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Project: Vibrations and Ground Deformations Due to Road Compaction (BED26-977-07)

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Vibrations and Ground Deformations due to Road Compaction

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Outline

- Brief project overview: benefits, objectives, scope
- Technical background
- Survey to practitioners
- Field testing in road compaction sites
- Numerical modeling of vibratory roller compaction
- Prediction equations and charts
- Implementations and recommendations

Review of Benefits

Qualitative:

- Reduce conservative limits for vibration monitoring and protection of existing structures.
- Assist designers during preparation of project documents and plans. More accurate estimates of required monitoring.
- Relationships between construction equipment and vibration effects on soils.
- Better definition of number of structures that require monitoring.

Quantitative:

- Provide a computational framework currently unavailable to designers.
- Develop a model to estimate zone of influence related to road compaction.
- Produce a ground deformation chart or correlation due to road compaction equipment relating PPV, Dr, distance from source, and input energy (e.g., centrifugal force and vibration frequency).

Review of Project Objectives

- Develop prediction method of dynamic ground deformations and vibrations caused by road compaction using field data and numerical modeling.

- Understand mechanisms of near-field and far-field deformations during road compaction.

- Investigate relationships among: ground deformations and vibrations (i.e., PPV), input energy (e.g., vibration frequency and centrifugal force), and distance from the source of road compaction. Affecting parameters: soil strength and stiffness, type of road compaction equipment, relative density, and characteristics of the energy source.

- Develop ground deformation charts (or correlations or equations) for road compaction as a function of PPV, Dr, distance from the source, soil shear strain, and/or input energy.

Tasks and Research Activities

Technical background → Survey → Field testing → Numerical models → Empirical prediction and correlations

Technical background

- Standards and design methods
- Case histories
- Vibration prediction methods
- Previously reported numerical models

Survey

- Survey to practitioners and geotechnical engineers
- Questions about road compaction effects on soils and structures

Field testing

- Five construction site visits in Central Florida
- Measured ground deformations and vibrations
- Site-specific conditions and geotechnical mechanisms

Numerical models

- Development of numerical models
- Model validation and comparison with field data
- Parametric study

Empirical prediction and correlations

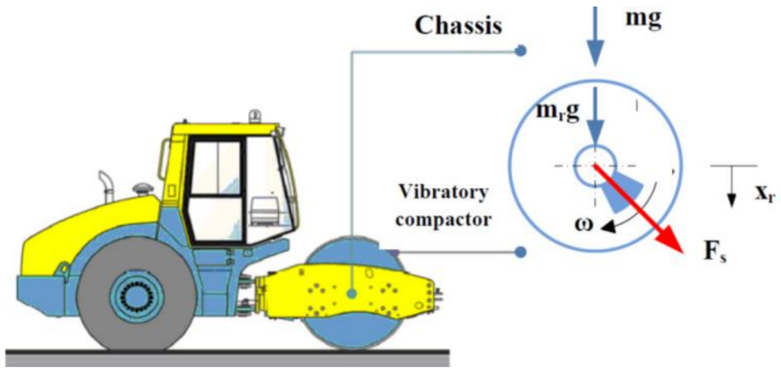
- Development of charts and equations

TECHNICAL BACKGROUND

UCF

Xu et al. (2022)

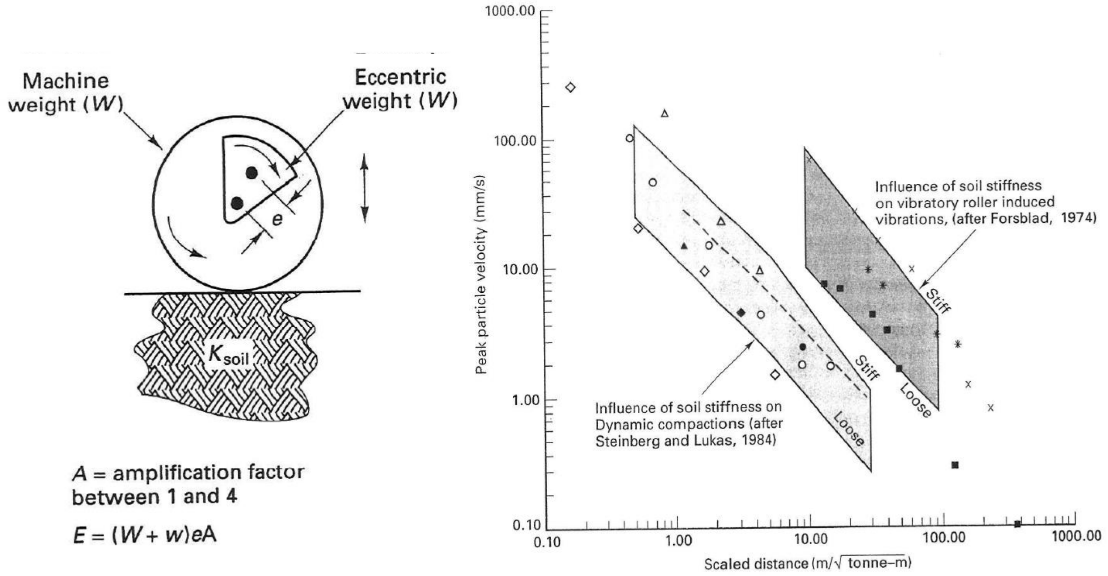
• Soil compaction is induced by combination of <u>static forces</u> (weights of frame and drum) and <u>dynamic forces</u> (rotation of the eccentric mass inside the drum)



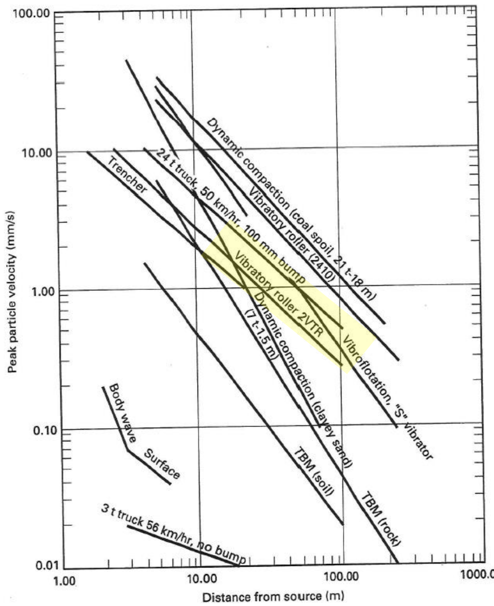
From Sergiu and Heriberto (2016)

Dowding (1996)

• Most studies focus on PPVs, ignoring energy transfer mechanisms
• Stiff soils lead to lower attenuation rate than soft soils due to material damping
• Energy transfer needs to consider relative masses of two components of the mechanism and relative stiffness of the reaction medium and machinery



From Dowding (1996)



Attenuation of PPV with absolute distance for different construction equipment

Standards and Specifications

FDOT Standard Specifications for Road and Bridge Construction (2021):

- Structures must be monitored within 75 ft of road compaction operations
- Equipment must be capable of detecting vibrations of 0.01 in/s or less
- The vibration threshold (PPV) defined by FDOT is 0.5 in/s
- Settlement limited to 0.01 ft

Section 108 Excerpt

108-2.1.3 Roadway Compaction Operations: When performing embankment and asphalt compaction, inspect and document the condition of the following existing structures, and survey and monitor for settlement the following existing structures:

1. as shown in the Plans.
2. within 75 feet of vibratory compaction (in any vibratory mode) operations.

Caltrans Transp. and Constr. Vibration Guidance Manual (2013):

- PPV limit criteria based on studies by Whiffin and Leonard (1971)
- Road compaction is a continuous sources of vibration
- Several limits defined depending on the use of the structure. The FDOT limit is comparable to new residential structures

Guideline Vibration Damage Potential Threshold Criteria

Structure and Condition	Maximum PPV (in/sec) Transient Sources	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.

FTA Transit Noise and Vibrations Impact Assessment (2006):

- Damage criteria depending on structure type (not its use)
- FDOT limit compared to building category I: reinforced concrete

Construction Vibration Damage Criteria

Building Category	PPV (in/sec)	Approximate L_v †
I. Reinforced-concrete, steel or timber (no plaster)	0.5	102
II. Engineered concrete and masonry (no plaster)	0.3	98
III. Non-engineered timber and masonry buildings	0.2	94
IV. Buildings extremely susceptible to vibration damage	0.12	90

† RMS velocity in decibels (VdB) re 1 micro-inch/second

Ground Vibrations: Prediction Methods

Hiller and Hope (1998):

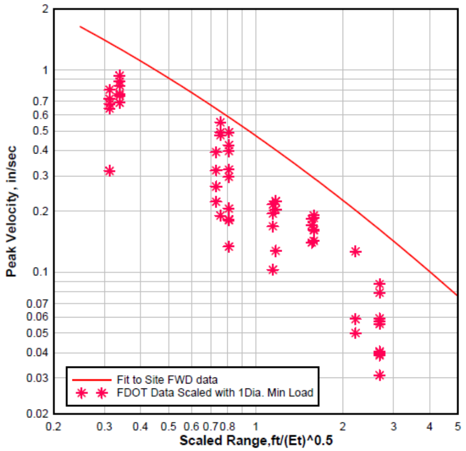
- Several attenuation equations depending on construction equipment
- The equation depends on the energy input per cycle (W_0) and distance from the roller
- Road compaction can damage infrastructure

Operation		Prediction
Piling	impact	$v_{res} \leqslant 1{\cdot}5 \frac{\sqrt{W}}{r}$ $\log v^{\dagger}_{res} = -0{\cdot}073 + 1{\cdot}38 \log\left[\frac{\sqrt{W}}{r}\right] - 0{\cdot}234 \log^2\left[\frac{\sqrt{W}}{r}\right]$
	vibro	$v_{res} \leqslant 1{\cdot}8 \frac{\sqrt{W_c}}{r}$ $\log v^{\dagger}_{res} = -0{\cdot}038 + 1{\cdot}64 \log\left[\frac{\sqrt{W_c}}{r}\right] - 0{\cdot}334 \log^2\left[\frac{\sqrt{W_c}}{r}\right]$
Vibratory compaction		$v_{res} \leqslant 3{\cdot}16 \frac{\sqrt{W_c}}{r}$
Dynamic compaction		$v_{res} \leqslant 0{\cdot}037 \left[\frac{\sqrt{W}}{r}\right]^{1{\cdot}7}$
Bored tunnelling		$v_{res} \leqslant 180x^{-1{\cdot}3}$

Empirical predictors of ground-borne vibration levels from construction works in mm/s

Jackson et al. (2007):

- FDOT funded project using Falling Weight Deflectometer (FWD) data to develop a PPV prediction equation
- This equation depended on roller energy, force, and distance to the structure



PPV attenuation curve validated with FWD results

Caltrans Transp. and Constr. Vibration Guidance Manual (2013):

- Suggested a PPV prediction equation for several vibratory equipment and soil conditions
- Based on a reference value at a reference distance of 25 ft

$$PPV_{vibratory\ roller} = PPV_{ref}(25/D)^n \quad [in/s]$$

Equipment	Reference PPV at 25 ft. (in/sec)
Vibratory roller	0.210
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003
Crack-and-seat operations	2.4

Reference vibration source amplitude

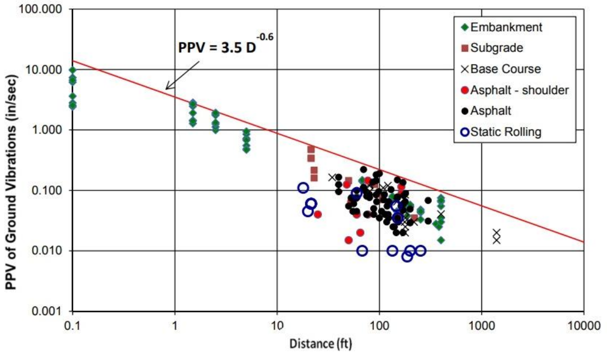
Soil Class	Description of Soil Material	Value of "n" measured by Woods and Jedele	Suggested Value of "n"
I	Weak or soft soils: loose soils, dry or partially saturated peat and muck, mud, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, top soil. (shovel penetrates easily)	Data not available	1.4
II	Competent soils: most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel)	1.5	1.3
III	Hard soils: dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, need pick to break up)	1.1	1.1
IV	Hard, competent rock: bedrock, freshly exposed hard rock. (difficult to break with hammer)	Data not available	1.0

Suggested "n" values based on the soil class

Selected Case Histories

Bayraktar et al. (2013):

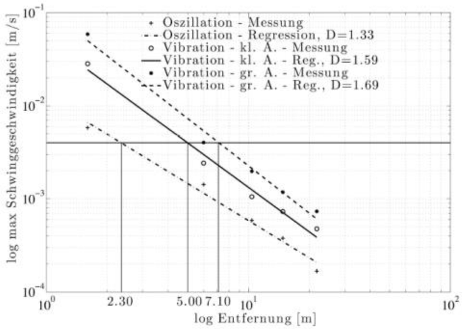
•FDOT-funded research project
•Florida's Turnpike- vibratory compaction projects
•40 different vibration monitoring- 170 data points
•FDOT PPV limit of 0.5 in/s was not often exceeded beyond approximately 20 ft



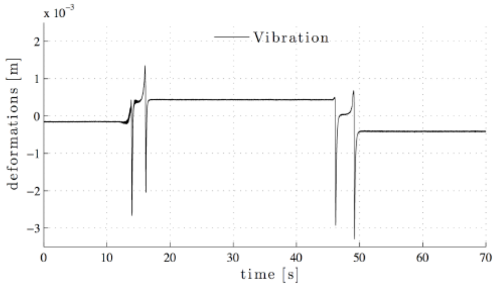
Distance versus PPV

Pistrol et al. (2014):

•Vibratory and oscillatory drum on a gravel pit
•HAMM HD+90 VO tandem roller
•Amplitude of 0.013 in (f=50 Hz)
•Amplitude of 0.024 in (f=40 Hz)
(Vibratory)
•Oscillatory: Amplitude=0.06 in (f=39 Hz)
•Measured accelerations and integrated for PPV
•Larger PPV measured with large amplitude



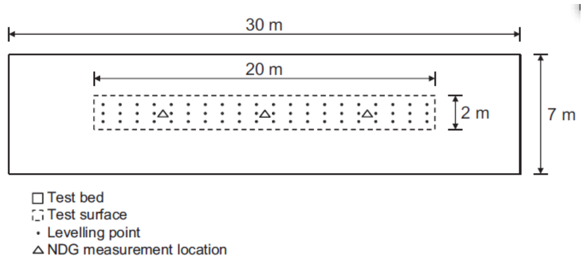
PPV by vibratory and oscillatory drums

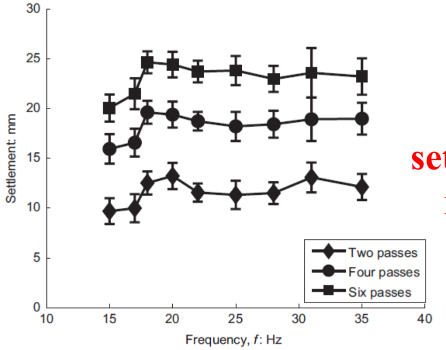


Vibratory drum- deformations in compacted soil

Wersäll et al. (2017):

•Full-scale tests: influence of operating frequency of a vibratory roller on well-graded gravel (GW)
•Dynapac CA3500D single drum soil compaction roller
• Tests: both fixed and variable frequencies (15-35 Hz)

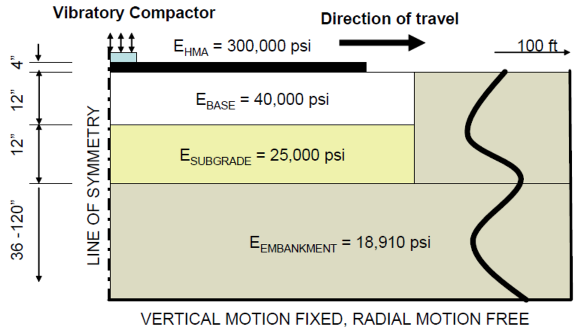


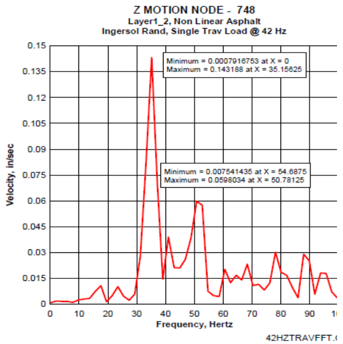


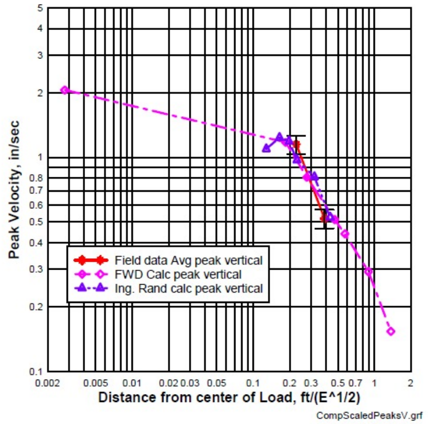
1 in settlement at resonant freq.

