# Settlement & Vibration Monitoring for Transmission Line Foundation Installation

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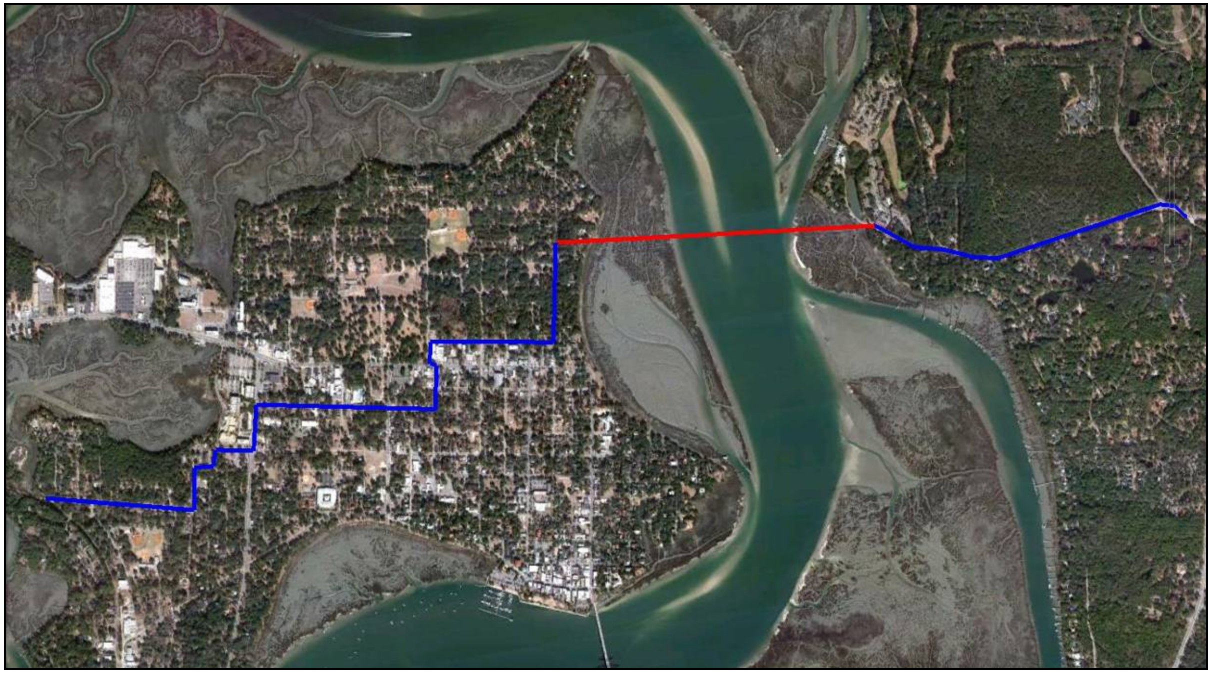
# Scenario

- New 4-mile long transmission line constructed through small town in SC Coastal Plain
- Proposed alignment passed near numerous residential and commercial structures.



# Project Details

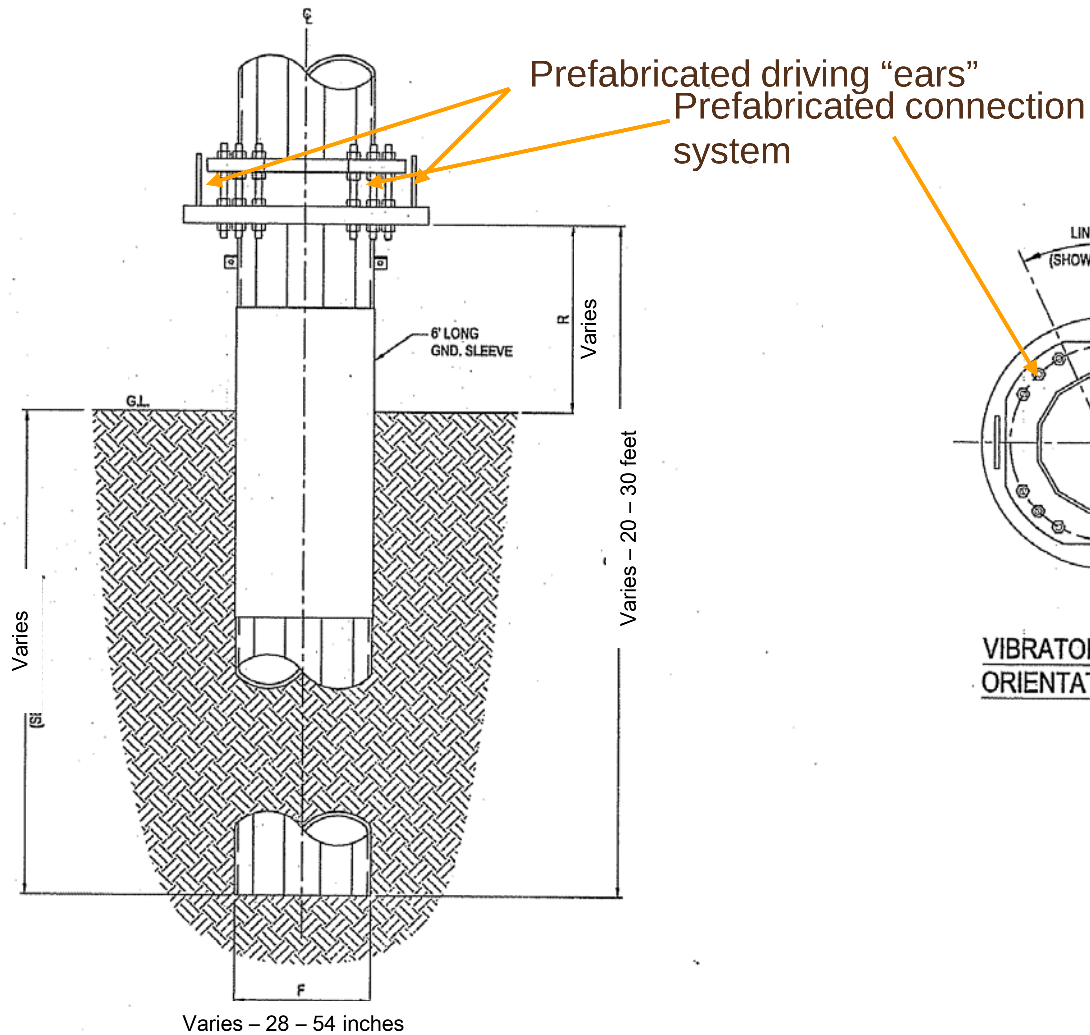
- Involved construction of 54 new poles.
- Existing timber poles replaced with taller, prefabricated steel poles.
- Vibratory “caisson” foundations selected to support new poles.
- Caissons were installed with vibratory hammers.
- Foundation locations generally within 50 ft from nearby structures, with some as close as 8 ft to 20 ft.

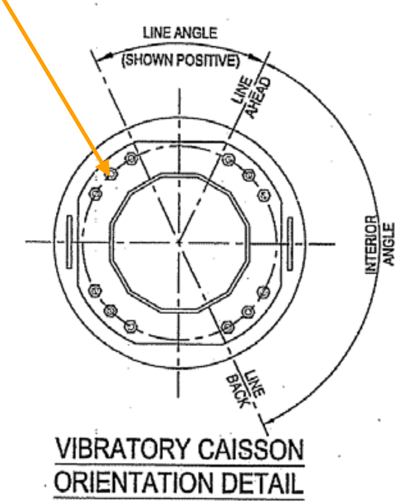
# Transmission Line Plan

# Pros and Cons of Vibratory Caissons

- Pros:
  - Quick installation.
  - Less expensive than alternative drilled foundations.
  - Easily customized for optimum design (different diameters and lengths at each foundation location).
- Cons:
  - Early refusal requires field retrofit.
  - Vibratory installation has potential to cause disturbance or damage.

