Exponent®

Principles of Construction Vibrations

January 27, 2018

David Sykora, Ph.D., P.E., D.GE

Brendan Casey, Ph.D., P.E.

Antonios Vytiniotis, Ph.D., P.E.

Introduction

- We're shifting gears away from earthquake-induced ground motions and its effects on soil deposits
- In the next two presentations, we'll be talking about man-made vibrations induced by various construction activities, people's perception of vibrations, and the potential effects on the built environment:
  - Principles of Construction Vibrations
  - Geotechnical Instrumentation

Relevance

Why is this relevant?

- Contract provisions may explicitly require the contractor to protect adjacent properties or provide specific limiting thresholds for ground vibrations, or both
- State statutes, building codes, and/or local ordinances may require the Contractor to protect adjacent properties
- Even in the absence of legal provisions, property owners may sue the contractors, designers, construction managers, and/or owners/authority of the property under construction

Agenda

- Wave Generation (Construction Sources)
- Energy Dissipation (Geometric and Material Damping)
- Data Scatter and Special Effects
- Human Perception
- Damage Thresholds
- Indirect Effects
- Analysis of Data

Not Included

Time will not allow for this presentation to cover the following topics:

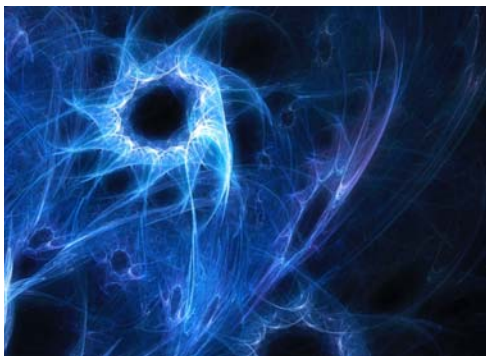
- Construction-induced noise
- Vibrations induced by air blasts
- Pre-construction condition assessment surveys
- Environmental effects and other causes for building finish distress
- Provisions in contracts and specifications related to ground vibrations

Key References

- Richart, FE, Jr., Hall, JR Jr., and Woods, RD,1970. Vibrations of Soils and Foundations, Prentice-Hall.
- Dowding, CH, 1996. Construction Vibrations, Prentice Hall.
- Woods, RD, 1997. “Dynamic Effects of Pile Installations on Adjacent Structures,” NCHRP Synthesis 253, TRB, NRC.
- Oriard, LL 1999. The Effects of Vibrations and Environmental Forces, ISEE.
- Siskind, D.E., Stagg, M.S., Kopp, J.W., and Dowding, C.H., 1980. “Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting,” U.S. Bureau of Mines, RI 8507
- Siskind, DE 2000. Vibrations from Blasting, ISEE.
- Caltrans, 2004. “Transportation- and Construction-Induced Vibration Guidance Manual,” prepared by Jones & Stokes, contract 43A0049.
- Federal Transit Administration, 2006. “Transit Noise and Vibration Impact Assessment,” FTA-VA-90-1003-06, DOT.
- AASHTO, 2009. “Standard Practice for Evaluation of Transportation-Related Earthborne Vibrations,” R 8-96.

Permissions

- Images from Wiss (1981), Hryciw et al (1990), and Woods and Jedele (1985) reprinted with permission from ASCE.
- Images from Richart, Hall, and Woods (1970) reprinted with permission of Professor Dick Woods.



Wave Generation (Construction Sources)

Construction Activities


ENTER
BLUE IRON

Elastic Waves

- In soil dynamics, we generally categorize waves as being:
  - A. Periodic
  - B. Random, or
  - C. Transient

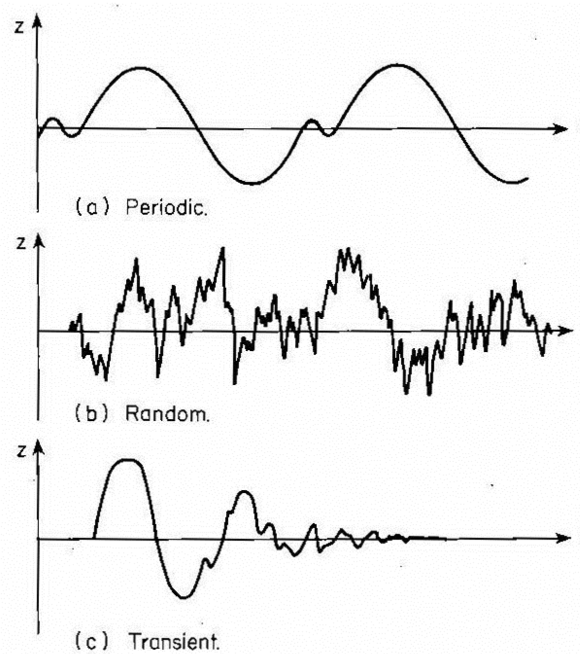


Figure 2-2. Periodic, random, and transient motion.

Richart, Hall and Woods (1970)

Harmonic Motion

- For the simplest wave form, a single-frequency harmonic wave, we generally look at seismic waves (“vibrations”) in two ways:
  - A. Time domain
  - B. Spatial domain
- The particle velocity represents the motion at a particular point in space; the peak (PPV) is correlated with damage

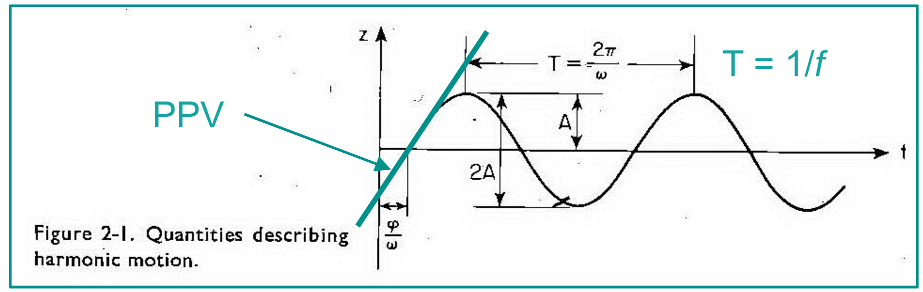


Figure 2-1. Quantities describing harmonic motion.

Time Domain
(a point in space)

Richart, Hall and Woods (1970)

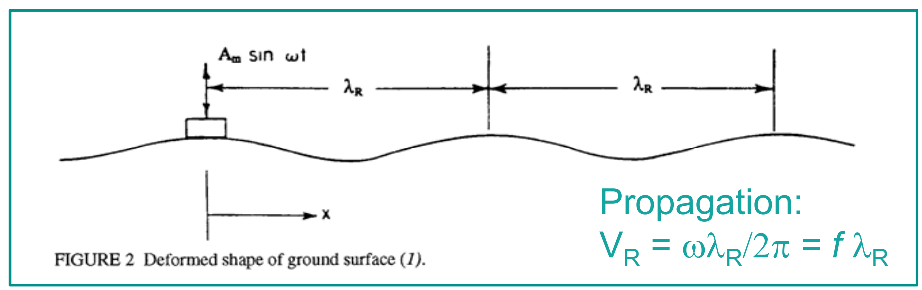


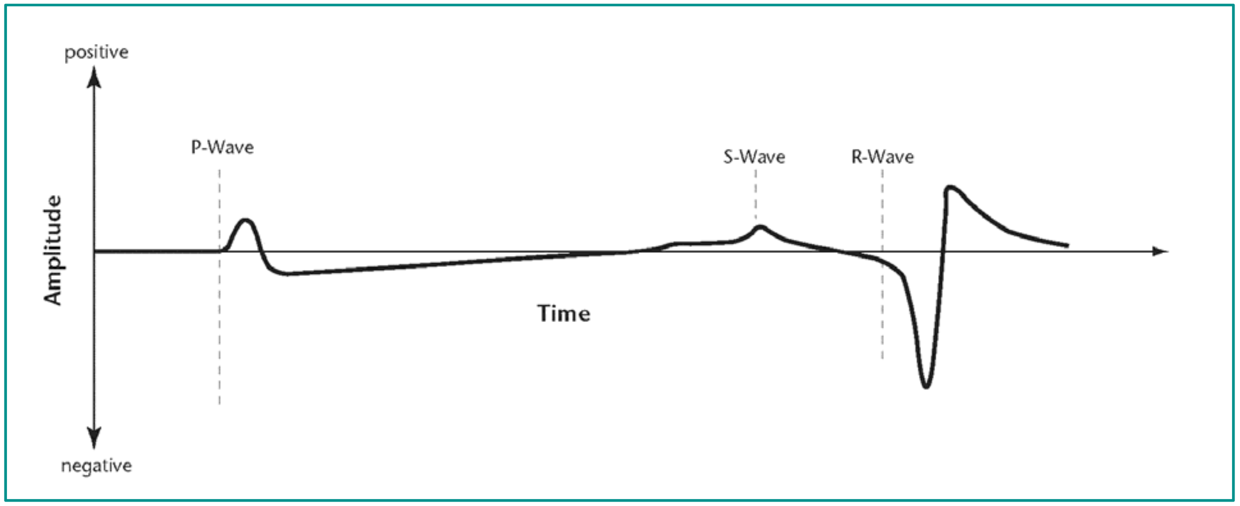
FIGURE 2 Deformed shape of ground surface (*1*).

Spatial Domain
(a point in time)

Woods (1997)

Wave Propagation

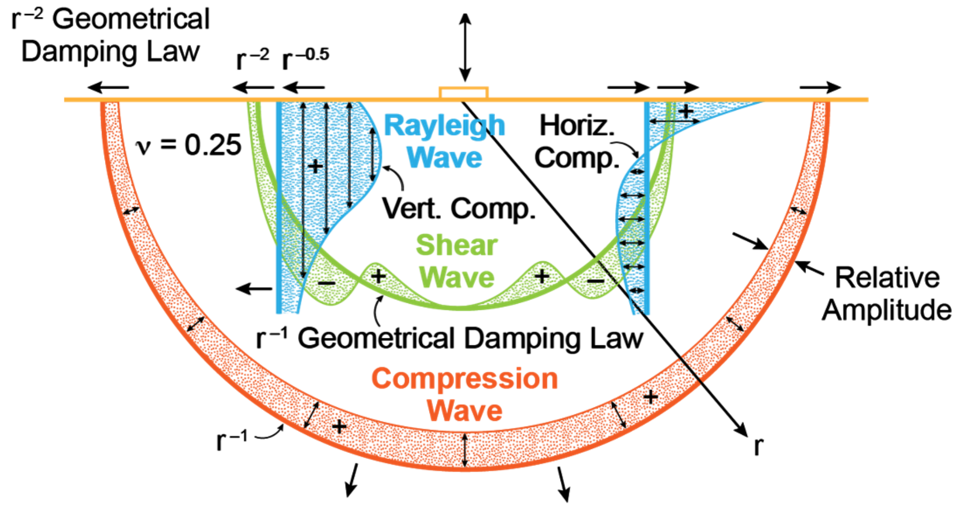
- Energy imparted into the ground propagates outward at different velocities:
  - Compression (P-wave)
  - Shear (S-wave)
  - Rayleigh (R-wave)



Jones & Stokes in Caltrans (2004)

Vibrations from Surface Excitations

- A surface excitation from construction equipment typically acts as a point source
- The seismic waves travel in in different patterns:
  - Semi-spherical (P and S)
  - Cylindrical (R)



Wave Type	Per Cent of Total Energy
Compression	7
Shear	26
Rayleigh	67

Modified from Richart, Hall and Woods (1970)

Propagation Velocities

- For elastic materials, the relationship between P-, S-, and R-wave velocities are defined by closed form solutions
- Propagation velocities depend on compression and shear moduli

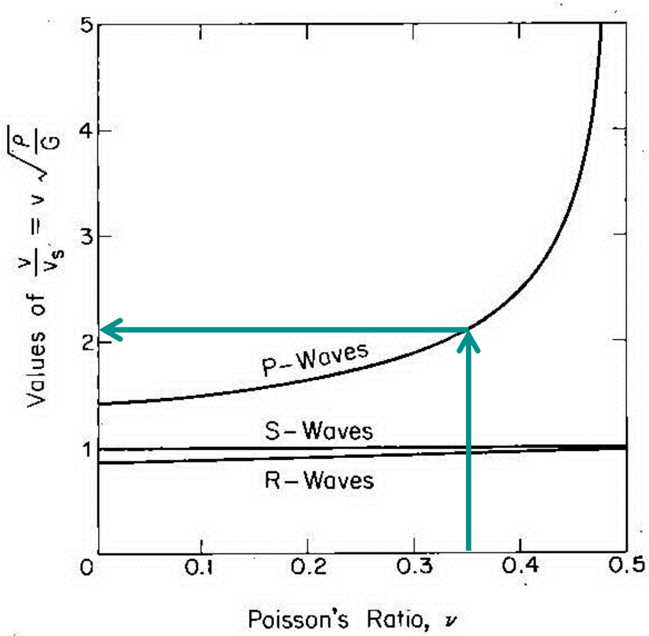


Figure 3-13. Relation between Poisson's ratio, ν, and velocities of propagation of compression (*P*), shear (*S*), and Rayleigh (*R*) waves in a semi-infinite elastic medium (*from Richart, 1962*).

