Foundations for Dynamic and Sensitive Equipment

University of Minnesota - Structures Seminar
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Structures | Vibration | Noise | Monitoring
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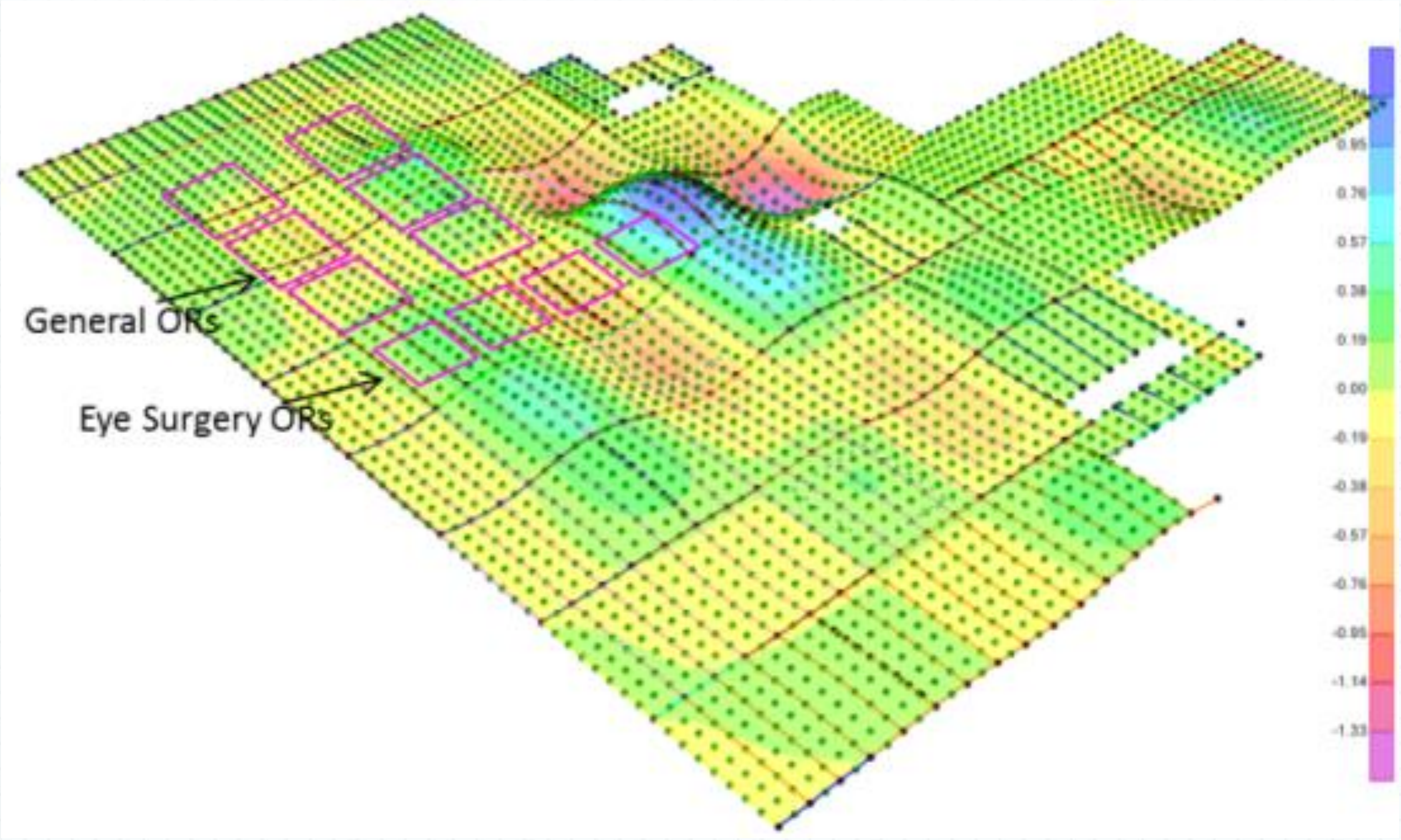
ESI's History

Our roots go back to a group of professors and graduate students at the U of M in the 1960's

Who We Are Today!

- Minnesota based consulting engineering firm since 1970
- Provide specialized engineering services
- Specialists in high force/shock, vibration and noise control

From small medical devices and consumer products to sensitive buildings and large industrial facilities, ESI helps clients with advanced analysis and design. Our professional engineering services are focused in the areas of structural dynamics and design, vibration control, noise and acoustics, and monitoring.



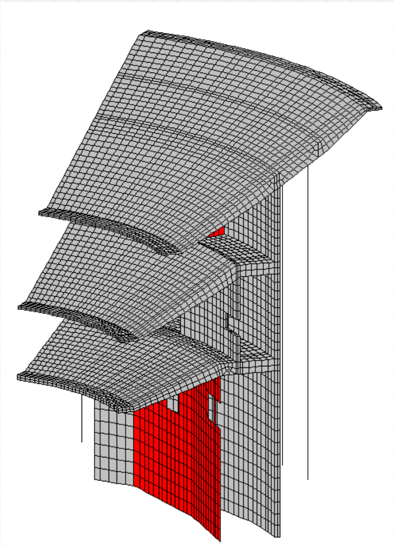
FEA and Structural Analysis

High Force Structures and Foundations

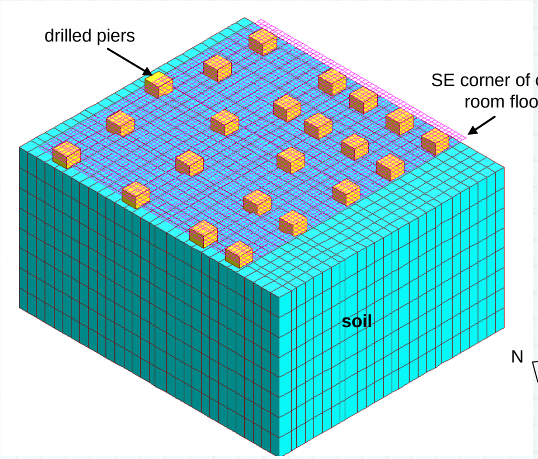
Vibration Measurements and Monitoring

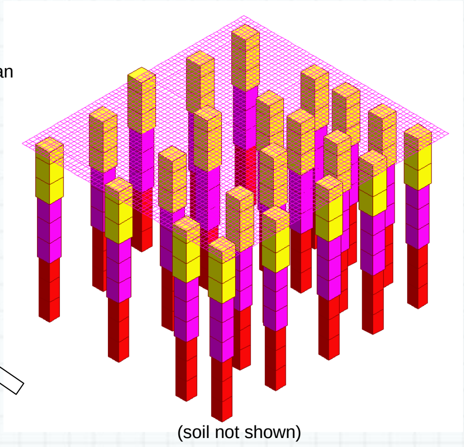
Vibration Analysis for Healthcare, Manufacturing and Research

Recent Projects at U of M

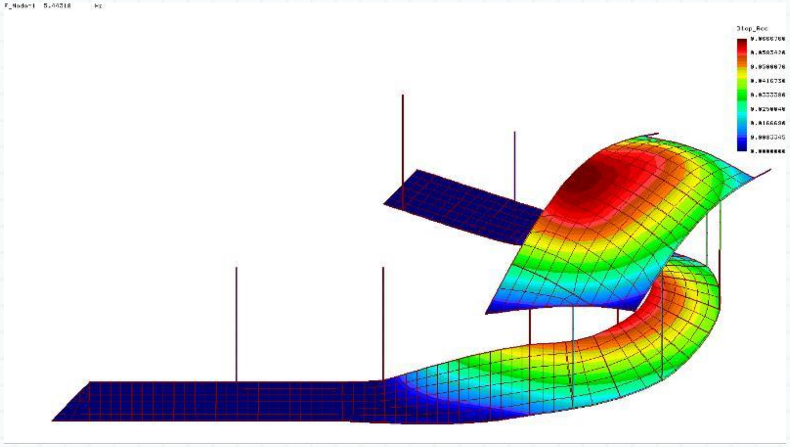


Northrop Balconies





Physics and Nanotechnology Cleanroom



Rec Center Expansion

Cancer and Cardio Research Building

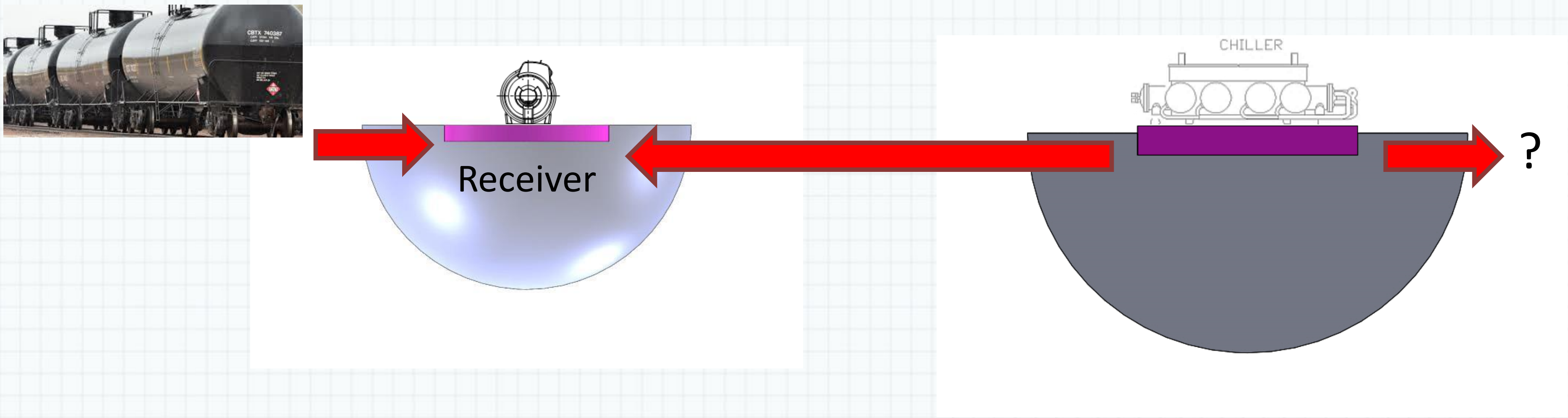
What we will talk about today

1. Types of Foundations for Equipment
   - Foundations for Sources
   - Foundations for Receivers
2. Vibration Control Methods for Foundations
   - In ground – Viper Example (Source), Physics & Nanotechnology Cleanroom Floor Example (Receiver)
   - Isolated – Toyota Example
3. Technical Discussion of Dynamic Foundation in Soil
   - Model, Equations
   - Example Calculations and Recommendations
4. References – ACI Committee 351, Books
5. Closing & Questions

