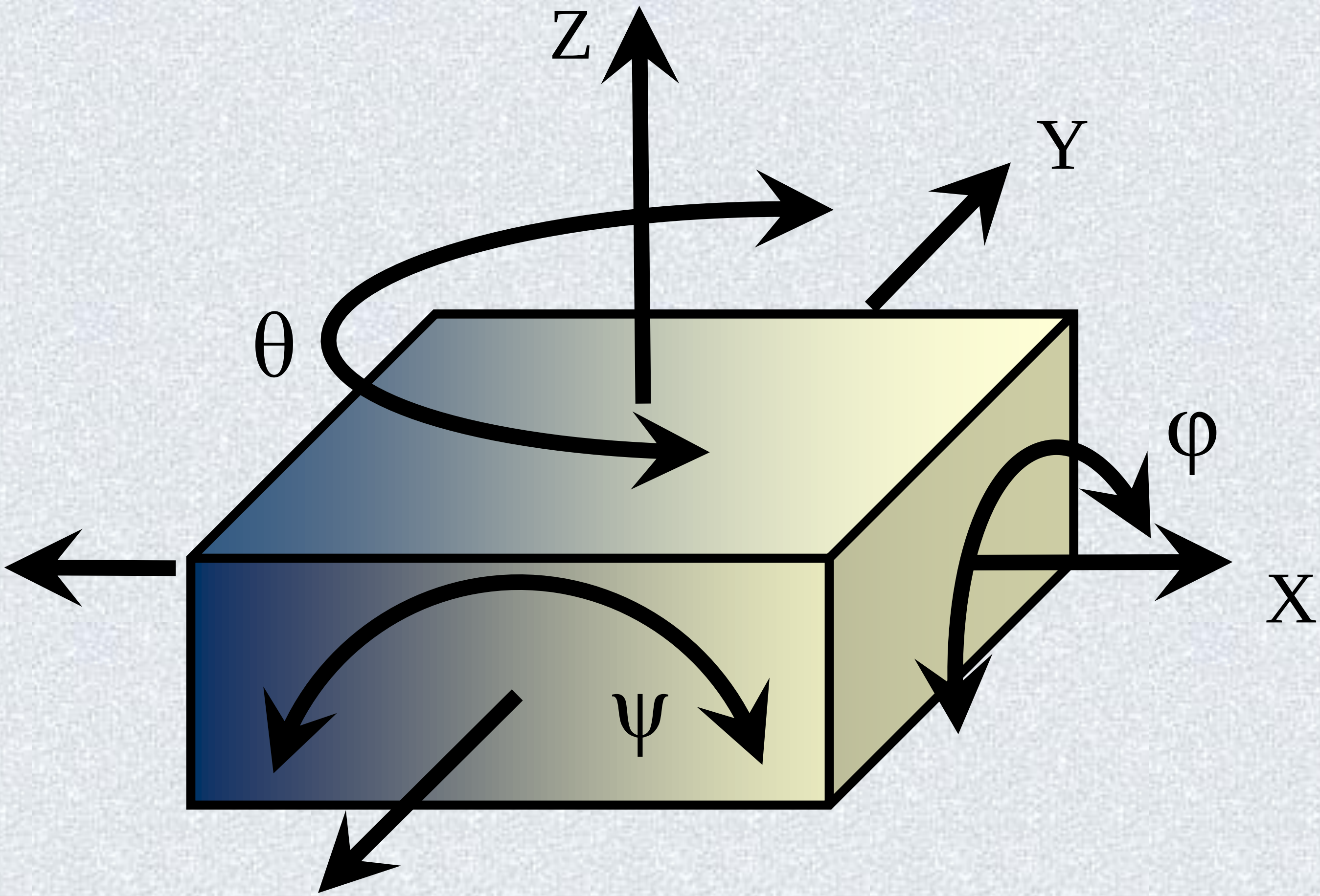
Vibrations
of
Machine Foundations

USC

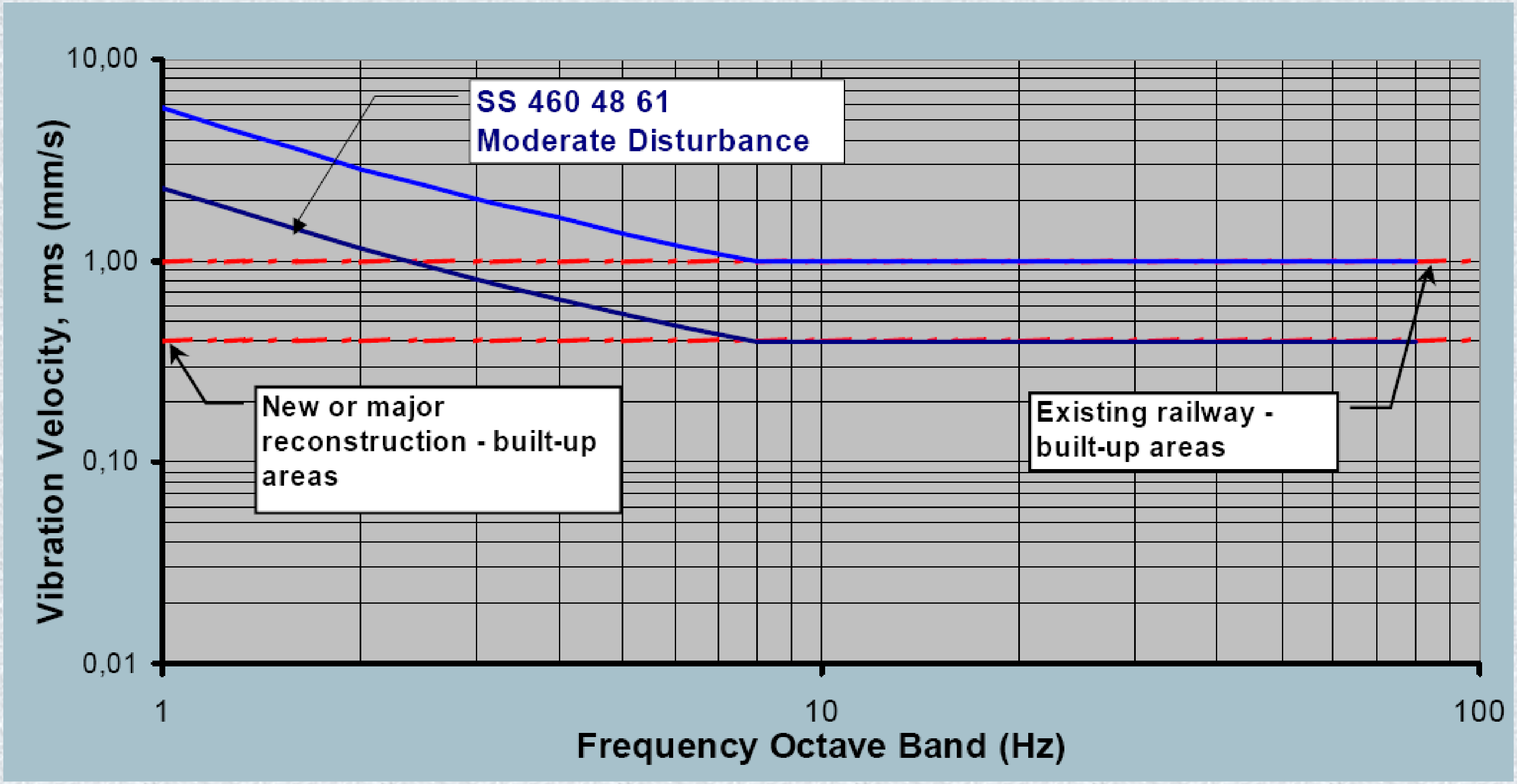
Foundation Movement



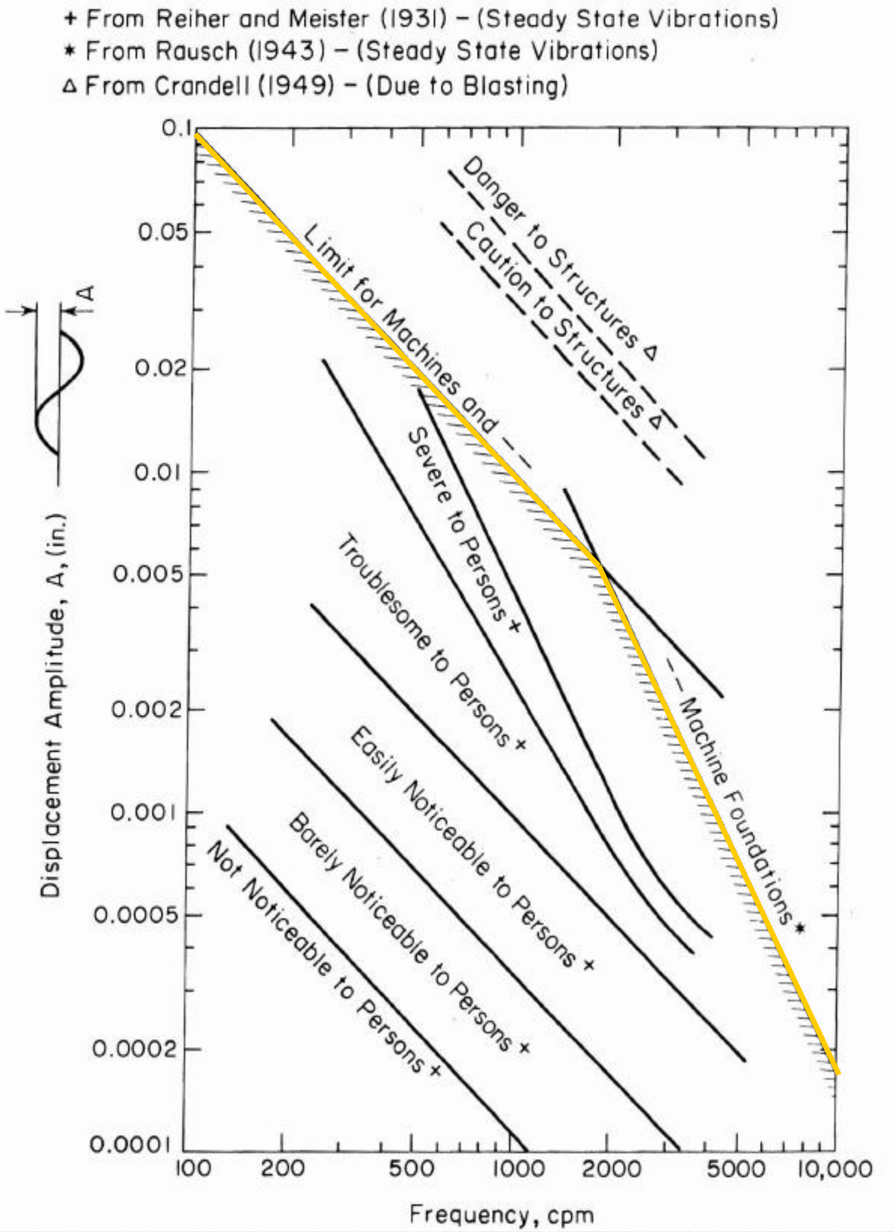
Design Questions (1/4)

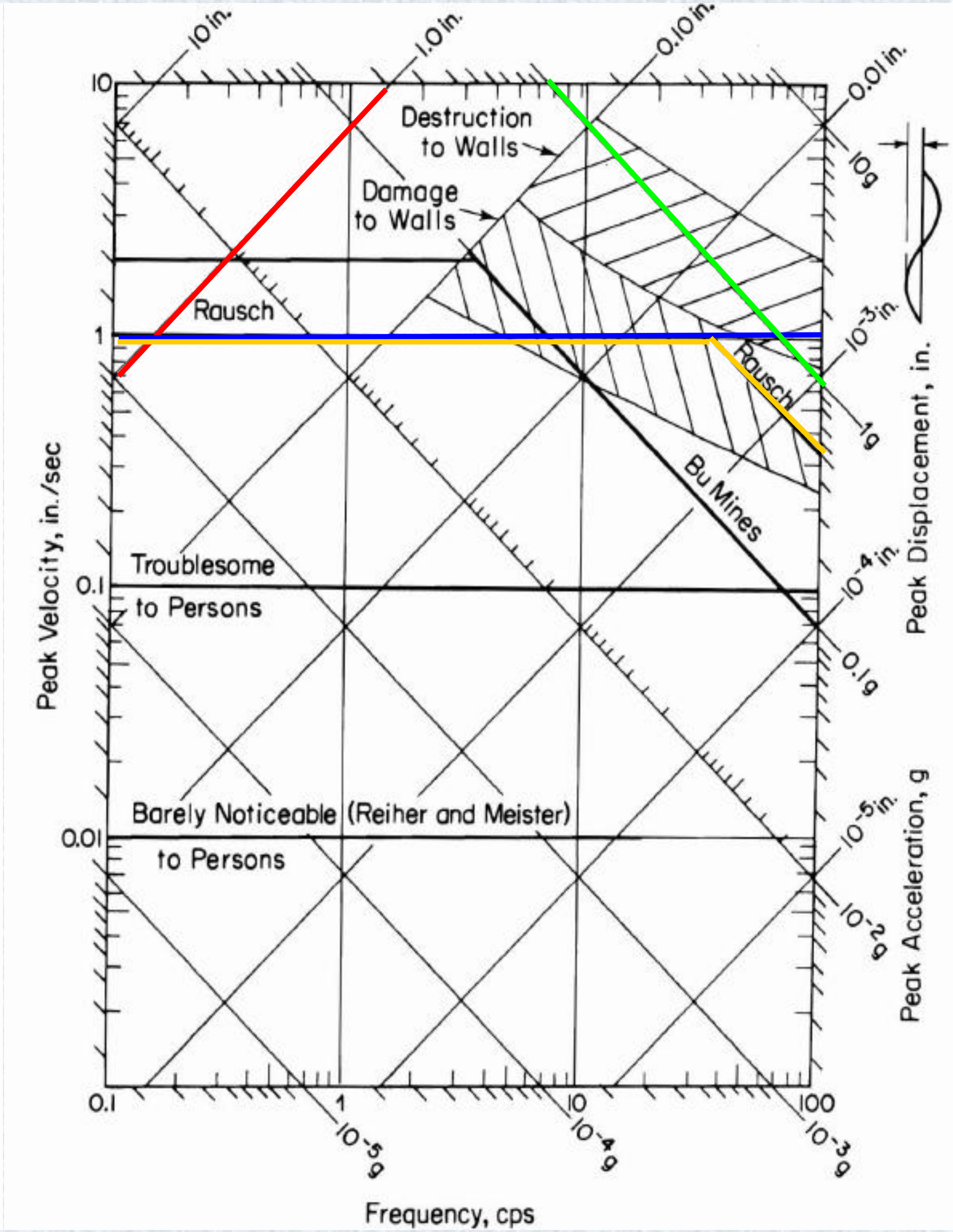
- How Does It Fail?
  - Static Settlement
  - Dynamic Motion Too Large (0.02 mm is large)
  - Settlements Caused By Dynamic Motion
  - Liquefaction
  - What Are Maximum Values of Failure? (Acceleration, Velocity, Displacement)

Velocity Requirements



Massarch (2004) "Mitigation of Traffic-Induced Ground Vibrations"


+ From Reiher and Meister (1931) – (Steady State Vibrations)
* From Rausch (1943) – (Steady State Vibrations)
Δ From Crandell (1949) – (Due to Blasting)
Danger to Structures Δ
Caution to Structures Δ
Limit for Machines and Machine Foundations *
Severe to Persons +
Troublesome to Persons +
Easily Noticeable to Persons +
Barely Noticeable to Persons +
Not Noticeable to Persons +
Displacement Amplitude, A, (in.)
A
0.1
0.05
0.02
0.01
0.005
0.002
0.001
0.0005
0.0002
0.0001
100
200
500
1000
2000
5000
10,000
Frequency, cpm

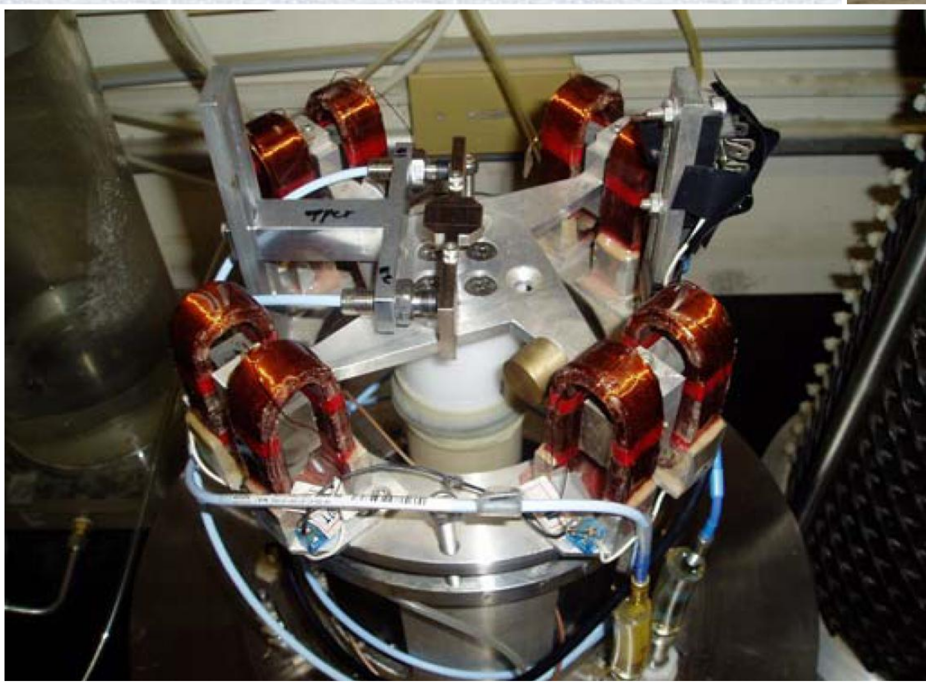

10 in.
1.0 in.
0.10 in.
0.01 in.
Destruction to Walls
Damage to Walls
Rausch
Rausch
Bu Mines
Troublesome to Persons
Barely Noticeable (Reiher and Meister) to Persons
Peak Velocity, in./sec
Peak Displacement, in.
Peak Acceleration, g
10
1
0.1
0.01
0.1
1
10
100
Frequency, cps
10g
1g
0.1g
10^{-2}g
10^{-3}in.
10^{-4}in.
10^{-5}in.
10^{-5}g
10^{-4}g
10^{-3}g

Design Questions (2/4)

- What Are Relations Between Loads And Failure Quantities
  - Loading -Machine (Periodic), Impluse, Natural
  - Relations Between Load, Structure, Foundation, Soil, Neighboring Structures
  - Generate Model: Deterministic or Probabilistic

Design Questions (3/4)

- How Do We Measure What Is Necessary?
  - Full Scale Tests
  - Prototype Tests
  - Small Scale Tests (Centrifuge)
  - Laboratory Tests (Specific Parameters)
  - Numerical Simulation



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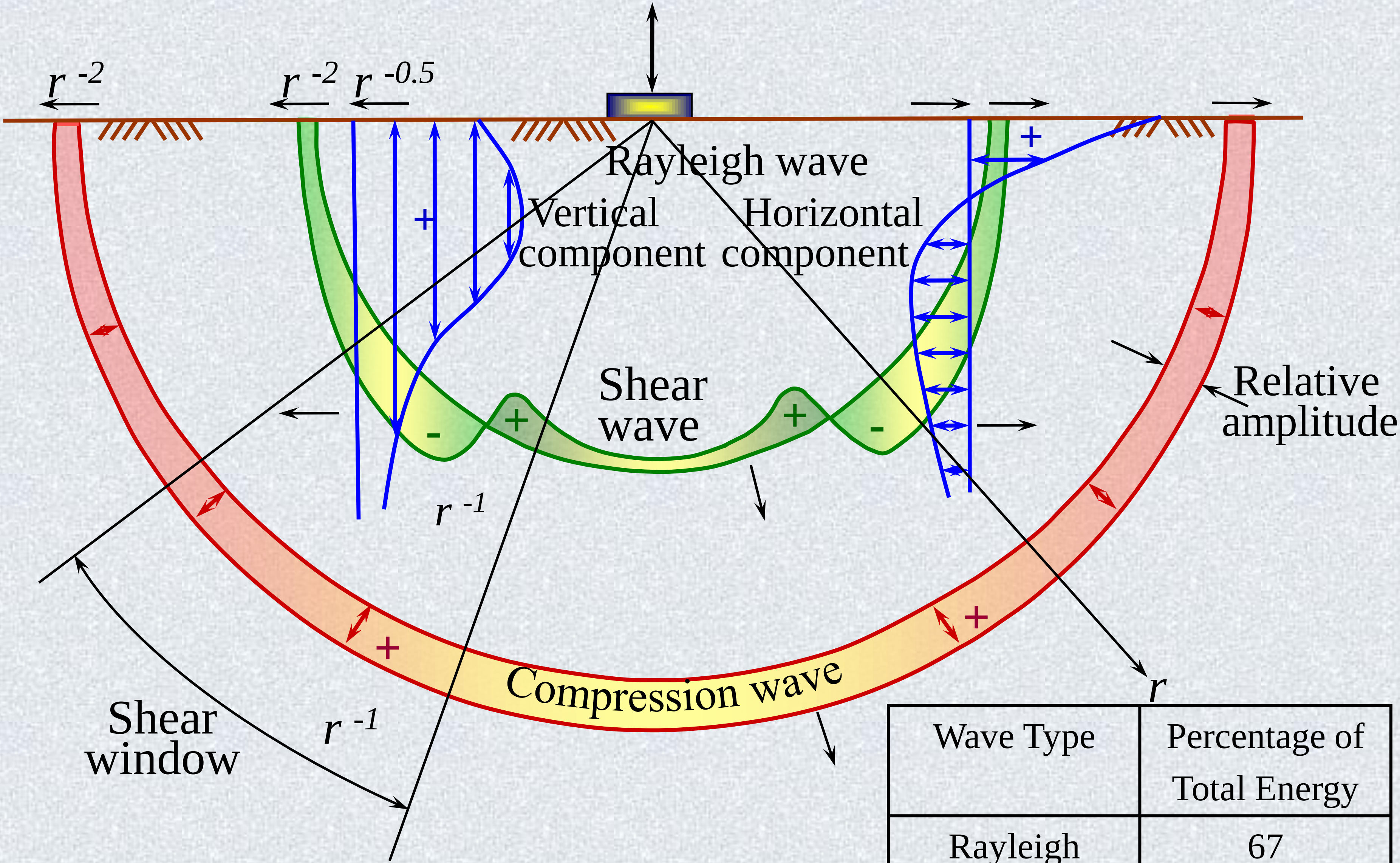
Design Questions (4/4)