Richart, Hall and Woods (1970)

Vibrations from Pile Driving

- Compression waves traveling in driven piles transmit shear energy from friction along the length of the shaft
- Tends to produce more S-wave energy
- The pattern of wave propagation is different than from surface excitation

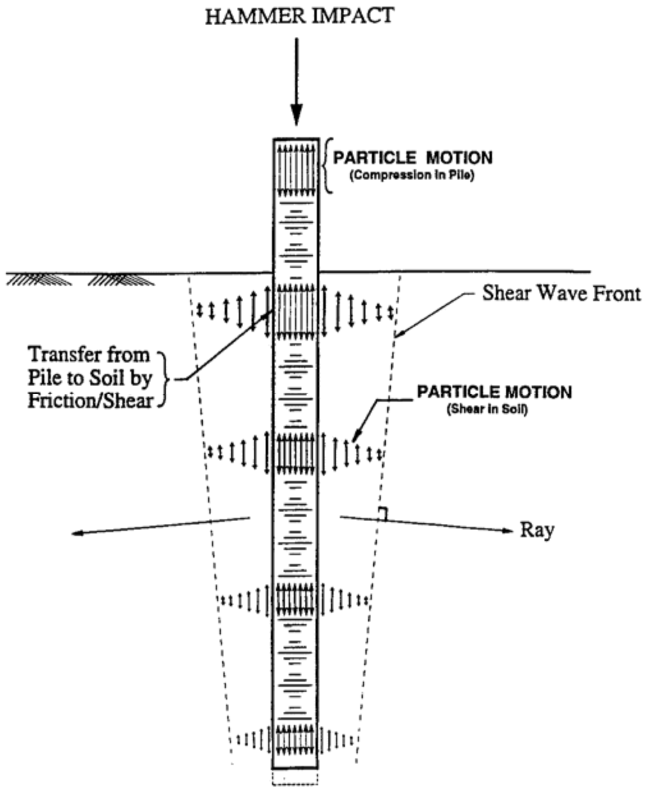


FIGURE 8 Ground waves from pile-soil shear.

Woods (1997)

Surface Vibrations in Layered Deposits

- Few soil deposits can be considered to be homogeneous and semi-infinite
- Incident body wave energy at layer boundaries is:
  - Transmitted,
  - Reflected, or
  - Refracted
- There are also wave conversions

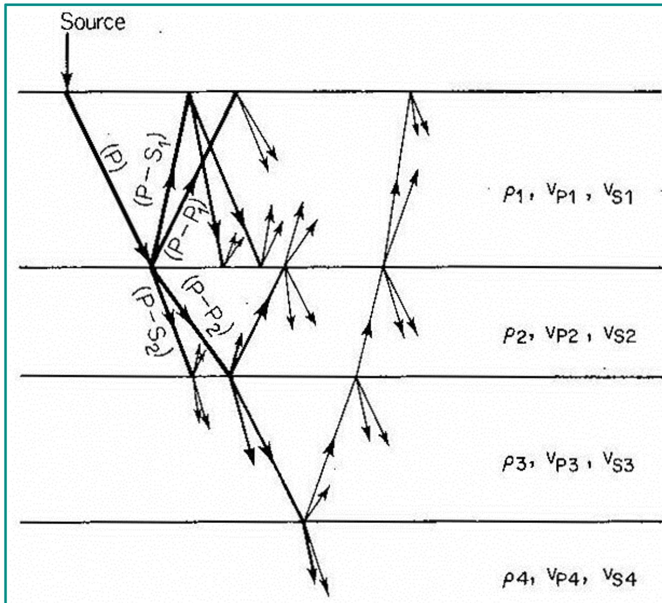


Figure 4-6. Multiple wave reflection and refraction in a layered half-space.

Richart, Hall & Woods (1970)

Pile Driving in Layered Deposits

- The amount of transmission, reflection, or refraction depends on the angle of incidence (α or β) and the impedance contrast
- The impedance contrast is essentially the ratio of stiffnesses; the greater the difference, the more reflected energy

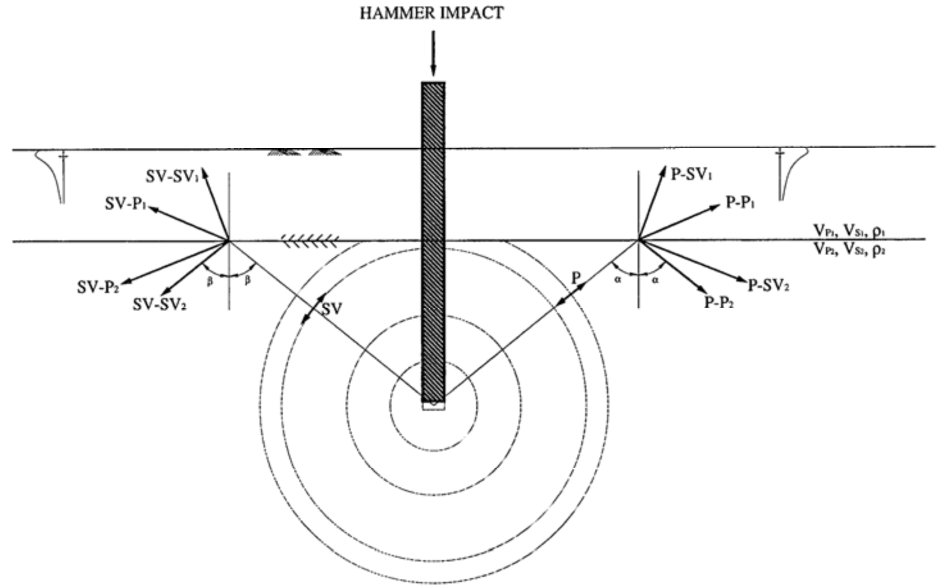
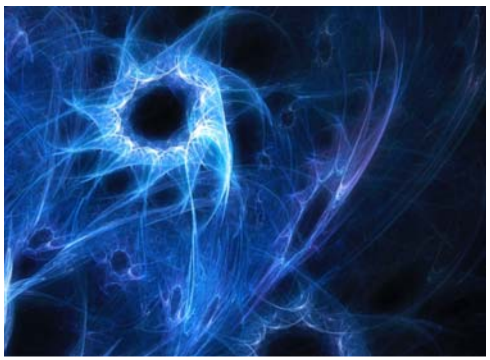


FIGURE 10 Partition of waves from impact-driven pile at soil layer boundary.

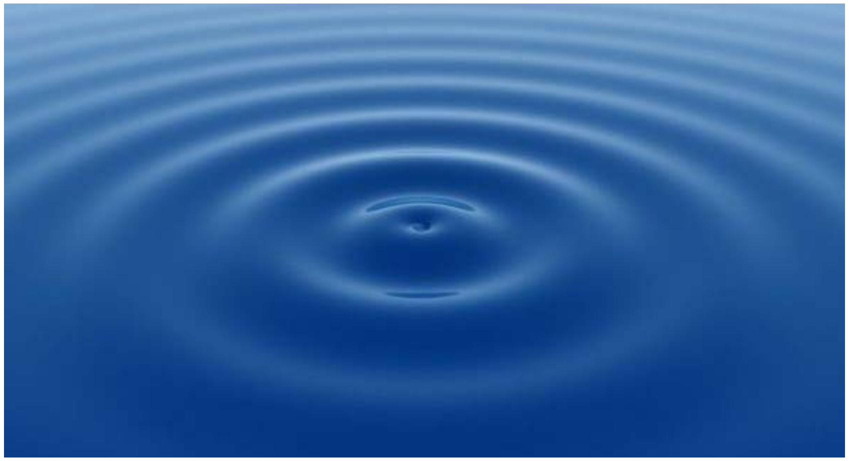
Woods (1997)



Energy Dissipation (Geometric and Material Damping)

Introduction

- Ripples in pond analogy
  - Water wave amplitudes decay as they spread
  - This is from geometric damping
- As we've seen, geometric damping occurs in waves propagating through soils, too
- Earth materials also have internal ("material") damping – energy that is lost as waves travel through the material



Attenuation

General equation:

$$w_2 = \boxed{w_1 \left(\frac{r_1}{r_2}\right)^n} \boxed{e^{-\alpha(r_2 - r_1)}}$$

Where: w_i = wave amplitudes
r_i = distances
1 = reference point
2 = point of interest

Woods and Jedele (1985)

Geometric Damping

- For surface waves, n = 0.5
- For body waves, n = 2 at surface and n = 1 in subsurface

Material Damping

- Damping coefficient, α, is dependent on material type, consistency/density, and frequency of vibration

Damping Coefficients

- The higher the attenuation coefficient, α, the greater the material damping
- Generally an order of magnitude increase in α with order of magnitude increase in frequency

TABLE 1

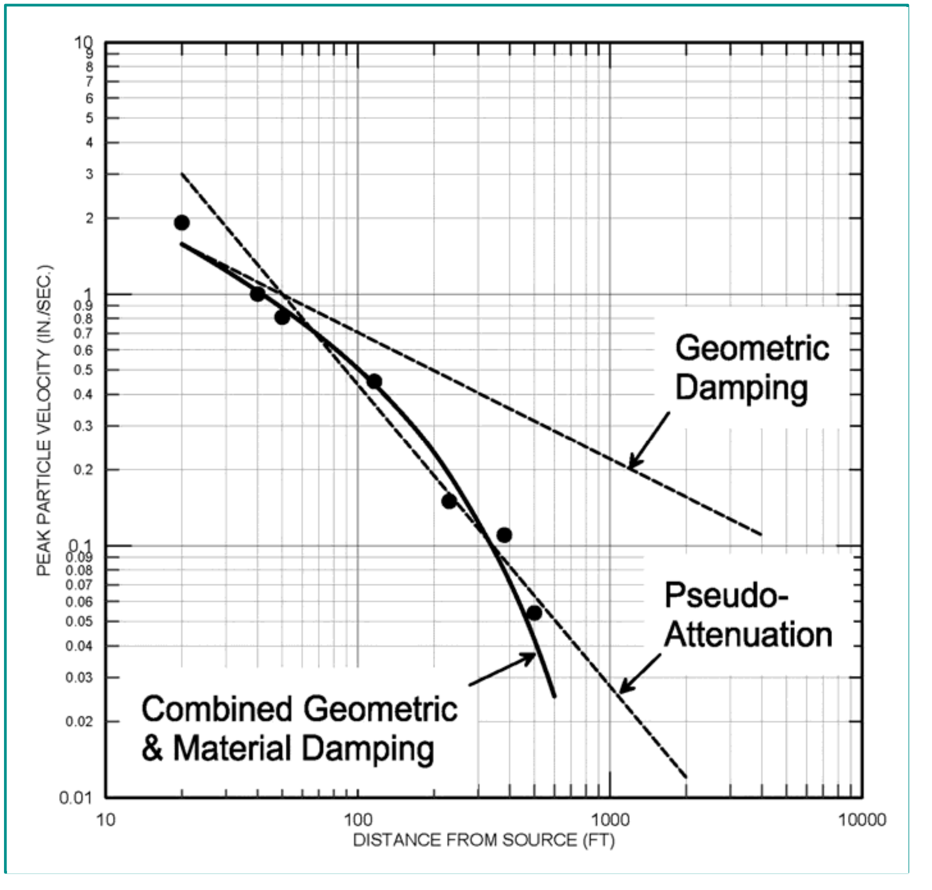
PROPOSED CLASSIFICATION OF
EARTH MATERIALS BY
ATTENUATION COEFFICIENT

CLASS	ATTENUATION COEFFICIENT α (1/ft) 5 Hz	50Hz	DESCRIPTION OF MATERIAL
I	0.003 to 0.01	0.03 to 0.10	Weak or Soft Soils-lossy soils, dry or partially saturated peat and muck, mud, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, toposoil. (shovel penetrates easily)
II	0.001 to 0.003	0.01 to 0.03	Competent Soils- most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel)
III	0.0001 to 0.001	0.001 to 0.01	Hard Soils- dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, must use pick to break up)
IV	<0.0001	<0.001	Hard, Competent Rock- bedrock, freshly exposed hard rock. (difficult to break with hammer)

Woods and Jedele (1985)

Pseudo-Attenuation

- Representing both damping components in attenuation plots is complicated
- Without material damping, you will over predict PPV
- Using a straight line ("Pseudo-attenuation") is a simplification for convenience and misses an important characteristic



Adapted from Woods and Jedele (1985)

Wiss (1974 and 1981)

- How many of you are familiar with this graph?
- What do these lines represent? Average? Upper bound?
- How were they developed?
- Have you ever measured vibrations that exceed lines?
- When/where are they applicable?