Settlement vs frequency

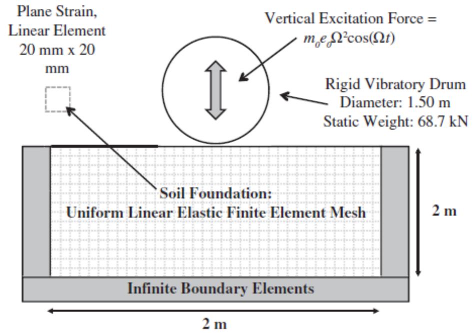
Jackson et al. (2007):
- Plane strain FE model
- Validated with field data from St Augustine, FL
- Linear elastic material
- Matched the predominant frequency and PPV





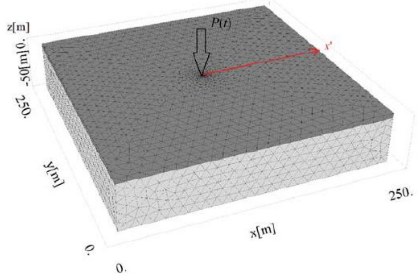


Kenneally et al. (2015):
- Plane strain linear elastic FE model
- Use of infinite boundaries to avoid wave reflection
- Static load: weight of drum
- Vertical harmonic excitation

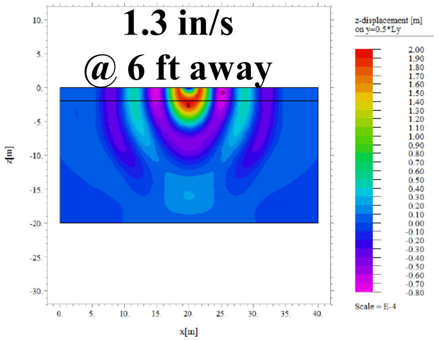


Schematic of 2D FE mesh in ABAQUS

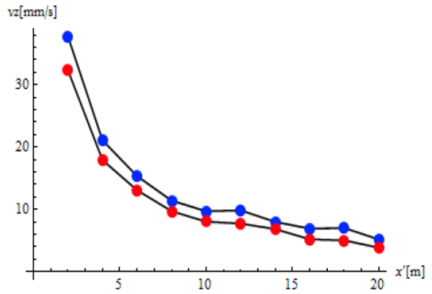
Herbut et al. (2019):
- FE model in FlexPDE 3D
- Compaction of STAVOSTROJ vibratory roller
- Linear elastic (1% damping)
- Force applied in a rectangular region (1x10 ft)
- Analysis time: 10 x period of the excitation
- Computed changes in soil response after compaction



Harmonic loading
Force: 73 lbf (324 kN)
Frequency: 29 Hz



Vertical displacements for t=0.072s

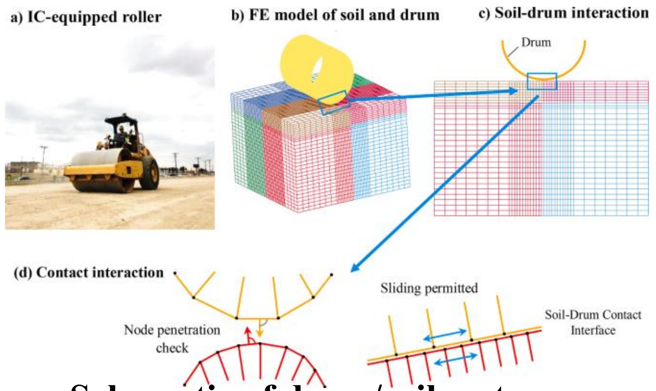


PPV attenuation before and after compaction

Numerical Modeling Approaches

Fathi et al. (2021):

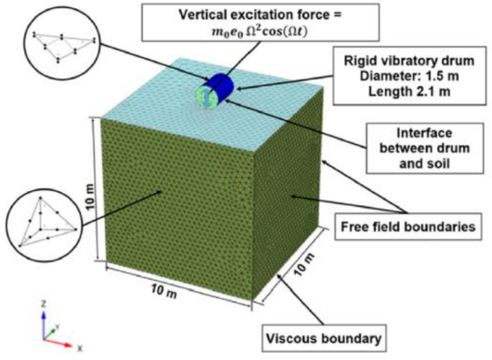
- Evaluation of depth of influence by a 3D FE model in LS-DYNA.
- Drum considered as a rigid body.
- Single contact interface between pavement and drum.
- Results matched both displacements and vibrations at selected depths



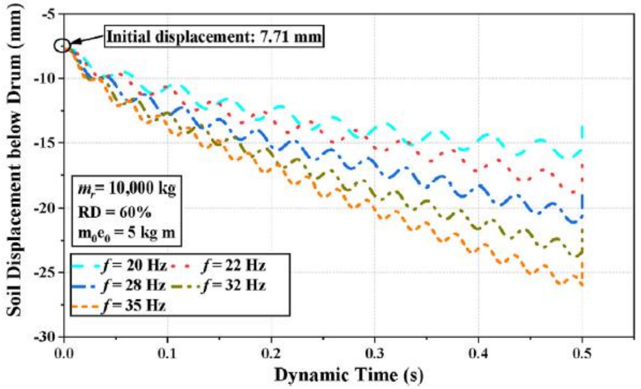
Schematic of drum/soil system

Xu et al. (2022):

- Estimation of soil stiffness from drum response.
- Simulations in PLAXIS 3D using HS-Small.
- Excitation modeled as harmonic
- Results showed increasing displacement as frequency increased



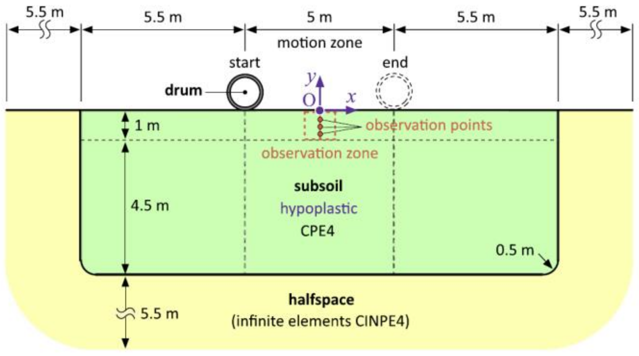
Adopted model



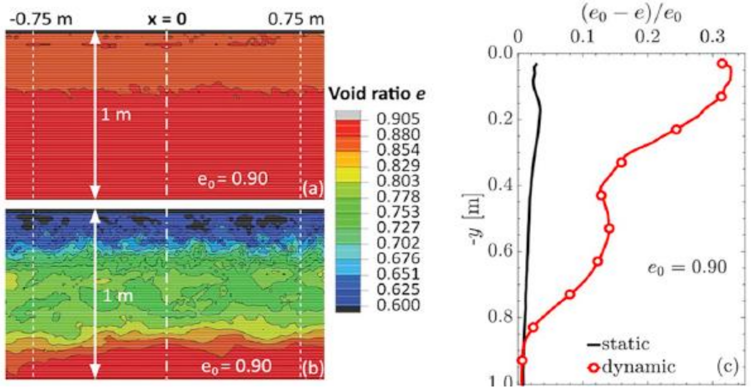
Soil settlement time history for different frequencies

Paulmichl et al. (2020):

- 2D plane strain FE model in ABAQUS.
- Hypoplasticity model for the soil to detect void ratio changes
- Contact between soil and drum using Coulomb's law.
- HAMM HD^{+} 90 VO roller
- Frequency of 39 Hz



Sketch of the 2D FE model

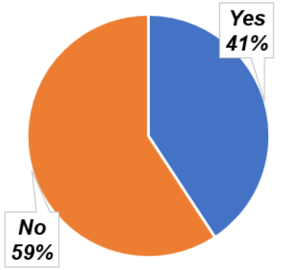


(a) static and (b) oscillatory roller pass

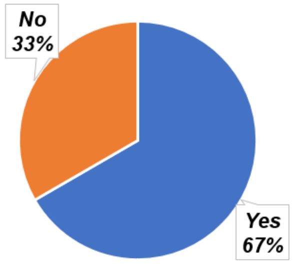
SURVEY TO PRACTITIONERS

Survey to Practitioners (Selected Responses)

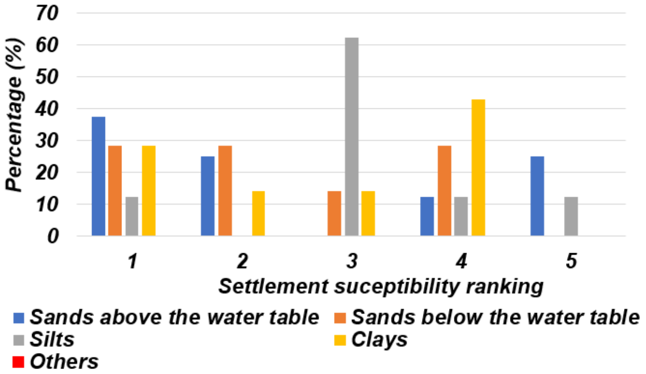
Question 1. Have you experienced in any past designs or construction projects any problem associated with ground surface settlement induced by vibratory roller compaction or road compaction in general?



Question 2. If your answer to **Question 1** was "Yes", did you observe or experience any type of damage to adjacent infrastructure during the road compaction because of high vibration levels (quantified in terms of high peak particle velocities) or large ground settlements or structural distortions?



Question 13. From your experience, ranking from 1-5 please provide what type of material is the most susceptible to develop the largest amount of settlement associated to vibratory roller compaction: (1 means the soil with the largest settlement).



General information:

- Web-based survey on the effects of road compaction-induced vibrations
- Survey common practices and experiences
- Database shared by FDOT
- 27 consultants participated, survey response rate of 18%

Main outcomes (1st part):

Regarding experience with damages/problems linked to this problem:

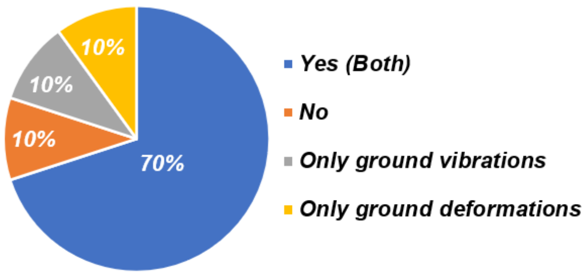
- 41% experienced problems regarding this phenomenon
- 67% of those issues were related to damages in adjacent infrastructure
- 50% who described issues did not report PPV and deformation values higher than FDOT limits
- Problematic soil conditions: mostly surficial sandy soils since those are susceptible to vibration-induced densification

Survey to Practitioners (Selected Responses)

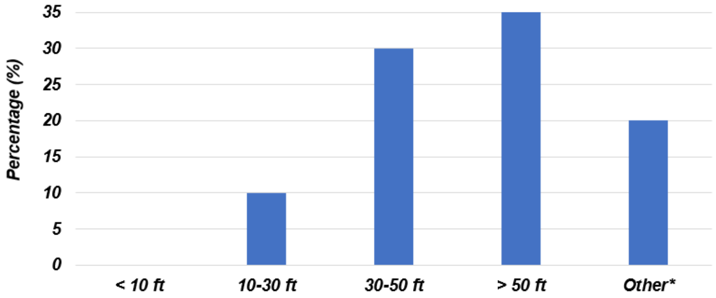
Main outcomes (2nd part):

- 70% considered important to monitor both vibrations and deformations
- Approx. 65% estimated the influence zone to be larger than 30 ft
- Three main sources of road compaction-induced deformations:
  - (i) relative density of soils,
  - (ii) soil grain re-arrangement,
  - (iii) roller characteristics (roller mass and centrifugal force)
- Subgrade and base compaction are the stages that trigger the largest deformations
- 40% is not familiar with any method to predict vibrations and deformations due to compaction

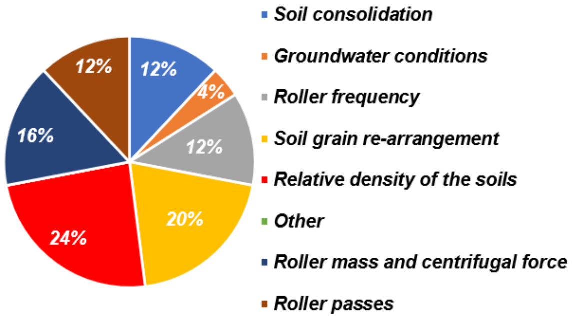
Question 8. Do you consider monitoring ground vibrations and ground deformations due to road compaction an important issue during the design phase of any road construction project?



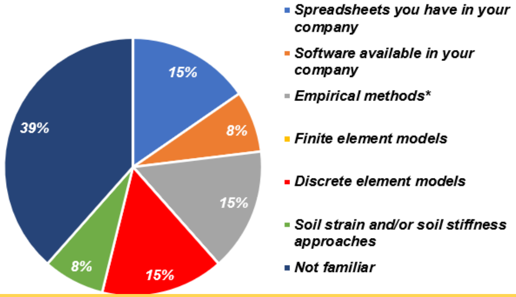
Question 16. From your experience, what is the maximum distance from the road compaction area at which infrastructure (e.g., buildings, public utilities, bridges, etc.) is not affected by the induced vibrations?



Question 14. From your experience, what are the main sources of vibratory roller-induced settlements in the surrounding soils? (You can select more than one choice)



Question 17. Which of the following methods and/or models do you use to estimate dynamic soil displacement due to vibratory roller compaction and/or to determine the impact of construction vibrations? (You can select more than one choice.)



