THE UNIVERSITY OF MICHIGAN
CIVIL AND ENVIRONMENTAL ENGINEERING
ANN ARBOR, MI

EFFECTS OF PILE-DRIVING INDUCED VIBRATIONS ON NEARBY STRUCTURES AND OTHER ASSETS

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MDOT
Department of Transportation

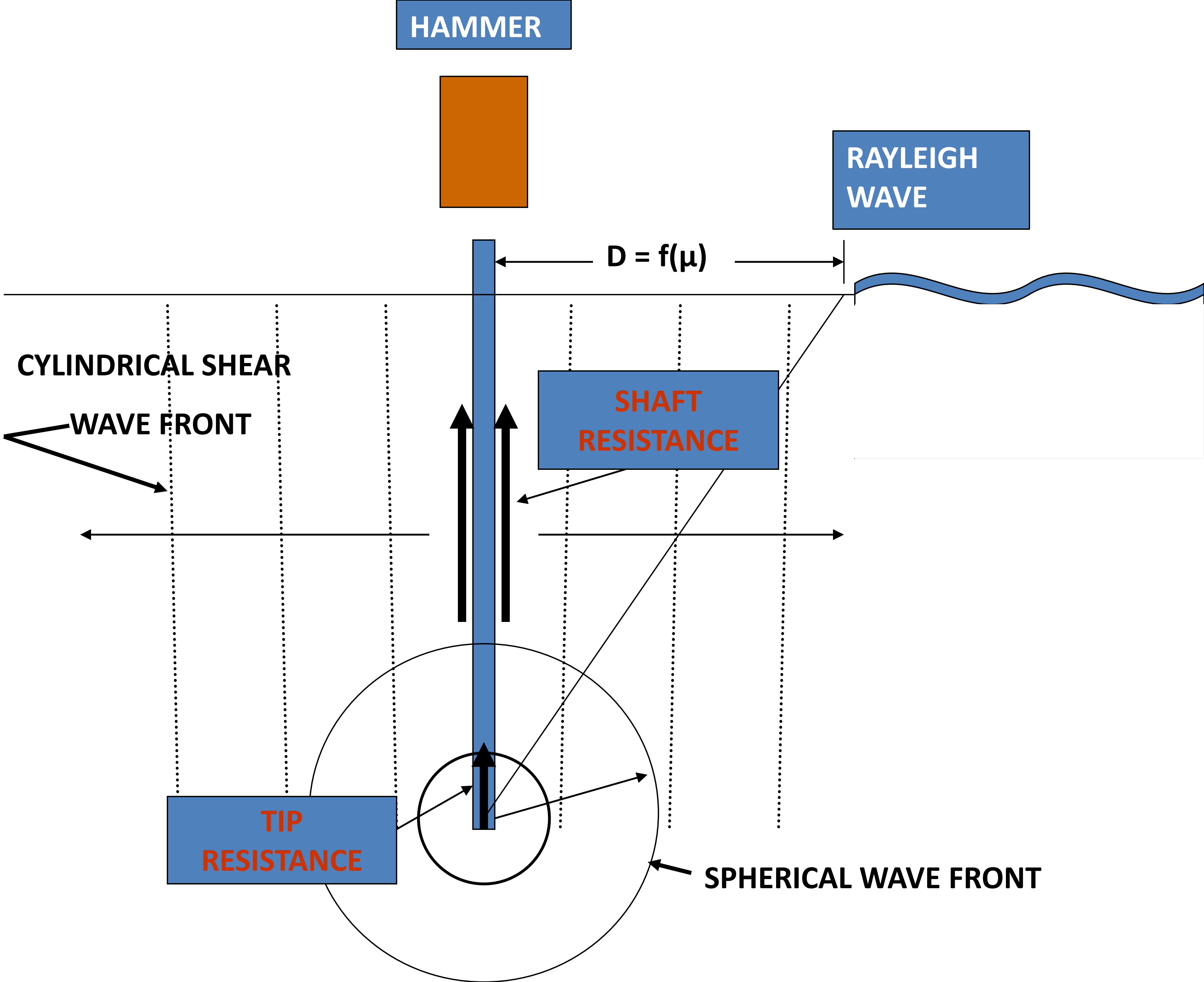
MICHIGAN BRIDGE CONFERENCE

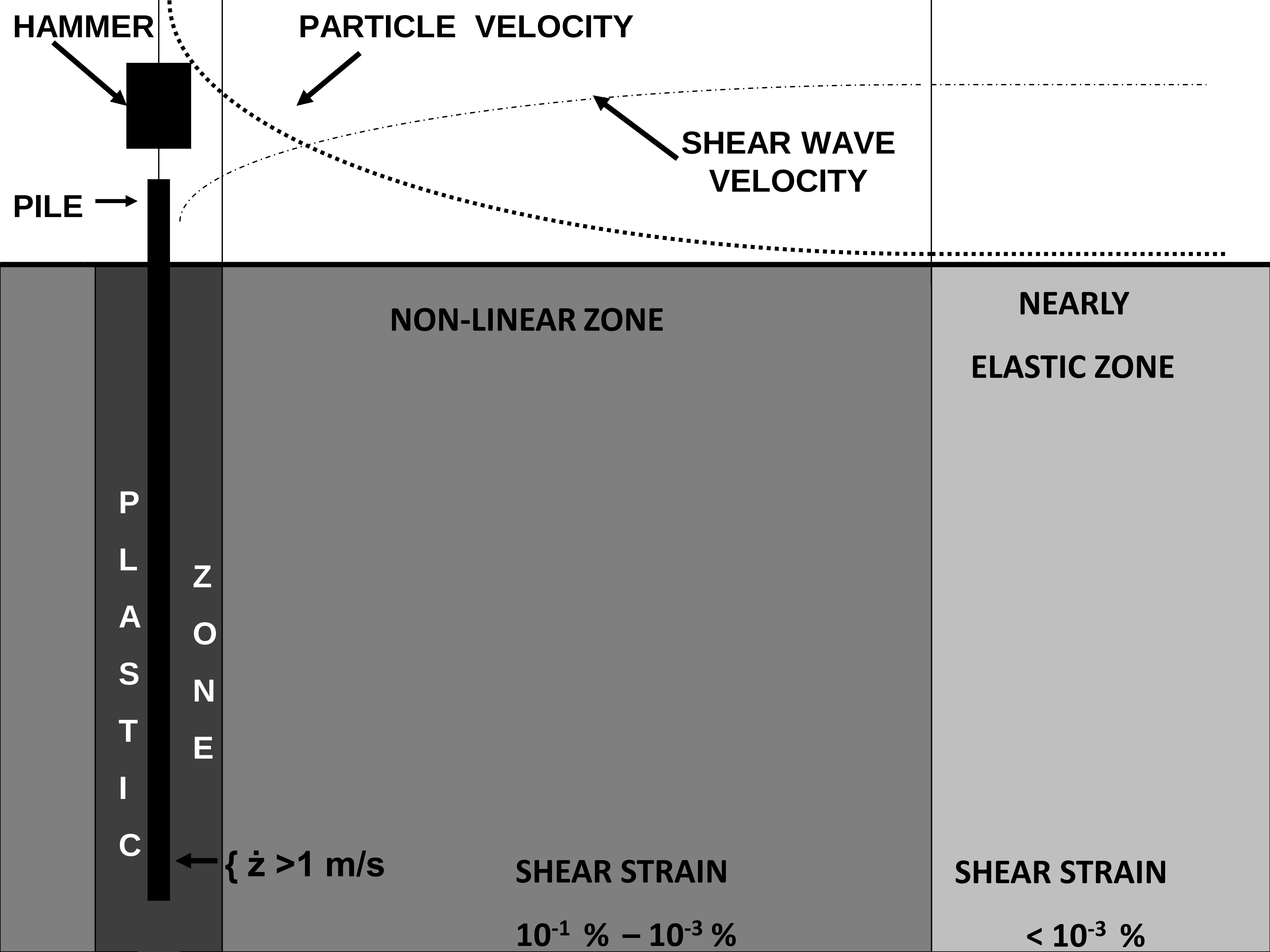
MARCH 18, 2015

The University of Michigan
Department of civil and Environmental Engineering
Geotechnical Engineering Group