# Vibratory Caisson Foundation



# Vibratory Caisson Foundation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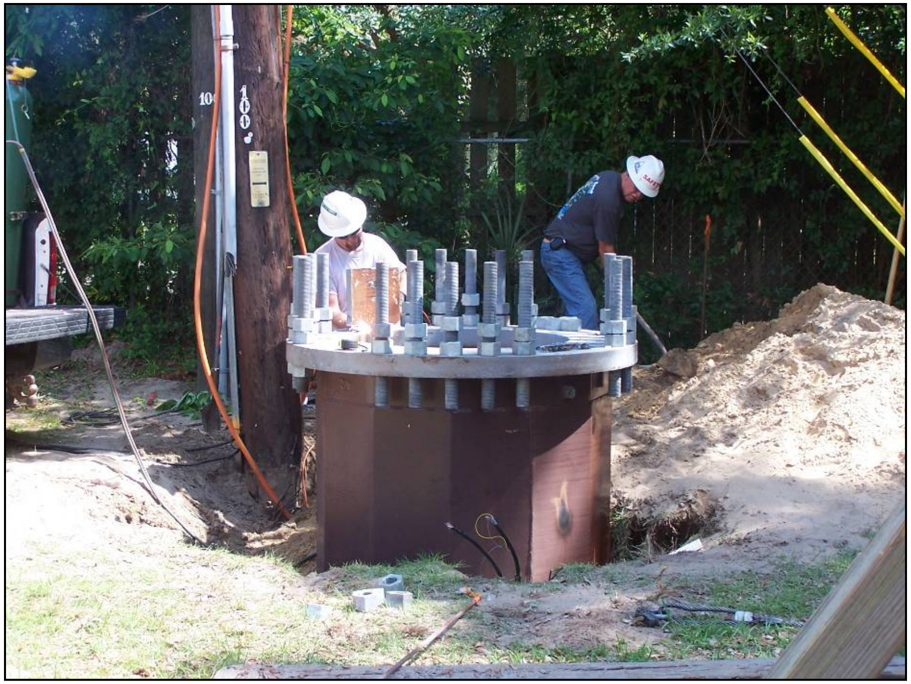
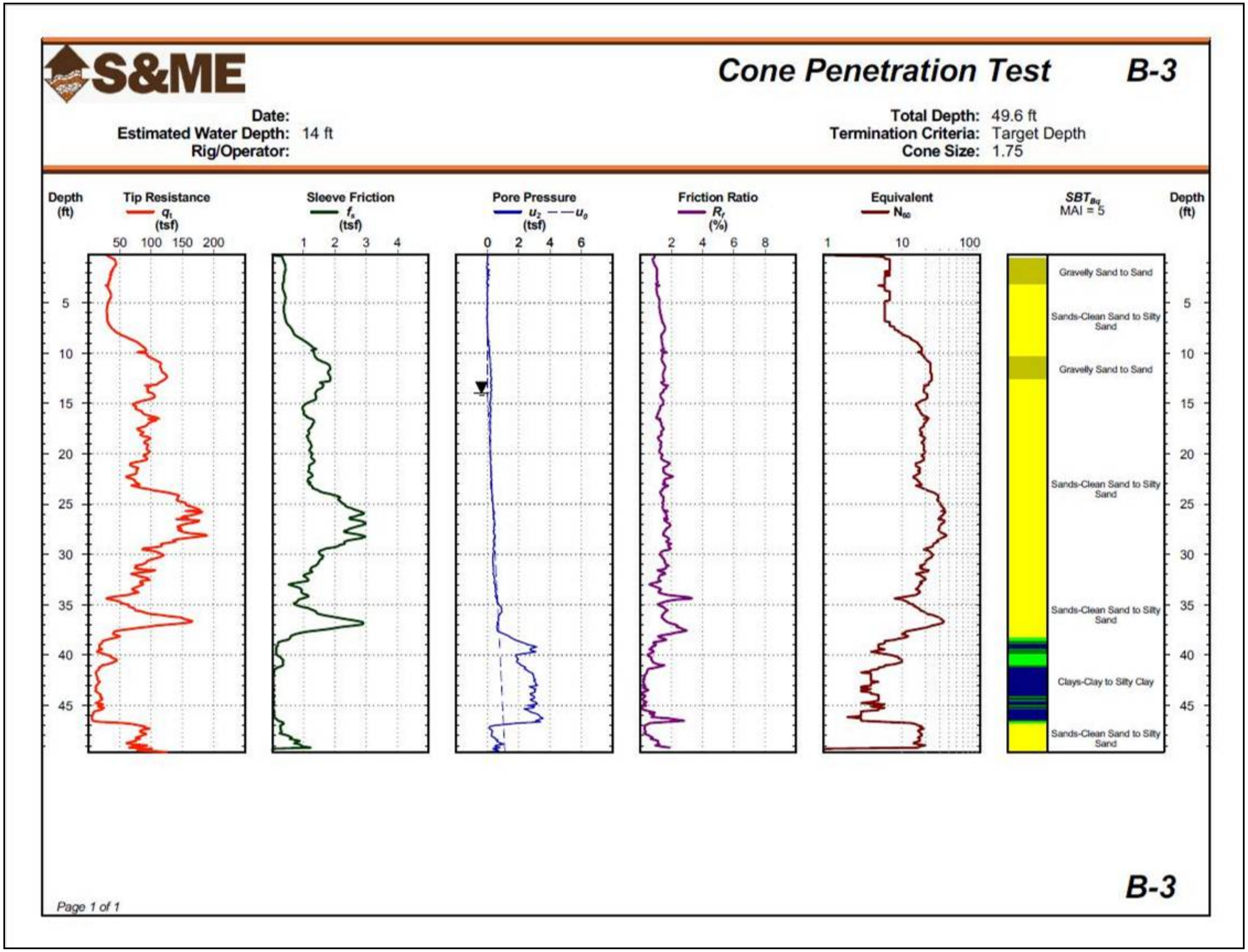


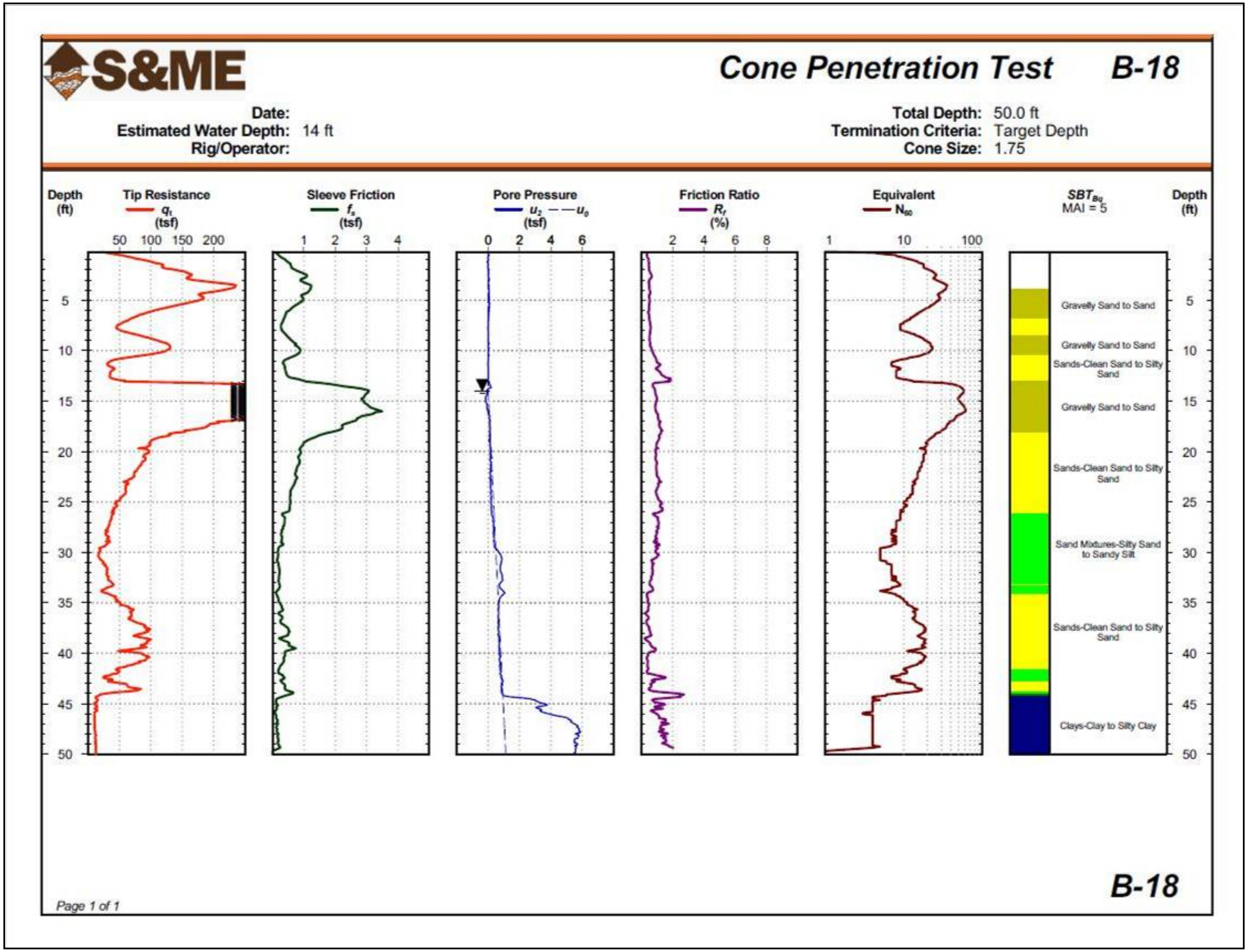
# Subsurface Conditions

- A widely-spaced exploration consisting of 20 Cone Penetrometer Test (CPT) Soundings was performed.
- Generally loose to medium dense slightly silty to silty sands within upper 40 to 50 feet.
- Tip stresses in the sands were generally 15 to 150 tsf.
- Groundwater was encountered at depths of 9 to 15 ft below ground surface.

# Example CPT Logs



# Example CPT Logs



# Construction Concerns

- Vibrations – potential for damage to nearby structures.
- Vibrations – human perception
- Settlement of loose sands.
- Hard driving may create higher vibrations.
- Proximity of foundation locations to nearby structures.

**Would the construction vibrations be detrimental to the nearby structures?**

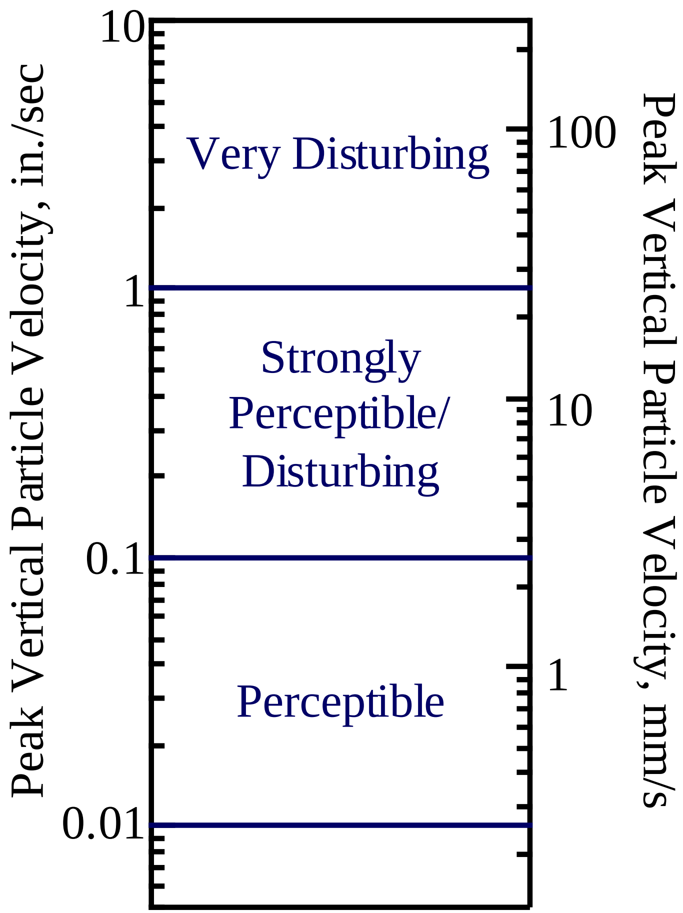
# Monitoring Program

- Vibration Monitoring:
  - Measure ground vibrations with seismographs.
- Settlement Monitoring:
  - Pre- and Post-installation ground elevation surveys.
- Limited Condition Assessment of Structures:
  - Visual and photographic documentation of existing condition of nearby structures.
  - Performed from utility Right-Of-Way and publicly accessible areas.

# Human Perception

- People sense or respond to very low vibrational intensities.
- Noise is often more disturbing than the vibration alone.
- Combination of noise and vibration draw attention to existing damage previously unnoticed.

