Intelligent Way to Simplify Seismic Stability Analysis for Embankment Dams under Earthquake Loading

土石壩受震反應分析智慧型簡化與功能的加強

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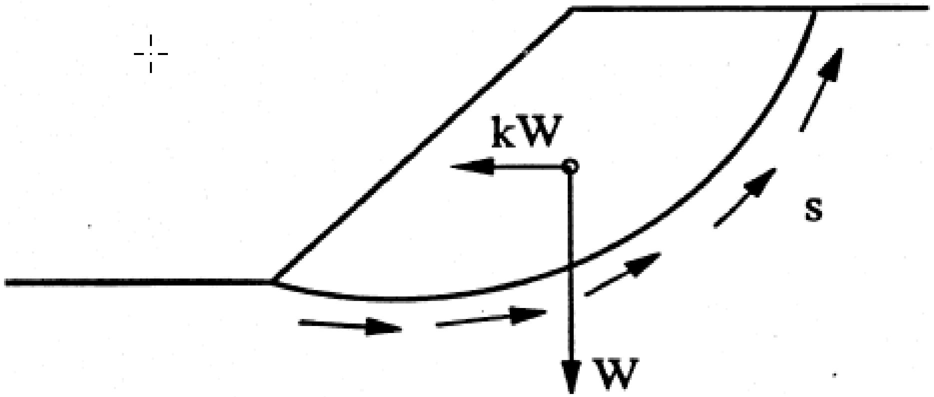
NCREE

Typical Pseudo Static Analysis for Slopes or Dams



$$FS = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

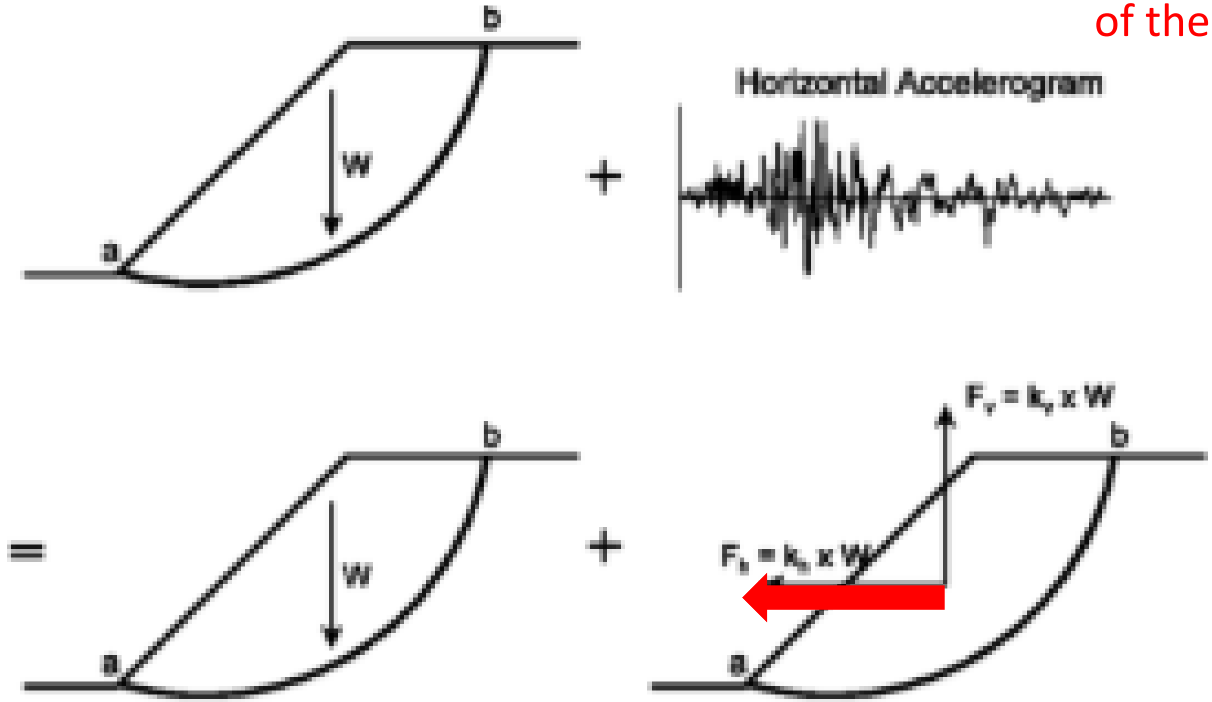
Figure 1. Pseudostatic slope stability analysis

Ky: Yield acceleration

FS = 1.0 when K=Ky

Pseudo Static Slope Stability Analysis

Input excitation or response time history of the soil mass?



1. What did we capture with K
2. What did we not capture with K
3. Is it related to the PGA
4. Duration of the excitation

Problems with Pseudo Static Analysis

- What Ks (pseudo-static coefficient) to use?
- What is your focus?
  - Factor of Safety ←Code requirement
  - How much will the slope move ← Performance requirement
  - What is more important for dam engineers
- You may have the shaking intensity right, but how do you estimate slope response?
  - Dam Height
  - Embankment material (earthfill, rockfill, hydraulic fill)
- With high Ks your stability program may not work (non-convergence)

Seed and his co-workers (1966, 1979, 1981, 1983)

Dam	Country	Seismic Coefficient	Safety Factor
Aviemore	New Zealand	0.10	1.50
Bersemisnoi	Canada	0.10	1.25
Digma	Chile	0.10	1.15
Globocica	Yugoslavia	0.10	1.00
Karamauri	Turkey	0.10	1.20
Kisenyama	Japan	0.12	1.15
Mica	Canada	0.10	1.25
Misakubo	Japan	0.12	--
Netzahualcovote	Mexico	0.15	1.36
Oroville	United States	0.10	1.20
Paloma	Chile	0.12 to 0.20	1.25 to 1.10
Ramganga	India	0.12	1.20
Tercan	Turkey	0.15	1.20
Yeso	Chile	0.12	1.50

Notes:
1. In California, k = 0.05 to 0.15 and FS > 1
2. In Japan, k ≤ 0.20 and FS > 1

The Corps of Engineers Manual EM-1110-2-1902 (1982)

Where earthquake threat is major and great, k = 0.10 and 0.15, respectively.

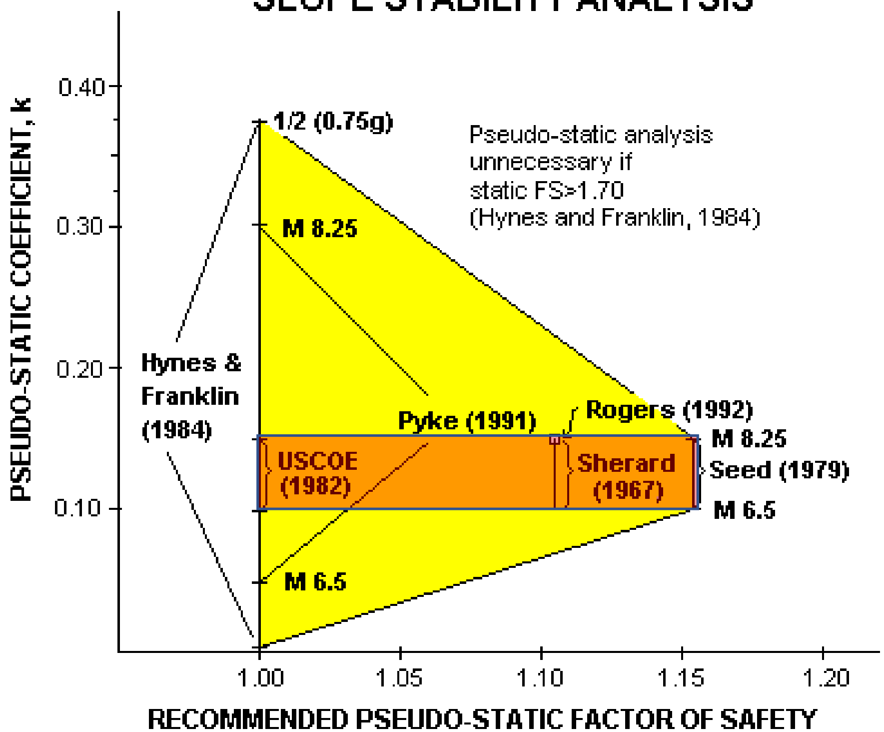
Marcuson and Franklin (1983)

k = ⅓ to ½ of MHA at the crest, with FS ≥ 1.0.

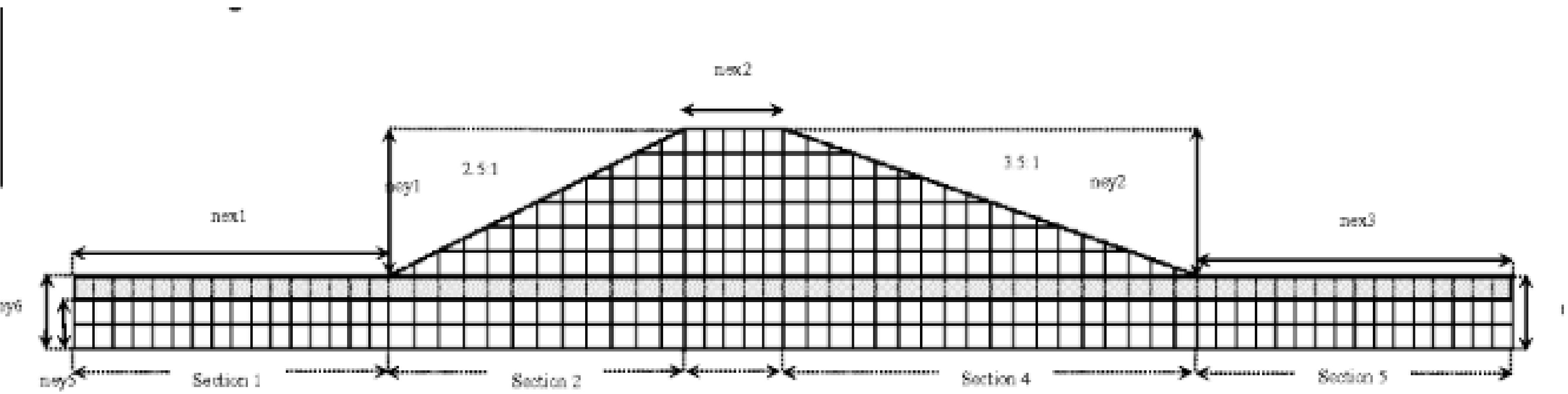
Hynes-Griffen and Franklin (1984)

k = ½ MHA of bedrock, with FS ≥ 1.0 and 20% reduction in material strengths.

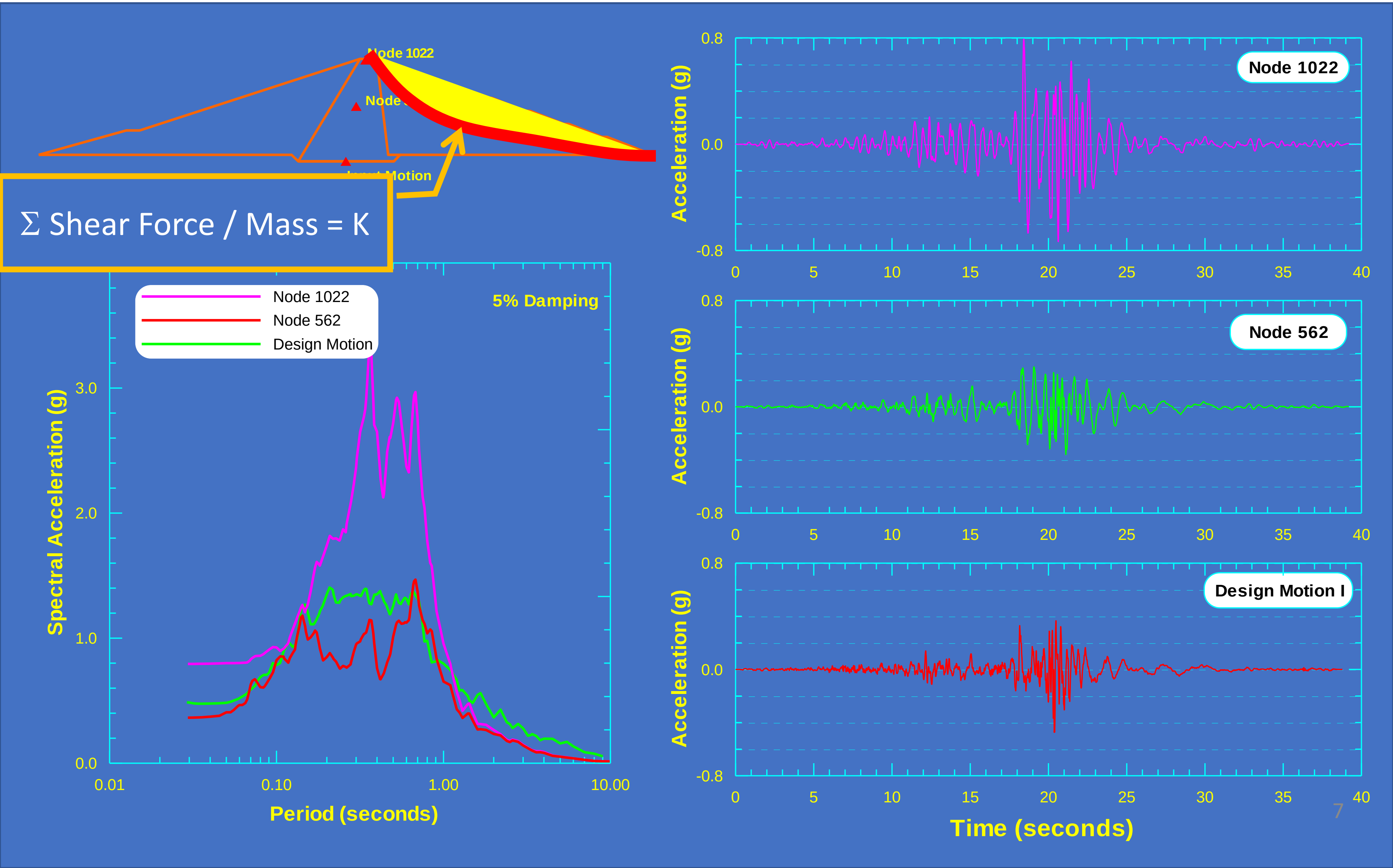
CRITERIA FOR PSEUDO-STATIC SLOPE STABILITY ANALYSIS



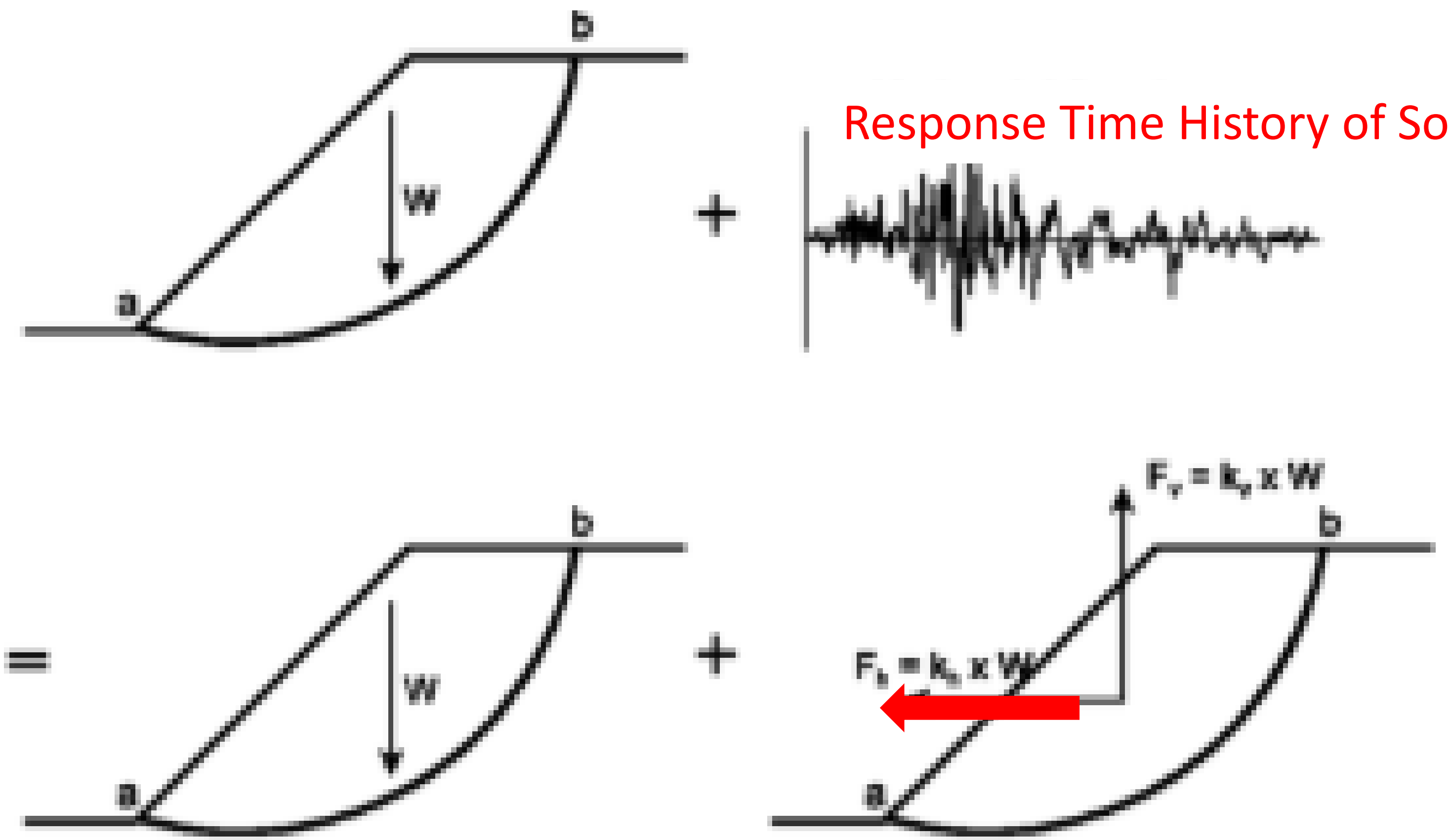
Finite Element Analysis



範例圖5 壩體內部反應譜及加速度歷時



Yield Acceleration



Yield Acceleration (Ky)

The pseudo-static seismic coefficient, k, that results in a factor of safety of 1.0 is determined by:

$$k_y = \frac{a_y}{g}$$

Equation 3

where the yield seismic coefficient is a ratio of the yield acceleration to the gravitational constant, g.