OBJECTIVES

- Attenuation rates for pile-driving induced vibration waves
- Effect of site conditions and pile/hammer characteristics on the attenuation
- Screening tool for soil shakedown potential during pile-driving


HAMMER
RAYLEIGH WAVE
D = f(μ)
CYLINDRICAL SHEAR
WAVE FRONT
SHAFT RESISTANCE
TIP RESISTANCE
SPHERICAL WAVE FRONT



HAMMER
PARTICLE VELOCITY
SHEAR WAVE VELOCITY
PILE
NON-LINEAR ZONE
NEARLY ELASTIC ZONE
PLASTIC ZONE
{ ż >1 m/s
SHEAR STRAIN
10-1 % – 10-3 %
SHEAR STRAIN
< 10-3 %

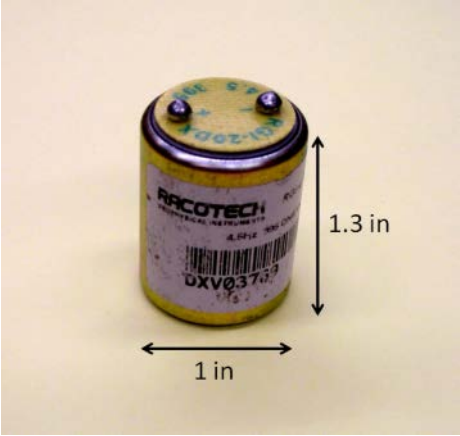
APPROACH

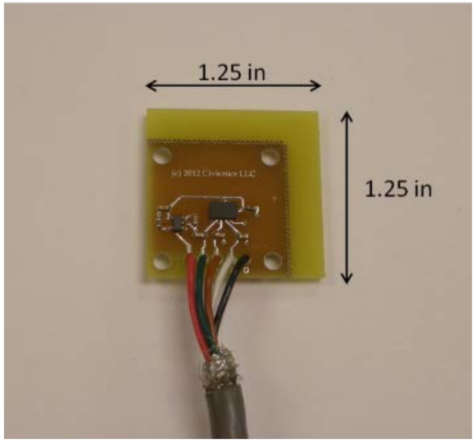
- Field Testing: Sensor installation and data acquisition
- Data processing and synthesis from all sites
- Development of screening tool for soil shakedown potential during pile-driving