# Human Perception Thresholds




*(from Bay, 2004)*

*(after AASHTO R 8-96, 2008)*

# Structural Response

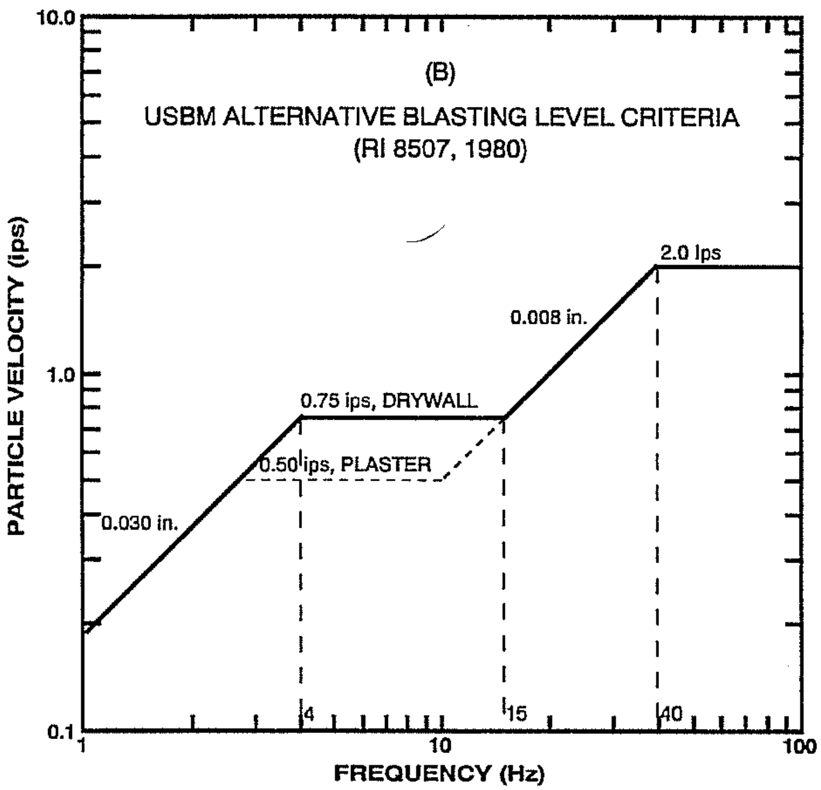
- Multiple published criteria for evaluating the damage potential of vibrations – majority developed for blasting/mining applications.
- Different basis for analysis
  - Peak Particle Velocity (PPV)
  - Weighted Root Mean Square Accelerations

# Common Vibration Criteria

- Frequency-dependent criterion
  - U.S. Bureau of Mines (Siskind et al., 1980).
  - OSMRE (Rosenthal, et al., 1987).
  - BS 7385 (British Standards Institute, 1993).
  - DIN 4150 (German Standards Org., 1999).
- Other frequency-independent criterion (e.g. Oriard, NAVFAC DM-7_02, Eurocode, Dowding, Bay, Jones and Stokes, etc.)

# USBM Criteria

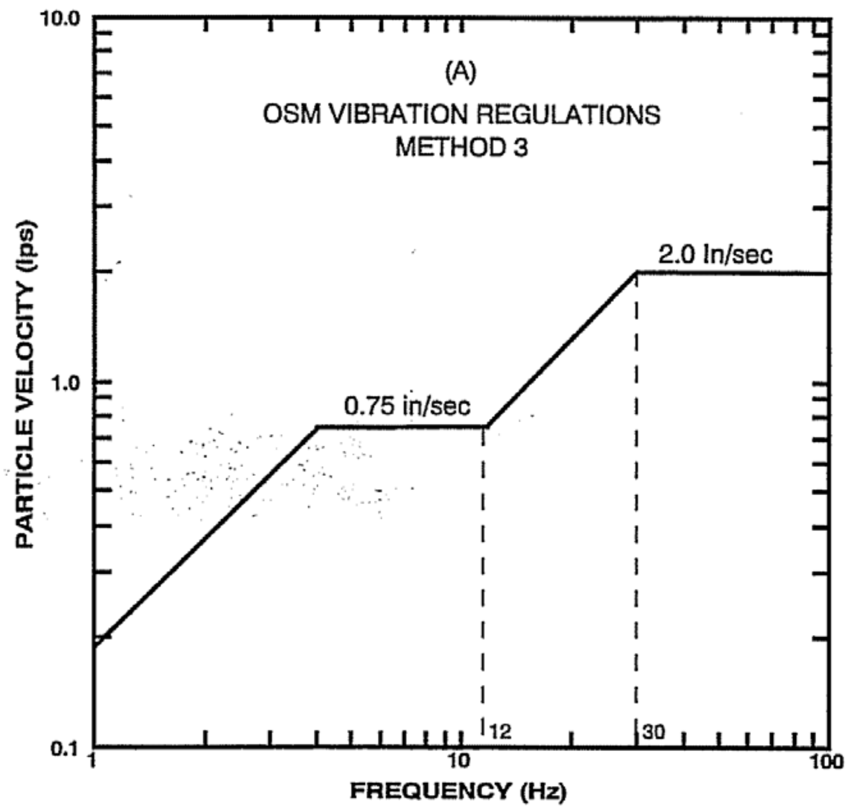
- USBM Report of Investigation 8507 (Siskind et al., 1980)
- Adopted by AASHTO and many others
- Limit corresponds to the development of hairline cracks in plaster or drywall joints (i.e., not structural damage)




*(from Oriard, 1999)*

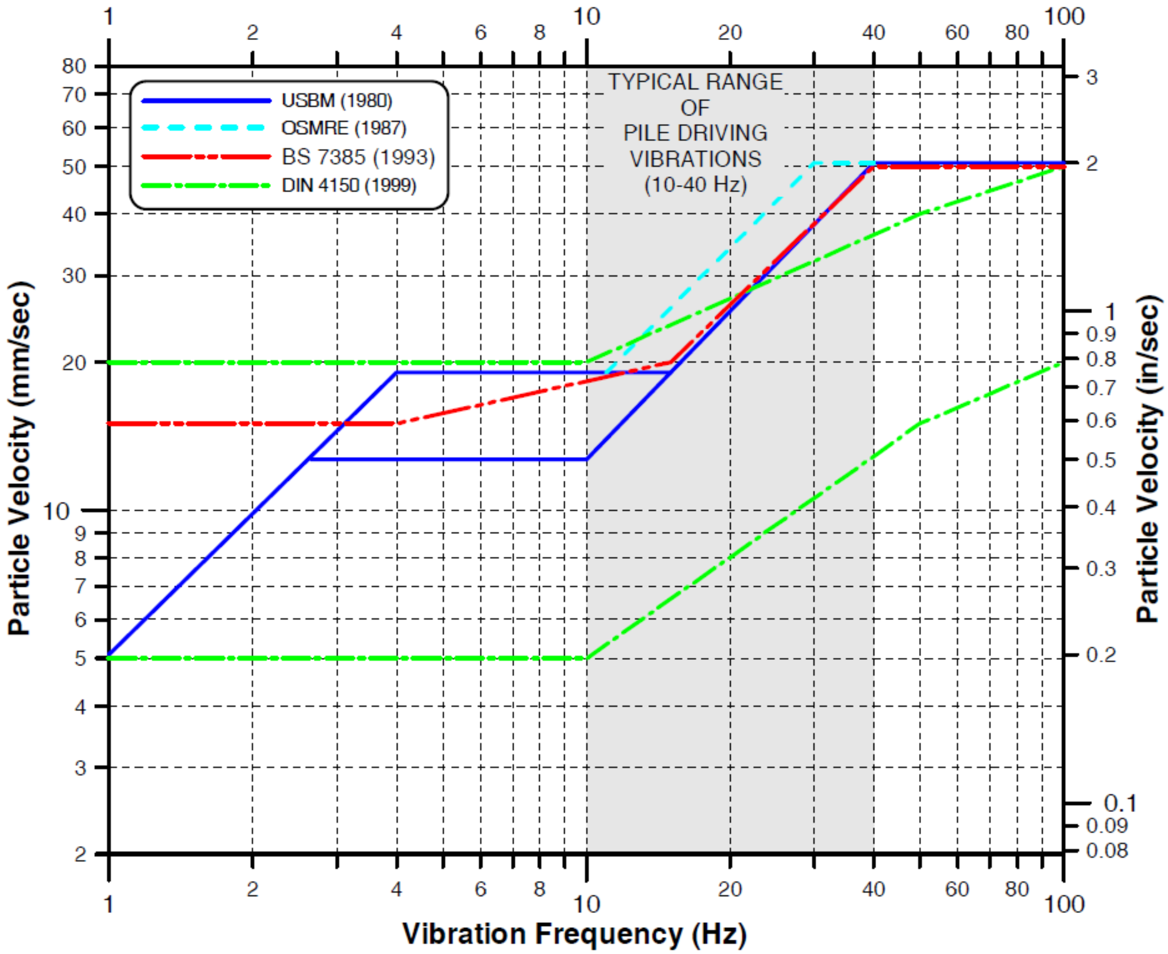
# OSMRE Criteria

- OSMRE 1987 – Office of Surface Mining and Reclamation and Enforcement (Rosenthal et al., 1987).
- Similar to USBM criteria
- Does not distinguish between construction material types.