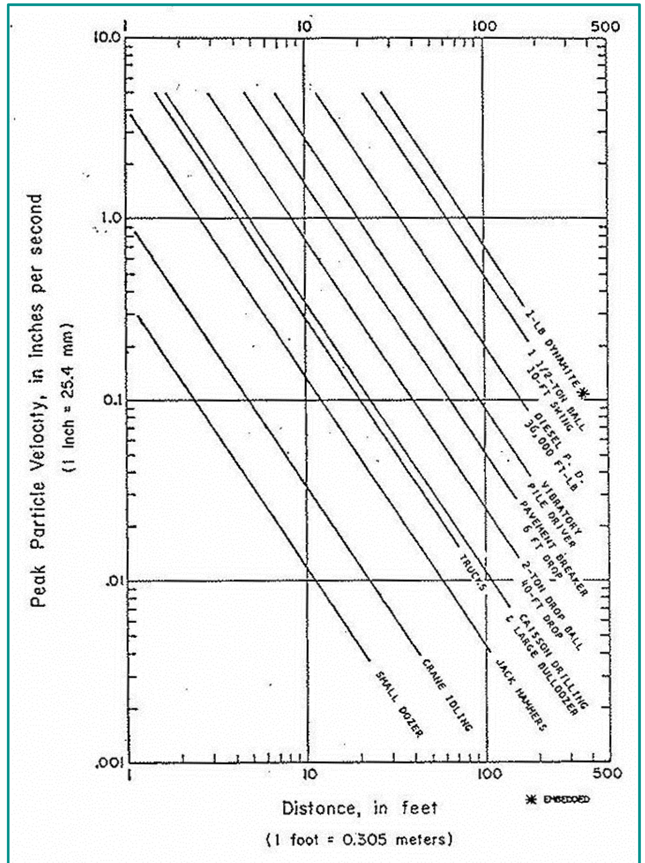


FIG. 5.—Relative Intensities of Construction Vibrations

Wiss (1981)

Wiss (1974 and 1981)

- Graph represents “***approximate values”; “typical intensities”*** of vibration
- Based on data recorded:
  - On surface of earth OR
  - IN residential or relatively small commercial buildings
- “The lines shown are for a particular set of soil conditions. The locations and slopes of lines for other conditions may be different.” (Wiss, 1981)

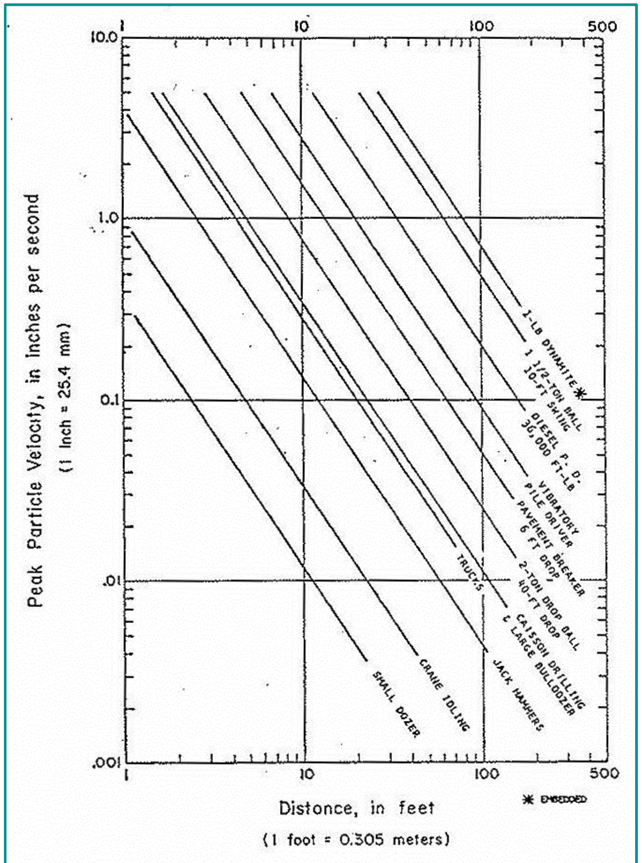
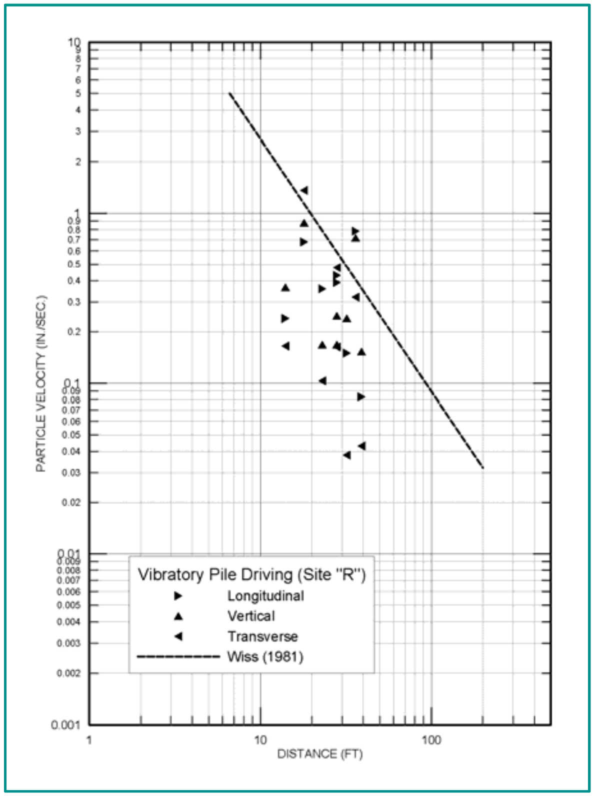
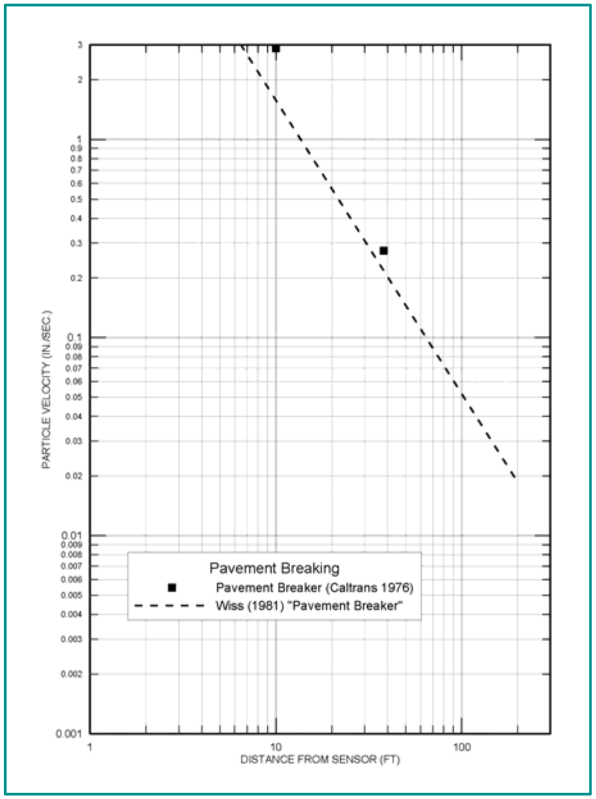


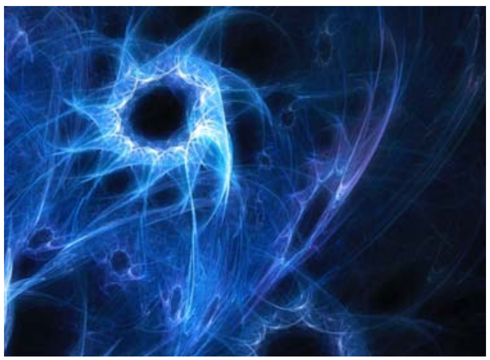
FIG. 5.—Relative Intensities of Construction Vibrations

Wiss (1981)

Examples of Exceedance







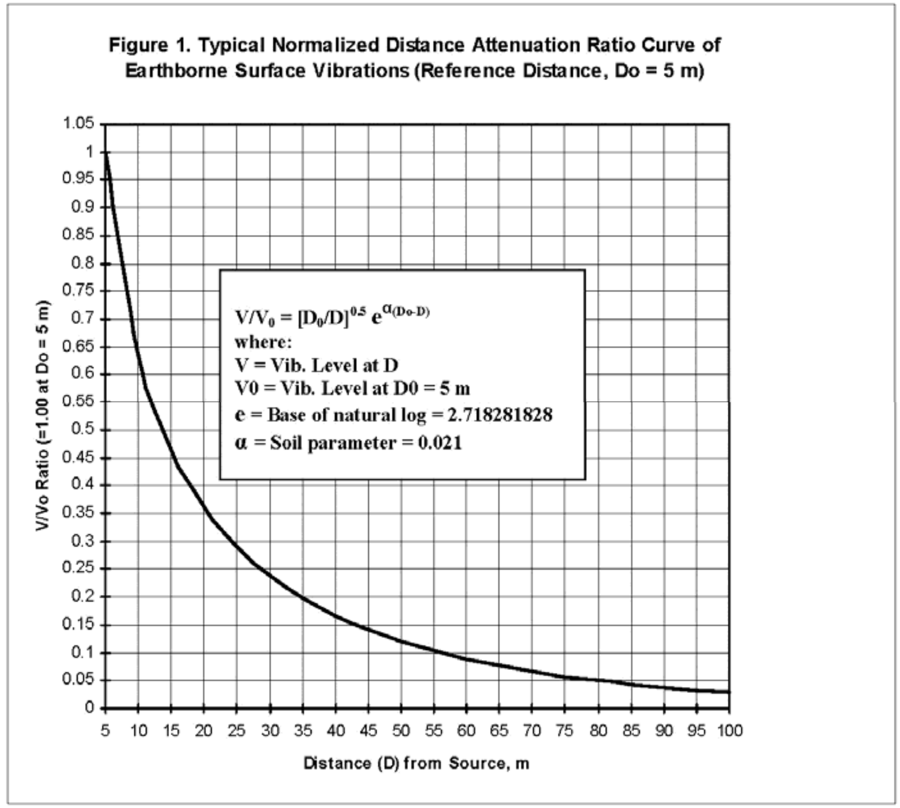
Data Scatter and Special Effects

Data Scatter and Special Effects

- The evaluation of construction vibrations is an empirical practice due to non-uniformity of:
  - Source energy
  - Earth materials
  - Human perception
  - Threshold vibrations causing physical damage
- Also, there is a reliance on a single parameter → PPV
- As it turns out, the scatter in data can be tremendous
- There is guidance, but data are proprietary and details regarding data sets are sparse; consider the source
- There are special situations that require special consideration

