EVALUATION OF VIBRATION LIMITS AND MITIGATION TECHNIQUES FOR URBAN CONSTRUCTION

2012 GEOTECHNICAL RESEARCH IN PROGRESS
GAINESVILLE, FL

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PRESENTATION OUTLINE

Background and Problem Description

Research Objectives and Methodology

Phase-I: Data Collection

- Literature Review
- Questionnaire Survey
- Vibration Data

Phase-II: Analysis and Recommendations

- Upcoming Tasks and Path Forward

Questions & Answers

BACKGROUND

- Construction-induced ground vibrations
  - Blasting
  - Pile driving
  - Dynamic compaction
  - Operation of heavy construction equipment
- Level of ground vibrations
  - Source energy
  - Distance from the source of vibration
  - Soil characteristics
  - Characteristics of wave propagation
- Concern to engineers
  - Annoyance to people in urban environment
  - Interference with sensitive devices
  - Architectural and structural damage
  - Soil settlement

FDOT Research Need Statement

- Work needed on:
  - Anticipated vibration levels generated by construction operations
    - Prediction of peak particle velocity (PPV)
    - Vibratory rollers, tandem rollers, sheet pile installation of particular interest in addition to pile driving
  - Evaluation of vibration limits
    - Currently, 0.5 in/sec is the general PPV limit in FDOT projects
  - Evaluation of vibration mitigation techniques
  - Standardized procedures for pre-construction surveys
- Recommendations for addressing vibration issues in the "Standard Specifications for Road and Bridge Construction" and/or "Soils and Foundations Handbook"
  - 455-1.1 "Structures Foundations" >> Protection of Existing Structures
  - 7.1.6 Vibration Monitoring; 9.2.4 Existing Structures Survey and Evaluation

BACKGROUND

BDK-80 #977-22

- *"Evaluation of Vibration Limits and Mitigation Techniques for Urban Construction"*
  - Project kick-off: January 18, 2012
  - Anticipated completion: September 30, 2013
- Team composition
  - Rodrigo Herrera, P.E. (Project Manager, FDOT)
  - M. Emre Bayraktar, Ph.D. (Florida International University, PI)
  - Boo H. Nam, Ph.D. (University of Central Florida, Co-PI)
  - Young C. Kang, Ph.D. (Florida International University, Co-PI)
  - Mark Svinkin, Ph.D. (VibraConsult, Co-PI)

OBJECTIVES OF THE PROJECT

1. Analysis of the current practice in assessment and control of the vibration effects of construction operations in Florida;
2. Development of appropriate equations for the calculation of expected ground vibrations prior to the beginning of construction activities;
3. Development of advance condition surveys of structures as an important step in decreasing vibration effects from construction operations;
4. Evaluation of diverse vibration limits of ground and structural vibrations for application to roadway and bridge construction in Florida;
5. Evaluation of mitigation strategies to control ground and structural vibrations from construction sources;
6. Development of recommendations for addressing vibration issues in FDOT Specifications;" and
7. Preparation of a final research report for the Florida DOT.

RESEARCH APPROACH

PHASE-I: DATA COLLECTION

Task-1: Conduct a literature review

Task-2: Conduct a survey on practice and policies for construction vibrations

Task-3: Collect and sort available field-measured data from construction operations

Task-4: Prepare an interim report

PHASE-II: ANALYSIS AND RECOMMENDATIONS

Task-5: Develop simple equations to calculate PPV of ground vibrations

Task-6: Develop criteria and standardized procedures for pre-construction surveys

Task-7: Evaluate existing vibration limits and develop flexible limits for FDOT projects