*(from Oriard, 1999)*

# Comparison of Frequency Dependent Criteria

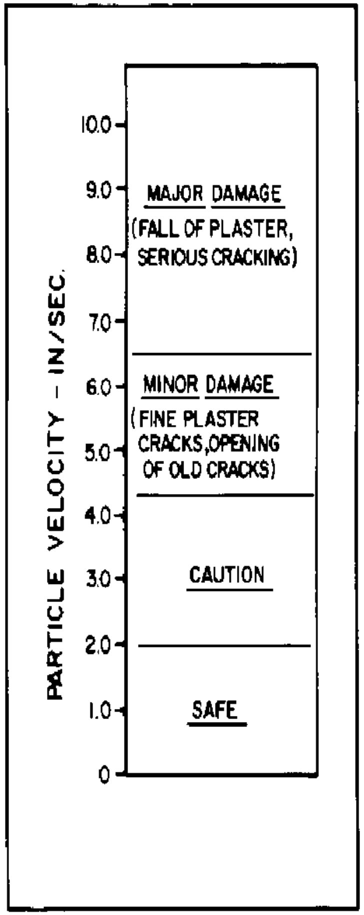



*(from Hajduk et al., 2009)*

# Oriard's and NAVFAC Criteria

| *Range of Common Residential Criteria and Observed Side Effects* | |
|---|---|
| 0.5 ips (1.27 cm/s) (12.7 mm/s) | Bureau of Mines recommended guideline for plaster-on-lath construction near surface mines (long-term, large-scale blasting operations, low-frequency vibrations (RI 8507). |
| 0.75 ips (1.91 cm/s) (19.1 mm/s) | Bureau of Mines recommended guideline for sheetrock construction near surface mines (RI 8507). |
| 1.0 ips (2.54 cm/s) (25.4 mm/s) | OSM regulatory limits for residences near surface mine operations at distances of 301-5000 ft. (long-term, large-scale blasting). |
| 2.0 ips (5.08 cm/s) (50.8 mm/s) | Widely accepted limit for residences near construction blasting and quarry blasting (BuMinBulletin 656, BuMin RI 8507, various codes, specifications and regulations). Also allowed by OSM for frequencies above 30 Hz. |
| 5.4 ips (13.7 cm/s) (137 mm/s) | Minor damage to the average house subjected to quarry blasting vibrations. (BuMin Bulletin 656). |
| 9 ips (22.9 cm/s) (229 mm/s) | About 90% probability of minor damage from construction or quarry blasting. Structural damage to some houses. Depends on vibration source, character of vibrations and the house. |
| 20 ips (50.8 cm/s) (508 mm/s) | For close-in construction blasting, minor damage to nearly all houses, structural damage to some. A few may escape damage entirely. For low-frequency vibrations of long duration, major damage to most houses. |

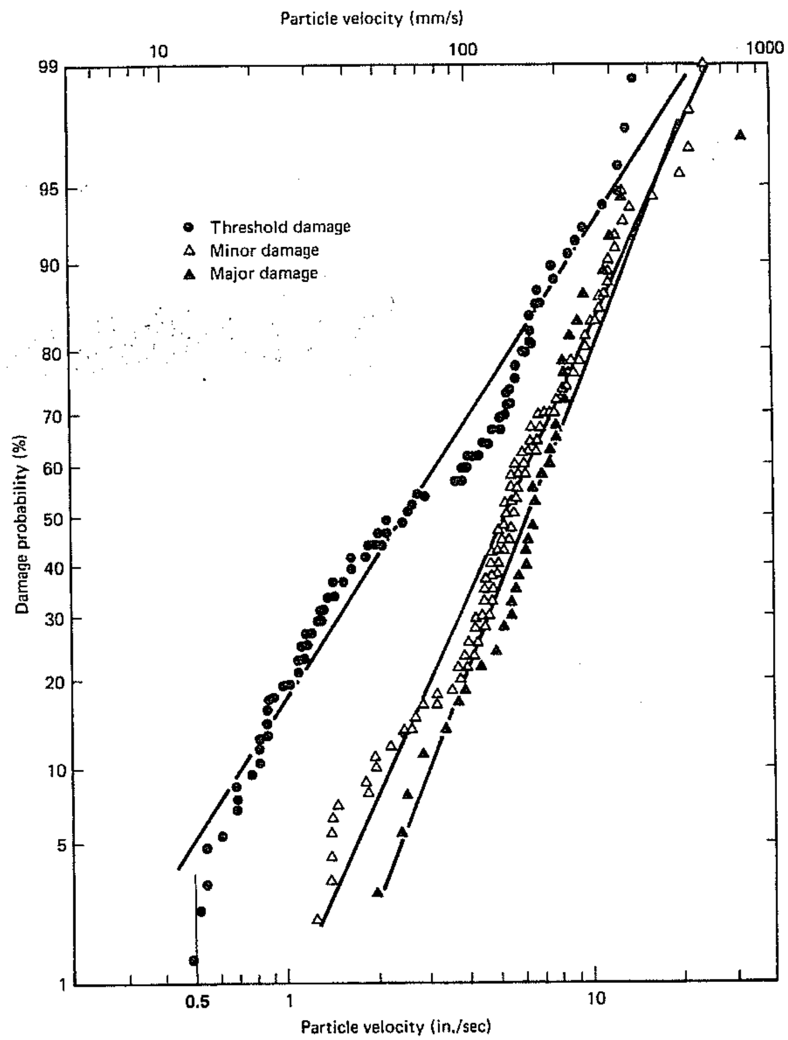
*(from Oriard, 1999)*




*(from NAVFAC DM-7, 1986)*

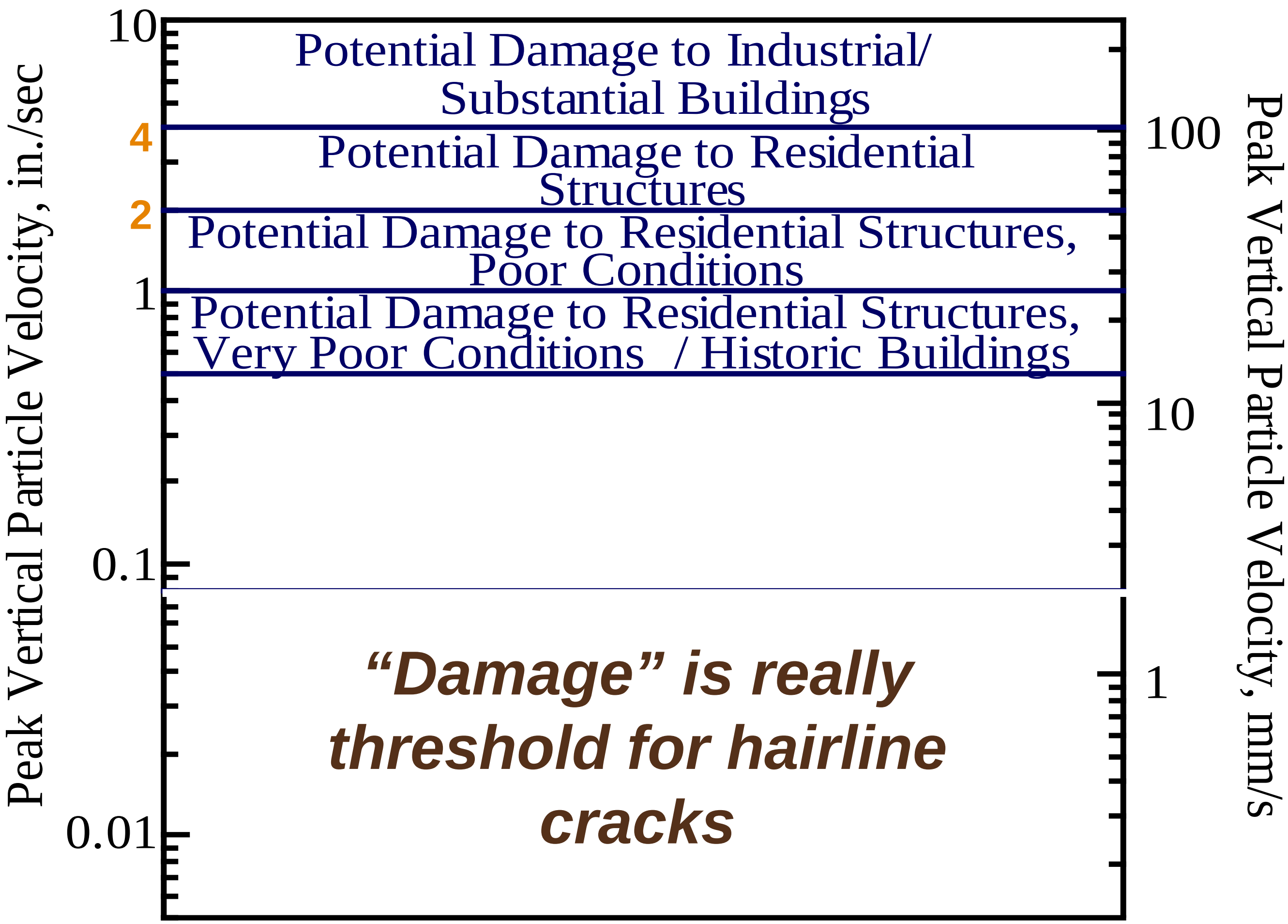
# Dowding's Criteria

- "Threshold damage" defined as development of hairline cracks.
- PPV of 0.5 ips or less will not cause threshold damage.




(from Dowding, 1996)

# Bay's Criteria




*(from Bay, 2004)*

# Eurocode Criteria

- Distinction in threshold for transient and continuous vibrations.
- Recommends 50% reduction in PPV threshold for continuous vibrations.

| Type of Property | Peak Particle Velocity, in/sec | |
|---|---|---|
| | Continuous Vibration | Transient Vibration |
| Ruins, building of architectural merit | 0.08 | 0.16 |
| Residential | 0.2 | 0.4 |
| Light Commercial | 0.4 | 0.8 |
| Heavy Industrial | 0.6 | 1.2 |
| Buried Services | 1.0 | 1.6 |

*(after Piling Handbook, 2005)*

# Jones and Stokes' Criteria

| Structure and Condition | Maximum PPV mm/sec (in/sec) |
|---|---|
| Fragile Buildings | 2.5 (0.1) |
| Historic and Some Old Buildings | 6.4 (0.25) |
| Older Residential Structures | 7.6 (0.3) ← |
| New Residential Structures | 12.7 (0.5) ← |
| Modern Industrial/Commercial Buildings | 12.7 (0.5) |

