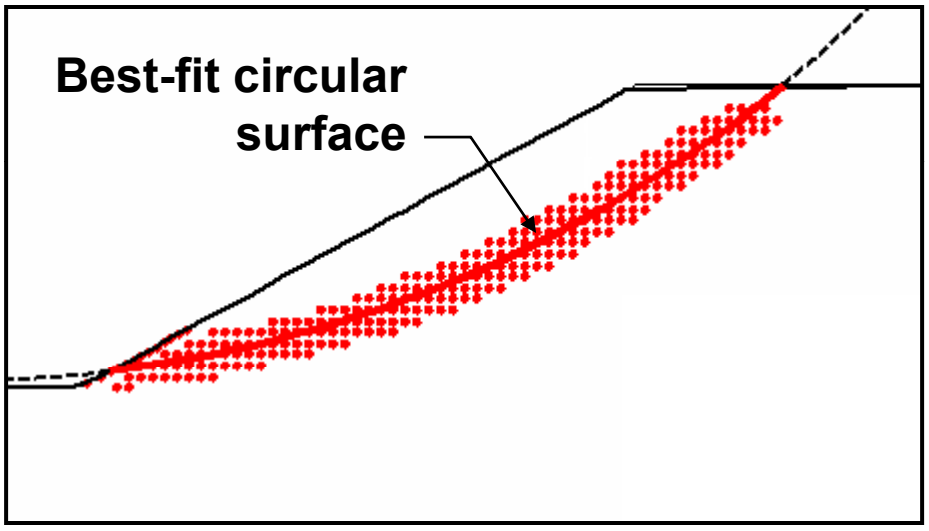
High λ/H *means* Low freq. motions

Quantifying the Results

Failure mechanism geometry:



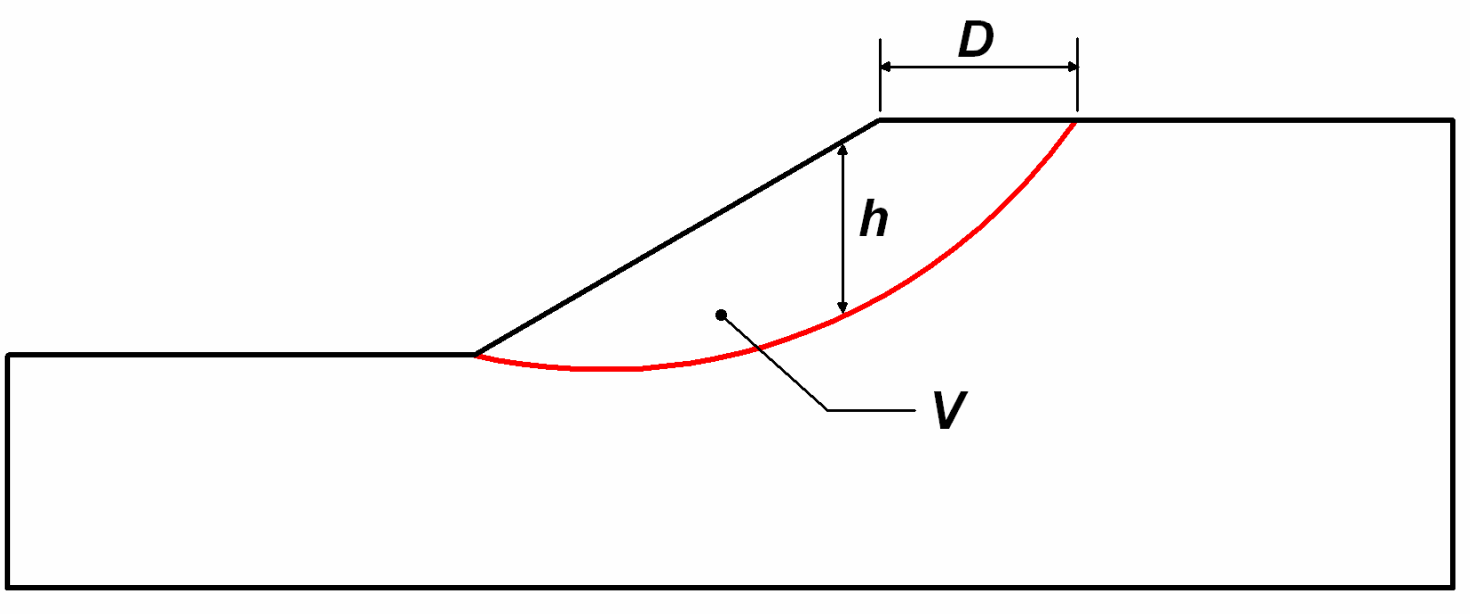
FLAC fully-coupled surface



Non-linear, least-squares best fit (MATLAB)