Sensors & Data Acquisition System

Cone casing and adaptor used to push the sensors to depth of interest

Cone casing with attached geophone

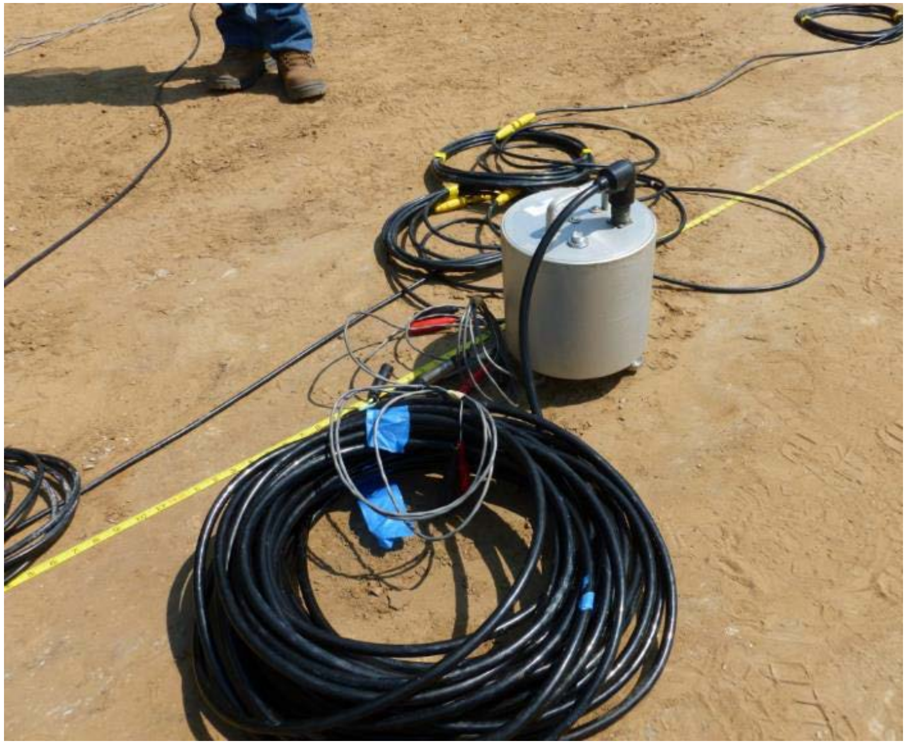




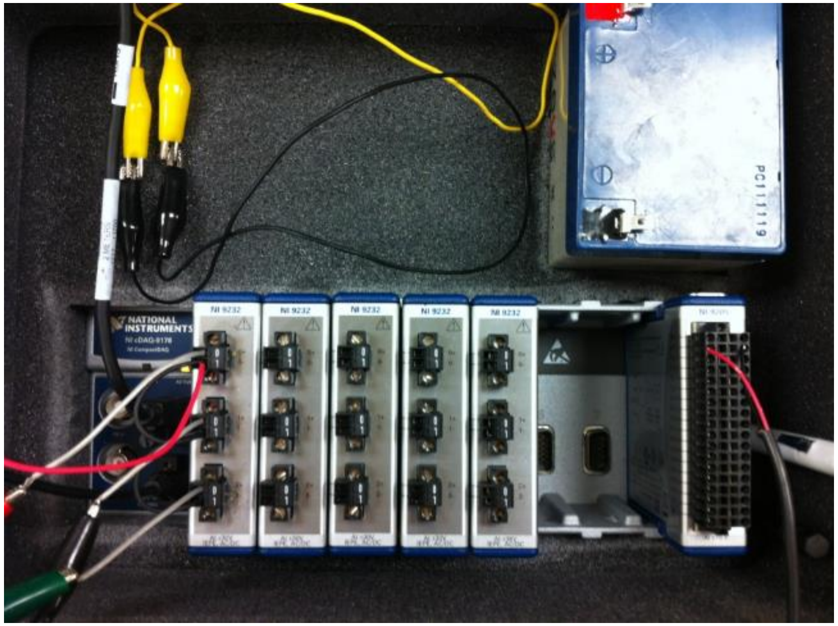
Geophone and Triaxial accelerometer

Cone casings with attached accelerometers

Sensors & Data Acquisition System



Surface geophone