Task-8: Evaluate mitigation techniques

Task-9: Develop recommendations

PHASE-1: DATA COLLECTION

Task 1: Literature Review

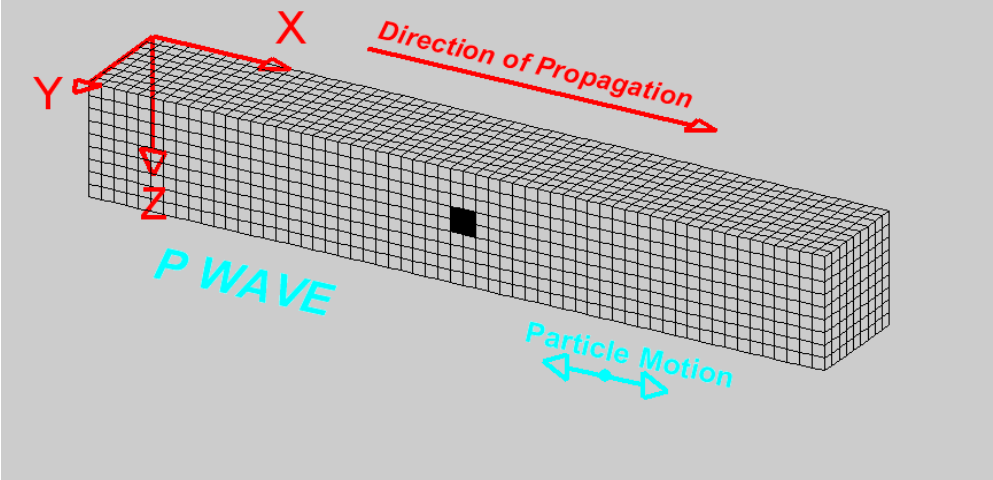
- Physics of ground vibrations
- Ground vibrations and construction operations
- Vibration effects of construction operations on structures
- Calculation, prediction and determination of ground and structural vibrations
- Vibration limits

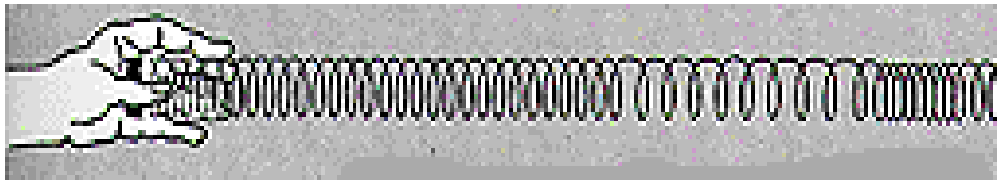
Earthborne Vibrations

- *Technical description*: generation of complex wave pattern due to energy reflection and refraction of the ground surface and subsurface interfaces between dissimilar materials (Dowding 1996)
- *Simplified description*: soil particle disturbance about its equilibrium position in a repetitive fashion
- Principal wave types of earthborne vibrations:
  - Compression or p-waves
  - Shear or s-waves
  - Surface or Rayleigh waves

P-Wave or Compression Wave (Seismic Body Wave)

- Expands from the energy source along a spherical wave front
- Wave propagation and particle motion in the same direction
- The ground is alternately compressed and dilated in the direction of propagation
- "Push-pull" manner

