# *Simplified Procedures for Estimating Seismic Slope Displacements*

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***Thanks to Thaleia Travasarou & Others,***
***and to NSF, Packard, & PEER***

# *Simplified Procedures for Estimating Seismic Slope Displacements*

## *OUTLINE*

I. Seismic Slope Stability

II. Seismic Slope Displacement Analysis

III. Simplified Slope Displacement Procedures

IV. Pseudostatic Slope Analysis

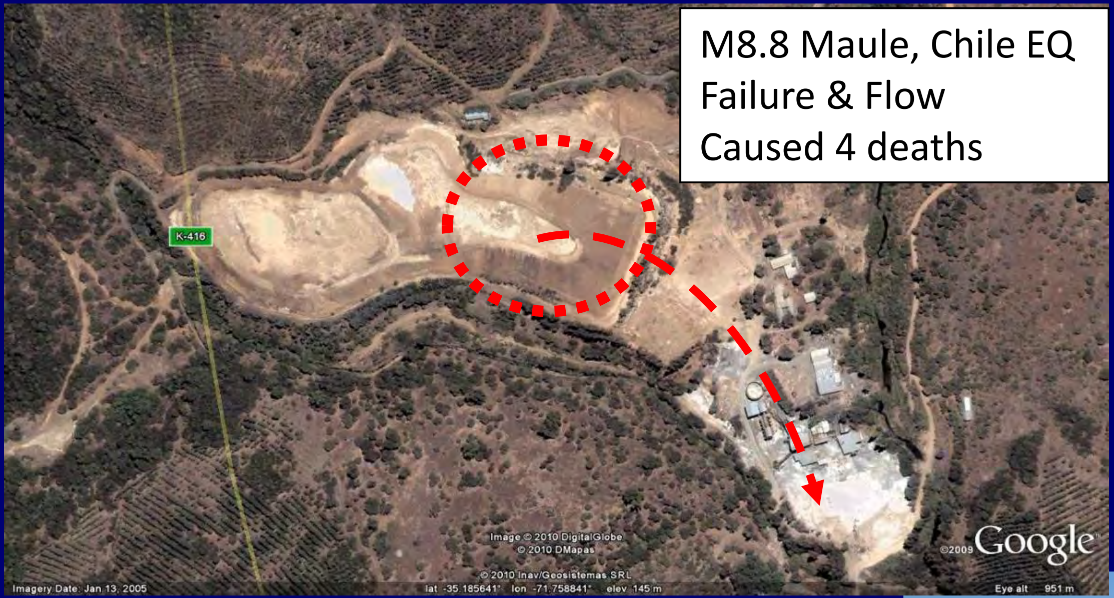
V. Conclusions

# Two Critical Design Issues

1. Are there materials that will lose significant strength as a result of cyclic loading?
   ***"Flow Slide"***

2. If not, will the earth structure or slope undergo significant deformation that may jeopardize performance?
   ***"Seismic Displacement"***

# Las Palmas Gold Mine Tailings Dam Failure





Bray & Frost 2010

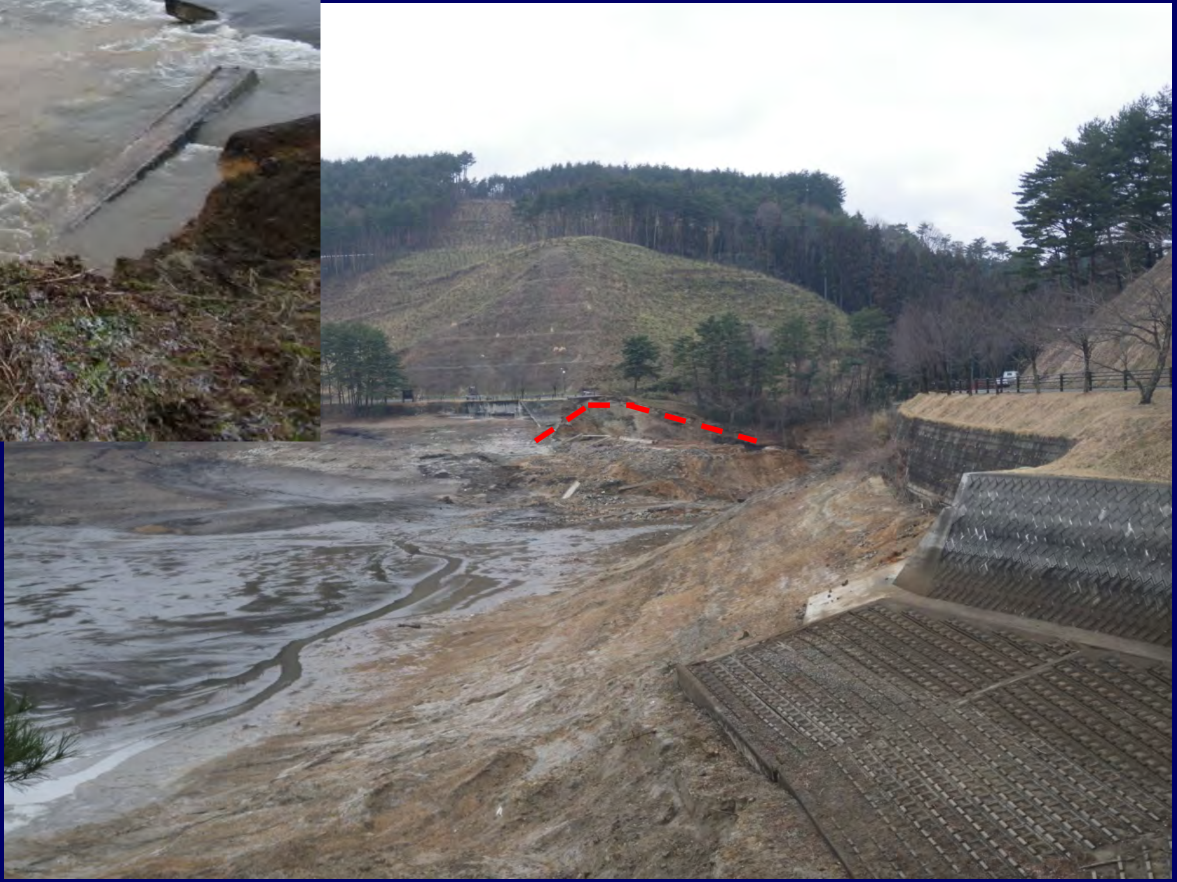
**(upstream method)**

Sand ejecta near toe of flow debris

View from scarp looking downstream

# Fujinuma Dam: 18.5 m high earthfill dam completed 1949

Uncontrolled release of reservoir led to 8 deaths downstream of dam



2011 Tohoku EQ

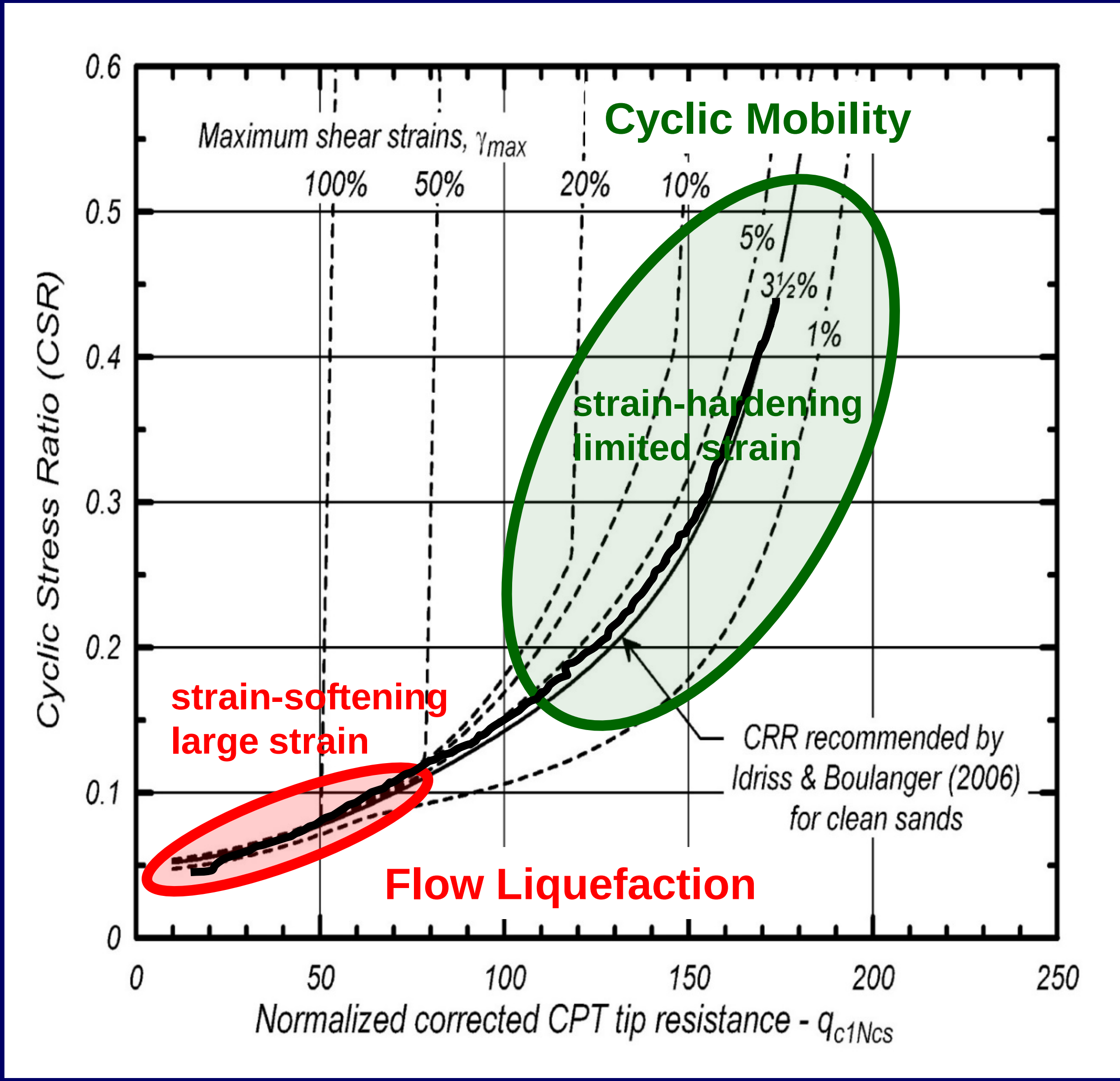
$M_w = 9.0$

R = 102 km

PGA = 0.33 g

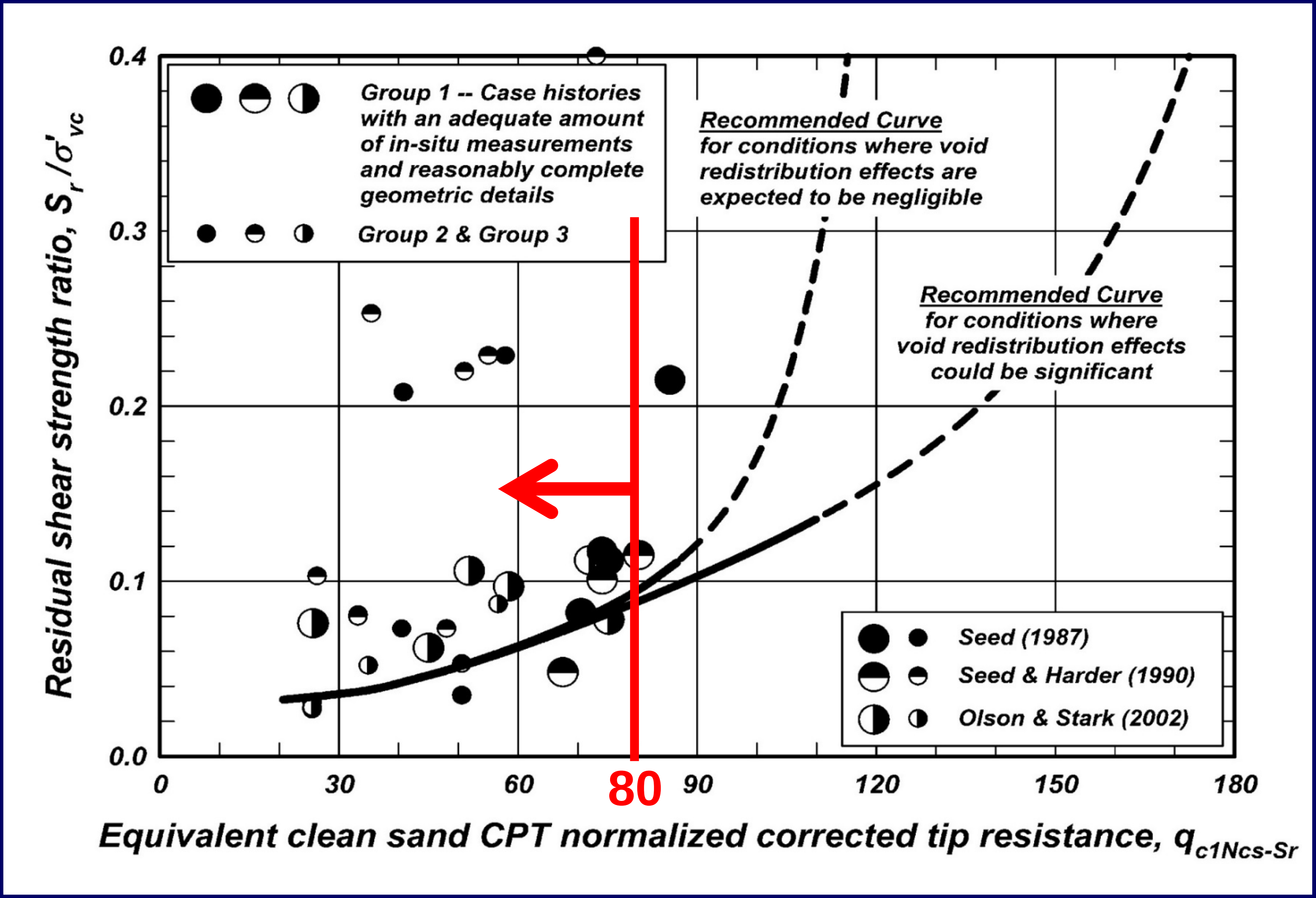
Bray et al. 2011; photographs from M. Yoshizawa