- What Factor of Safety Do We Use?
  - Does FOS Have Meaning
  - What Happens After There Is Failure
    - Loss of Life
    - Loss of Property
    - Loss of Production
  - Purpose of Project, Design Life, Value



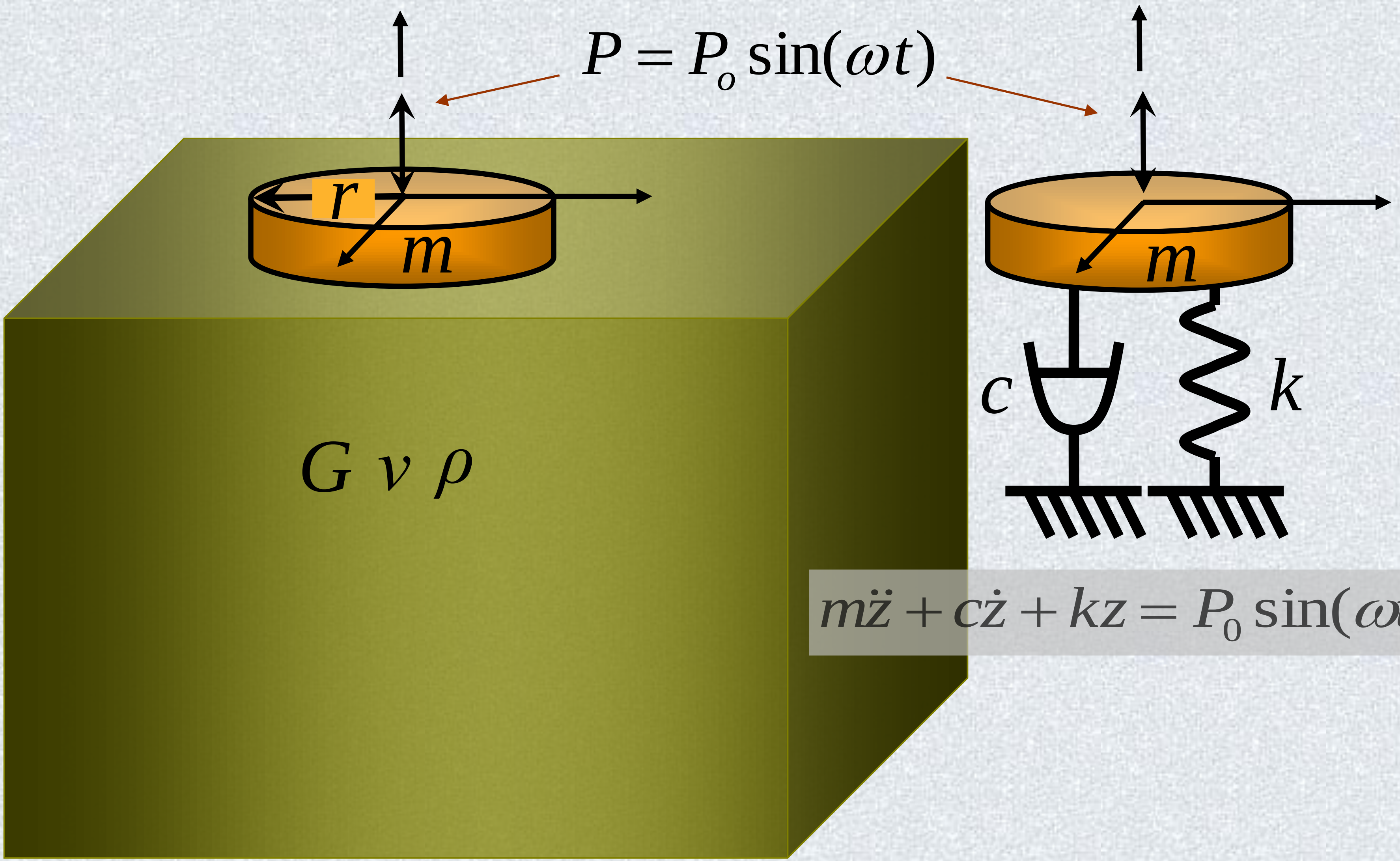
Wave Type	Percentage of Total Energy
Rayleigh	67
Shear	26
Compression	7

Waves

Modeling Foundations

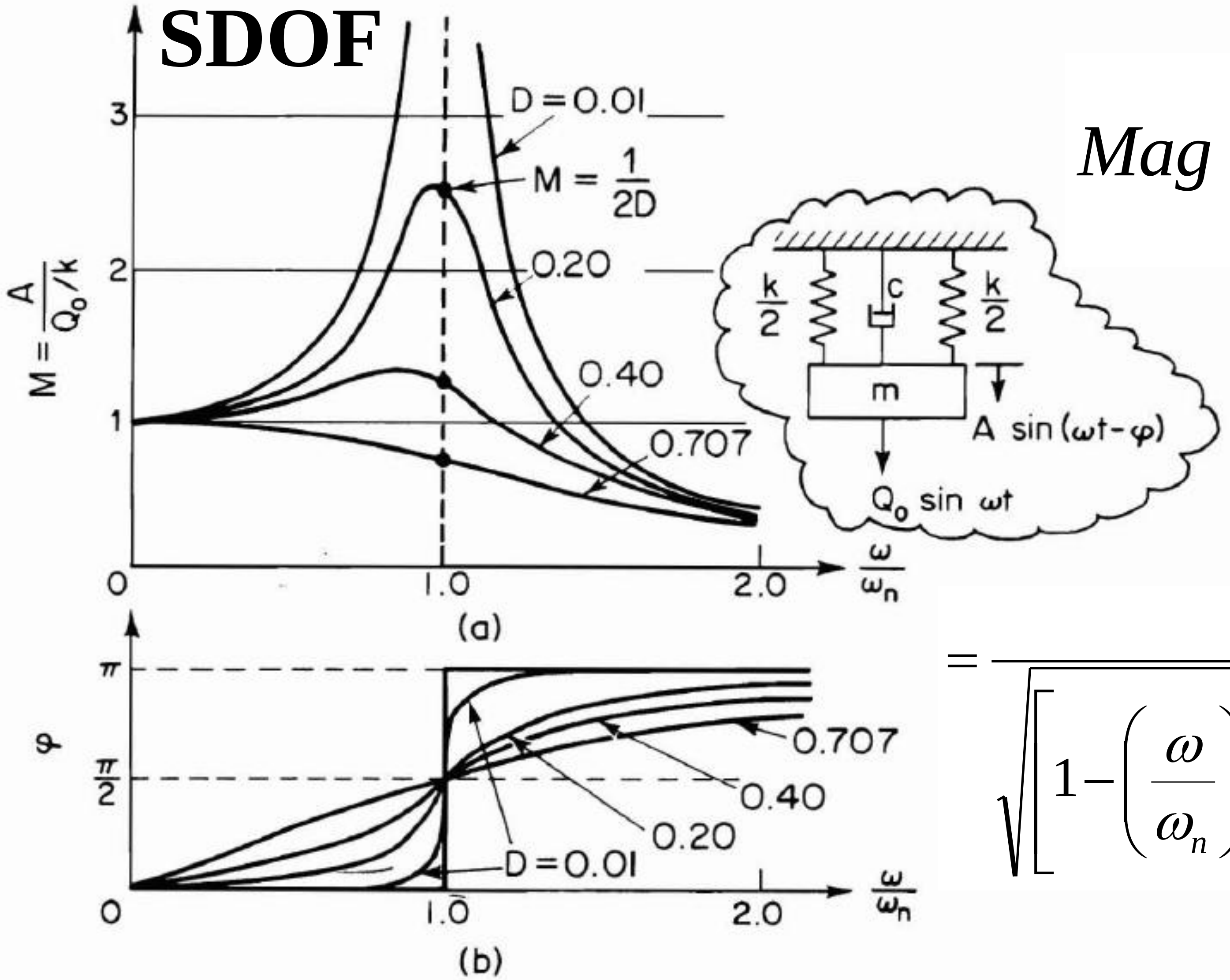
- Lumped Parameter (m,c,k) Block System
  - Parameters Constant, Layer, Special
- Impedance Functions
  - Function of Frequency (ω), Layers
- Boundary Elements (BEM)
  - Infinite Boundary, Interactions, Layers
- Finite Element/Hybrid (FEM, FEM-BEM)
  - Complex Geometry, Non-linear Soil

Lumped Parameter



$$m\ddot{z} + c\dot{z} + kz = P_0 \sin(\omega t)$$

SDOF



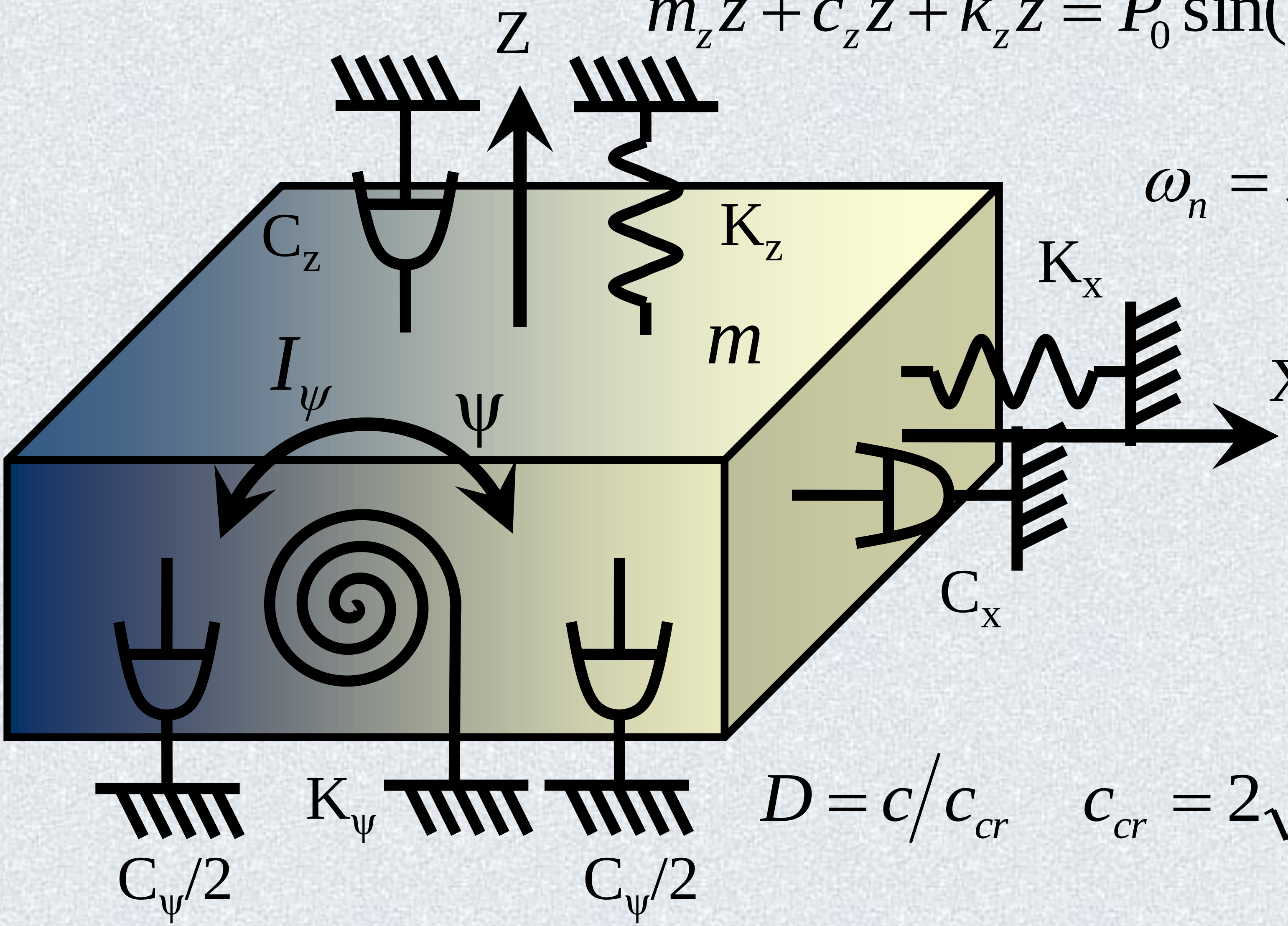
$$Mag = \frac{A_{dynamic}}{A_{static}}$$

$$= \frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2D\frac{\omega}{\omega_n}\right]^2}}$$

Lumped Parameter System

$$m_z \ddot{z} + c_z \dot{z} + k_z z = P_0 \sin(\omega t)$$

$$\omega_n = \sqrt{\frac{k}{m}}$$



$$D = c / c_{cr} \qquad c_{cr} = 2\sqrt{km}$$

Lumped Parameter Values

Mode	Vertical	Horizontal	Rocking	Torsion
Stiffness k	$\frac{4Gr}{1-\nu}$	$\frac{8Gr}{2-\nu}$	$\frac{8Gr^3}{3(1-\nu)}$	$\frac{16Gr^3}{3}$
Mass Ratio $\hat{m}$	$\frac{m(1-\nu)}{4\rho r^3}$	$\frac{m(2-\nu)}{8\rho r^3}$	$\frac{3I_\psi(1-\nu)}{8\rho r^5}$	$\frac{I_\theta}{\rho r^5}$
Damping Ratio, D	$\frac{0.425}{\hat{m}^{1/2}}$	$\frac{0.288}{\hat{m}^{1/2}}$	$\frac{0.15}{(1+\hat{m})\hat{m}^{1/2}}$	$\frac{0.50}{1+2\hat{m}}$
Fictitious Mass	$\frac{0.27m}{\hat{m}}$	$\frac{0.095m}{\hat{m}}$	$\frac{0.24I_x}{\hat{m}}$	$\frac{0.24I_z}{\hat{m}}$

$D=c/c_{cr}$ G=Shear Modulus ν=Poisson's Ratio r=Radius
ρ=Mass Density I_ψ,I_θ=Mass Moment of Inertia

Mass Ratio

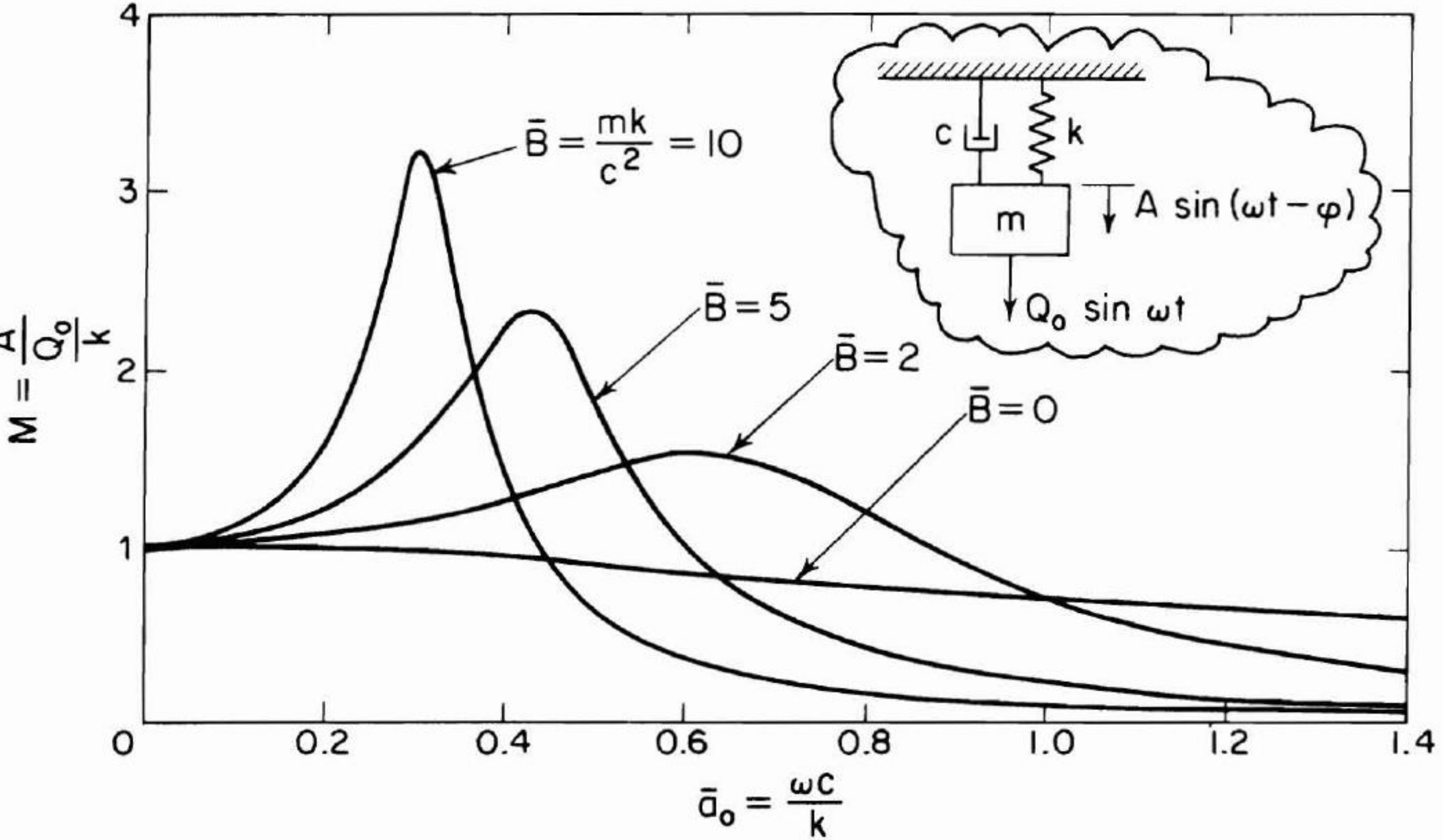


Figure 2-22. Response curves for a single-degree-of-freedom system with the effect of mass and frequency separated (*after Lysmer, 1965*).