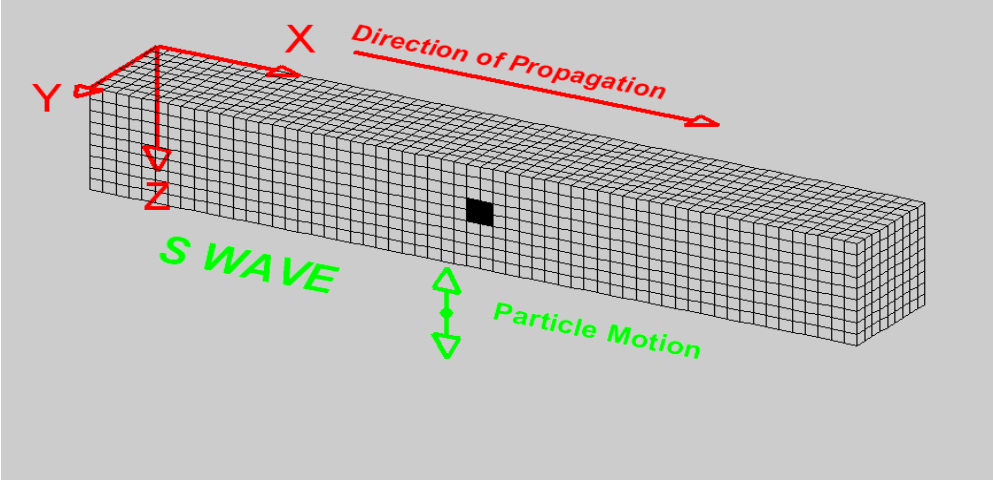


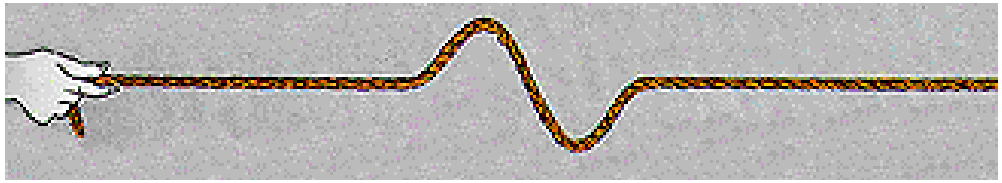


http://web.ics.purdue.edu/~braile/edumod/waves/Pwave.htm

S-Wave or Shear Wave (Seismic Body Wave)

- Also expands from the energy source along a spherical wave front
- Wave propagation and particle motion are perpendicular to each other





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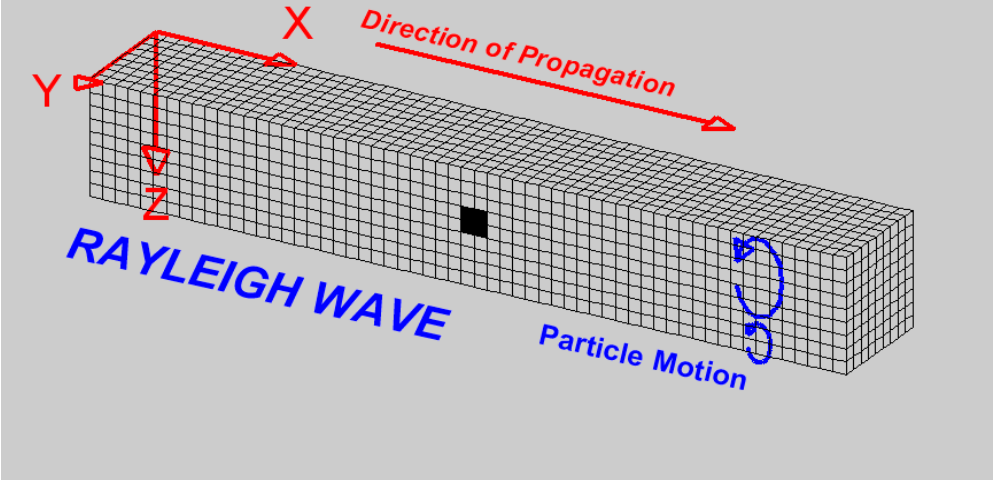
Rayleigh or Surface Wave (Seismic Surface Wave)

- Expands from the energy source along a cylindrical wave front
- Particle motion has both vertical and horizontal components
- Like ripples formed by dropping a pebble into a body of water



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Construction Operations and Earthborne Vibrations

- Compression (p) and shear waves (s) should be taken into consideration at relatively small distances from the construction sources
- Rayleigh waves have the largest practical interest for engineers
  - foundations are generally placed near the ground surface
  - contain more than 2/3 of the total vibration energy
  - peak particle velocity is dominant on velocity records
- In a horizontally layered soil medium, a large transverse component of motion could be caused by a second type of surface wave called Love waves