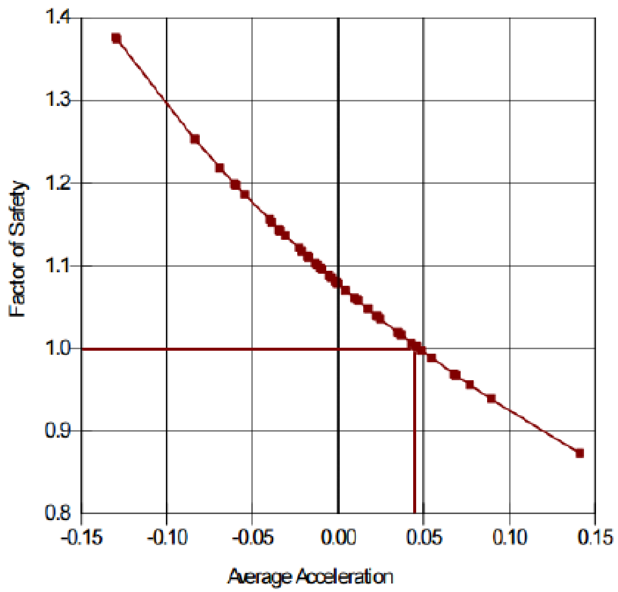
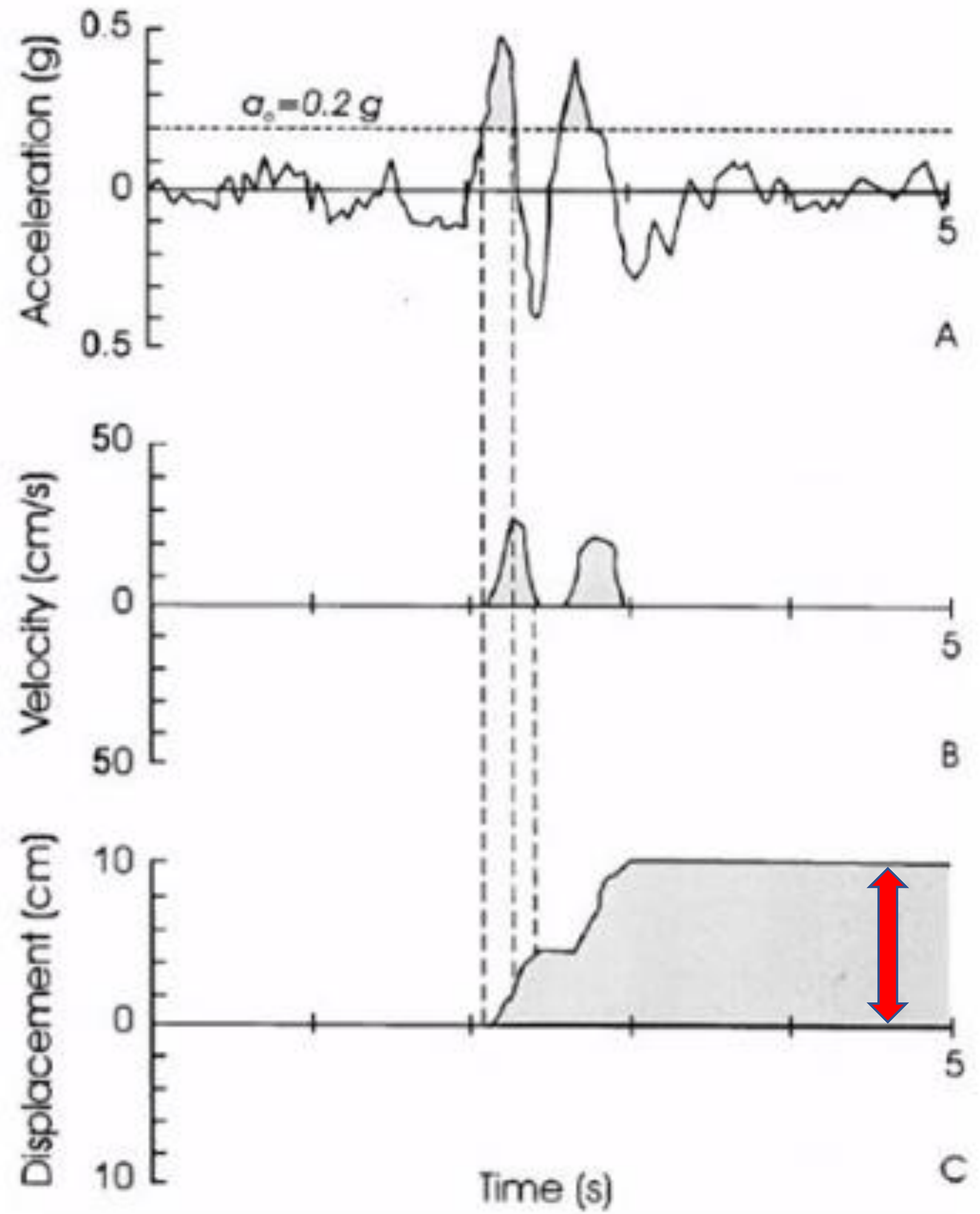


Figure 1: Comparison of the computed factor of safety and average acceleration.

Newmark Sliding Block procedure

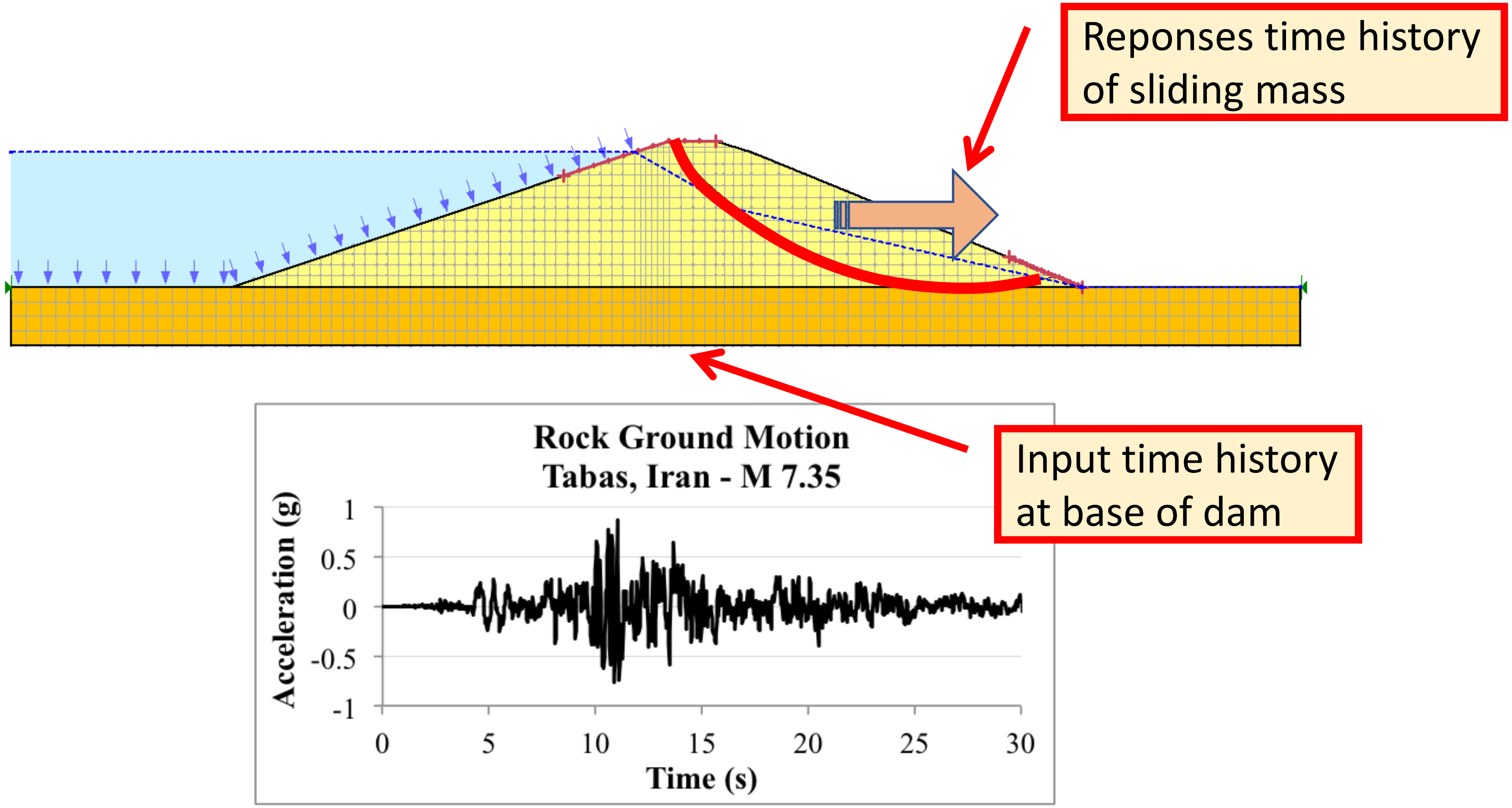


Good Dam Deformation Needs

- Good and defendable ground motion
- Ability to qualify ground motion uncertainty
- Geotechnical drilling at multiple dam locaitons
  - Cost
  - Hydraulic fracturing the dam during drilling
  - Introduce artificial weak zone
- Finite Element analysis of dam
- Seldon verify if the dam model is correct
- New ideas?????

Development of Model step by step example

Key to approach is transfer function



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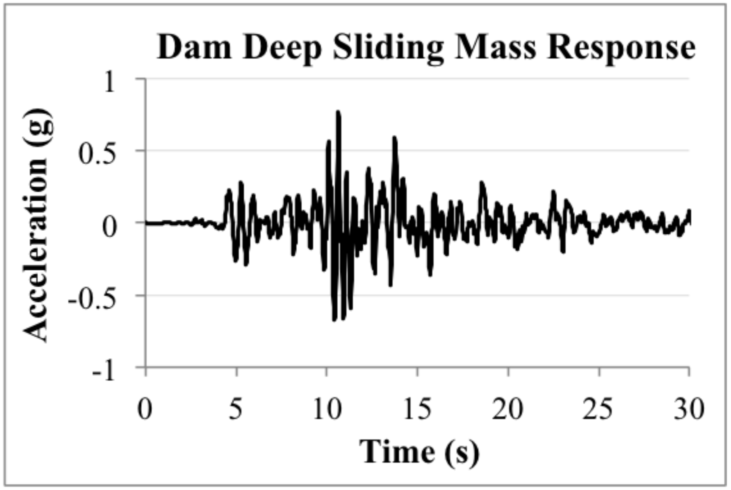

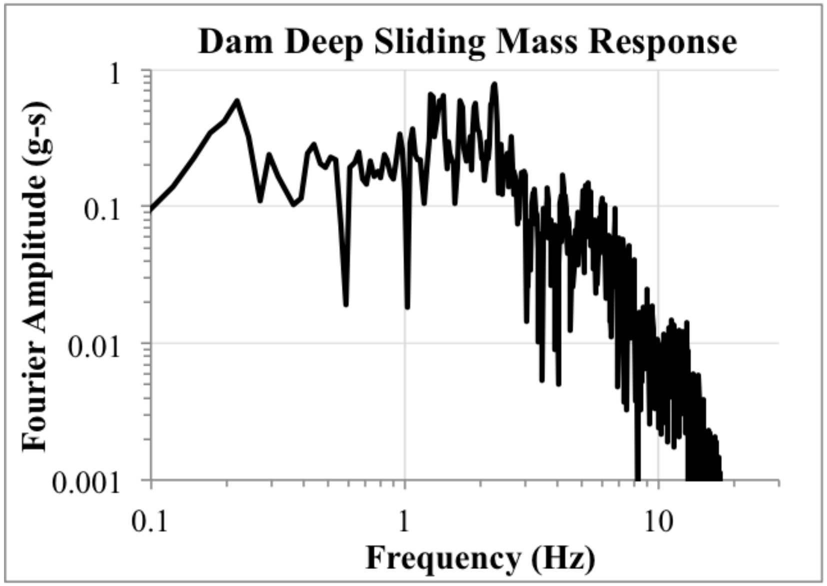

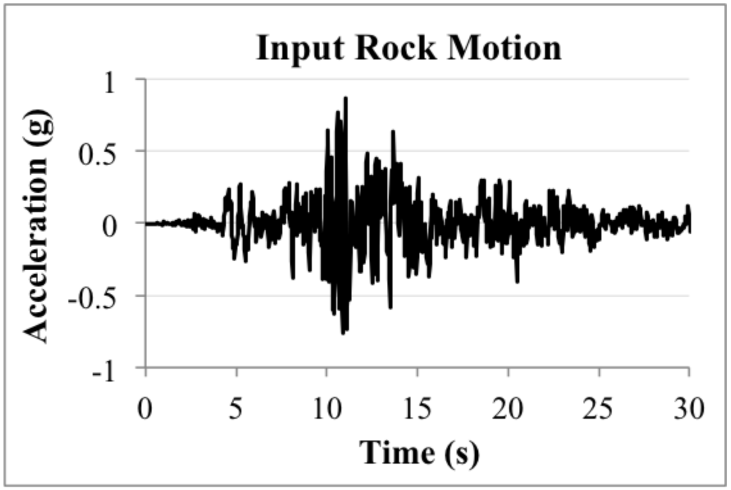

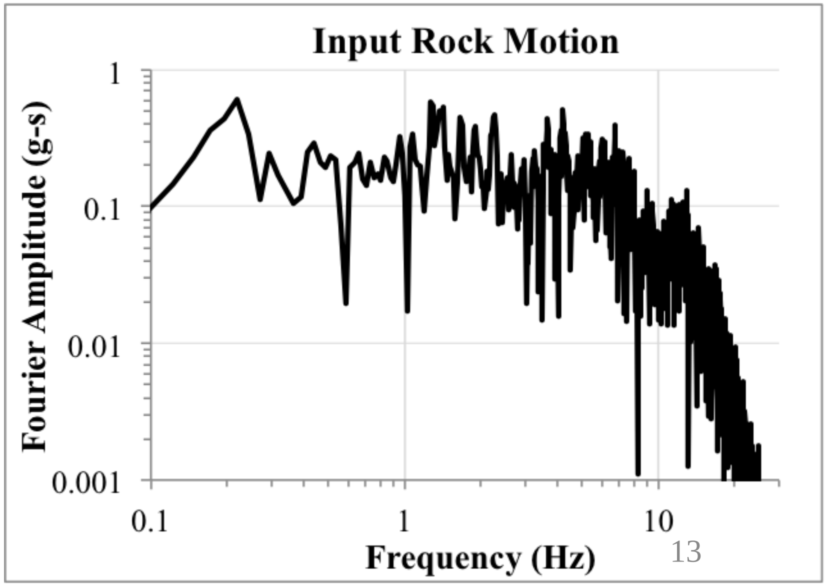

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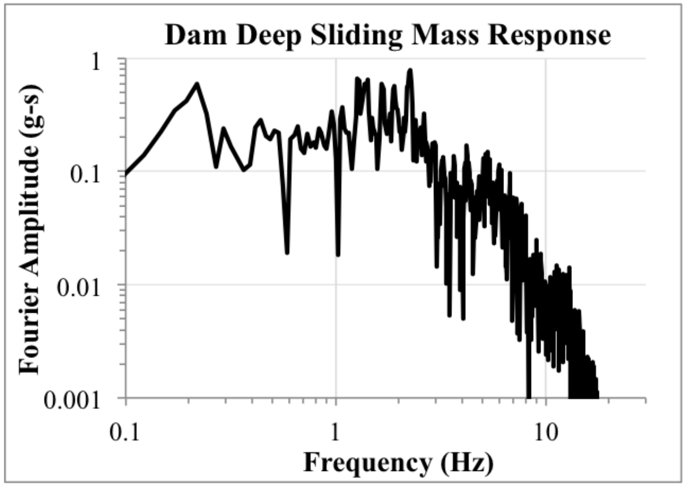
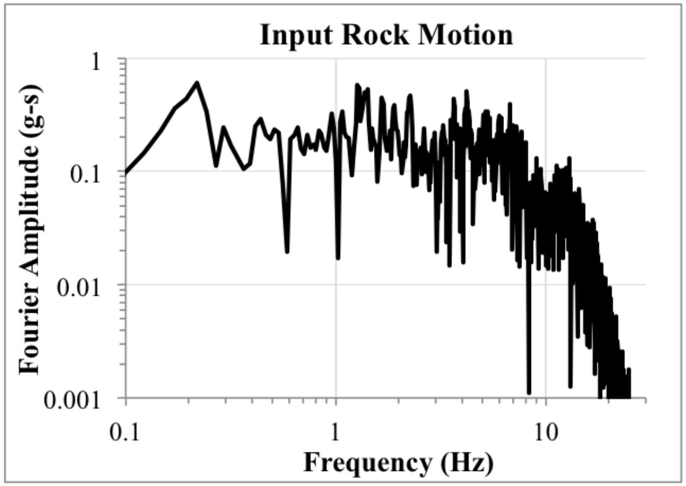
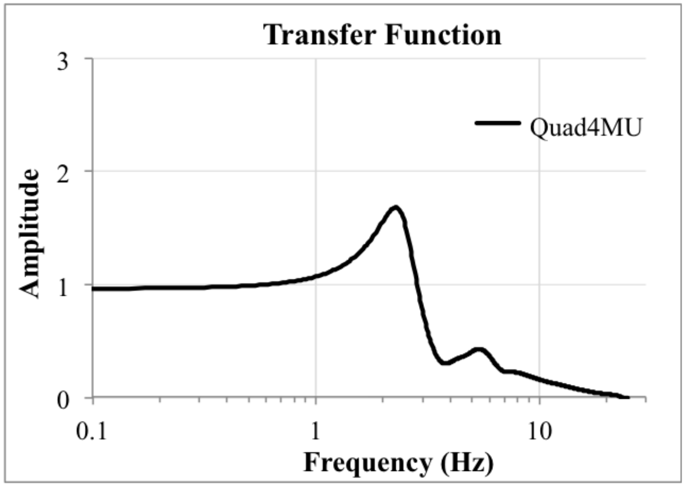
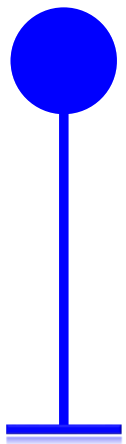