Proposed Attenuation

- The guidance in publications has not improved since Wiss (1981)
- Caltrans no longer shows actual vibration data as it did in 1976 report
- These smooth curves do not depict scatter and variability and can be misleading



Caltrans (2002)

Scatter in Attenuation from Pile Driving, Multiple Sites

- A 1982 example of scatter in measured vibrations for vibratory pile driving at multiple “soft soil” sites
- Data exceed guidance from Wiss (1981) for “vibratory pile driver”

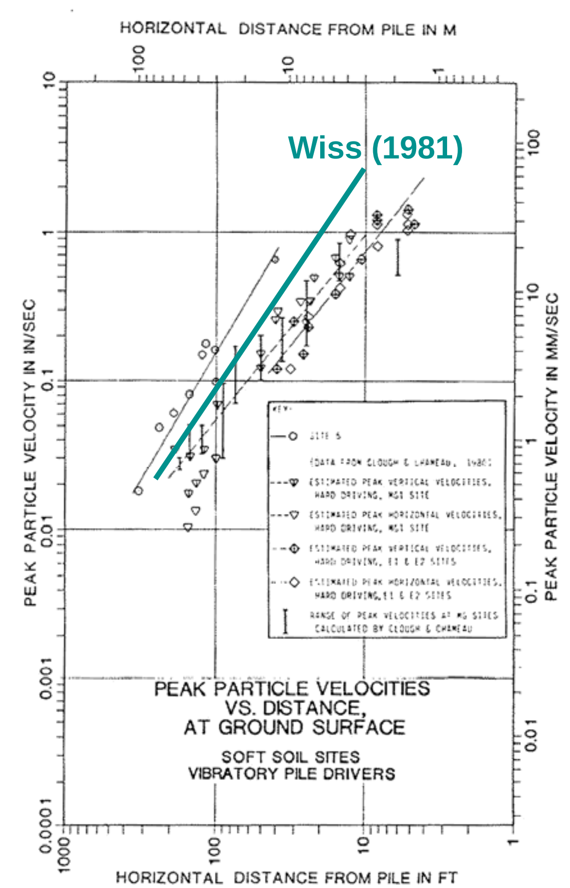
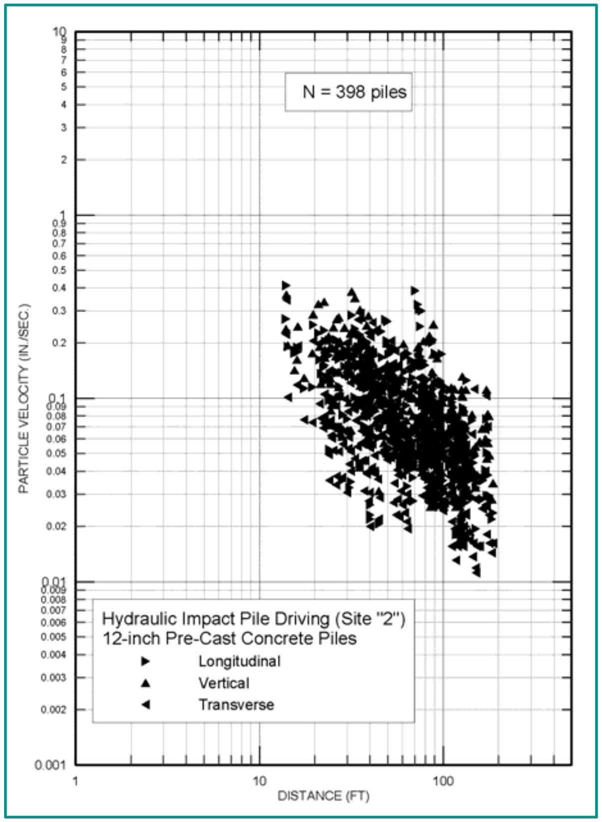


FIG. 5

Wood and Theissen (1982)

Scatter in Attenuation from Impact Pile Driving, Single Site

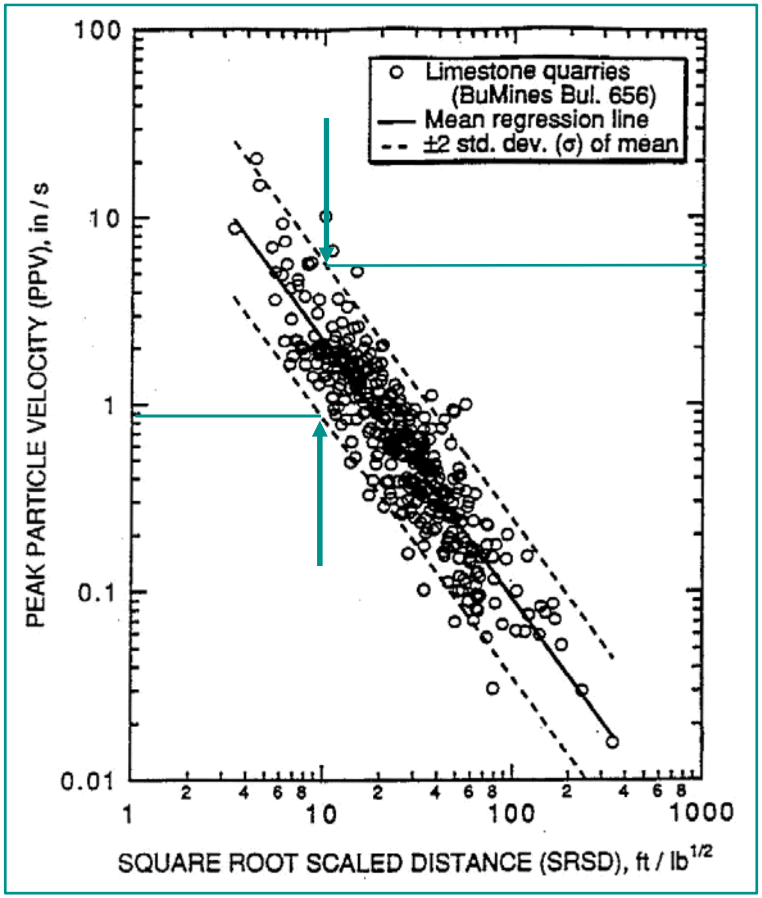
- An example of scatter in measured vibrations from driving 12-inch pre-cast concrete piles:
  - Single site
  - Hydraulic impact hammer
  - 398 piles
  - 3 components of PPV recorded
- How would you represent this data, all from one site, with a pseudo-attenuation line?



http://www.piledrivers.org/noise-vibration-database.htm

Scatter in Attenuation from Blasting, Multiple Sites

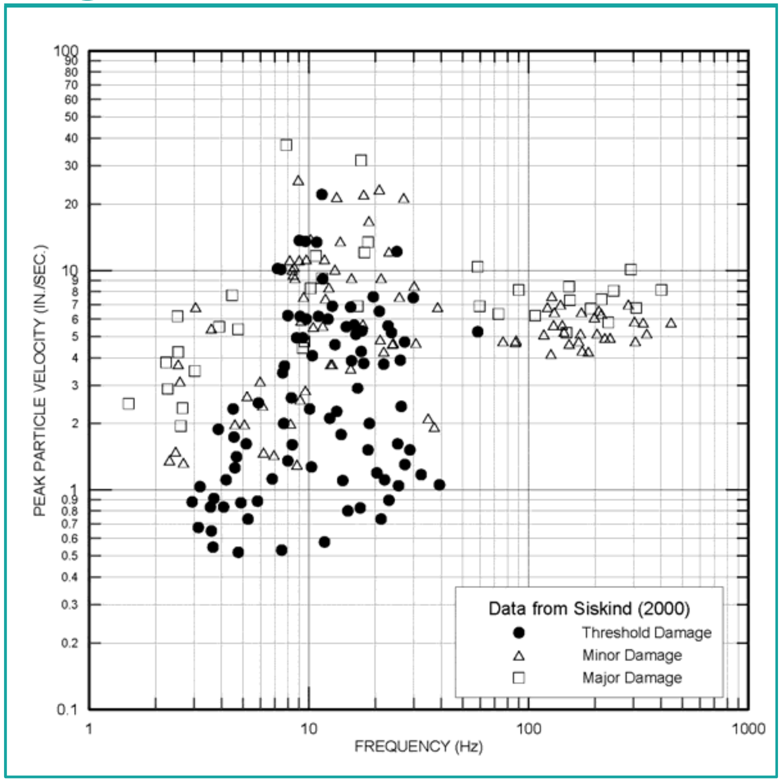
- Substantial data base of records
  - 11 limestone quarries
  - 171 blasts
  - 26 recording sites
  - Multiple distances per site
- Use “scaled distance” (SRSD) to normalize energy delivered for blasting
- At a SRCD of 10, PPV ranges from 0.9 to >5 ips at $\pm$ 2 σ



Crum et al (1995)

Scatter in Damage from Blasting

- The scatter in observed damage from blasting is substantial, too:
  - 553 observations
  - 240 blasts
  - 76 homes in 10 states
- Buildings with no damage not plotted
- Significant overlap among buildings with “threshold”, minor, and major damage



Adapted from Siskind (2000)

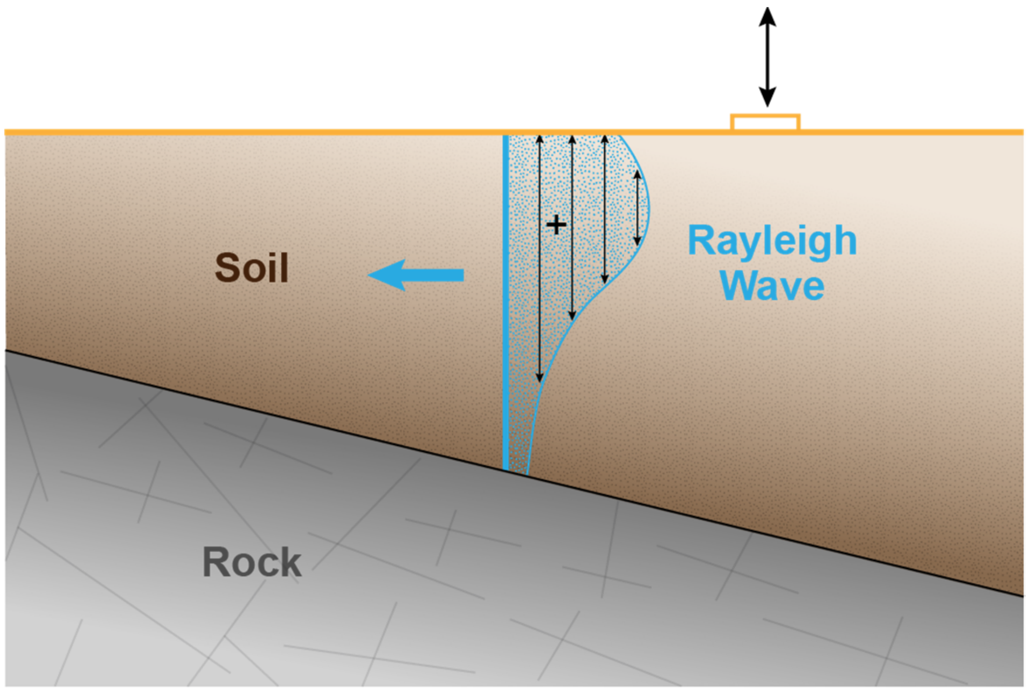
Resonance

- Soil layers can also be excited into resonance (higher amplitude) from construction vibrations, particularly with a high impedance contrast (e.g., silt over rock) or in a basin
- This effect is not captured in published attenuation relationships
- Resonance periods (or frequency) can be estimated by:
  - $T_n = 4H / V_s$ (sec) OR
  - $f_n = V_s / 4H$ (Hz)