*(Jones and Stokes, 2004)*

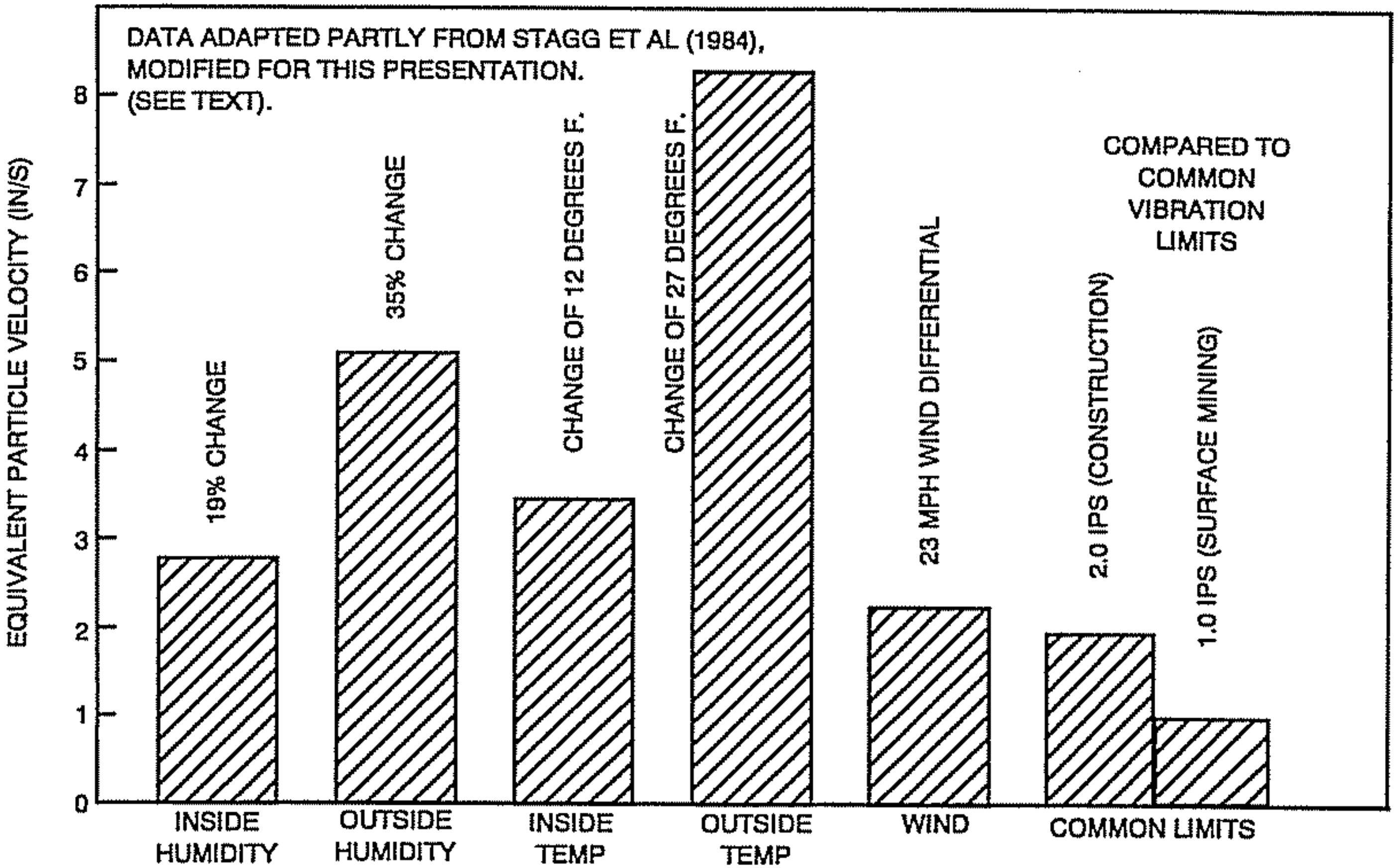
# Summary of Vibration Criteria

- Wide lack of agreement between criteria.
- Recommended maximum peak particle velocities range from 0.2 to 5.5 ips.
- Most of the common thresholds were developed for blasting scenarios.
- Dowding (1996) states blast-related thresholds are appropriate for most construction-generated vibrations – except for activities producing continuous vibrations.

# What's Appropriate for This Project?

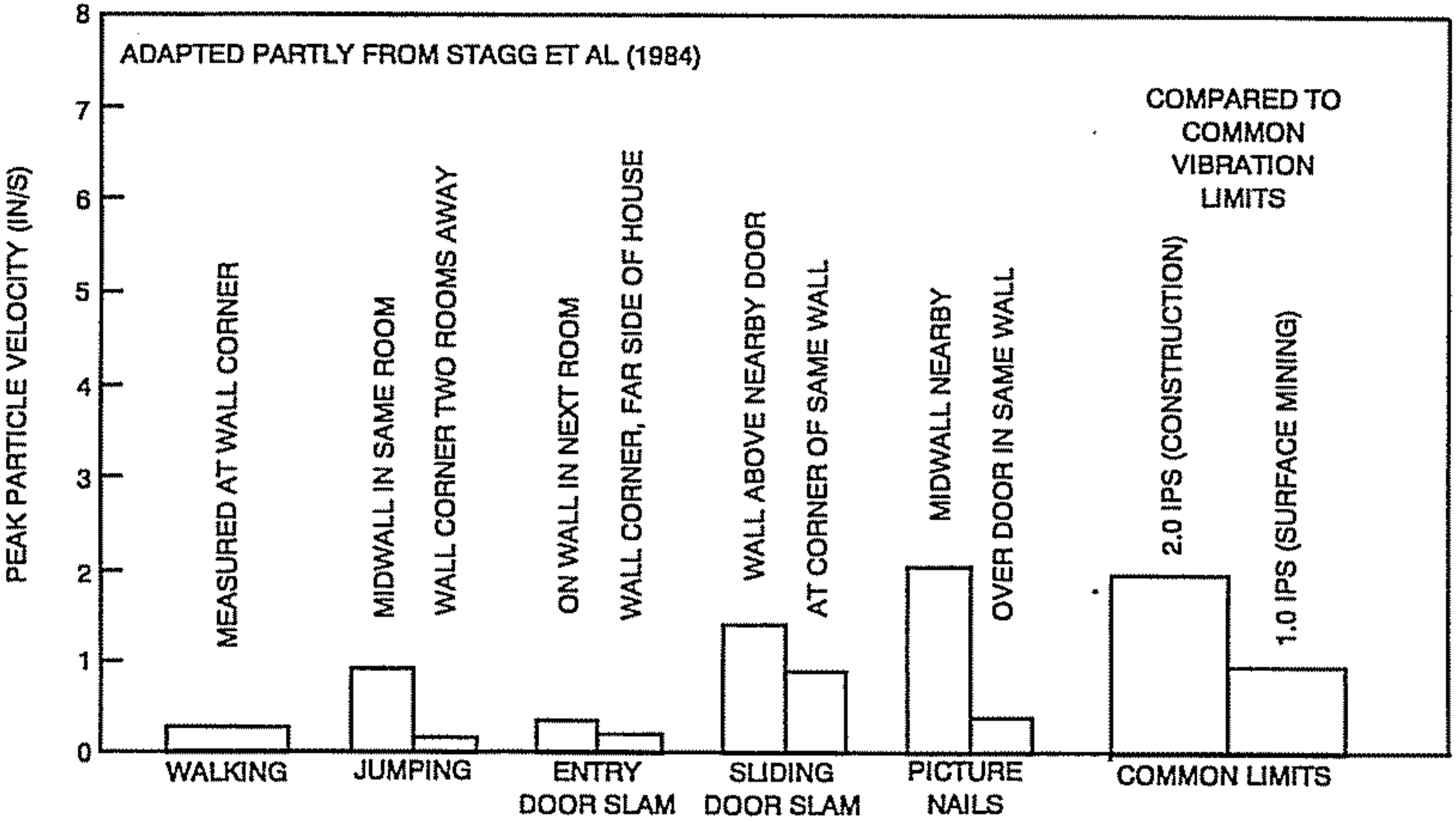
- According to Oriard (1999), structures are affected more by environmental effects (e.g. temperature and humidity) than vibrations with relatively high PPV's.

# Environment Effects on Structures




(from Oriard, 2004)

# Vibrations from Common Everyday Activities




*(from Oriard, 2004)*

# What's Appropriate for This Project?

- According to Oriard (1999), structures are affected more by environmental effects (e.g. temperature and humidity) than vibrations with relatively high PPV's.
- Low PPV threshold seemed overly conservative.
- Duration of the continuous vibrations would be relatively short.

# Selected Criteria

- The USBM criteria was deemed reasonable as an initial action level.
- Frequency-based threshold, which was deemed appropriate for the project.
- Inherently conservative (i.e. PPV threshold established for cosmetic cracking, not structural damage).

# Monitoring Details

- Three vibration monitoring points established at each foundation location - coincident to distance from nearby structures.
- Settlement monitoring performed at each vibration monitor location.
- Limited structural condition survey performed from utility right-of-way and other public access areas.
- Considering the uncertainty of the criteria and potential vibrations, construction began in less critical areas (furthest from structures).

# Monitoring Equipment

- Instantel Blastmate and Minimate Seismographs
  - Triaxial geophone array
  - Measured PPV and Hz in three directions – longitudinal, transverse, and vertical.
- Trimble 5603 Robotic Total Station with Recon Datalogger


# Foundation Installation Details

- 54 foundations ranging in diameter from 28 to 54 inches and lengths from 20 to 30 feet.
- Most foundations within 8 to 50 feet from nearby structures.
- Caissons installed with APE 100 vibratory hammer with a Model 260 Power Unit.
- Four caissons refused early – installation was completed with APE 200 vibro-hammer with a Model 630 Power Unit.