Quantifying the Results

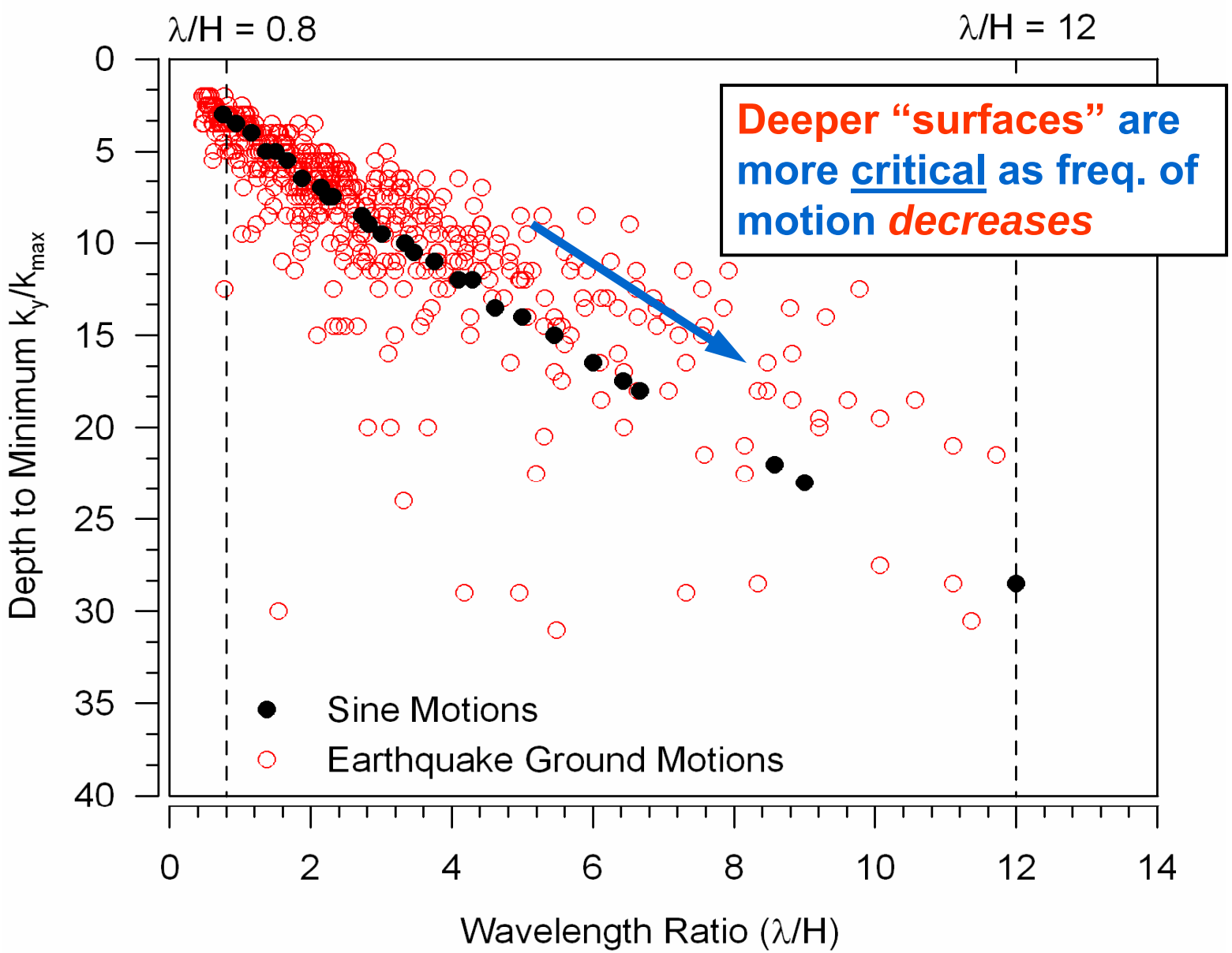
Failure mechanism geometry:



Surface descriptors:

- Maximum slide mass thickness (h)
- Crest distance (D)
- Volume (V) (per unit length)