# LIQUEFACTION EFFECTS




Idriss & Boulanger 2008

# Liquefaction Flow Slides when $q_{c1N} < 80$




Idriss & Boulanger 2008

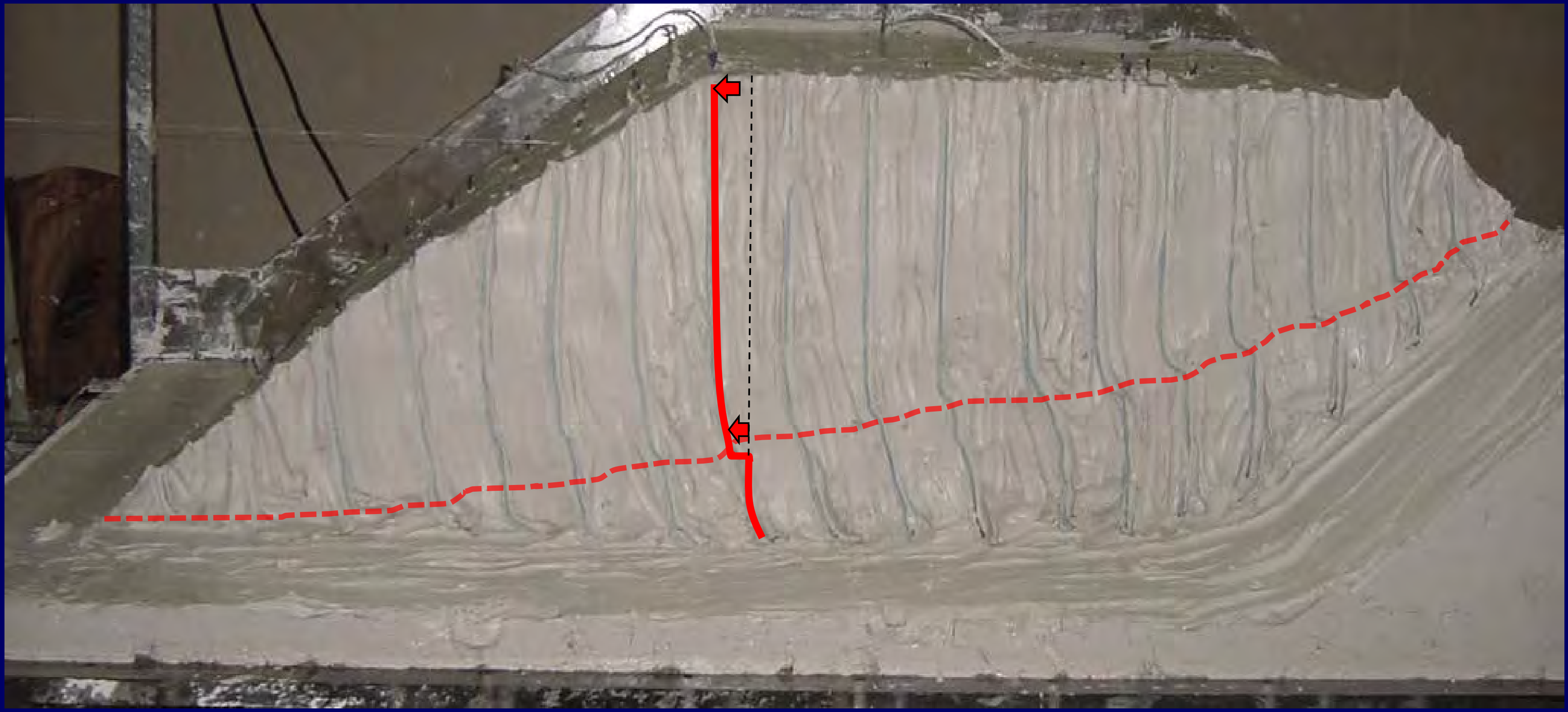
# Post-Liquefaction Residual Strength is a System Property

# Seismic Slope Displacement

- **Slip along a distinct surface**
- **Distributed shear deformation**

**Newmark-type seismic displacement**

- **Add volumetric-induced deformation, when appropriate**



# *II. Seismic Slope Displacement Analysis*

## *CRITICAL COMPONENTS*

a. Dynamic Resistance

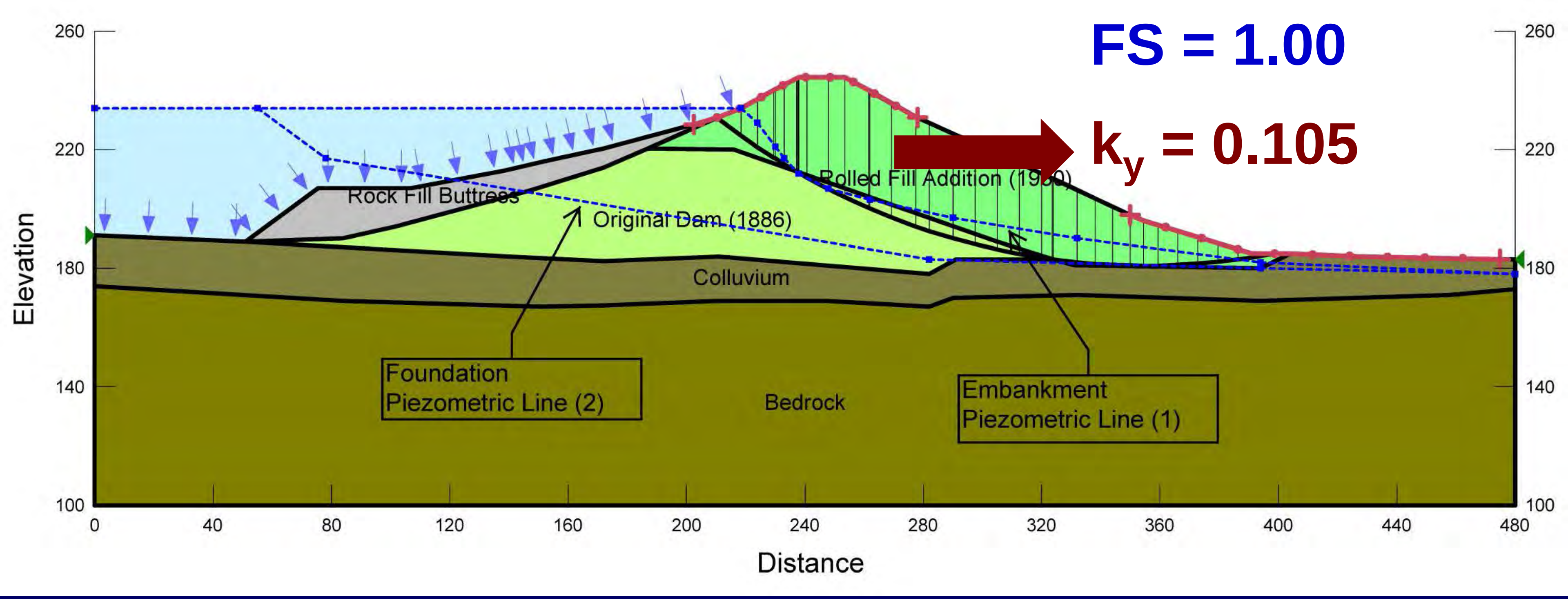
b. Earthquake Ground Motion

c. Dynamic Response of Sliding Mass

d. Seismic Displacement Calculation

# a. Dynamic Resistance

***Yield Coefficient ($k_y$):*** **seismic coefficient that results in FS=1.0 in pseudostatic stability analysis**




**Use method that satisfies all three conditions of equilibrium and focus on unit weight, water pressures, and soil strength**

# Peak Dynamic Strength of Clays

Chen, Bray, and Seed (2006)

- $S_{dynamic,\ peak} = S_{static,\ peak}\ (C_{rate})\ (C_{cyc})\ (C_{prog})\ (C_{def})$
- Rate of loading: $C_{rate} > 1$
- Number of significant cycles: $C_{cyc} < 1$
- Progressive failure: $C_{prog} < 1$
- Distributed deformation: $C_{def} < 1$

Typical values often lead to:

$S_{dynamic,\ peak} \approx S_{static,\ peak}\ (1.4)\ (0.85)\ (0.9)\ (0.9) \approx S_{static,\ peak}$

But $S_{dynamic,\ peak}$ can vary depending on EQ motion

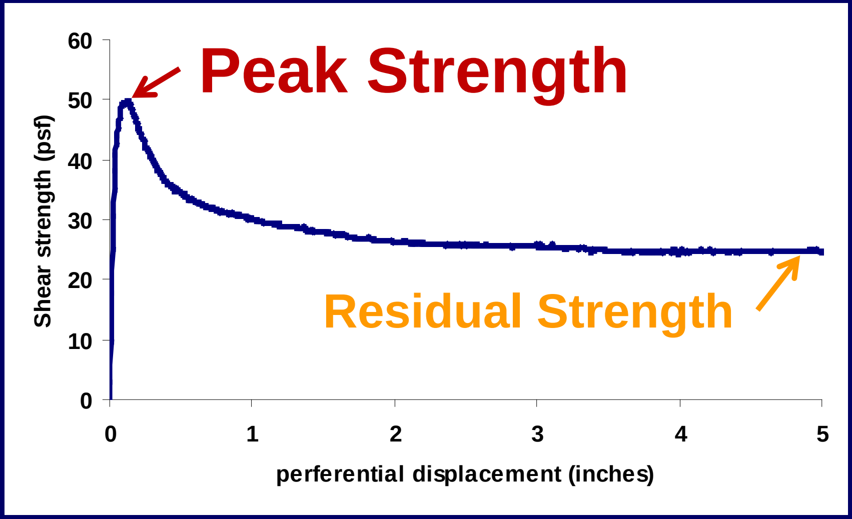
# Dynamic Strength of Clays

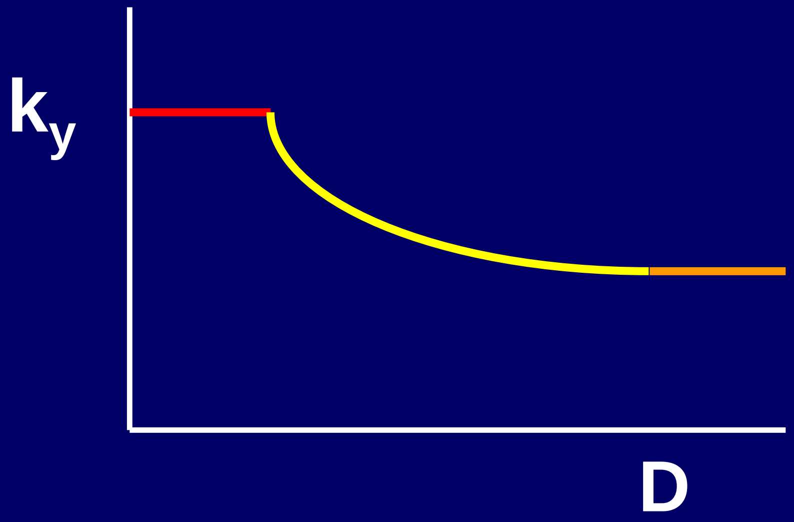
Chen, Bray, and Seed (2006)

Peak dynamic strength is used for strain-hardening soils or limited displacements

As earthquake-induced strain exceeds failure strain, dynamic strength reduces for strain-softening soils

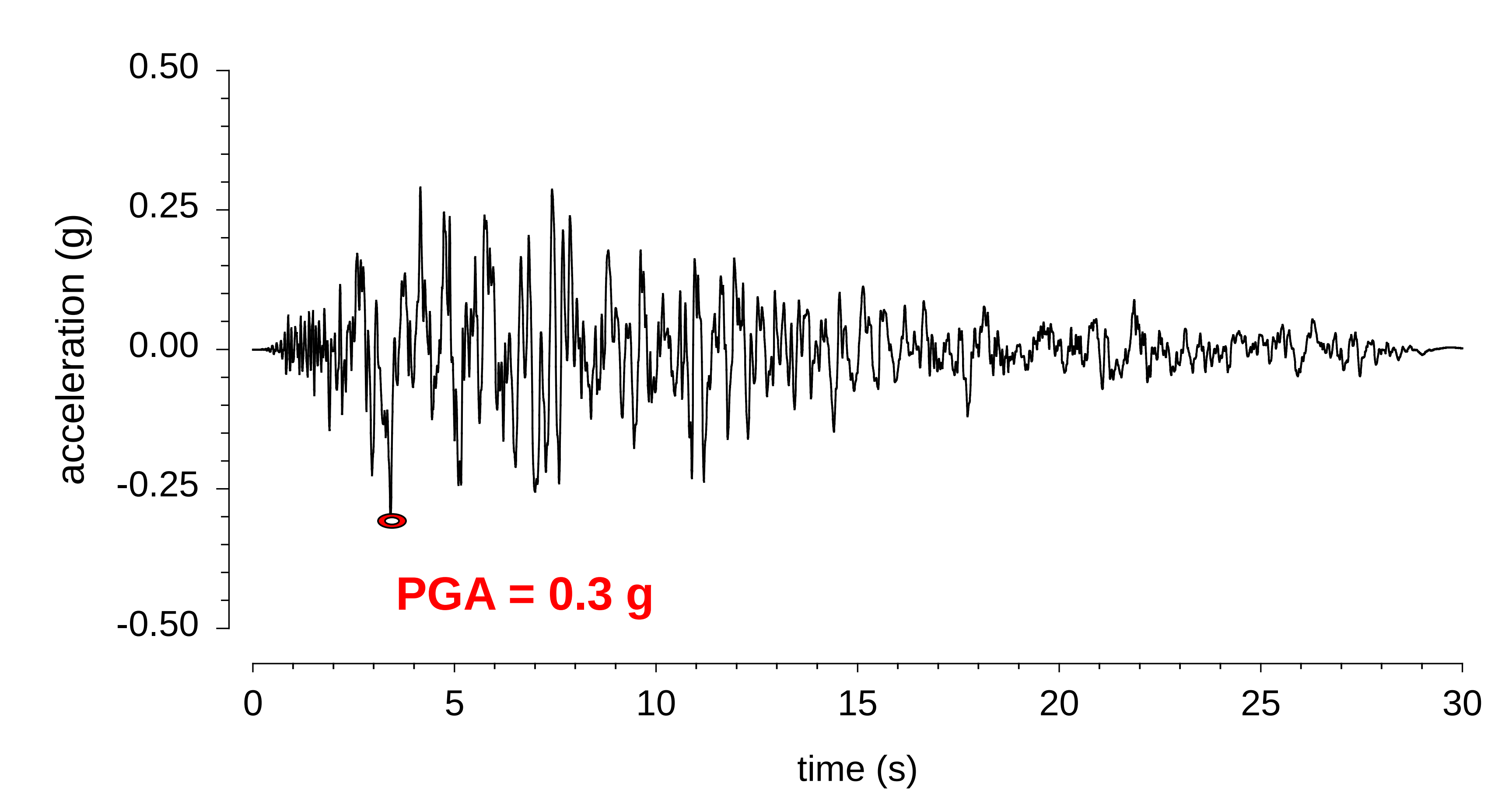
Thus, $k_y$ is also a function of displacement