Design Example 1

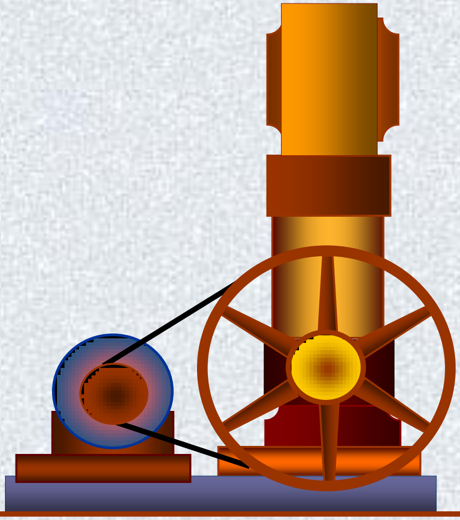
VERTICAL COMPRESSOR

Unbalanced Forces

- Vertical Primanry = 7720 lb
- Vertical Secondary = 1886 lb
- Horzontal Primary = 104 lb
- Horizontal Secondary = 0 lb

Operating Speed = 450 rpm

Wt Machine + Motor = 10 900 lb



Soil Properties

Shear Wave Velocity V_s = 680 ft/sec

Shear Modulus, G = 11 000 psi

Density, γ = 110 lb/ft^3

Poisson's Ratio, ν = 0.33

DESIGN CRITERION:

Smooth Operation At Speed

Velocity <0.10 in/sec

Displacement < 0.002 in

Jump to Chart

$$A_{zs} = \frac{Q_0}{k_z} = 0.002'' = \frac{(1-\nu)Q_0}{4Gr} = \frac{0.667(7720+1885)}{4 \times 11\,000 \times r}$$

$$r = 72.8'' = 6.07'$$

Try a 15 x 8 x 3 foundation block, Area = 120 ft^2 and r = 6.18 ft

Weight = 54,000 lb Total Weight = 54 000 + 10 900 = 64 900

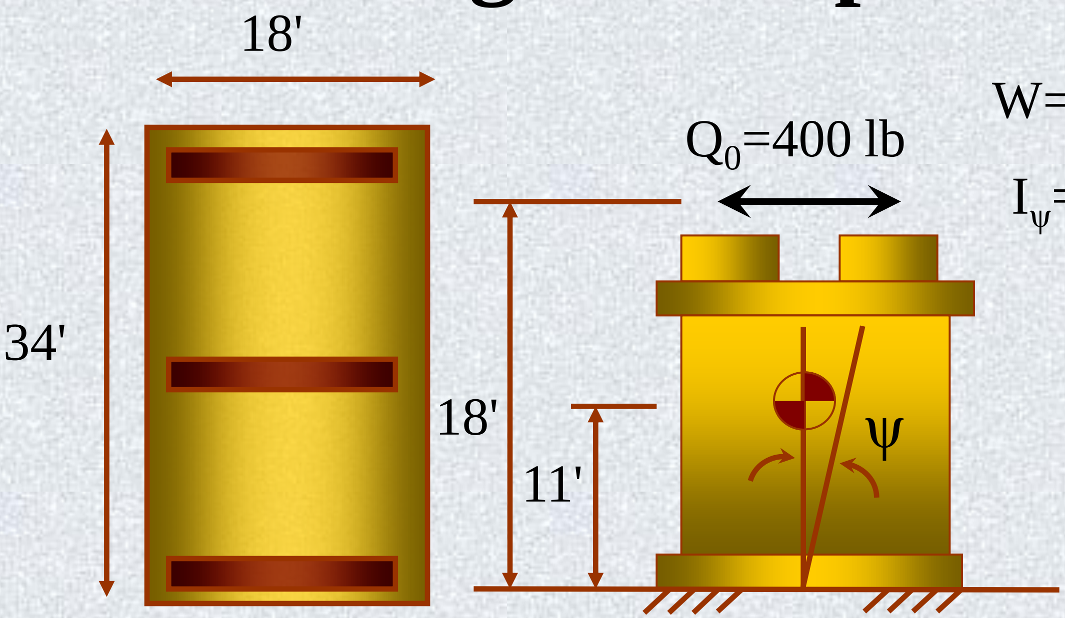
$$\hat{m} = \frac{(1-\nu)}{4r^3}\frac{W}{g}\frac{g}{\gamma} = \frac{0.67 \times 64\,900}{4 \times 110(6.18)^3} = 0.42$$

$$D = \frac{0.425}{\sqrt{\hat{m}}} = 0.66 \quad M_z \approx 1.0 \quad \left(\frac{1}{2D}\right)$$

Jump to Figure

$$A_{z\,dynamic} = A_{z\,static} = 0.002''$$

Design Example - Table Top



W=550 000 lb

I_ψ=2.88 x 10^6 ft-lb-sec^2

Soil Properties

Shear Wave Velocity V_s = 770 ft/sec

Shear Modulus, G = 14 000 psi

Density, γ = 110 lb/ft^3

Poisson's Ratio, ν = 0.33

DESIGN CRITERION

0.20 in/sec Horizontal Motion at Machine Centerline

Ax = 0.0015 in. from combined rocking and sliding

Speed = 160 rpm

Slower speeds, Ax can be larger

Horizontal Translation Only

$$Equivanlent \quad r=\sqrt{\frac{4cd}{\pi}}=\sqrt{\frac{4\times 18\times 34}{\pi}}=13.96\,ft \qquad \hat{m}=\frac{2-\nu}{8}\frac{m}{\rho r^3}=0.38$$

$$D=\frac{0.288}{\hat{m}^{1/2}}=0.465 \quad \therefore Mag_x \approx 1.0 \quad A_{x\,static}=\frac{Q_0}{k_x}=\frac{Q_0}{8}\frac{2-\nu}{Gr}=3.0\times 10^{-5}\ in$$

Rocking About Point "O"

$$Equivalent \quad r=\sqrt[4]{\frac{16cd^3}{3\pi}}=\sqrt[4]{\frac{16\times 17\times 9^3}{3\pi}}=12.0\,ft \qquad \omega=120\,rpm=12.5\,rad/sec$$

$$k_\psi=\frac{8Gr}{2-\nu}=\frac{8\times(14\,000\times 144)\times 12.04}{2-0.33}=2.90\times 10^8\,lb/\,ft \qquad \omega_n=\sqrt{\frac{k_\psi}{I_\psi}}=\sqrt{\frac{2.90\times 10^8}{2.88\times 10^6}}=10\,rad/sec$$

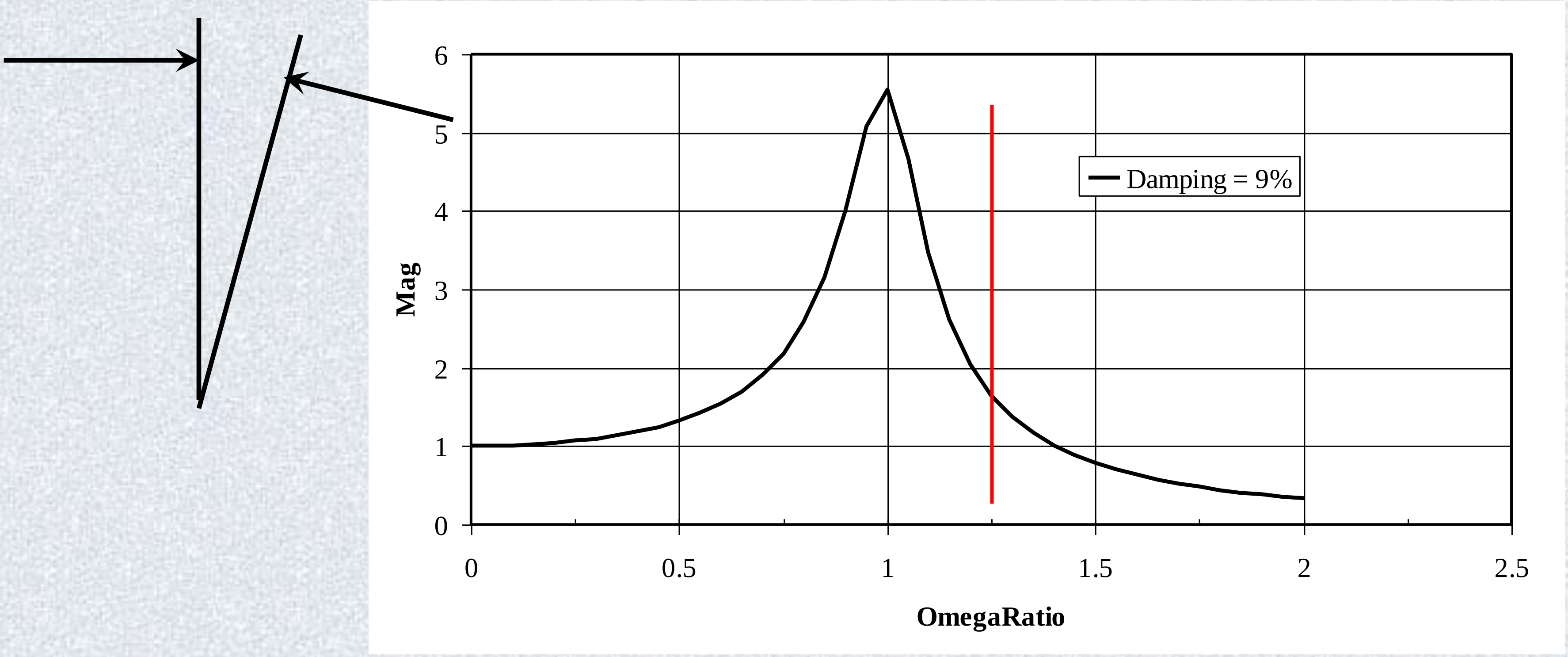
$$\hat{m}_\psi=\frac{3(1-\nu)}{8}\frac{I_\psi}{\rho r^5}=\frac{3(0.67)}{8}\frac{2.88\times 10^6}{\frac{110}{32.2}(12.04)^5}=0.83$$

$$D_\psi=\frac{0.15}{(1+\hat{m}_\psi)\sqrt{\hat{m}_\psi}}=0.09 \quad \therefore Mag_\psi=5.6 \quad Static\ \ Moment=M_o=400\times 18=7200\,ft-lbs.$$

$$\textit{Static Angular Deflection} = \psi_s = \frac{M_o}{k_\psi} = \frac{7200 \times 3(0.67)}{2.9 \times 10^8} = \frac{0.50}{10^6}\ rad$$

$$\textit{Horizontal Motion} = A_{xs} = \psi_s \times h = \frac{0.50}{10^6}(18 \times 12) = 1.0 \times 10^{-4}\ in$$

$$\textit{At Resonance} = 5.6(1.0 \times 10^{-4}) = 5.6 \times 10^{-4}\ in.$$

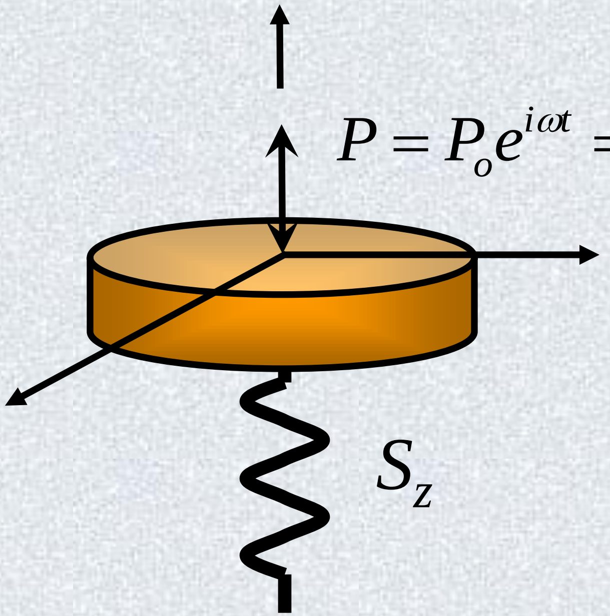


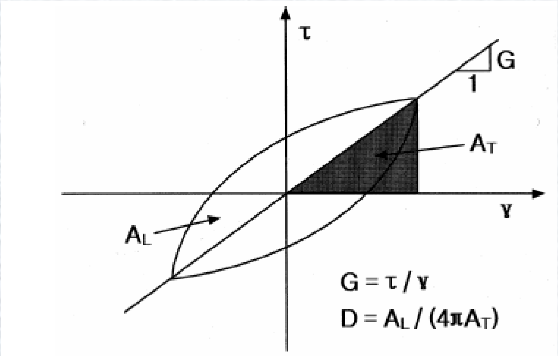
Impedance Methods

- Based on Elasto-Dynamic Solutions
- Compute Frequency-Dependent Impedance Values (Complex-Valued)
- Solved By Boundary Integral Methods
- Require Uniform, Single Layer or Special Soil Property Distribution
- Solved For Many Foundation Types

Impedance Functions

$$P = P_o e^{i\omega t} = P_o\left(\cos(\omega t) + i\,\sin(\omega t)\right)$$





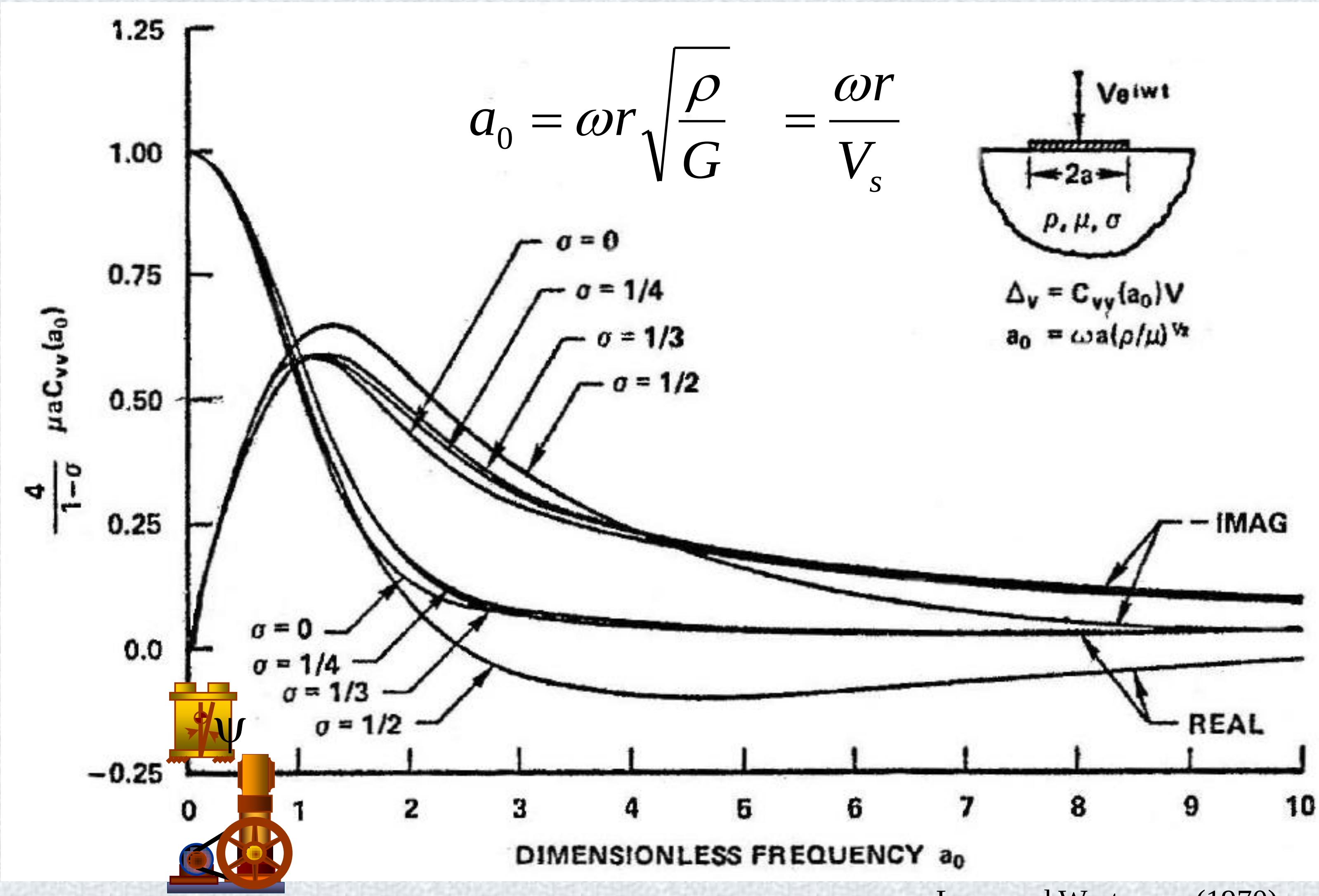
$$S_z = \frac{R_z}{A_z} = \overline{K} + i\omega C = \left(K_{STATIC} \times k(\omega)\right) + i\omega\left(C + \frac{2\overline{K}}{\omega} D_{SOIL}\right)$$

Radiation Damping

Soil Damping

Jump Wave

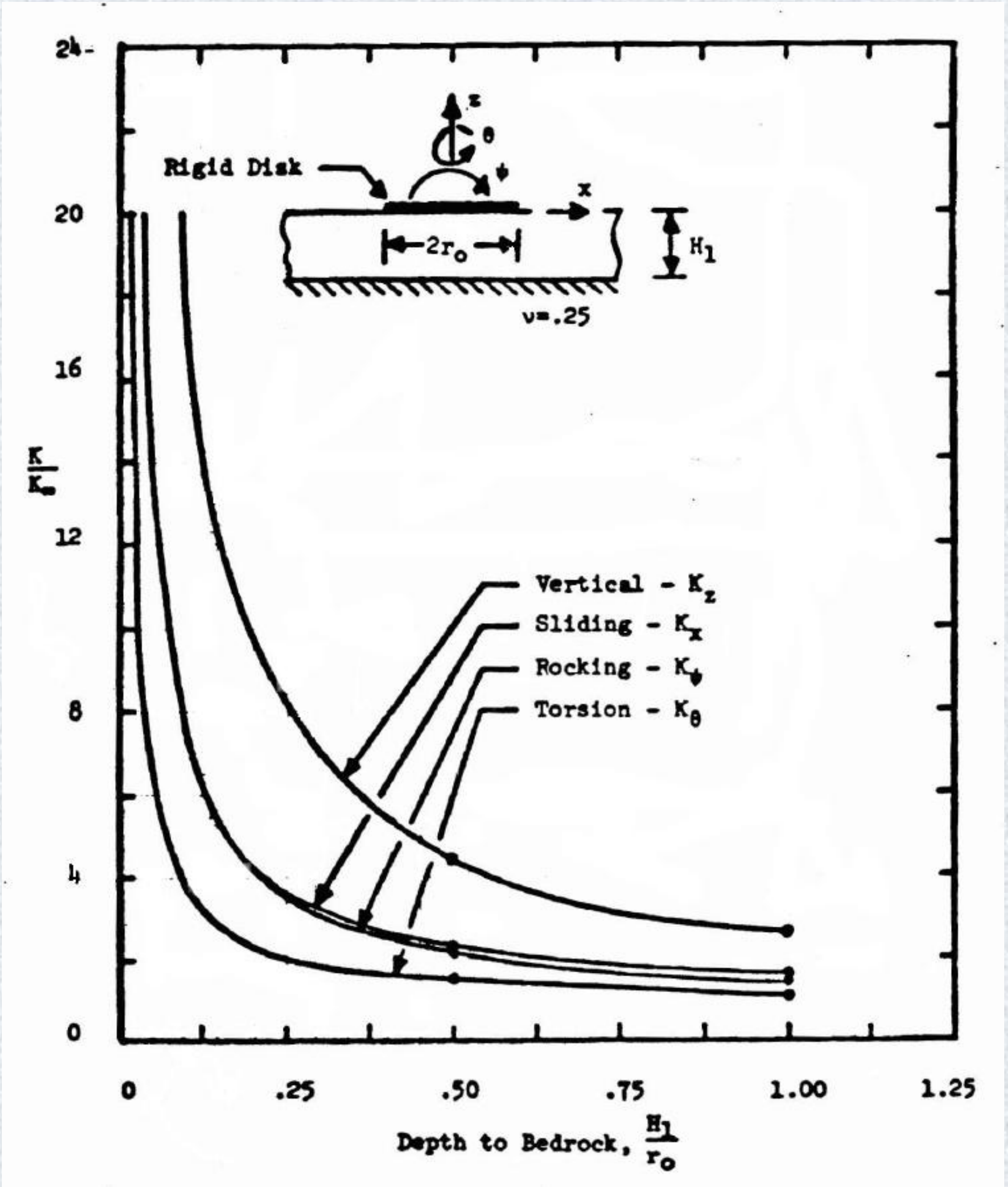
Impedance Functions



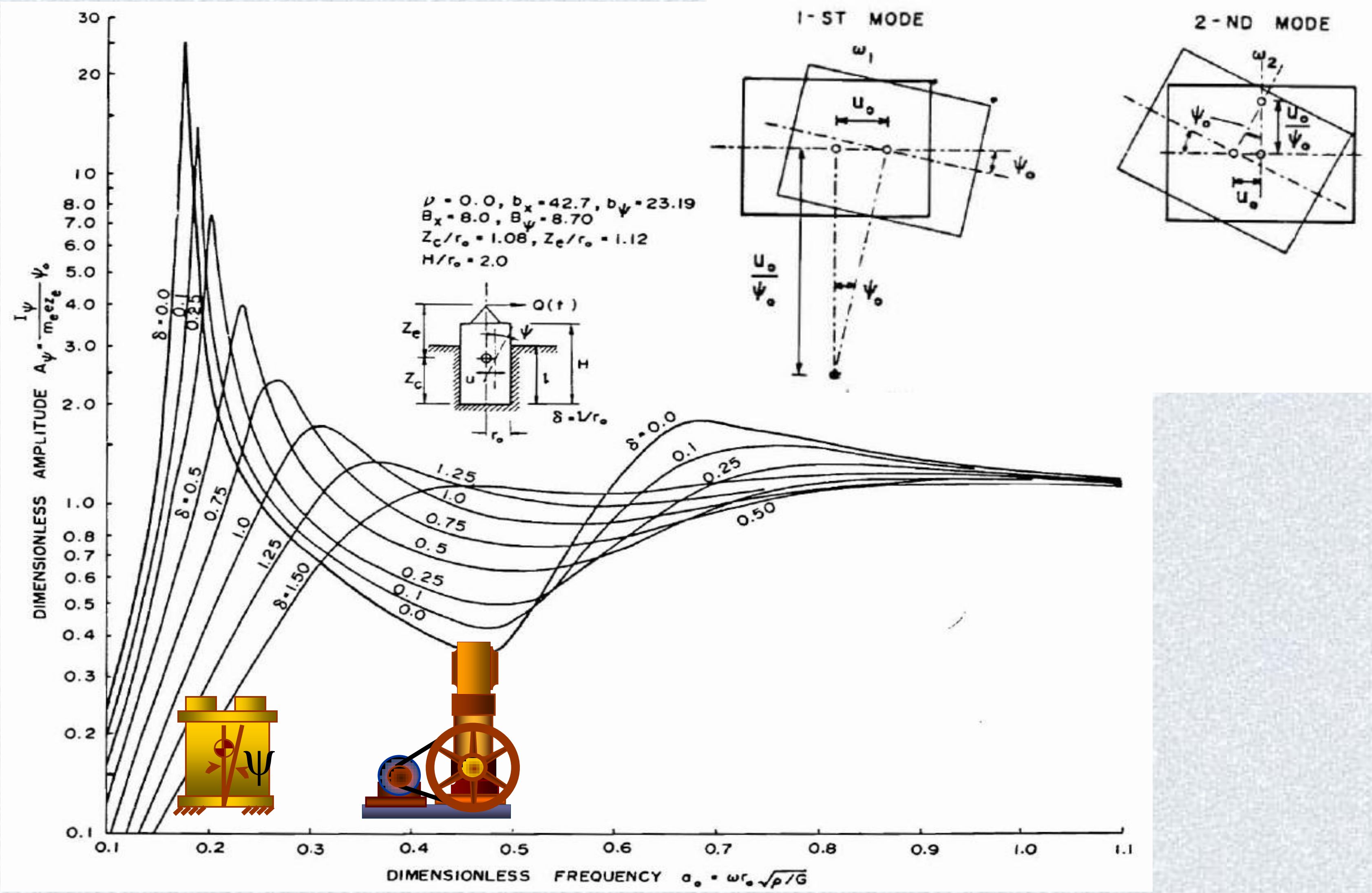
$$a_0 = \omega r\sqrt{\frac{\rho}{G}} = \frac{\omega r}{V_s}$$