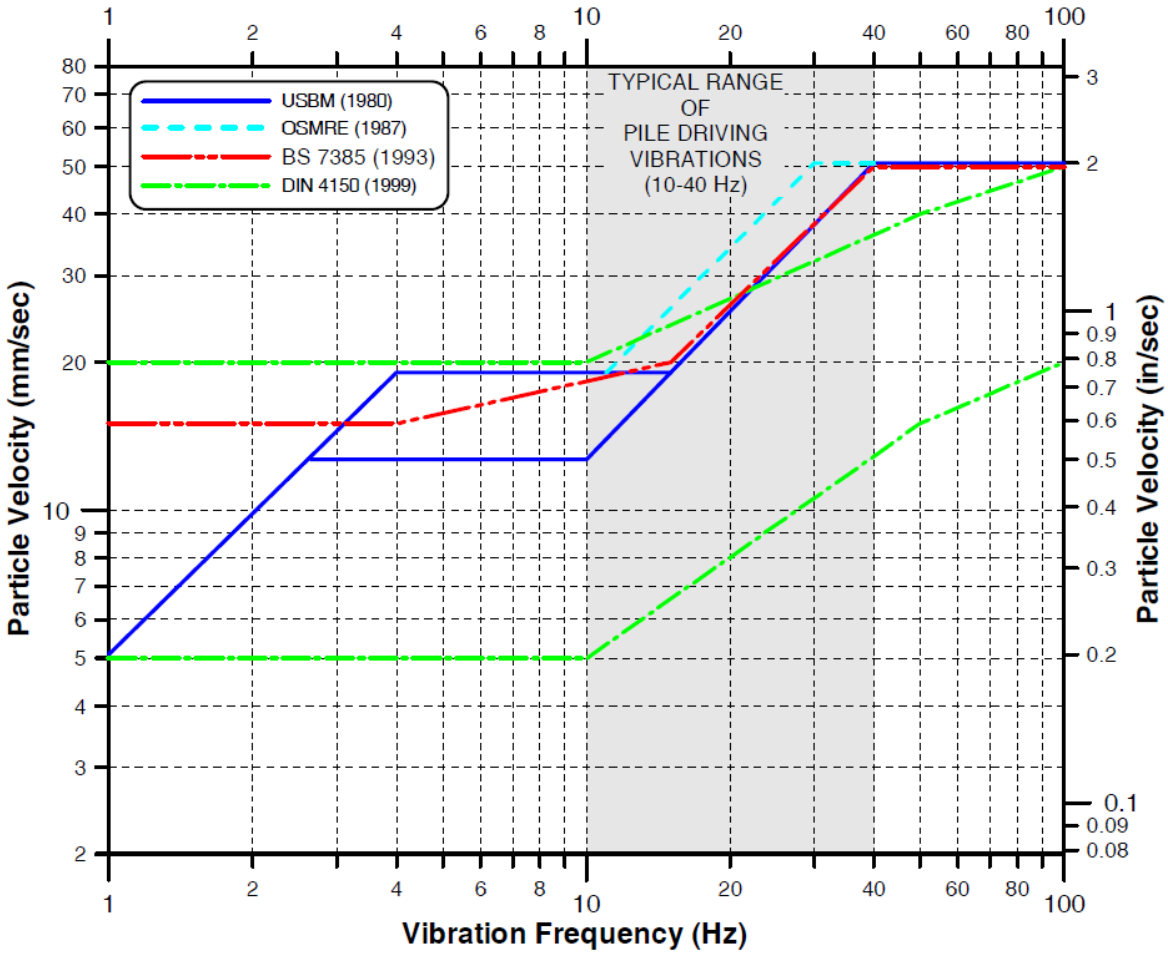
# Foundation Installation Details

- Hammer was initially operated at a low frequency while the caissons were plumbed.
- Once plumb, the hammer frequency was incrementally increased based on caisson penetration rate and measured PPV.

# Vibration Monitoring Results

- Vibration data collected at 162 locations along the transmission line alignment.
- Vibration monitor locations established at distances of 8 to 200 feet from foundations.
- Measured PPV's ranged from 0.05 to 3.28 ips, with a majority less than 1.75 ips.
- 98% of vibration frequencies ranged from 10 to 40 Hz, with 74 % between 20 and 30 Hz.

# Comparison of Frequency Dependent Criteria

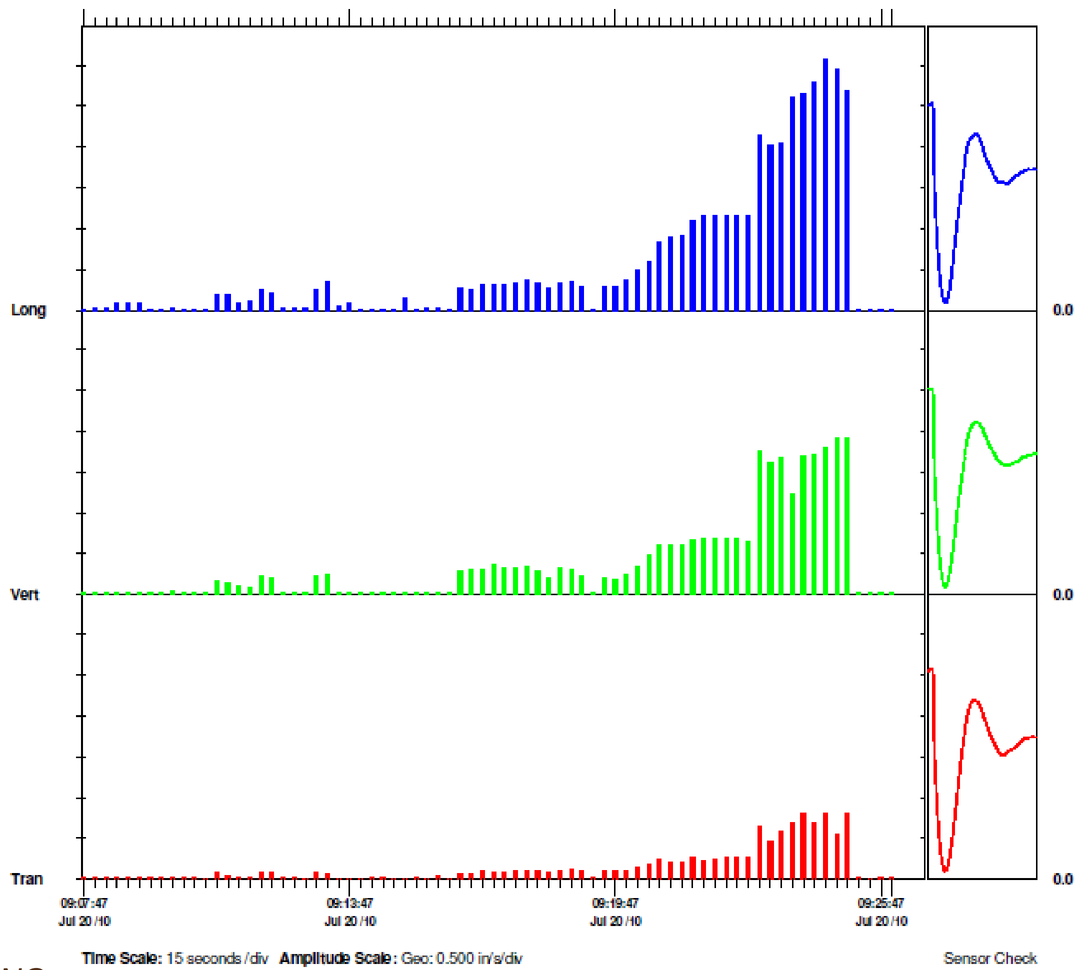



*(from Hajduk et al., 2009)*

# Vibration Data - Histogram

| | Tran | Vert | Long | |
|---|---|---|---|---|
| PPV | 0.810 | 1.91 | 3.06 | in/s |
| ZC Freq | 24 | 24 | 28 | Hz |
| Date | Jul 20 /10 | Jul 20 /10 | Jul 20 /10 | |
| Time | 09:24:32 | 09:25:02 | 09:24:32 | |
| Sensor Check | Passed | Passed | Passed | |
| Frequency | 7.6 | 7.3 | 7.6 | Hz |
| Overswing Ratio | 3.2 | 3.8 | 3.4 | |

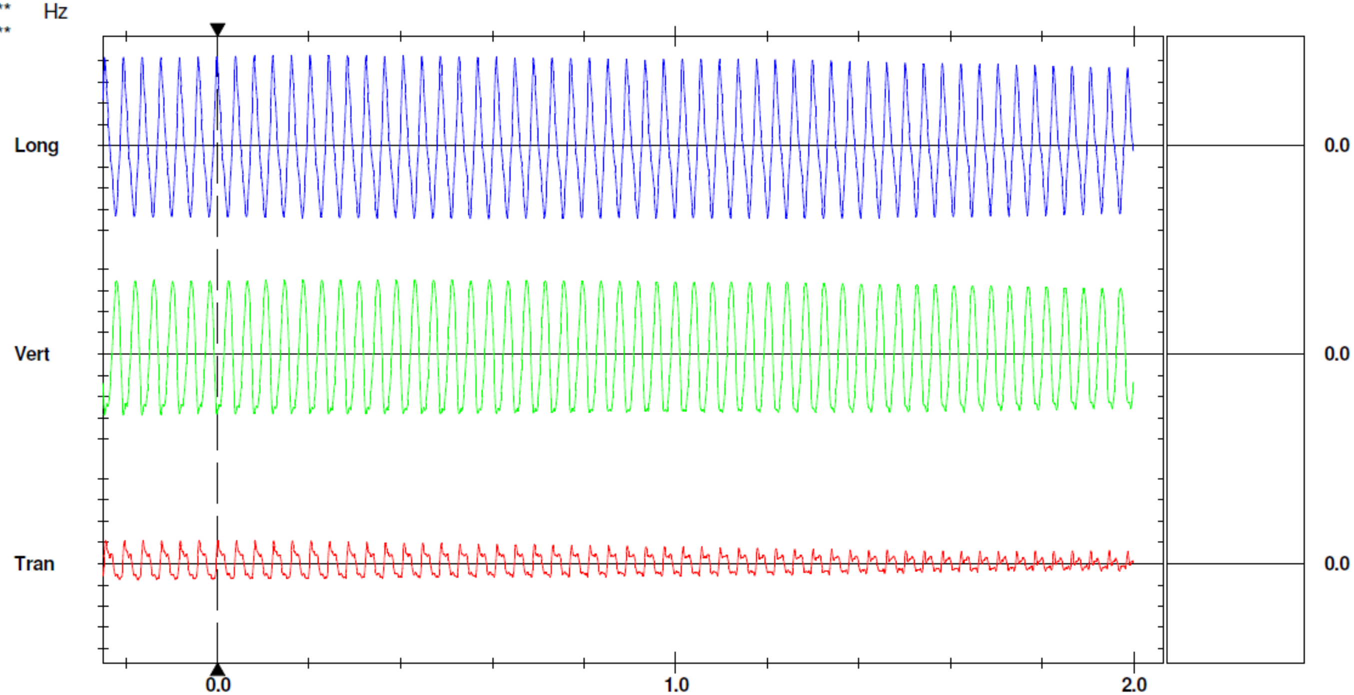
Peak Vector Sum 3.49 in/s on July 20, 2010 at 09:24:32



# Vibration Data - Waveform

| | Tran | Vert | Long | |
|---|---|---|---|---|
| **PPV** | 0.545 | 1.75 | 2.13 | in/s |
| **ZC Freq** | 24 | 26 | 28 | Hz |
| **Time (Rel. to Trig)** | -0.244 | 0.350 | 0.202 | sec |
| **Peak Acceleration** | 0.610 | 1.02 | 1.01 | g |
| **Peak Displacement** | 0.00277 | 0.0108 | 0.0104 | in |
| **Sensor Check** | Disabled | Disabled | Disabled | |
| **Frequency** | *** | *** | *** | Hz |
| **Overswing Ratio** | *** | *** | *** | |