Types of Foundations For Equipment

1. Not Dynamic (Inertial Forces are Not Significant)
2. Foundations for Dynamic Sources
   a) Isolated
   b) On ground
3. Foundations for Sensitive Receivers
   a) Isolated
   b) On ground

Sources



Foundation Types
- not dynamic -

React forces, provide a stable base and maintain alignment

Not Dynamic (Inertial Forces are Not Significant)

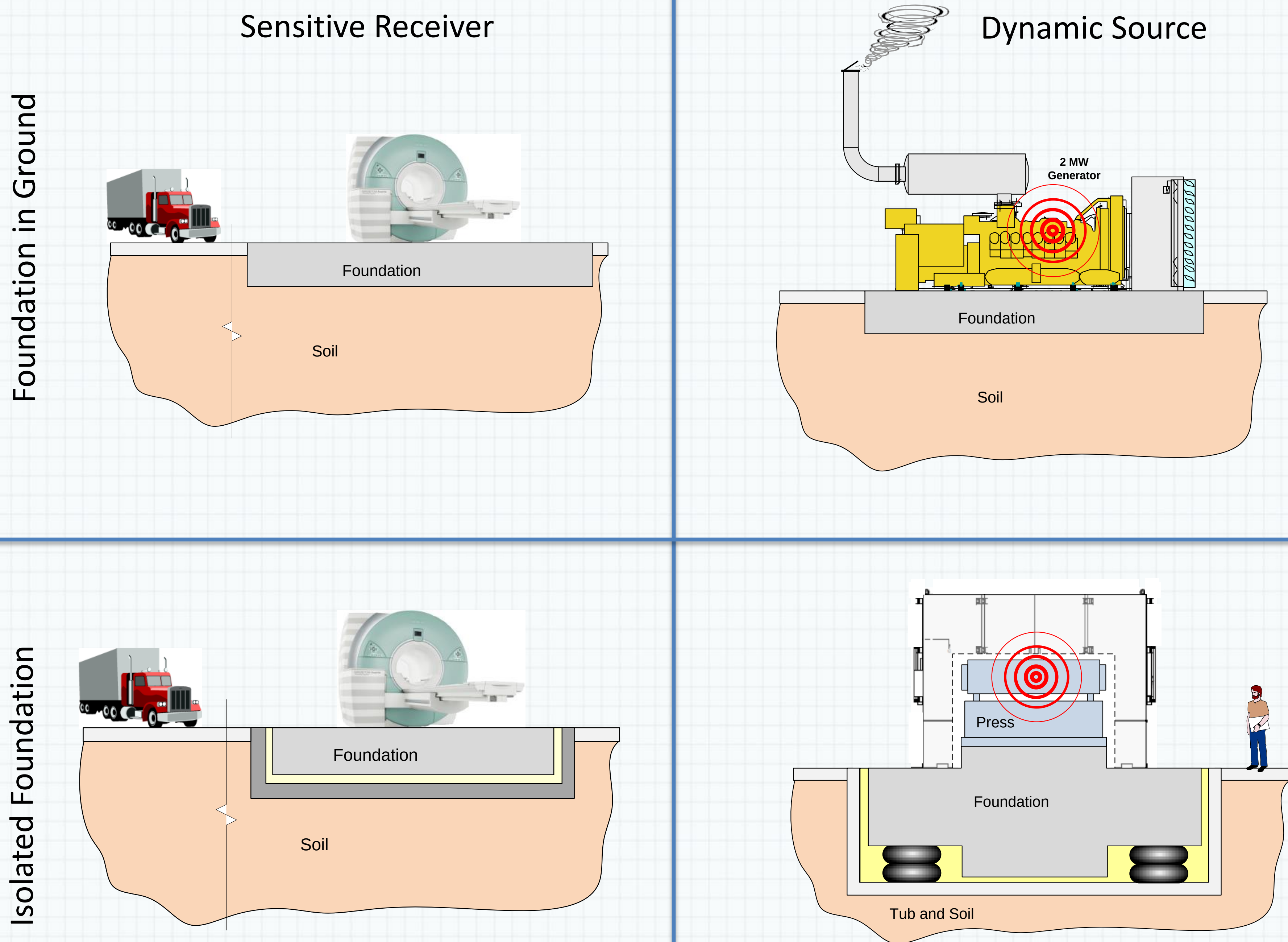
Multi-Axial Subassembly Testing (MAST) Laboratory

Foundations For Dynamic Sources

- React forces
- Provide a stable base and maintain alignment
- Minimize motion, on and off foundation

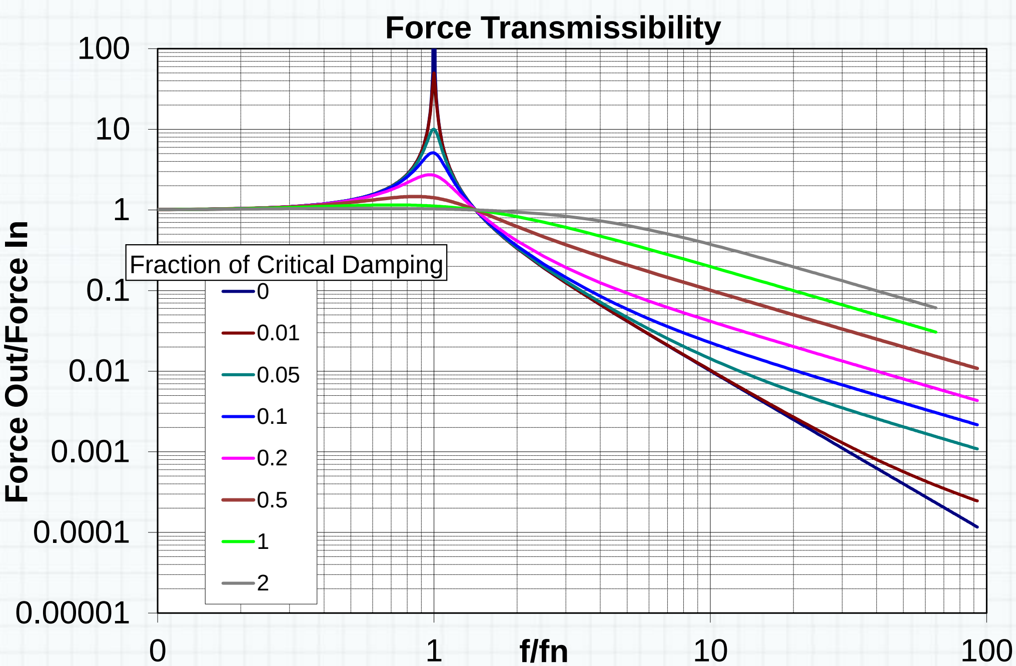
Sensitive Receiver

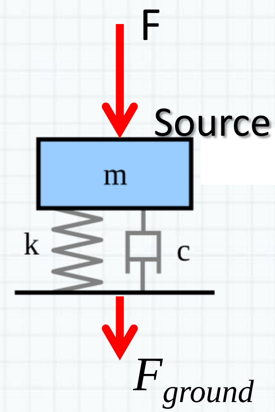
Dynamic Source



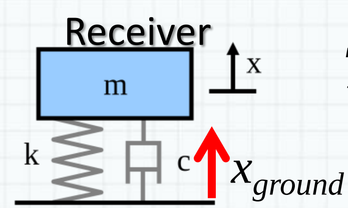
The Concept of Transmissibility

Transmissibility applies (exactly the same equation!) to both source force transmissibility and receiver displacement transmissibility





$$T = \left| F_{ground} / F \right|$$



$$T = \left| x / x_{ground} \right|$$

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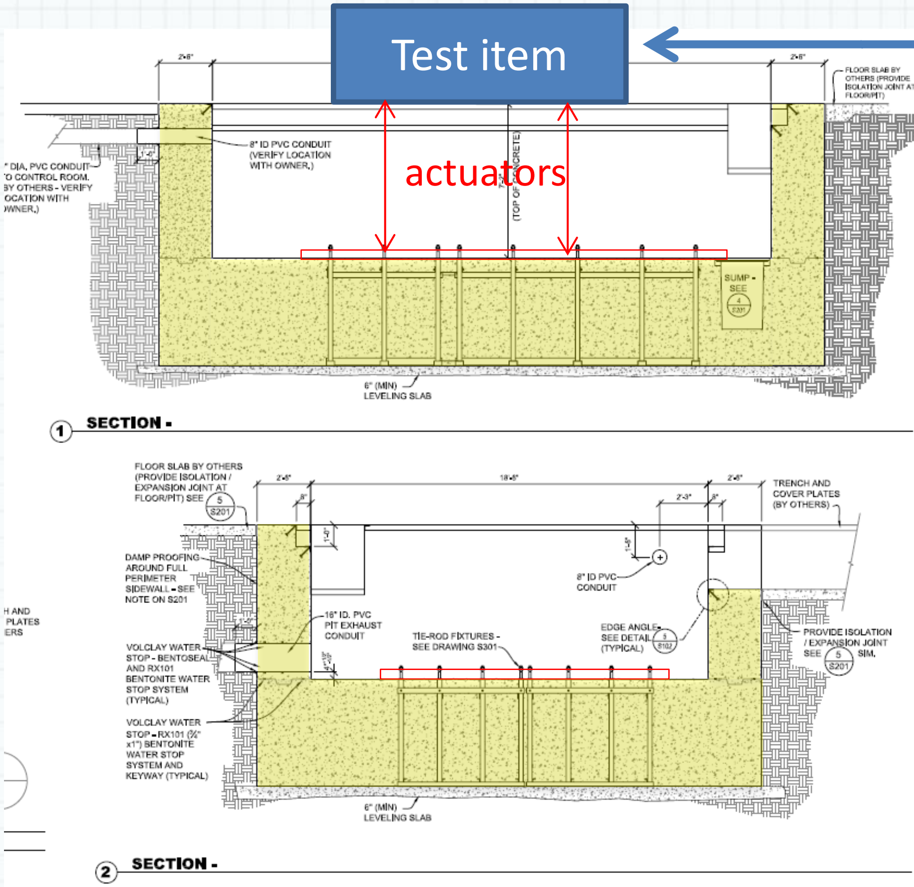
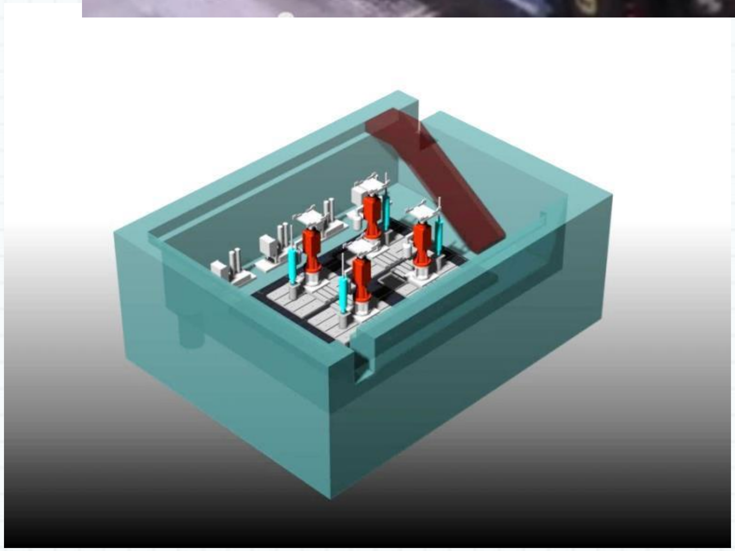
Foundations for Dynamic Sources