Development of Model step by step example

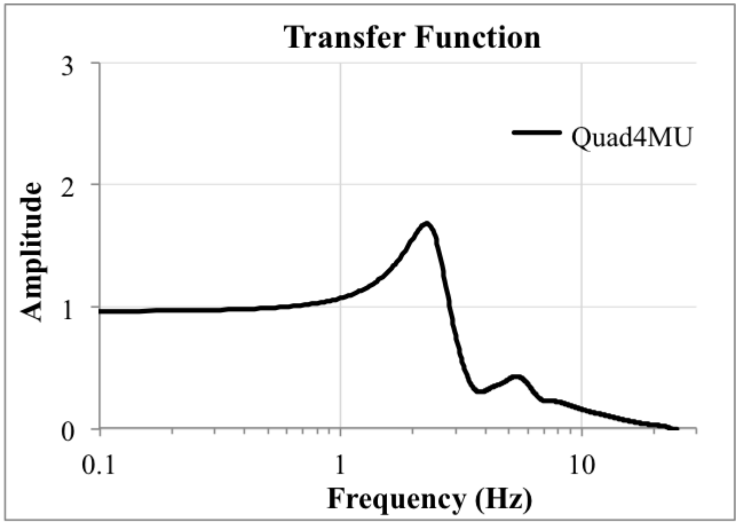


SDOF parameters

f_n = natural frequency

β = damping

Development of Model step by step example



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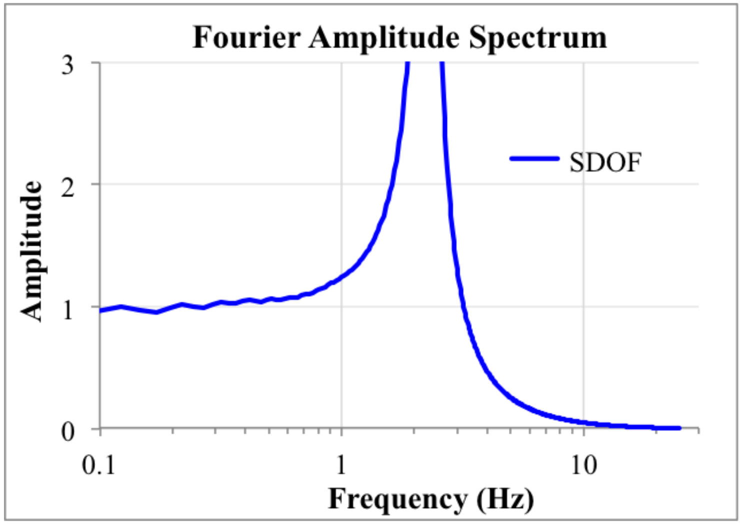
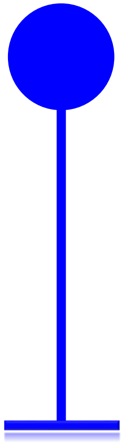


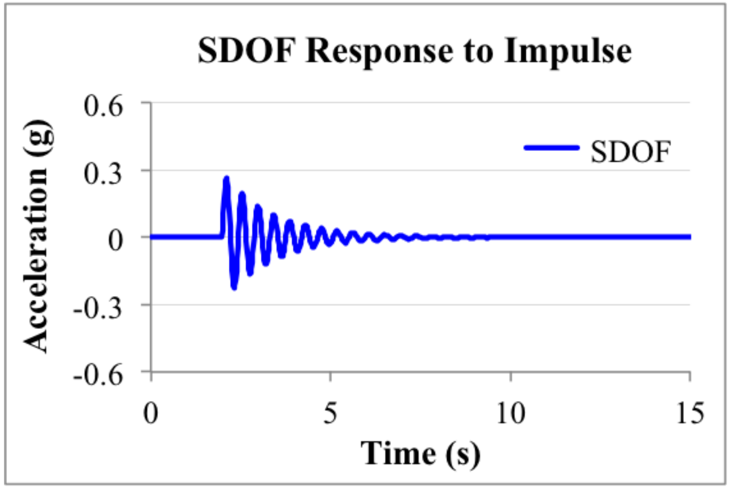
Development of Model step by step example

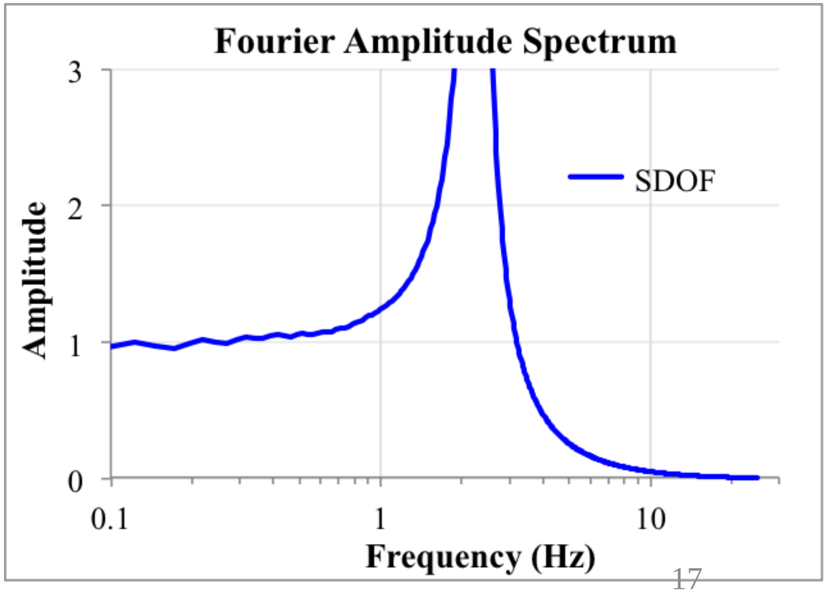


SDOF parameters

f_n = **2.27 Hz**

β = **0.05**





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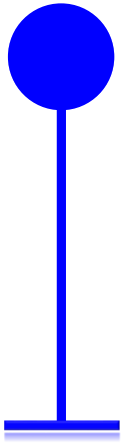

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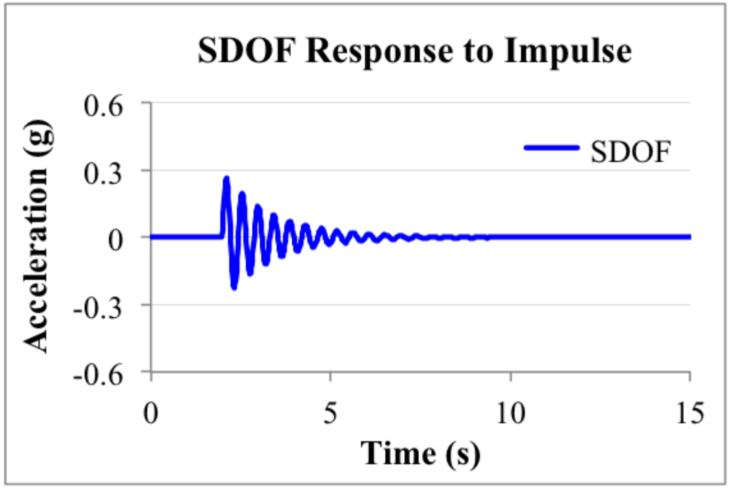

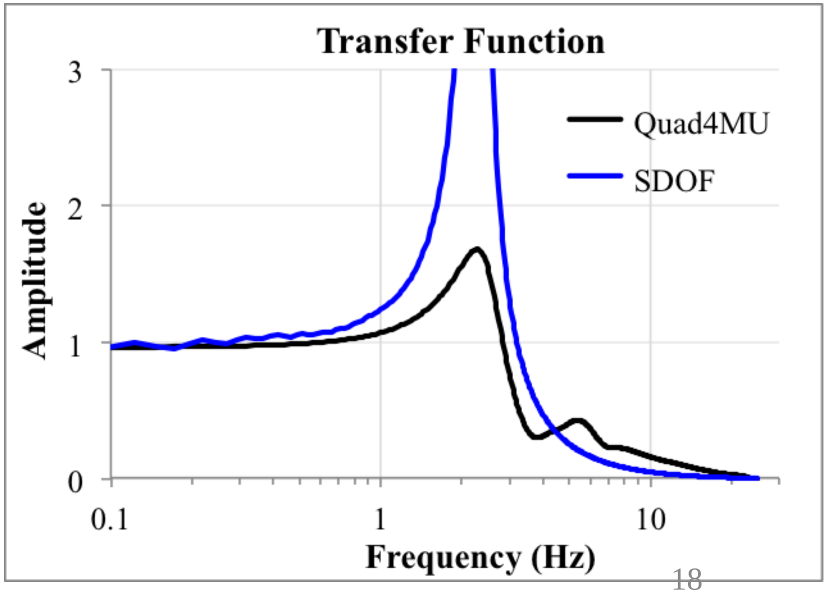

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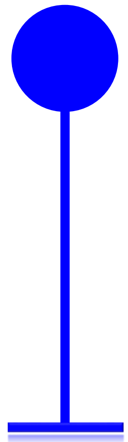
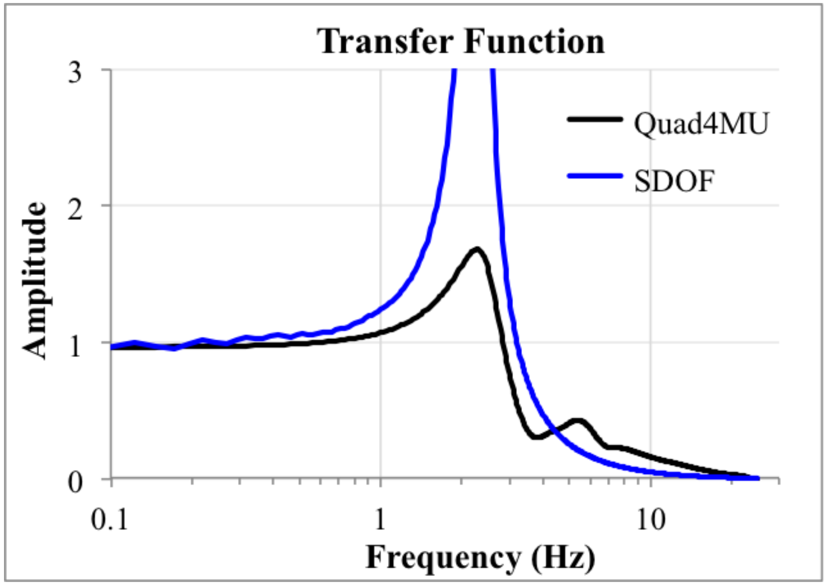


SDOF parameters

f_n = **2.27 Hz**

β = **0.05**



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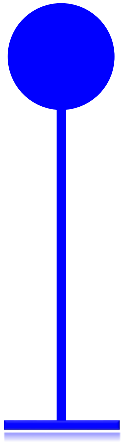
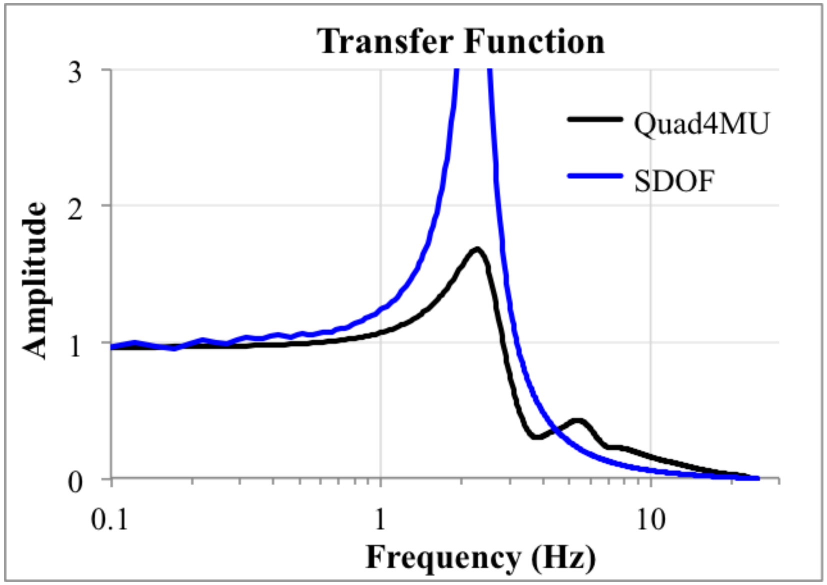


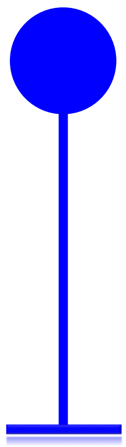
SDOF parameters

f_n = **2.27 Hz**

β = **0.10**



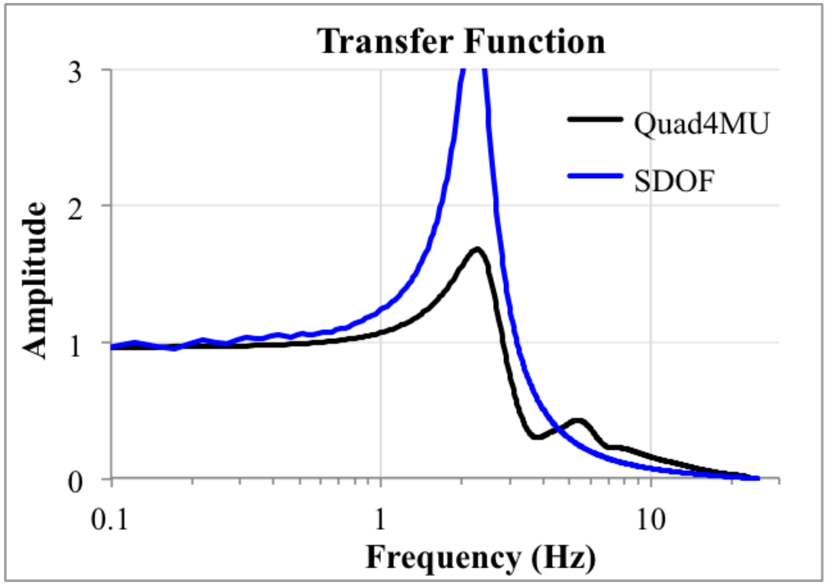
Development of Model step by step example



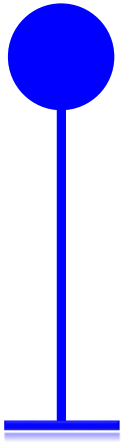
SDOF parameters

f_n = **2.27 Hz**

β = **0.15**



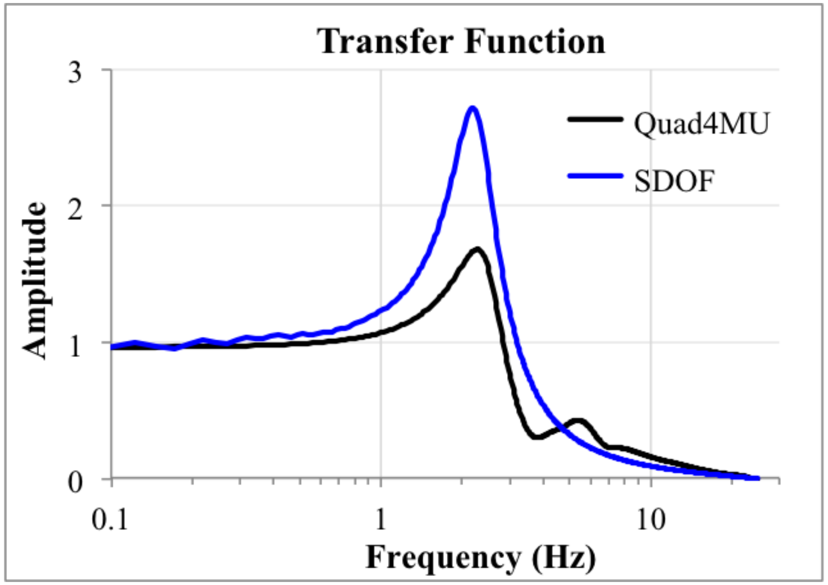
Development of Model step by step example



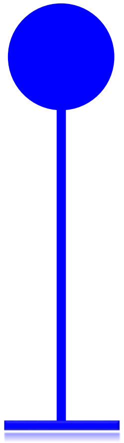
SDOF parameters

f_n = **2.27 Hz**

β = **0.20**



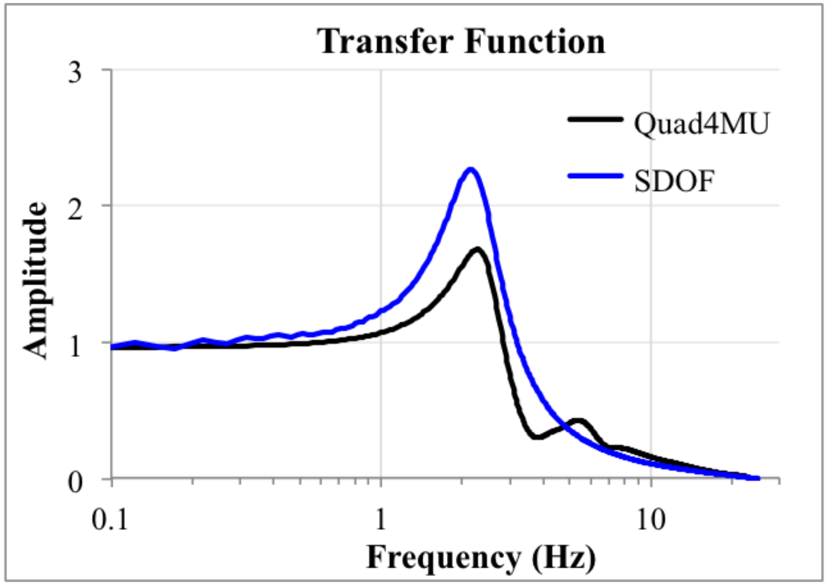
Development of Model step by step example