**Peak Vector Sum** 2.57 in/s at 0.202 sec




**Time Scale:** 0.20 sec/div **Amplitude Scale:** Geo: 0.500 in/s/div

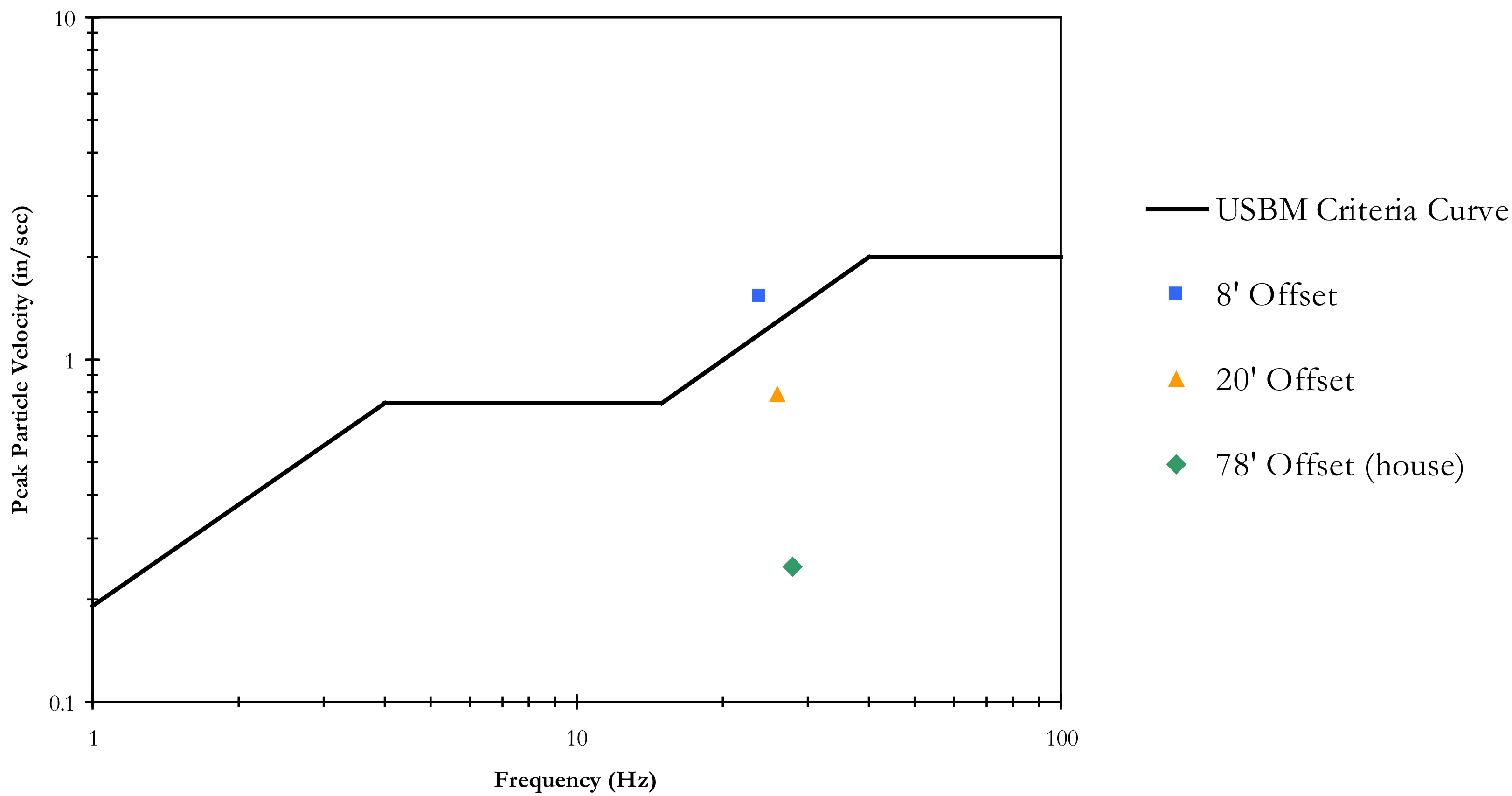
Sensor Check

**Trigger =** ▶—— ——◀

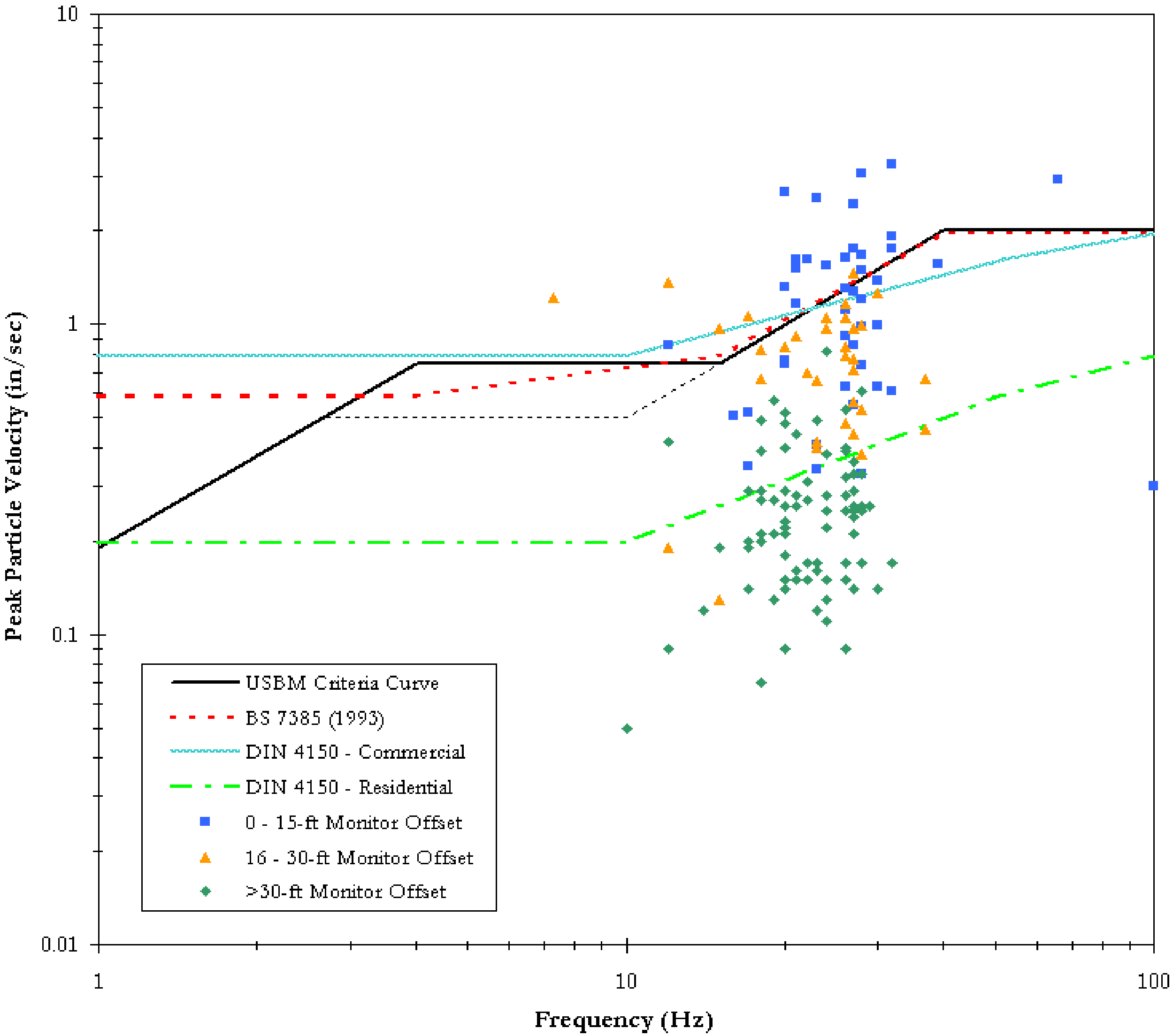
# Vibration Results

S&ME

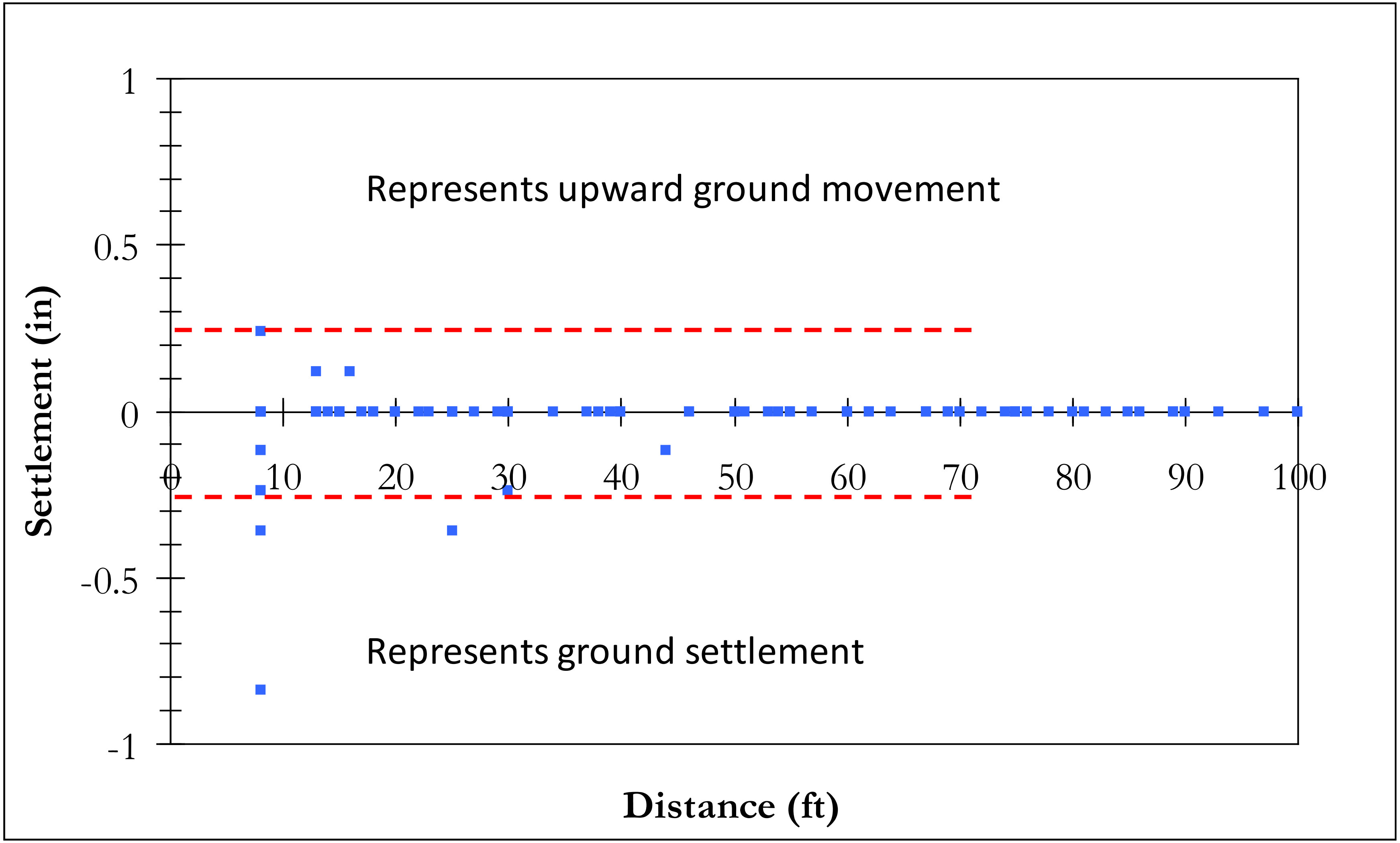
Maximum Vibration Levels - Foundation #48