Soil Supported Viper Test Rig at Virginia International Speedway





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Foundations for Dynamic Sources

Soil Supported Viper Test Rig at Virginia International Speedway

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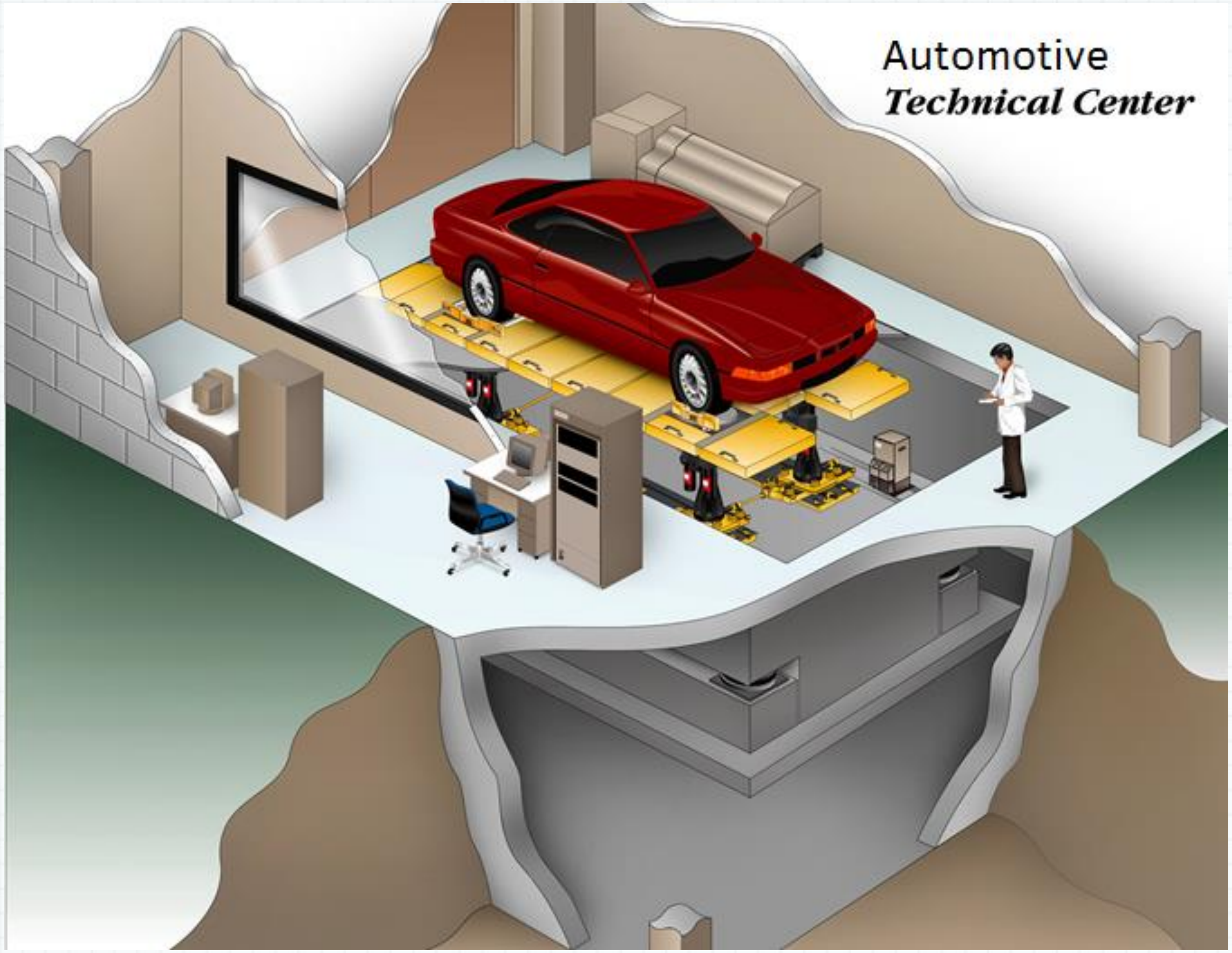
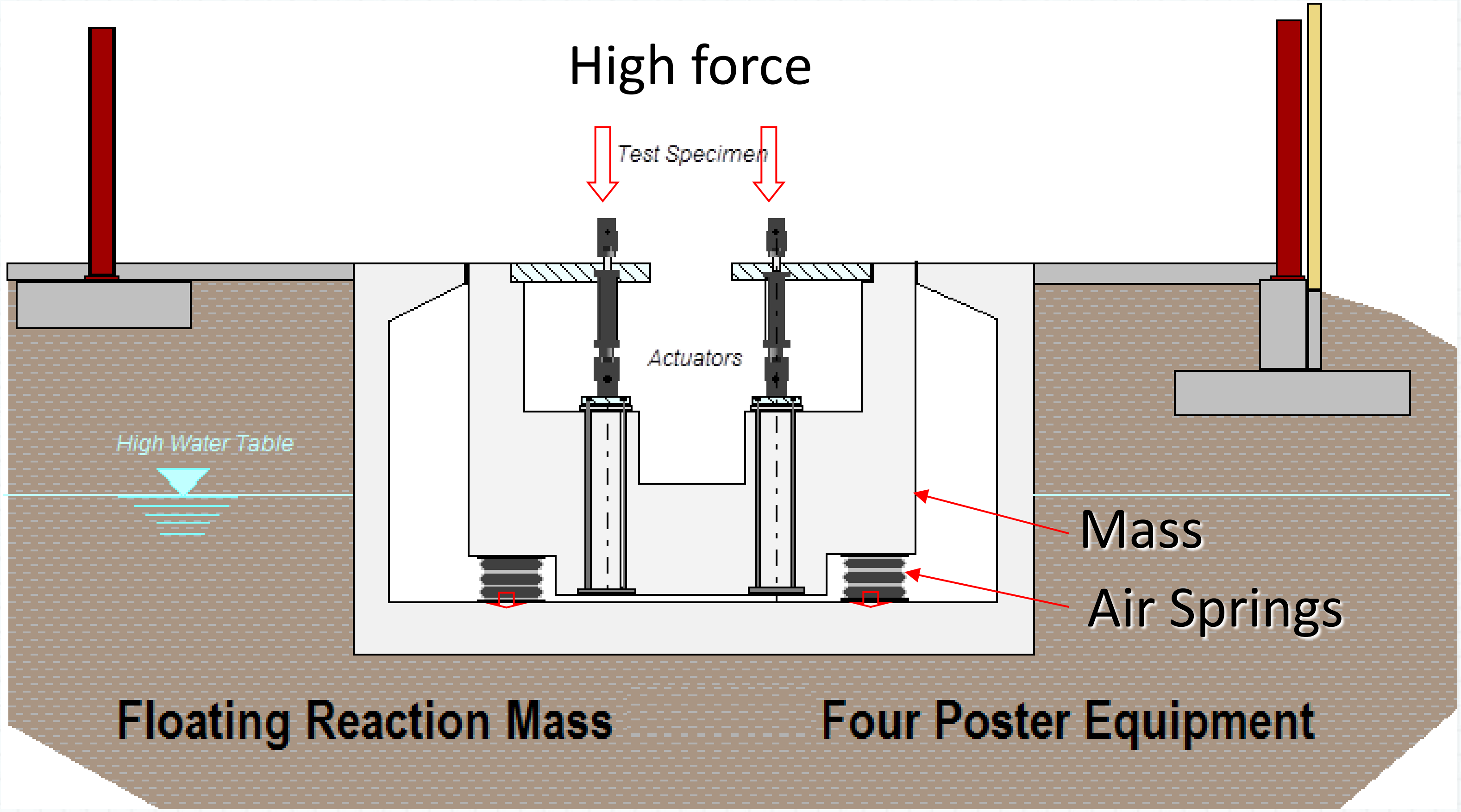
Foundations for Dynamic Sources

Air Mount Isolated with Foundation



Foundation Isolation with Air Mounts



- Attenuated force transmitted to foundation
- Minimize motion at actuator base

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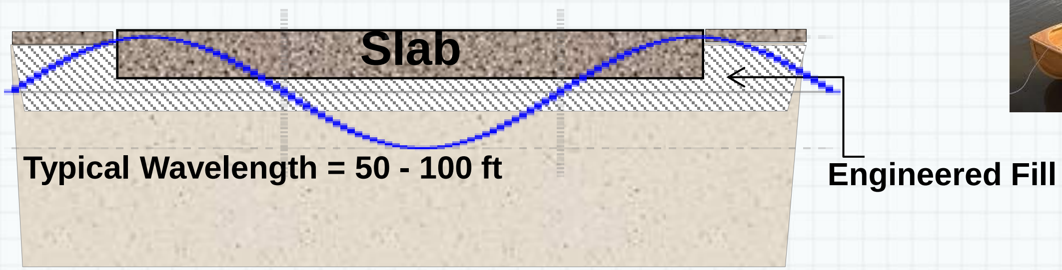
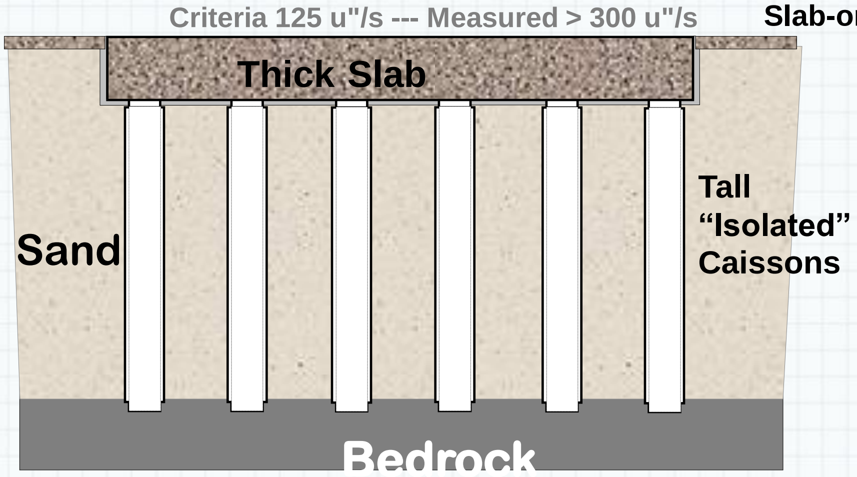
Soil Supported Foundations for Sensitive Receiver
Overview of Concepts