# b. Earthquake Ground Motion:

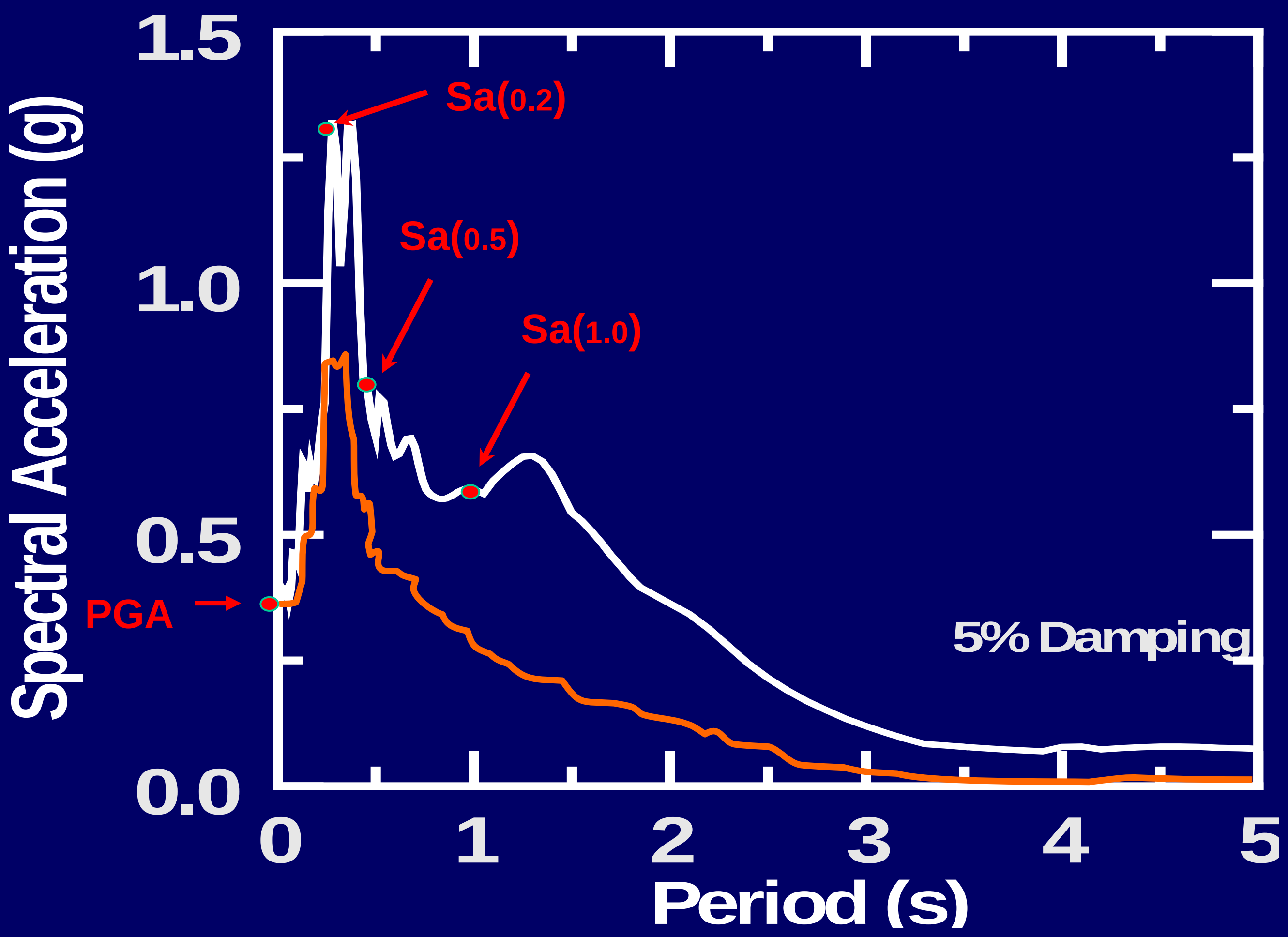
# Acceleration – Time History



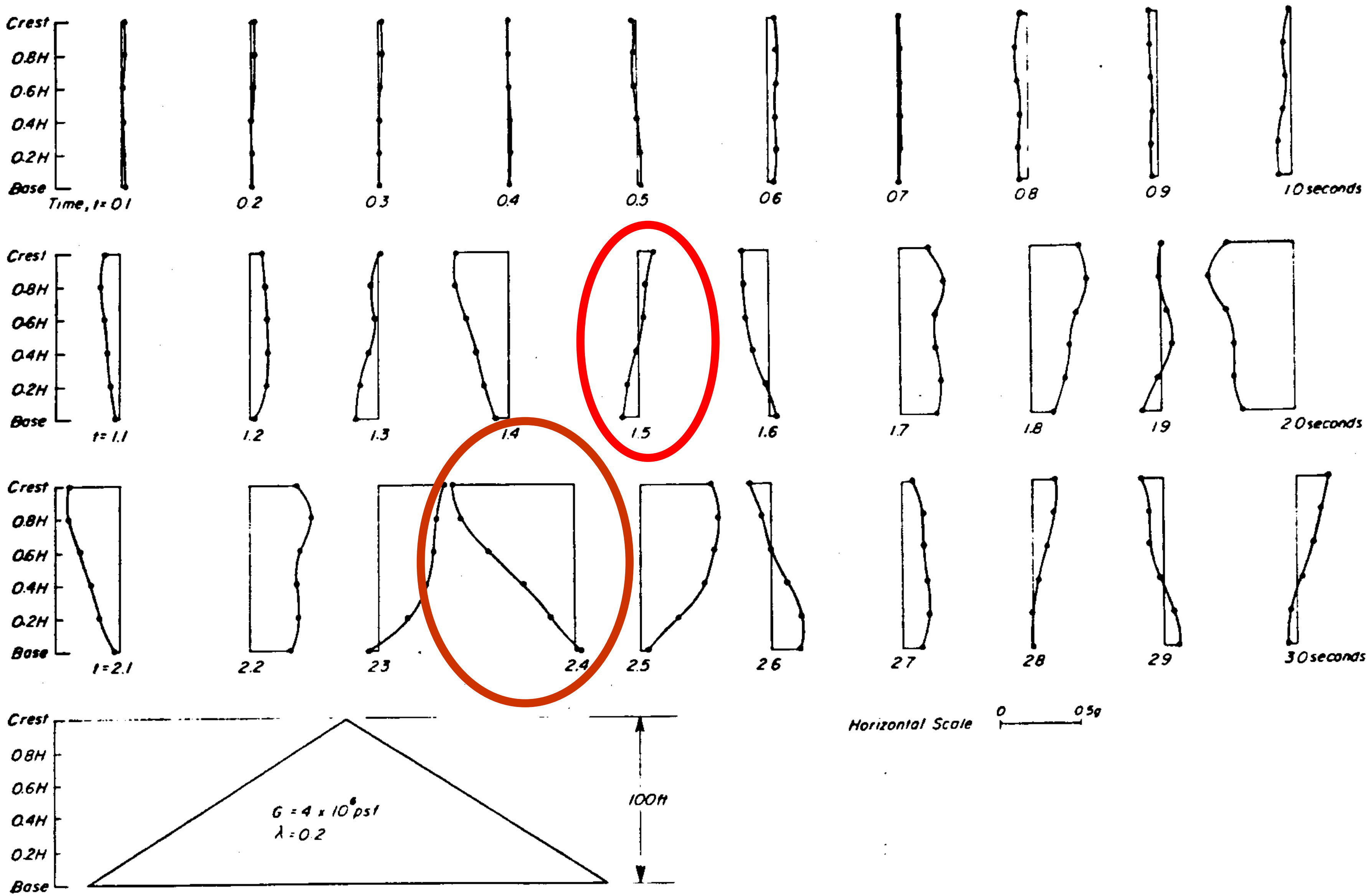

**Izmit (180 Comp) 1999 Kocaeli EQ ($M_W$=7.4) scaled to MHA = 0.30 g**

# Acceleration Response Spectrum

***(provides response of SDOF of different periods at 5% damping, i.e., indicates intensity and frequency content of ground motion)***



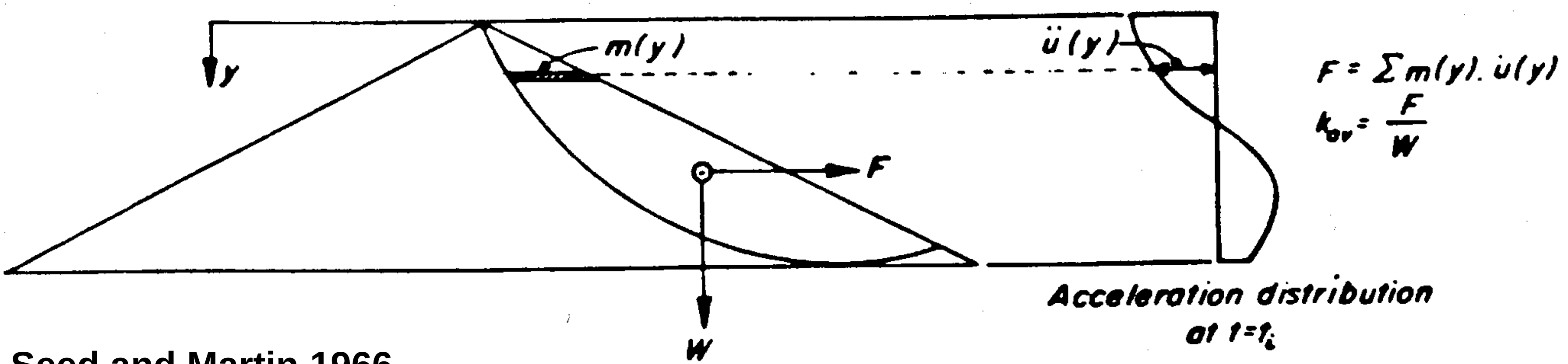
# c. Dynamic Response of Sliding Mass




ACCELERATION DISTRIBUTION AT 0.1-SEC INTERVALS FOR 100-FT-HIGH DAM SUBJECTED TO EL CENTRO EARTHQUAKE

**Seed and Martin 1966**

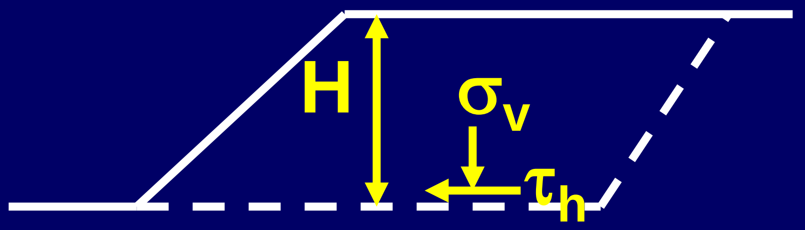
# Equivalent Acceleration Concept



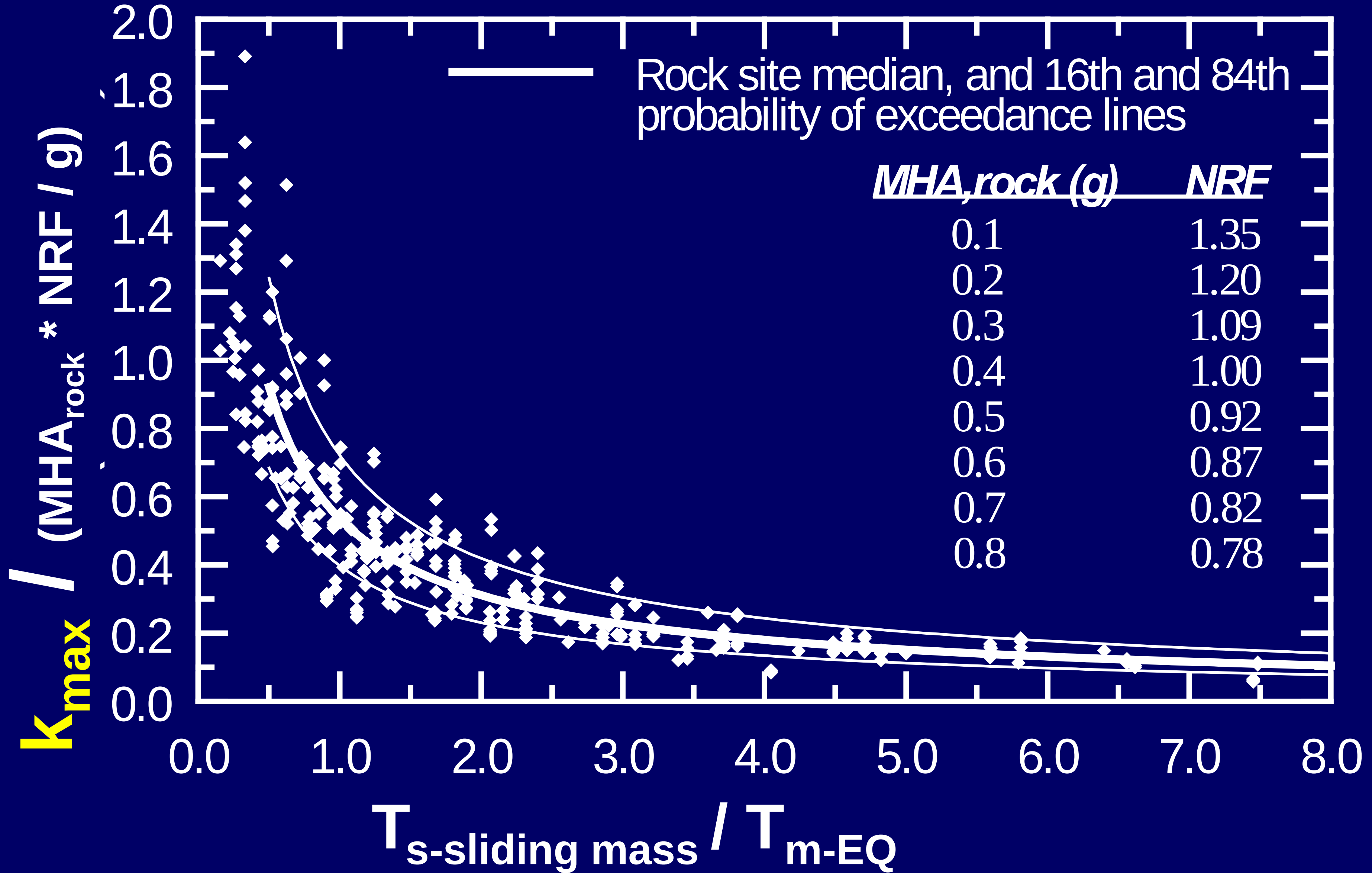

Seed and Martin 1966

accounts for cumulative effect of incoherent motion in deformable sliding mass

- **Horz. Equiv. Accel.: HEA = $(\tau_h/\sigma_v)$ g**
  - **MHEA = max. HEA value**
  - **$k_{max}$ = MHEA / g**



# FACTORS AFFECTING MAXIMUM SEISMIC LOADING




(Bray & Rathje 1998)

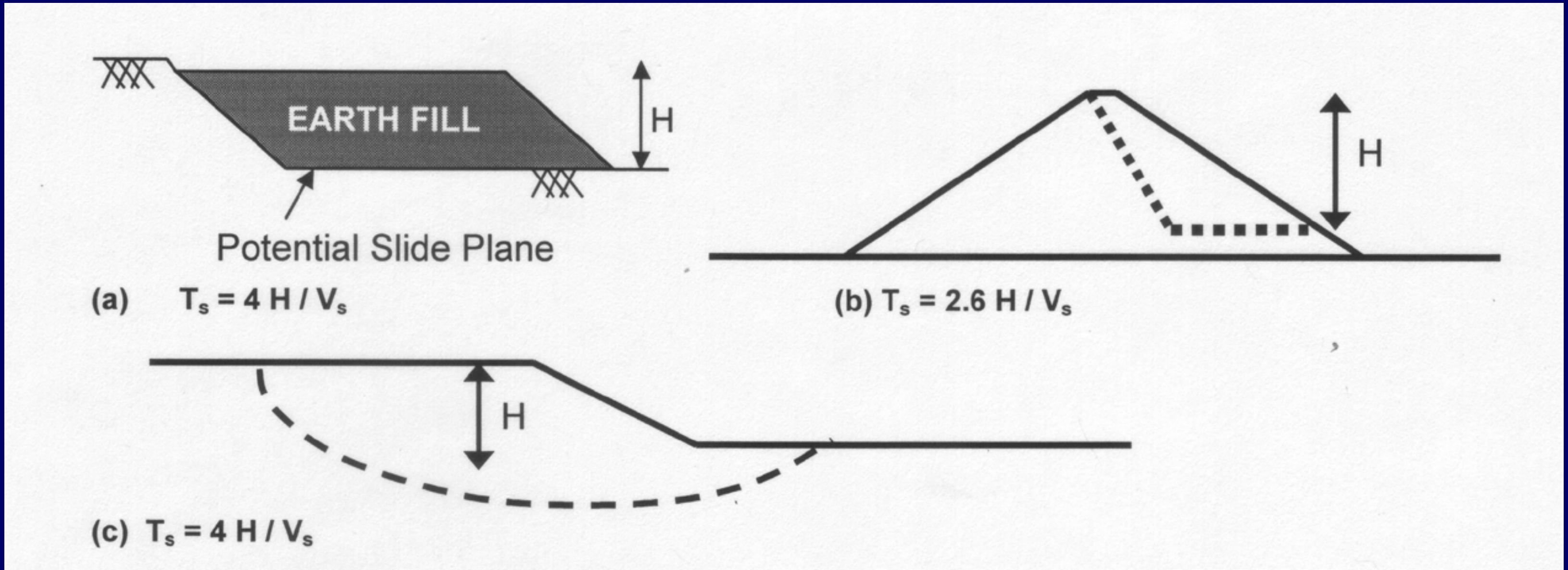
# $k_{max}$ depends on stiffness and geometry of the sliding mass (i.e., its fundamental period)

