Settlement & Vibration Monitoring for Transmission Line Foundation Installation


Presented By:

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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

Varies – 28 – 54 inches
Varies – 20 – 30 feet
Varies
Varies
Prefabricated driving “ears”
Prefabricated connection system

Vibratory Caisson Foundation Orientation Detail

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Vibratory Caisson Foundation
Vibratory Caisson Foundation
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).
  – 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

<table>
<thead>
<tr>
<th>Range of Common Residential Criteria and Observed Side Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 ips (1.27 cm/s) (12.7 mm/s)</td>
</tr>
<tr>
<td>Bureau of Mines recommended guideline for plaster-on-lath construction near surface mines (long-term, large-scale blasting operations, low-frequency vibrations (RI 8507).</td>
</tr>
<tr>
<td>0.75 ips (1.91 cm/s) (19.1 mm/s)</td>
</tr>
<tr>
<td>Bureau of Mines recommended guideline for sheetrock construction near surface mines (RI 8507).</td>
</tr>
<tr>
<td>1.0 ips (2.54 cm/s) (25.4 mm/s)</td>
</tr>
<tr>
<td>OSM regulatory limits for residences near surface mine operations at distances of 501-5000 ft. (long-term, large-scale blasting).</td>
</tr>
<tr>
<td>2.0 ips (5.08 cm/s) (50.8 mm/s)</td>
</tr>
<tr>
<td>Widely accepted limit for residences near construction blasting and quarry blasting (BuMin Bulletin 656, BuMin RI 8507, various codes, specifications and regulations). Also allowed by OSM for frequencies above 30 Hz.</td>
</tr>
<tr>
<td>5.4 ips (13.7 cm/s) (137 mm/s)</td>
</tr>
<tr>
<td>Minor damage to the average house subjected to quarry blasting vibrations. (BuMin Bulletin 656).</td>
</tr>
<tr>
<td>9 ips (22.9 cm/s) (229 mm/s)</td>
</tr>
<tr>
<td>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.</td>
</tr>
<tr>
<td>20 ips (50.8 cm/s) (508 mm/s)</td>
</tr>
<tr>
<td>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.</td>
</tr>
</tbody>
</table>

(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

“Damage” is really threshold for hairline cracks

(from Bay, 2004)
Eurocode Criteria

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

<table>
<thead>
<tr>
<th>Type of Property</th>
<th>Peak Particle Velocity, in/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Continuous Vibration</td>
</tr>
<tr>
<td>Ruins, building of architectural merit</td>
<td>0.08</td>
</tr>
<tr>
<td>Residential</td>
<td>0.2</td>
</tr>
<tr>
<td>Light Commercial</td>
<td>0.4</td>
</tr>
<tr>
<td>Heavy Industrial</td>
<td>0.6</td>
</tr>
<tr>
<td>Buried Services</td>
<td>1.0</td>
</tr>
</tbody>
</table>

(after Piling Handbook, 2005)
## Jones and Stokes’ Criteria

<table>
<thead>
<tr>
<th>Structure and Condition</th>
<th>Maximum PPV mm/sec (in/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fragile Buildings</td>
<td>2.5 (0.1)</td>
</tr>
<tr>
<td>Historic and Some Old Buildings</td>
<td>6.4 (0.25)</td>
</tr>
<tr>
<td>Older Residential Structures</td>
<td>7.6 (0.3)</td>
</tr>
<tr>
<td>New Residential Structures</td>
<td>12.7 (0.5)</td>
</tr>
<tr>
<td>Modern Industrial/Commercial Buildings</td>
<td>12.7 (0.5)</td>
</tr>
</tbody>
</table>

*(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

Data adapted partly from Stagg et al. (1984), modified for this presentation. (See text.)