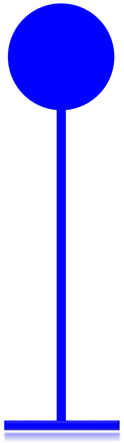
SDOF parameters

f_n = **2.27 Hz**

β = **0.25**



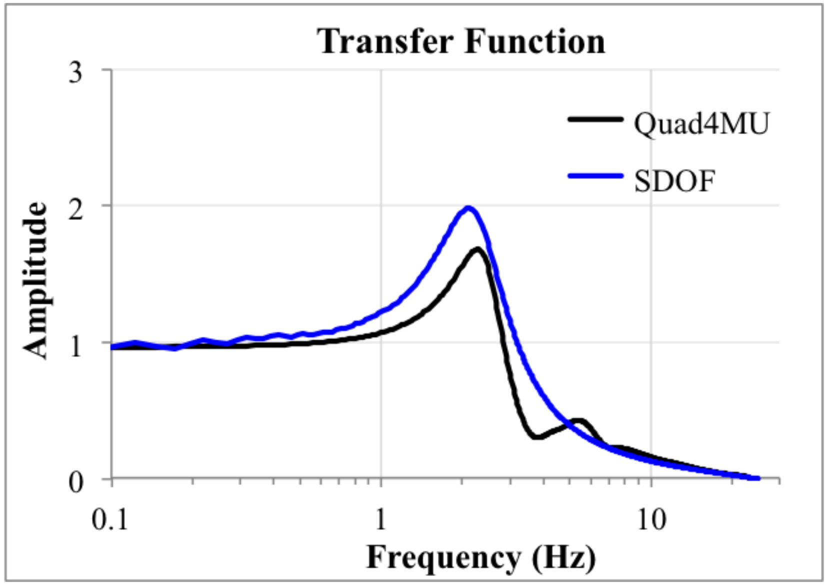
Development of Model step by step example



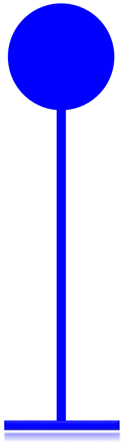
SDOF parameters

f_n = **2.27 Hz**

β = **0.30**



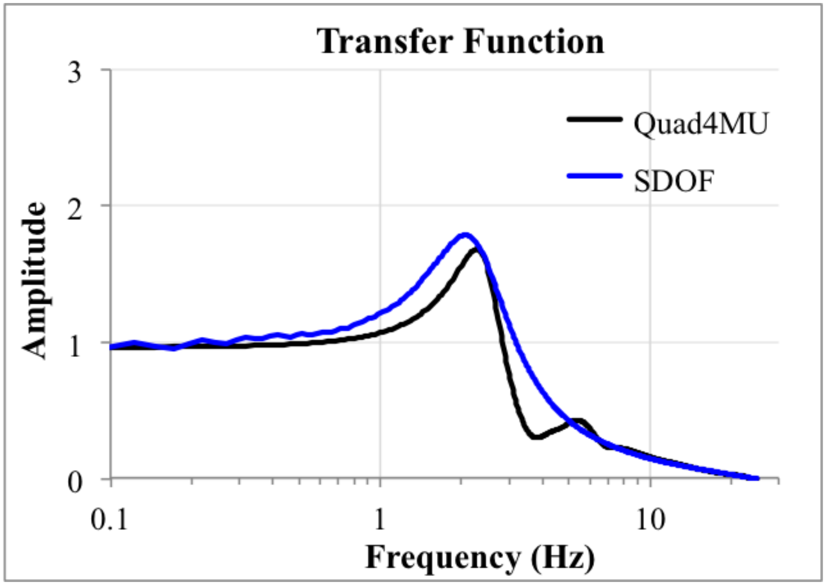
Development of Model step by step example



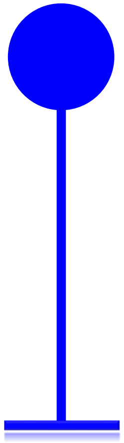
SDOF parameters

f_n = **2.27 Hz**

β = **0.35**



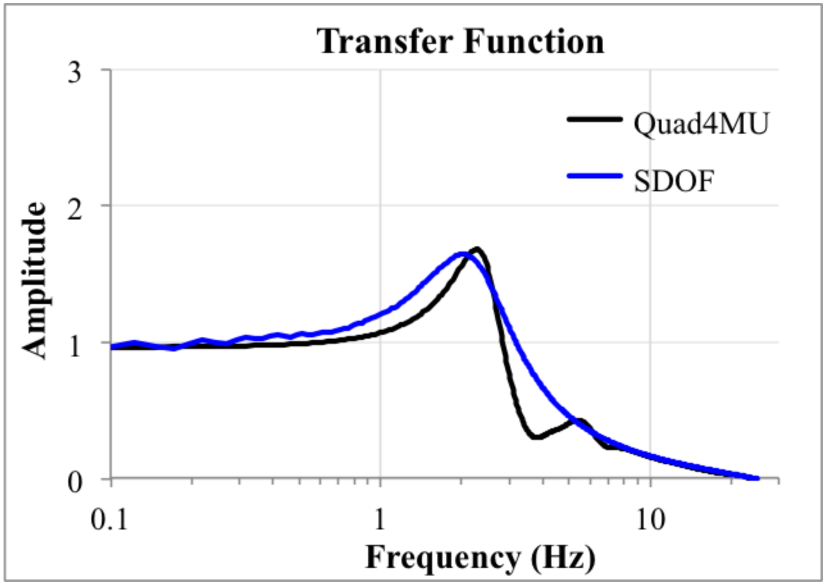
Development of Model step by step example



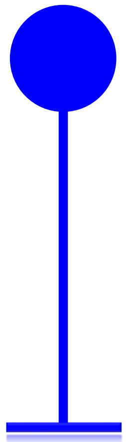
SDOF parameters

f_n = **2.27 Hz**

β = **0.40**



Development of Model step by step example



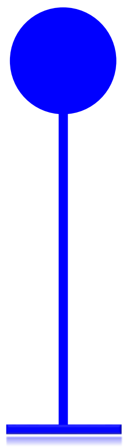
SDOF parameters

f_n = natural frequency

β = damping

α = scale factor

Development of Model step by step example

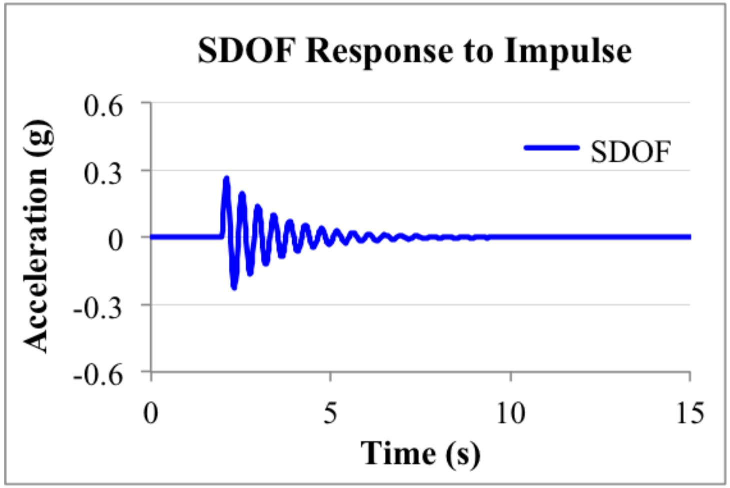


SDOF parameters

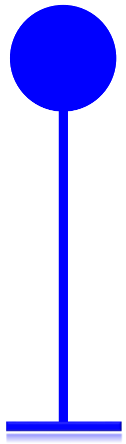
f_n = **2.27 Hz**

β = **0.05**

α = **1.0**



Development of Model step by step example

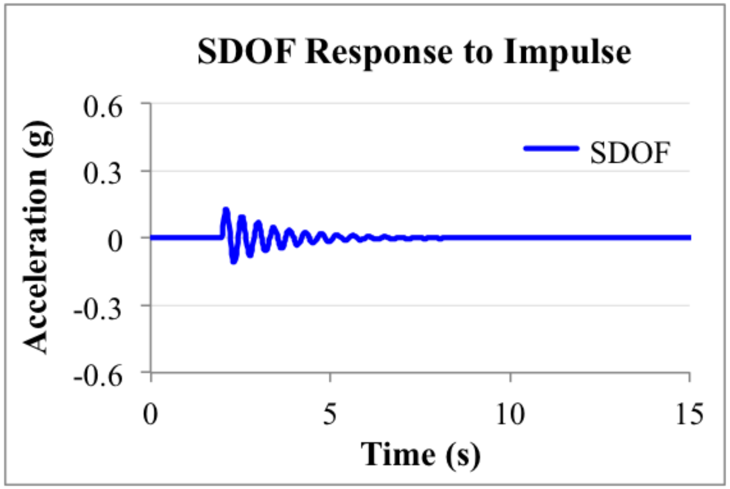


SDOF parameters

f_n = **2.27 Hz**

β = **0.05**

α = **0.5**



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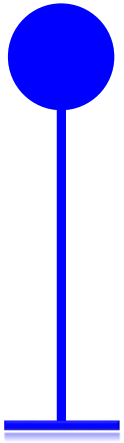
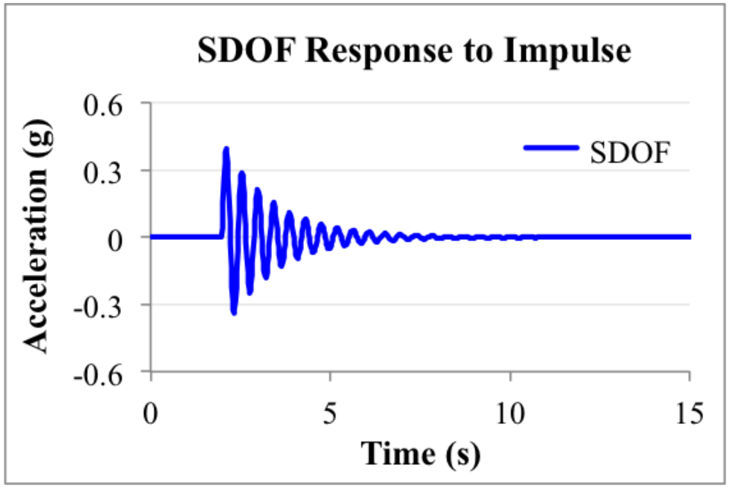


SDOF parameters

f_n = **2.27 Hz**

β = **0.05**

α = **1.5**



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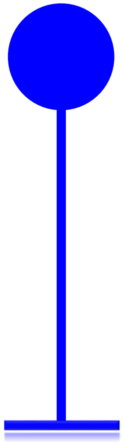
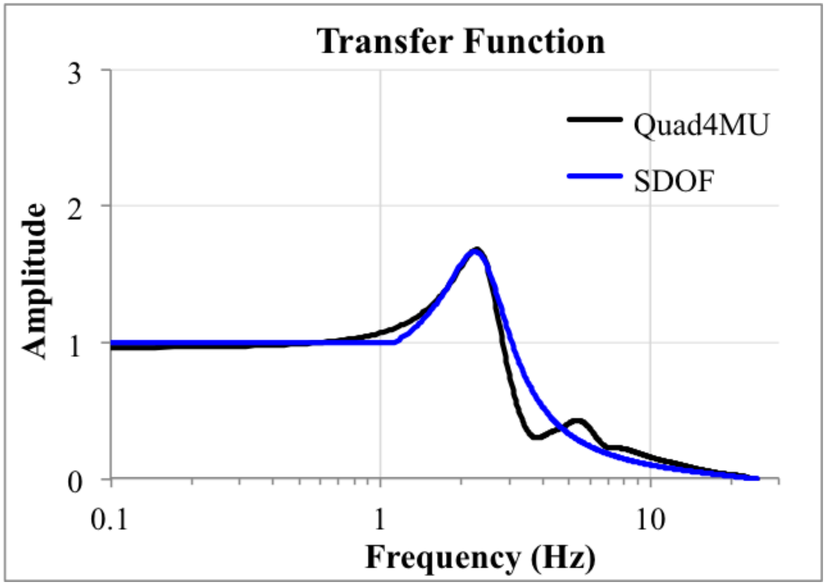


SDOF parameters

f_n = **2.27 Hz**

β = **0.28**

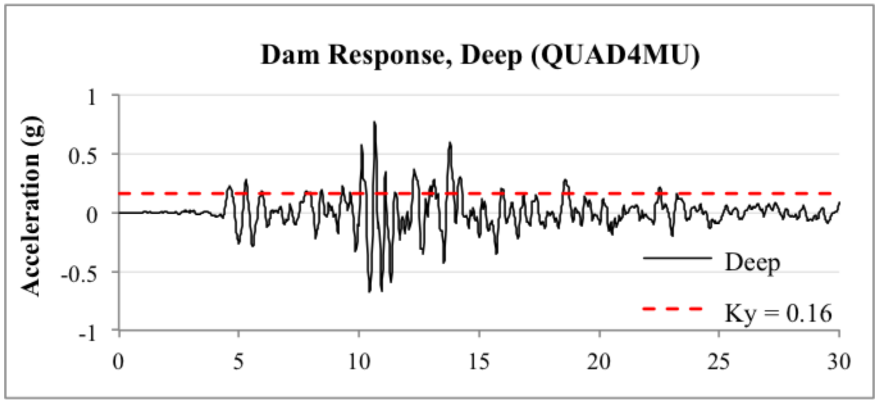
α = **0.8**

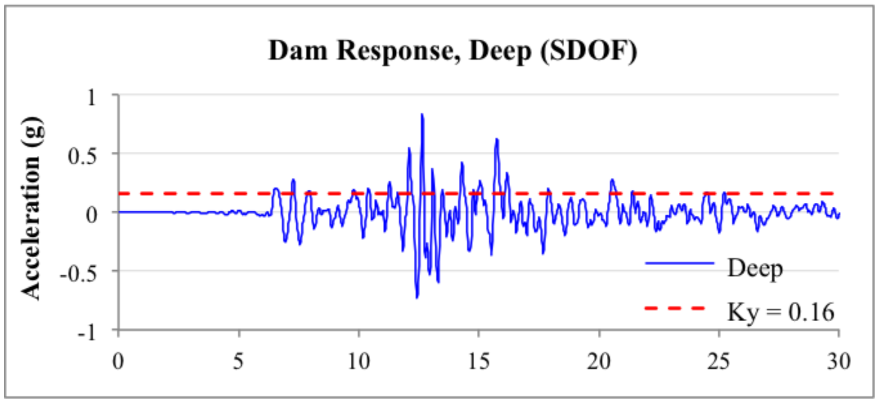


QUAD4M (FEM) Versus SDOF

QUAD4MU Dam Response

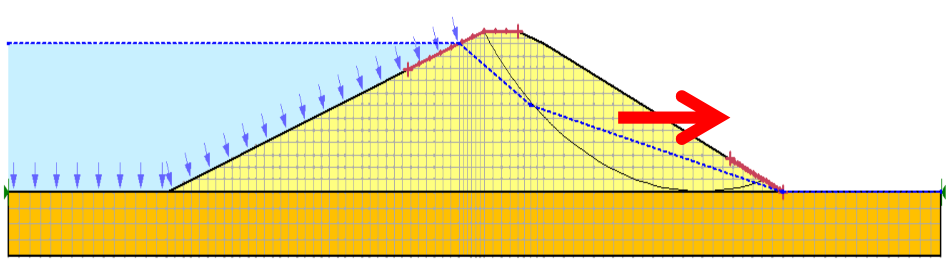
SDOF Dam Response

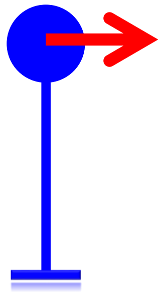




Displacement = **80.09 cm**

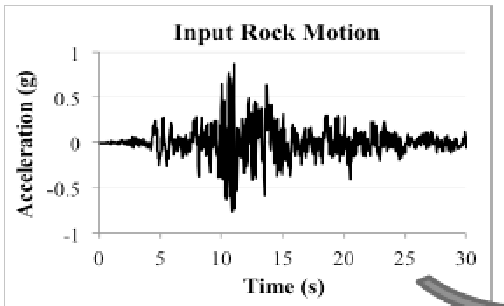
Displacement = **80.02 cm**



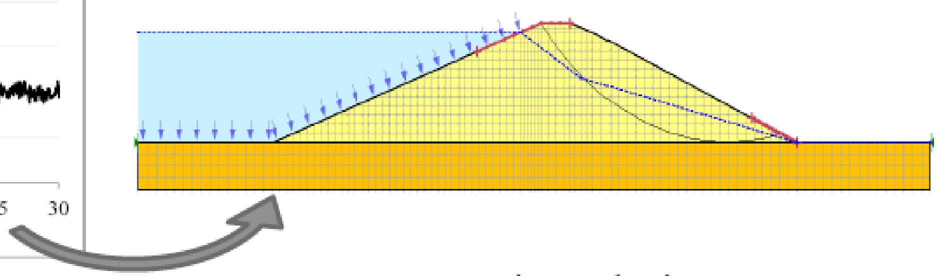


Modeling process

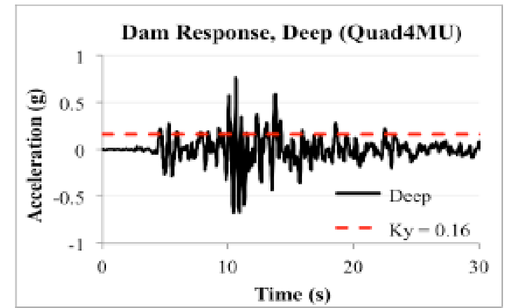
Dynamic analyses to estimate shear induced deformations