Where: H = layer thickness
V_s = shear wave velocity

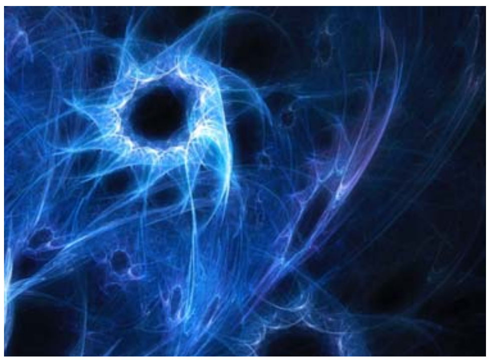
Dipping Ledge (Rock)

- A shallow, dipping rock layer beneath soil can have tremendous effect on the magnitude of ground motions
- Apply basic principles of reflection, refraction, and conservation of energy
- Energy is trapped and vibrations are amplified



Dipping Ledge (Rock)

- This effect has been studied for surface waves, e.g.:
  - Kane & Spence (1963)
  - Mal & Knopoff (1965)
  - Fuji et al (1980)
  - Ohtsuki & Yamahara (1984)
- This “basin edge” effect has been verified during earthquakes, including 1994 Northridge (e.g., Graves et al. 1998) and 1995 Kobe earthquakes
- This effect is not captured in published attenuation relationships



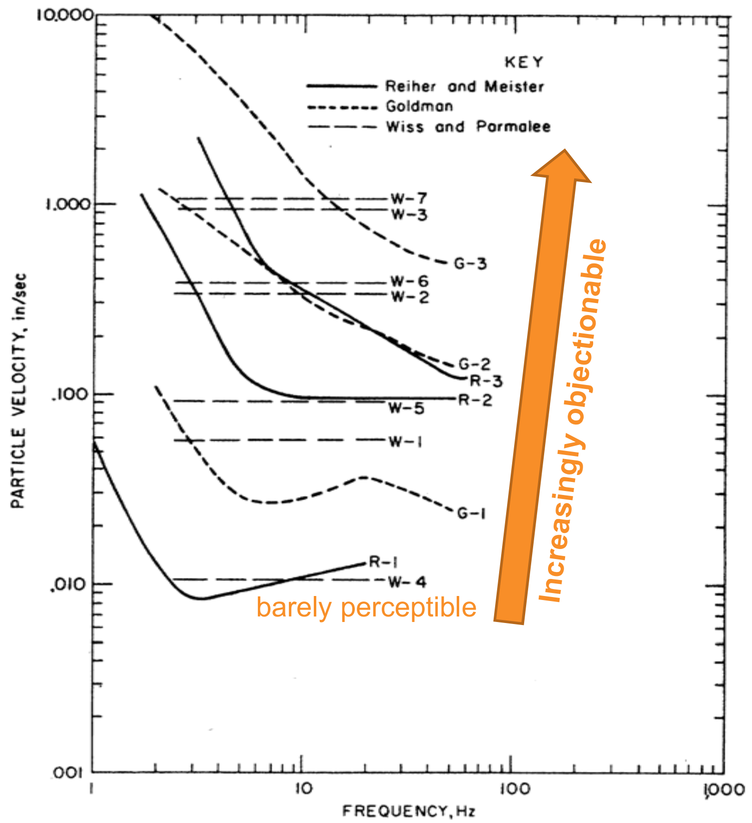
Human Perception

Human Perception

- Studies on human perception of vibrations date to early 20th century

Figure ID	Reiher and Meister (1931)	Goldman (1948)	Wiss and Parmalee (1974)
R-1	Barely Noticeable	-	-
R-2	Objectionable	-	-
R-3	Uncomfortable	-	-
G-1	-	Perceivable	-
G-2	-	Unpleasant	-
G-3	-	Intolerable	-
W-1	-	-	Barely Perceivable*
W-2	-	-	Distinctly Perceptible*
W-3	-	-	Strongly Perceptible*
W-4	-	-	Barely Perceptible**
W-5	-	-	Distinctly Perceptible**
W-6	-	-	Strongly Perceptible**
W-7	-	-	Severe**

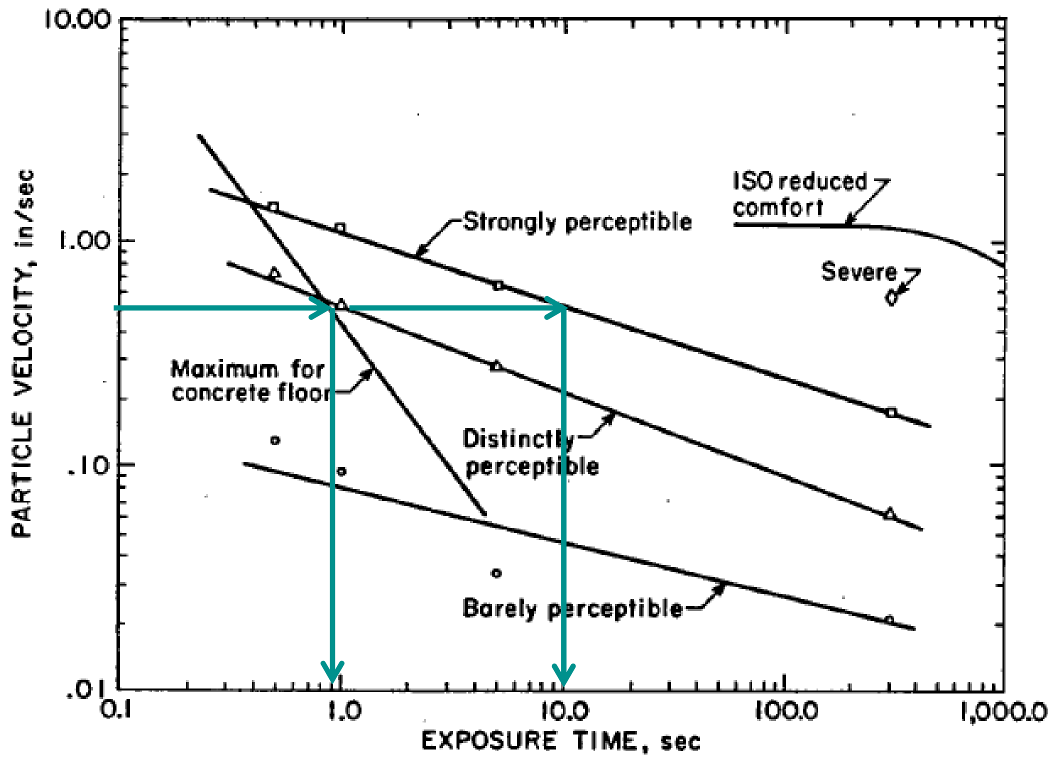
* Mean of all data ** Threshold for this level



Siskind et al (1980)

Human Perception (*cont.*)

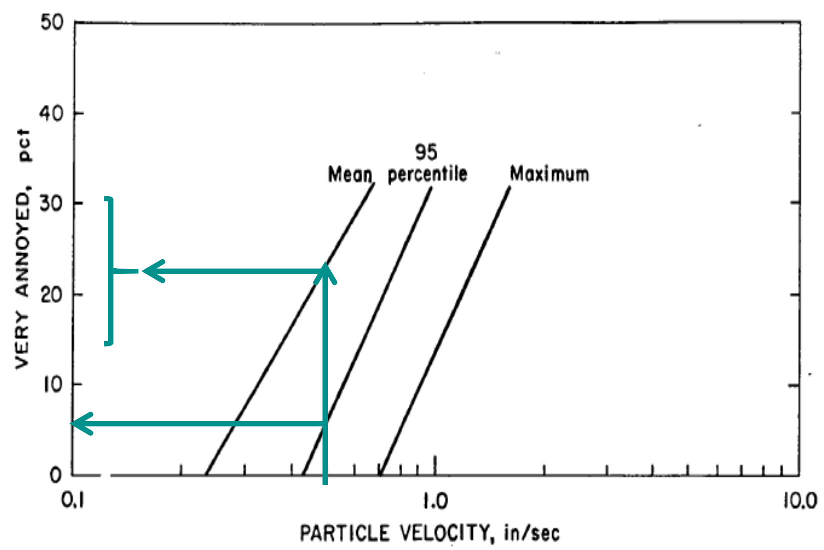
- Human perception is affected by length of exposure
- At 0.5 ips, vibrations change from “distinctly perceptible” to “strongly perceptible” as exposure time extends from 1 to 10 sec.



Siskind et al (1980). ISO values from Standard 2631.

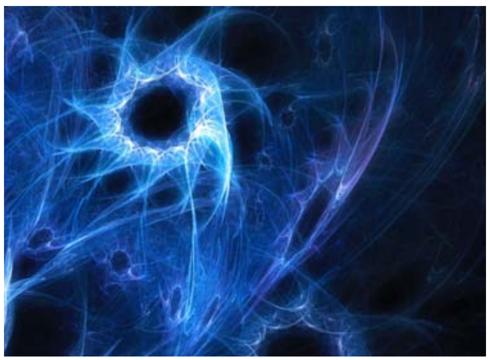
Human Perception (*cont.*)

- Human perception varies widely
- "*…it is expected that a mean ground vibration level of 0.50 in/sec in a community will produce 15 to 30 pct "very annoyed" neighbors. The 95-pct line gives 5 pct very annoyed at 0.5 in/sec.*" (Siskind et al. 1980)



Fi; ure 67.—Reactions of persons subjected to blasting vibration in their homes.

Siskind et al (1980)



Damage Thresholds

Damage Thresholds

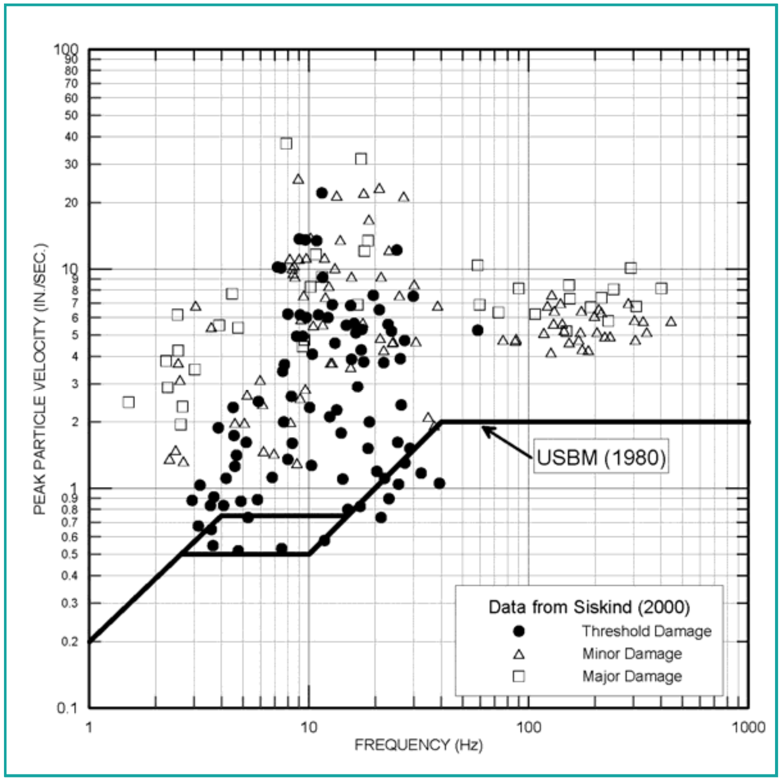
- The most comprehensive studies of vibration-induced damage on structures are based on blasting data from mining industry
- Somewhat consistent findings from other sources of construction vibrations

Occurrence	Lowest ground shaking	Source
Cracking of finishes (plaster) in residences	0.51 ips	*Siskind (2000)*
Drywall cracking	0.79 ips	*Wiss and Nicolls (1974)*
Cracking of concrete block	> 3.0 ips	*Crawford and Ward (1965)*

Damage to Residential Buildings from Blasting

- Threshold damage: "*loosening of paint; small plaster cracks at joints between construction elements; lengthening of old cracks*."
- Minor damage: "*loosening and falling of plaster; cracks in masonry around openings near partitions; hairline to 3-mm cracks (0 to 1/8 in.); fall of loose mortar*."
- Major damage: "*cracks of several millimeters in walls; rupture of opening in vaults; structural weakening; fall of masonry, e.g., chimneys; load support ability affected*."