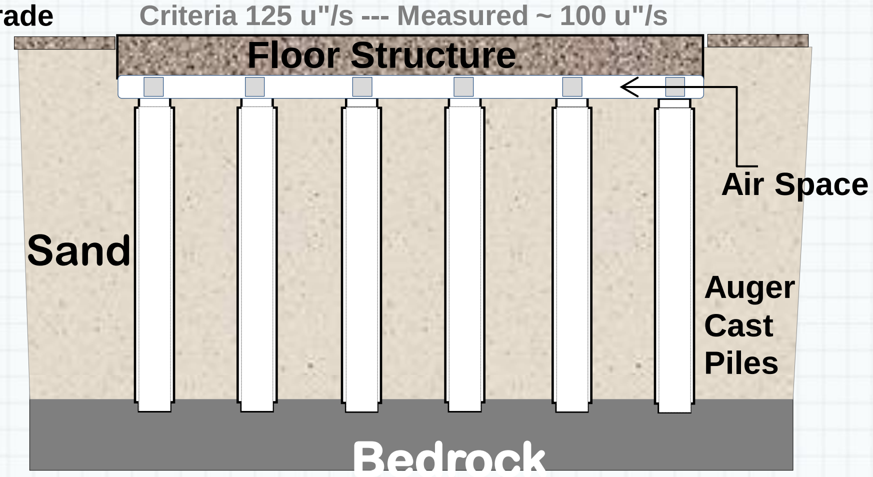


1. Simple Thick Slab on Ground – Wavelength Effect

Slab-on-Grade



2. Isolated Slab for Electron Microscopy Center - Shepherd Laboratories



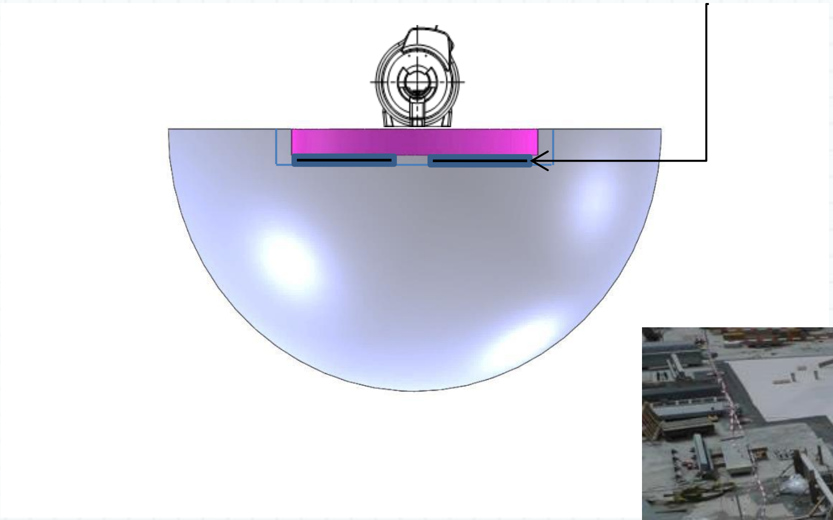
3. Physics and Nanotechnology Cleanroom – U of M

Foundations for Sensitive Equipment

Isolated with Various Types of Isolators

Sensitive Equipment Isolation Techniques

- Air Mounts (<2 Hz)
- Steel Springs (2-5 Hz)
- Resilient Pad or Sheets (>6 Hz)



Entire Building Isolation

Drachen-Center Basel Switzerland

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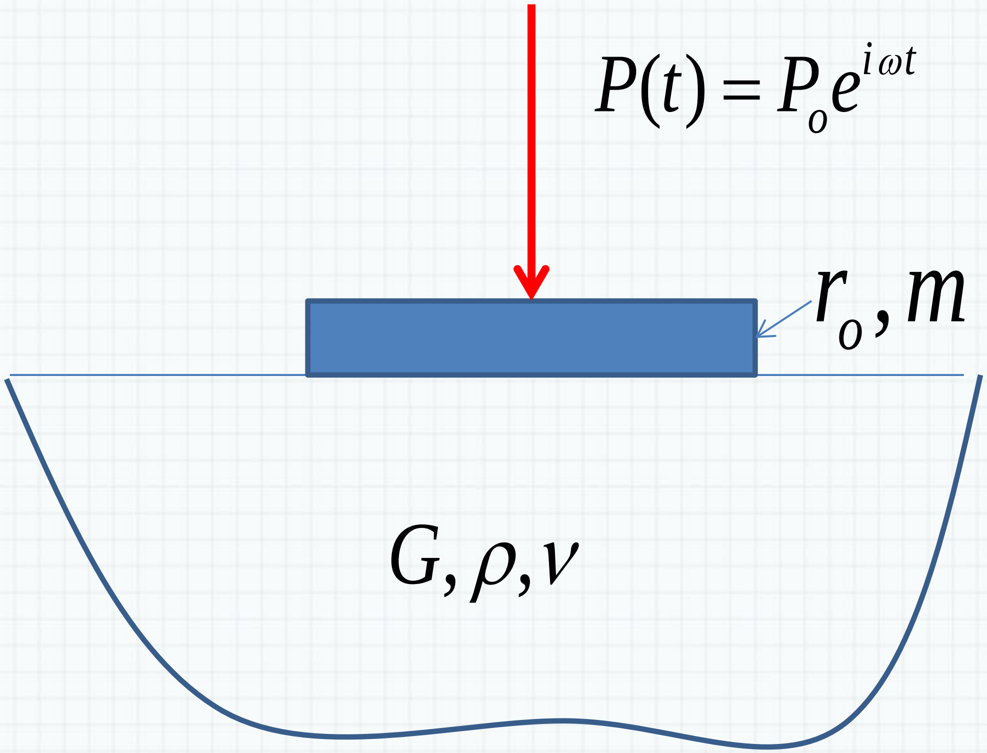
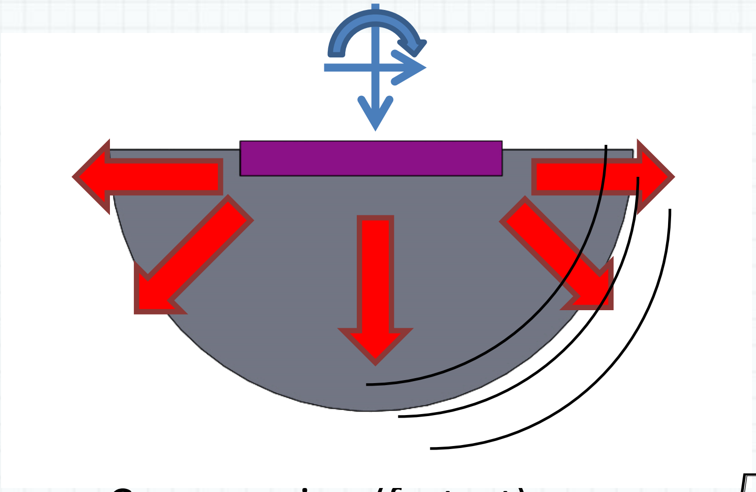
What do all these foundations have in common?

Rigid Foundation on Elastic Halfspace under harmonic loading



Two Minutes on Elastic Wave Propagation



P Waves – Compression (fastest) $V_P = \sqrt{\frac{\lambda + 2G}{\rho}}$ $\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}$

S Waves – Shear $V_s = \sqrt{\frac{G}{\rho}}$

Rayleigh Waves – Speed close to that of S waves

Amplitude decreases with $\sqrt{\frac{1}{r}}$

Accounts for 2/3 of the energy

(See Figure 3-16 on p. 91 in Richart, Hall, and Woods)