FIELD TESTS

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Instrumentation Plan

Procedure:

Site selection → Instrumentation → Data collection → Analysis

Field testing EDPs:

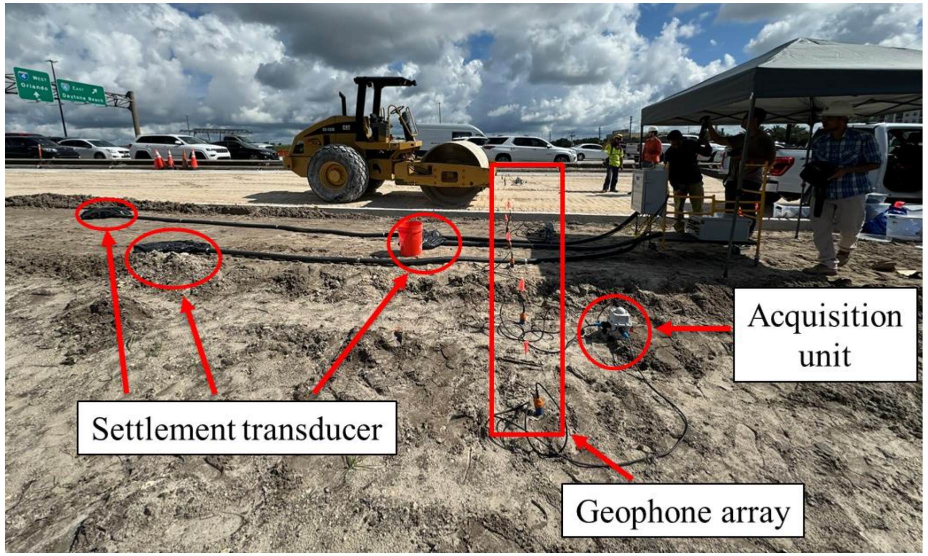
Measure Velocity Time Histories

Measure Ground Deformations

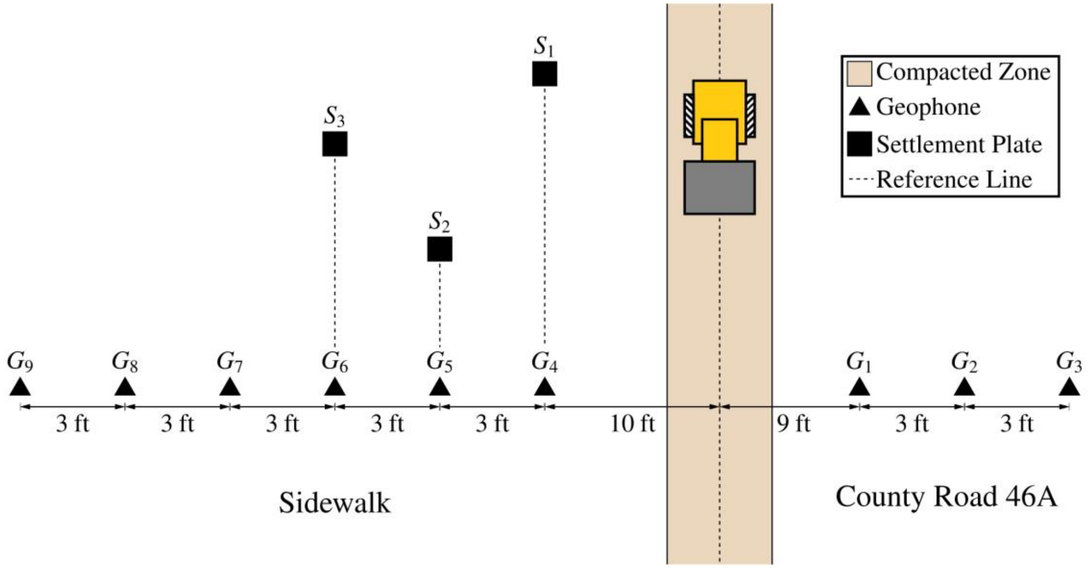
- Eighteen 5 Hz geophones
- Acquisition units
- Three vibrating wire settlement transducers

Field monitoring schedule during the road compaction test

Stage N_o	Roller movement	Roller setting	Duration (s) /#Passes
I	Fixed	Low	20 seconds
II	Fixed	High	20 seconds
III	Passing by	High	5 passes
IV	Passing by	Low	5 passes

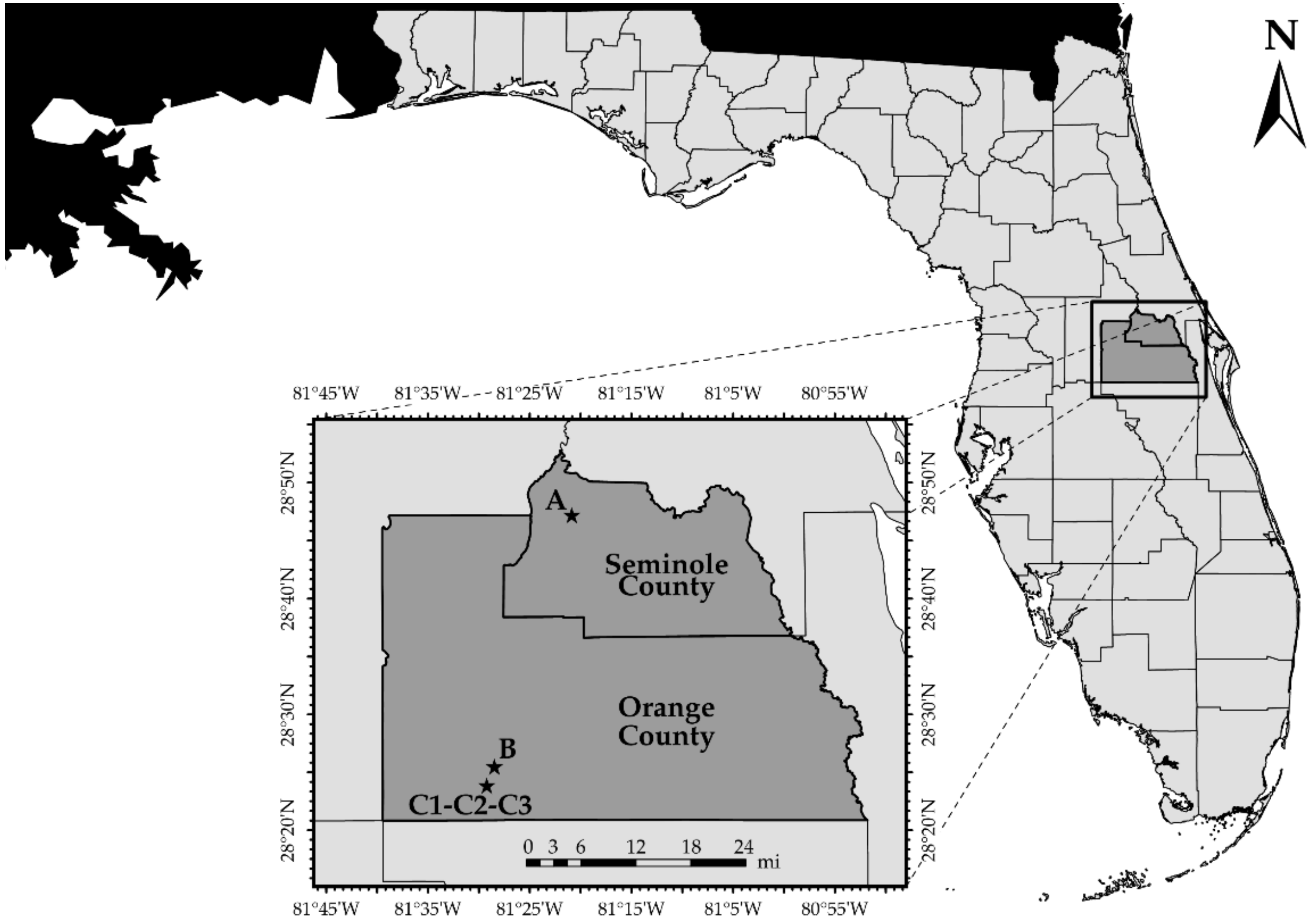


Instrumentation deployed in the field



Example plan view of the instrumentation layout

Site Locations



Site A:

- Lane widening at intersection between CR46A and Rinehart Road (Lake Mary, Seminole County, Florida).

Site B:

- MSE wall at connection ramp between the I-4 interstate and SR 528 (Dr. Phillips, Orange County, Florida).

Sites C1, C2, and C3:

- Interchange between the I-4 interstate and Daryl Carter Parkway (Dr. Phillips, Orange County, Florida).
- Subdivided in three sites due to multiple visits at multiple compaction stages.

Sites Description

Site A

- 28 ft-wide lane and sidewalk
- Previously compacted
- Caterpillar CS-533E

Site B

- Access road already compacted
- Sakai SV400D

Site C1

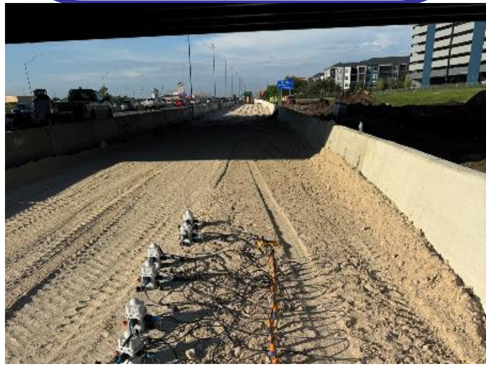
- 48 ft-wide two-lane exit ramp
- Very dense limerock
- Bomag 211D

Site C2

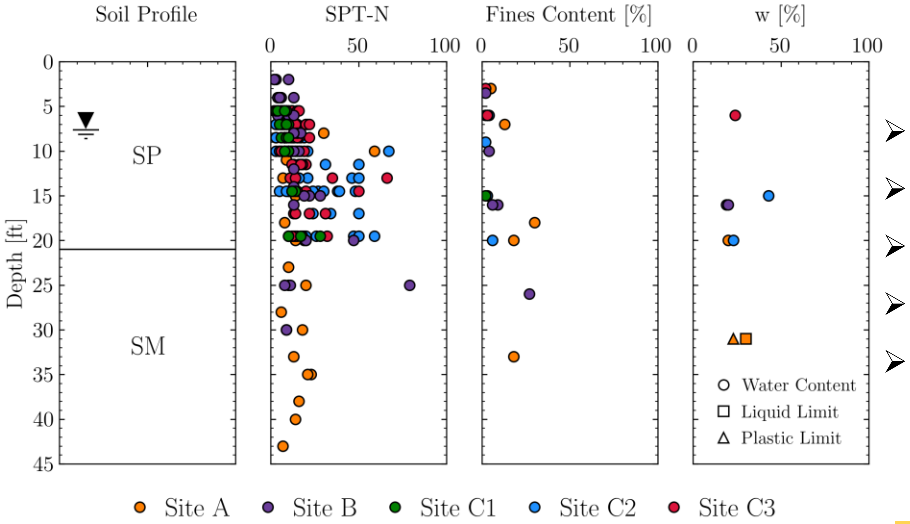
- 15 ft-wide ramp
- Very dense limerock
- Bomag 211D

Site C3

- 15 ft-wide acceleration lane
- Subbase was already compacted
- Concrete barrier between sensors and roller
- Bomag 211D



Typical Soil Conditions



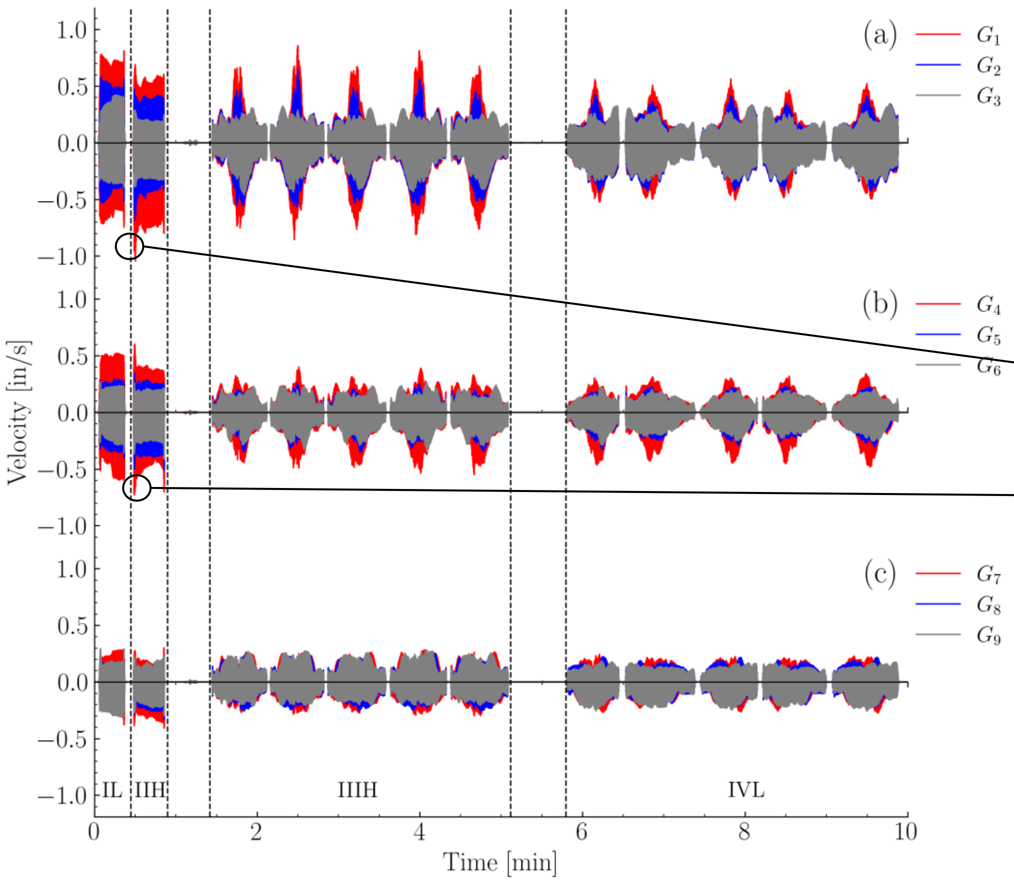
- Poorly graded sands (SP) and silty sands (SM).
- Water table was 6 ft below the ground surface.
- SPTs from 10 to 30 blows on average.
- Fine content varies between 0% and 30%.
- Water content ranges from 20% to 40%.

Typical Results: PPV

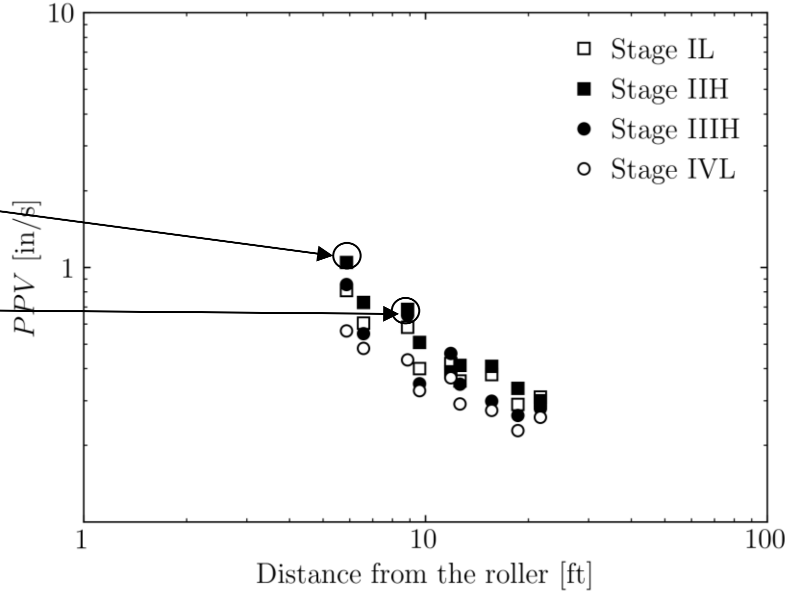
Lessons Learned

- Highest velocities measured during high setting stages. Higher centrifugal force causes higher PPVs.
- Quantification of energy from the roller is very important for charts.
- No significant difference in response from stationary roller or moving back and forth.

Velocity time history during entire road compaction test (Site A)



PPV attenuation with distance (Site A)



Typical Results: PPD

Lessons Learned

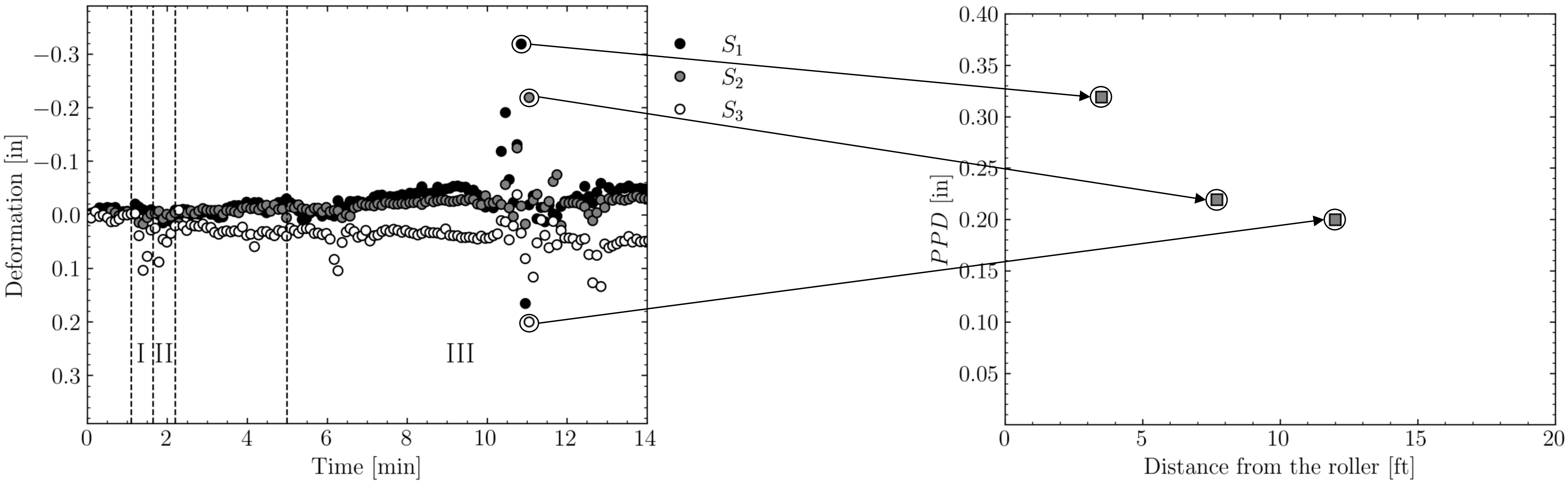
- PPD selected from maximum deformation in time history
- Ground deformations were transient
- Largest deformations occurred during high setting stages. More energy transmitted to the soil in that early stage.