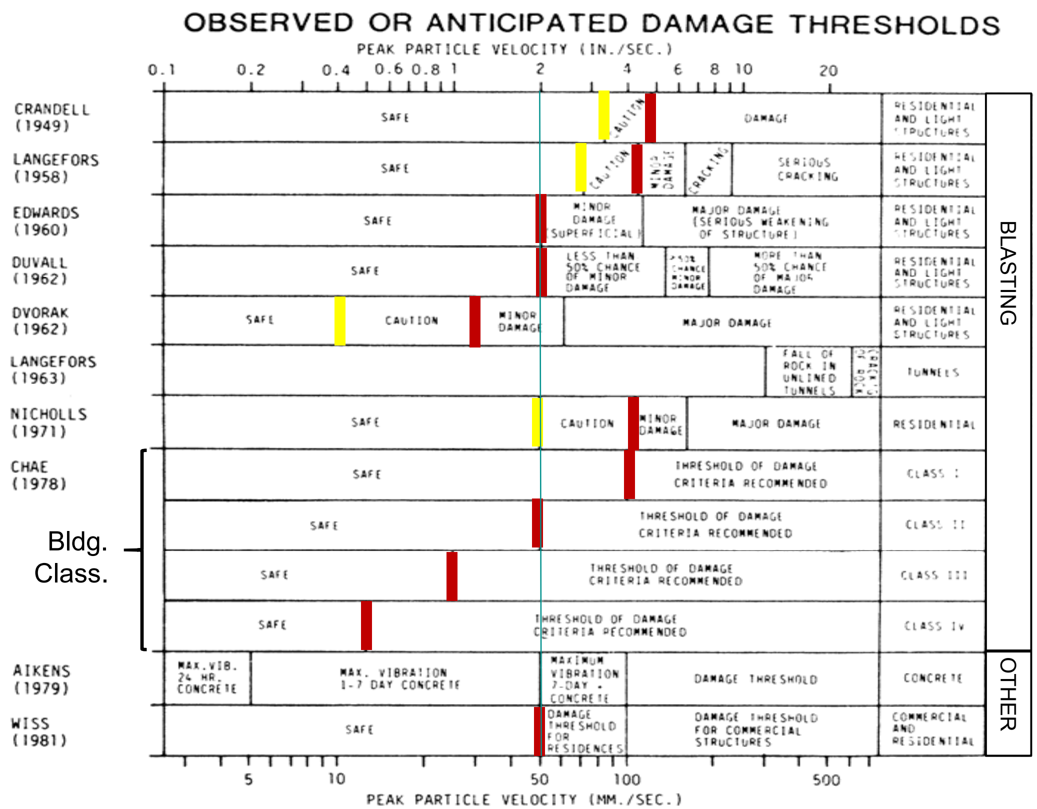
Siskind et al. (1980)



Adapted from Siskind (2000)

Historic Comparison

- Comparison of various published damage criteria, mostly from blasting
- Most not focused on cosmetic damage
- Typically minor damage requires PPV >2 ips
- Dvorak (1962) suggested caution for PPV >0.4 ips for brick homes in Europe
- Chae (1978) based on construction type



Adapted from Wood and Thiessen (1982)

Damage Thresholds

Table 19. Guideline Vibration Damage Potential Threshold Criteria

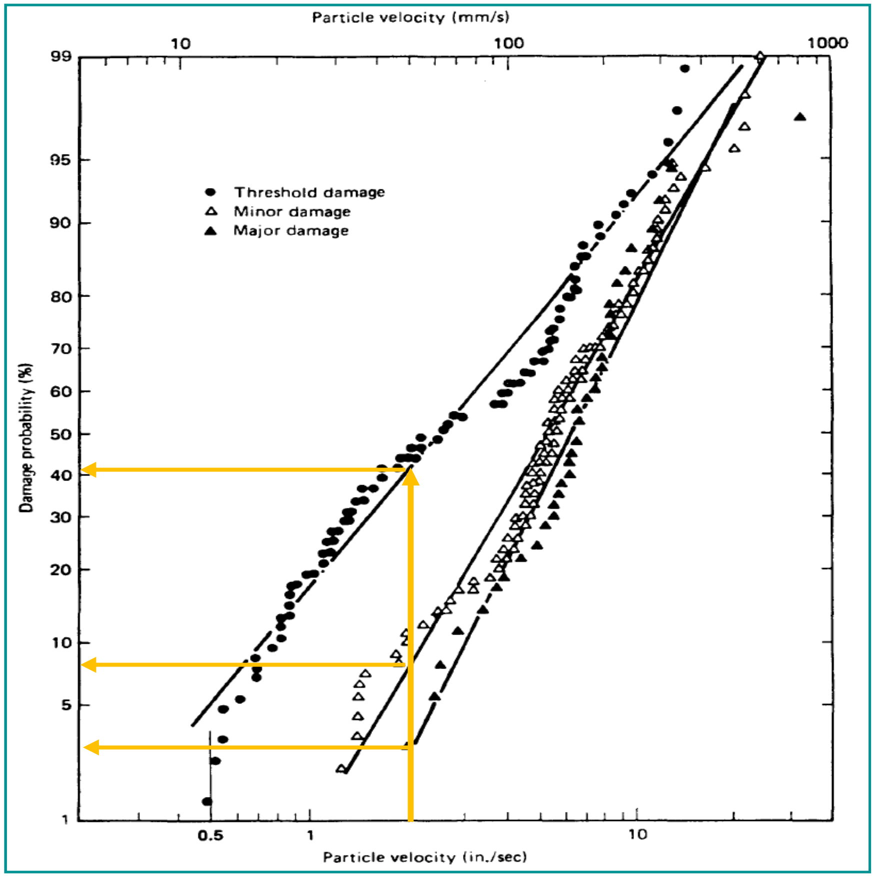
Structure and Condition	Maximum PPV (in/sec) Transient Sources	Maximum PPV (in/sec) Continuous/Frequent Intermittent Sources
Extremely fragile historic buildings, ruins, ancient monuments	0.12	0.08
Fragile buildings	0.2	0.1
Historic and some old buildings	0.5	0.25
Older residential structures	0.5	0.3
New residential structures	1.0	0.5
Modern industrial/commercial buildings	2.0	0.5

Note: Transient sources create a single isolated vibration event, such as blasting or drop balls. Continuous/frequent intermittent sources include impact pile drivers, pogo-stick compactors, crack-and-seat equipment, vibratory pile drivers, and vibratory compaction equipment.

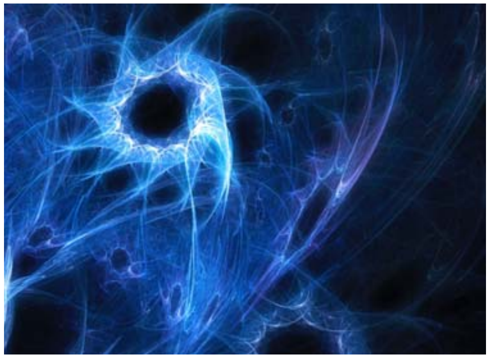
Caltrans (2004)

Damage Thresholds

- Just because a threshold is exceeded does not mean damage will occur
- Using vibrations from blasting, e.g., at PPV = 2 ips:
  - ~3% probability of major damage
  - ~7% probability of minor damage
  - ~40% probability of threshold damage



Siskind et al (1980)



Indirect Effects

Indirect Effects

- Vibrations can cause densification of soil, which can induce ground settlement; this is referred to as an indirect effect
- Densification is most prominent in granular soils; effects have been identified in some clayey soils, too
- Densification of soils owing to cyclic shear strains have been studied in the laboratory by:
  - Les Youd
  - Marshall Silver
  - Ricardo Dobry
  - Mladin Vucetic

Threshold Shear Strain for Granular Soils

- The concept of *threshold shear strain*, γ_t , was developed based on these studies and championed by Prof. Ricardo Dobry
- Typically, a γ_t of 0.01% is accepted for granular soils

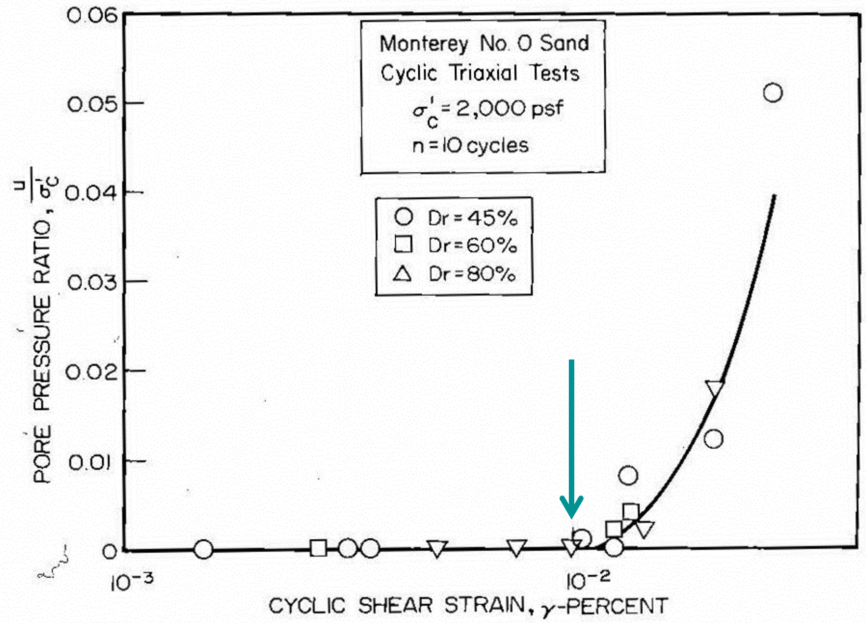


FIGURE 2-30 Pore pressure ratio versus cyclic shear strain, illustrating the concept of a threshold strain required to cause generation of excess pore water pressures. Source: Dobry et al. (1981a).

NRC (1985); from Dobry et al (1981)

Threshold Shear Strain for Cohesive Soils

- Cohesive soils are less likely to densify
- The γ_t is strongly dependent on plasticity index
- See, for example:
  - Vucetic (1994)
  - Hsu and Vucetic (2006)
  - Vucetic, Doroudian, and Sykora (2010)

Number of Cycles of Loading and Shear Strain

- The number of cycles of loading is important to estimate the amount of densification (i.e., change in void ratio)
- Applies to impulsive waves (e.g., blasting) and periodic waves (e.g., vibratory rollers)

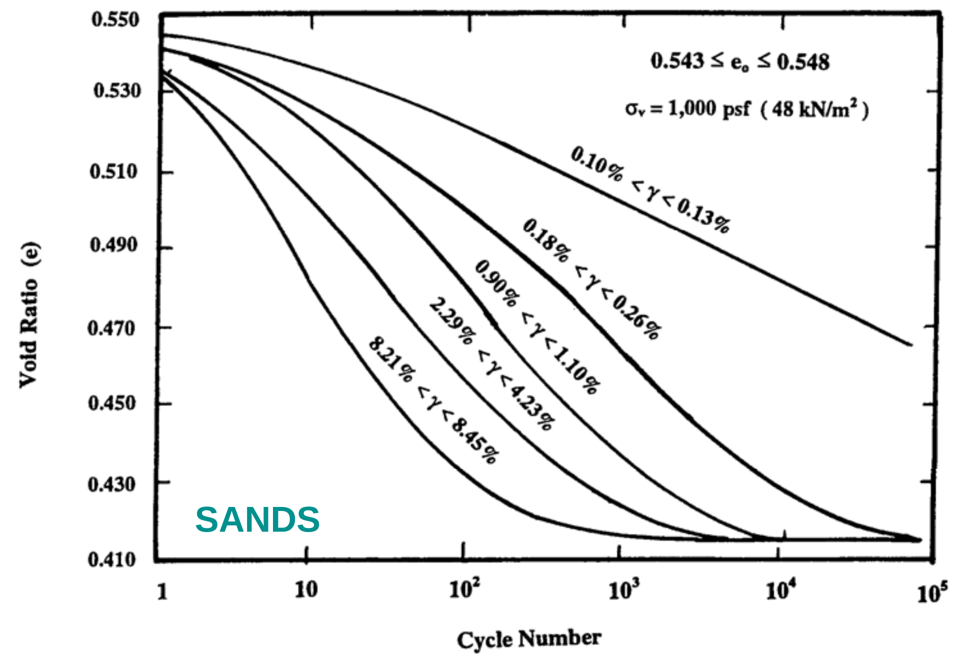


FIGURE 23 Effect of shear-strain amplitude on compaction (27).