Soil Column Results



Simple Slope Results

$$\text{Ratio} = \frac{\text{"coupled"}}{\text{"pseudostatic"}}$$

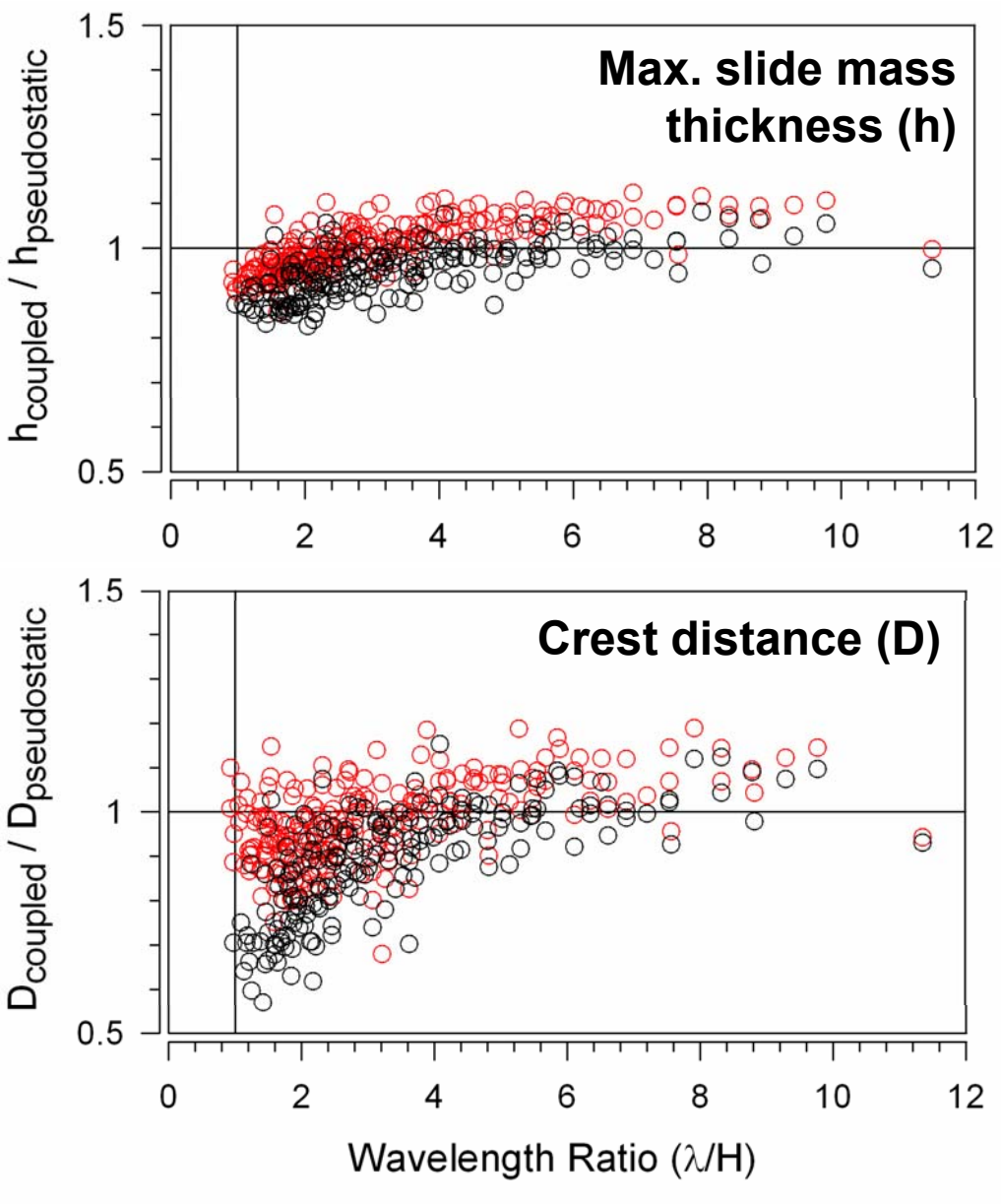
***Similar trend* to soil column results**