Field monitoring schedule during the road compaction tests (Site C3)

Stage N$_o$	Roller movement	Roller setting	Duration (s) /#Passes
I	Fixed	High	20 seconds
II	Fixed	Low	20 seconds
III	Passing by	High	2 passes

Ground deformation time history at each settlement plate (Site C3)

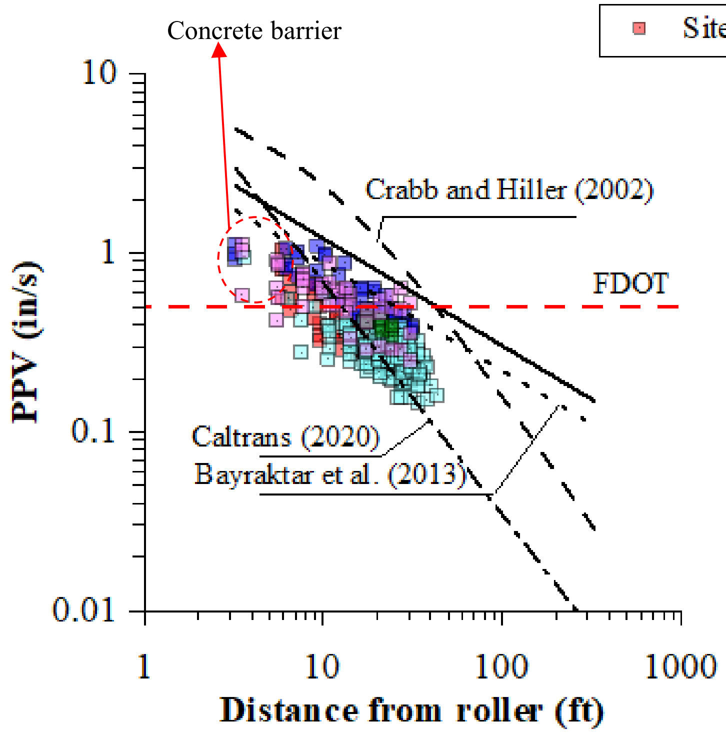
PPD attenuation with distance (Site C3)



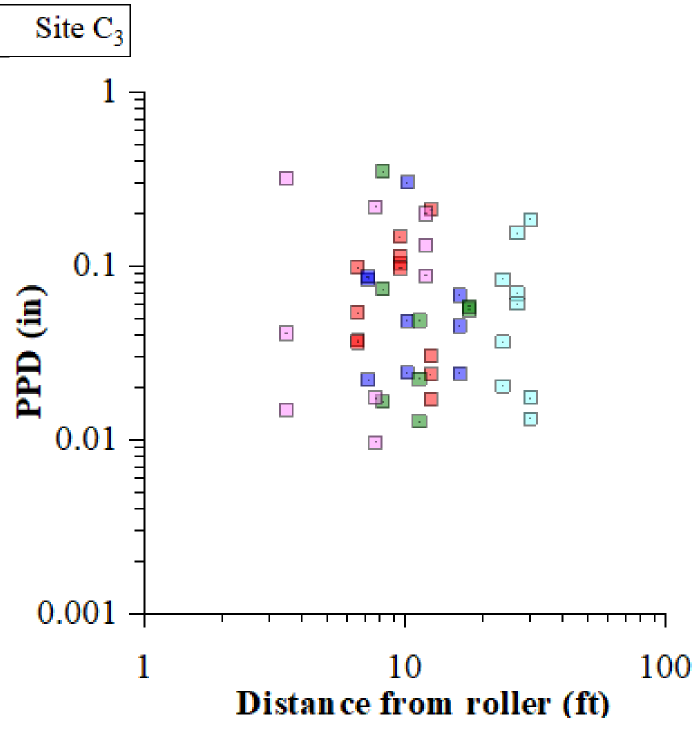
Summary of Field Test Results

Lessons learned

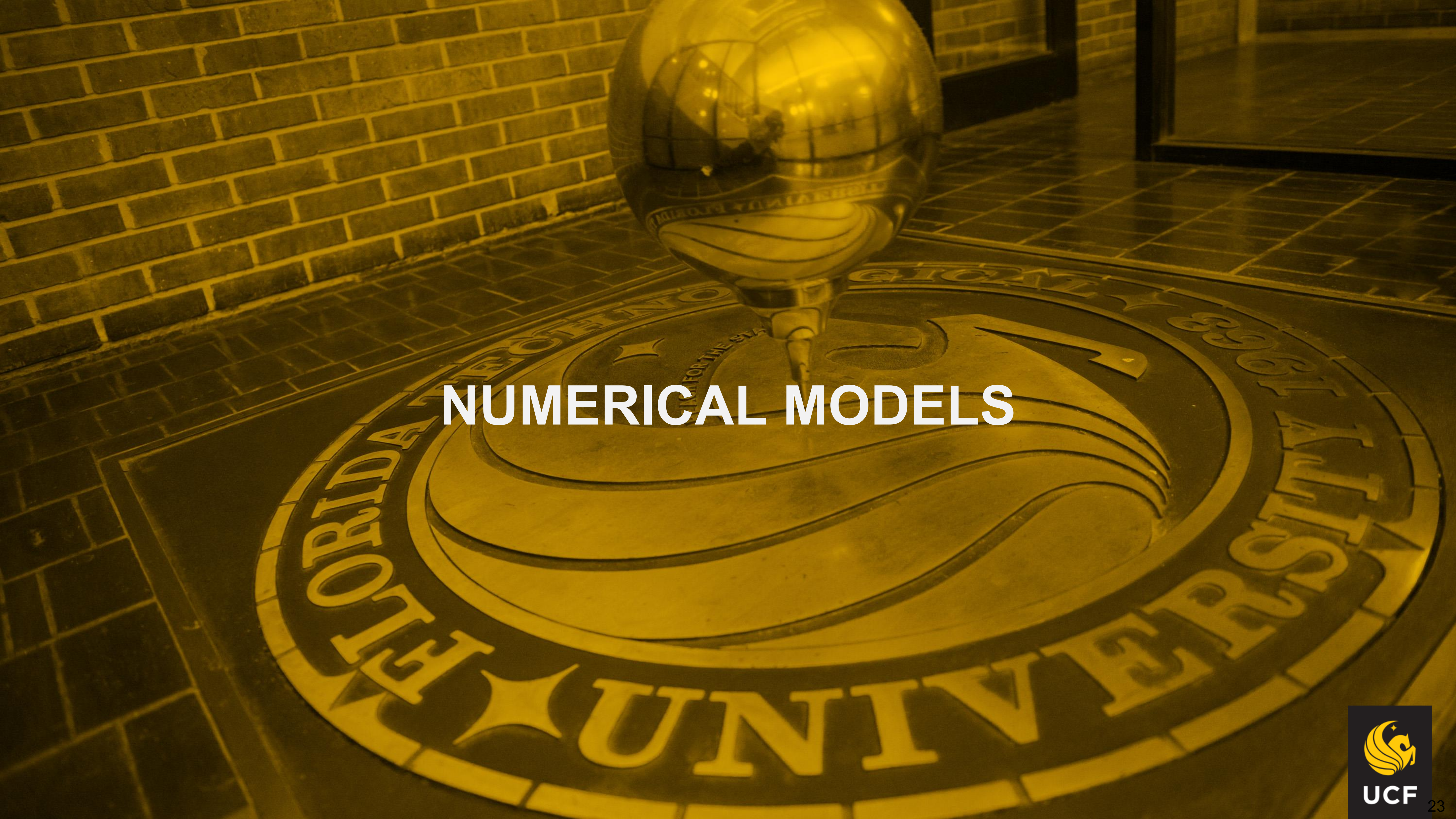
- The FDOT PPV limit of 0.5 in/s was not exceeded beyond approximately 40ft from the roller
- PPV measurements behind concrete barrier were affected by wave reflection
- Sites C2 and C3 showed the highest displacements due to the roller's higher centrifugal force
- PPD values were negligible at most sites, likely attributed to the high level of compaction performed before the tests
- PPD of approximately 0.3 in measured up to a distance of 10 ft



PPV attenuation with distance (All sites)



PPD attenuation with distance (All sites)



NUMERICAL MODELS

Modeling Framework

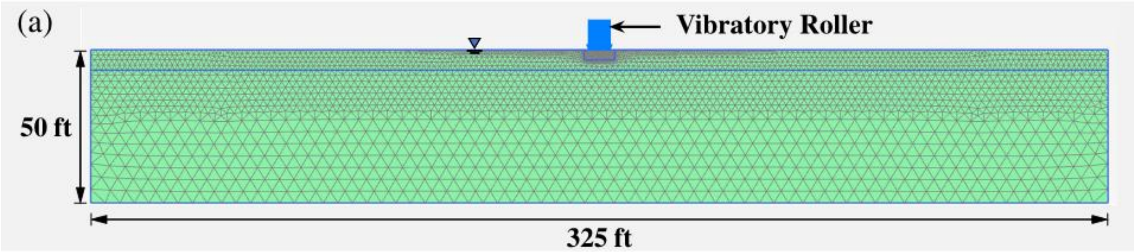
Testing site selection → **Summarize soil profile** → **Obtain vibratory roller specifications** → **Finite element modeling**

- Testing site selection: 5 construction sites
- Summarize soil profile: From soil borings and FDOT soil boring viewer
- Obtain vibratory roller specifications: To compute forcing function and vibration cycles
- Finite element modeling: Apply force time history to analyze response in soil continuum

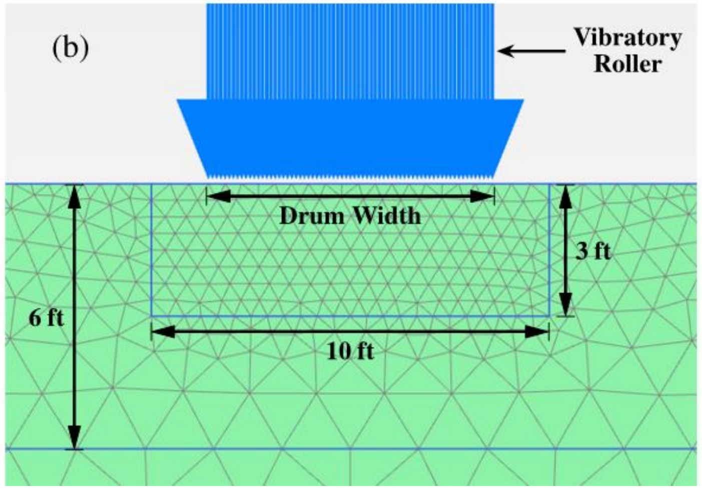
Model characteristics

- 2D FE model in PLAXIS 2D.
- Plane strain conditions.
- Single layer of a sandy soil.
- Constitutive model: Hypoplasticity Sand.
- Vibratory roller modeled as uniformly distributed static + dynamic loads.
- Water table at the ground surface.
- Viscous boundaries.

Overall mesh dimensions



Detailed view of the refined mesh under the roller



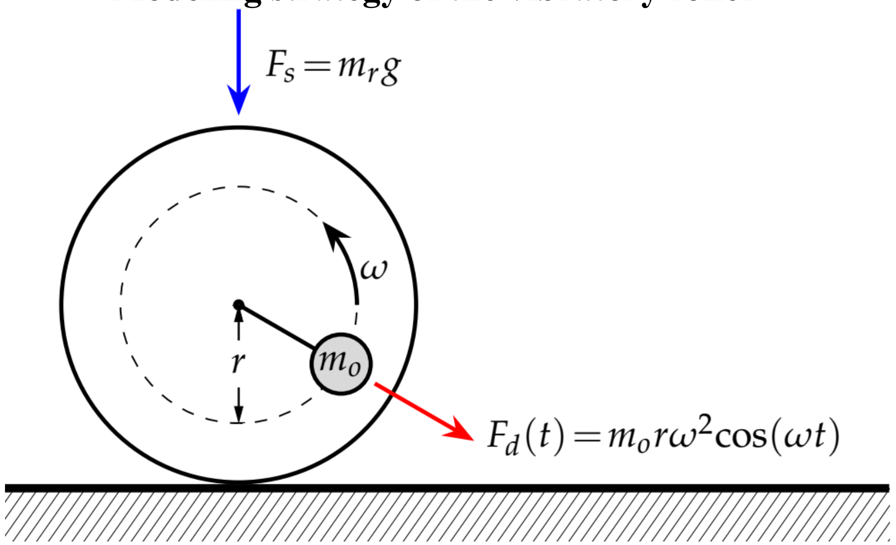
Steps for numerical simulations

1. Definition of material properties and drainage conditions.
2. Type of analysis: dynamic with consolidation
3. Definition of model geometry (drum width, soil clusters) and mesh
4. Initialization of soil stress field
5. Application of initial compression: static weight
6. Dynamic analysis: application of vibration cycles until reaching e_{min}

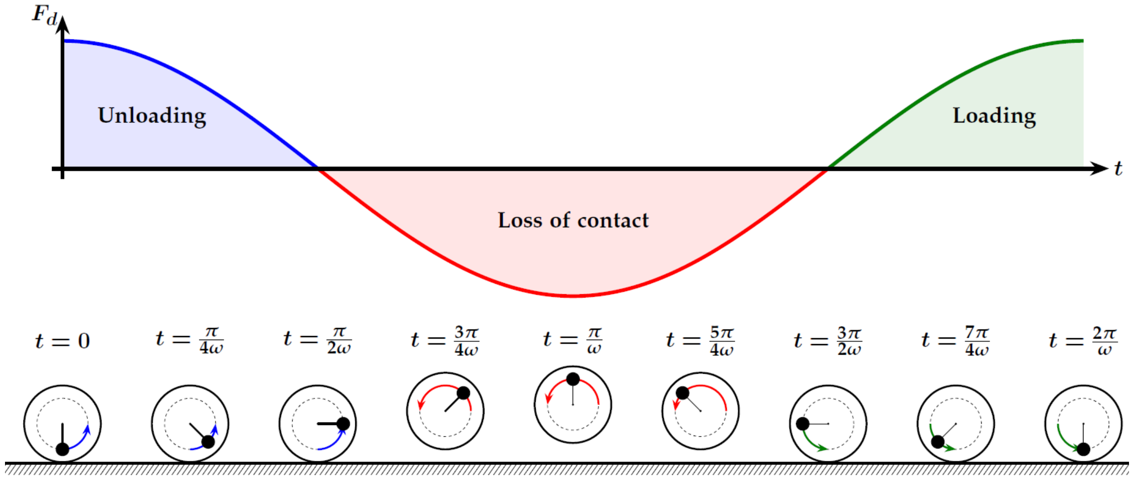
Modeling Strategy for the Vibratory Roller

- Static load ⟶ Axle load
- Dynamic load ⟶ Centrifugal force
- New non-contact modeling strategy proposed
- Energy ⟶ $E = 2 \cdot Amplitude \cdot (2F_s + F_d)$

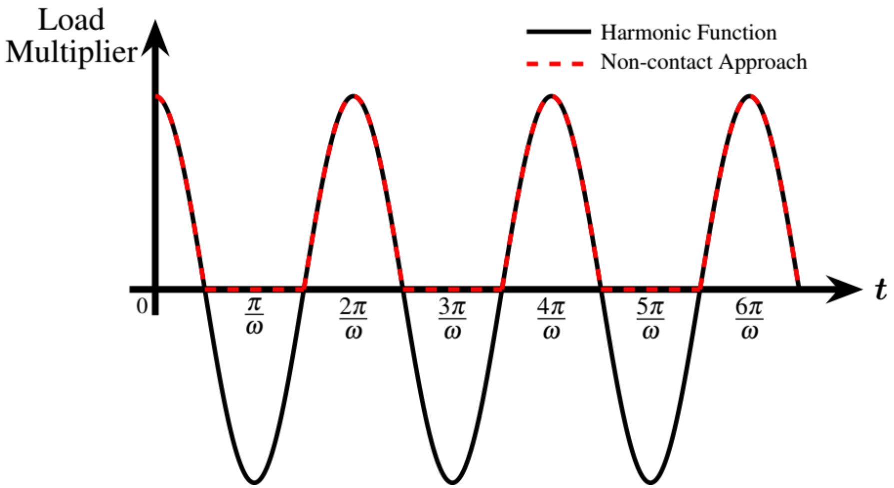
Modeling strategy of the vibratory roller