$$T_{S,1\text{-}D} = 4\,H / V_S$$

$T_{S,\,1\text{-}D}$ = Initial Fundamental Period of Sliding Mass

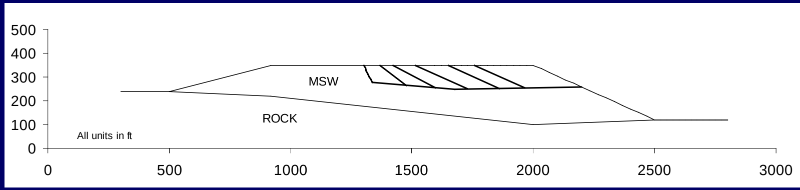
H = Height of Sliding Mass

$V_S$ = Average Shear Wave Velocity of Sliding Mass



# $k_{max}$ also depends on the length of the sliding mass

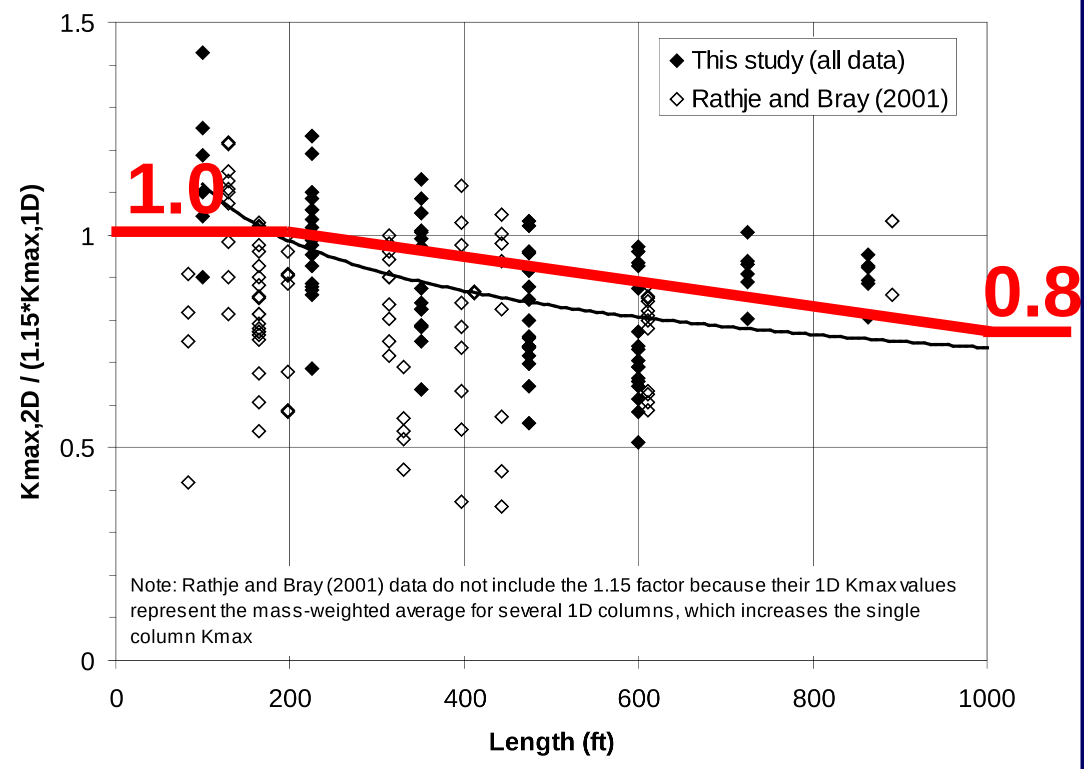
$$k_{max\_2D} = C_L \, k_{max\_1D}$$




$C_L$ = **1.0** for $L$ < 60 m & $C_L$ = **0.8** for $L$ > 300 m

$C_L$ = **1.0 – [($L$ – 60 m) / 1200]** for 60 m < $L$ < 300 m

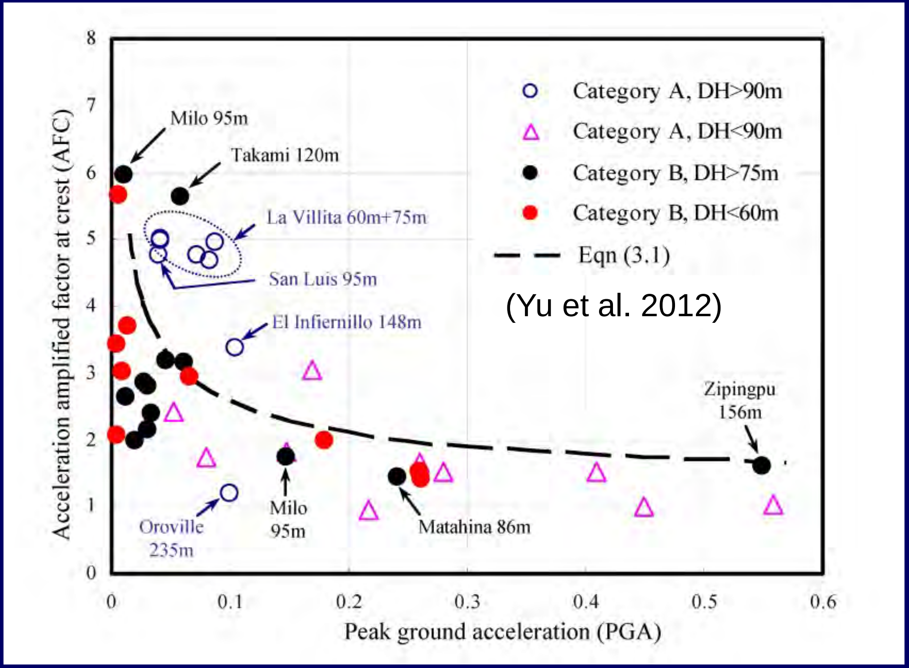
**where $L$ = Length of Potential Sliding Mass (m)**




Rathje & Bray 2008

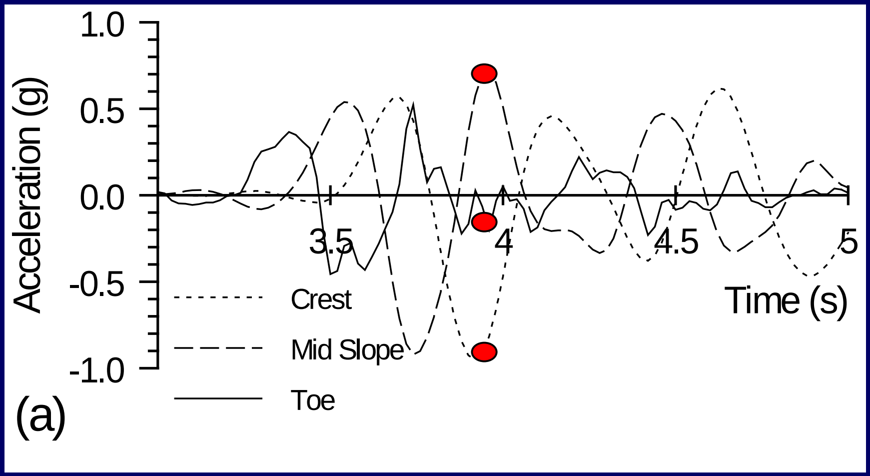
# Topographic Amplification of PGA

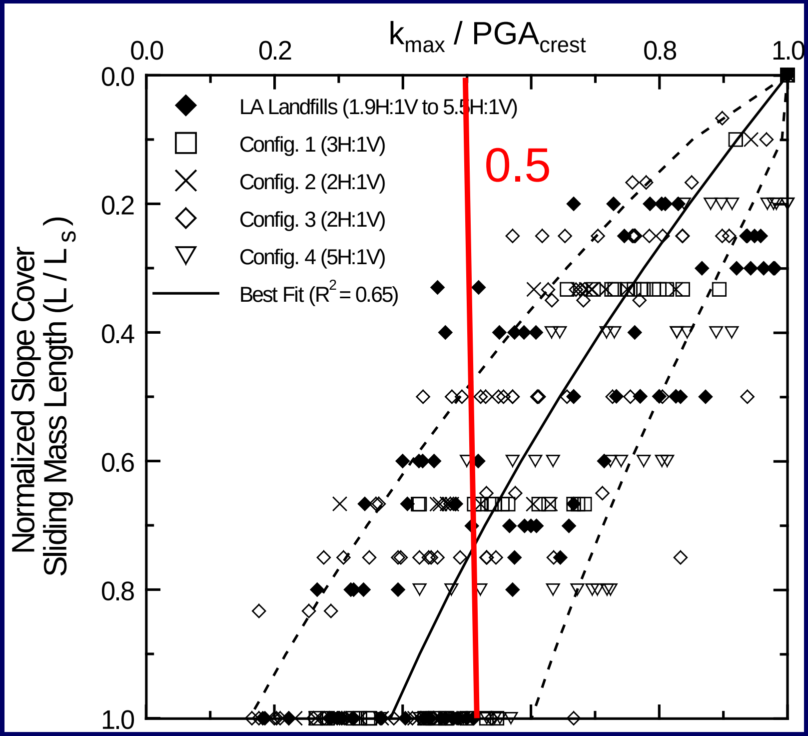
- **Steep Slope (>60º): $PGA_{crest} \approx 1.5\ PGA_{1D}$**
  **(Ashford and Sitar 2002)**
- **Moderate Slope: $PGA_{crest} \approx 1.3\ PGA_{1D}$**
  **(Rathje and Bray 2001)**
- **Dam Crest: $PGA_{crest} \approx (0.5(PGA)^{-0.5} + 1)\ PGA$**
  **(Yu et al. 2012)**



# Topographic Effects on $k_{max}$

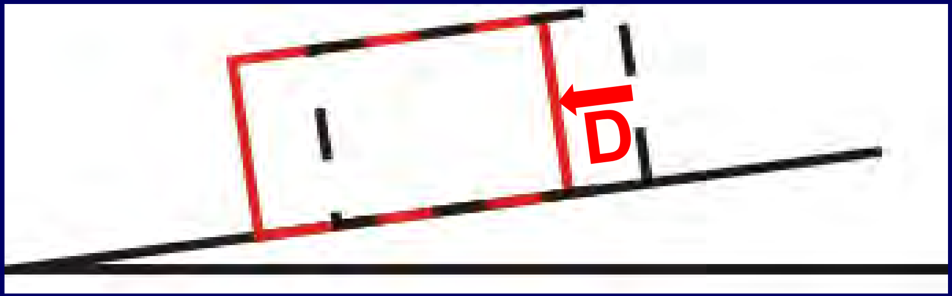
- **Localized shallow sliding near crest**
  - $k_{max} \approx PGA_{crest} / g$
- **Long shallow sliding surface**
  - $k_{max} \approx 0.5\ PGA_{crest} / g$



# *d. Seismic Displacement Calculation*

## *Newmark (1965) Rigid Sliding Block Analysis*




## Assumes:

- Rigid sliding block
- Well-defined slip surface develops
- Slip surface is rigid-perfectly plastic
- Acceleration-time history defines EQ loading

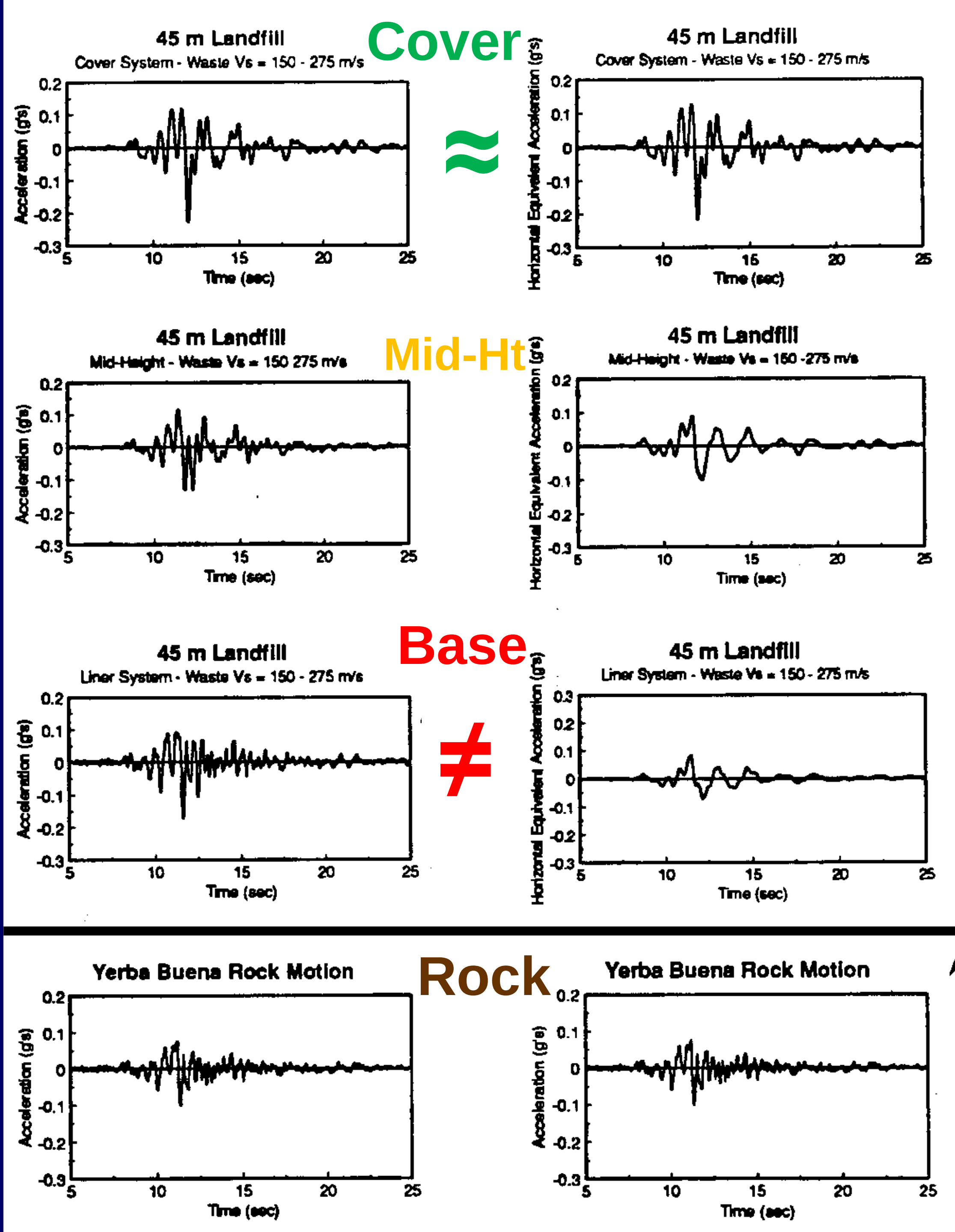
## Key Parameters:

- $k_y$ - Yield Coefficient (max. dynamic resistance)
- $k_{max}$ - Seismic Coefficient (max. seismic loading)
- $k_y / k_{max}$ (if > 1, D = 0; but if < 1, D > 0)

**Rigid Sliding Block:**

uses accel.-time hist.