Categories of Ground Construction Vibrations

- transient vibrations(*dominant frequency: 3 and 60 Hz*)
  - single event or sequences of transient vibrations
  - caused by blasting and air, diesel or steam impact pile drivers
- steady-state vibrations (*dominant frequency: 5 to 30 Hz*)
  - continuous harmonic forms of relatively constant amplitude
  - caused by vibratory pile drivers and heavy machinery
- pseudo-steady state vibrations *(dominant frequency: 7 to 60 Hz)*
  - series of transient vibrations merged into continuous waveforms or quasi-harmonic motion with variable amplitude
  - caused by double-acting impact hammers

Vibration Effects of Construction Operations on Structures

- Direct vibration effect
  - frequency of ground vibration do not match and natural frequency of structure
  - direct minor and major structural damage
  - at one-pile length or 300 ft from blast (or larger)
- Resonant structural vibration
  - dominant frequency of ground vibrations and building's natural frequency match (amplification or resonance)
  - vibratory drivers may produce resonant floor vibrations and affect precise and sensitive devices on floors
- Resonant soil vibration

Direct vibration effect

Resonant structure vibration

Massarsch 2000

Vibration Effects of Construction Operations on Structures

- Dynamic settlement
  - soil and structure settlements due to pile installation
  - can be caused by relatively small ground vibrations
  - may happen in sand and clay soils

. Dynamic settlement

Massarsch 2000

Prediction and Determination of Ground and Structural Vibrations

- Golitsin's Equation
  - developed for surface waves generated by earthquakes
  - calculates a reduction of the maximum particle displacement of ground vibrations between two points

$$A_2 = A_1 \sqrt{r_1 / r_2}\, e^{-\gamma (r_2 - r_1)}$$

- Scaled-distance Approach
  - assessment of ground vibration attenuation generated by blasting, pile driving, and other construction sources