Luco and Westmann (1970)

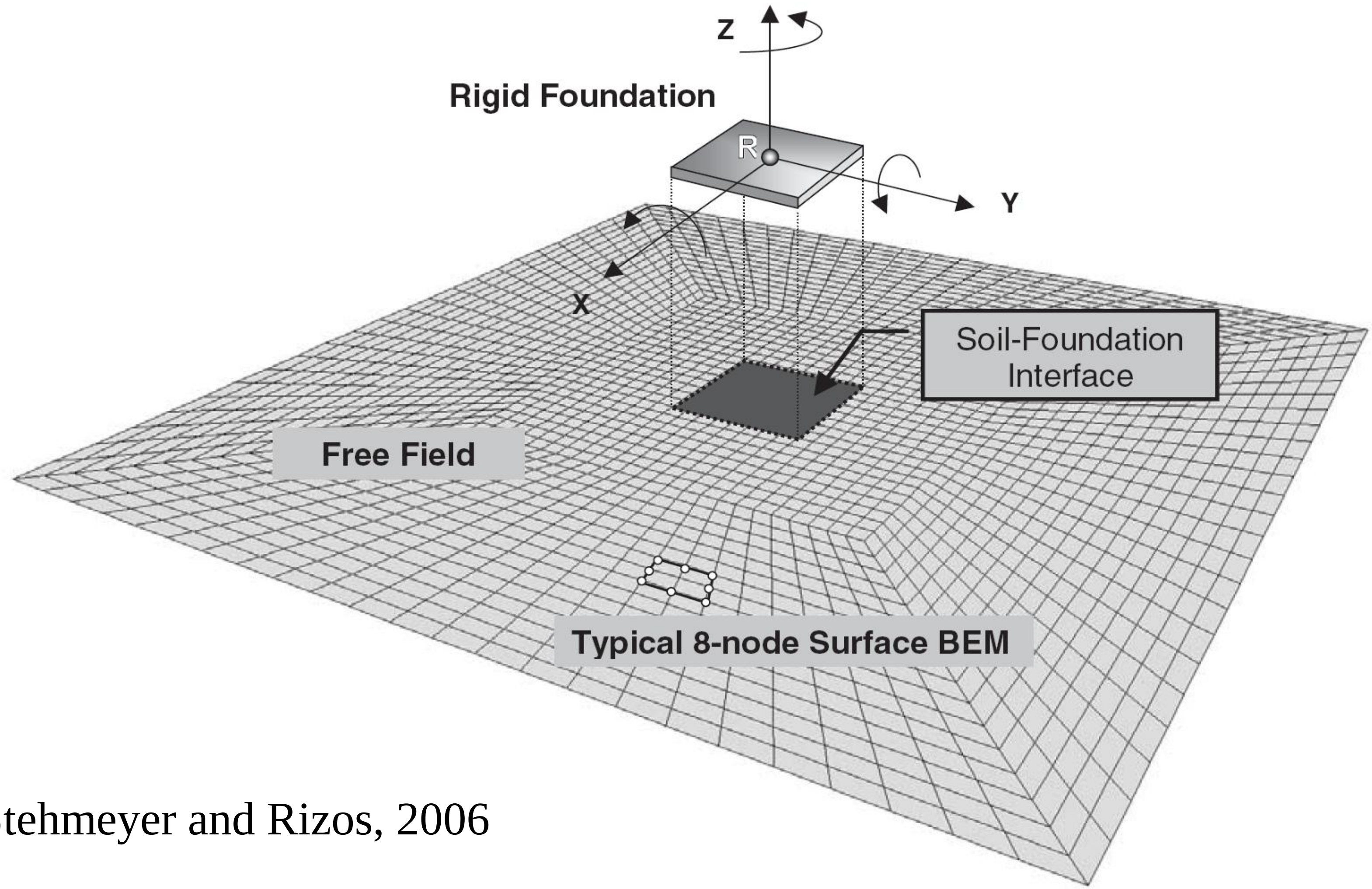
Layer Effects



Impedance Functions

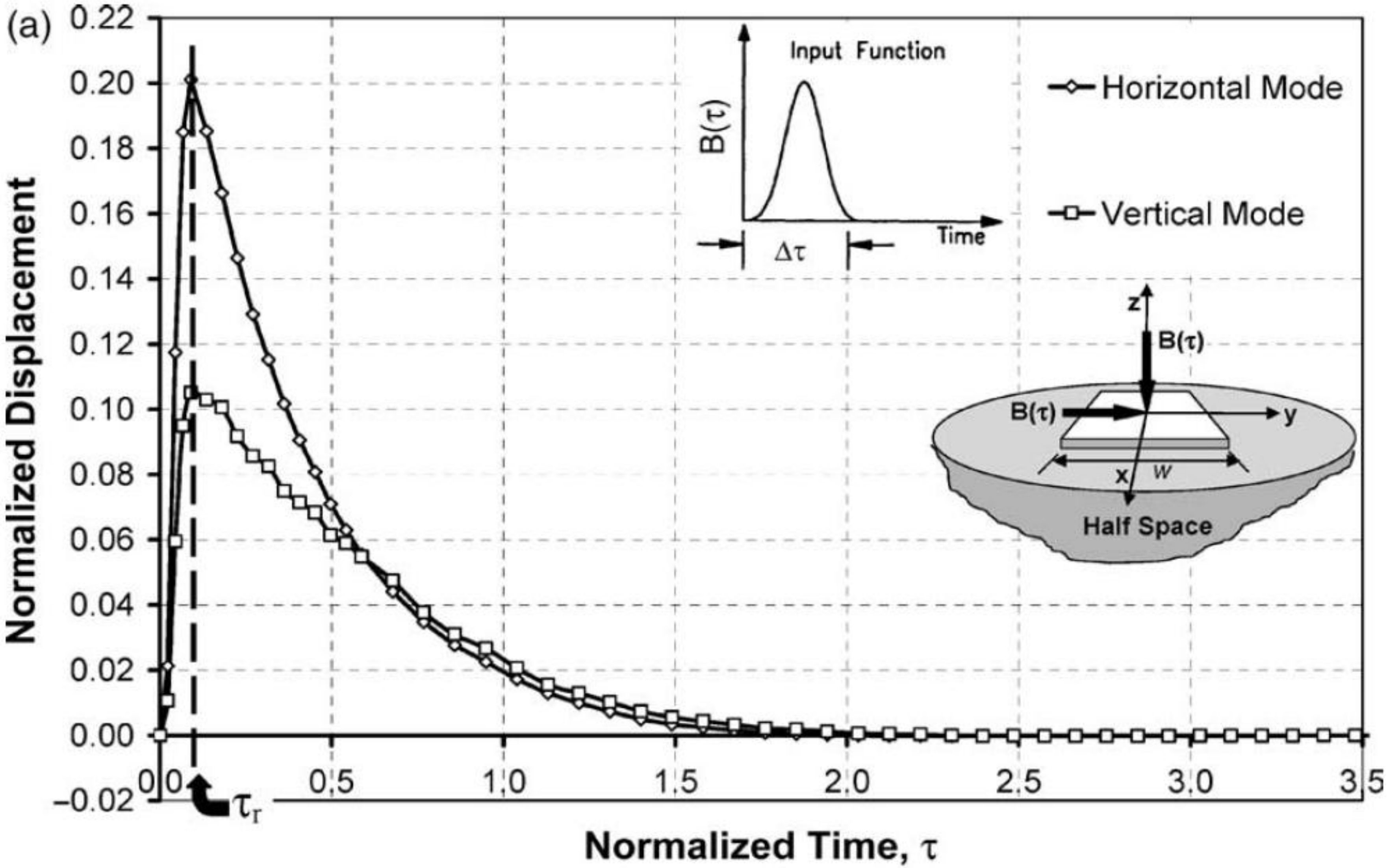


Boundary Element



Stehmeyer and Rizos, 2006

B-Spline Impulse Response Approach



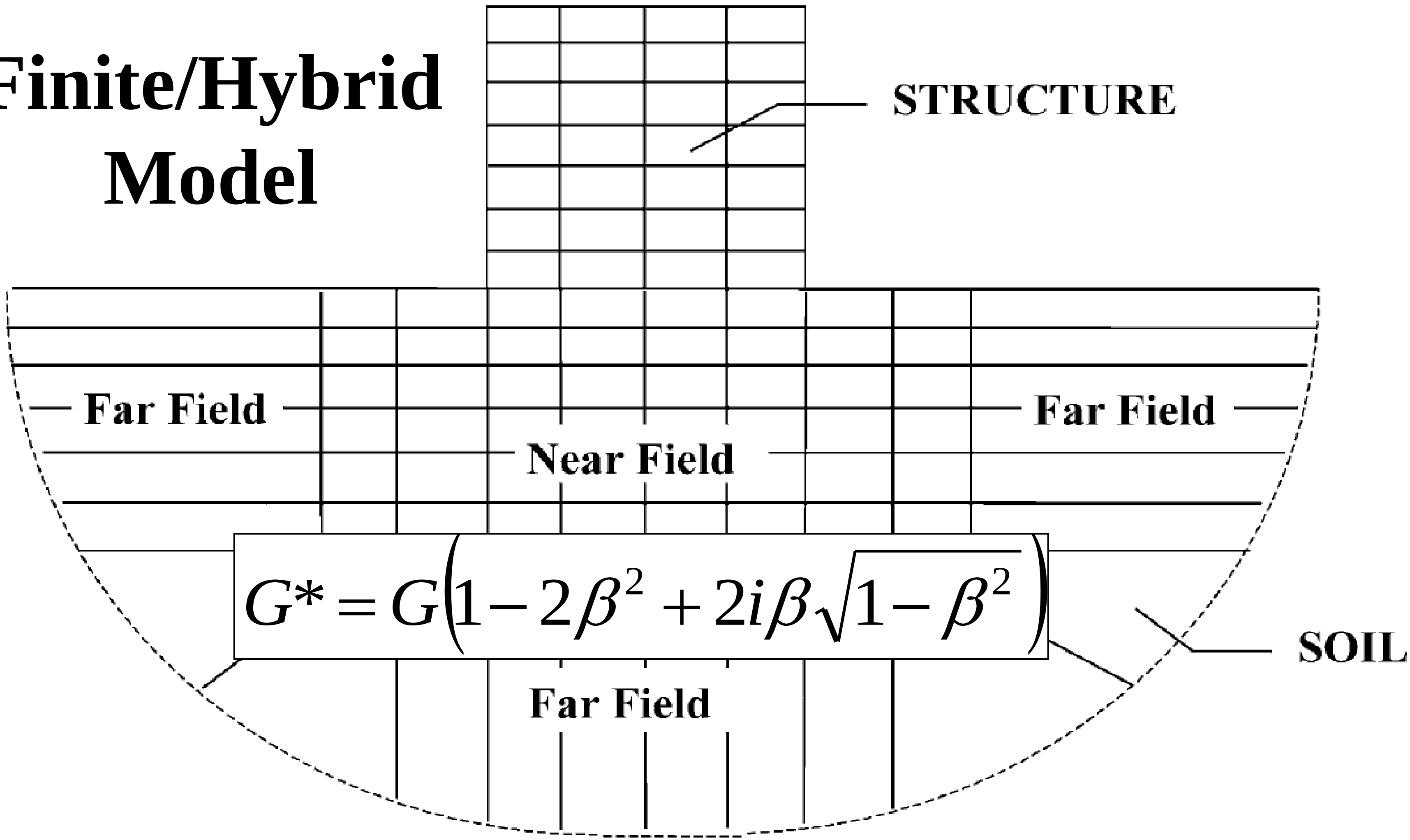
Fundamentals-Modeling-Properties-Performance

$$[\mathbf{M}]\{\ddot{\mathbf{z}}\}+[\mathbf{K}]\{\mathbf{z}\}=\{\mathbf{p}\}e^{i\omega t}$$

$$\{\mathbf{z}\}=\{\mathbf{Z}\}e^{i\omega t}\ \textit{then}$$

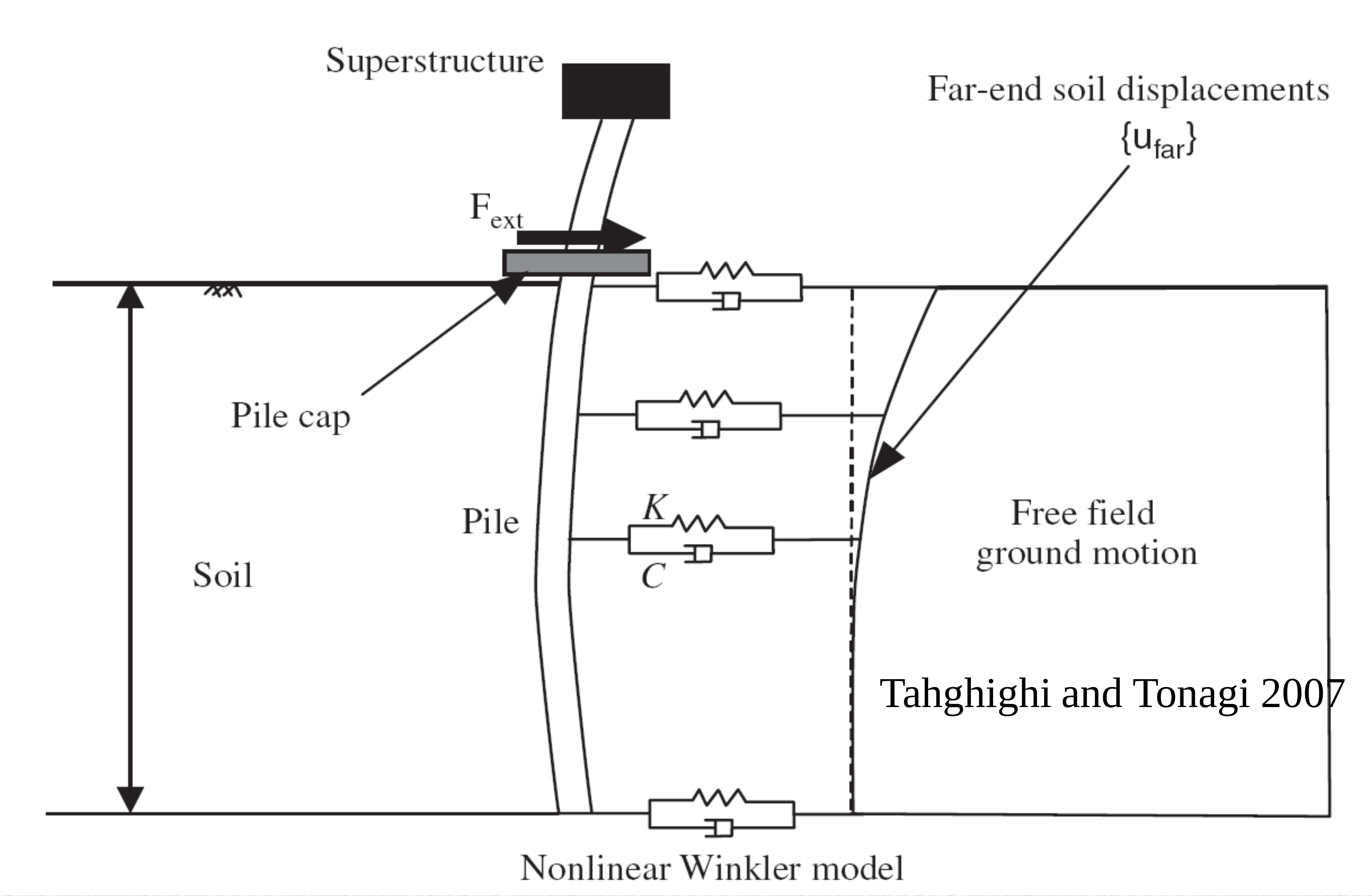
$$\{[\mathbf{K}]-\omega^2[\mathbf{M}]\}\{\mathbf{Z}\}=\{\mathbf{p}\}$$