Idealization of the drum-soil interaction for one cycle of dynamic load



Load multiplier considering the non-contact approach



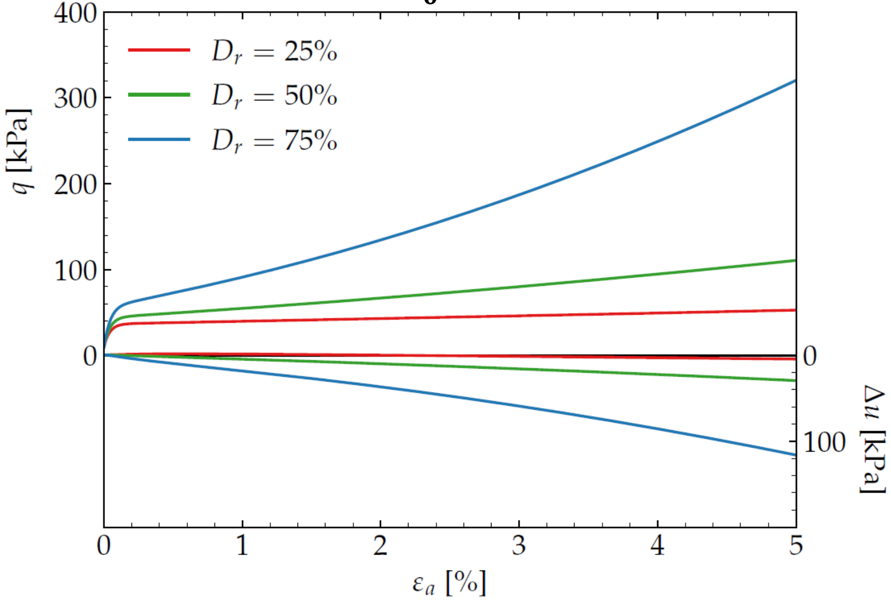
Definition of Soil Parameters

- Constitutive model: Hypoplasticity Sand.
- Relative densities: 25%, 50%, and 75%.
- Calibrated from numerical laboratory tests and published stiffness degradation curves.
- Initial cell pressure: 200 psf. (i.e., equivalent to depth 7.0 ft)
- $K_0 = 0.5$

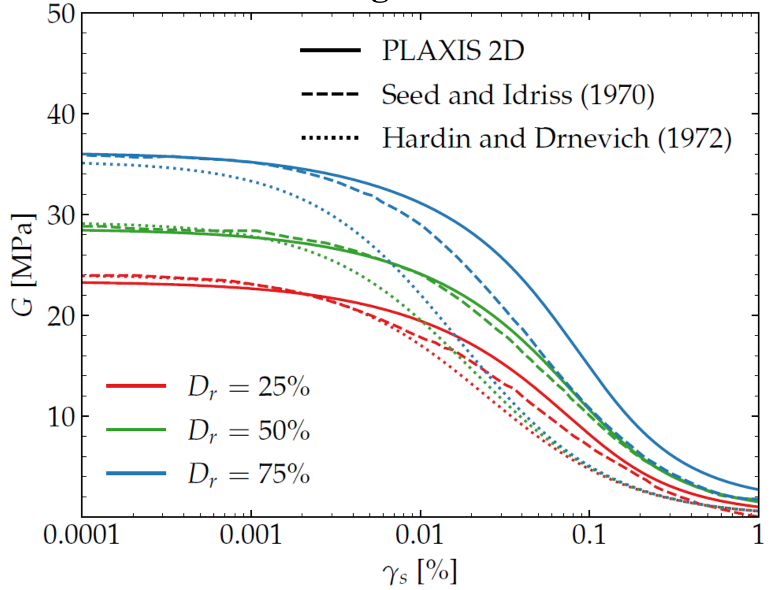
Soil properties obtained from the calibration

No.	Parameter	Description	Value	Unit
1	ϕ_c	Critical state friction angle	31	°
2	pt	Shift of the mean stress due to cohesion	0	psf
3	h_s	Granular hardness	25062	ksf
4	n	Exponent for pressure sensitive of a grain skeleton	0.37	-
5	e_{d0}	Minimum void ratio at zero pressure (ps = 0)	0.58	-
6	e_{c0}	Critical void ratio at zero pressure (ps = 0)	1.096	-
7	e_{i0}	Maximum void ratio at zero pressure (ps = 0)	1.315	-
8	α	Exponent for transition between peak and critical stresses	0.05	-
9	β	Exponent for stiffness dependency on pressure and density	1.4	-
10	m_R	Stiffness increase for 180° strain reversal	5	-
11	m_T	Stiffness increase for 90° strain reversal	2	-
12	R_{max}	Size of elastic range	5.00×10^{-5}	-
13	β_r	Material constant representing stiffness degradation	0.1	-
14	χ	Material constant for evolution of intergranular strains	1.0	-

Results $CK_0U - TXC$ tests

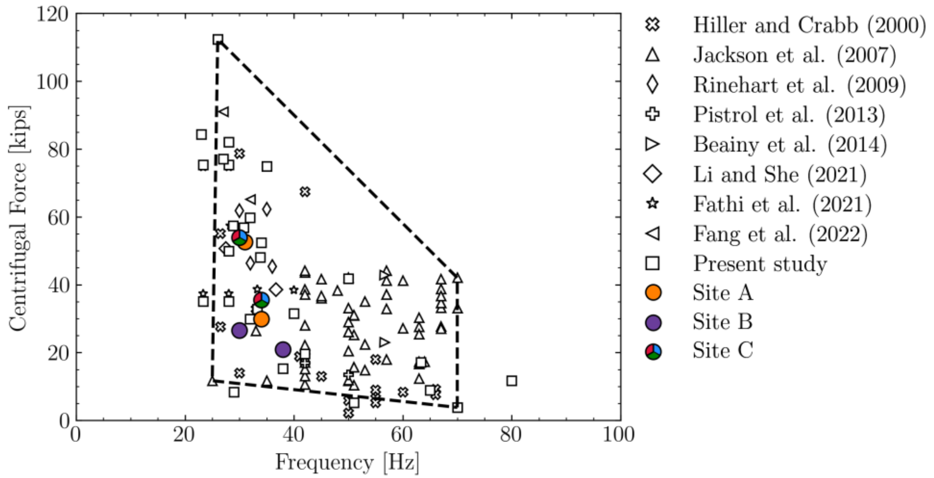


Stiffness degradation curves

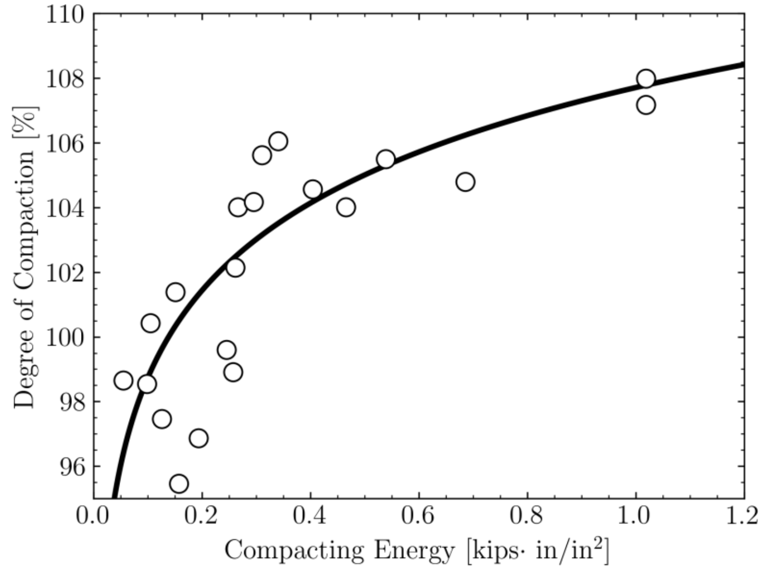


Definition of Numerical Simulation Time

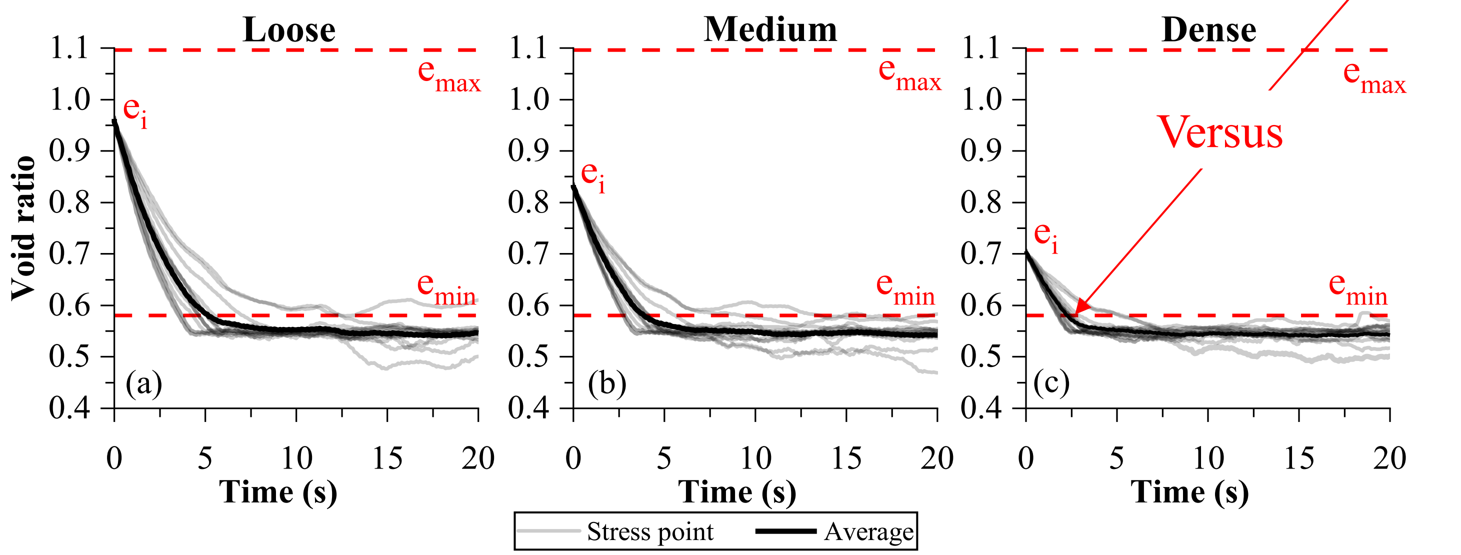
Graphical representation of the database



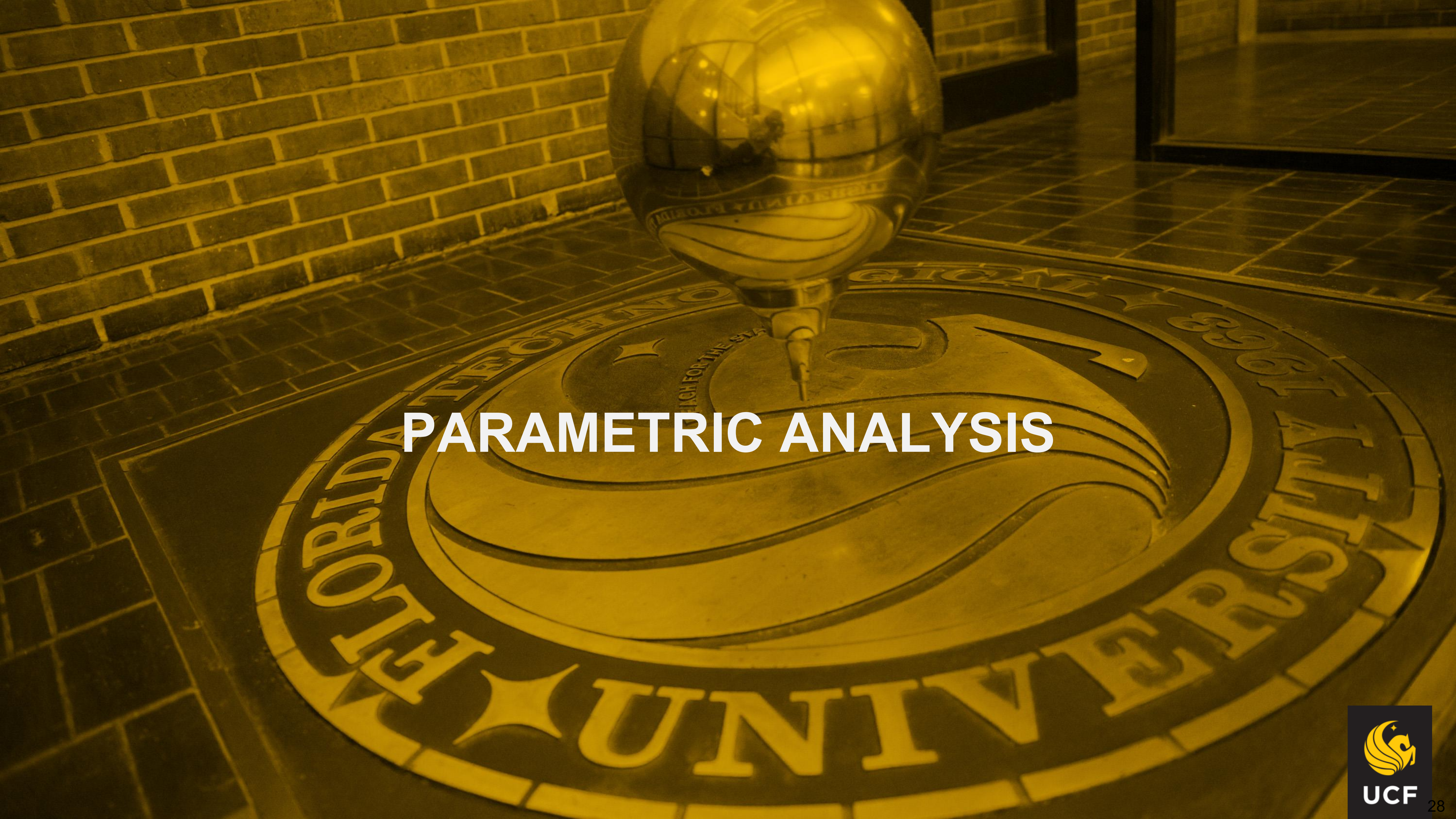
Degree of Compaction vs Compacting Energy (after Sakai 1996)



- Compacting Energy: $$E_c = 2a\left(F_s + \frac{1}{2}F_c\right)\cdot\frac{L}{V}\cdot f\cdot N\cdot\frac{1}{BL}\cdot Z$$
- Energy to achieve a D.C. of 100%: $E_c = 0.17\ kips \cdot in/in^2$
- Database with 50 rollers
- Assuming $N = 1\ pass$, $Z = 1\ drum$ and $V = 3$ mph
- Time per pass: $$t_{pass} = \frac{D}{V}$$
- e.g.,: required time for compaction computed: heaviest roller 2.3 s