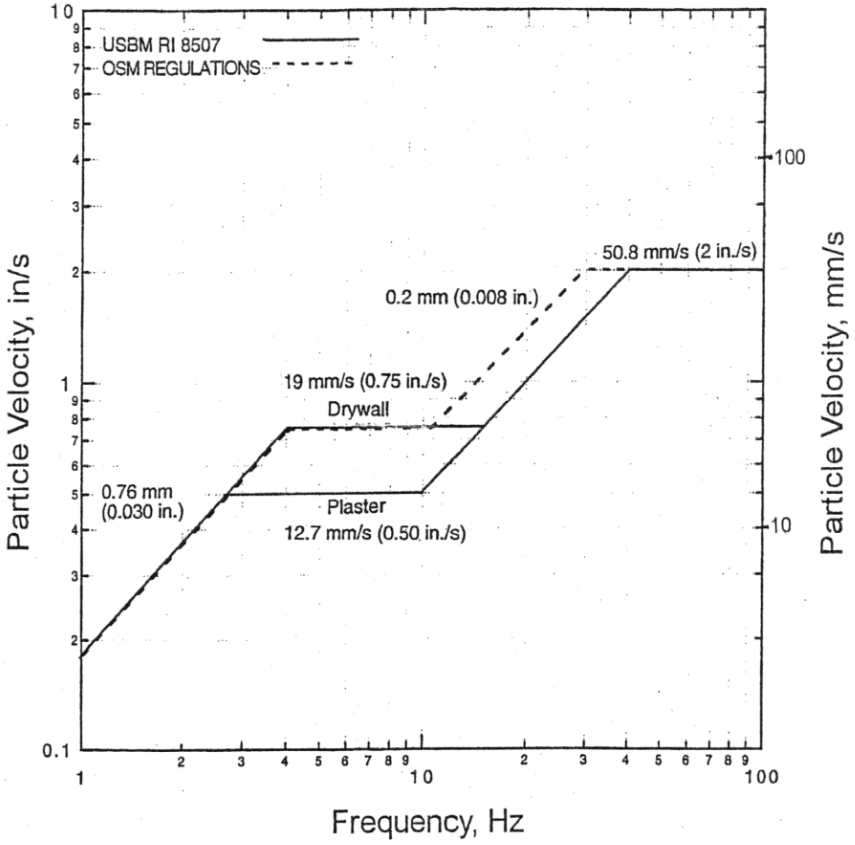
$$v = k[D/\sqrt{W_r}]^{-n}$$

Prediction and Determination of Ground and Structural Vibrations

- IRFP Method
  - prediction of ground vibrations using the impulse response function (IRF) technique
  - impulse loads of known magnitude applied on the ground and induced vibrations are recorded at the points of interest
- Pile Capacity and Ground Vibrations
  - Hajduk and Adams (2008) found that ground vibrations can be correlated with pile capacity determined during pile driving
  - however, this may not be accurate because ground vibrations and pile capacity are outcomes of the same pile driving process. During pile installation, ground vibrations should be measured, not calculated.

Vibration Limits

- USBM (US Bureau of Mines) and OSM (Office of Surface Mining) Criteria
  - frequency-based safe limits for cosmetic cracking threshold (due to mining blasting)
  - for one- to two-story residential structures
  - good for the specific blast design, soil conditions, and types of structures for which they were developed but cannot be automatically used in different cases



(Siskind 2000)

Vibration Limits

- Standard ANSI S2.47-1990
  - U.S. counterpart of the International Standard ISO 4866-1990
  - the standard presents the preferred frequency and velocity range for structural vibrations with various sources of vibrations
  - procedure available in the Standard can be used for the evaluation of measured structural vibrations generated by construction operations
- Russian Criteria
  - the Russian limits of1.18 to 1.97 in/s for the vibrations of sound structures was set by the Moscow Institute of Physics of the Earth to assess the affects of the blasts in the air, on the ground and under the ground at the time of the 2nd world war

Vibration Limits

- Dynamic Settlement
  - aforementioned vibration limits have nothing to do with the structural damage caused by plastic soil deformations
  - no federal, state, or local regulations of the critical ground vibration levels which may trigger dynamic settlements beyond the densification zone
  - attempts to use the decreased values of the USBM limits for preventing dynamic settlements have been unsuccessful
  - Lacy and Gould (1985) suggested a PPV of 0.098 in/s as the threshold of significant settlements at sand sites

Florida Studies

- Siskind and Stagg (2000) suggested the limit of 0.12 in/s, which is four time less than the lowest limit of the USBM criteria, for a soil stratification with a high water table and low wave attenuation in Miami-Dade county.
- Hesham et al. (2003) studied how construction related vibrations impacted existing structures proximate to the areas of a large construction site in Palm Beach County.
- Svinkin and Saxena (2004) performed a study of vibration effects of stormwater treatment construction on residential houses in Pensacola and concluded that environmental forces and aging processes in house materials appeared to be the actual causes of the damages to houses.
- Heung et al. (2007) presented the results of vibration monitoring studies conducted during pile driving operations on Turnpike projects in central and south Florida and underlined the importance of predrilling to penetrate through a shallow medium dense layer and underlined to use correlations with scaled horizontal distance.

PHASE-1: DATA COLLECTION

Questionnaire survey

- Survey design
  - Three survey types

FDOT Districts

- Experience with vibration issues
- Causes of damage to structures & settlement
- Vibration monitoring requirements
- Pre-construction condition survey requirements
- Unique geological profiles or soil conditions in the District

Contractors

- Experience with vibration issues
- Causes of damage to structures & settlement
- Management of vibration monitoring
- Mitigation measures
- Record keeping

Vibration Consultants

- Vibration monitoring procedures
- Experience with on-site vibration monitoring
- Mitigation measures
- Record keeping

PHASE-1: DATA COLLECTION

- Survey implementation
  - survey delivered as an online link embedded in an e-mail cover letter customized to the participant
  - survey process professionally managed using Qualtrics™, an online survey tool for designing, distributing, and evaluating survey results

Evaluation of Vibration Limits and Mitigation Techniques for Urban Construction

FDOT-DISTRICT QUESTIONNAIRE

Dynamic Effects of Pile Driving and Other Construction Equipment on Adjacent and Remote Structures

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Confidentiality Statement

All the information gathered here will be kept strictly confidential and will be used solely for research and analysis without mentioning the person or company names.