Finite/Hybrid Model



$$G^*=G\left(1-2\beta^2+2i\beta\sqrt{1-\beta^2}\right)$$

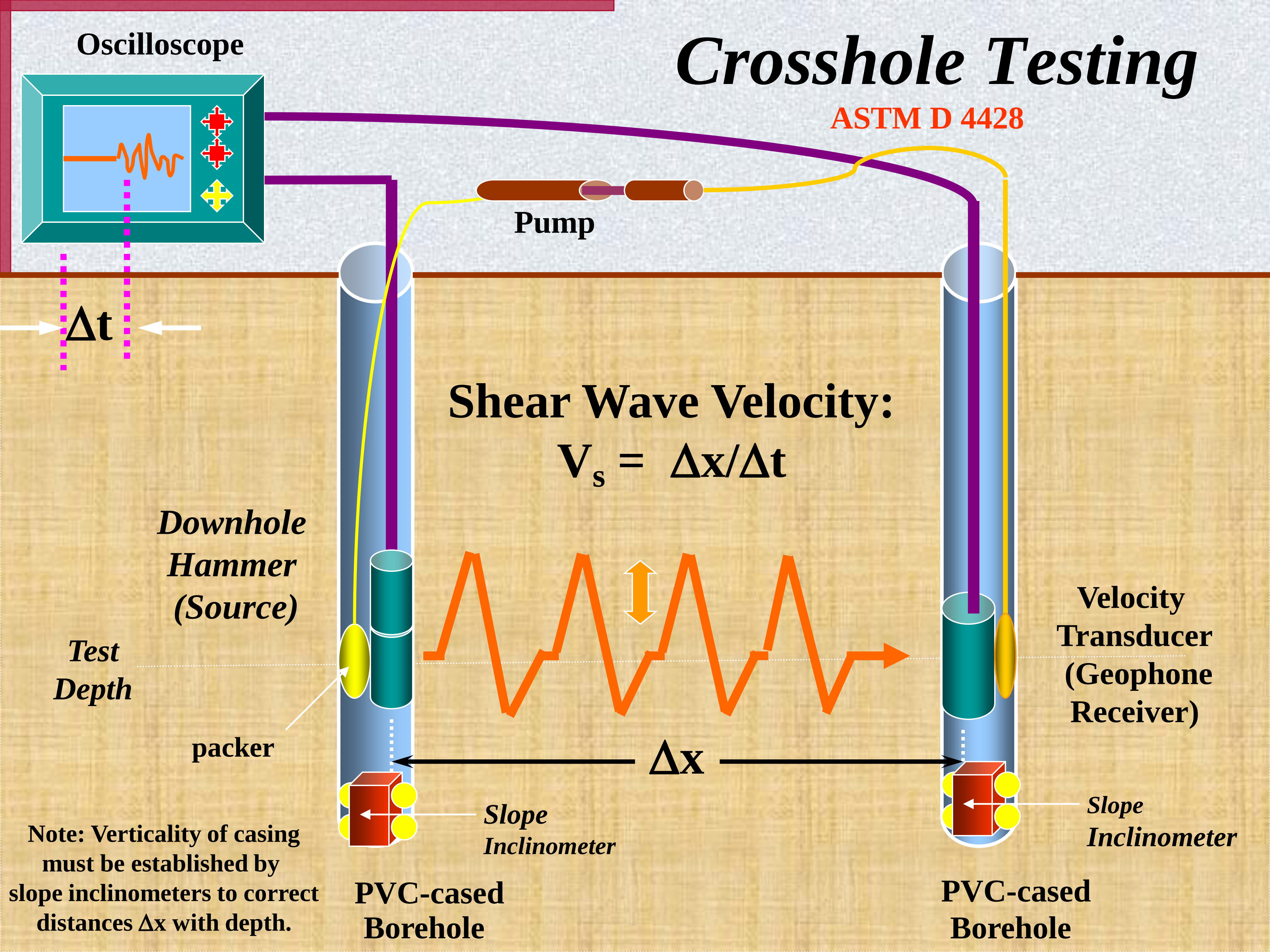
Dynamic p-y Curves



Tahghighi and Tonagi 2007

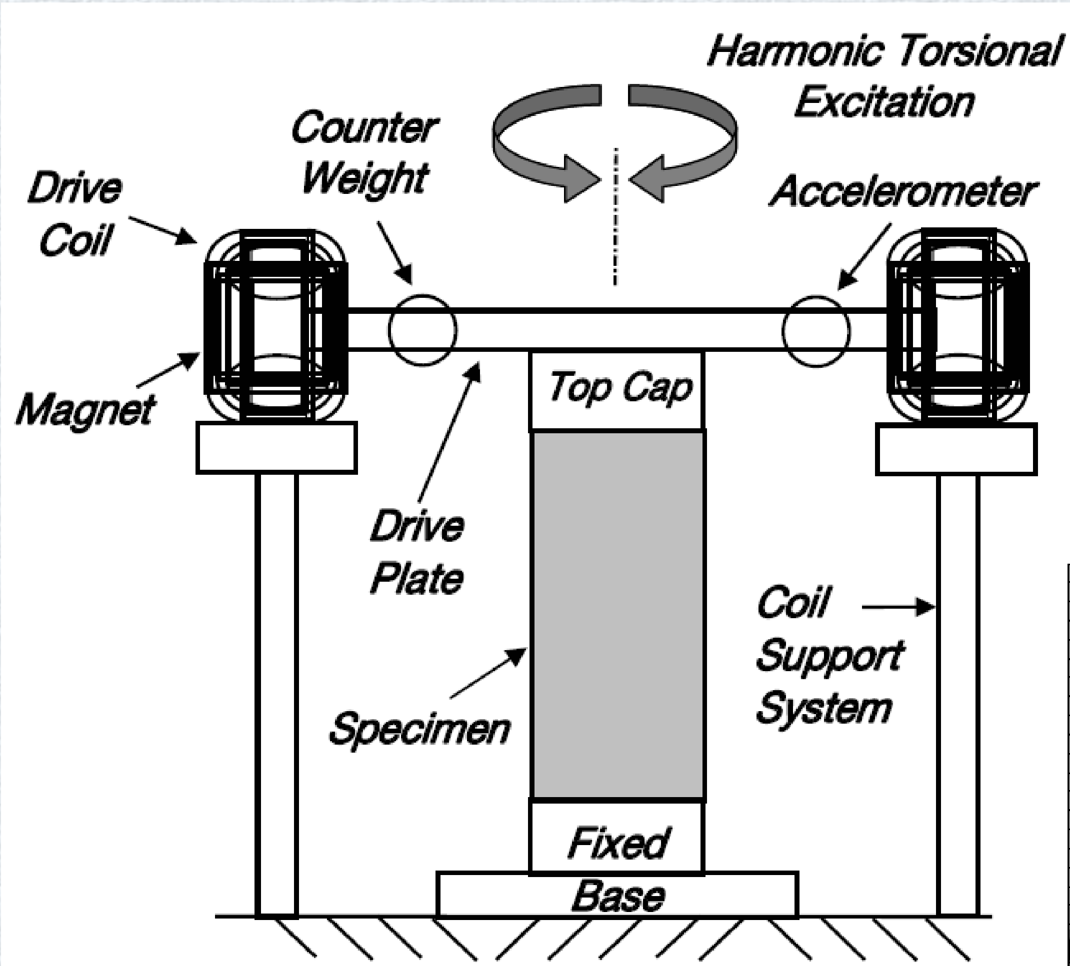
Soil Properties

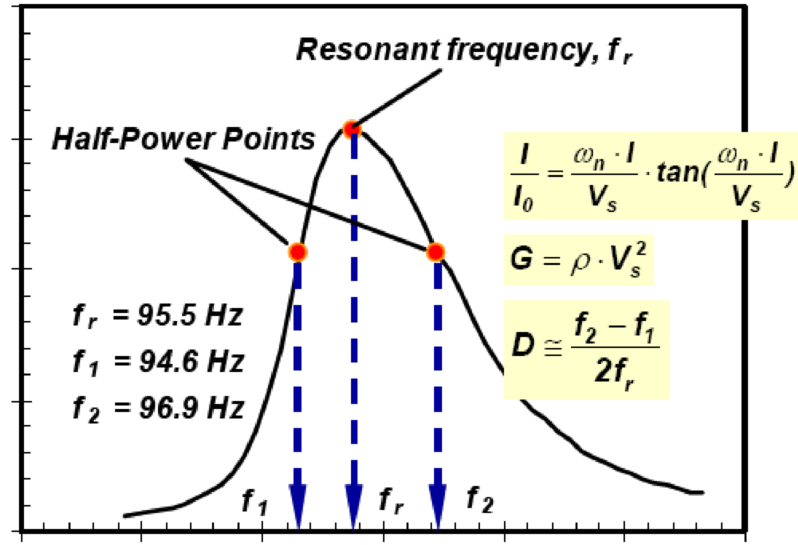
- Shear Modulus, G and Damping Ratio, D
  - Soil Type
  - Confining Stress
  - Void Ratio
  - Strain Level
- Field: Cross-Hole, Down-Hole, Surface Analysis of Seismic Waves SASW
- Laboratory: Resonant Column, Torsional Simple Shear, Bender Elements

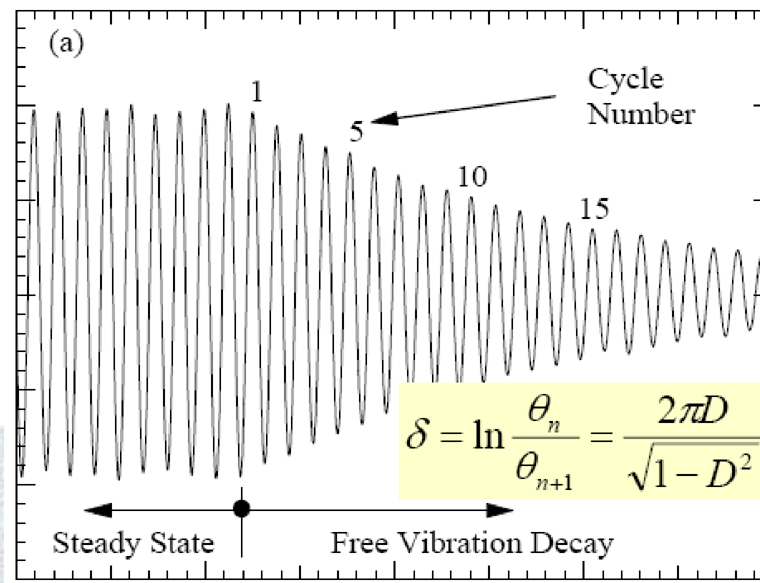


Crosshole Testing
ASTM D 4428
Oscilloscope
Pump
Δt
Shear Wave Velocity:
$V_s = \Delta x / \Delta t$
Downhole Hammer (Source)
Test Depth
packer
Velocity Transducer (Geophone Receiver)
Δx
Slope Inclinometer
Slope Inclinometer
Note: Verticality of casing must be established by slope inclinometers to correct distances Δx with depth.
PVC-cased Borehole
PVC-cased Borehole

Resonant Column Test





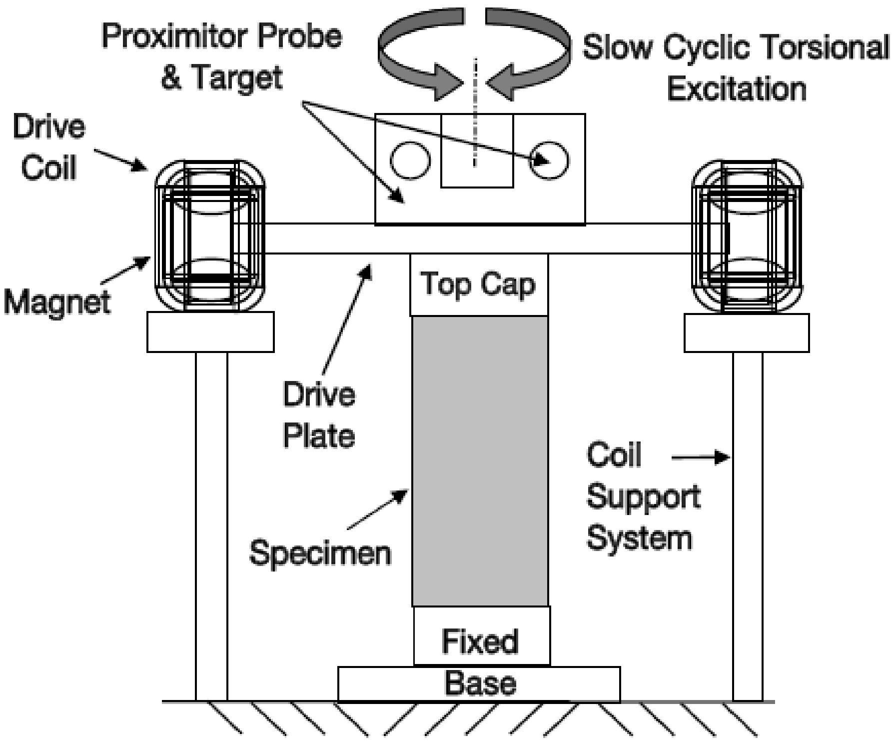


G, D for Different γ

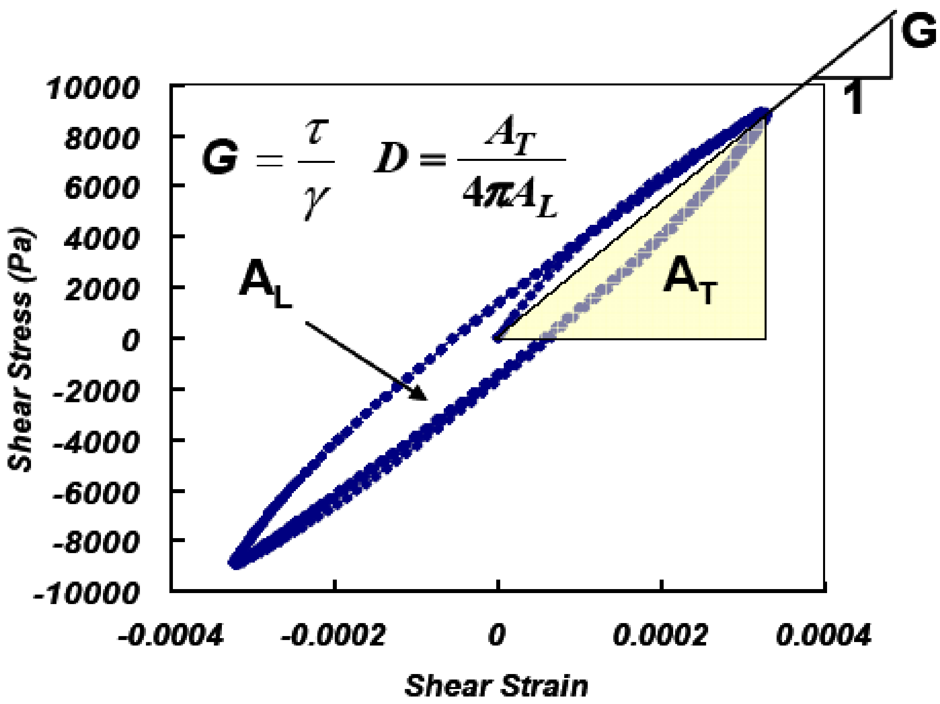
Fundamentals-Modeling-Properties-Performance

USC

Torsional Shear Test

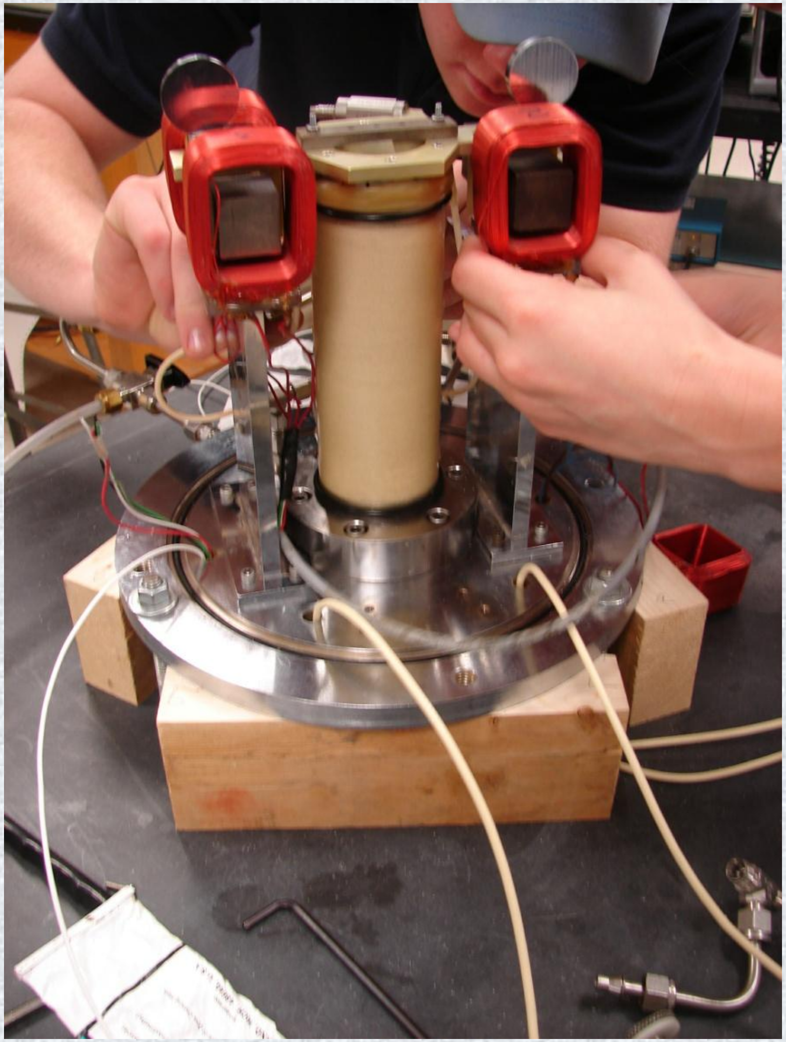


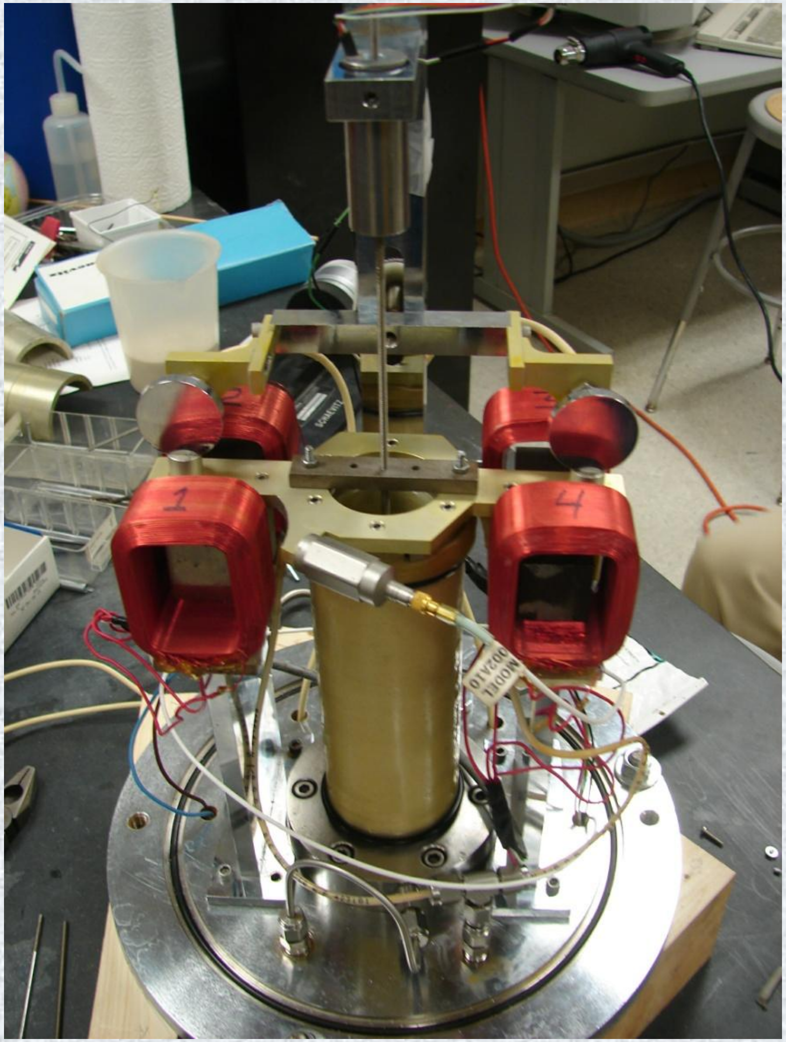
Schematic



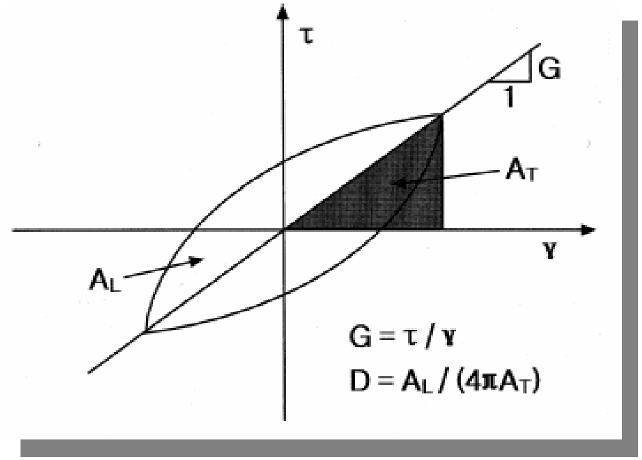
Stress-Strain

Hollow Cylinder RC-TOSS

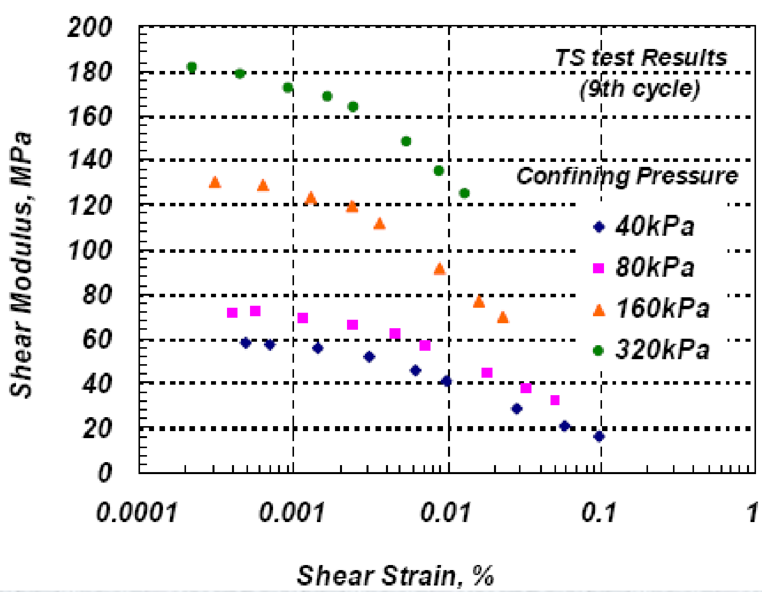


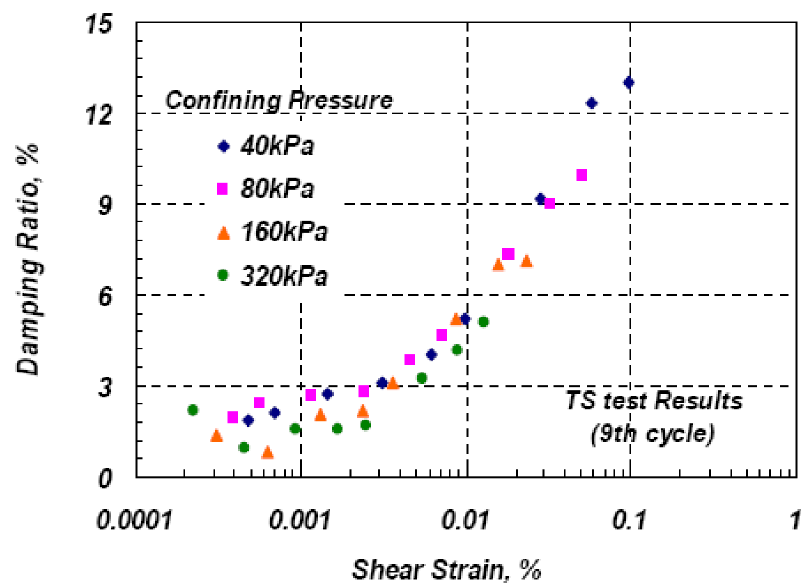


TOSS Test Results



G/G_{max} – logγ , D - logγ





Steam Turbine-Generator
(Moreschi and Farzam, 2003)

Machine Foundation Design Criteria

- Deflection criteria: maintain turbine-generator alignment during machine operating conditions
- Dynamic criteria: ensure that no resonance condition is encountered during machine operating conditions