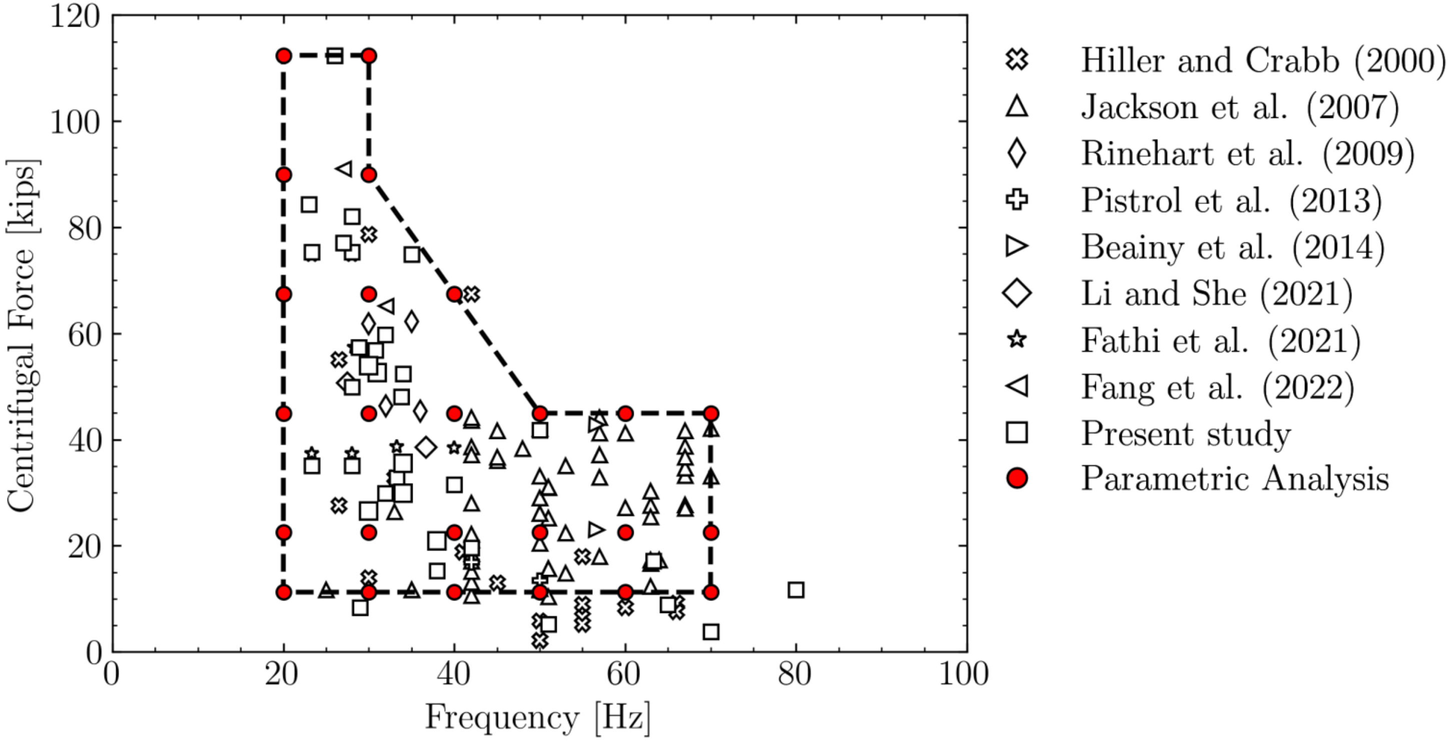
Example of compaction process by the heaviest roller: Bomag BW 226 BVC-5



PARAMETRIC ANALYSIS

Summary of the Parametric Analyses Performed

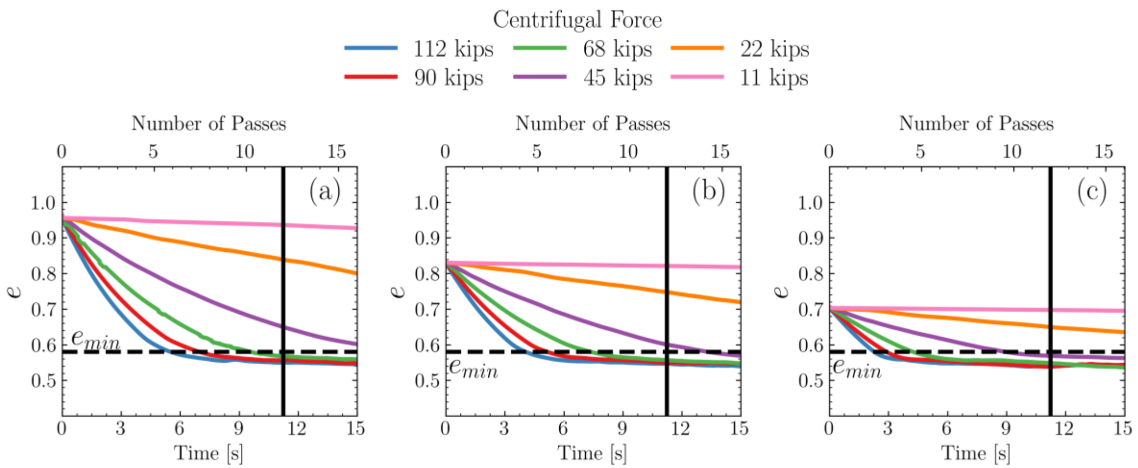
Combinations of centrifugal force and vibration frequency



- Study the effects of:
  - i) soil relative density,
  - ii) centrifugal force,
  - iii) vibration frequency.
- 75 numerical simulations, 1800 hours of computational effort.
- Output values:
  - i) Compaction efficiency,
  - ii) ground vibrations (PPV),
  - iii) ground deformations (PPD).

Effect of Soil Relative Density

Computed compaction performance

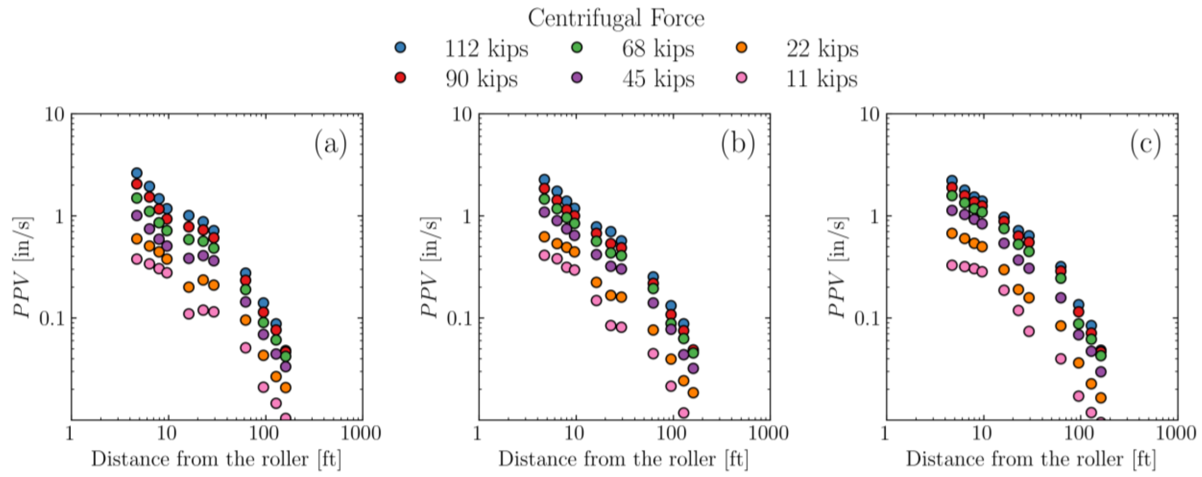


$D_r = 25\%$ $D_r = 50\%$ $D_r = 75\%$

Lessons learned

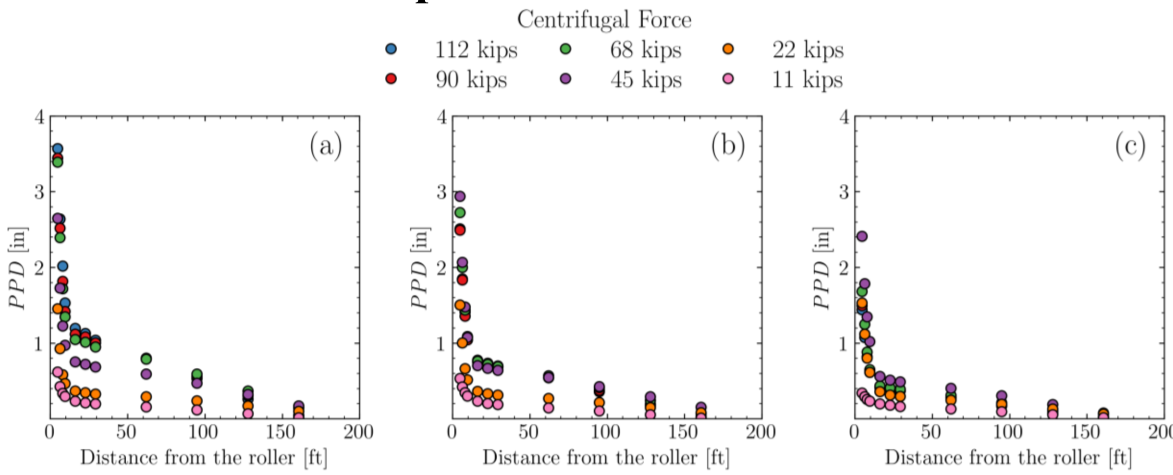
- Soil relative density is important to define how minimum void ratio is reached
- Time to reach target void ratio depends on relative density
- PPV attenuation curves are similar across all relative densities
- Regardless of relative density, 0.5 in/s is exceeded up to ~35 ft from roller
- The lower the relative density the larger the PPD. More densification occurs for low relative densities.

Computed PPV attenuation



$D_r = 25\%$ $D_r = 50\%$ $D_r = 75\%$

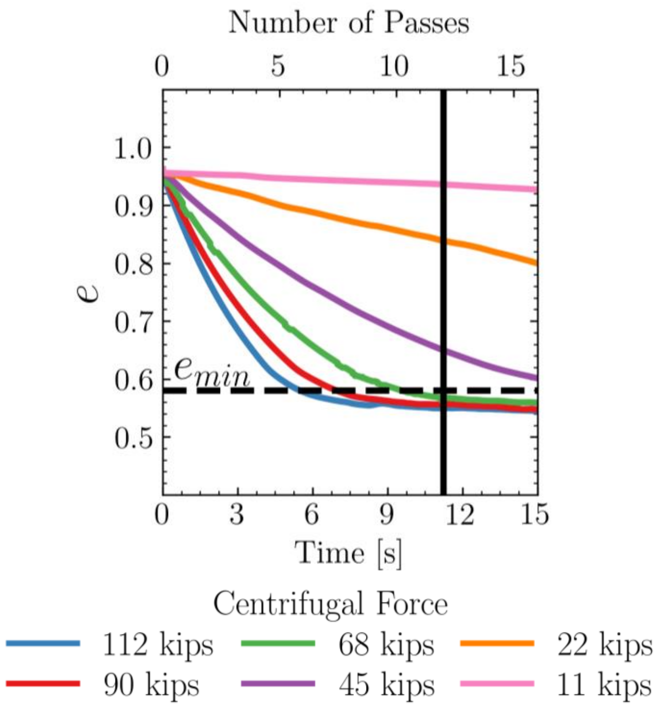
Computed PPD attenuation



$D_r = 25\%$ $D_r = 50\%$ $D_r = 75\%$

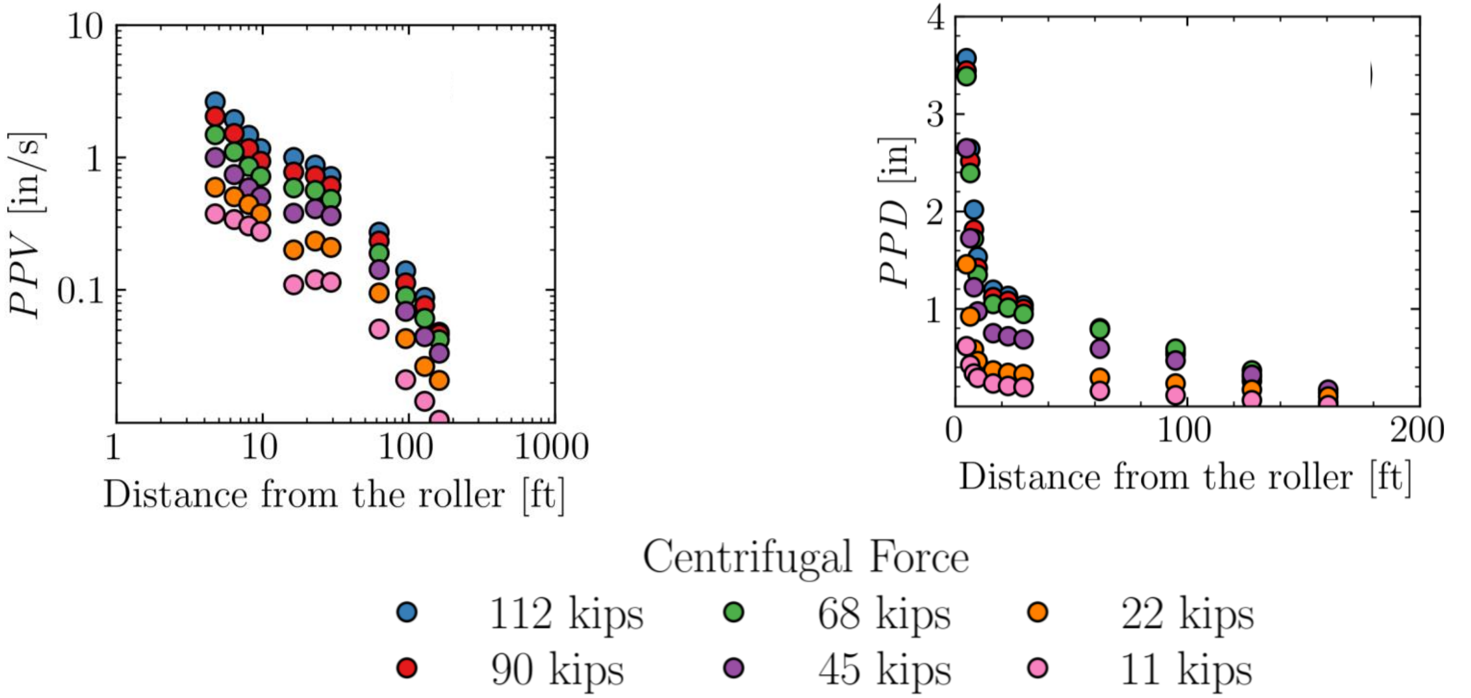
Effect of Centrifugal Force

Computed compaction performance



Computed PPV attenuation

Computed PPD attenuation

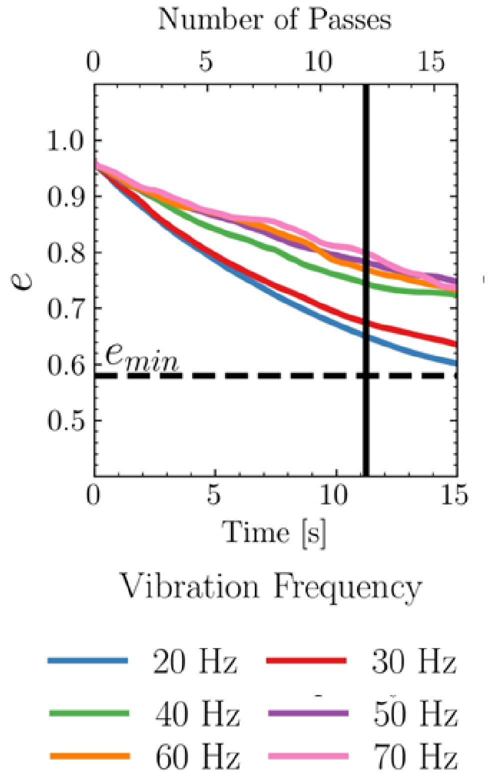


Lessons learned

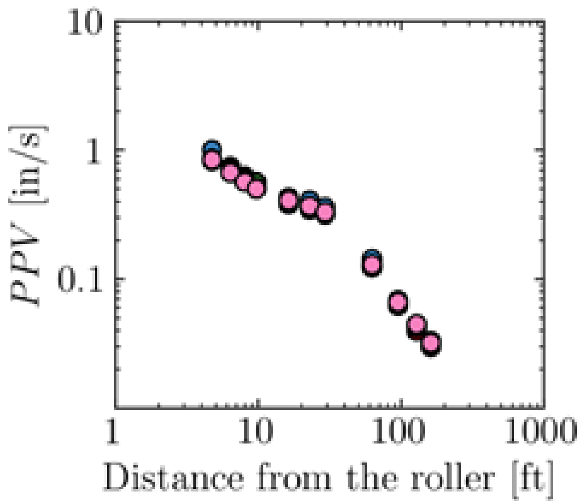
- The higher the centrifugal force, the faster the rate of changes in void ratio
- More energy transferred to the soil improves the compaction efficiency
- PPV levels increase with the centrifugal force
- PPV attenuation rate is soil dependent (damping), and not necessarily related to the centrifugal force
- PPDs increase with centrifugal force
- The magnitude and duration (i.e., number of vibration cycles) affect ground displacements; for example, a lower centrifugal force (68 kips) applied over a longer time generated more displacement than a higher force (90 kips).