Select ground motions

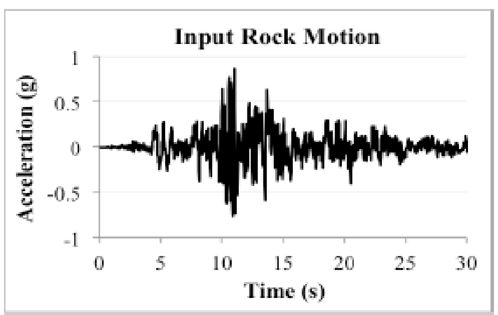


Dynamic analysis

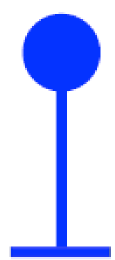


Calculate deformations

Simplified method to estimate shear induced deformations



Select ground motions

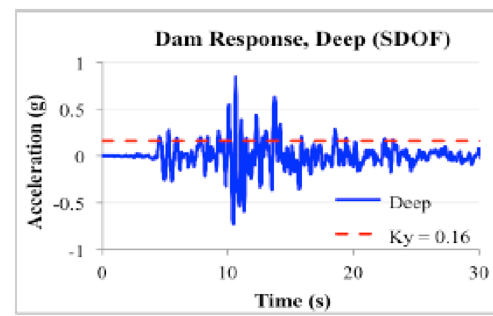


SDOF Oscillator

f_n = natural frequency

β = damping

Model sliding mass



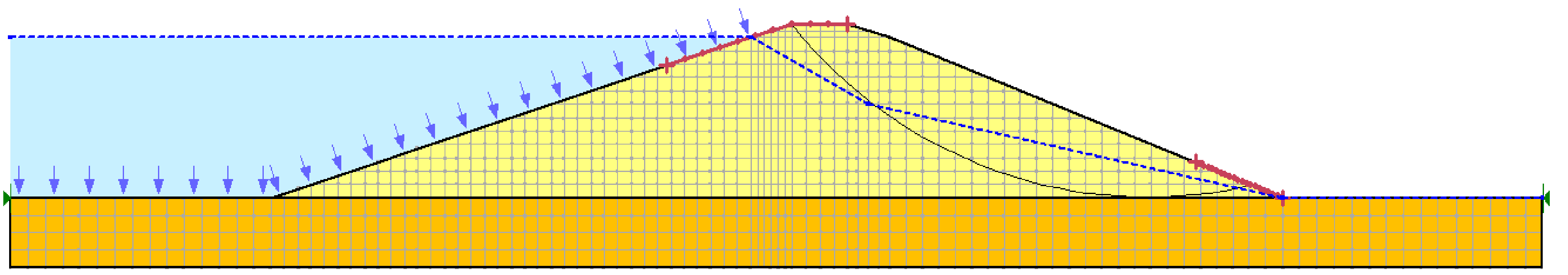
Calculate deformations

Dam4, Dam5, Dam6

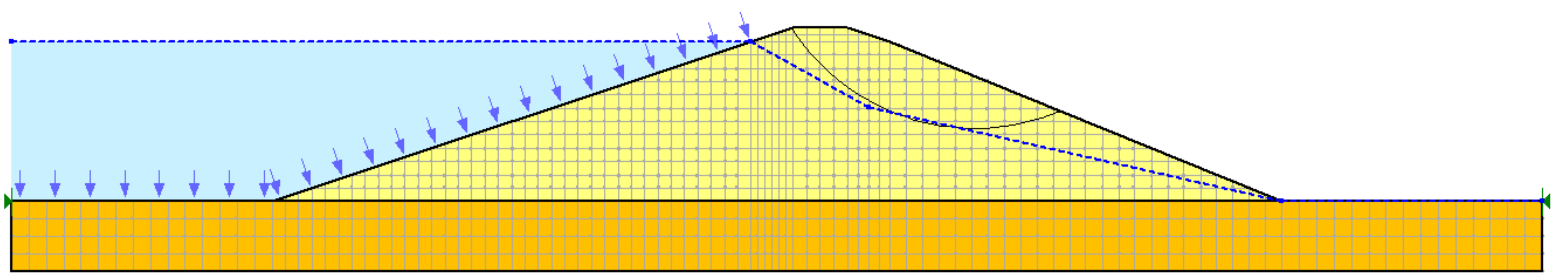
Height: 50 ft

Crest Width: 16 ft

(Deep slip surface)

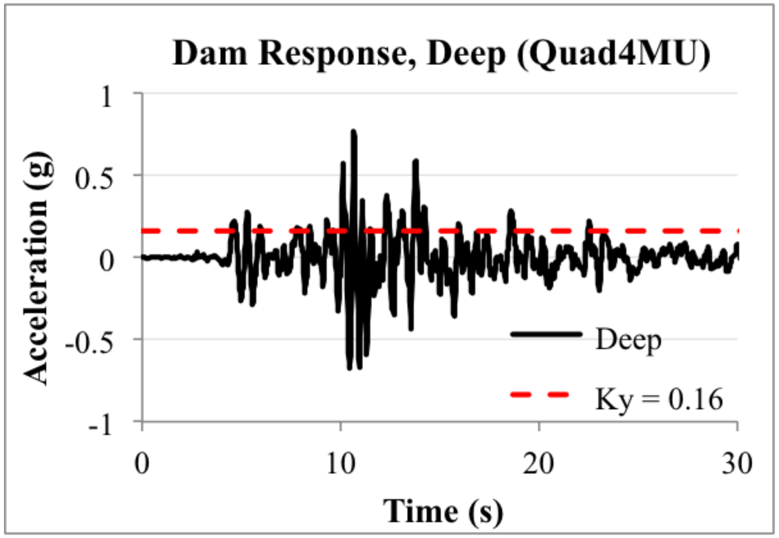


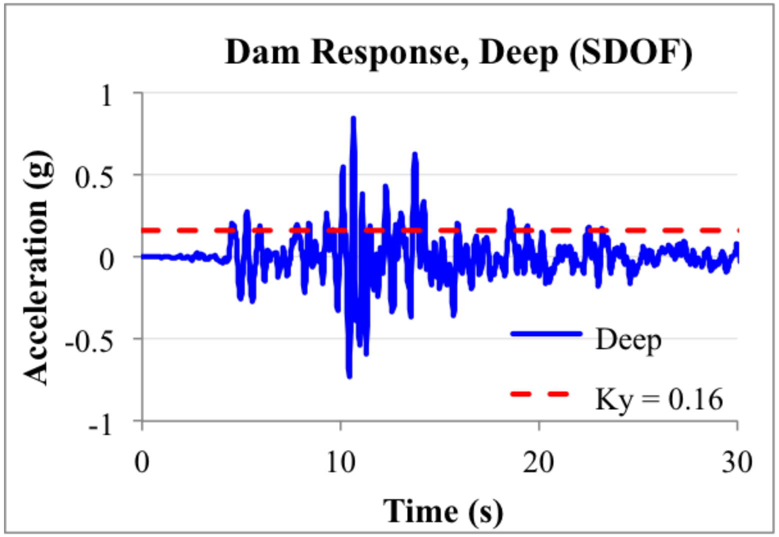
(Shallow slip surface)



Development of Model step by step example

Deformations from Newmark sliding block analysis





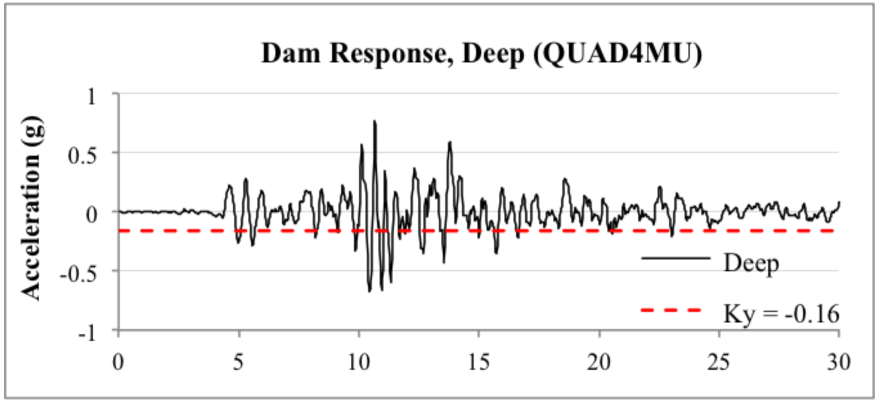
Deformation = **80 cm**

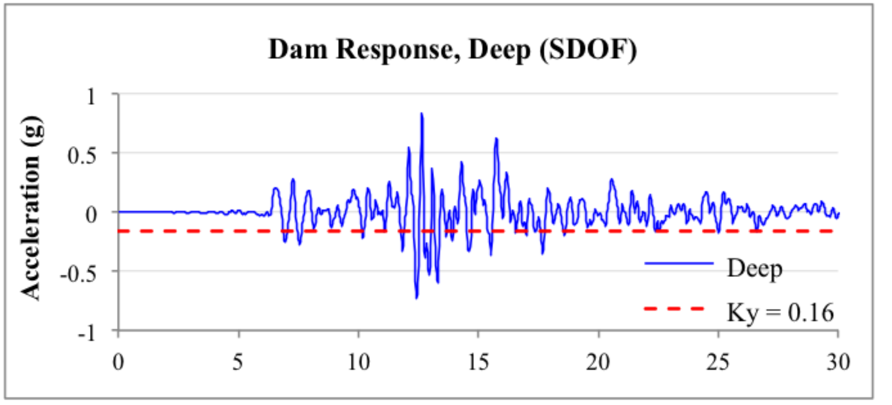
Deformation = **80 cm**

Displacements (“negative”)

QUAD4MU Dam Response

SDOF Dam Response





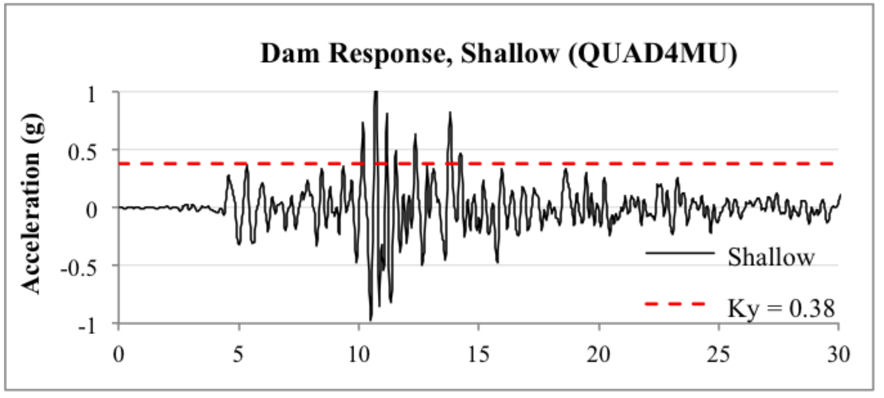
Displacement = **58.40 cm**

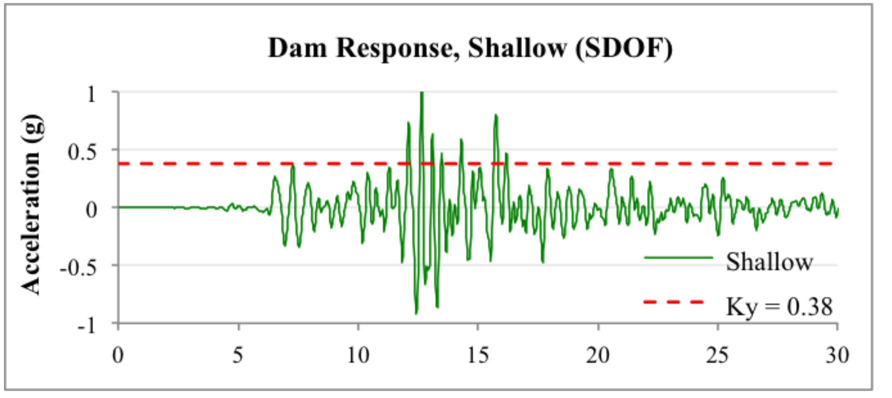
Displacement = **60.82 cm**

Displacements

QUAD4MU Dam Response

SDOF Dam Response





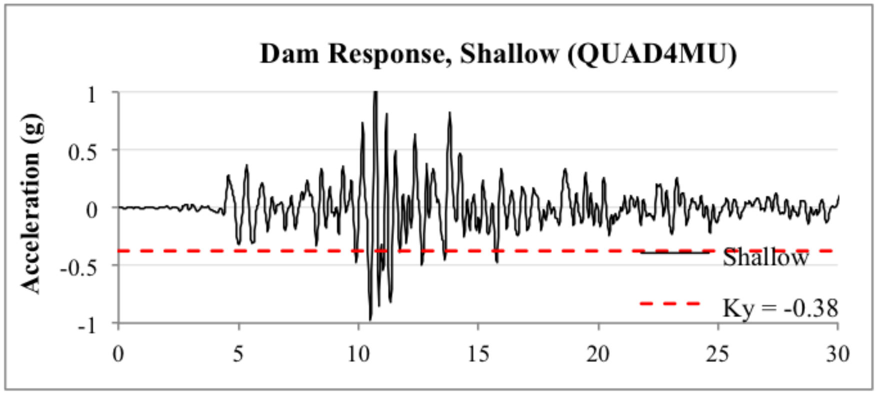
Displacement = **25.03 cm**

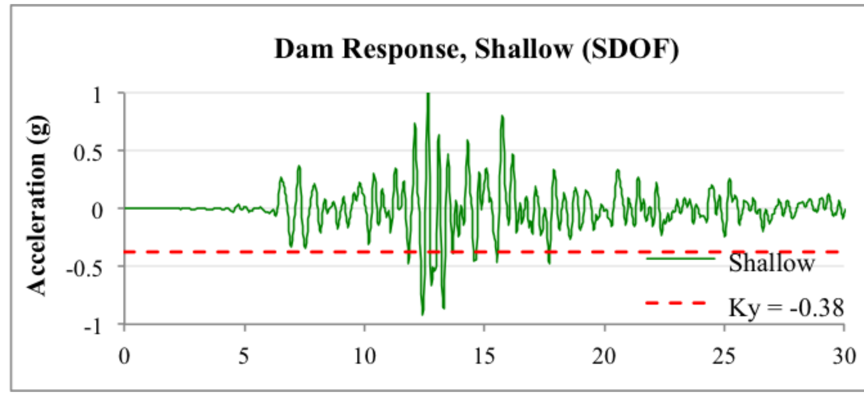
Displacement = **24.10 cm**

Displacements ("negative")