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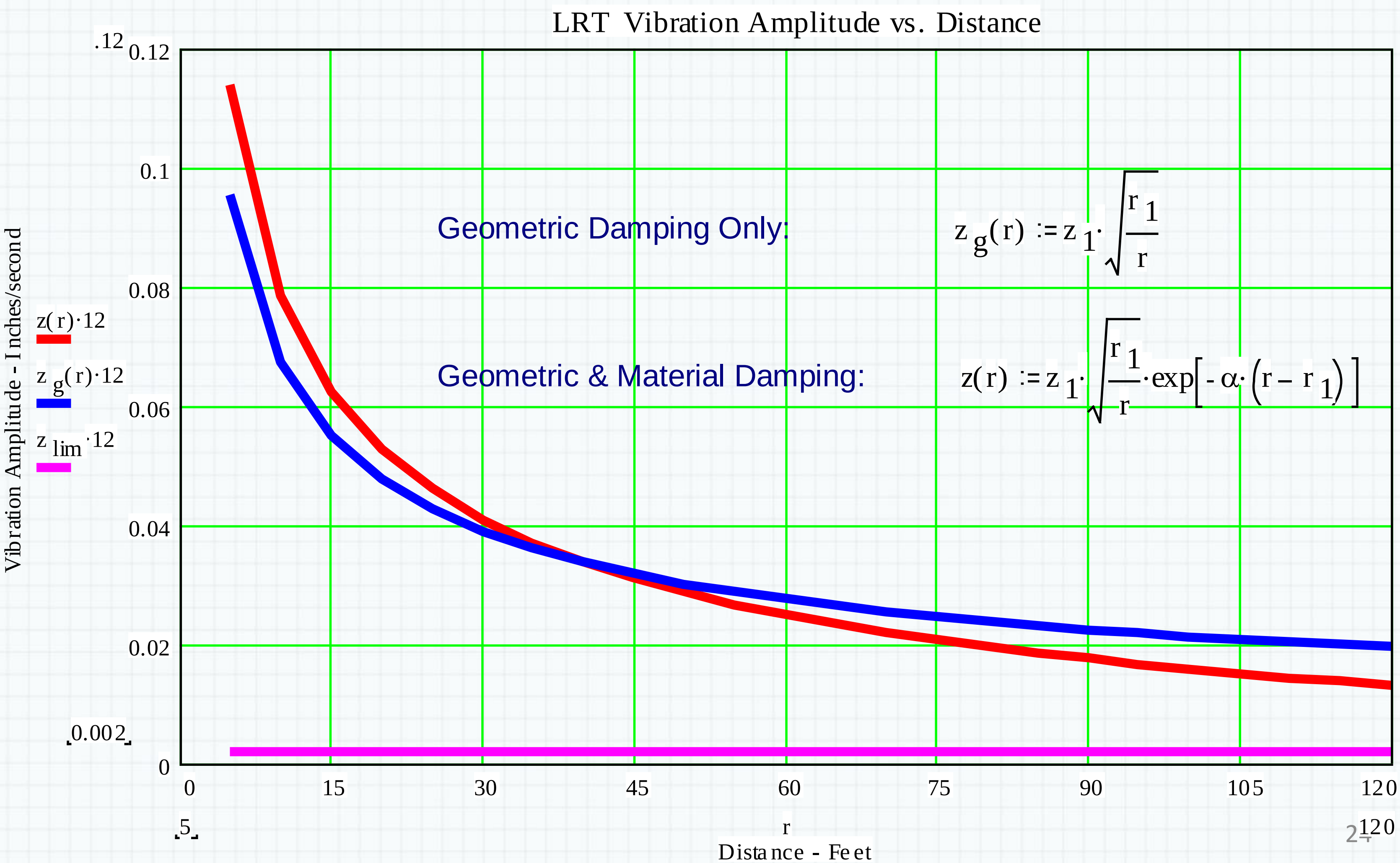
Predicting Vibration Versus Distance



Some History
Development of Techniques

<u>Early</u>

Boussinesq (1885), Lamb (1904) – static, dynamic load on the surface of elastic halfspace
Riessner (1936) – Dynamically loaded, rigid circular foundation on elastic halfspace
Lysmer and Richart – "Dynamic Response of Footings to Vertical Loading," ASCE Journal of the Soil Mechanics and Foundations Division, January 1966.
"Lysmer's Analog"

<u>Numerical Methods</u>

Many Contributors – FEA, Boundary Element Method
Beskos and Co-Workers and the University of Minnesota (1970s-80s)

Approaches to the Dynamic Foundation Problem

Complicated!

Still Complicated!

Winkler Foundation

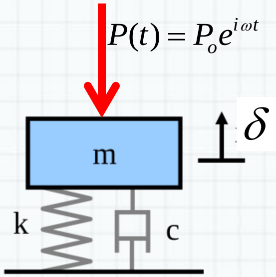
Plate on Elastic Halfspace

Rigid Plate on Elastic Halfspace

But…

Lysmer's Analogue (1966)

Lysmer's Analog



$$\delta = \frac{P}{k} F(\omega)\, e^{i\omega t}$$

F is a dimensionless displacement function with real and imaginary parts

$$F(\omega) = F_1(\omega) + i\, F_2(\omega)$$

Introducing the dimensionless ratios

$$a_o = \frac{c}{k}\omega = 2\zeta \frac{\omega}{\omega_n}$$

$$B = \frac{k\, m}{c^2}$$

$$F(\omega) = \frac{1}{(1 - Ba_o^2) + i\, a_o} = \frac{(1 - Ba_o^2) - i\, a_o}{(1 - Ba_o^2)^2 + a_o^2}$$

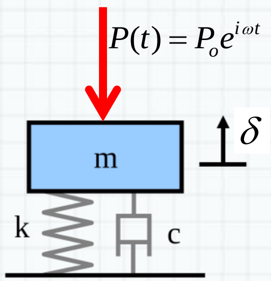
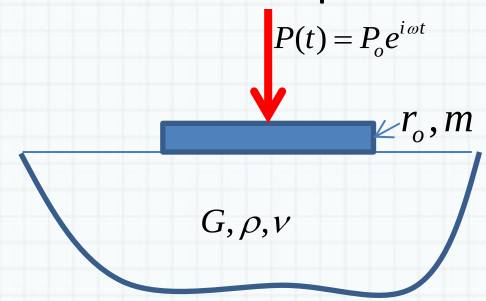
$$M = |F| = \frac{1}{\sqrt{(1 - Ba_o^2)^2 + a_o^{\,2}}}$$

Magnification Factor

Textbook so far, but with slightly unfamiliar notation

Lysmer's Analog

$$|F| = \frac{1}{\sqrt{(1-Ba_o^2)^2 + a_o^{\ 2}}}$$

Simple Damped Oscillator	Model	Rigid Circular Foundation on Elastic Halfspace
	Model	
k	Static vertical stiffness	$k = \frac{4G\, r_o}{1-\nu}$
$a_o = \frac{c}{k}\omega = 2\zeta\frac{\omega}{\omega_n}$	Dimensionless frequency $\frac{c}{k}\omega \Leftrightarrow \frac{r_o}{V_s}\omega$	$a_o = r_o\sqrt{\frac{\rho}{G}}\,\omega = \frac{r_o}{V_s}\omega$
$B = \frac{k\, m}{c^2}$	Dimensionless mass	$B = \frac{m}{k}\left(\frac{V_s}{r_o}\right)^2 = \frac{1-\nu}{4}\,\frac{m}{\rho\, r_o^2}$
$m\ddot{\delta} + c\,\dot{\delta} + k\,\delta = P_o\, e^{i\omega t}$	Equation of motion $c \Leftrightarrow k\frac{r_o}{V_s}\omega$	$m\ddot{\delta} + c_1\frac{k\, r_o}{V_s}\dot{\delta} + k_1 k\,\delta = P_o\, e^{i\omega t}$

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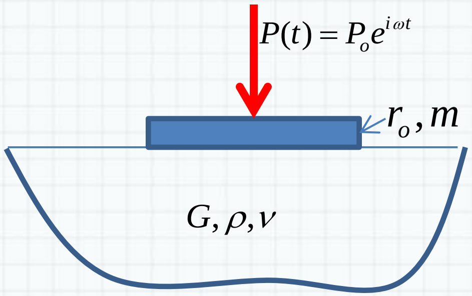
Lysmer's Analog



$$m\ddot{\delta} + c_1 \frac{k\, r_o}{V_s}\dot{\delta} + k_1 k\,\delta = P_o\, e^{i\omega t}$$

- The rigorous solution for the elastic halfspace requires the solution of the wave equation with mixed boundary conditions.
- Lysmer assumed $\nu = \frac{1}{3}$ and was able to solve the halfspace problem in a form that could be compared with the analog.
- The parameters c_1= 0.85 and k_1 = 1 were found to bring the analog into reasonable agreement with this solution.

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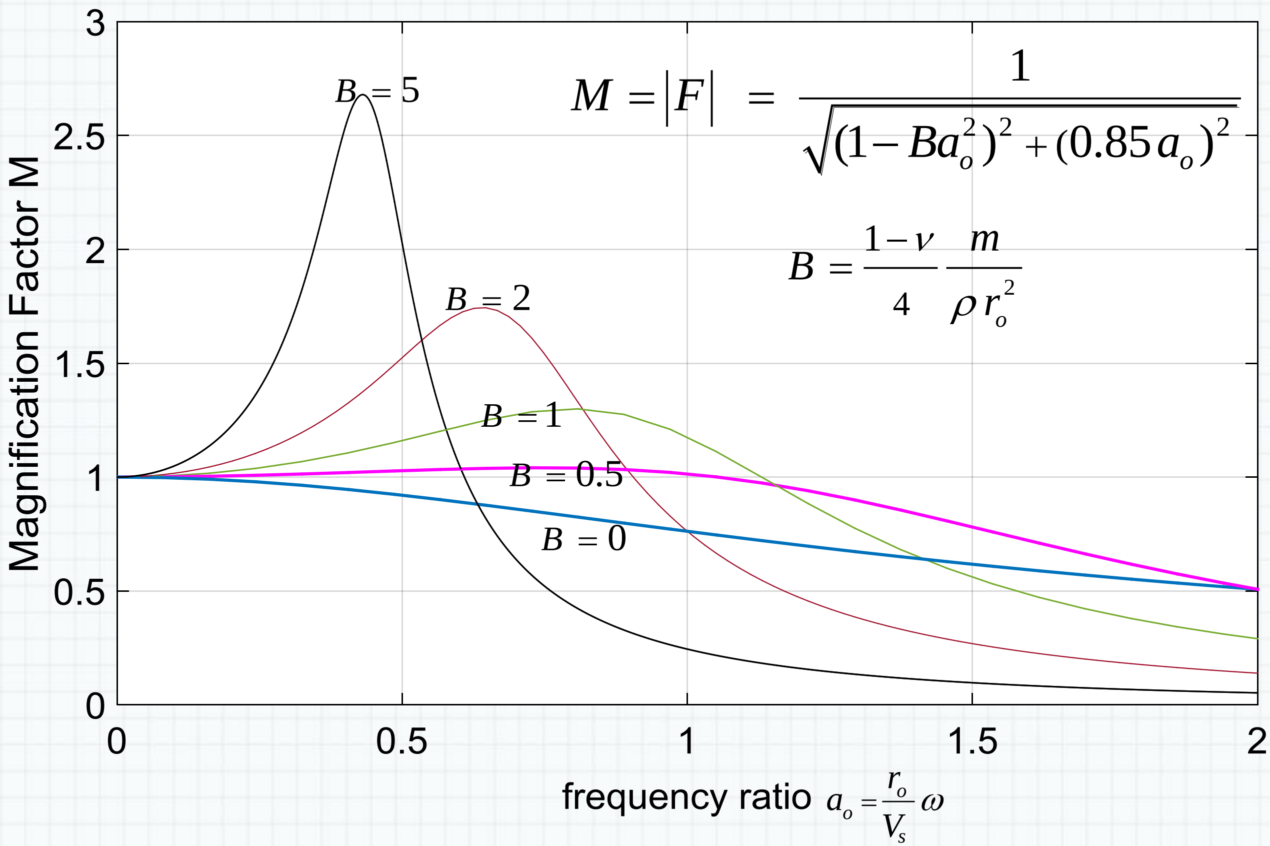
Magnification Factor vs. Frequency and Mass Ratio