$k_{max}$ = PGA/g



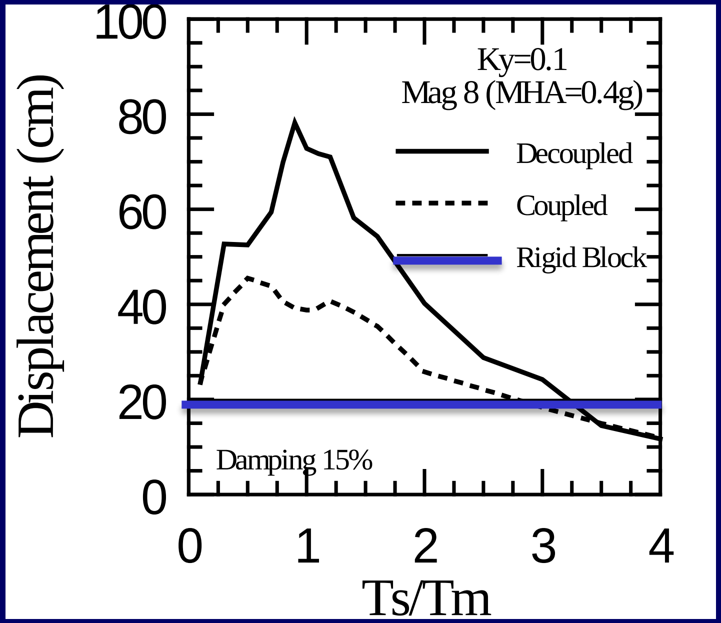

**Deformable Sliding Block:**

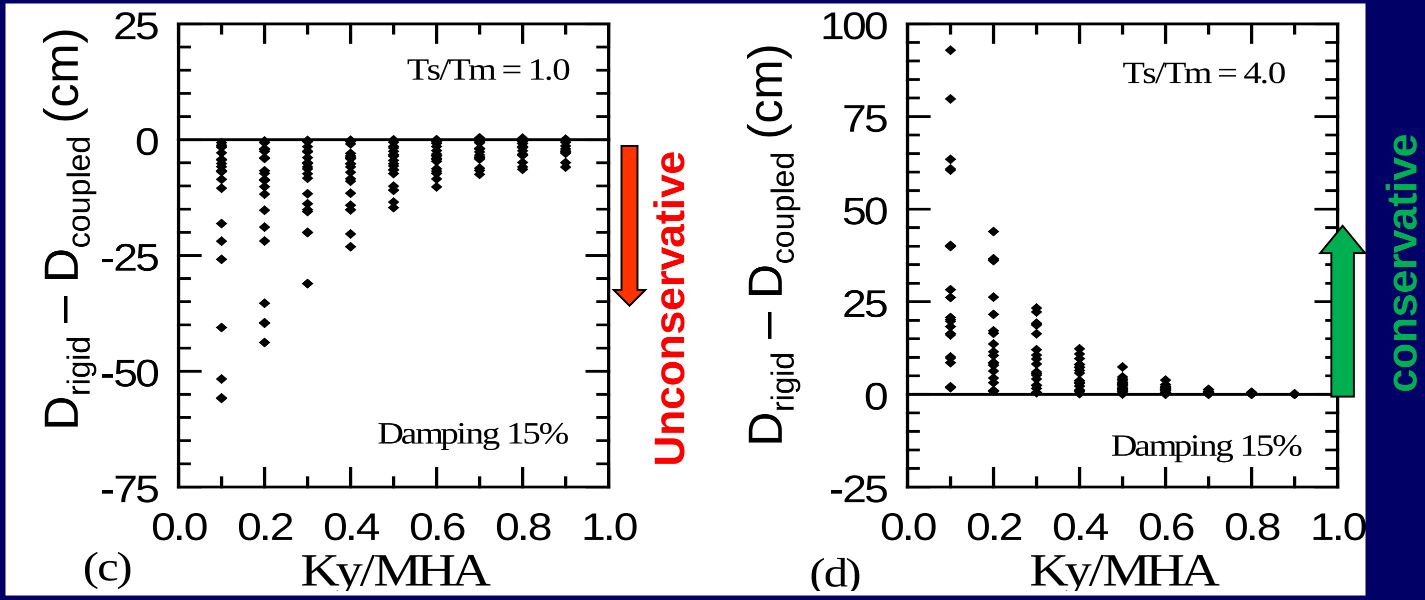
uses equiv. accel.-time hist.

$k_{max}$ = MHEA/g

# Limitations of Rigid Sliding Block Models

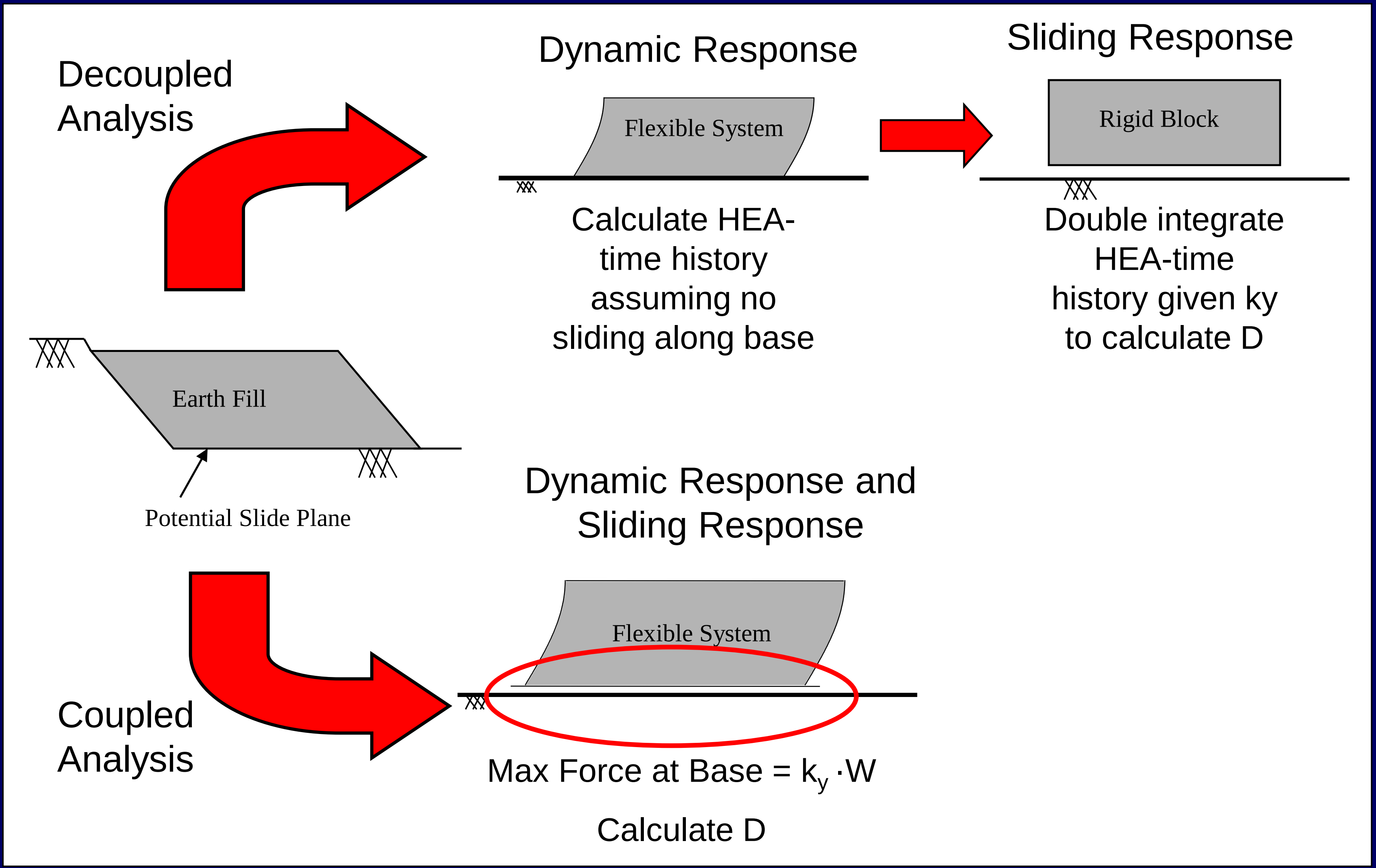
Rathje and Bray (1999, 2000)



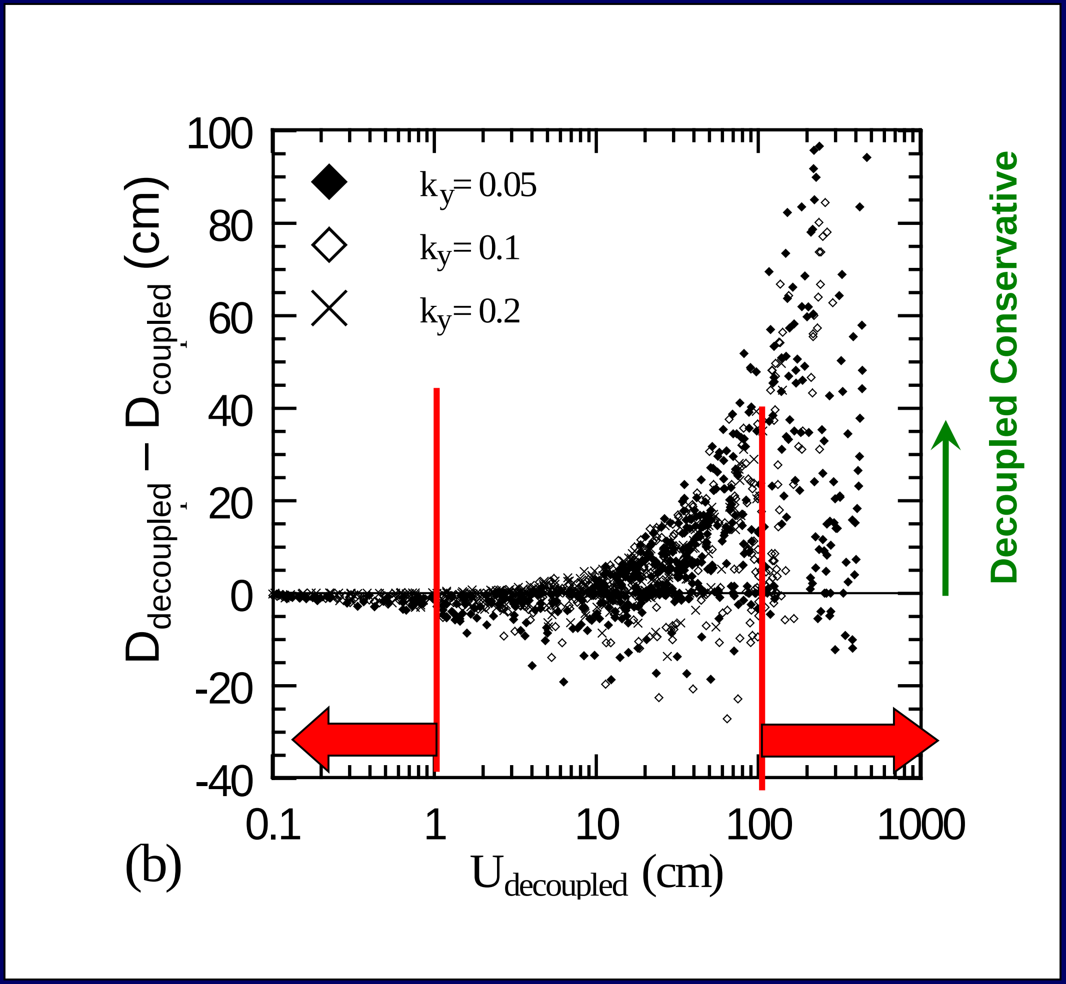



# *Seismic Displacement Calculation*

## Deformable Sliding Block Analysis



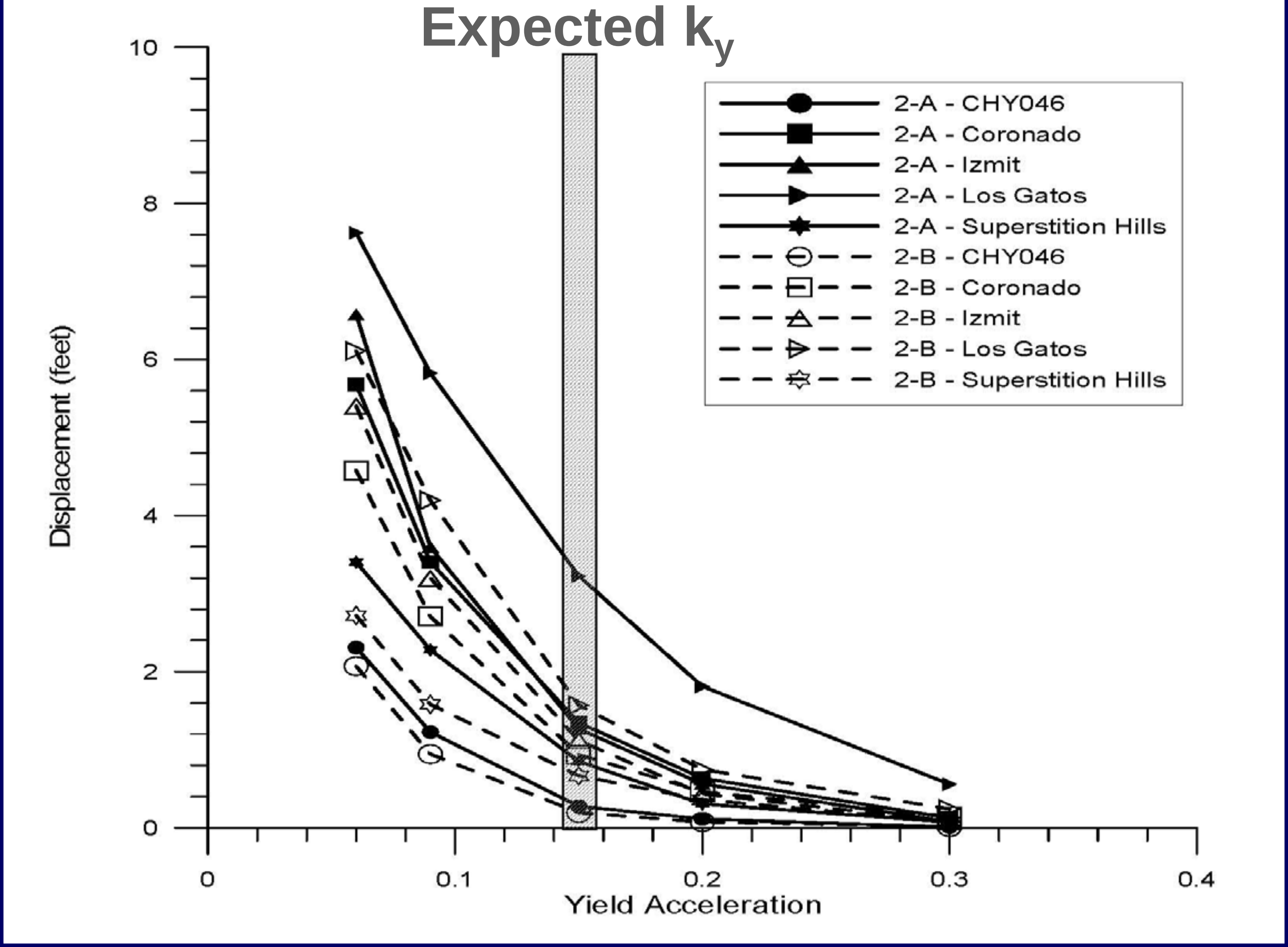
# Decoupled vs. Coupled Analysis




- Insignificant difference for $D_{decoupled}$ < 1 cm
- Conservative for $D_{decoupled}$ > 1 m
- Between 1 cm and 1 m, could be meaningfully unconservative

From Rathje and Bray (2000)