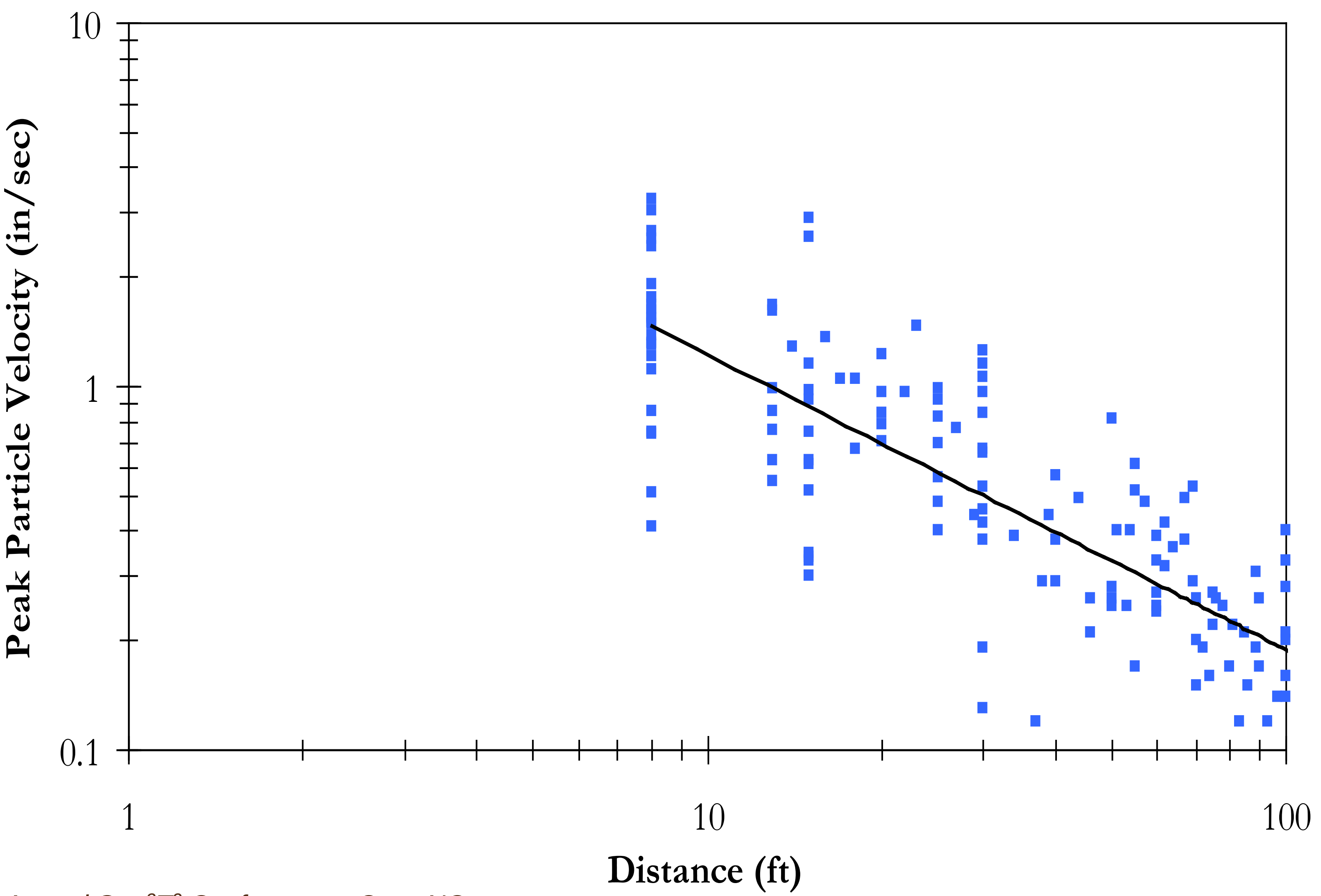
# Vibration Results



# Settlement Results



# Vibration Attenuation Plot



# Vibration Attenuation Factor

- Factors used to estimate vibrations at sites of unknown attenuation characteristics.
- An attenuation factor of n = 0.81 was calculated from measured PPV.

$PPV = kD^{-n}$ *(Wiss, 1987)*

where: k = value of PPV at 1 unit distance
D = distance from source
n = pseudo-attenuation coefficient

| **Reference** | **Site** | **Soil Type** | ***n*** |
|---|---|---|---|
| Hajduk (2004) | 1-8 | Sand | 0.496 – 1.03 |
| | All | Sand | 0.972 |
| Ali et al (2003) | | Sands | 0.88 – 1.02 |
| Brenner and Chittikuladiok (1999) | | Surface Sands | 1.5 |
| | | Sand fill, over soft clays | 0.8 – 1.0 |
| Wiss (1981) | | Sands | 1.0 |
| Woods and Jedele (1985) | | Dense compacted sands (15<N<50) | 1.1 |
| | | Most sands (5<N<15) | 1.5 |

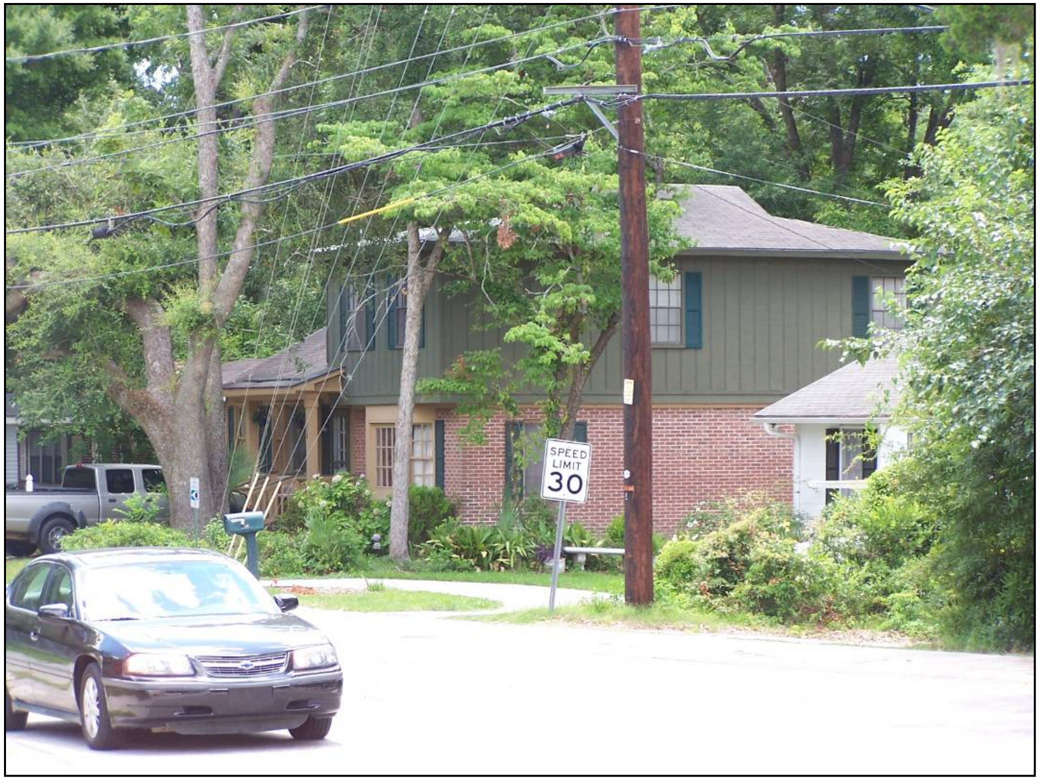
*(from Hajduk et al., 2004)*

# Claim #1

- Alleged damage to front porch slab.
- Structure located 60 feet from foundation.
- Measured PPV of 0.48 ips at 20 Hz.
- Investigation by others determined alleged damage was existing – claim dismissed.

# Claim #2

- Alleged damage to structural foundation.
- Structure located more than 200 ft from foundation.
- Measured PPV of 0.24 ips at 24 Hz at monitor 113 ft from foundation.
- Alleged damage was existing – claim dismissed.



# Claim #3

- Alleged damage to china, glassware, and artwork which fell off a bookshelf along an exterior wall adjacent to construction.
- Structure located 8 ft from foundation.
- Measured PPV of 3.06 ips at 28 Hz.

# Claim #3

- Investigation performed by others immediately after foundation installation.
- Claim deemed legitimate.

# Summary

- New transmission line was constructed through residential and commercial areas – very near existing structures.
- Subsurface conditions generally consisted of loose to medium dense sand with relatively shallow groundwater table.
- The utility owner was concerned the vibratory construction would result in numerous claims and complaints.
- Project completed with no major problems and only one legitimate claim.

# Summary

- Majority of the vibration measurements fell below the USBM threshold.
- When they exceeded the threshold, the vibrations occurred over a short period without causing damage.
- No settlement issues were encountered.
- The monitoring program proved useful in providing data necessary for the owner to proceed with confidence in the most challenging areas, and also helped defend against meritless claims.

# Thank You

S&ME

*NCDOT 7th Annual Geo³T² Conference – Cary, NC*
*Heath Forbes – April 4, 2013*

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