Jump to Resonance

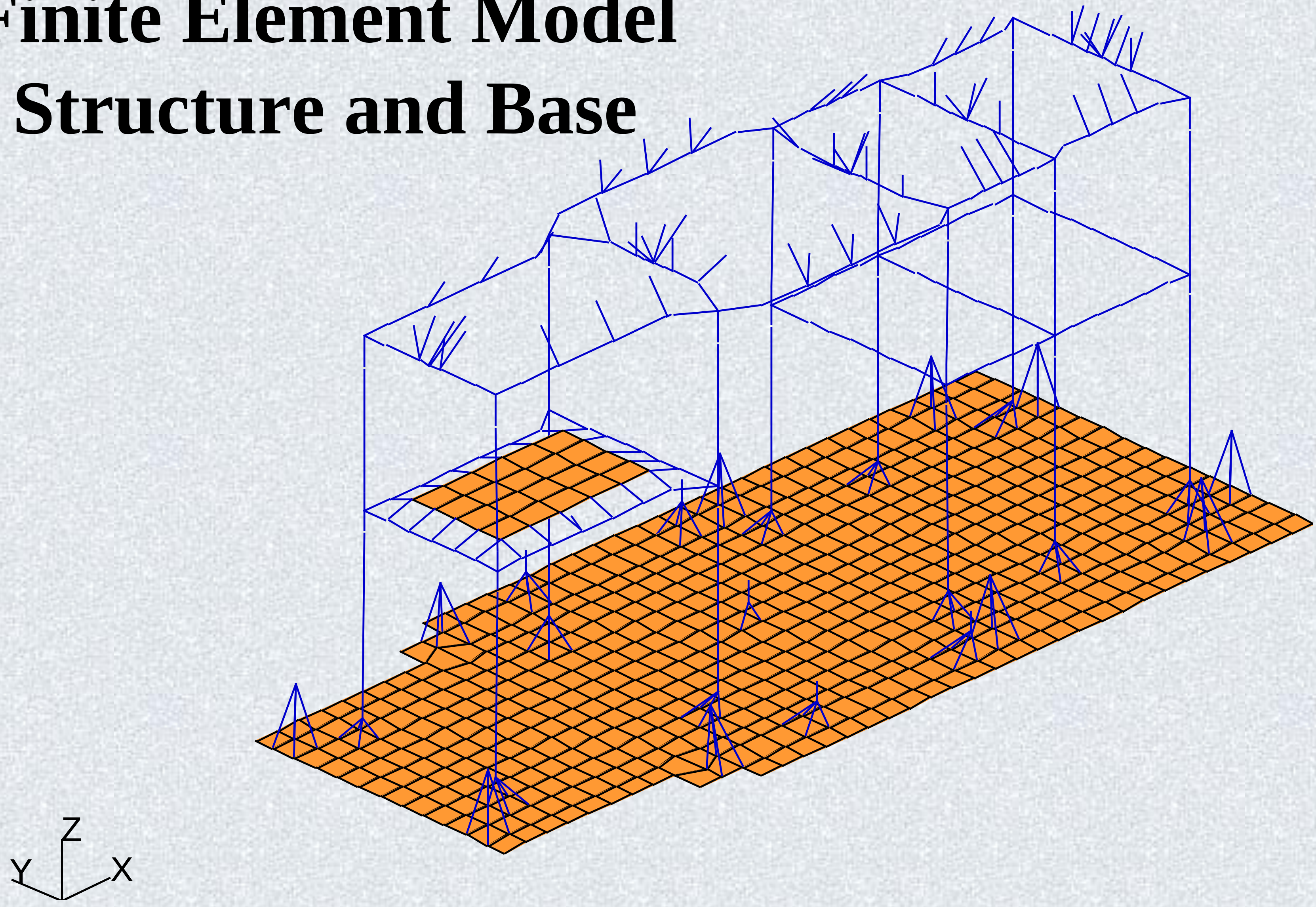
- Strength criteria: reinforced concrete design

STG Pedestal Structure

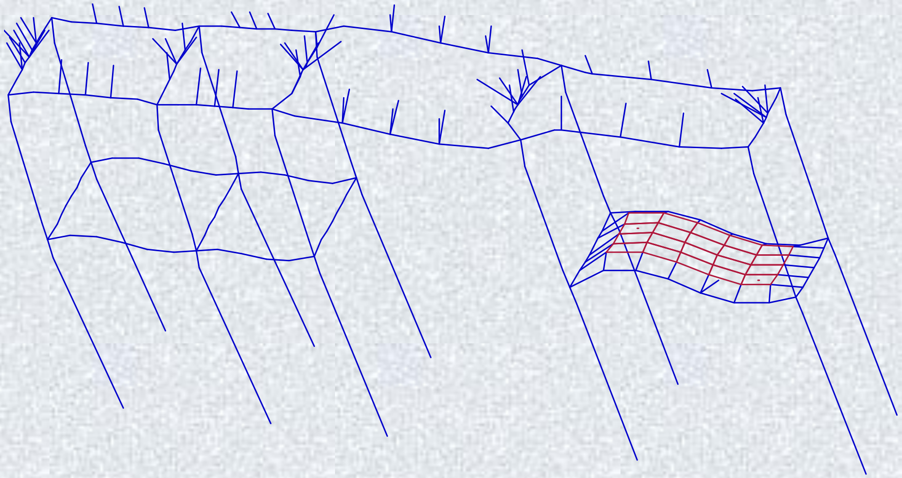
Vibration Properties Evaluation

- Identification of the foundation natural frequencies for the dominant modes
- Frequency exclusion zones for the natural frequencies of the foundation system and individual structural members (±20%)
- Eigenvalue analysis: natural frequencies, mode shapes, and mass participation factors

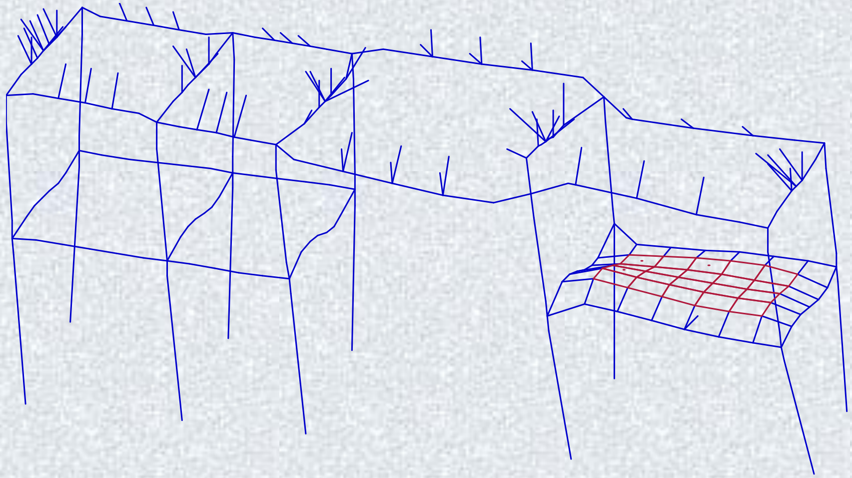
Finite Element Model
Structure and Base



Low Frequency Modes

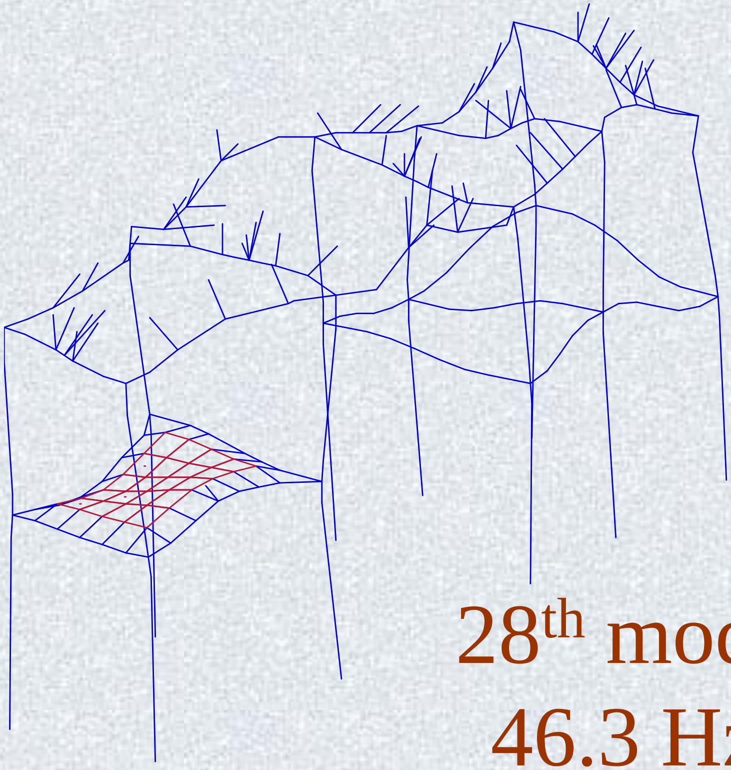


1st mode
6.5 Hz
95 % m.p.f.



2nd mode
7.2 Hz
76 % m.p.f

High Frequency Modes



28th mode
46.3 Hz
0.3% m.p.f

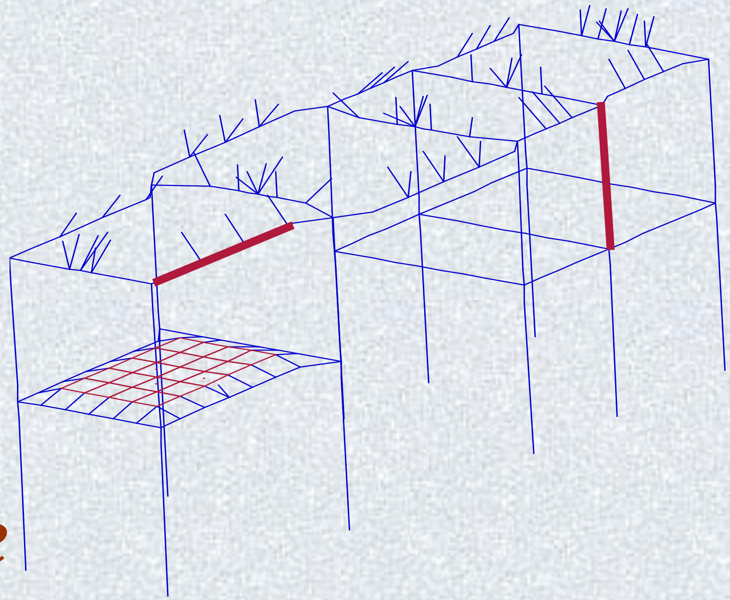
42nd mode
64.6 Hz
0.03% m.p.f

Excitation frequency: 50-60 Hz

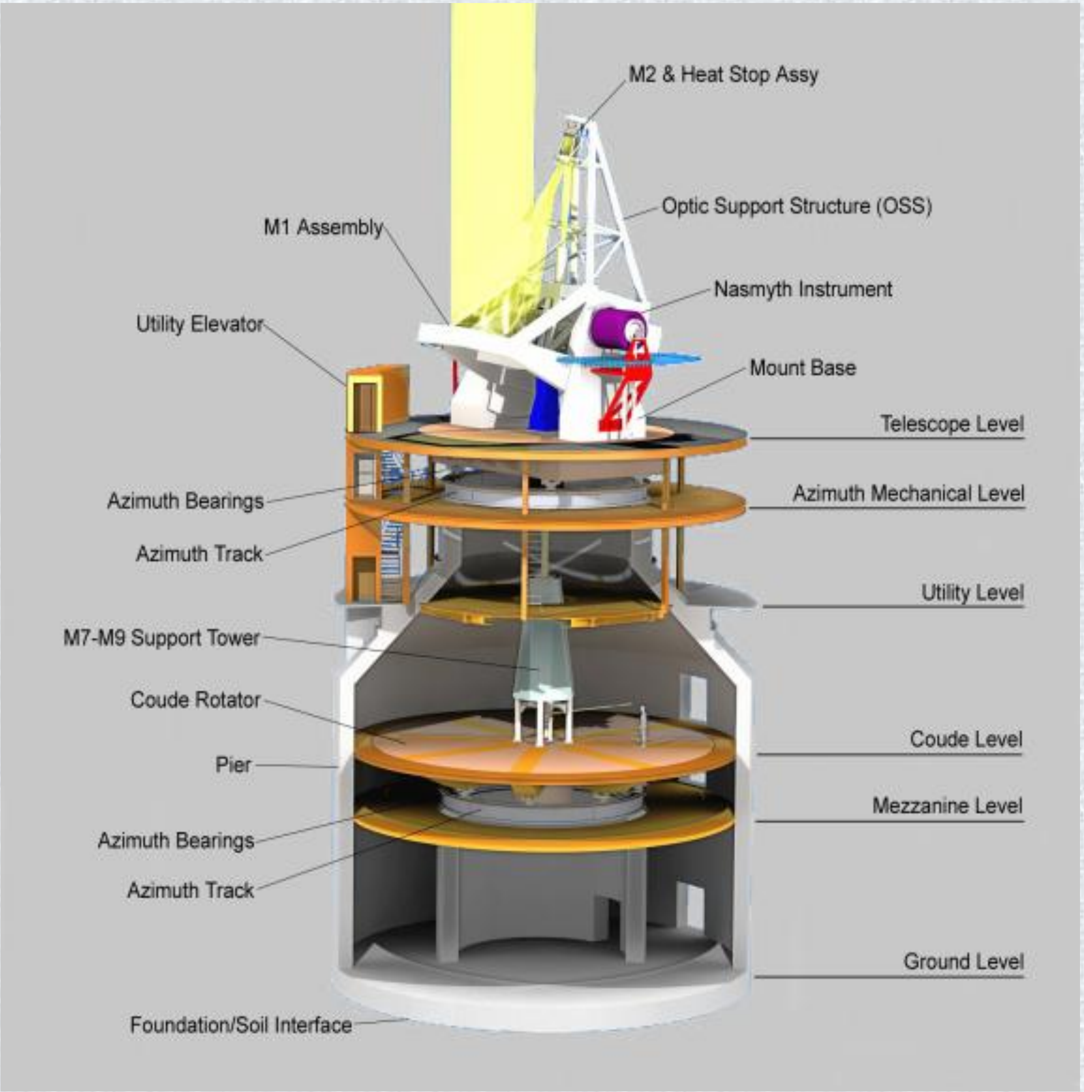
Local Vibration Modes

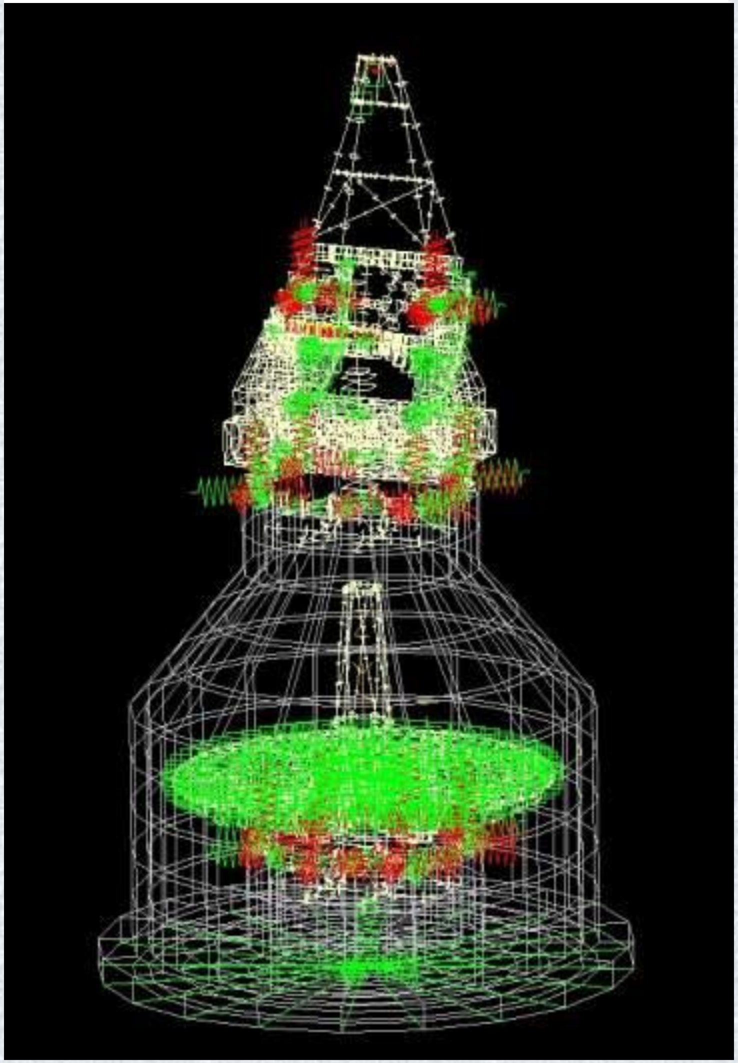
- Identification of natural frequencies for individual structural members

- ***Quantification of changes on vibration properties due to foundation modifications***



ATST Telescope and FE Model





Assumptions in FE analyses

- Optics Lab mass/Instrument weight = 228 tons
- Wind mean force = 75 N, RMS = 89 N
- Ground base excitation PSD = 0.004 g^2/hz
- Concrete Pier
  - High Strength Concrete ($E=3.1\times10^{10}$ N/m^2, $\nu=0.15$)
- Soil Stiffness, k
  - Four different values using Arya & O'Neil's formula based on the site test data (Shear modulus:30~75ksi, Poisson's ratio:0.35~0.45)

Frequency vs Soil Stiffness

Stiffness units = SI, frequency mode (hz)

MODE \ Stiffness		min	min+33.3%	min+66.6%	max
	Kx	1.19E+10	1.83E+10	2.48E+10	3.12E+10
	Ky	1.19E+10	1.83E+10	2.48E+10	3.12E+10
	Kz	1.48E+10	2.45E+10	3.41E+10	4.38E+10
	Krx	1.34E+12	2.21E+12	3.09E+12	3.96E+12
	Kry	1.34E+12	2.21E+12	3.09E+12	3.96E+12
	Krz	1.74E+12	2.61E+12	3.49E+12	4.36E+12
1		**6.3**	**7.0**	**7.4**	**7.5**
2		**6.4**	**7.1**	**7.5**	**7.7**
3		**9.4**	**9.7**	**9.9**	**10**
4		**9.4**	**10.3**	**11.1**	**11.8**
5		**10.4**	**11.9**	**12.6**	**13.3**
6		**11.2**	**13.0**	**13.6**	**13.7**

- Soil property range: Shear modulus (30~75ksi), Poisson’s ratio (0.35~0.45)
- Pier Footing: Diameter (23.3m)
- “min” for shear modulus of 30 ksi; “max” for 75 ksi

Summary and Conclusions (Cho, 2005)

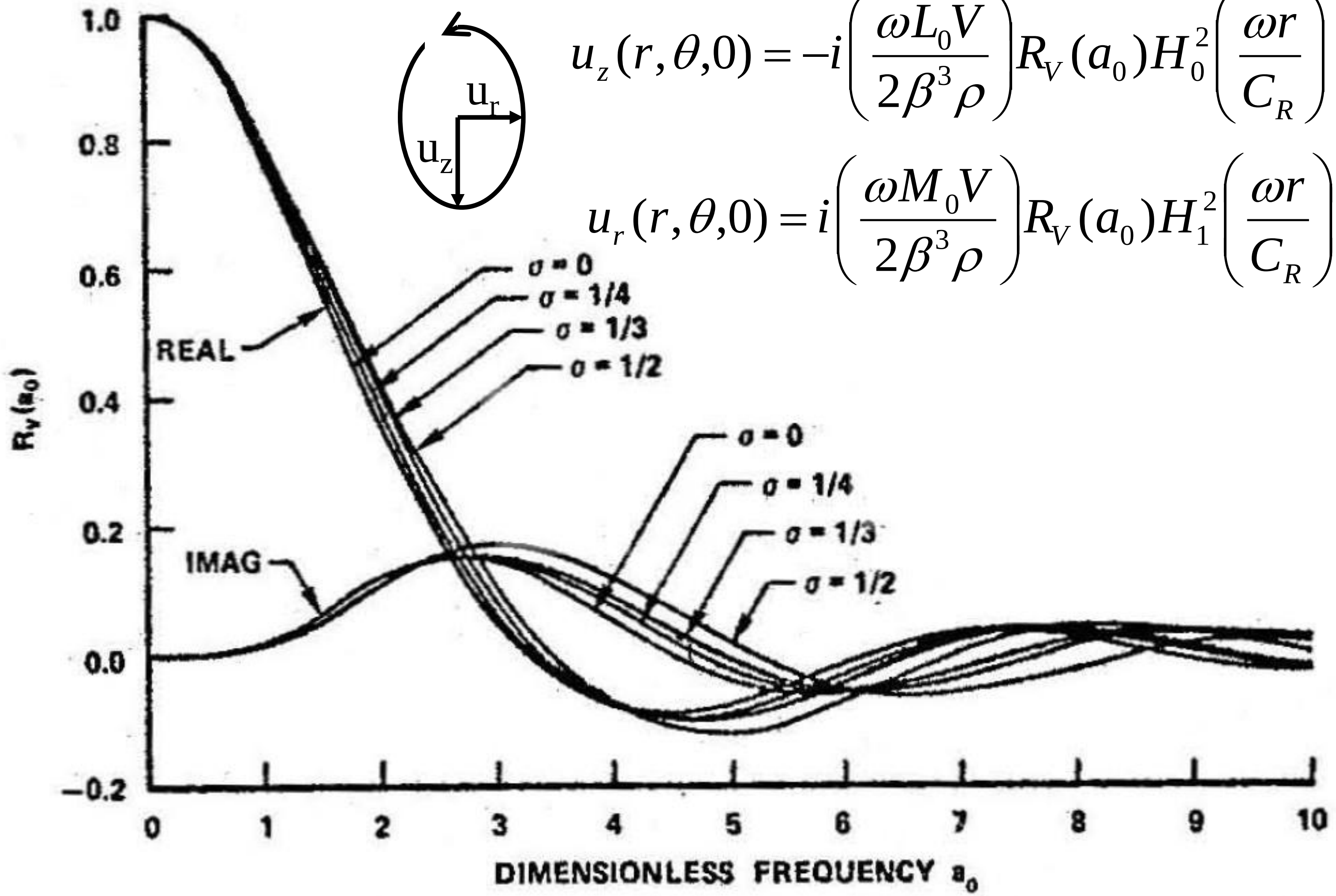
1. High fidelity FE models were created
2. Relative mirror motions from zenith to horizon pointing: about 400 μm in translation and 60 μrad in rotation.
3. Natural frequency changes by 2 hz as height changes by 10m.
4. Wind buffeting effects caused by dynamic portion (fluctuation) of wind
5. Modal responses sensitive to stiffness of bearings and drive disks
6. ***Soil characteristics were the dominant influences in modal behavior of the telescopes.***
7. Fundamental Frequency (for a lowest soil stiffness):