# Calculated Seismic Displacement

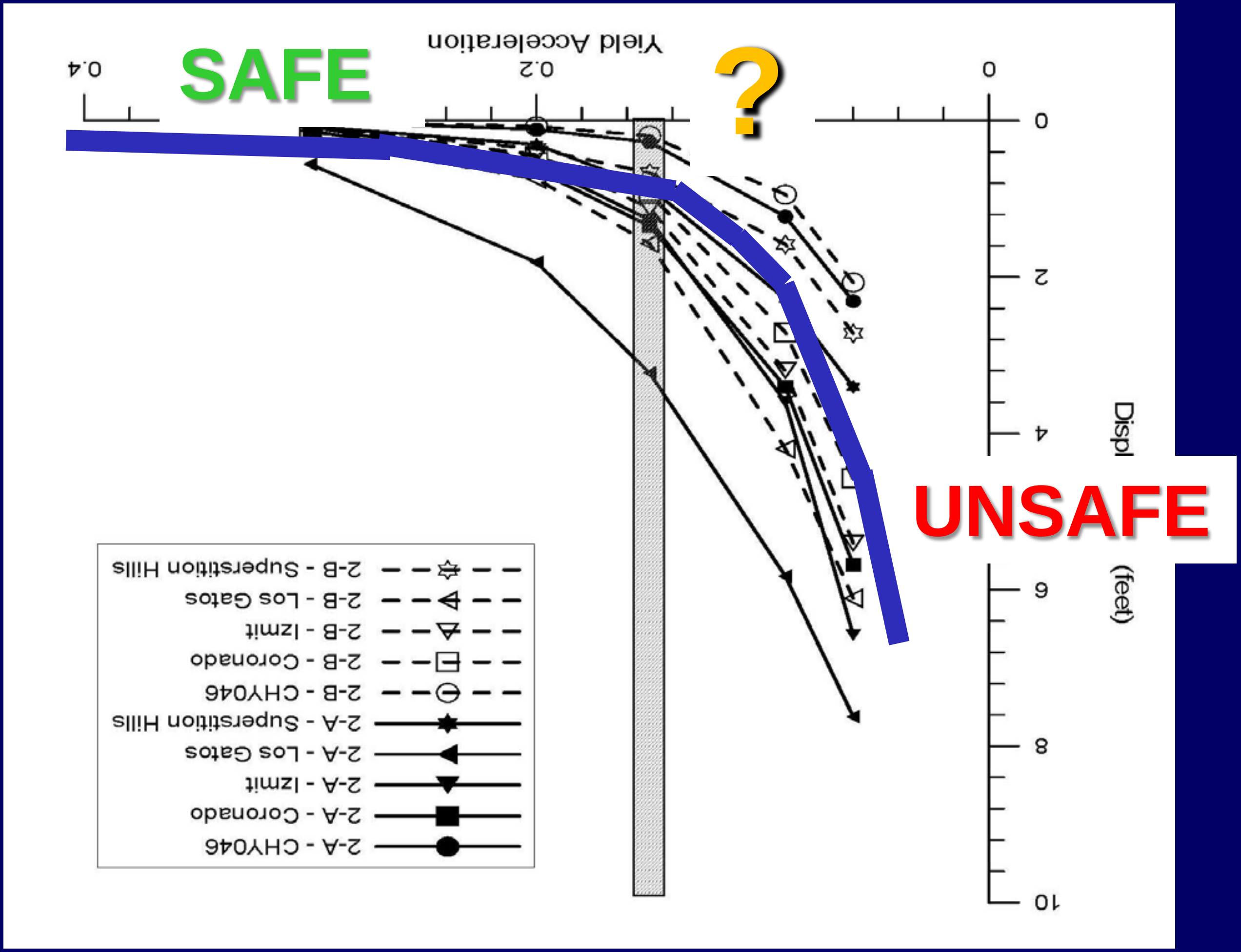



See programs such as SLAMMER by Jibson et al. (2013)

http://pubs.usgs.gov/tm/12b1/O-F Report 03-005

# Think About It as a "Cliff"

## Calculated Seismic Displacement is an *Index* of Performance



# Evaluate Seismic Performance

**Given seismic displacement estimates:**

- Minor (e.g., $D < 15$ cm)
- Major (e.g., $D > 1$ m)

**Evaluate the ability of the earth structure and structures founded on it to accommodate the level of deformation**

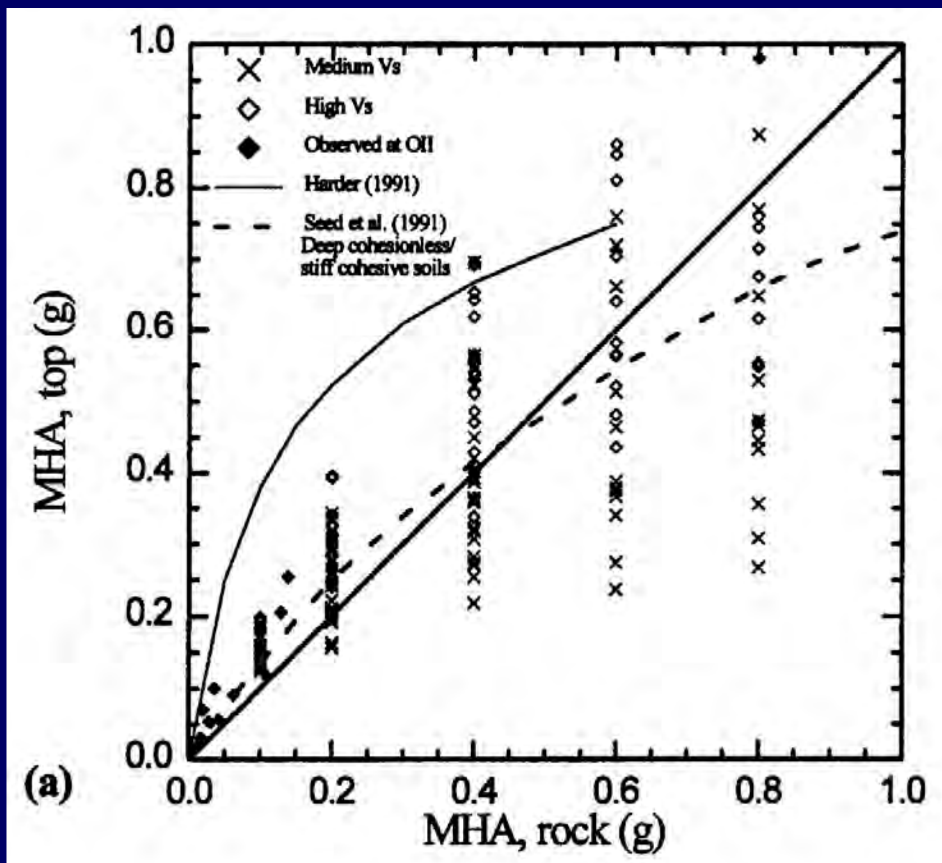
**Consider:**

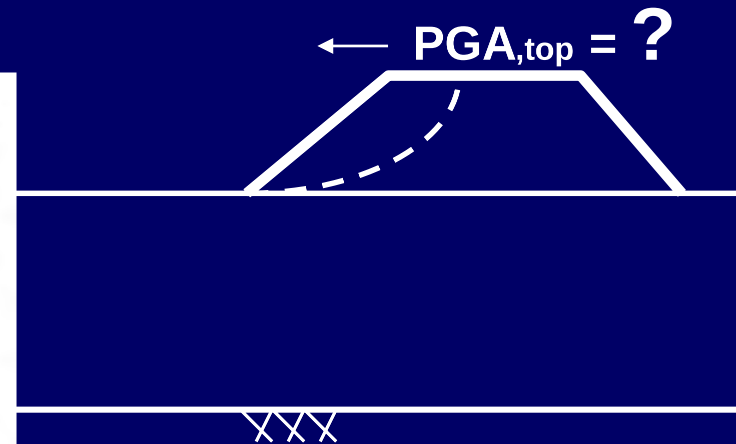
- **Consequences of failure and conservatism of hazard assessment and stability analyses**
- **Defensive measures that provide redundancy, e.g., crack stoppers, filters, and chimney drain for dams, & robust mat foundations, slip layer, and ductile structure**

# III. Simplified Seismic Slope Procedures

## *Makdisi & Seed (1978)*

## Estimate PGA at crest

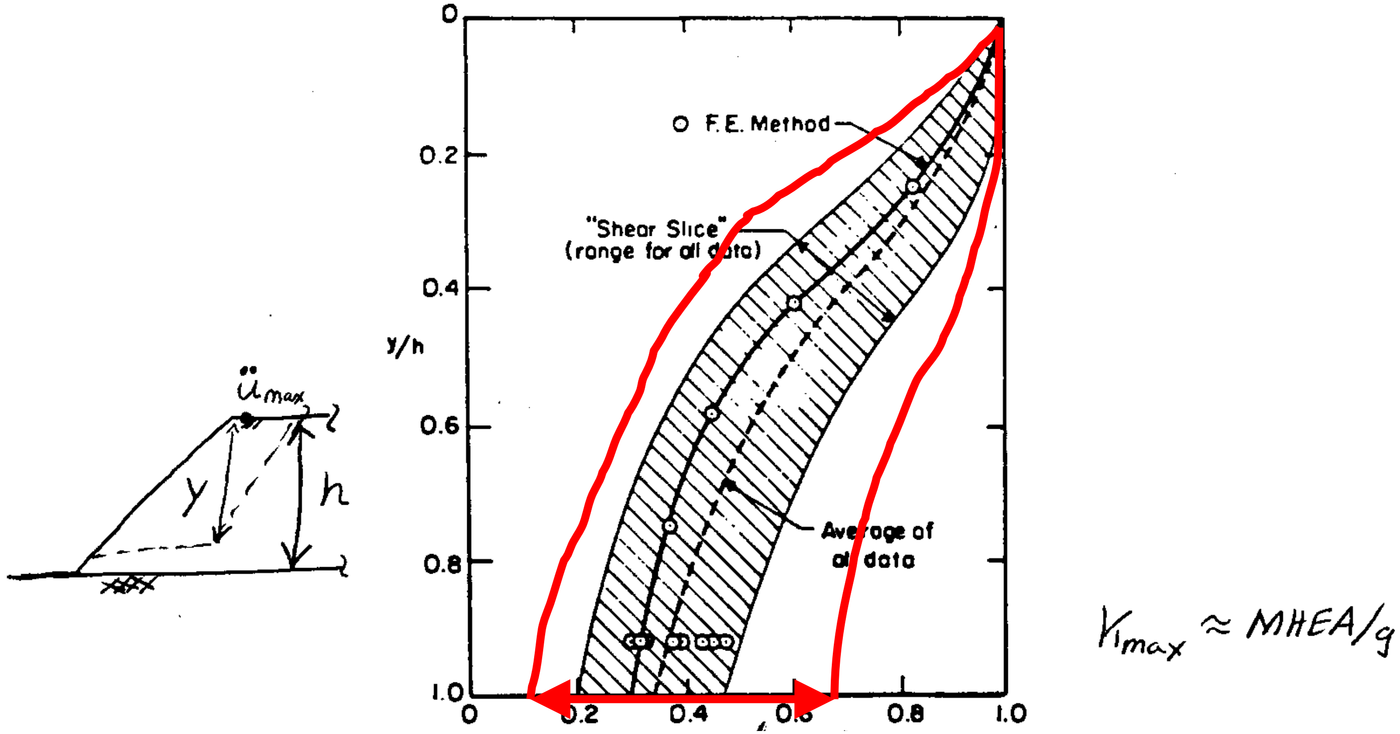



**MHA at Top vs. Base Rock MHA for Some Solid-Waste Landfills**
**(Bray & Rathje 1998)**

# *Makdisi & Seed (1978)*

## Estimate $k_{max}$ for sliding mass as $f$ ($PGA_{crest}$ & y/h)

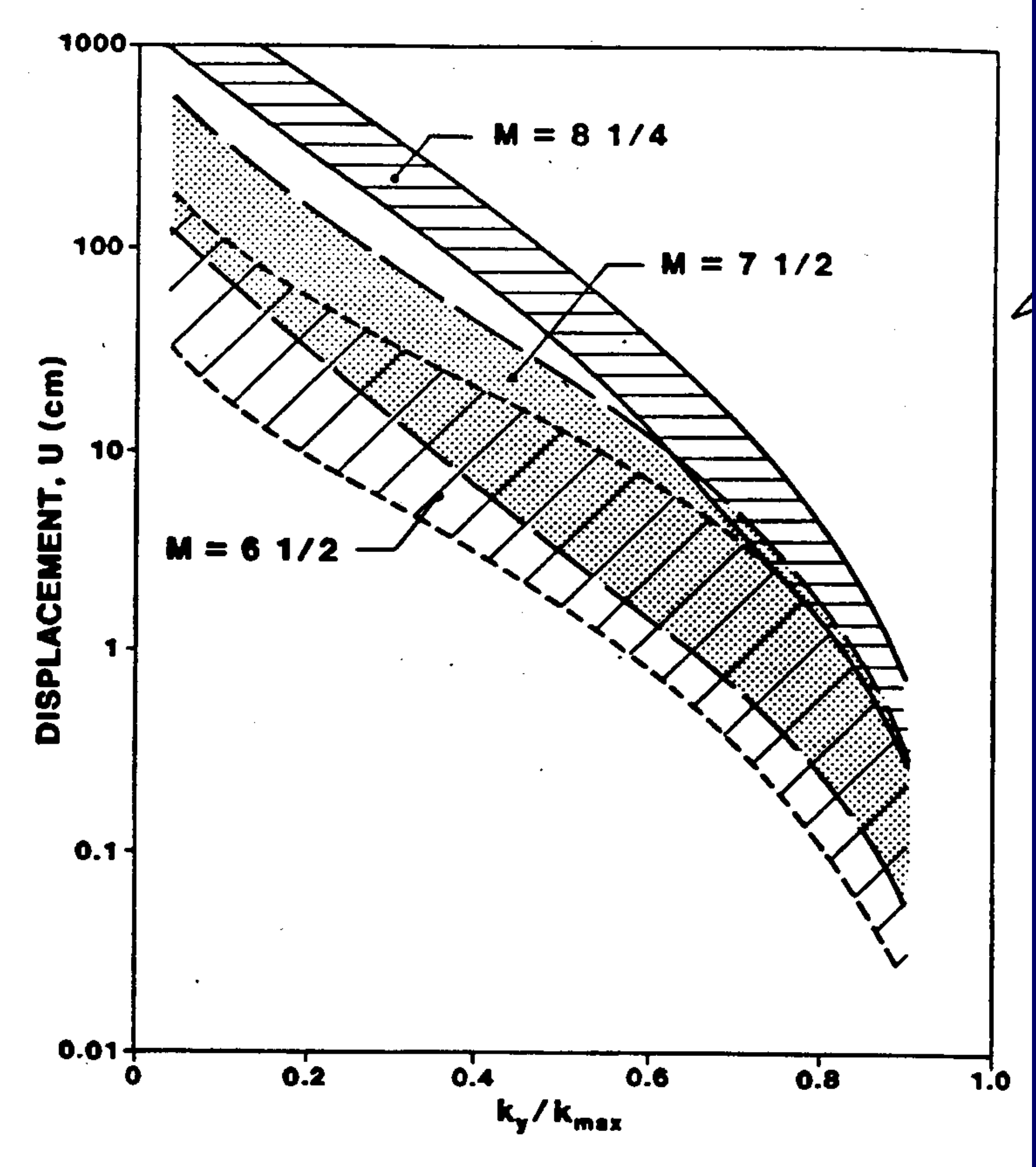



**$K_{max}$ varies with $T_s$**

Makdisi, F.I., and Seed, H.B. (1978)