Effect of Vibration Frequency

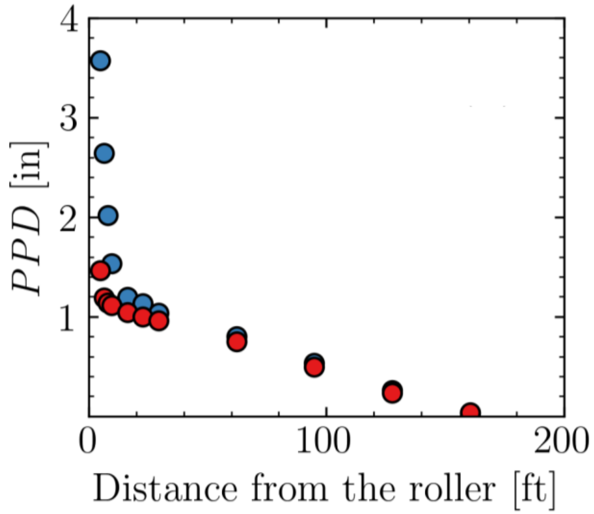
Computed compaction performance



Computed PPV attenuation

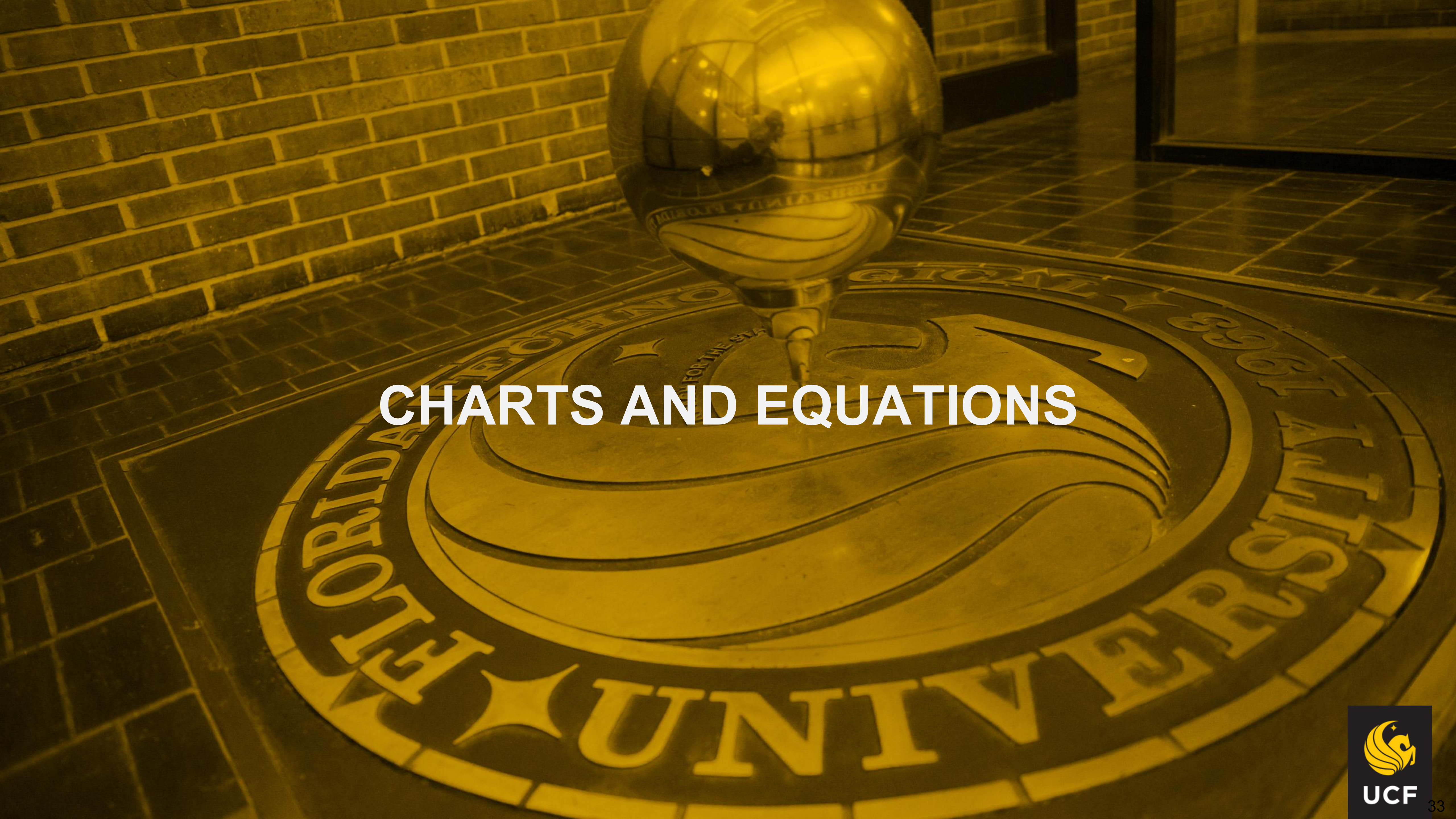


Computed PPD attenuation



Lessons learned

- At high centrifugal forces, compaction mostly unaffected by frequency
- At low centrifugal forces, compaction affected by frequency
- PPVs controlled by energy and number of cycles, not much by vibration frequency
- PPDs mostly unaffected by frequency, but low vibration frequencies cause larger PPDs as frequency natural frequency of surficial soils

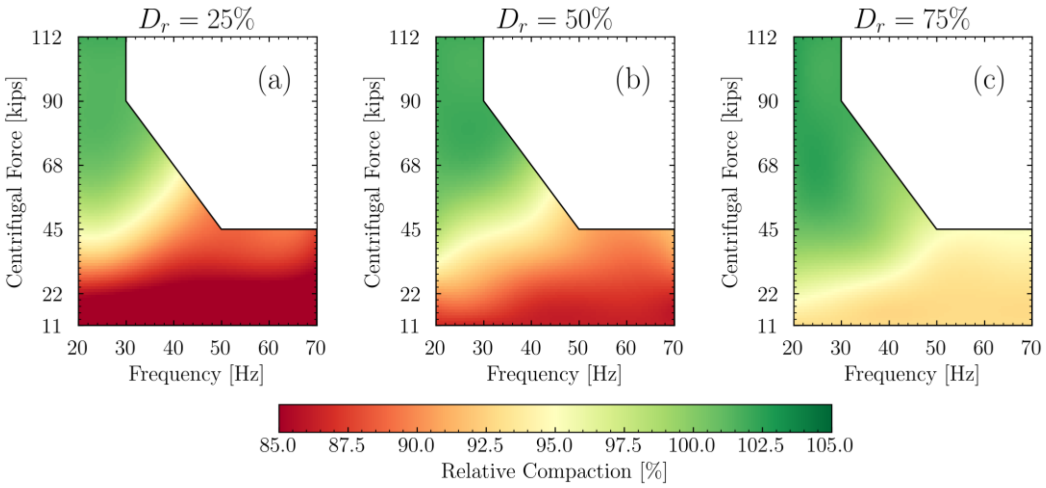


CHARTS AND EQUATIONS

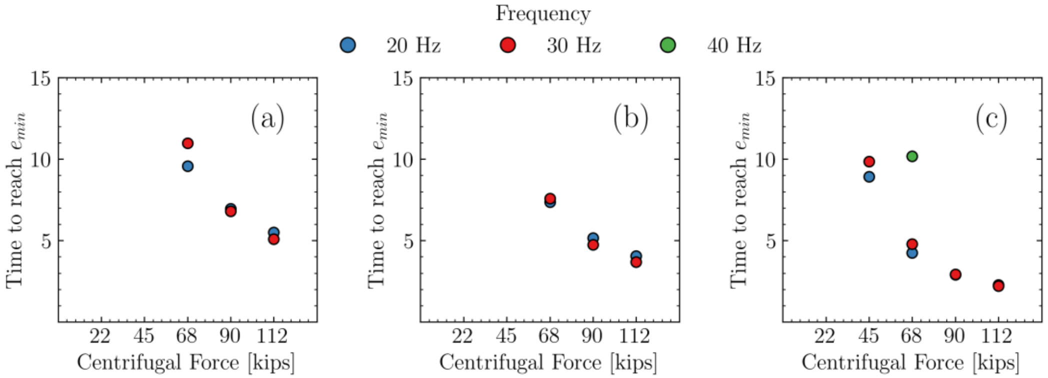
UCF

Summary Charts: Compaction Performance

Relative compaction efficiency chart after 12 roller passes



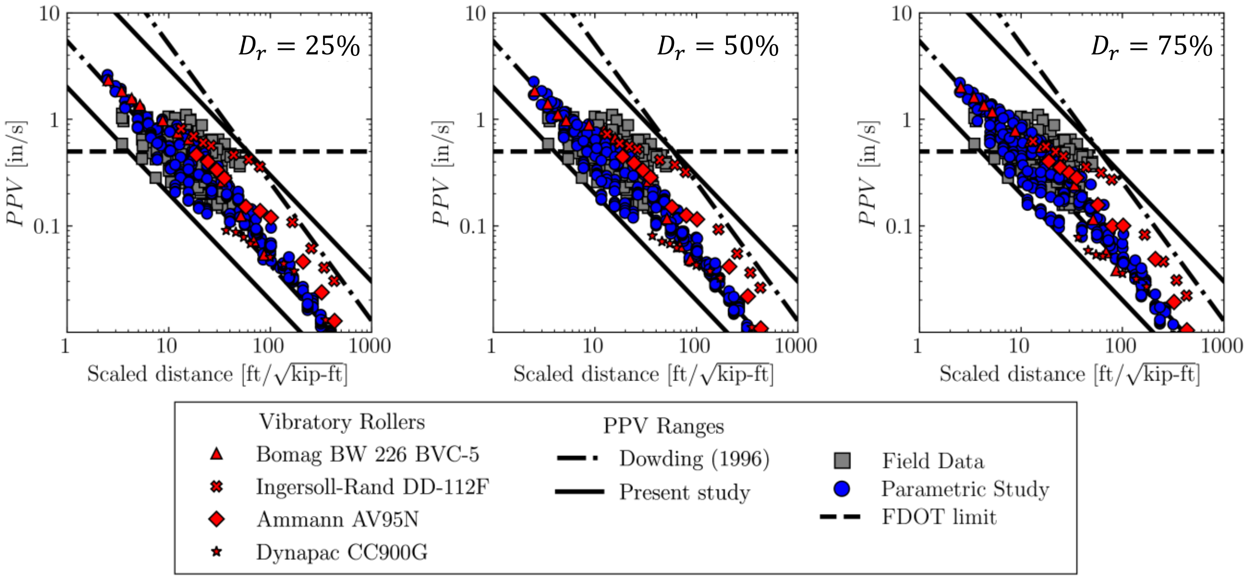
Centrifugal force and vibration frequency effect on the time required to reach the minimum void ratio



Lessons learned

- High centrifugal force and low frequency: most effective to achieve target compaction
- Low force and high frequency: unsuitable for compacting soils, more energy and roller passes needed
- Compaction time decreases with increasing centrifugal force
- Compaction efficiency is governed mainly by the energy transmitted to the soil, not much by the vibration frequency

Summary Charts: PPV Envelopes

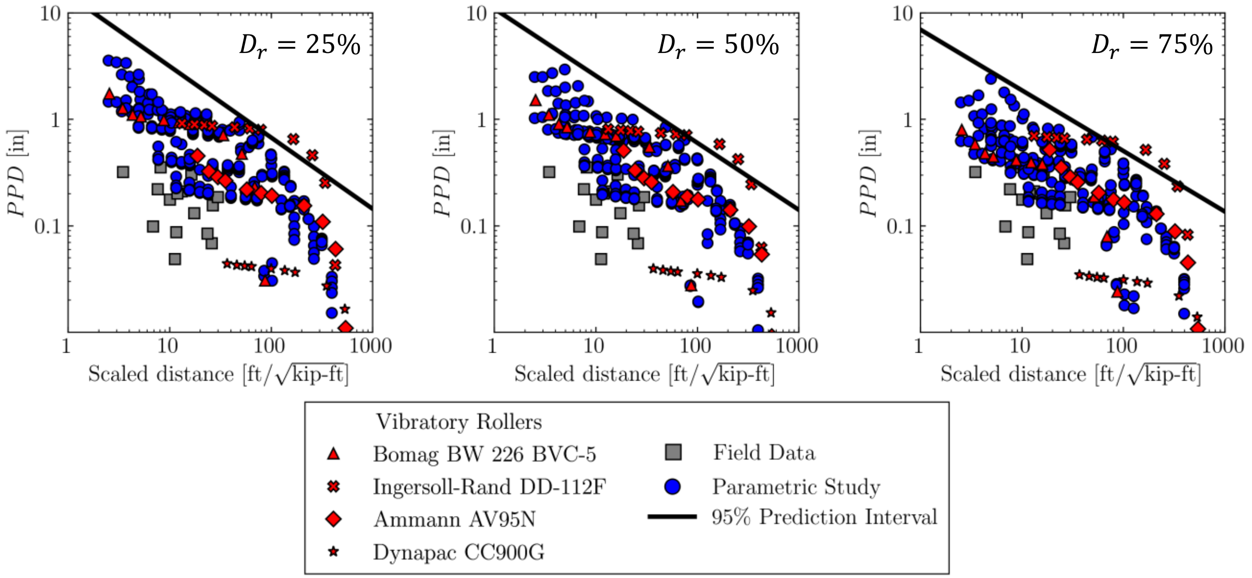


- ➢ Upper bound ⟶ $PPV = 30\left(\frac{D}{\sqrt{E}}\right)^{-1}$
- ➢ Lower bound ⟶ $PPV = 2\left(\frac{D}{\sqrt{E}}\right)^{-1}$

Lesson learned

- ➢ Scaled distance normalization reduces scatter
- ➢ Most PPVs fall within Dowding's proposed range, but new PPV range is proposed
- ➢ Same attenuation curves are proposed for all relative densities
- ➢ FDOT PPV limit of 0.5in/s not exceeded beyond 60 $ft/\sqrt{kip-ft}$, corresponding to distances between 20 ft and 110 ft, depending on roller energy
- ➢ FDOT zone of 75 ft can both over or underpredict influence zones. Energy must be considered in the design specifications

Summary Charts: PPD Envelopes



$$PPD = \beta \left(\frac{D}{\sqrt{E}} \right)^{-\alpha}$$

Parameters β and α

Relative Density	β [in]	α
25%	14.75	0.67
50%	10.94	0.63
75%	6.95	0.57

Lessons learned

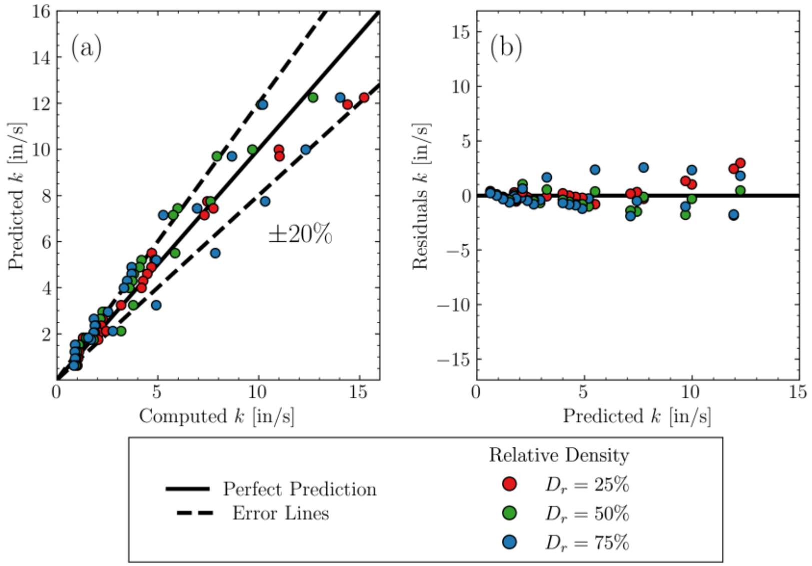
- Loose sands show higher PPDs
- Three separate envelopes proposed as a function of relative density
- Envelopes follow a power law equation with β and α used as fitting parameters
- β and α values decrease as density increases
- Proposed envelopes are conservative compared to field measurements