QUAD4MU Dam Response

SDOF Dam Response



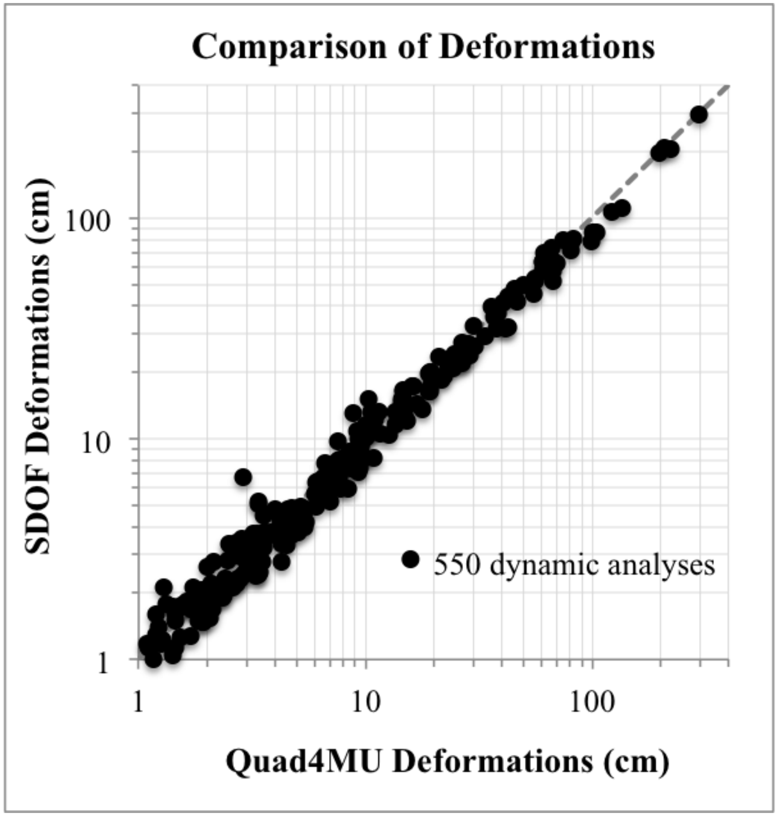


Displacement = **26.98 cm**

Displacement = **25.06 cm**

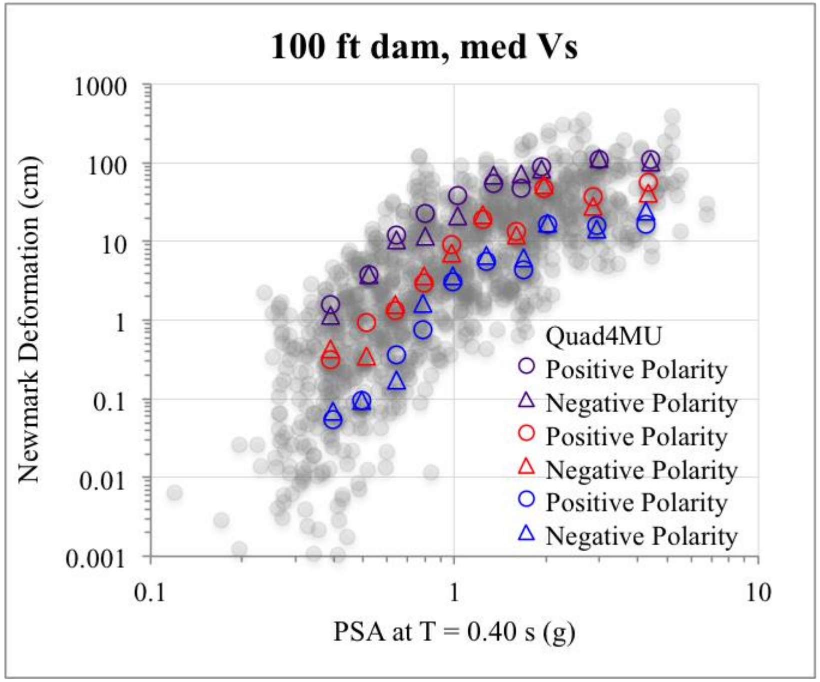
Development of Model

Compare deformations

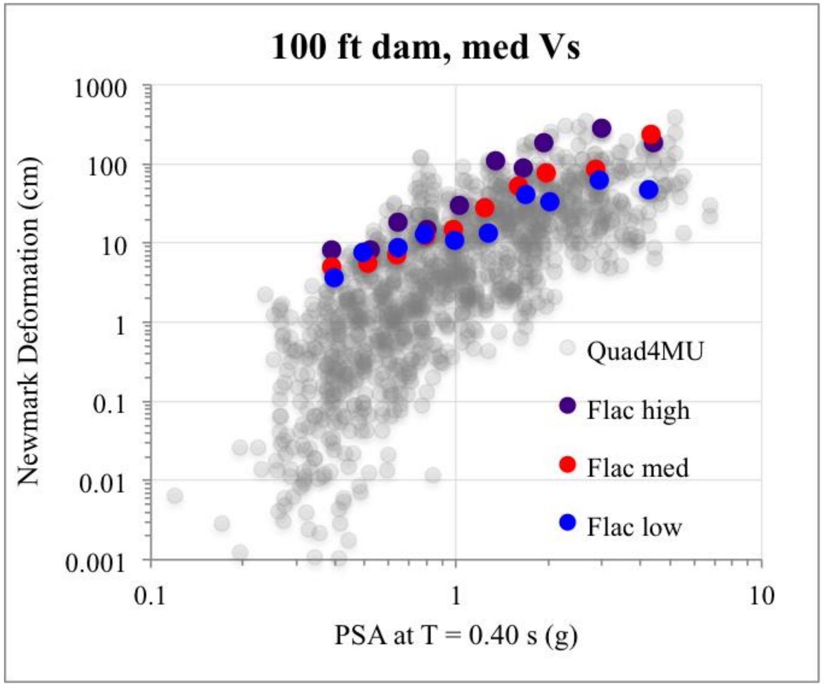


Maximum horizontal

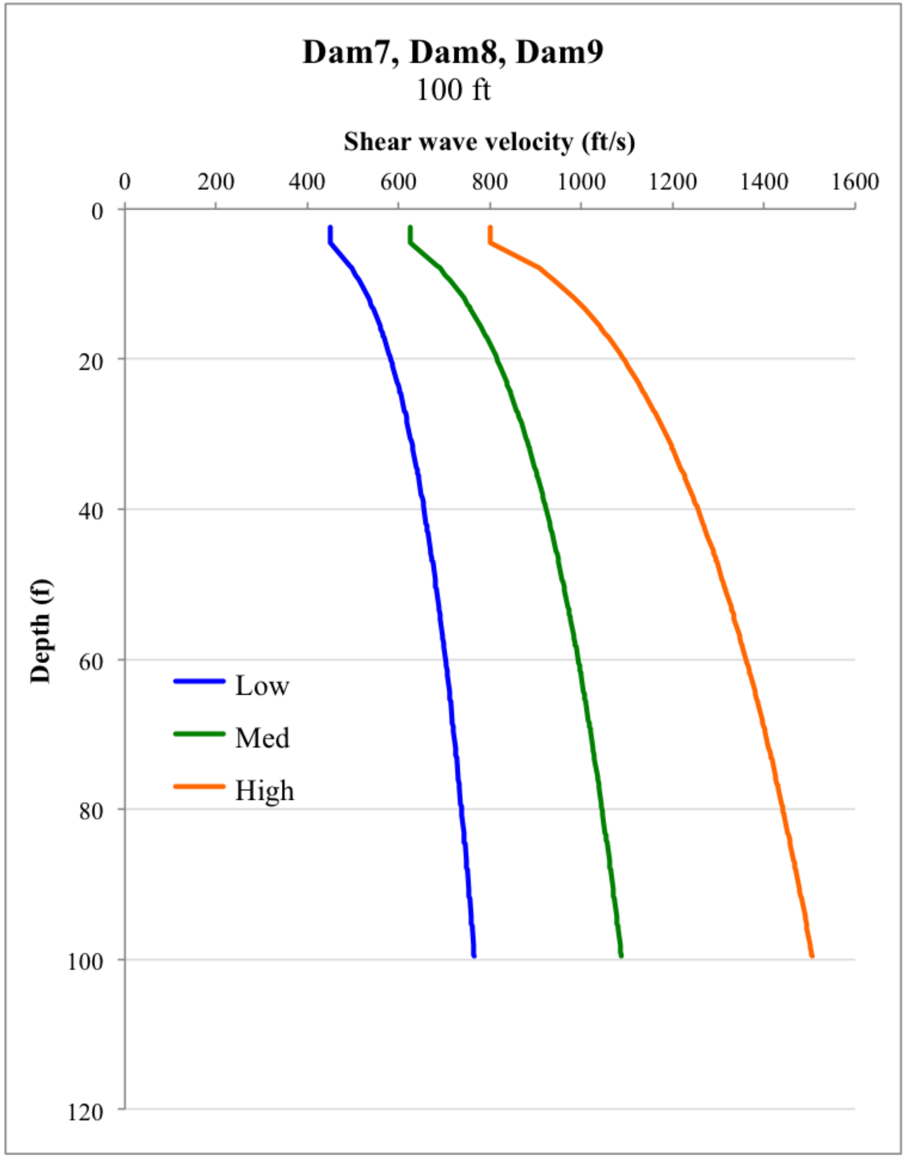
QUAD4M & Newmark



FLAC: Horizontal

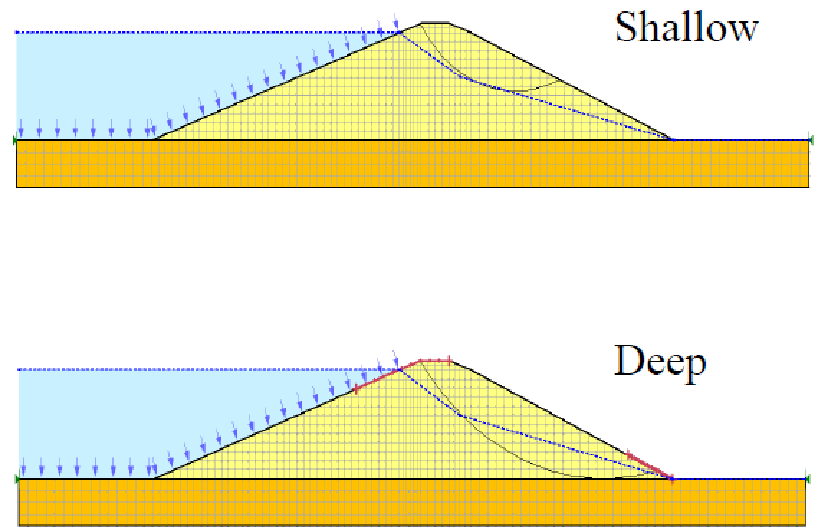


Shear Wave Velocity Profiles



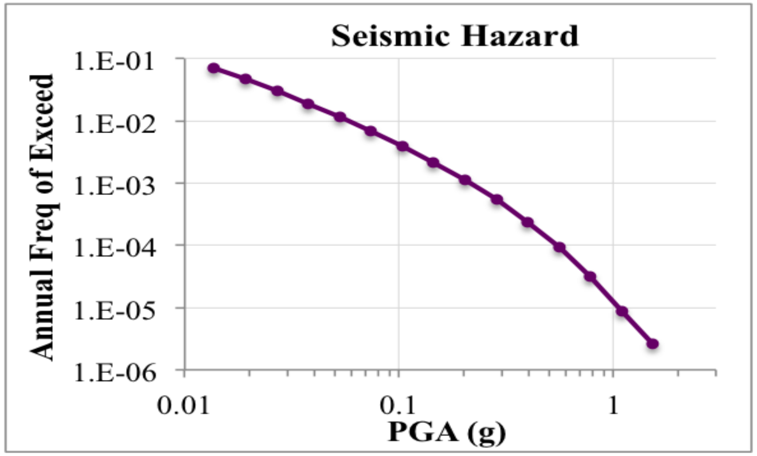
Dam configurations

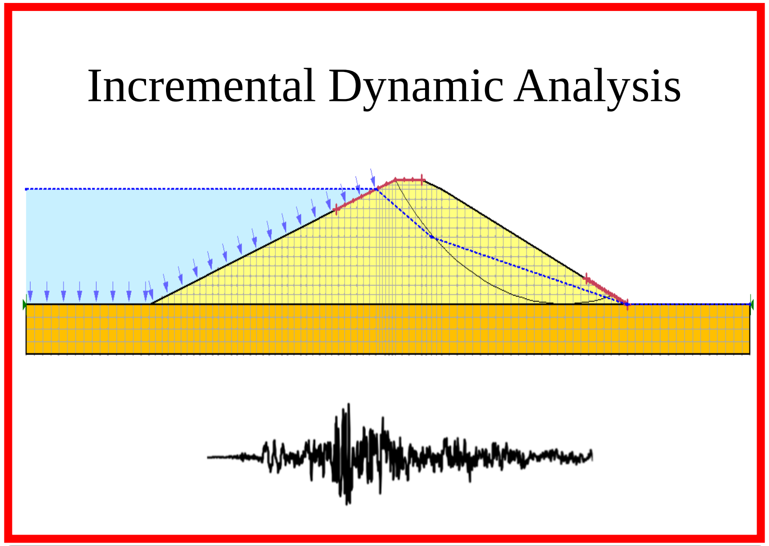
- Heights:
  25, 50, 100, & 150 ft
- Velocity profiles:
  low, medium, high
- Slip surface:
  toe and mid-height

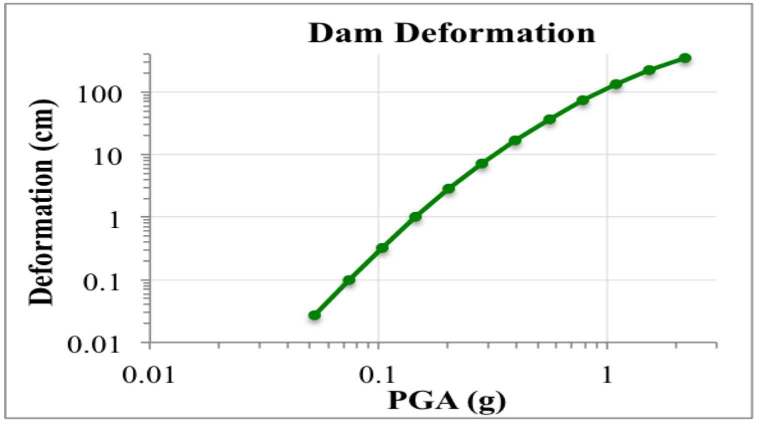


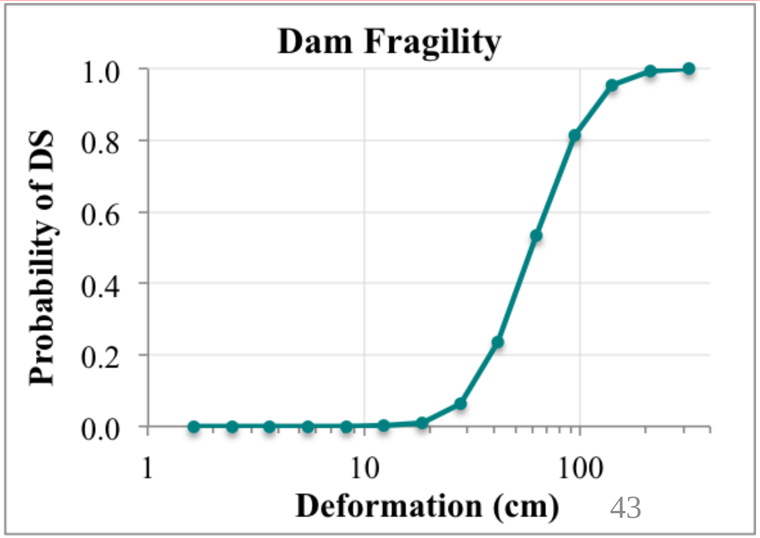
Introduction and Motivation

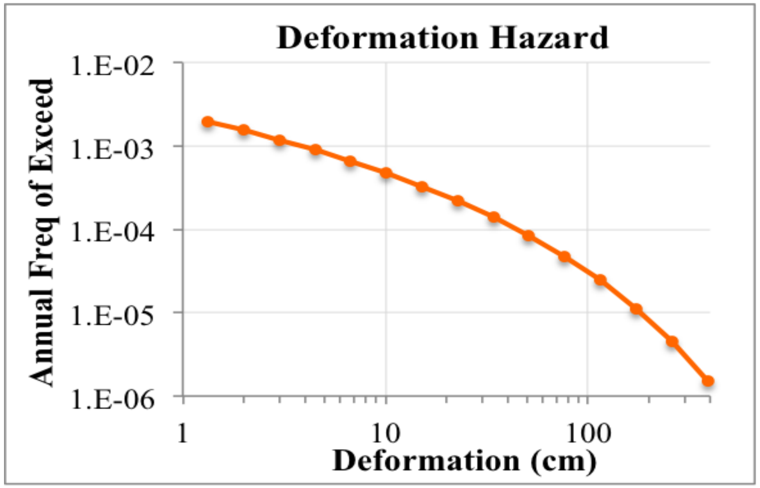
What does a quantitative risk analysis lo





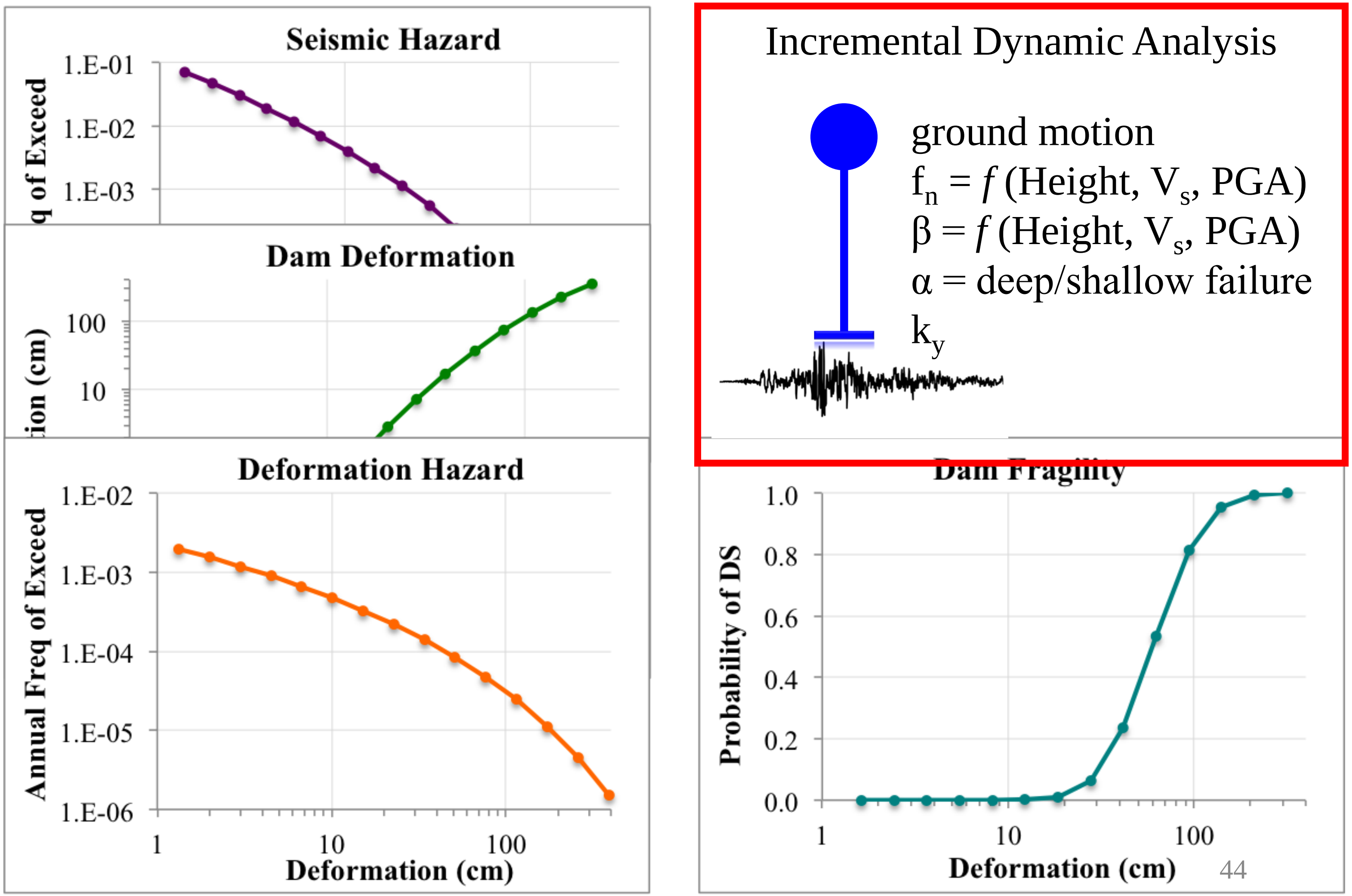






Implementation of Model

What does a quantitative risk analysis look like?