SUBMIT

Contact information:

Name of the Respondent:

Title/Designation:

FDOT District:

Phone Number:

E-Mail Address:

1. Has your district experienced vibration damage caused by construction operations in the past?

Yes No

If yes, what type of construction operation(s) was/were involved (pile driving, asphalt compaction, earthwork compaction, sheetpile installation, etc.)?

2. Did you investigate and identify the causes of damage to structures during pile driving and other construction operations?

Yes No

If yes, what was/were the cause(s)?

PHASE-1: DATA COLLECTION

- Survey participation
  - total invitations sent: 40
  - responses received: 4 districts, 3 construction companies, 2 vibration monitoring firms

SURVEY LINKS

- FDOT Districts
- Contractors
- Vibration Consultants

- Findings
  - a majority (75%) have experienced vibration damage caused by construction operations in the past
  - 50% experienced claims due to vibration issues
  - cited causes: pile/sheet pile driving, asphalt compaction
  - no knowledge of unique geological profiles leading to problems with vibration
  - pre-drill and fuel setting adjustment mentioned as preventive measures
  - all responding districts and contractors mentioned 455.1.1 as the sole reference related to vibration monitoring, condition surveys, and PPV limits (except one District mentioned use of 0.2 in/sec as the PPV limit)
  - vibration monitoring records are maintained by contractors

PHASE-1: DATA COLLECTION

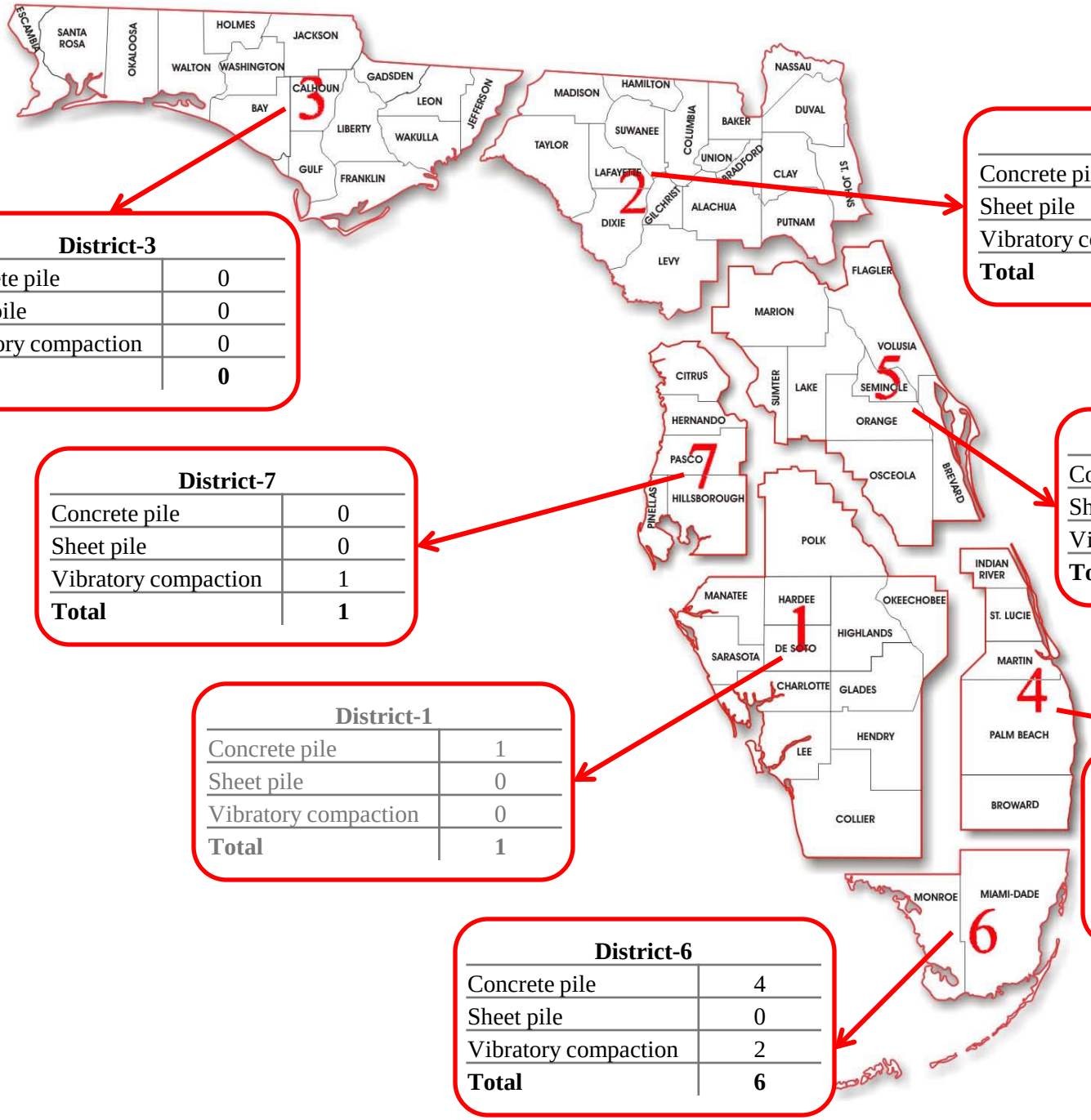
- Other State DOTs' Survey participation
  - total invitations sent: 80
  - responses received: 12