For $1 < \frac{\lambda}{H} < 4$

Coupled surface "shallower" than pseudostatic surface

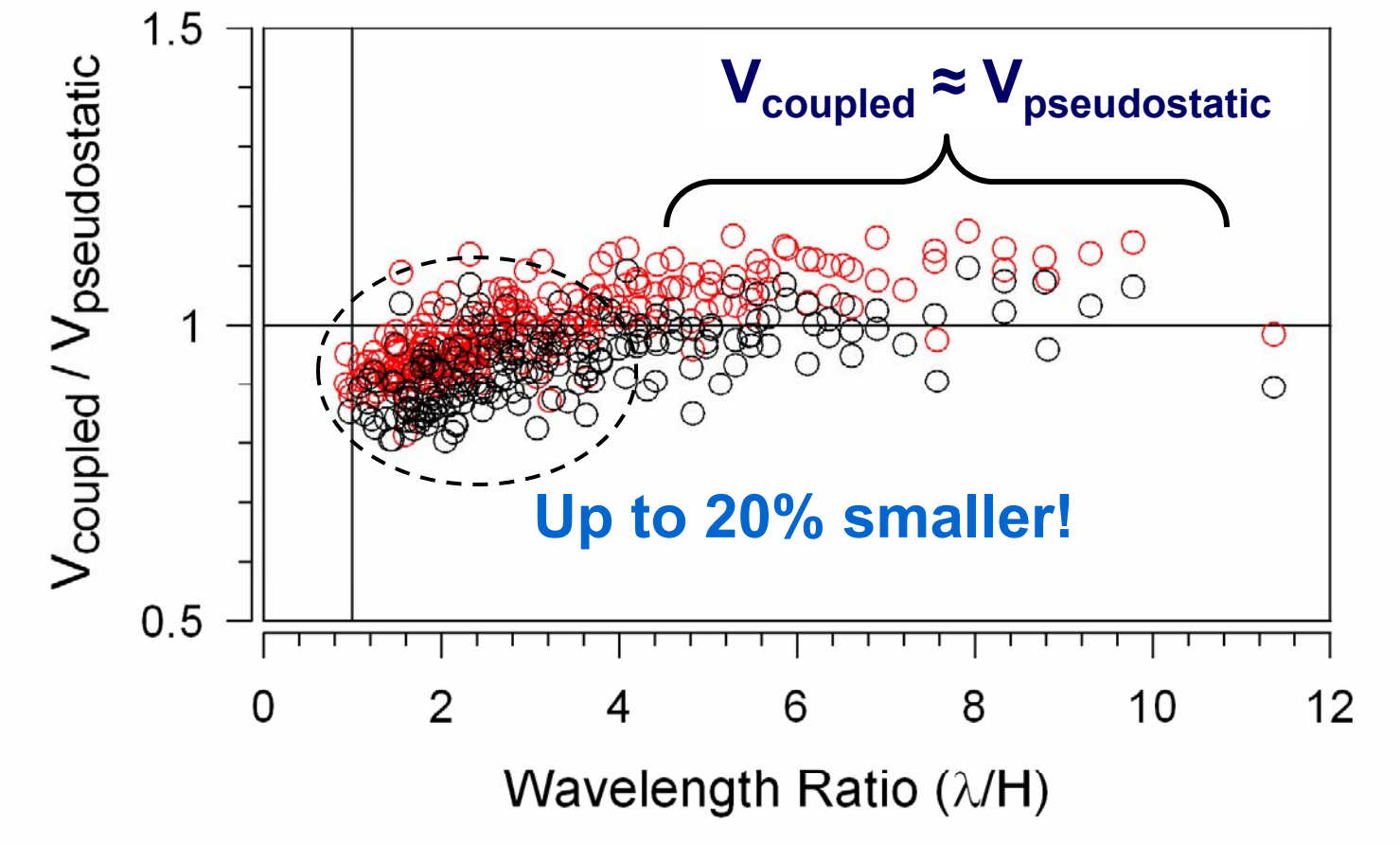
For $\frac{\lambda}{H} > 4$

Coupled surface "matches" the pseudostatic surface

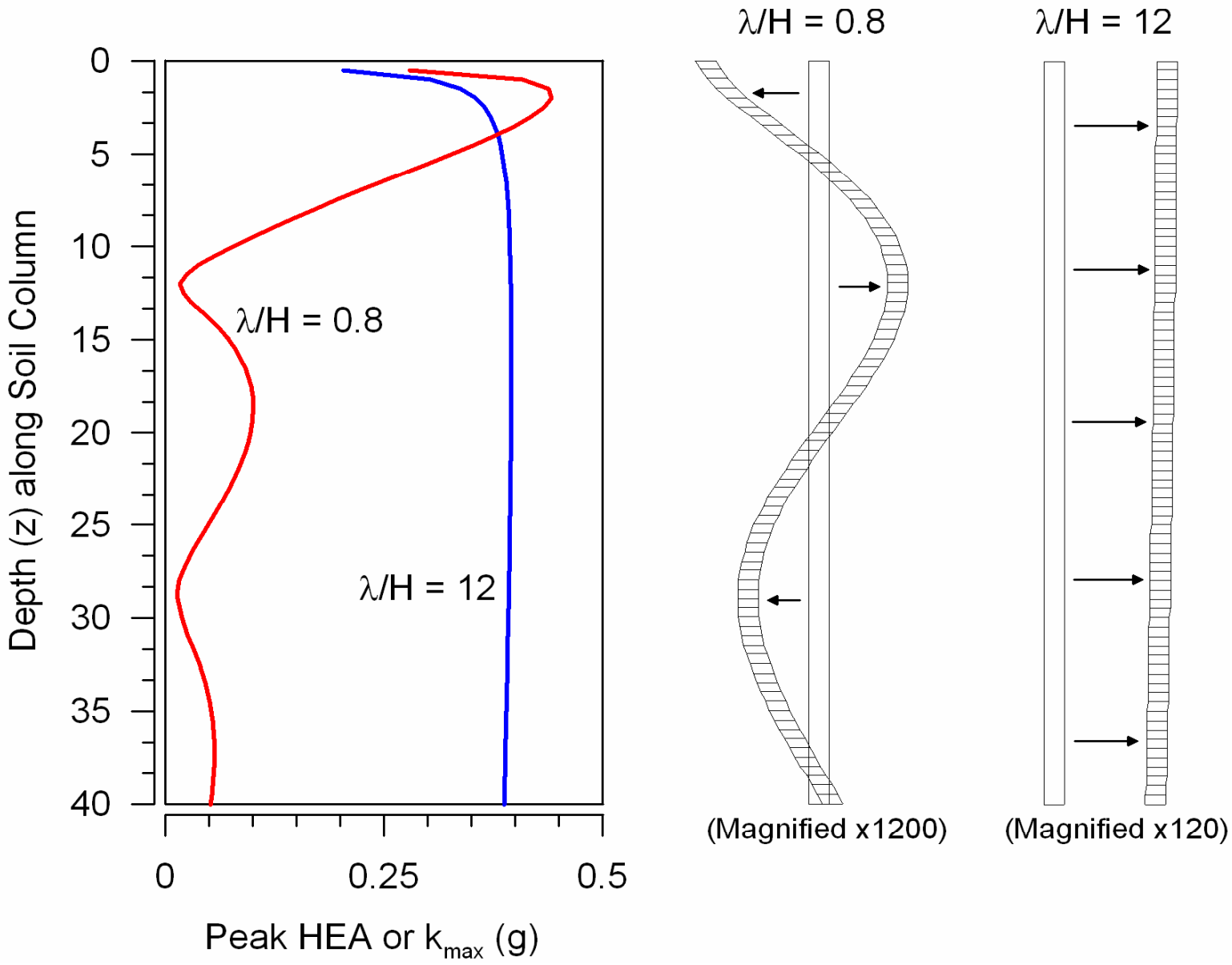


Simple Slope Results

Slide mass volume (V)



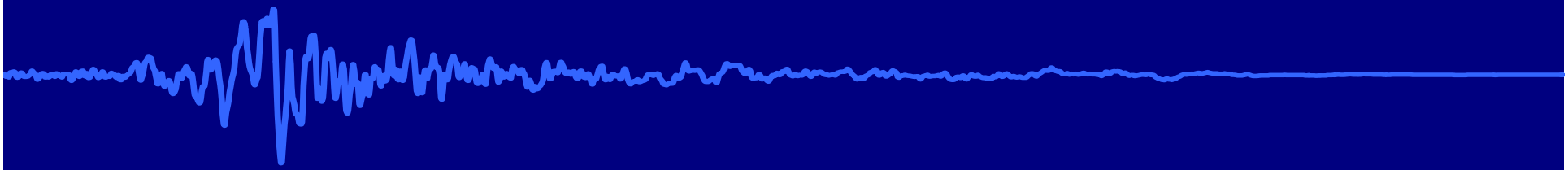
Discussion


λ/H = 0.8
λ/H = 12
0
5
10
15
20
25
30
35
40
Depth (z) along Soil Column
λ/H = 0.8
λ/H = 12
0
0.25
0.5
Peak HEA or k_max (g)
λ/H = 0.8
λ/H = 12
(Magnified x1200)
(Magnified x120)

Conclusions

- Developed the "pseudostatic-stepping" method to find pseudostatic surface and k_y – no a priori assumptions as with LEM.
- Dynamic response has a *more pronounced* effect at λ/H ratios between 1 and 4
  - Surfaces are up to 20% shallower and smaller in volume
  - Fully-coupled analyses are recommended
- Dynamic response has *less of an effect* at λ/H greater than 4
  - Surfaces "approximate" the FLAC pseudostatic surface
  - Other deformation-based procedures (rigid-block or decoupled) can be used - "pseudostatic surface assumption" applies

Thank you!



Questions?