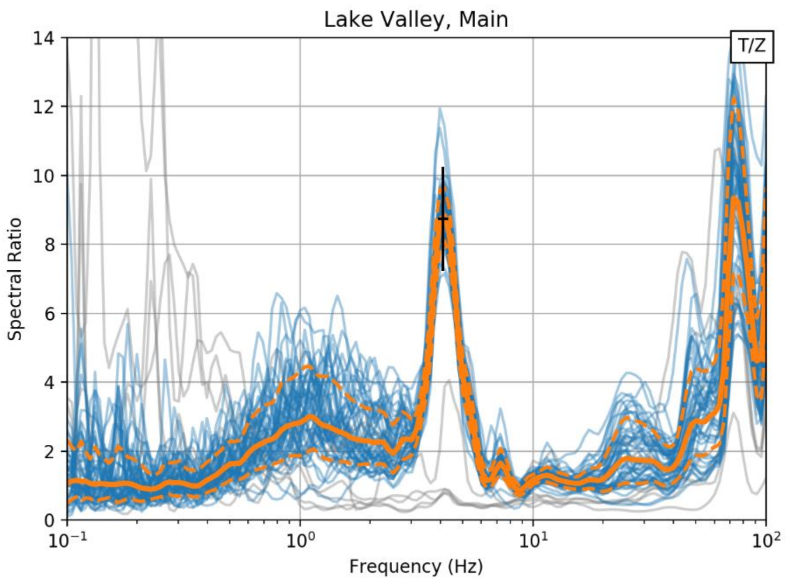
H/V spectral ratio

- Collect 3-component ambient noise on dam crest
- No active source required
- Record for 30 to 90 minutes based on height of dam

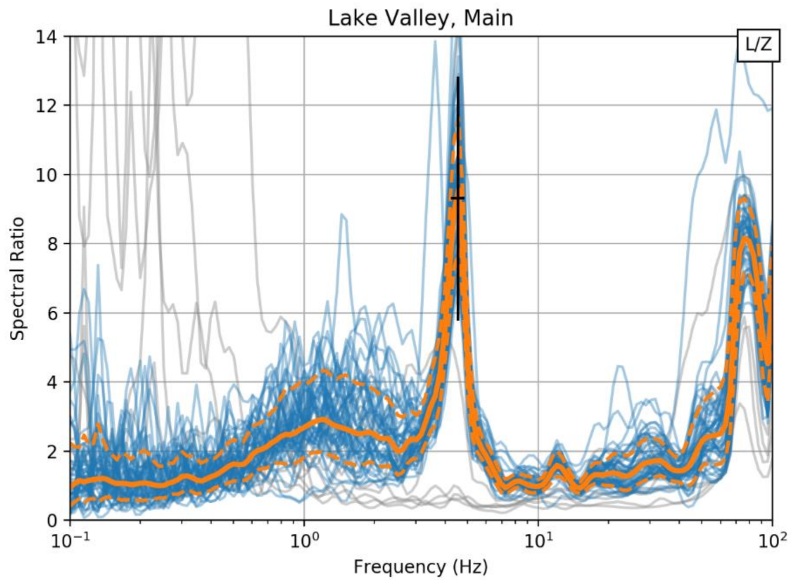
- Ratio of horizontal to vertical:
  - Natural frequency
  - Estimate of damping

Spectral ratios

Transverse/Vertical

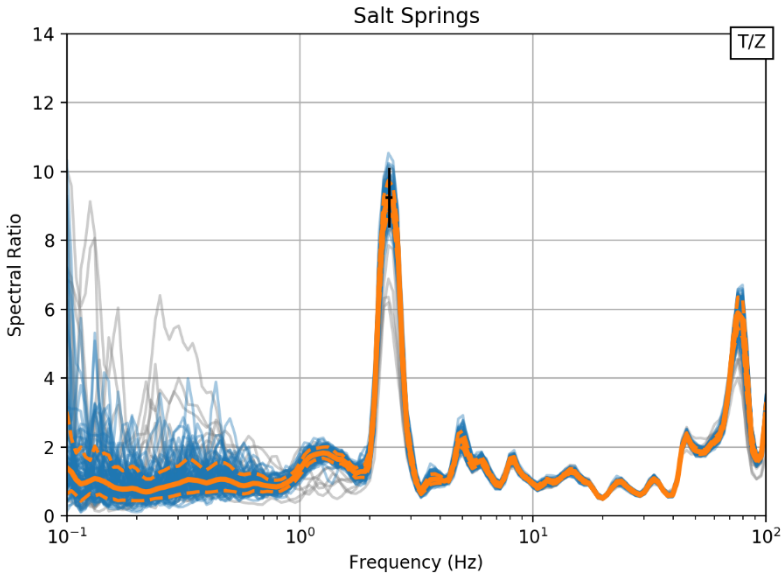


Longitudinal/Vertical

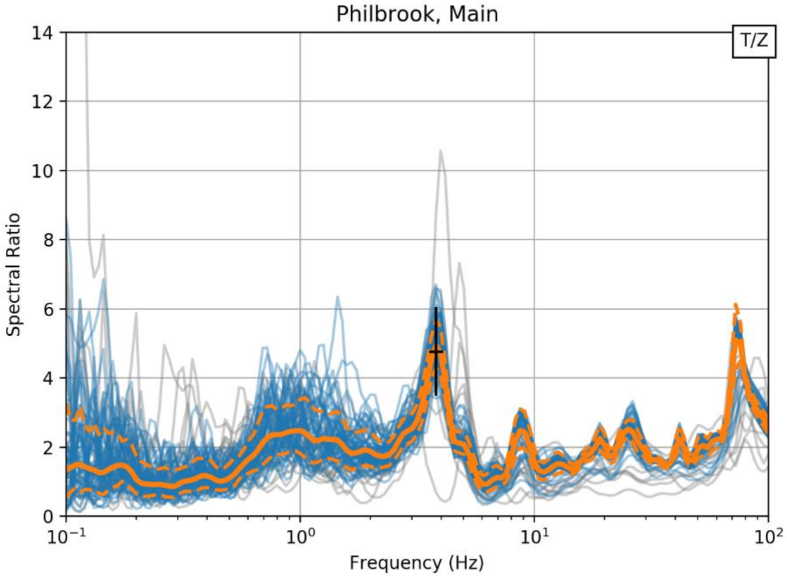


Additional spectral ratios

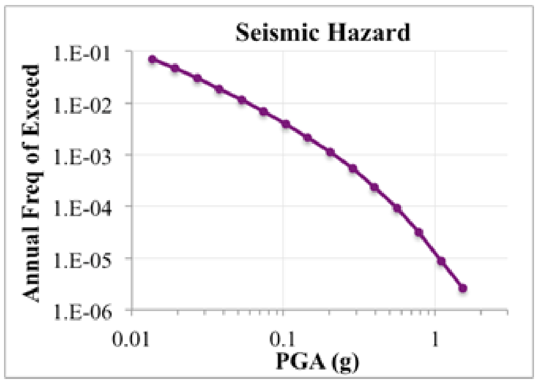
Salt Springs (328 ft)

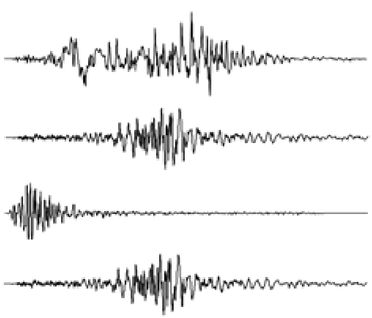


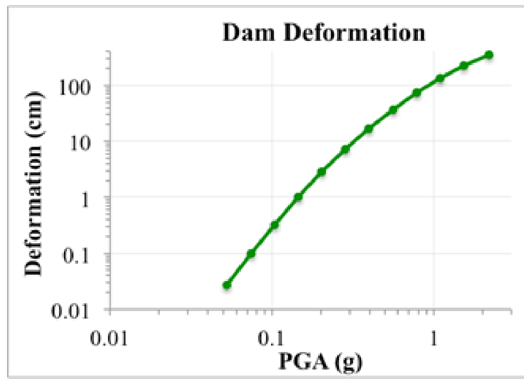
Philbrook Main (87 ft)

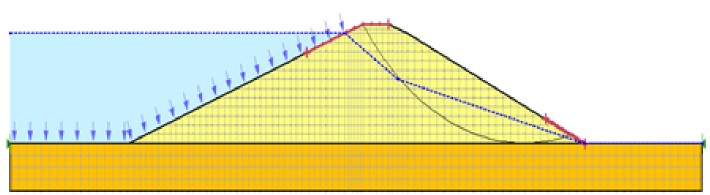


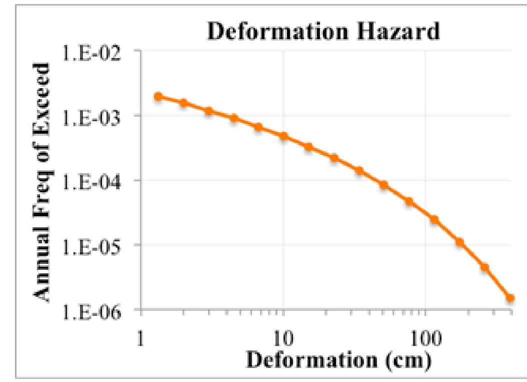
PSHA / Select Ground Motions + Dam Response Model → Risk inputs

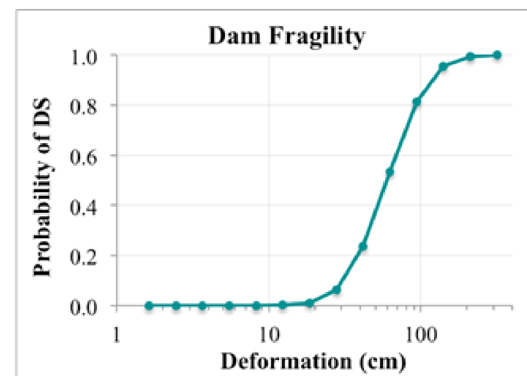




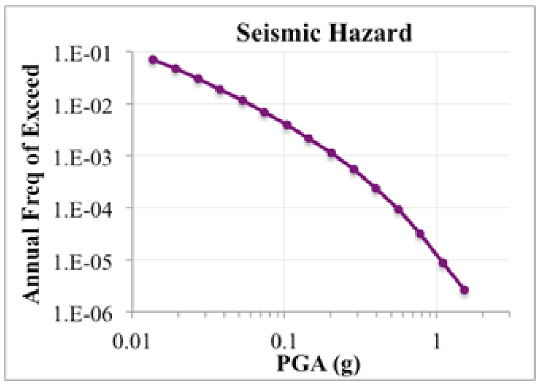


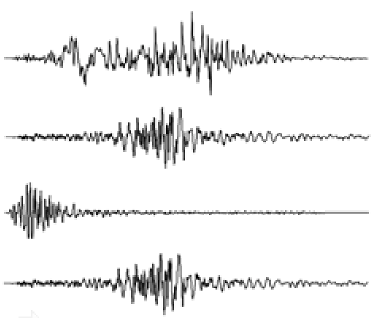


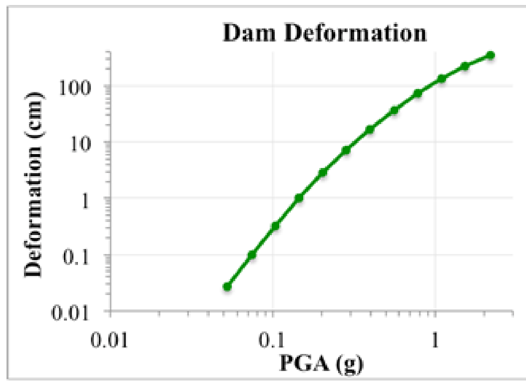


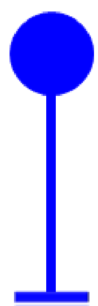


PSHA / Select Ground Motions + Dam Response Model → Risk inputs







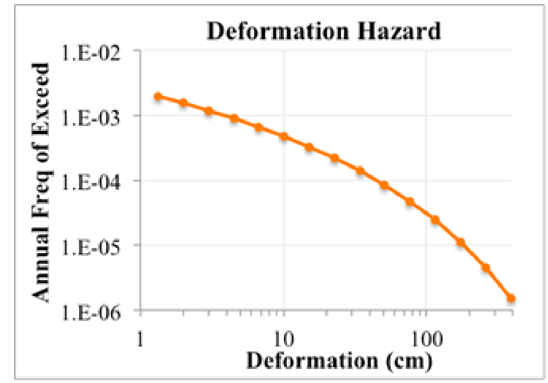


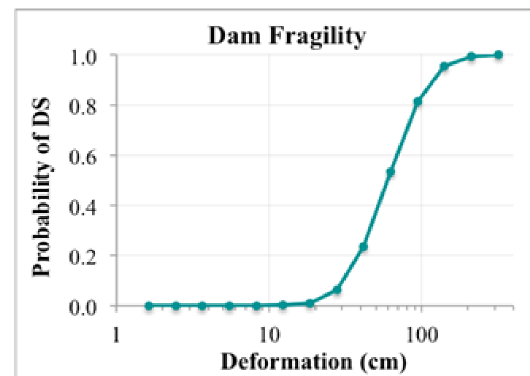
$f_n = f\,(\text{Height, } V_s, \text{ PGA})$

$\beta = f\,(\text{Height, } V_s, \text{ PGA})$

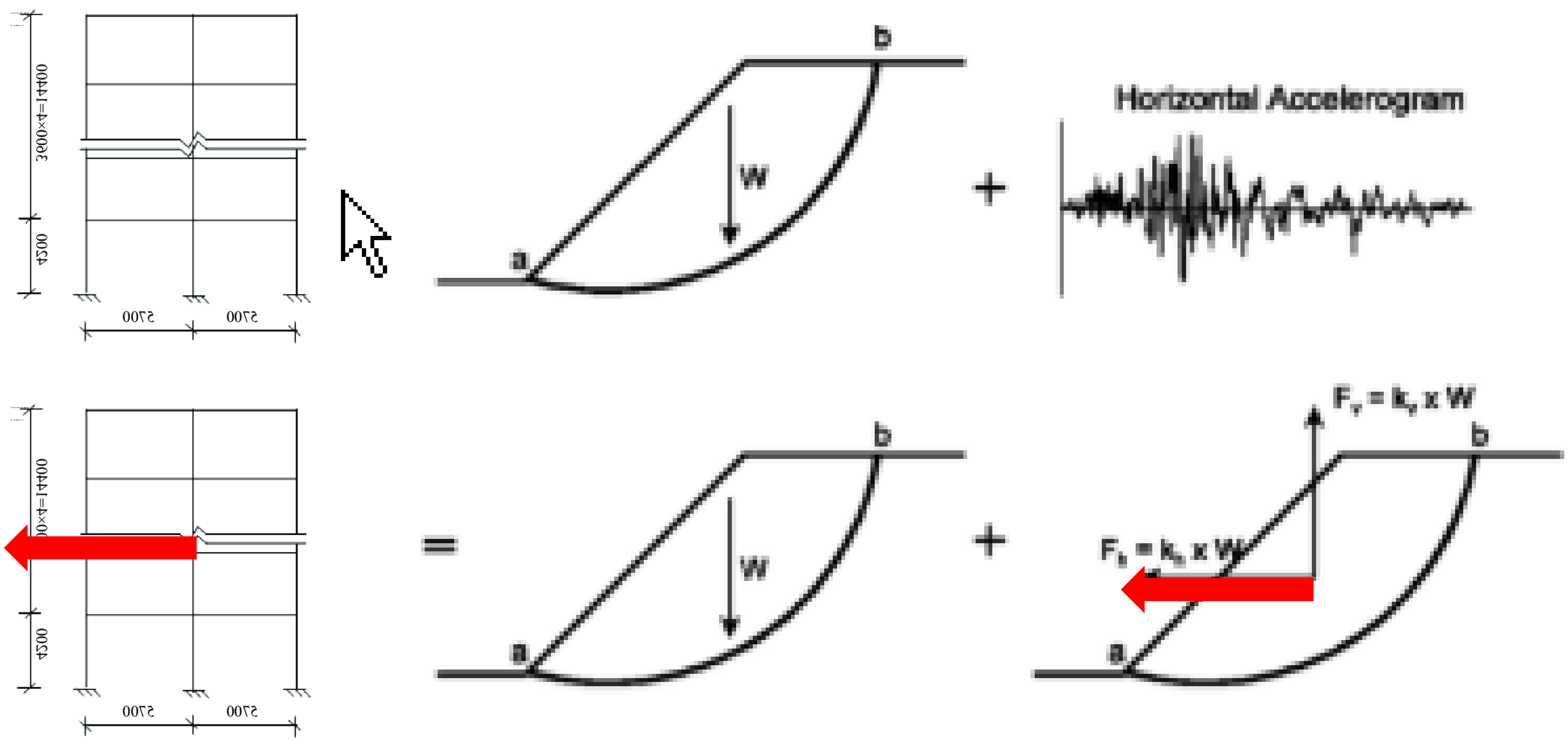
$\alpha = f\,(\text{failure surface})$

k_y





Pseudo Static Structural Analysis



Conclusions

- New method improves analytical dam model
- Computing SDOF response is fast
- Can better assess ground motion uncertainty impact on dam displacement
- Can produce dam displacement hazard and quantify uncertainty
- Fundamentally Improve dam risk calculation and facilitate Risk Informed Decision Making
- Problems: Does not compare well for Mag 6 or below earthquakes. Why?

Seed建議方法演變
(Prof. Idriss 於民國八十九年在水利處之演講)

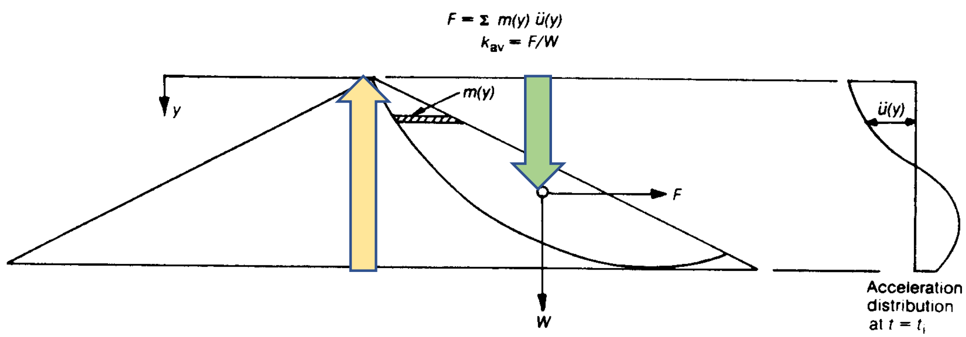


Fig. 18. **Determination of effective acceleration for potential slide mass**

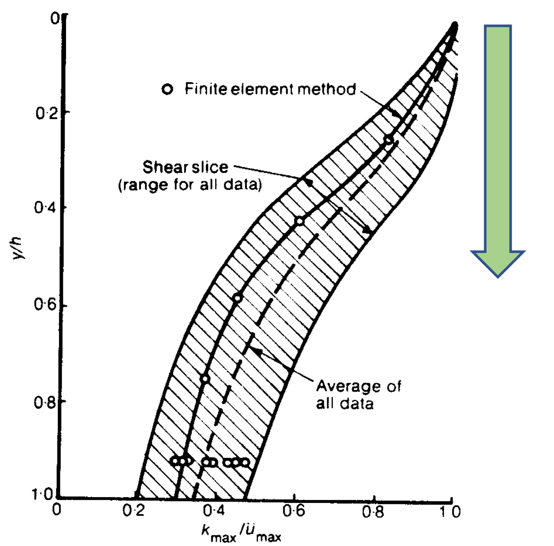


Fig. 19. **Variation of effective peak acceleration, k_{max}, with depth of base of potential slide mass (after Makdisi and Seed)**