   OSS=20.5hz; OSS+base=9.9hz; SS+base+Coude+soil=6.3hz
8. A seismic analysis was made with a sample PSD
9. ATST structure assembly is adequately designed:
   1. Capable of supporting the OSS
   2. Dynamically stiff enough to hold the optics stable
   3. Not significantly vulnerable to wind loadings

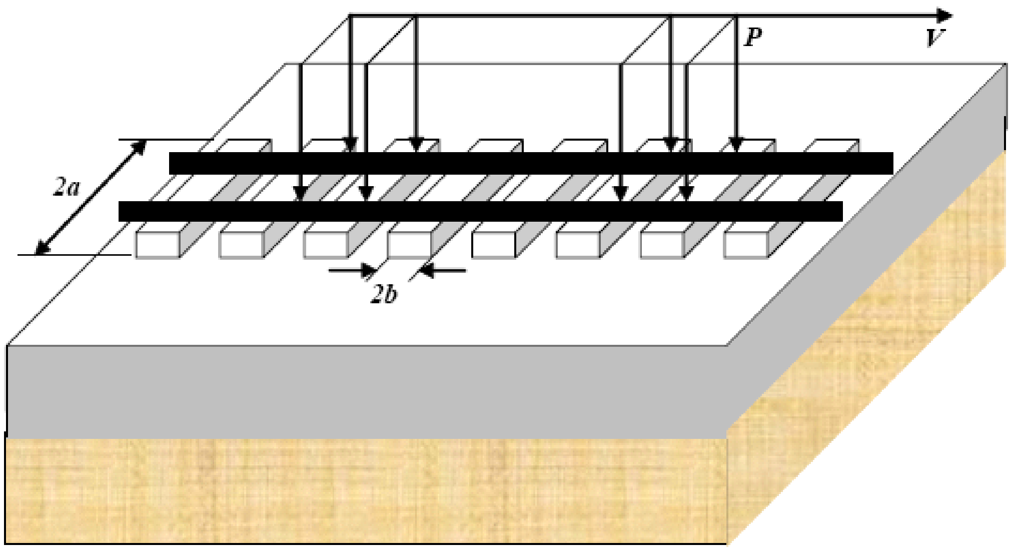
Free-Field Analytical Solutions

$$u_z(r,\theta,0) = -i\left(\frac{\omega L_0 V}{2\beta^3\rho}\right) R_V(a_0) H_0^2\left(\frac{\omega r}{C_R}\right)$$

$$u_r(r,\theta,0) = i\left(\frac{\omega M_0 V}{2\beta^3\rho}\right) R_V(a_0) H_1^2\left(\frac{\omega r}{C_R}\right)$$

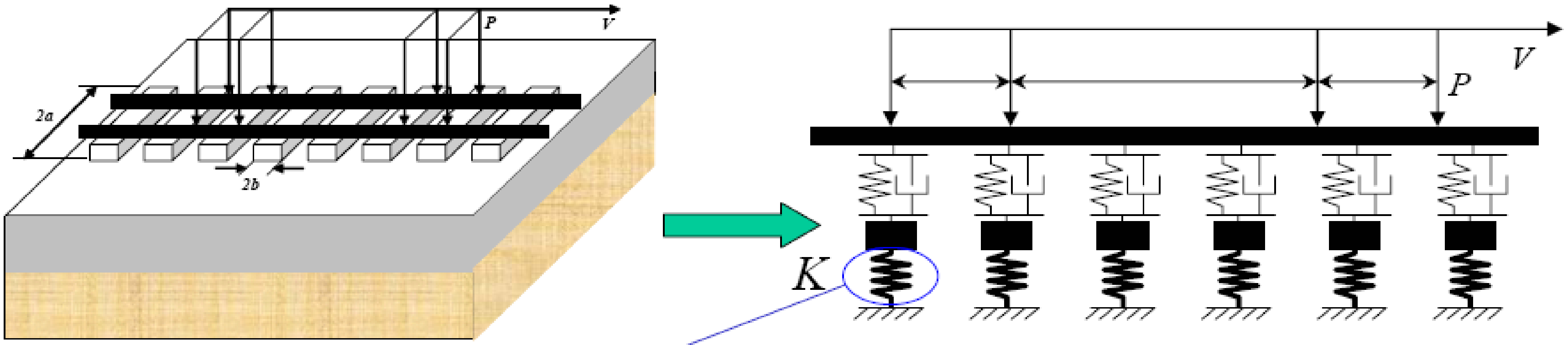


Project 1 (completed). **Three-dimensional modelling of the steady-state dynamic response of a railway track to a high-speed train.**



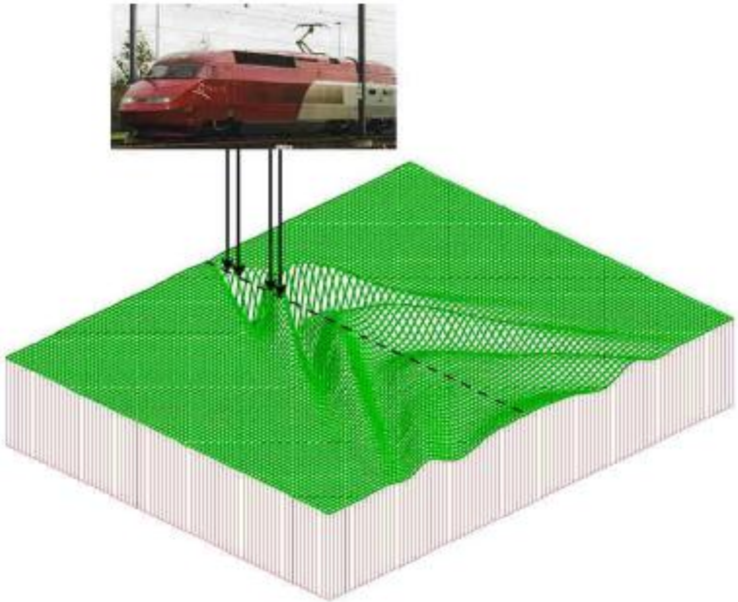
Components of the model:

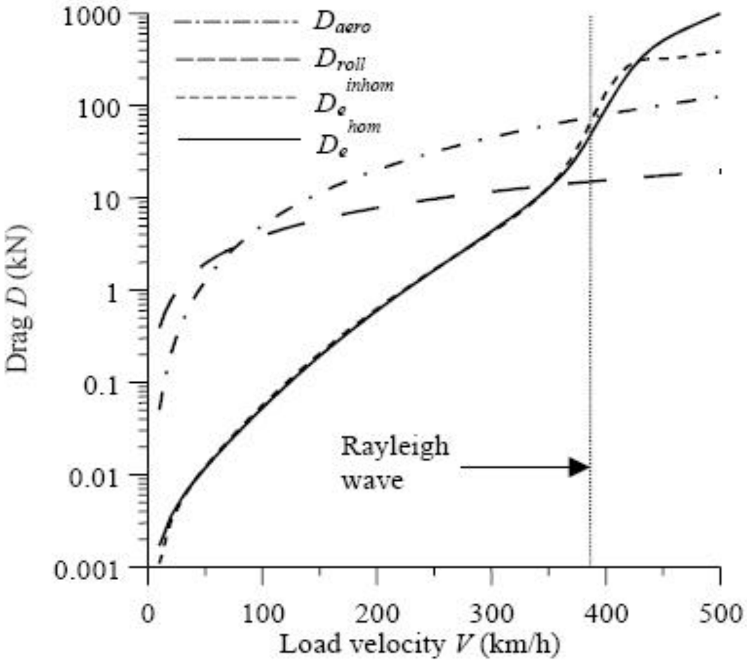
- Multilayered, visco-elastic half-space
- Periodically spaced rigid sleepers
- Two beams (rails)
- Moving loads (train)



The dynamic stiffness of the ground is a function of the frequency and the wavelength of waves in the rails

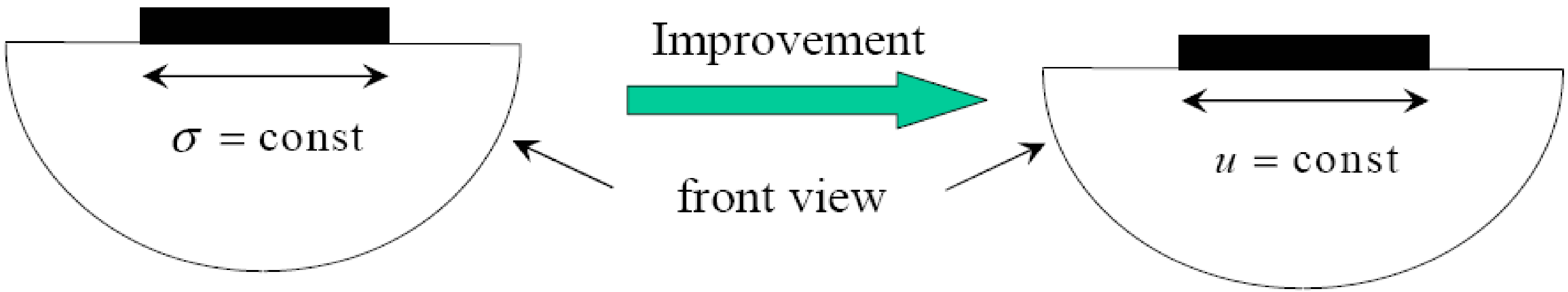
$$K^{-1} = \frac{1}{4\pi^2\tilde{\mu}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} a_{ij}(\omega, k_1, k_2)\frac{\sin k_1 b}{k_1 b}\frac{\sin k_2 a}{k_2 a}\sum_{l=-\infty}^{\infty}\exp\left(i\left(k_1 d - q\right)l\right)dk_1 dk_2$$



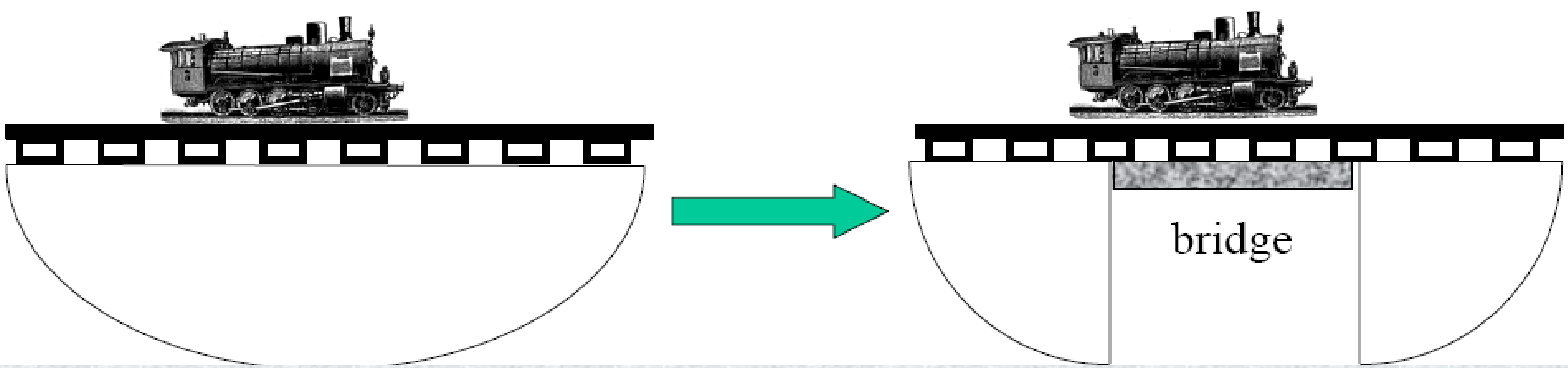


Waves radiated into the ground consume train's energy! → 'Elastic drag' (resistance to train's motion)

- Poor description of the ground-sleeper contact (easy to improve)

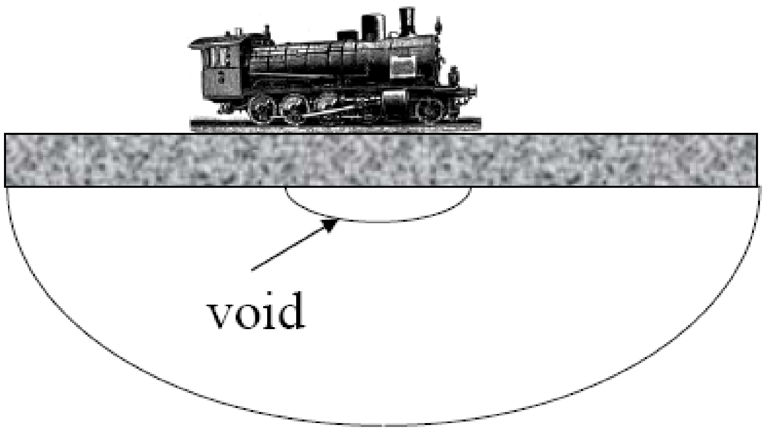


- Assumption that both the railway track and the soil are regular (either homogeneous or periodically inhomogeneous) along the track

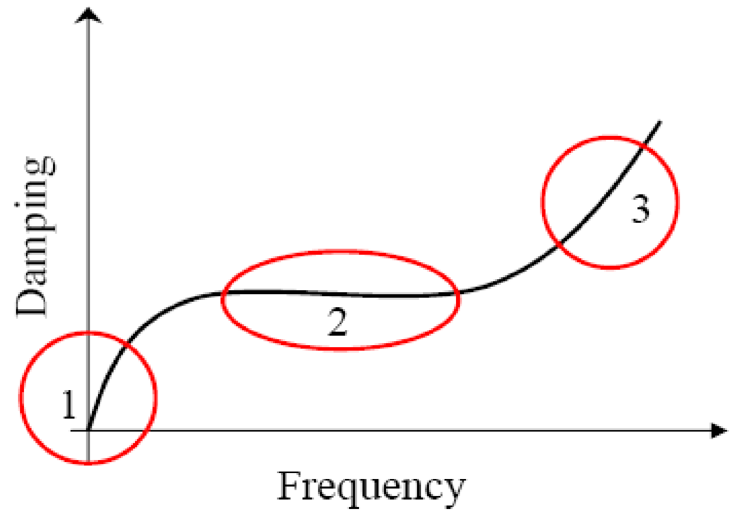


Linear description of the soil dynamics

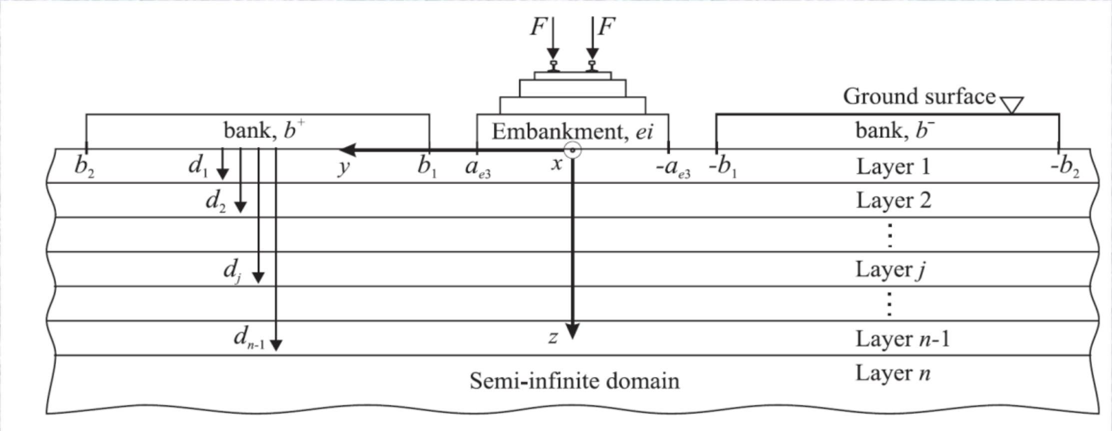
No possibility to describe dynamically-induced settlements