# Makdisi & Seed (1978)

## Estimate seismic displacement as $f$ ($k_y/k_{max}$ & $M_w$)




**<u>WARNING</u>: Do not use figure in original Makdisi & Seed (1978) paper; it is off by an order of magnitude**

# *Limitations*

***"… design curves … are derived from a limited number of cases.  These curves should be updated and refined as analytical results for more embankments are obtained."***

**Makdisi & Seed (1978)**

**Limited number of earthquake ground motions used**

**Estimating PGA at the crest to estimate $k_{max}$ is difficult**

**Simple shear slice analysis employed**

**Decoupled analysis to calculate seismic displacement**

**Bounds are not true upper and lower bounds**

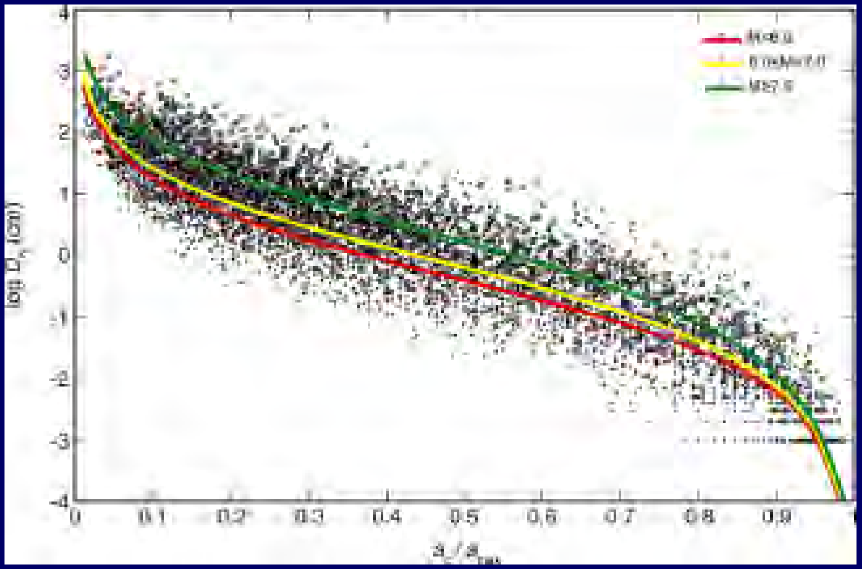
**Only a few analyses & no estimate of uncertainty**

# *Jibson (2007)*

Used rigid sliding block model with acceleration-time histories (original Newmark 1965 approach)

Used several hundred EQ records

**Estimate seismic displacement as $f$ ($k_y$, $a_{max}$ & $M_w$)**



# *Jibson (2007)*

Jibson (2007) states:

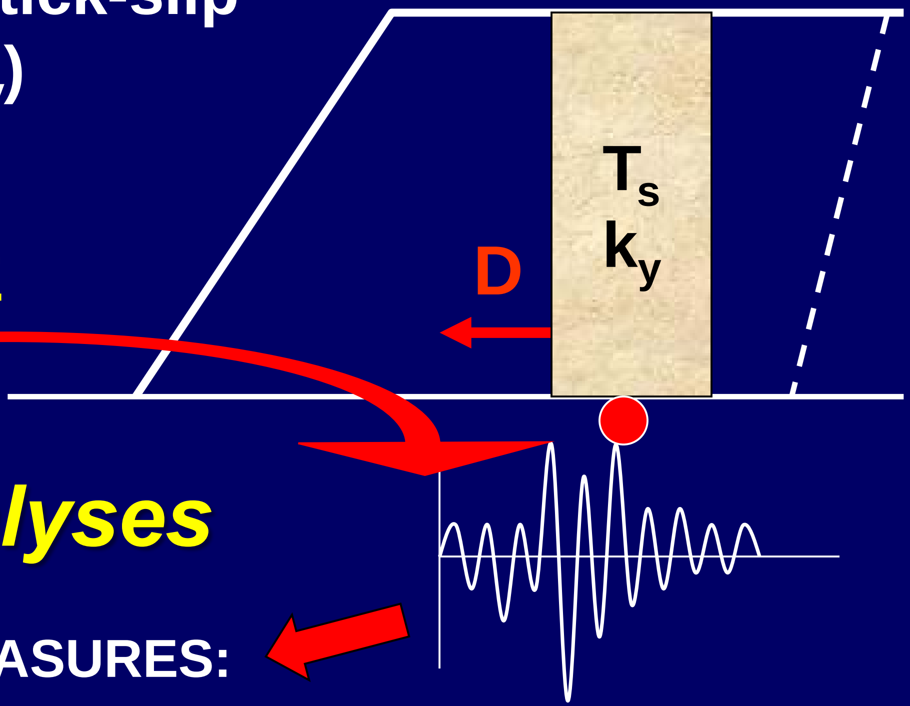
*Newmark's method treats a landslide as a rigid-plastic body: the mass does not deform internally ...*

*Therefore, the proposed models … are most appropriately applied to thinner landslides in more brittle materials rather than to deeper landslides in softer materials.*

**Only Models Rigid Sliding Mass (i.e., $T_s = 0$)**

# Bray & Travasarou (2007)

1. SLOPE MODEL
   nonlinear soil response
   fully coupled deformable stick-slip
   stiffness ($T_s$) & strength ($k_y$)
   8 $T_s$ values & 10 $k_y$ values




2. EARTHQUAKE DATABASE
   688 records (41 EQs)

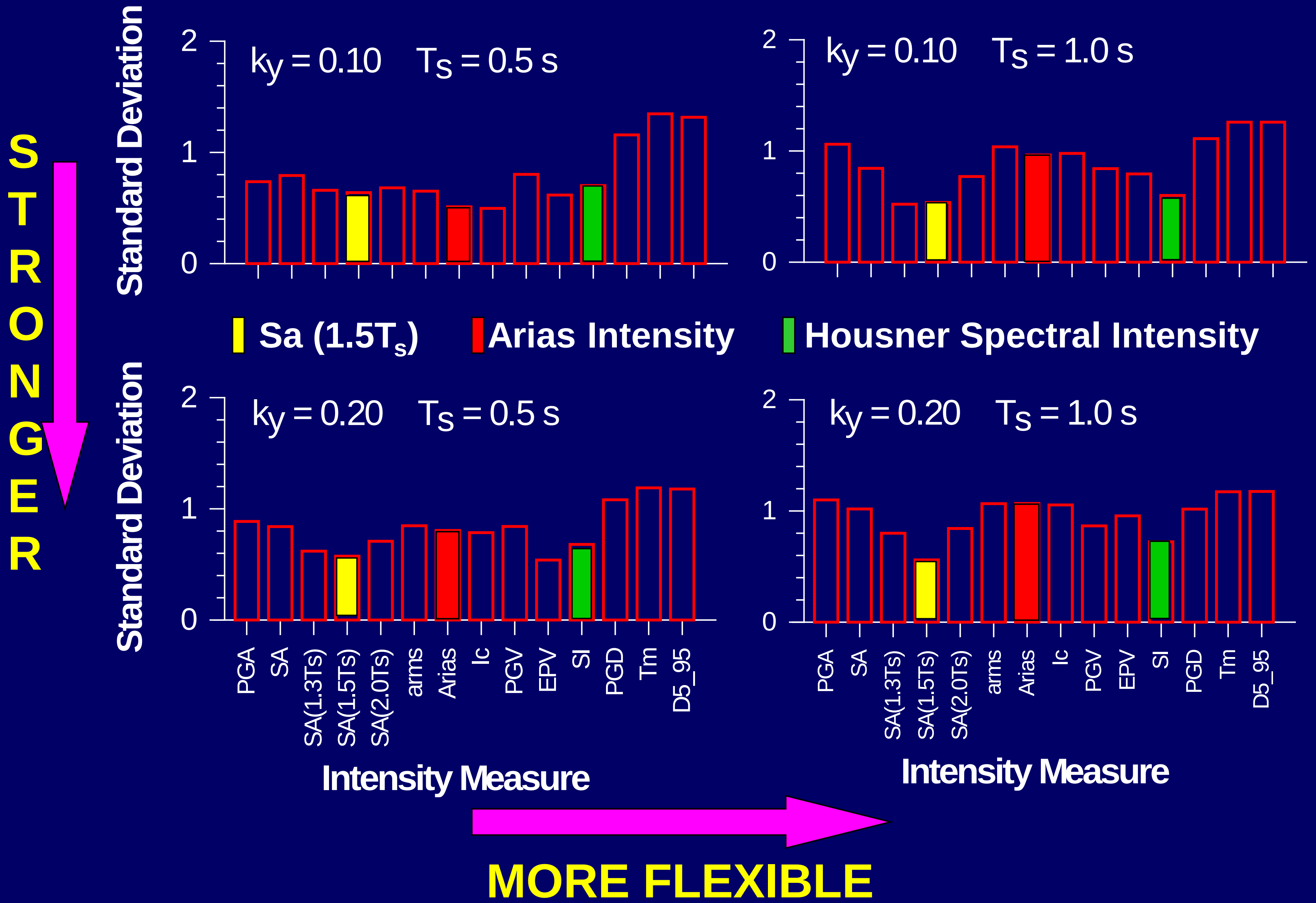
***Over 55,000 analyses***

**OPTIMAL INTENSITY MEASURES:**

$S_a(1.5\ T_s)$ & $M_w$ of outcropping motion below slide

3. CALIBRATION
   16 case histories

# EFFICIENCY of Ground Motion Intensity Measures



# Bray & Travasarou (2007): $D = f(k_y, S_a(1.5T_s), T_s, M_w)$

## 1) "Zero" Displacement Estimate

$$P(D = "0") = 1 - \Phi\left(-1.76 - 3.22\ln(k_y) - 0.484\ln(k_y)T_s + 3.52\ln(S_a(1.5T_s))\right)$$

**Φ is the standard normal cumulative distribution function (NORMSDIST in Excel)**

## 2) "NonZero" Displacement Estimate

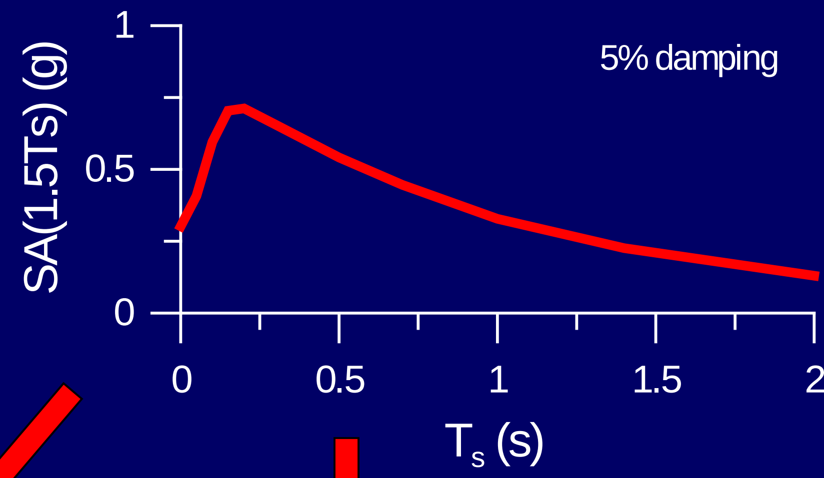
$$\ln(D) = -1.10 - 2.83\ln(k_y) - 0.333\left(\ln(k_y)\right)^2 + 0.566\ln(k_y)\ln(S_a(1.5T_s)) + 3.04\ln(S_a(1.5T_s)) - 0.244\left(\ln(S_a(1.5T_s))\right)^2 + 1.50T_s + 0.278(M - 7) \pm \varepsilon$$

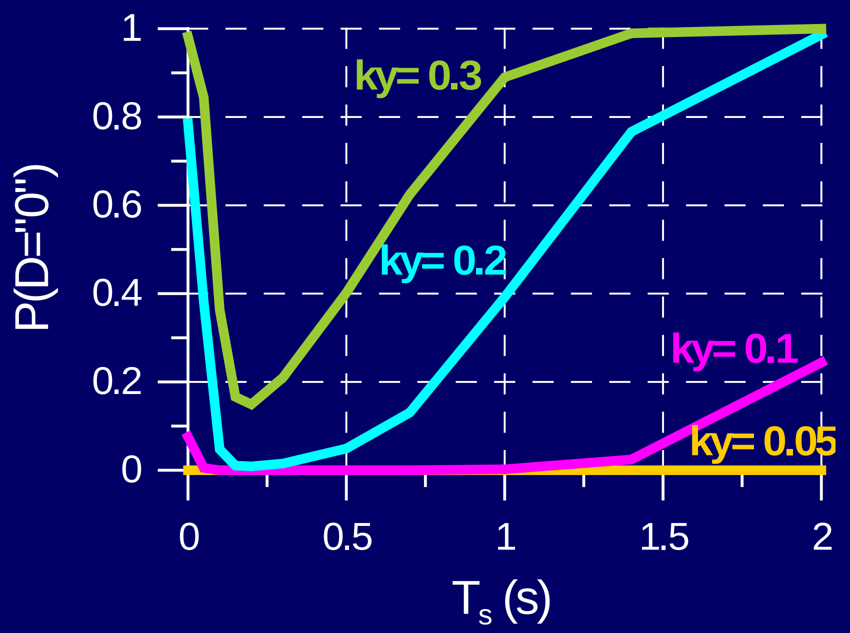
**ε is a normally-distributed random variable with zero mean and standard deviation σ = 0.66**

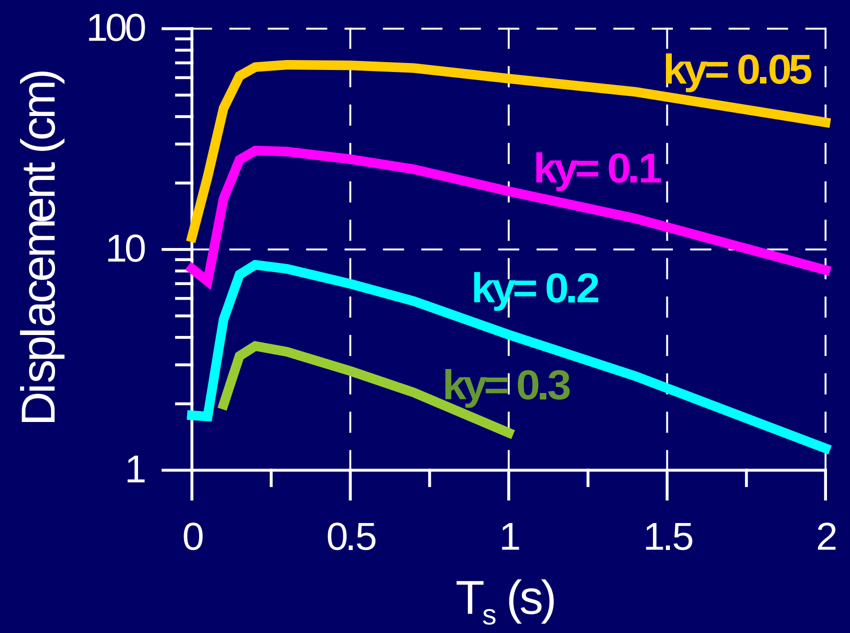
***Replace first term (i.e., -1.10) with -0.22 for cases where $T_s$ < 0.05 s**

# Bray & Travasarou (2007): MODEL TRENDS

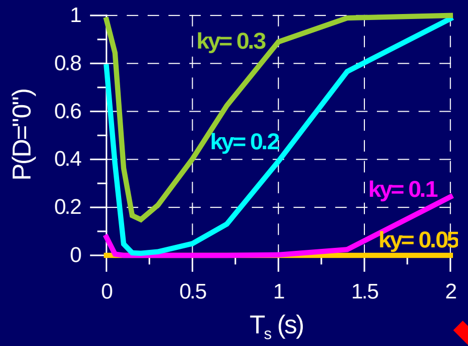
**Scenario Event:**
**M 7 at 10 km**
**“Soil” – SS fault**