See Fig. 11 of Lysmer (1966) to see how well this compares to the elastic halfspace solution

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Sample Calculations

Reciprocating Compressor

Soil properties, medium dense silty sand

$V_s := 750 \cdot \frac{ft}{s}$ $\rho := 115 \cdot \frac{lbm}{ft^3}$ $G := \rho \cdot V_s^2 = 13962 psi$

$S_{allowable} := 2000 psf$ $\nu := 0.35$

Foundation pad properties

$L := 25 ft$ $b := 15 ft$ $r_o := \sqrt{\frac{b \cdot L}{\pi}} = 10.925 ft$ $t := 4.5 ft$

$W_f := \pi \cdot r_o^2 \cdot t \cdot 150 pcf = 2.531 \times 10^5 \cdot lbf$

$k := \frac{4 \cdot G \cdot r_o}{1 - \nu} = 11.26 \times 10^6 \cdot \frac{lbf}{in}$ **Vertical stiffness**

Compressor Weight

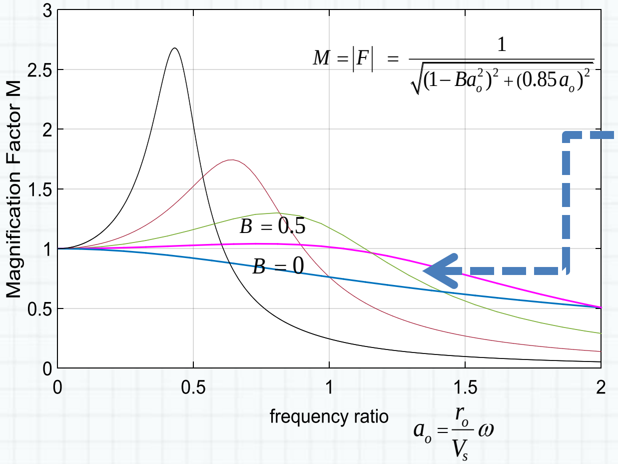
$W_{equip} := 50000 lbf$ $\frac{W_f}{W_{equip}} = 5.062$ >5

$\frac{W_f + W_{equip}}{b \cdot L} = 808 psf$ < $0.5 S_{allowable} = 1000 psf$

$m := \frac{W_f + W_{equip}}{g}$ **Total mass of foundation plus equipment**

$B := \frac{1 - \nu}{4} \frac{m}{\rho \cdot r_o^3} = 0.328$ **Mass ratio**

$f_n := \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m}} = 19.06 \frac{1}{s}$ **Vertical natural frequency**

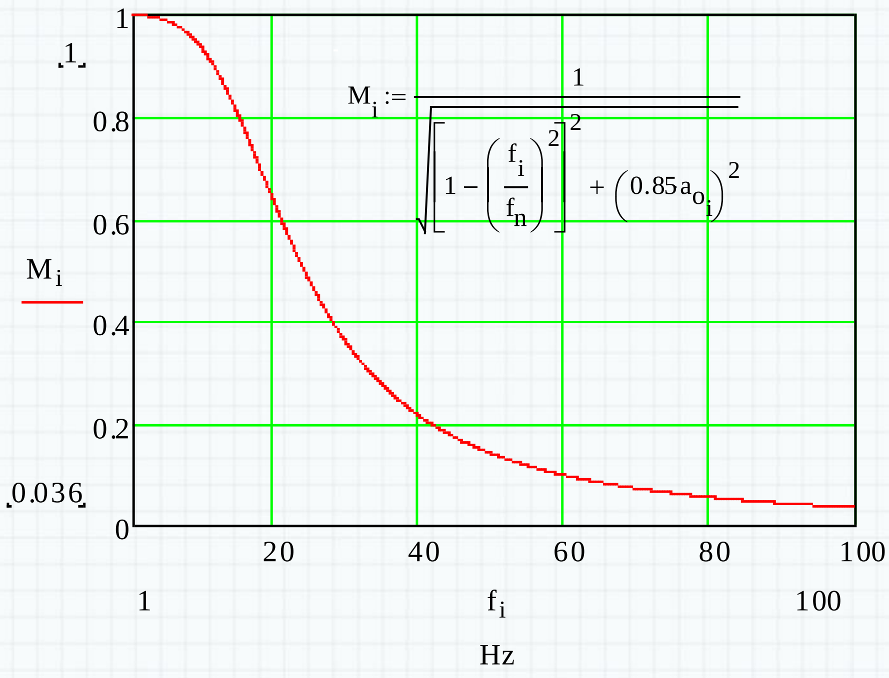


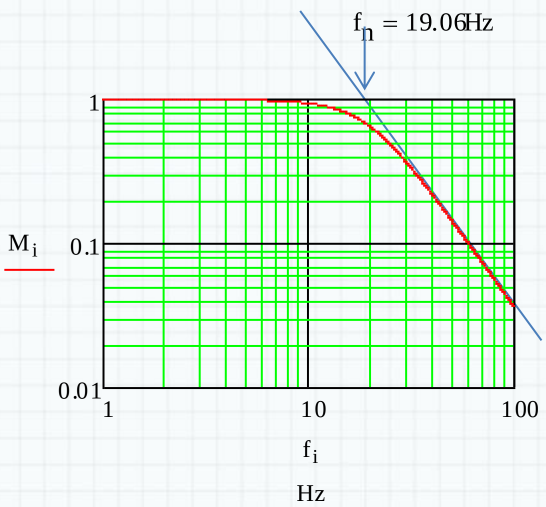
Note that B will generally be in this range

Sample Calculations

More Plots

In terms of actual frequency…



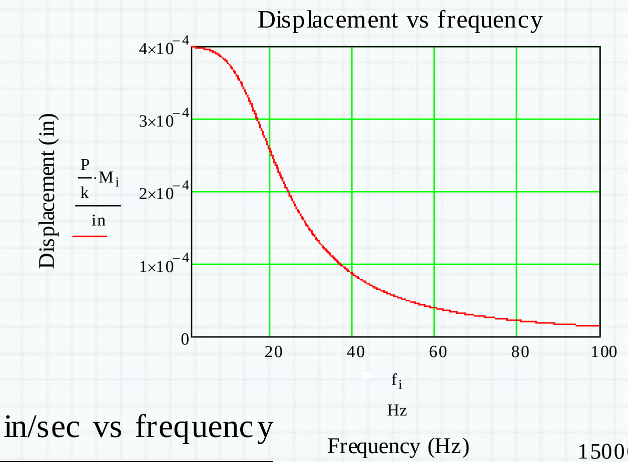


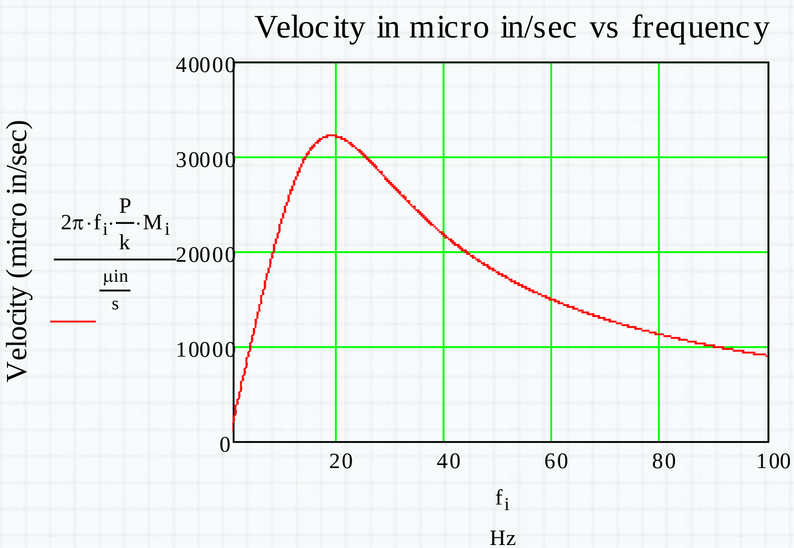
Sample Calculations

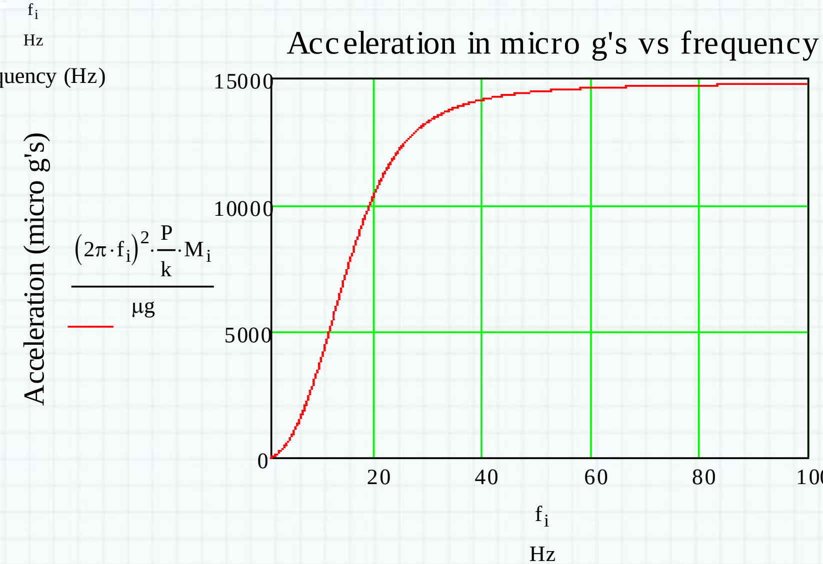
Let's get down to some real numbers. Suppose that the compressor exerts a vertical force of 4500 lb at a frequency of 600 rpm (10 Hz).