Woods (1997); from Youd (1972)

Test for Exceedance

- Assuming that the energy is propagating as shear waves, then one can estimate the shear strains (γ) induced by vibrations:

$$\gamma = PPV / V_s$$

- Compare with threshold shear strain
- This chart simplifies the computation
- For Vs = 500 fps and PPV of 0.5 ips, γ =0.1%, which exceeds γ_t

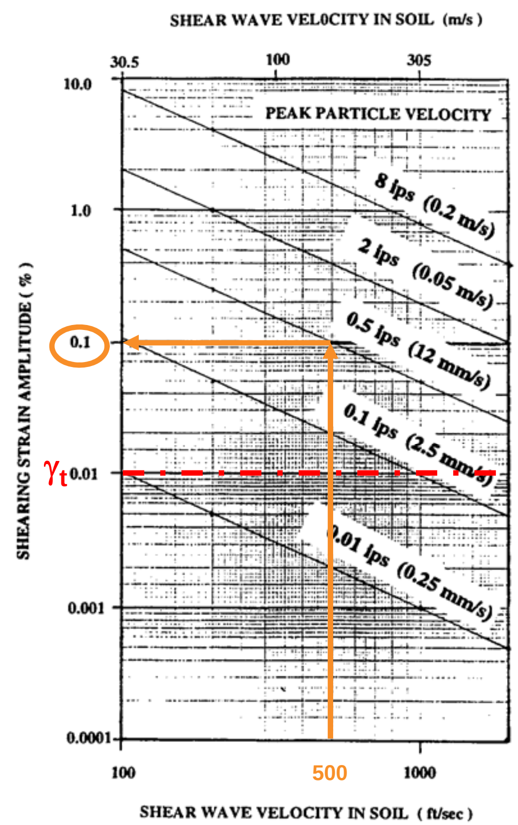


FIGURE 24 Shear wave velocity and particle velocity versus shearing strain.

Woods (1997)

Shear Wave Velocity Estimates

- If you don't have a measured shear wave velocity of the soil, use a lower bound estimate based on correlations with SPT N-value or effective stress to compute a conservative value of γ :

e.g., $(V_s)_{min} = 4N_{60} + 375$ (fps)
(Granular Soils)

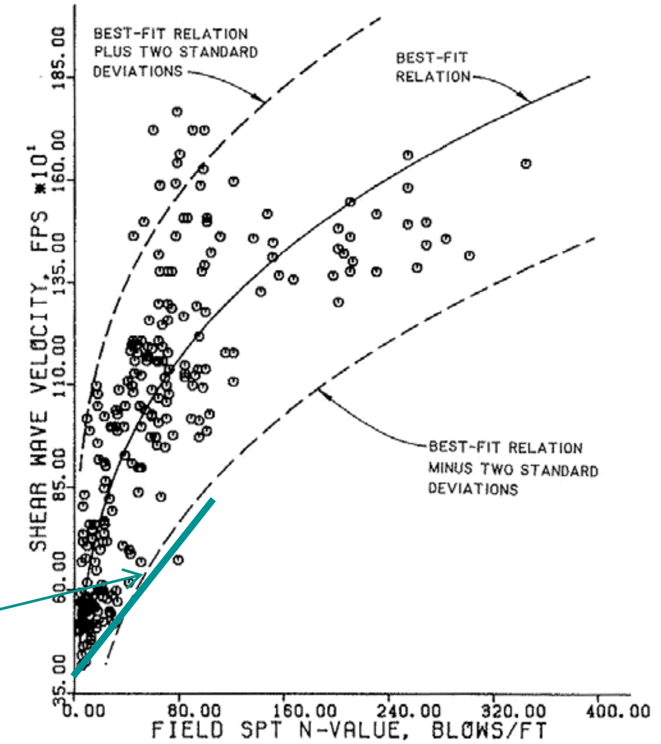


Figure 10. Correlation between SPT N-value and V_s using crosshole methods as performed by Sykora and Stokoe (1983)

Sykora (1987)

Dynamic Settlement Estimate from Shear Strain

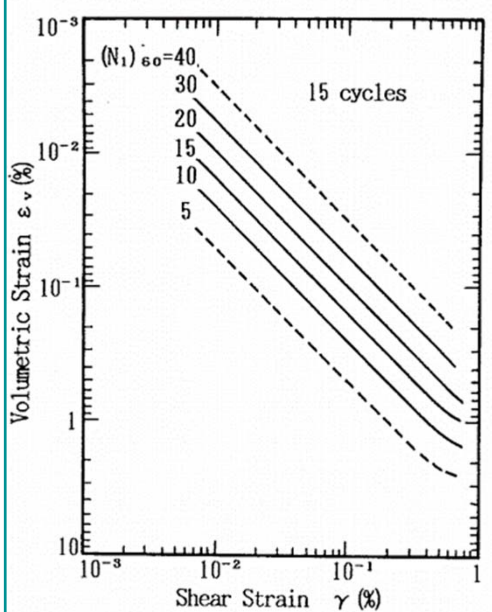


Fig. -2 Cyclic Shear Strain, $(N_1)_{60}$ vs. Volumetric Strain

Ishii and Tokimatsu (1988)

to ε_{15}. The following equation gives a good prediction that falls inside the relatively narrow band found experimentally by Silver and Seed:

$$\varepsilon_{Nc} = \varepsilon_{15} \cdot \left(\frac{N_c}{15}\right)^{0.45} \quad (11)$$

This prediction is shown in Fig. 4.

The predictions obtained using (11) are based on unidirectional simple shear tests. Multidirectional tests by Pyke et al. (1975) showed that the volumetric strains need to be doubled in order to take into account the multidirectional nature of earthquake shaking. Therefore, settlement, ΔS, of a layer with thickness Δh is given by

$$\boxed{\Delta S = 2 \cdot \Delta h \cdot \varepsilon_{Nc}} \quad (12)$$

Liquefaction

- Under extreme circumstances, vibroseis machines have induced liquefaction in loose, hydraulic fill
- $(N_1)_{60}$ of 1-4 blows/ft
- Shear strains (estimated maximum 0.055%) exceeded threshold shear strain (0.01%)

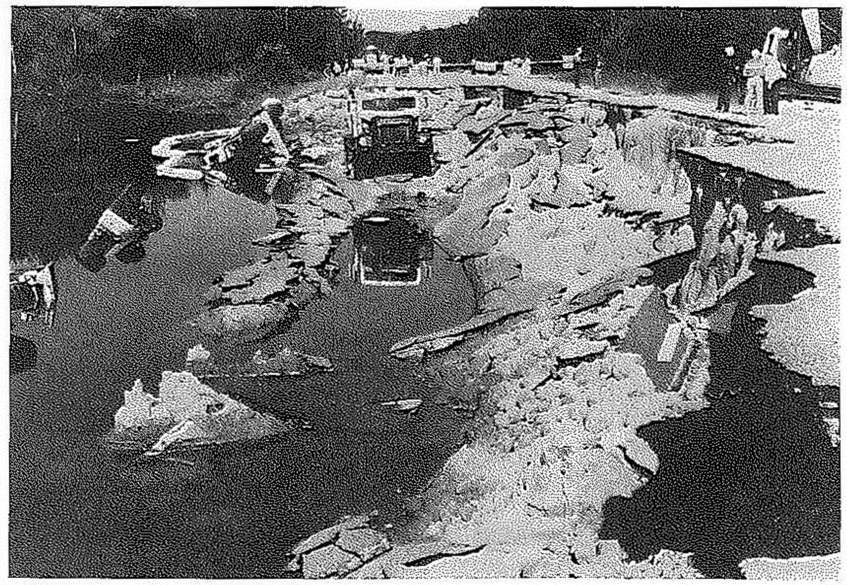
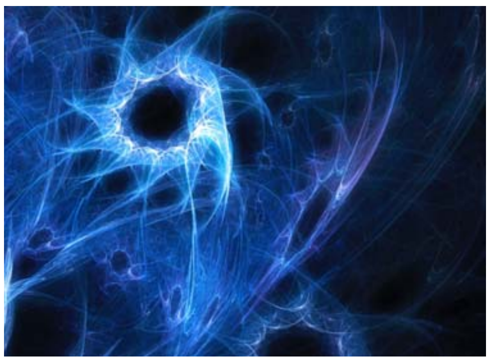


FIG. 4. Failed Embankment (View Looking West). Trucks No. 2 and No. 3 Are Almost Submerged on Left Side of Photograph

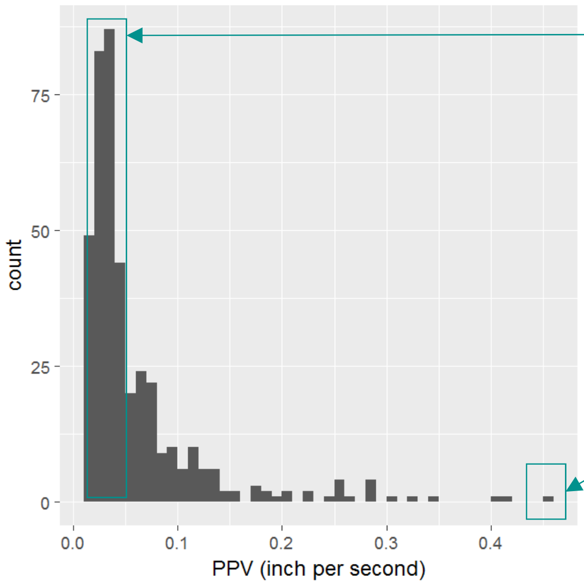
Hryciw et al (1990)



Analysis of Data

Histogram of PPV

- Measure peaks and quantify number



Smaller PPVs will normally have a higher frequency of occurrence

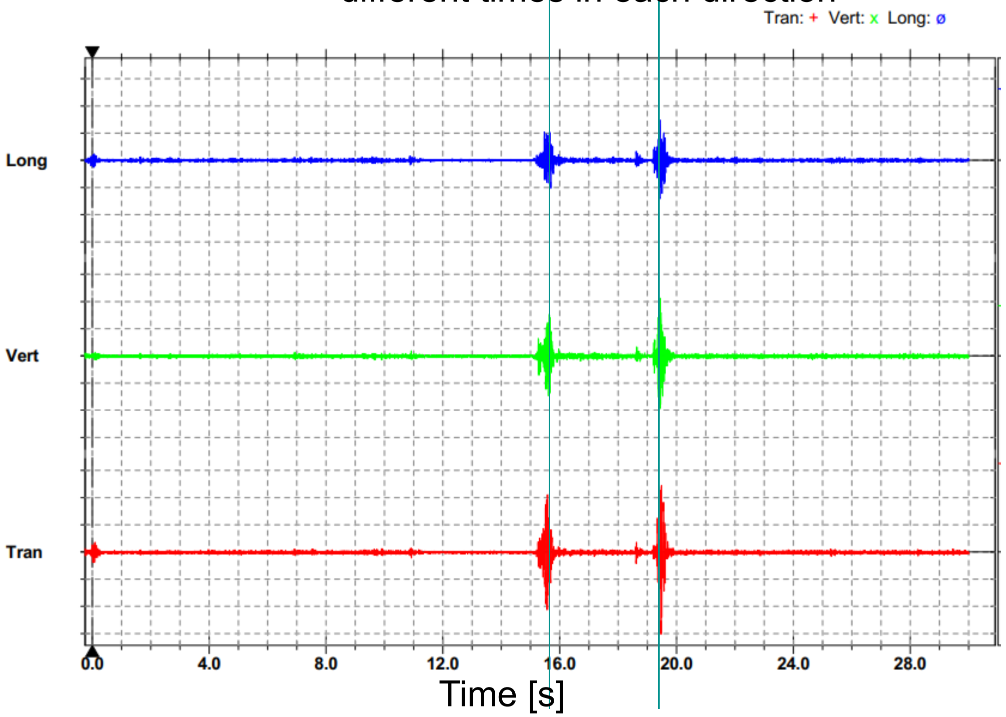
Max PPV measured has low occurrence frequency

Question: Is recording only the highest PPV sufficient?