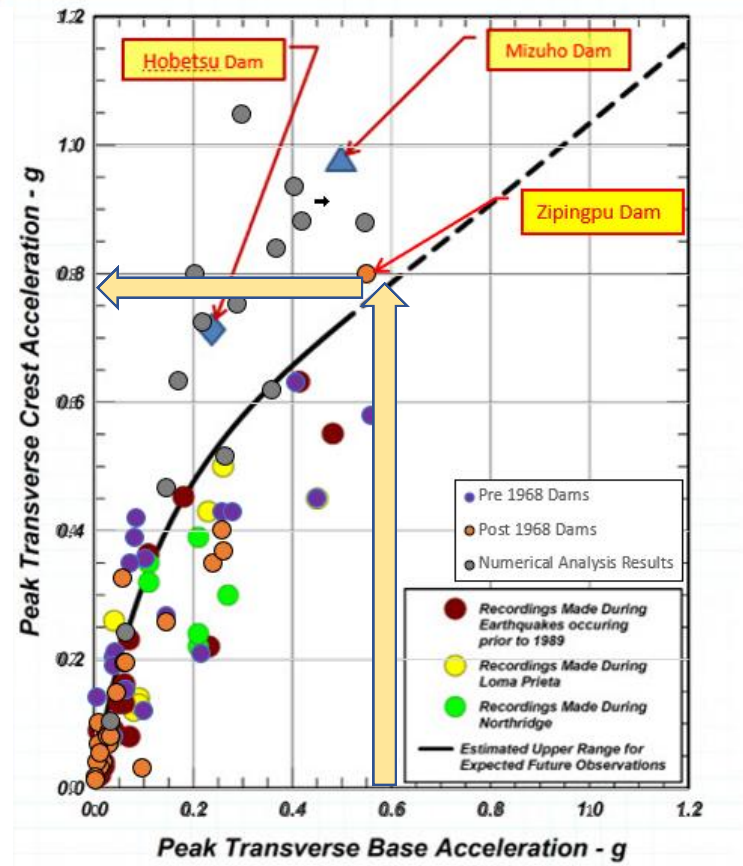
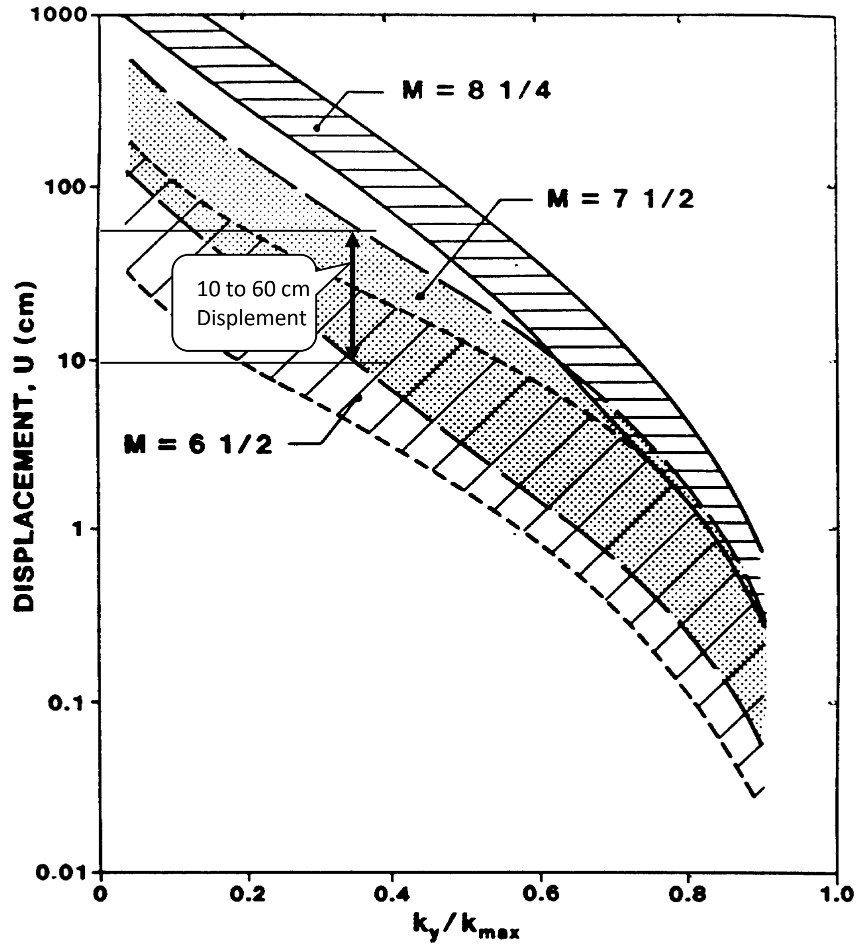


Fig. Variations of Recorded Peak Crest Accelerations With Those Recorded at the Base of Earth- & Rockfill Dams

(source of recorded values from Loma Prieta & prior earthquakes: Harder, 1993)

Figure 1 Abutment Versus Crest Acceleration Developed by (I.M. Idriss)

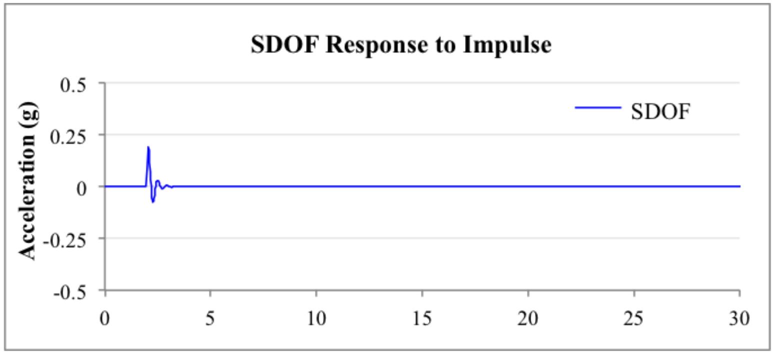


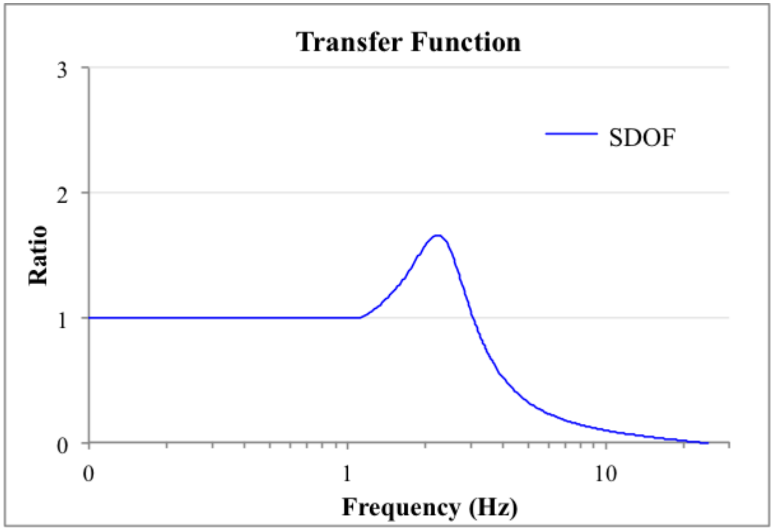
M = 8 1/4
M = 7 1/2
M = 6 1/2
10 to 60 cm
Displement
DISPLACEMENT, U (cm)
1000
100
10
1
0.1
0.01
0
0.2
0.4
0.6
0.8
1.0
k_y/k_{max}

Time Domain

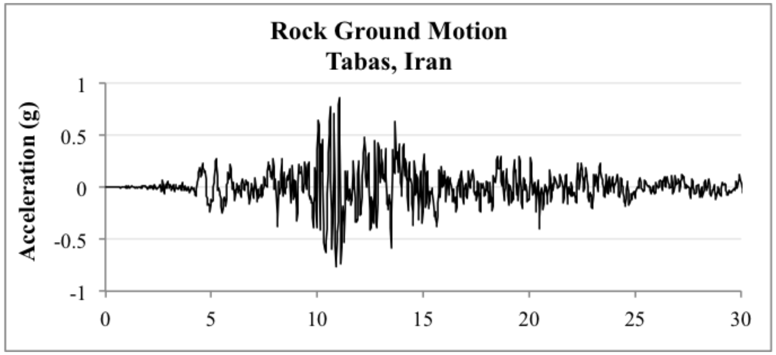
Frequency Domain

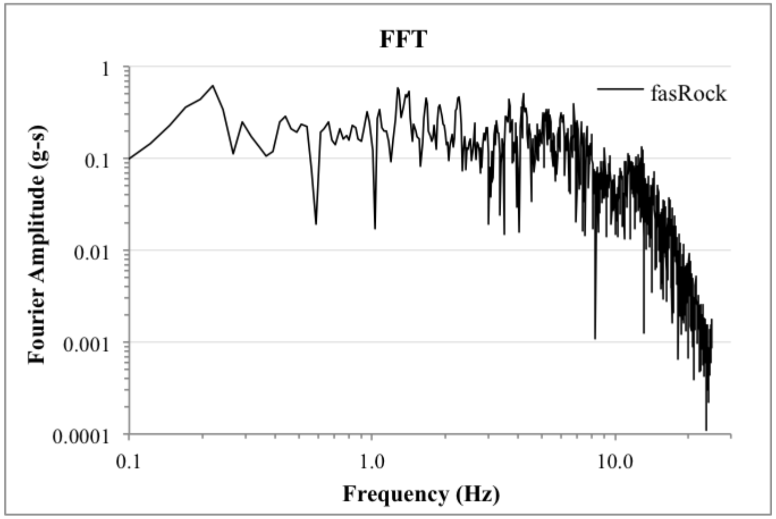
TF



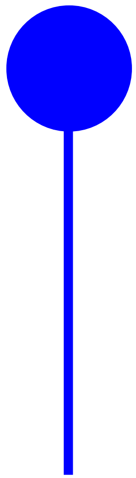


Rock





Simplified Dam Response Model

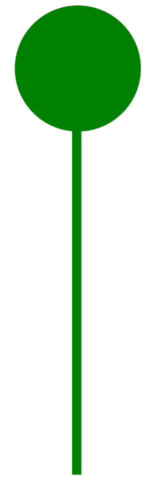


SDOF parameters

f_n = **2.27 Hz**

β = **0.28**

α = **0.8**



SDOF parameters

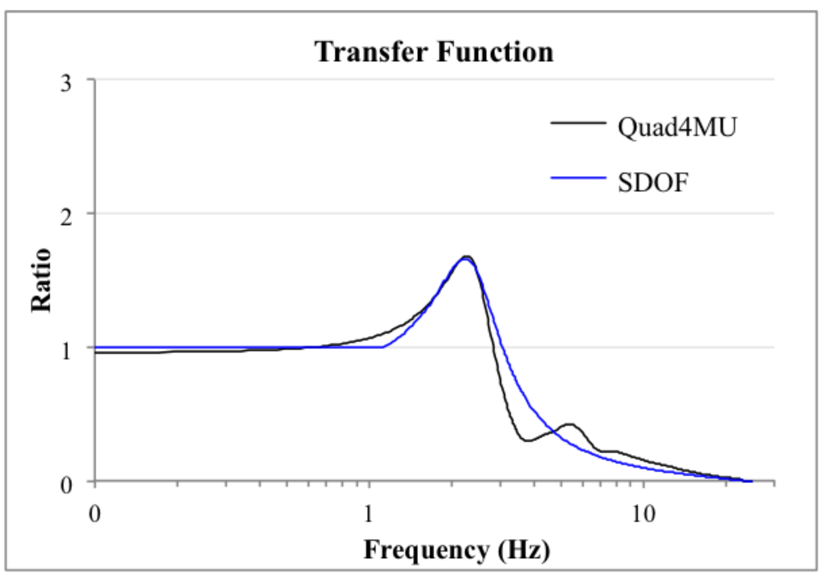
f_n = **2.42 Hz**

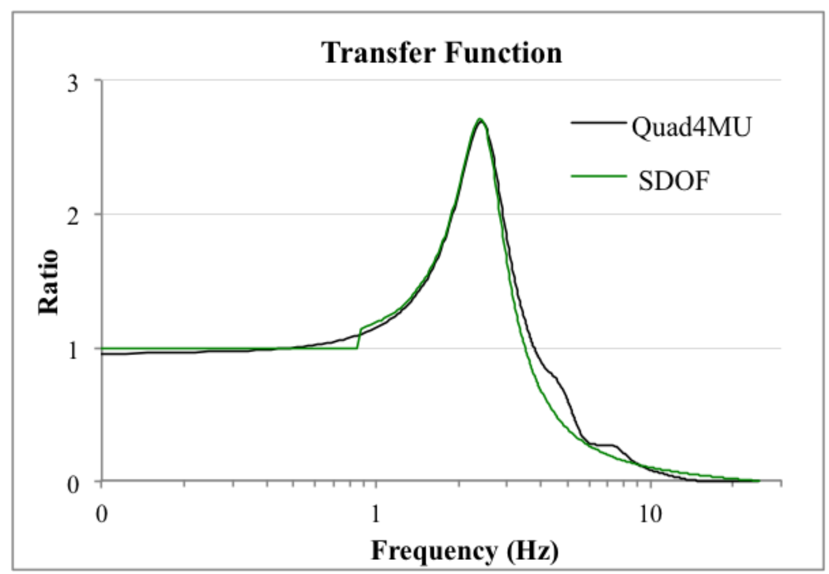
β = **0.20**

α = **1.0**

Deep Failure Surface

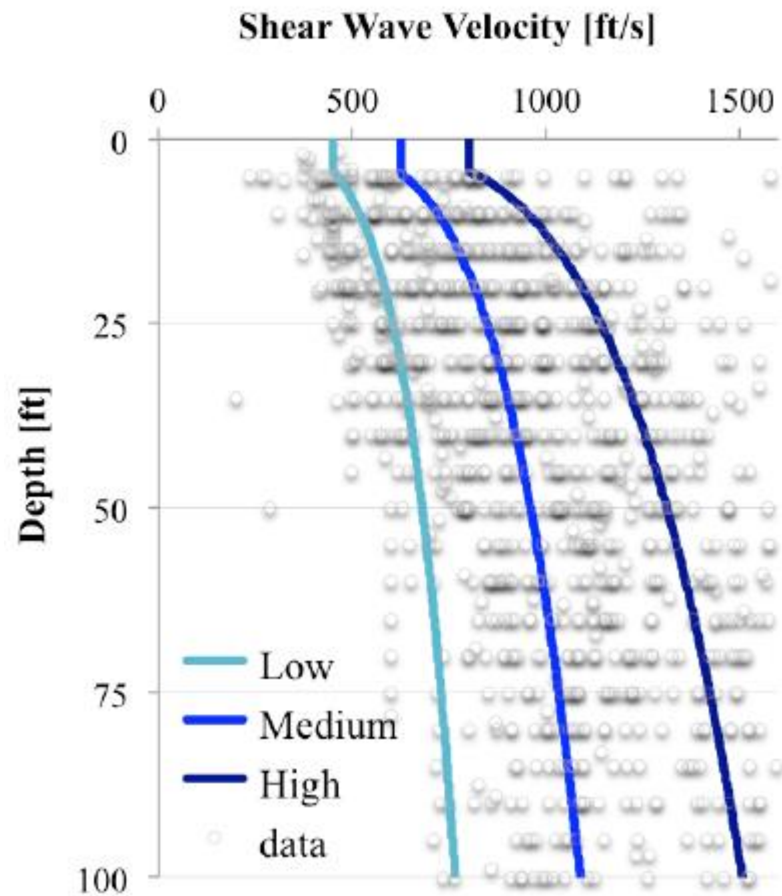
Shallow Failure Surface





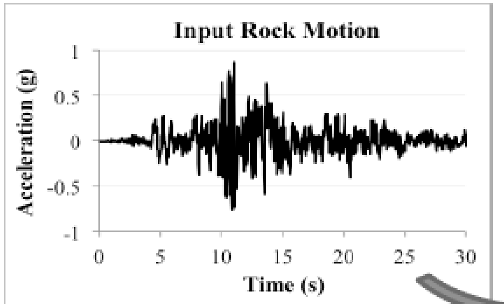
Dam configurations

- Heights:
  25, 50, 100, & 150 ft
- Velocity profiles:
  low, medium, high
- Slip surface:
  toe and mid-height

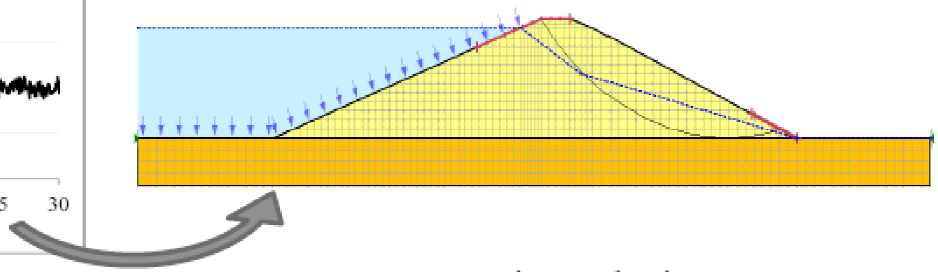


Modeling process

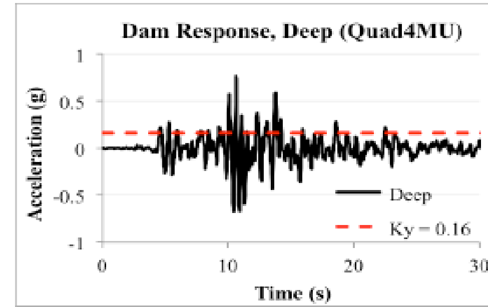
Dynamic analyses to estimate shear induced deformations



Select ground motions

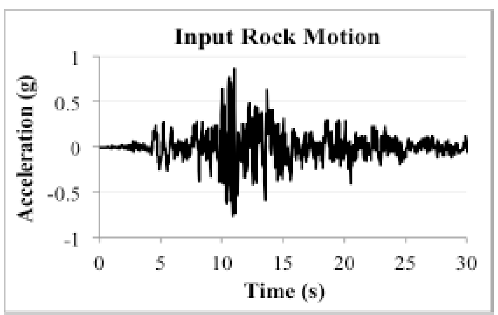


Dynamic analysis

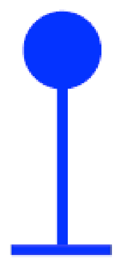


Calculate deformations

Simplified method to estimate shear induced deformations



Select ground motions

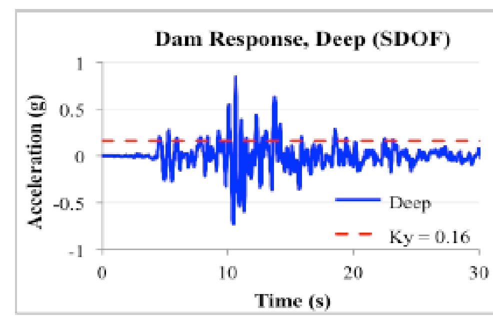


SDOF Oscillator

f_n = natural frequency

β = damping

Model sliding mass



Calculate deformations

Development of Model

Natural frequency (f_n)