Equivalent particle velocity (in/s)

- 19% change
- 35% change
- Change of 12 degrees F.
- Change of 27 degrees F.
- 23 mph wind differential
- 2.0 IPS (construction)
- 1.0 IPS (surface mining)

Compared to common vibration limits

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(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

InstaT2el

<table>
<thead>
<tr>
<th>PPV</th>
<th>Tran</th>
<th>Vert</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.810</td>
<td>1.91</td>
<td>3.06</td>
</tr>
</tbody>
</table>

| ZC Freq | 24 | 24 | 28 | Hz |

<table>
<thead>
<tr>
<th>Date</th>
<th>Jul 20</th>
<th>Jul 20</th>
<th>Jul 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>09:24:32</td>
<td>09:25:02</td>
<td>09:24:32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor Check</th>
<th>Frequency</th>
<th>Overswing Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passed</td>
<td>7.6 Hz</td>
<td>3.2</td>
</tr>
<tr>
<td>Passed</td>
<td>7.6 Hz</td>
<td>3.8</td>
</tr>
<tr>
<td>Passed</td>
<td>7.6 Hz</td>
<td>3.4</td>
</tr>
</tbody>
</table>

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

Time Scale: 15 seconds/div | Amplitude Scale: 0.500 in/s/div

Sensor Check
Vibration Data - Waveform

<table>
<thead>
<tr>
<th>PPV</th>
<th>Tran</th>
<th>Vert</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.545</td>
<td>1.75</td>
<td>2.13</td>
<td>2.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ZC Freq</th>
<th>24</th>
<th>26</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (Rel. to Trig)</td>
<td>-0.244</td>
<td>0.350</td>
<td>0.202</td>
</tr>
<tr>
<td>Peak Acceleration</td>
<td>0.610</td>
<td>1.02</td>
<td>1.01</td>
</tr>
<tr>
<td>Peak Displacement</td>
<td>0.00277</td>
<td>0.0108</td>
<td>0.0104</td>
</tr>
<tr>
<td>Sensor Check</td>
<td>Disabled</td>
<td>Disabled</td>
<td>Disabled</td>
</tr>
<tr>
<td>Frequency</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Overswing Ratio</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

Peak Vector Sum: 2.57 in/s at 0.202 sec
Vibration Results

Maximum Vibration Levels - Foundation #48

Peak Particle Velocity (in/sec) vs. Frequency (Hz)

- USBM Criteria Curve
- 8' Offset
- 20' Offset
- 78' Offset (house)
Vibration Results

![Graph showing vibration results](image)

- **Title:** Vibration Results
- **Keywords:** Frequency (Hz), Peak Particle Velocity (in./sec)
- **Graph Description:**
  - USEM Criteria Curve
  - BS 7385 (1993)
  - DIN 4150 - Commercial
  - DIN 4150 - Residential
  - 0 - 15-ft Monitor Offset
  - 16 - 30-ft Monitor Offset
  - >30-ft Monitor Offset

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Settlement Results

- Represents upward ground movement
- Represents ground settlement

Distance (ft)

Settlement (in)
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 = $kD^{-n}$  \hspace{1cm} (Wiss, 1987)

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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Site</th>
<th>Soil Type</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hajduk (2004)</td>
<td>1-8 Sand</td>
<td>0.496 – 1.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All Sand</td>
<td>0.972</td>
<td></td>
</tr>
<tr>
<td>Ali et al (2003)</td>
<td>Sands</td>
<td>0.88 – 1.02</td>
<td></td>
</tr>
<tr>
<td>Brenner and Chittikuladiok (1999)</td>
<td>Surface Sands</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand fill, over soft clays</td>
<td>0.8 – 1.0</td>
<td></td>
</tr>
<tr>
<td>Wiss (1981)</td>
<td>Sands</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Woods and Jedele (1985)</td>
<td>Dense compacted sands (15&lt;N&lt;50)</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Most sands (5&lt;N&lt;15)</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>
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
References

- ORIARD, L. L., 1999. The Effects of Vibrations and Environmental Forces, International Society of Explosives Engineers, Cleveland, OH.