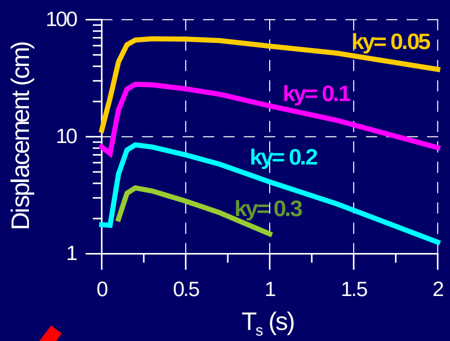



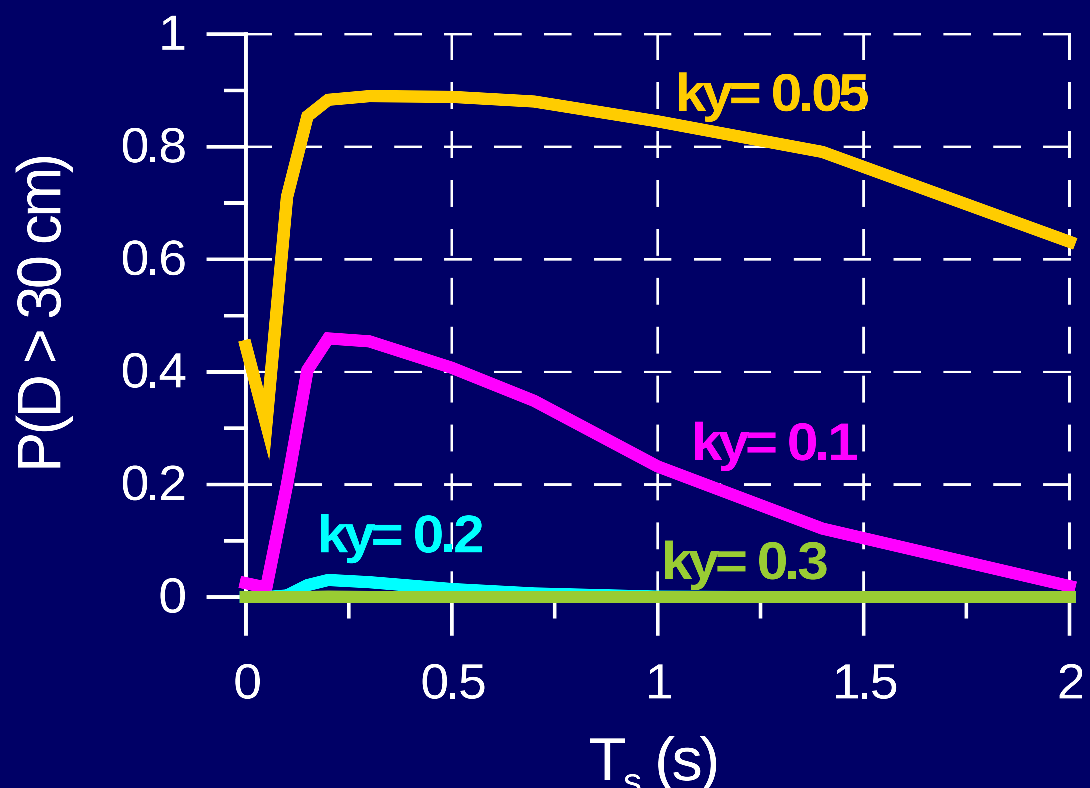



# PROBABILITY OF EXCEEDANCE




**Scenario Event:**
**M 7 at 10 km**
**"Soil" – SS fault**

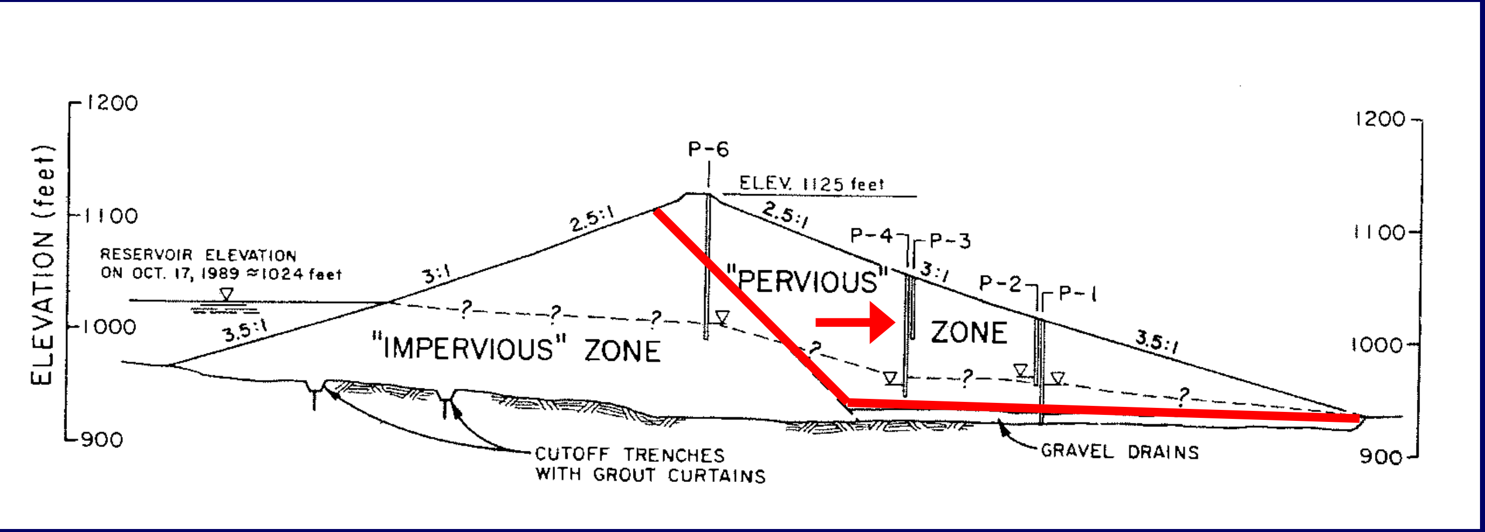


# Validation of Bray & Travasarou Simplified Procedure

| Earth Dam or Landfill | EQ | Obs. $D_{max}$ (cm) | Bray & Travasarou 2007 | |
|---|---|---|---|---|
| | | | P (D = "0") | Est. Disp (cm) |
| Chabot Dam | SF | **Minor** | **0.35** | **0 - 5** |
| Guadalupe LF | LP | **Minor** | **0.95** | **0.3 - 1** |
| Pacheco Pass LF | LP | **None** | **1.0** | **0 - 0.1** |
| Austrian Dam | LP | **50** | **0.0** | **20 - 70** |
| Lexington Dam | LP | **15** | **0.0** | **15 - 65** |
| Sunshine Canyon LF | NR | **30** | **0.0** | **20- 70** |
| OII Section HH LF | NR | **15** | **0.1** | **4 - 15** |
| La Villita Dam | S3 | **1** | **0.95** | **0.3 - 1** |
| La Villita Dam | S4 | **1.4** | **0.5** | **1 - 5** |
| La Villita Dam | S5 | **4** | **0.25** | **3 - 10** |

# Example: 57 m-High Earth Dam Located 10 km from M = 7.5 EQ




**No liquefaction or soils that will undergo significant strength loss**

**Undrained Strength: c = 14 kPa and $\phi = 21^o$ so $k_y = 0.14$**

**Triangular Sliding Block with avg. $V_s$ ~ 450 m/s & H = 57 m**

$$T_s = \frac{2.6 \cdot H}{\overline{V}_s} = \frac{2.6 \cdot 57m}{450m/s} \approx 0.33s$$

# Deterministic Analysis:

**$k_y$ = 0.14; $T_s$ = 0.33 s; & $M_w$ = 7.5 at R = 10 km;**

**Using 1.5 $T_s$ = 1.5 (0.33 s) = 0.5 s & NGA GMPE for rock with $V_{s30}$ = 600 m/s for strike-slip fault: median $S_a$(0.5 s) = 0.483 g**

**Probability of “Zero” Displacement (i.e., D < 1 cm):**

$$P(D = \text{"0"}) = 1 - \Phi\left(-1.76 - 3.22\ln(0.14) - 0.484\ln(0.14)(0.33) + 3.52\ln(0.483)\right) = 0.01$$

**Nonzero Median Seismic Displacement Estimate (ε = 0):**

$$\ln(D) = -1.10 - 2.83\ln(0.14) - 0.333\left(\ln(0.14)\right)^2 + 0.566\ln(0.14)\ln(0.483) +$$

$$3.04\ln(0.483) - 0.244\left(\ln(0.483)\right)^2 + 1.50(0.33) + 0.278(7.5 - 7) \pm 0$$

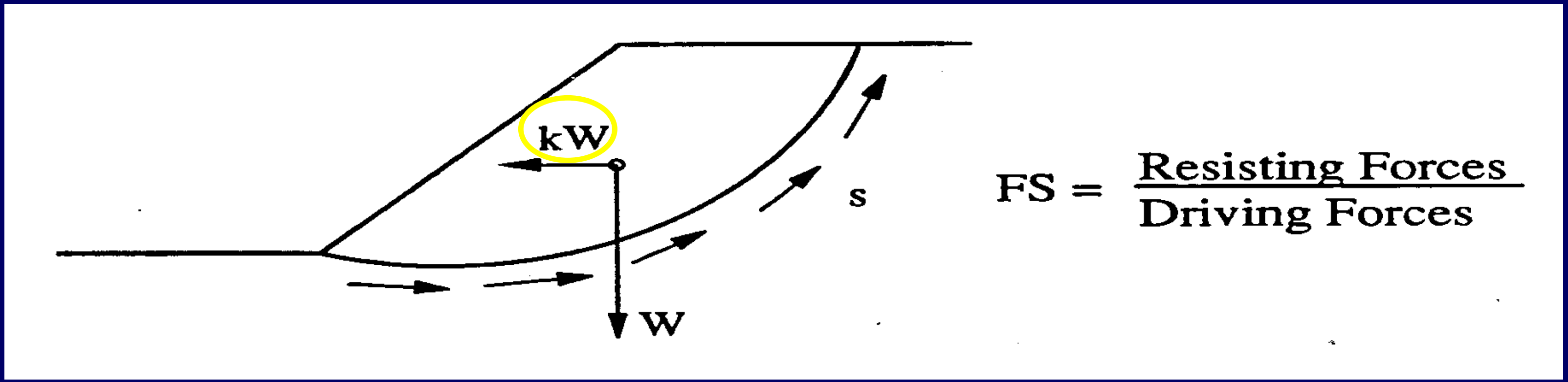
$$D = \exp(\ln(D)) = \exp(2.28) \approx 10cm$$

**Design Seismic Displacement Estimate (16% and 84%):**

***D ≈ 0.5 to 2 times median D = 5 cm to 20 cm***

***For fully probabilistic implementation see Travasarou et al. 2004***

# Pseudostatic Slope Stability Analysis




1. k = seismic coefficient; represents earthquake loading
2. S = dynamic material strengths
3. FS = factor of safety

***Selection of acceptable combination of k, S, & FS requires calibration through case histories or consistency with more advanced analyses***

# *A Prevalent Pseudostatic Method*

**<u>Seed (1979)</u>**

- **“appropriate” dynamic strengths**
- **k = 0.15**
- **FS > 1.15**

**BUT this method was calibrated for cases where 1 m of displacement was judged to be acceptable**

**WHAT about other levels of acceptable displacement?**

**IS k = 0.15 reasonable for all sites regardless of M & R?**

***FS > 1.15 does not mean the system is safe!***

# *Seismic Coefficient*

**k should depend on level of shaking, i.e., R, M, & dynamic response of earth structure**

**k should also depend on criticality of structure and acceptable level of seismic performance, i.e., amount of allowable seismic displacement**

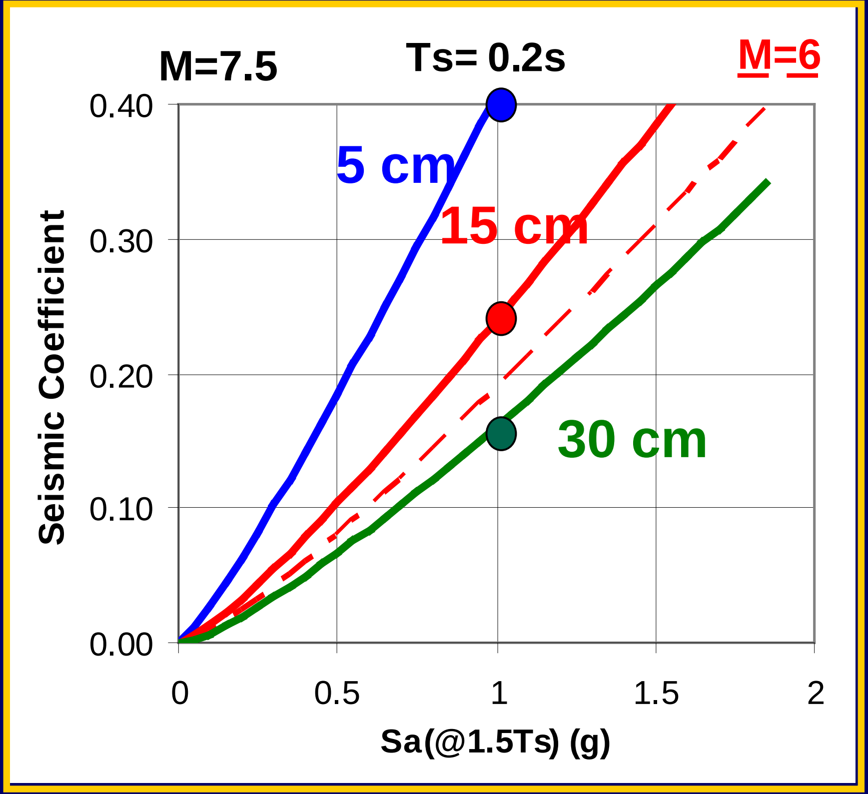
## How does one then select k?

# Seismic Coefficient from Allowable Displacement

*Bray &Travasarou (2009)*

$$\ln(D) = -1.10 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 + 0.566\ln(k_y)\ln(S_a) + 3.04\ln(S_a) - 0.244(\ln(S_a))^2 + 1.50T_s + 0.278(M_w - 7)$$

## Instead, calculate *k* as function of $D_a$, $S_a$, $T_s$, $M_w$, & $\varepsilon$



# *Pseudostatic Slope Stability Procedure*

1. **Can materials lose significant strength?**
   **If so, use post-shaking reduced strengths.**
   **Otherwise, use strain-compatible dynamic strengths.**

2. **Select allowable displacement: $D_a$ and select exceedance probability (e.g., use $\varepsilon = 0.66$ for 84%)**

3. **Estimate initial period of sliding mass: $T_s$**

4. **Characterize seismic demand: $S_a(1.5T_s)$ & $M_w$**

5. **Calculate seismic coefficient: k = $f\,(D_a, S_a, T_s, M_w \;\&\; \varepsilon)$**
   **& perform pseudostatic analysis using k.**
   **If FS ≥ 1, then $D_{calc} < D_a$ at selected exceedance level**

# IV. Conclusions

- <u>First question</u>: will materials lose strength?
- <u>If not</u>, evaluate seismic slope stability in terms of seismic displacements
- Bray & Travasarou (2007) approach with deformable sliding mass captures:
  a. Dynamic resistance of slope - $k_y$
  b. Earthquake shaking - $S_{a(1.5\ T_s)}$ & $M_w$
  c. Dynamic response of sliding mass - $T_s$
  d. Coupled seismic displacement - D

***"Earthquake and material characterization are most important"***

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