$P := 4500\,\text{lbf}$ $\quad\quad \frac{P}{k} = 3.99\times 10^{-4}\,\text{in}$ $\quad\quad \mu\text{in} := 10^{-6}\cdot\text{in}$ $\quad\quad \mu\text{g} := 10^{-6}\cdot\text{g}$

$$\delta_o = \frac{P}{k}M$$







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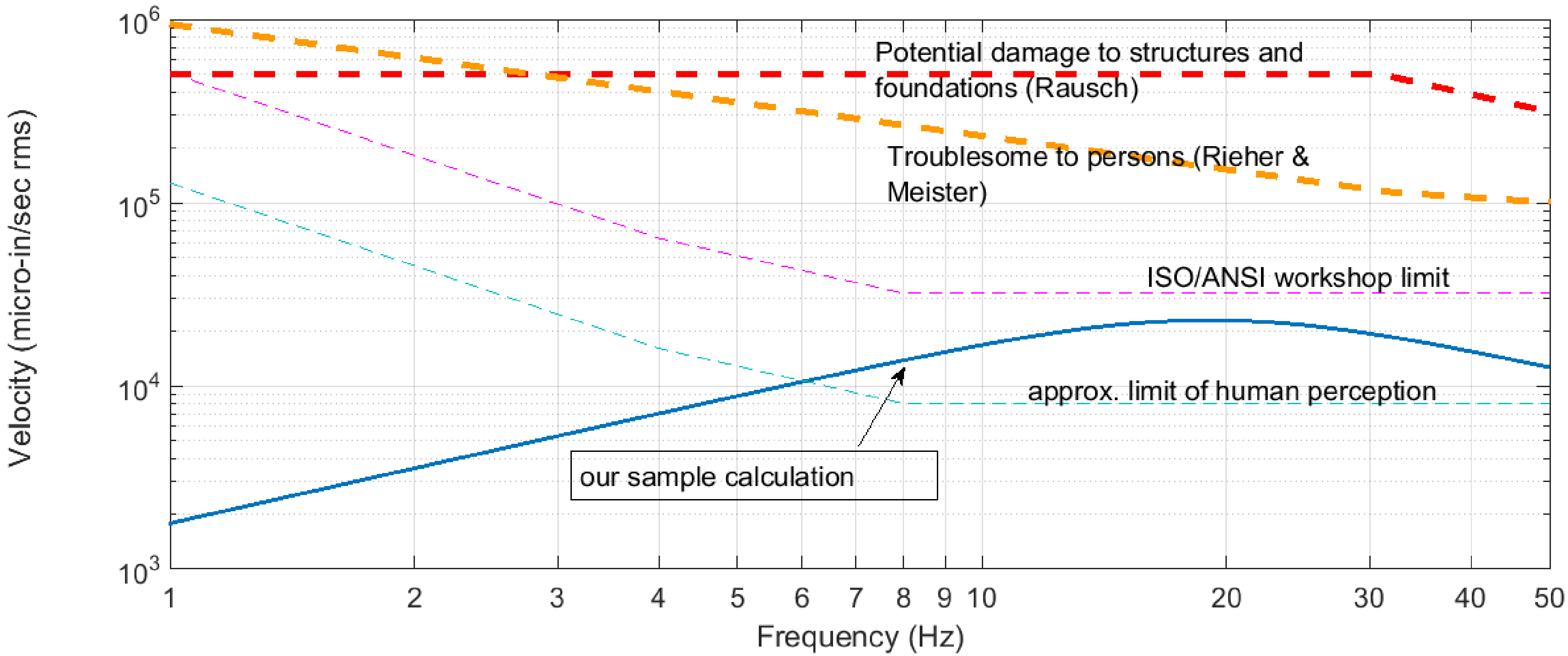
Sample Calculations

Let's see how this compares to some vibration criteria



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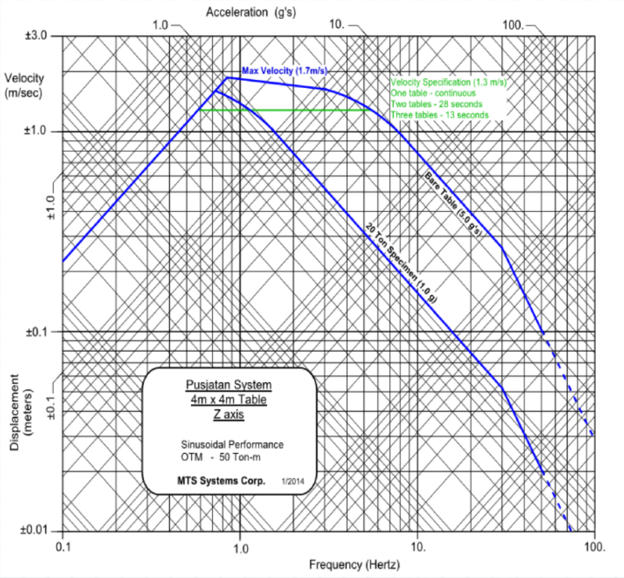
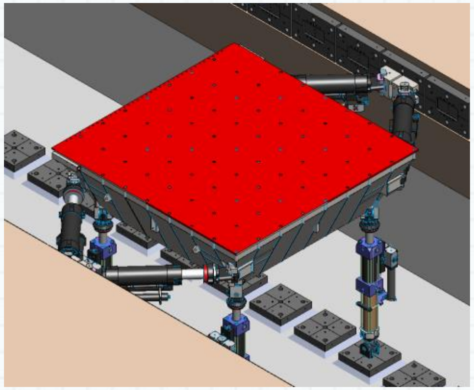
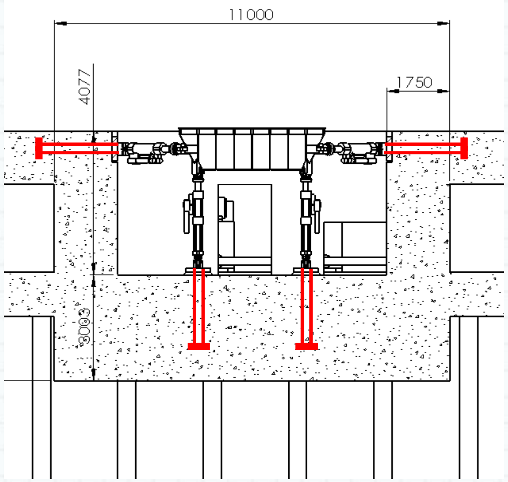
Sample Calculations

Forces exerted by seismic tables with heavy specimens can be large







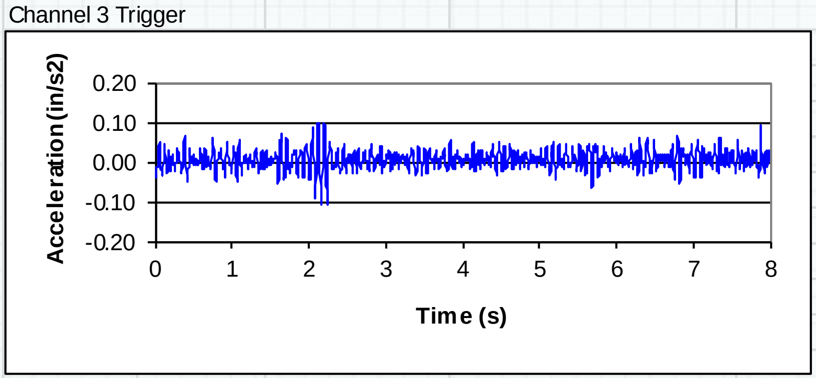
The system shown above has a 4m x 4m table with 8 actuators. The four vertical actuators are capable of generating a total of 343 kN (77 kips) at frequencies from 1 to 30 Hz.

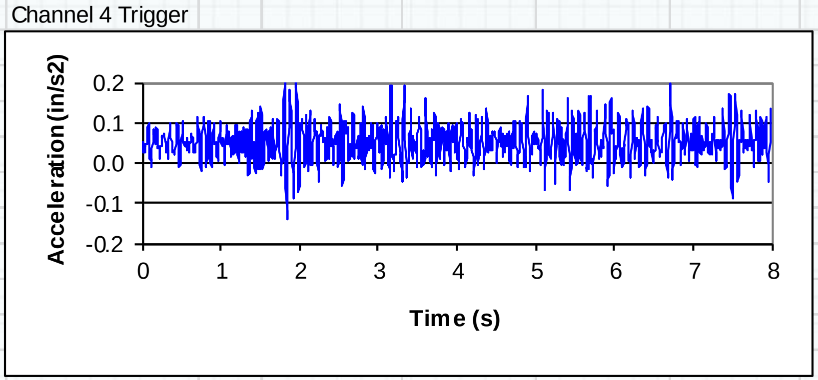
Note the size of the foundation mass reacting the actuator forces..

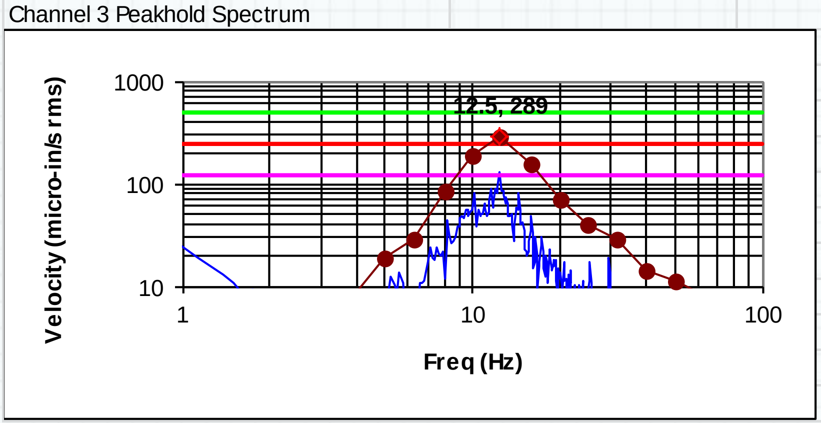
Case Study

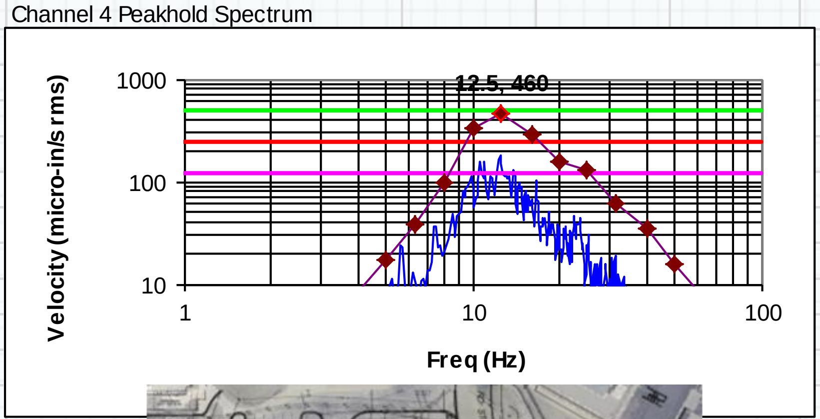
Foundations for Sensitive Equipment- Soil Supported