Prediction Equations: PPV

$$PPV = kD^{-1}$$
$$k = 1.6 - 0.03f + 0.1F_c$$

- Proposed equation to estimate PPVs considering distance, frequency, and centrifugal force
- Strong match between predicted and computed results
- High R^2 values confirm strong correlation among variables involved
- Validation with field data shows good fit for sites A, C1, C2, and C3, mismatch at site B was due to uncertain roller settings

Parity and residual plots of *k*



Coefficients of determination (R^2) for *k*

Relative Density	R^2
25%	0.95
50%	0.93
75%	0.90

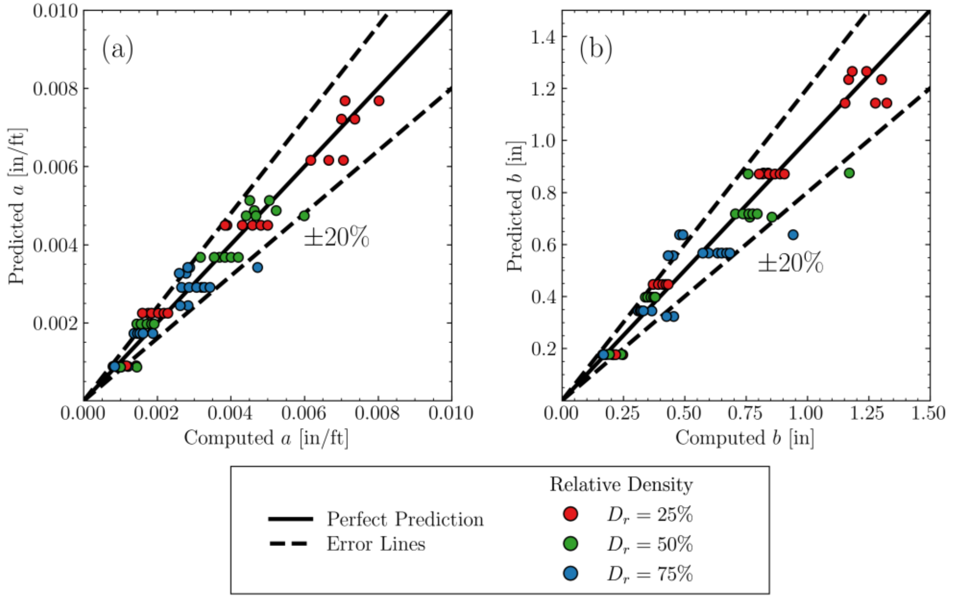
Prediction Equations: PPD

$$PPD = -aD + b$$
$$a = a_1 F_c^2 + a_2 F_c + a_3$$
$$b = b_1 F_c^2 + b_2 F_c + b_3$$

Parameters *a* and *b*

Relative Density	a [in/ft]			b [in]		
	$a_1 \times 10^{-7}$	$a_2 \times 10^{-4}$	$a_3 \times 10^{-4}$	$b_1 \times 10^{-4}$	$b_2 \times 10^{-2}$	$b_3 \times 10^{-1}$
25%	−5.9	1.40	−6.0	−1.5	2.9	−1.30
50%	−6.5	1.20	−4.0	−1.6	2.5	−0.83
75%	−6.6	0.97	−1.2	−1.5	2.0	−0.29

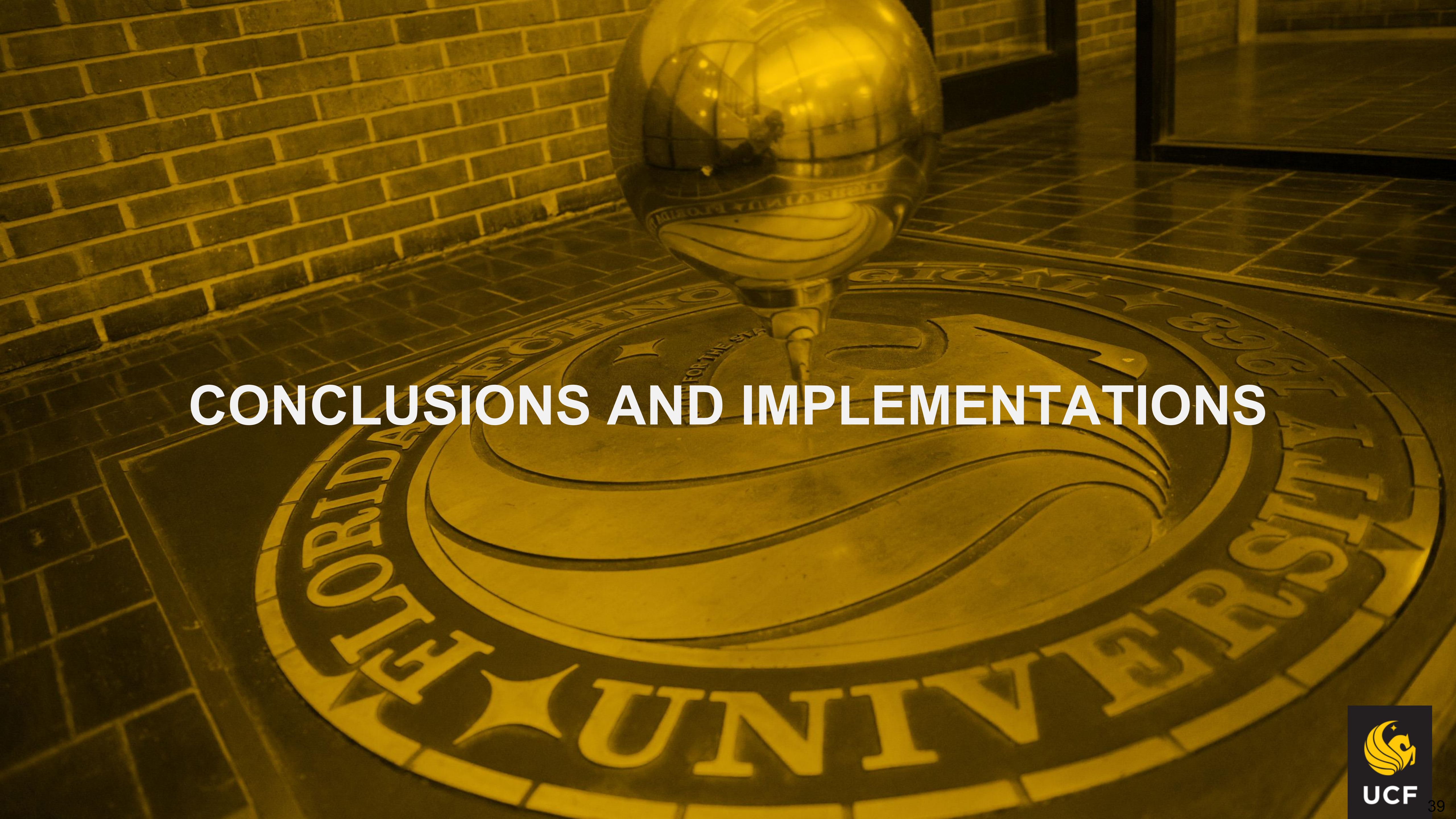
Parity plots of *a* and *b*



Coefficients of determination (R^2) for a and b

Relative Density	R^2	
	a	b
25%	0.97	0.98
50%	0.94	0.92
75%	0.84	0.76

- PPDs decrease with distance from vibratory roller
- Vibration frequency excluded from proposed equation due to minimal influence
- Parity plots confirm strong match between predicted and computed results
- Validation with field data shows the model reasonably bounded measured PPDs



CONCLUSIONS AND IMPLEMENTATIONS

Conclusions and Recommendations

1. Field data showed that quantification of transmitted energy is very important. It largely influences particle rearrangement.

2. Field data showed transient ground deformations peaking when the roller is directly in front but reducing after excitation finishes, indicating small residual deformation.

3. Geostructures provide some protection barrier against vibratory roller-induced vibrations and deformations.

4. Significant vibrations occur at high roller settings due to the high energy transmitted to the soil and amplification occurs when excitation frequencies are close to the natural frequency of the soil.

6. Parametric study: i) large centrifugal forces increase ground vibrations and deformations, ii) vibration frequency has minor effect except for low forces near natural frequency of soil, and iii) loose soils experience large deformations due to long densification process.

7. Proposed envelope to estimate maximum expected ground vibrations in terms of PPV by incorporating the scaled distance in ft/√kips-ft.

$$PPV = 30\left(\frac{D}{\sqrt{E}}\right)^{-1} \quad [in/s]$$

$$E = A \cdot a \cdot (2F_s + F_c) \quad [kip - ft]$$

8. PPV influence zone defined as 60 ft/√kips-ft. That is equivalent to 20 ft for light rollers and 110 ft for heavy rollers. FDOT standard requires monitoring within 75 ft.

Conclusions and Recommendations

9. PPD versus scaled distance in ft/√kips-ft :

- Loose sands:

$$PPD = 14.75\left(\frac{D}{\sqrt{E}}\right)^{-0.67} \ [in]$$

- Medium-dense sands:

$$PPD = 10.94\left(\frac{D}{\sqrt{E}}\right)^{-0.63} \ [in]$$

- Dense sands:

$$PPD = 6.95\left(\frac{D}{\sqrt{E}}\right)^{-0.57} \ [in]$$

10. PPV prediction equation as a function of vibration frequency (Hz), centrifugal force (kips) and the distance from the roller (ft).

$$PPV = (1.6 - 0.03f + 0.1F_c)D^{-1} \ [in/s]$$

11. PPD prediction equations as a function of distance from the roller (ft) and centrifugal force (kips)

$$PPD = -aD + b \ [in]$$

- Loose sands:

$$a = -5.9 \times 10^{-7}F_c^2 + 1.4 \times 10^{-4}F_c - 6.0 \times 10^{-4} \ [in/ft]$$

$$b = -1.5 \times 10^{-4}F_c^2 + 0.029F_c - 0.13 \ [in]$$

- Medium-dense sands:

$$a = -6.5 \times 10^{-7}F_c^2 + 1.2 \times 10^{-4}F_c - 4.0 \times 10^{-4} \ [in/ft]$$

$$b = -1.6 \times 10^{-4}F_c^2 + 0.025F_c - 0.083 \ [in]$$

- Dense sands:

$$a = -6.6 \times 10^{-7}F_c^2 + 9.7 \times 10^{-5}F_c - 1.2 \times 10^{-4} \ [in/ft]$$

$$b = -1.5 \times 10^{-4}F_c^2 + 0.02F_c - 0.029 \ [in]$$

Suggested Revisions to Specifications

Changes and/or additions to FDOT Standard Specifications for Road and Bridge Construction

108-2.1.3 Roadway Compaction Operations: When performing embankment and asphalt compaction, inspect and document the condition of the following existing structures, and survey and monitor for settlement the following existing structures:

1. as shown in the Plans.
2. within 75 feet of vibratory compaction (in any vibratory mode) operations.

108-2.2 Vibration Monitoring: When shown in the Contract Documents, employ a Specialty Engineer to provide a system which will continuously monitor and record ground vibration levels near the structures shown in the Plans during the operation of any equipment causing vibrations or during blasting operations. Provide vibration monitoring equipment capable of detecting velocities of 0.01 inches per second or less. Obtain the Engineer's approval of the number and locations of the monitoring points and install the system per the Specialty Engineer's recommendations. Submit the vibration records to the Engineer within 24 hours of performing the monitoring activity.

Upon either detecting vibration levels reaching 0.5 inches per second or damage to the structure, immediately stop the source of vibrations, backfill any open excavations, notify the Engineer and submit a corrective action plan for acceptance by the Engineer.

- PPVs below 0.5 in/s occurred beyond a scaled distance of 60 ft/√kips-ft.
- FDOT recommends a monitoring distance of 75 ft, which becomes too conservative for light rollers (~20 ft) and underpredicts for heavy rollers (~110 ft).
- The authors encourage the adoption of the scaled distance in FDOT standards for ground vibrations and deformations due to road compaction.
- Authors recommend adding the proposed equations and charts to predict maximum ground vibrations and deformations.

Selected Publications

- One conference paper was presented in Geofrontiers Conference 2025.

Ballesteros J, Orozco-Herrera JE, Shin GB, Arboleda-Monsalve LG (2025). “Numerical Study on Ground Vibrations and Deformations Induced by Vibratory Rollers in Central Florida” Geotechnical Frontiers 2025, Louisville, KY, March 3-5, 2025.

- One journal paper to the Journal of Geotechnical and Geoenviromental Engineering, ASCE is under preparation.

Orozco-Herrera JE, Ballesteros J, Arboleda-Monsalve LG, Herrera R (2025). “Measured and Computed Ground Vibrations and Deformations Induced by Vibratory Rollers in Central Florida” J. of Geotech. and Geoenv. Eng., ASCE, Under Preparation.

Acknowledgments

To the project manager for his guidance: Rodrigo Herrera (FDOT).

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- Curtis Brown at RS&H (Site C1, C3, and C3)

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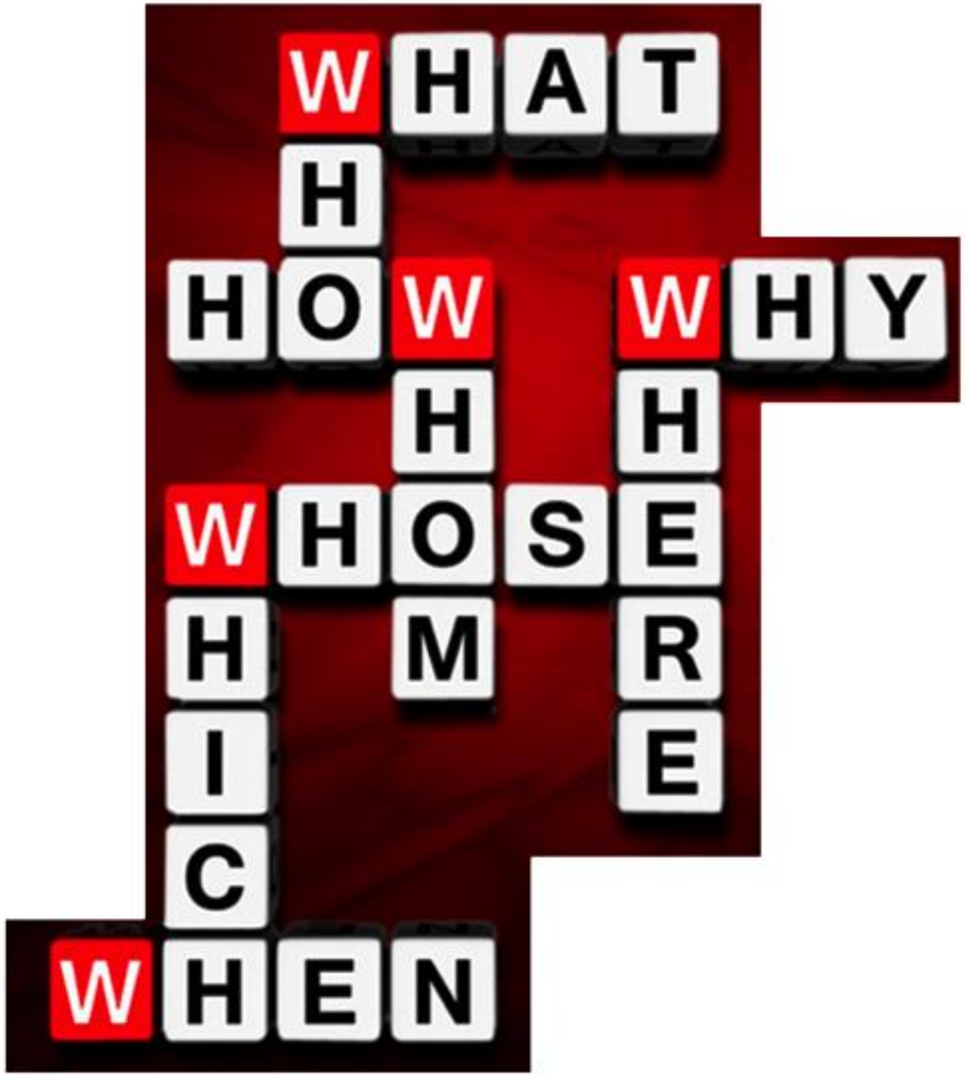

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