Construction operations which led to vibration damage	Pile driving, earthwork compaction, rock blasting, sheet pile installation and extraction, micro-pile installation (rarely), earthwork or compaction (rarely), removal of pile driving casing, asphalt compaction
Causes of damage	Peak Particle Velocity/frequency, in case of micro-pile usually poor construction practices cause damage
Preventive measures	Vibration monitoring, using drilled shaft foundations where possible, restrict use of vibratory hammer, not extracting sheet pile, measurement of peak particle velocity and establishing threshold limits, special provisions have been written to limit vibration damage (Utah)
Vibration limits	Siskind Curve, 2 in/sec (typical for pile), 1 in/sec (historical/critical structures for pile), 0.2 in/sec (typical for roller), 0.1 in/sec (critical structures for roller)

PHASE-1: DATA COLLECTION

Project Data Collection

- Data collected
  - hammer/equipment characteristics: (manufacturer, model, maximum energy, maximum stroke, etc.)
  - pile information: material, length, cross-section
  - pile driving logs
  - soil conditions
  - results of measurements of ground vibrations
  - results of static and dynamic pile testing
- Challenges
  - scattered data
  - long lead times
  - vibration measurement reports with minimal information



District-2

Concrete pile	6
Sheet pile	1
Vibratory compaction	2
Total	**9**

District-3

Concrete pile	0
Sheet pile	0
Vibratory compaction	0
Total	**0**

District-5

Concrete pile	12
Sheet pile	2
Vibratory compaction	9
Total	**23**

District-7

Concrete pile	0
Sheet pile	0
Vibratory compaction	1
Total	**1**

District-1

Concrete pile	1
Sheet pile	0
Vibratory compaction	0
Total	**1**

District-4

Concrete pile	17
Sheet pile	8
Vibratory compaction	8
Total	**33**

District-6

Concrete pile	4
Sheet pile	0
Vibratory compaction	2
Total	**6**

Remaining Tasks and Path Forward

Task-5: Develop simple equations to calculate PPV of ground vibrations

Task-6: Develop criteria and standardized procedures for pre-construction surveys

Task-7: Evaluate existing vibration limits and develop flexible limits for FDOT projects

Task-8: Evaluate mitigation techniques

Task-9: Develop recommendations