Physics and Nanotechnology Clean Floor Design at U of M



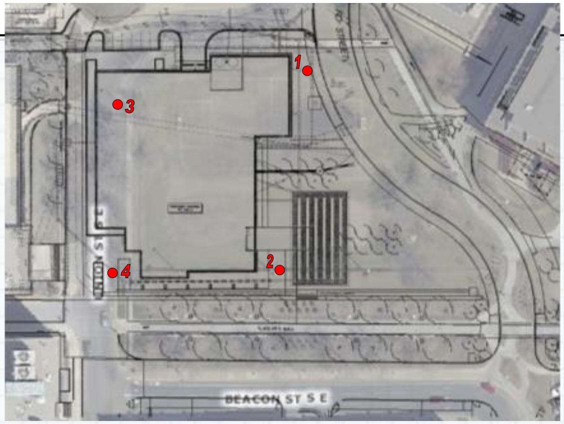






Sample of Ground Vibration Measurements Prior to Construction

Measurement Locations



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Case Study

Foundations for Sensitive Equipment- Soil Supported

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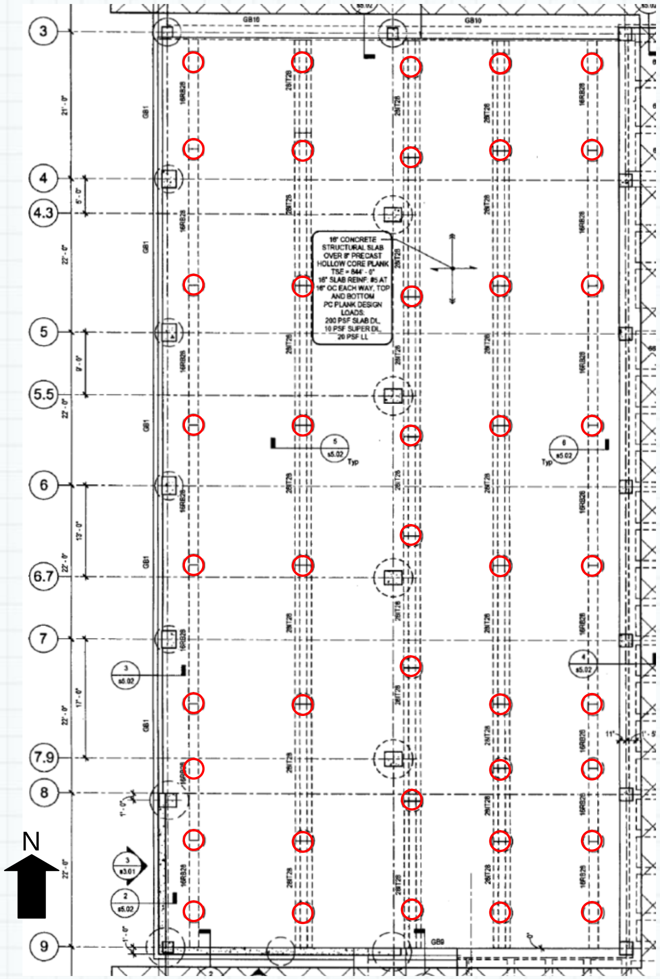
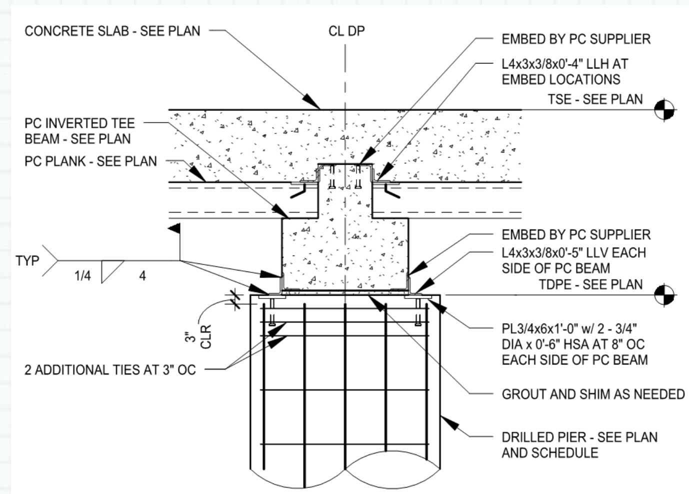


Foundation Plan

Auger Cast Pile Placement

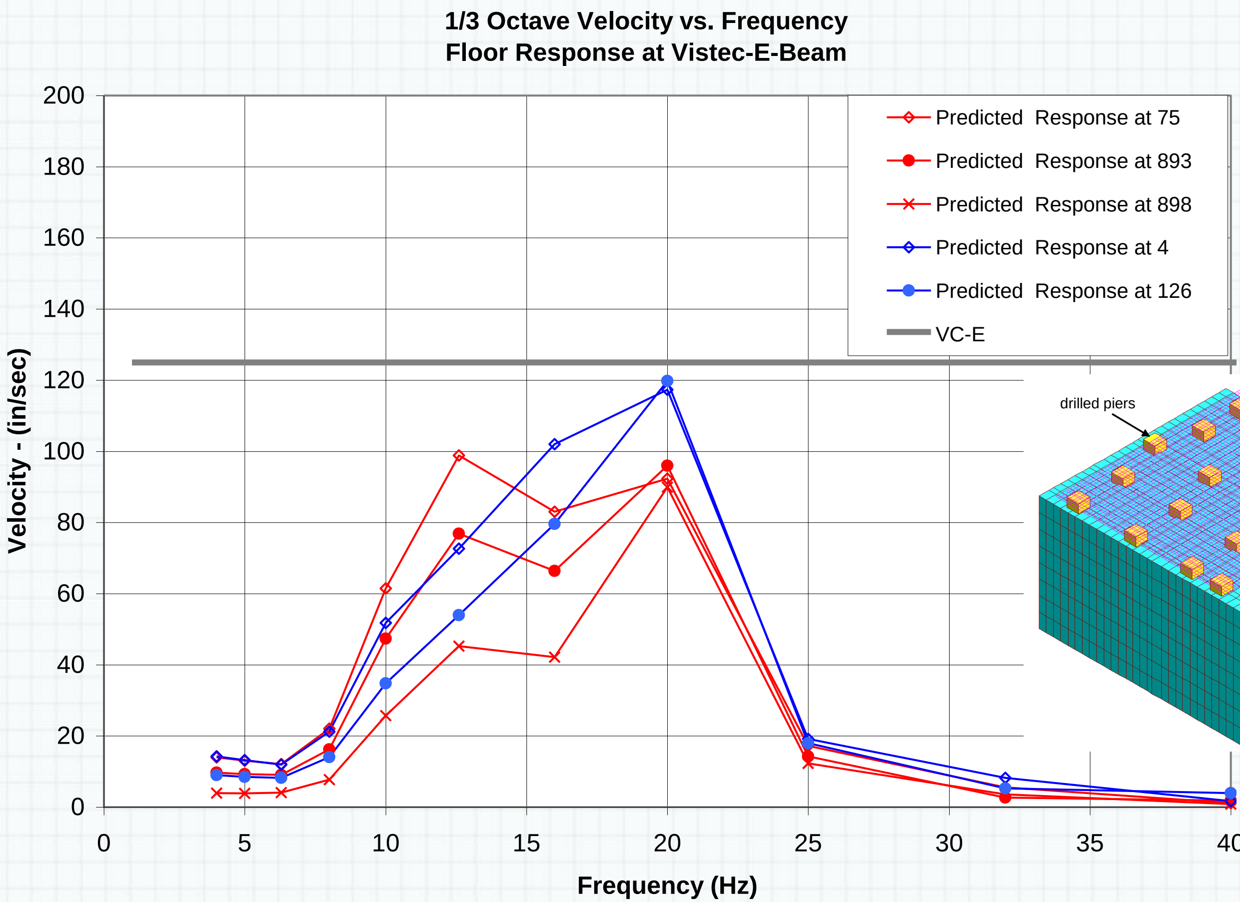


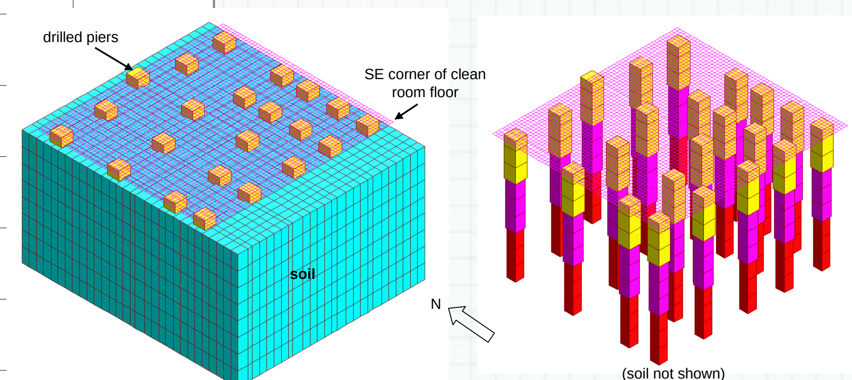
Pile Top and Floor Detail

Case Study

Foundations for Sensitive Equipment- Soil Supported

Physics and Nanotechnology Clean Floor Design at U of M





FEA Model (COSMOS)

Predicted Velocity on Cleanroom Floor

ACI Committee 351 –
Foundations for Equipment and Machinery

Active Committee Documents:
• 351.1R-12: Report on Grouting between Foundations and Bases for Support of Equipment and Machinery
• 351.2R-10: Report on Foundations for Static Equipment
• 351.3R-04: Foundations for Dynamic Equipment
• 351.4-14: Specification for Installation of Cementitious Grouting between Foundations and Equipment Bases
• 351.5-15 Specification for Installation of Epoxy Grout between Foundations and Equipment Bases

Documents Under Development:
• 351.3R: Foundations for Dynamic Equipment
• 351.4M-14: Specification for Installation of Cementitious Grouting between Foundations and Equipment Bases
• 351.5M-15: Specification for Installation of Epoxy Grouting between Foundations and Equipment Bases

Wrap Up

Important Topics We Have Not Talked About Today

Rotational and Horizontal Modes
Embedment Effects
Strength Requirements
Anchorage
Numerical Methods/Software

Questions?

Thank you for inviting us!