Answer: Not necessarily, particularly for soil densification.

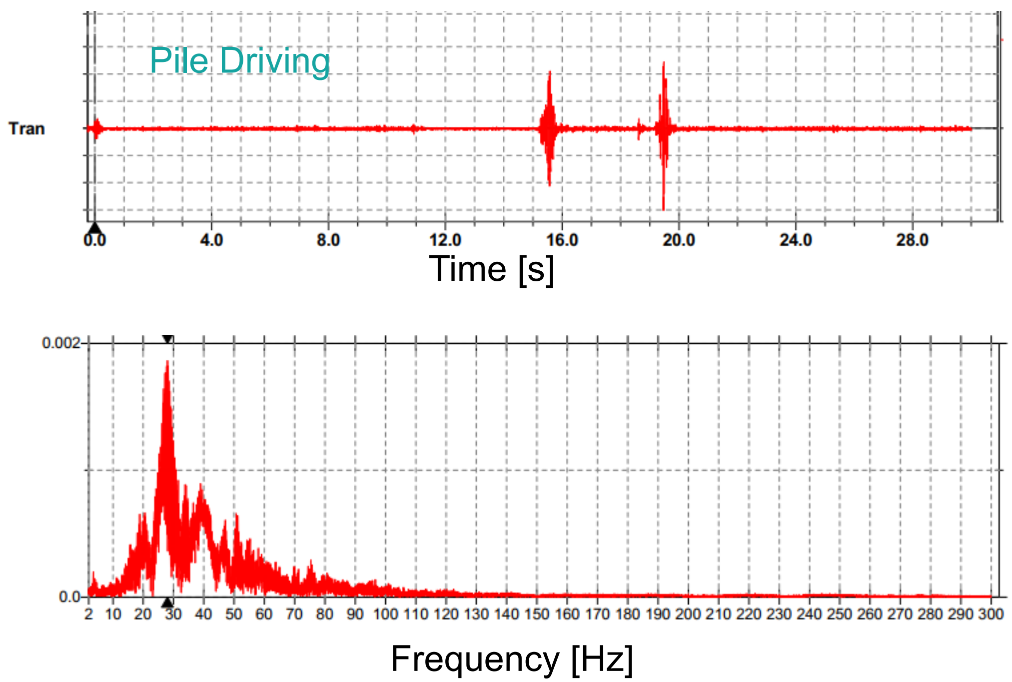
Velocity Time Histories and Peak Vector Sum

Peaks may occur at slightly different times in each direction



- Rather than using the peak of the three components separately, one can also consider the peak of the combined time history, which can be computed if time histories are available
- Provides a more accurate reflection of peak motion

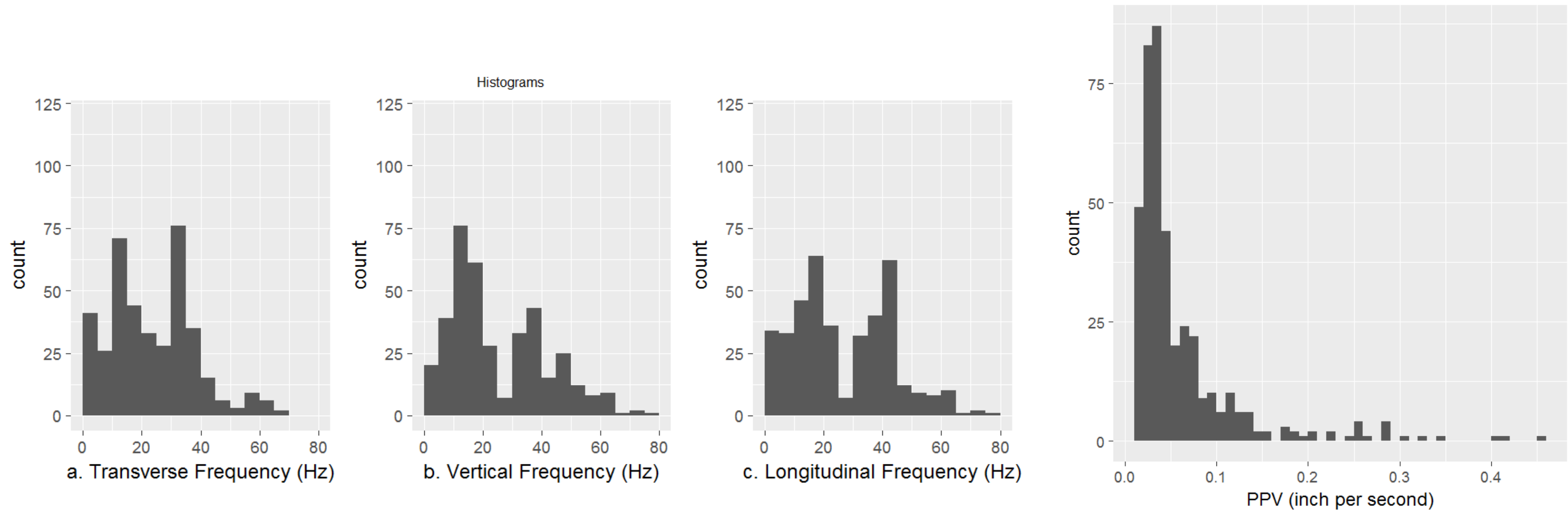
Fast Fourier Transform (FFT)



- FFT allows for evaluation of frequency content
- Important to carefully choose time window for FFT, e.g.:
  - entire record: 28 Hz
  - 2 s around peak: 29 Hz

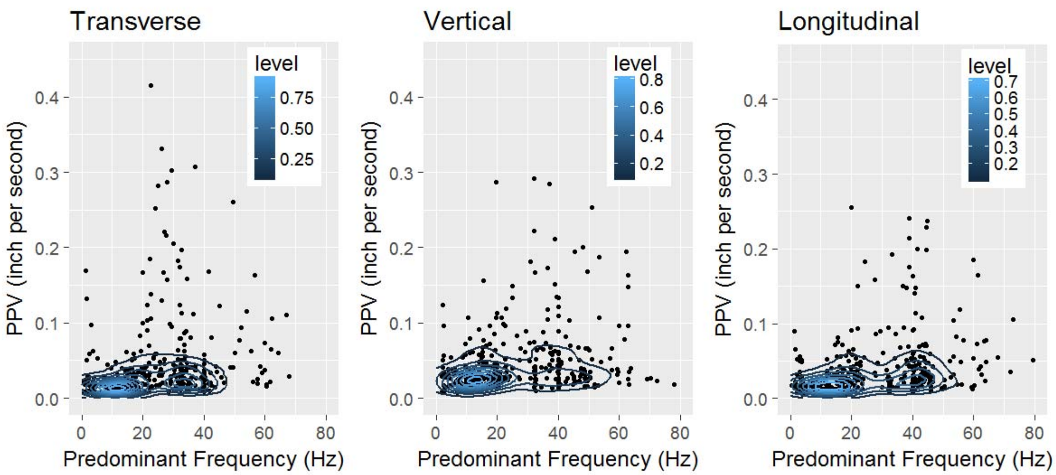
Directionality

- With 3-D time history data, one can quantify PPVs and frequency content in each direction



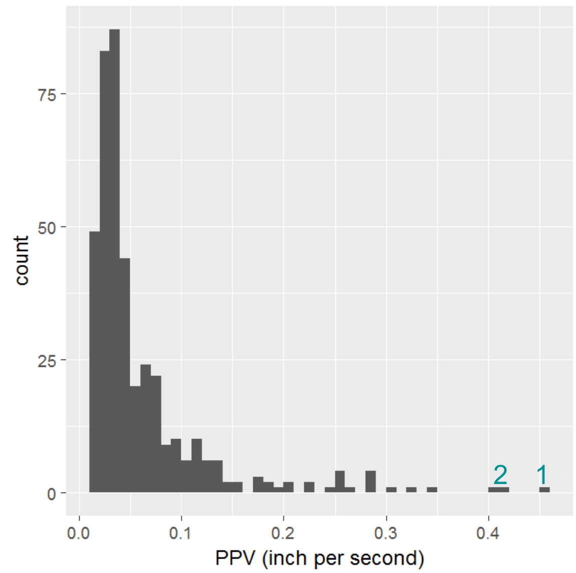
Predominant Frequency

- PPV vs. # occurrences may not be sufficient to estimate "important" frequencies
- PPV vs. Predominant Frequency maps may allow for estimation of the "important" site specific frequencies

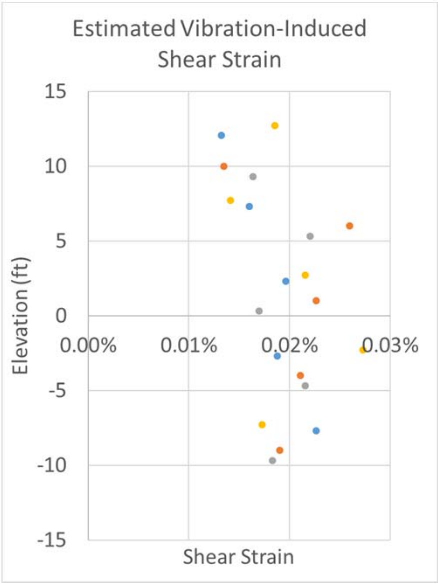


Example of Calculated Soil Shear Strains

Measured PPVs

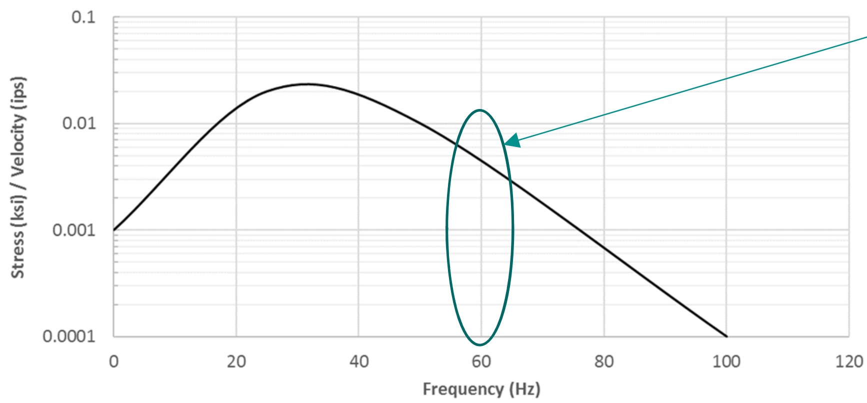


Maximum vibration induced shear strain based on SPT N-value



Compare Data with Structure Specific Transfer Functions

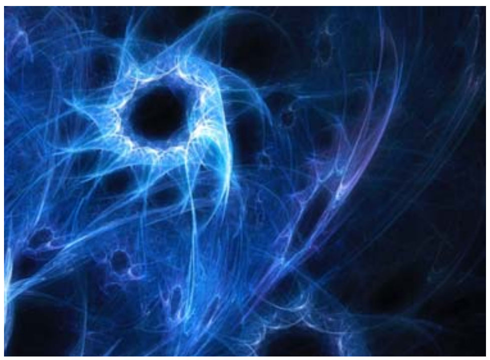
Structure Specific Transfer Function



Find expected response based on excitation frequency

Question: How can one create a structure specific transfer function?

Answer: Through structure vibration monitoring, laboratory testing or FE analysis



Discussion