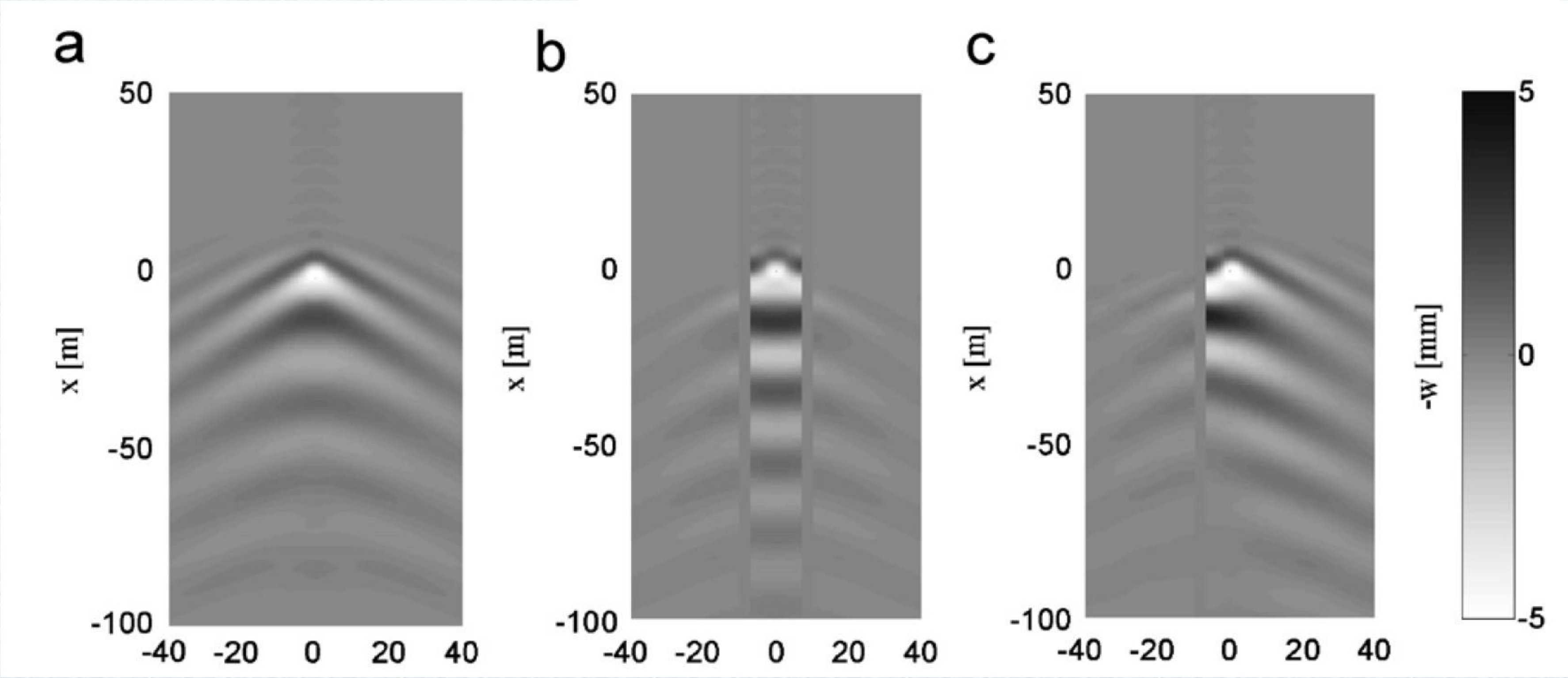


Problems with description of material damping in the ground

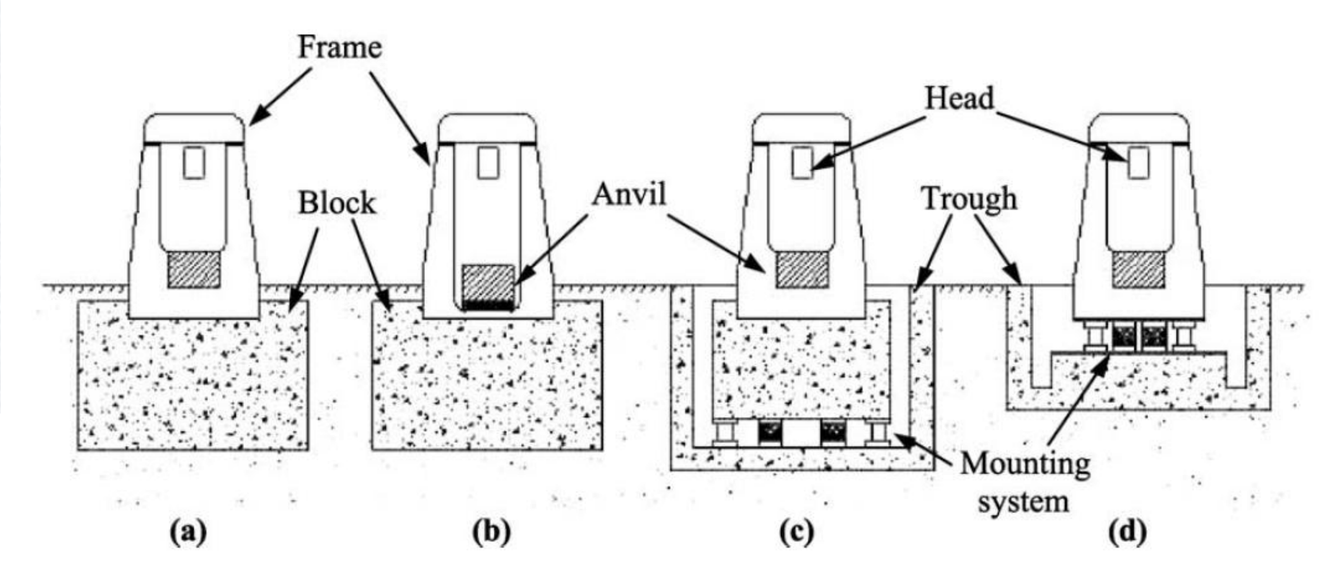


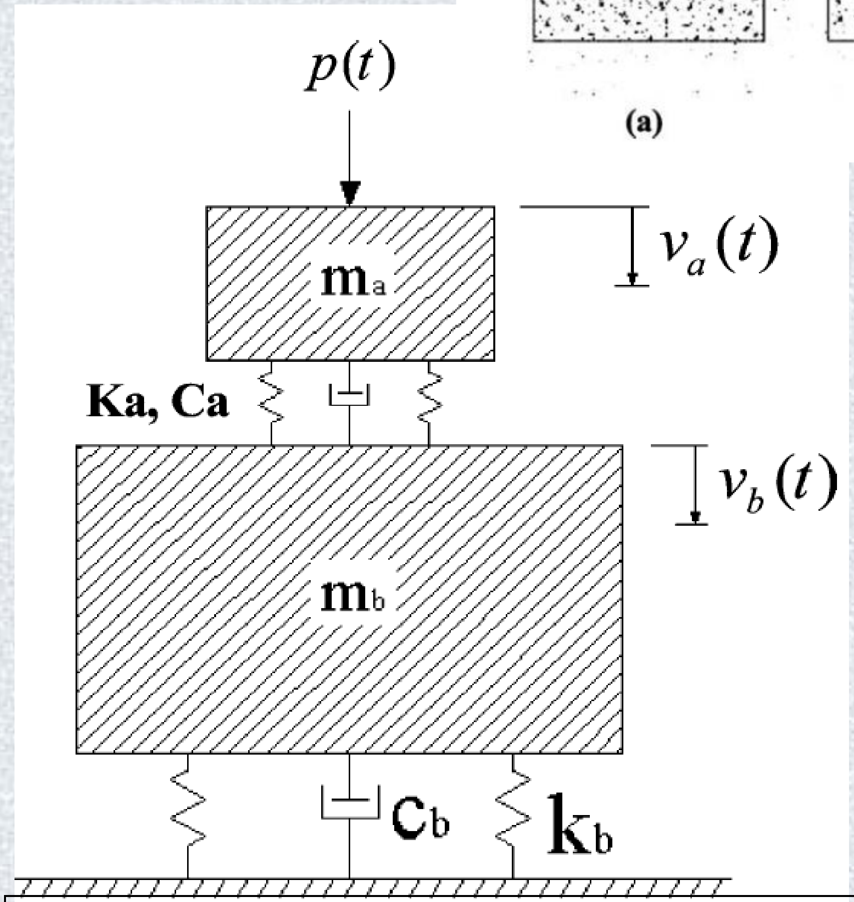
Trench Isolation



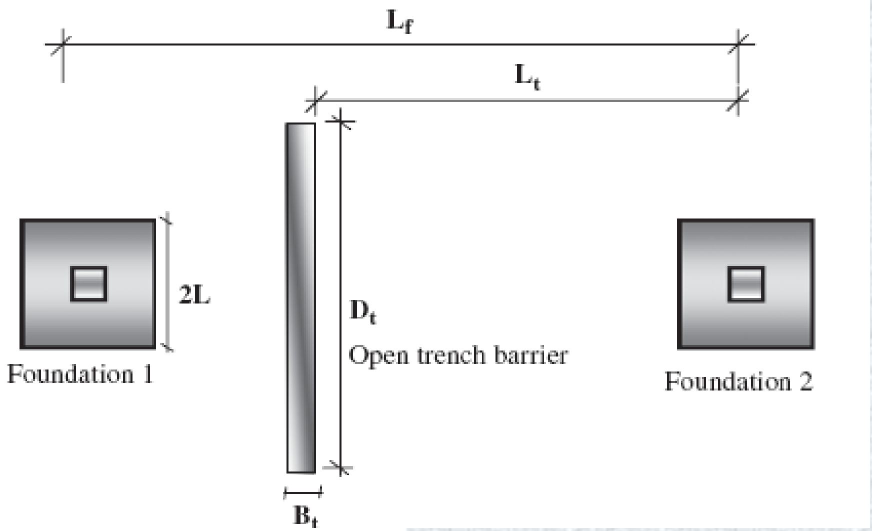


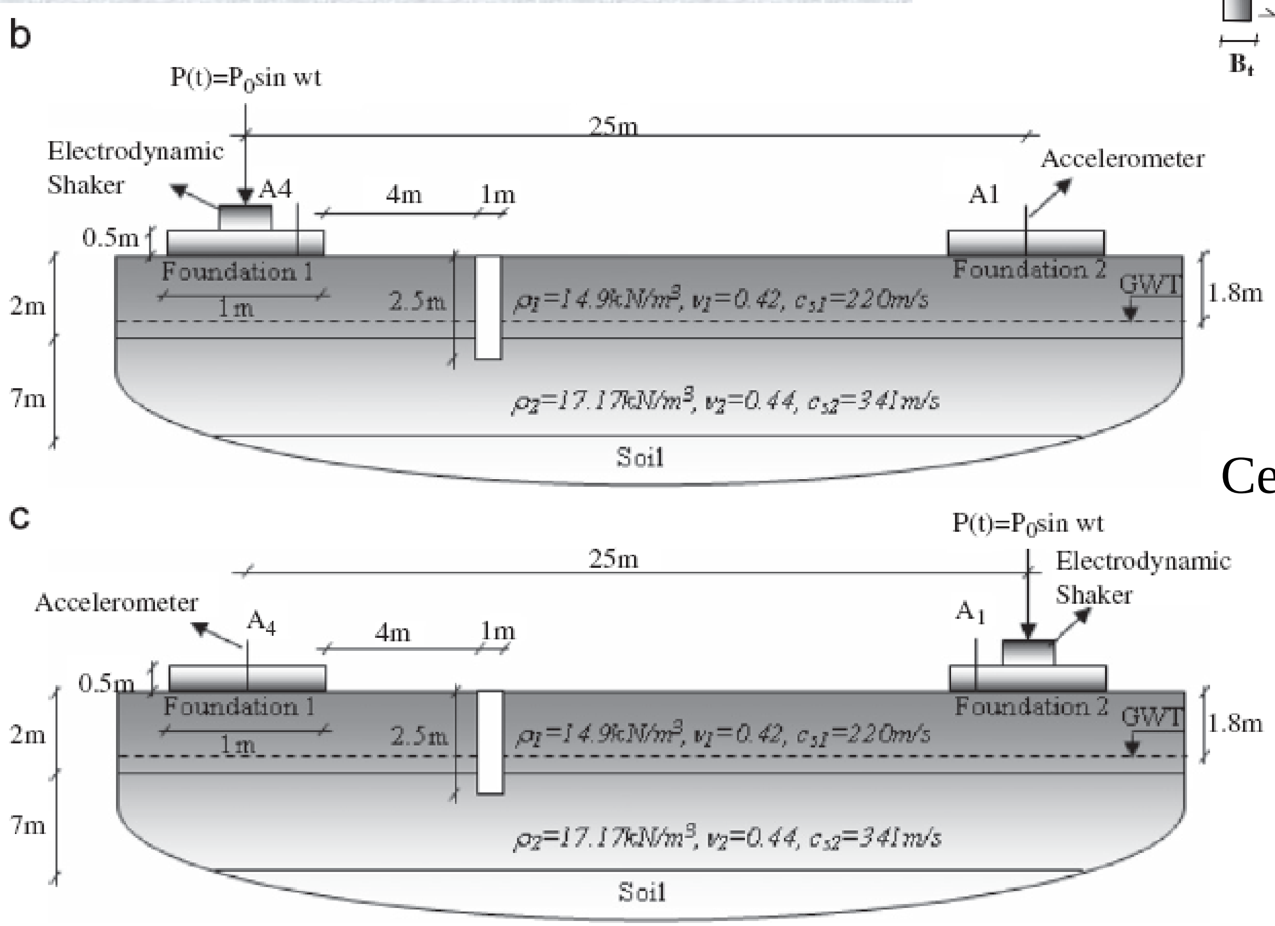
Karlstrom and Bostrom 2007





Chehab and Nagger 2003

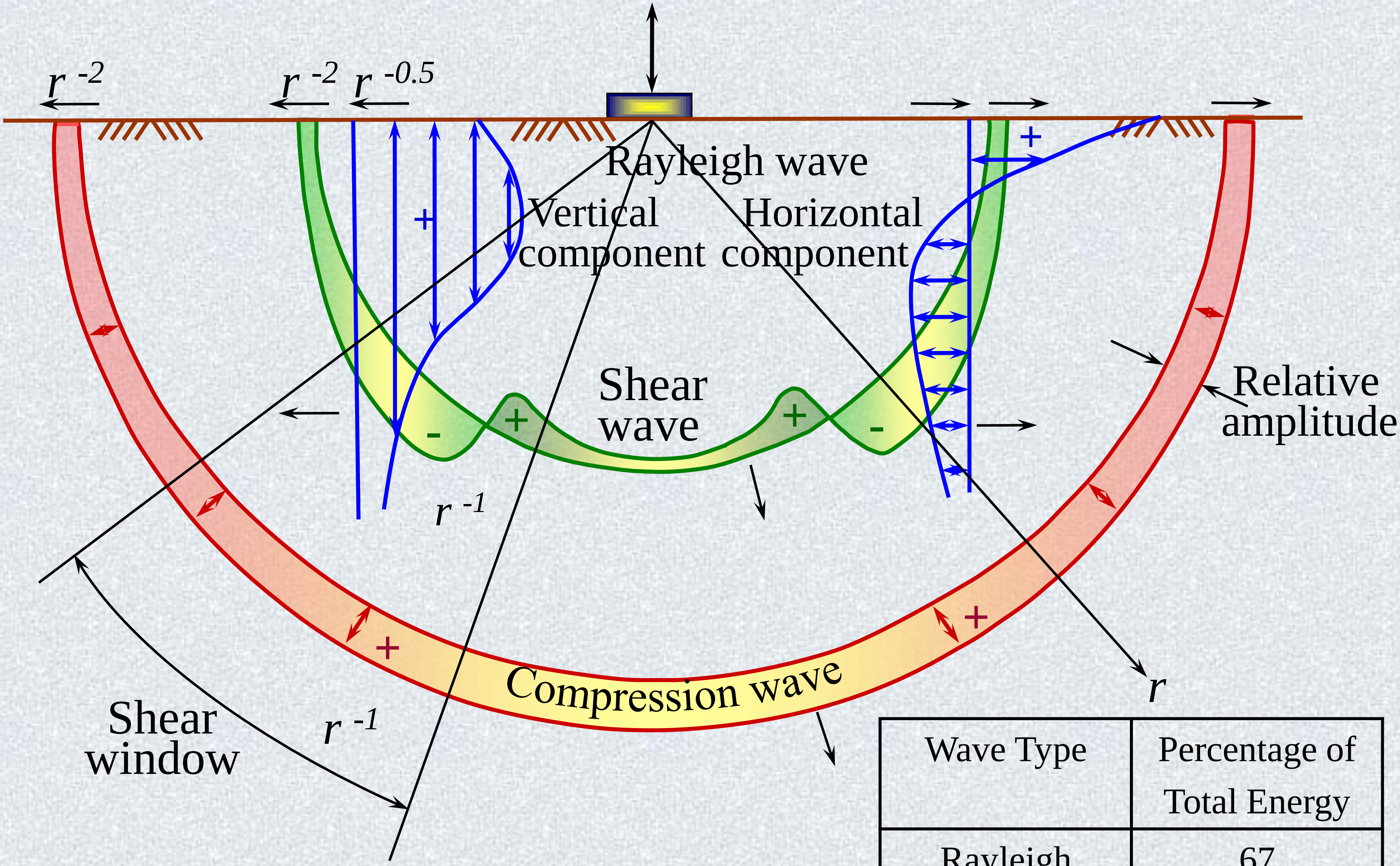




Celibi et al (in press)

Fig. 1. Field-test model for active and passive isolation cases, (a) plan view, (b) active isolation and (c) passive isolation.

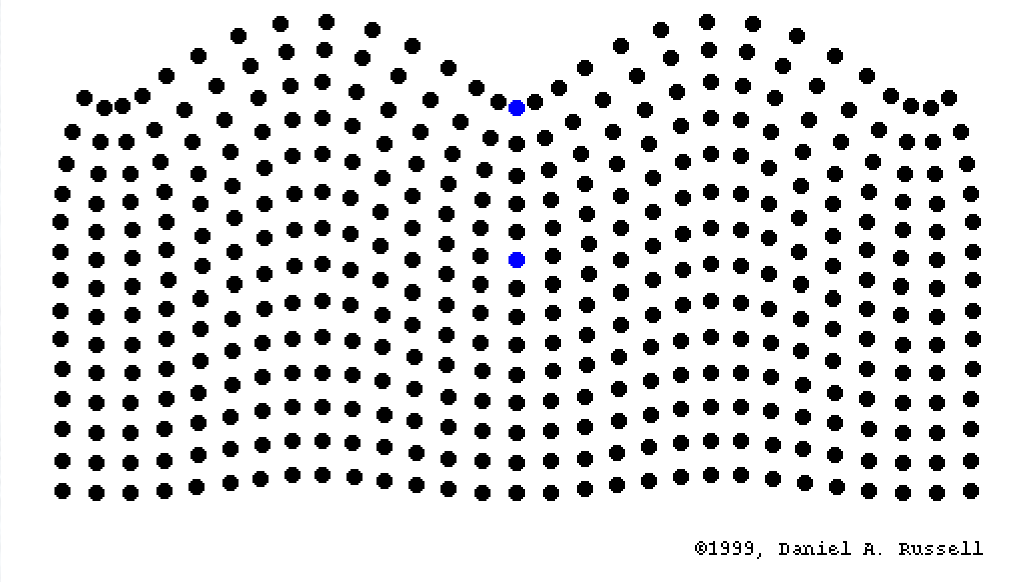
USC



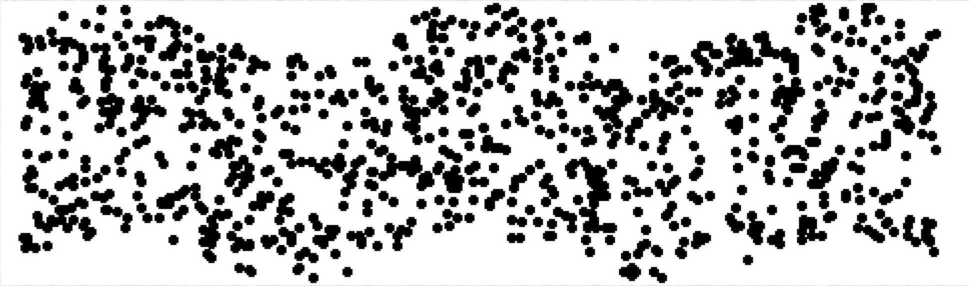
Wave Type	Percentage of Total Energy
Rayleigh	67
Shear	26
Compression	7

Waves

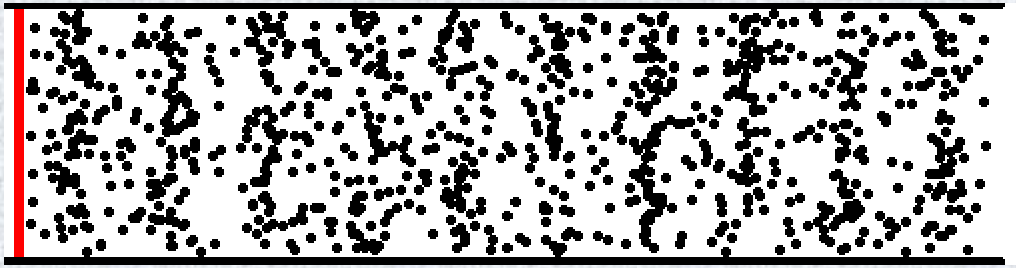
Rayleigh, R
Surface



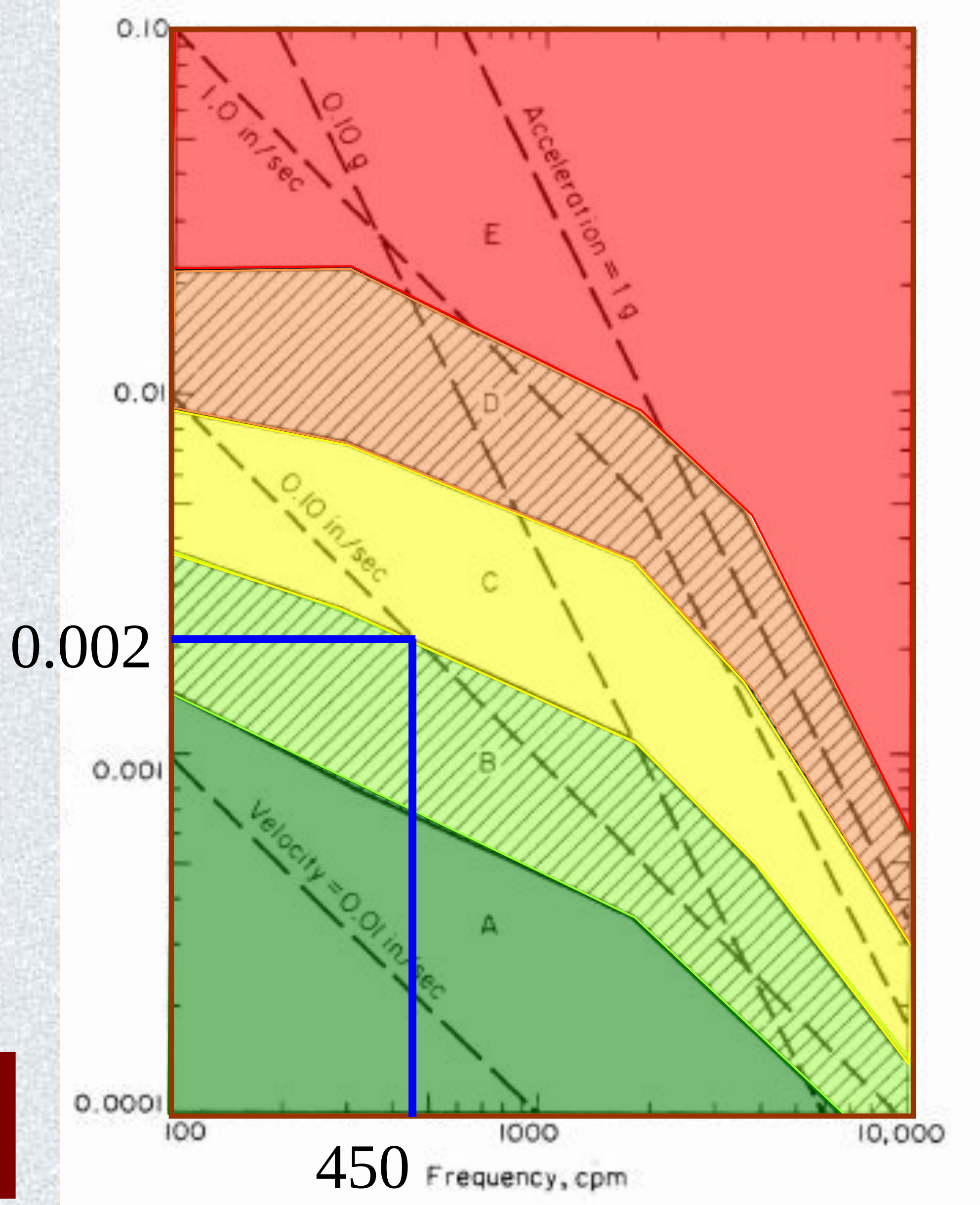
Shear,S
Secondary



Compression, P
Primary



Machine Performance Chart



Performance Zones

A=No Faults, New

B=Minor Faults, Good Condition

C = Faulty, Correct In 10 Days To Save $$

D = Failure Is Near, Correct In 2 Days

E = Stop Now

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