Data acquisition system used to record the signals from sensors

Sites Monitored and Procedure

Positions for sensor installation

Installation of casing

Sites Monitored and Procedure

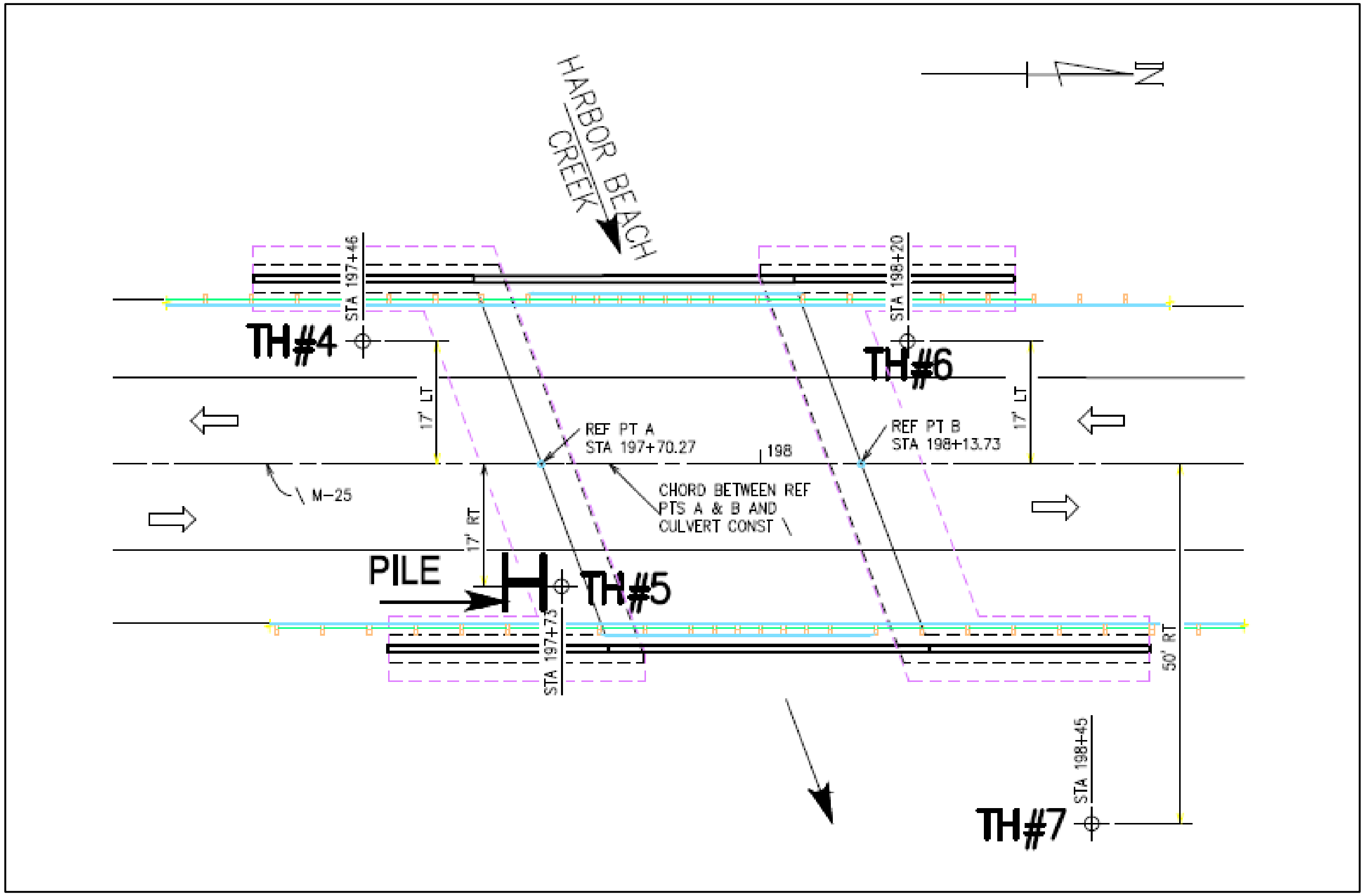
Pile driving and monitoring

Sites Monitored and Procedure

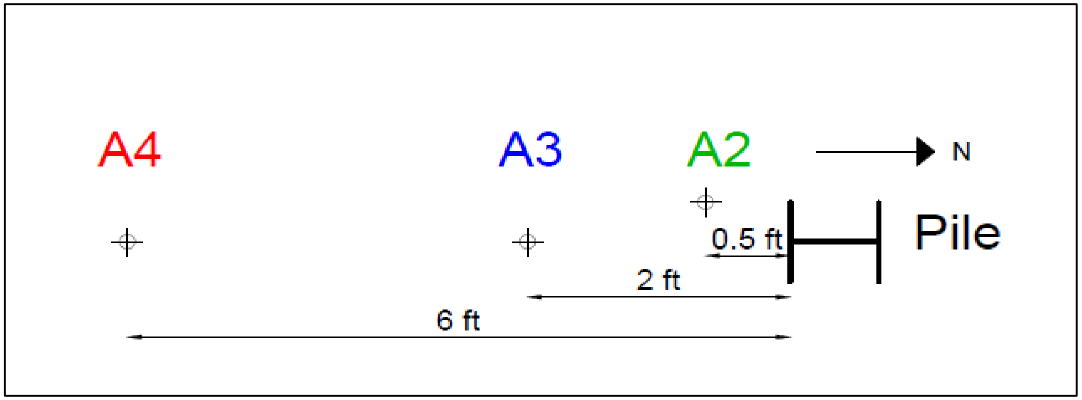
Data acquisition

Field Testing Sites

Site M-25 (Harbor Beach)

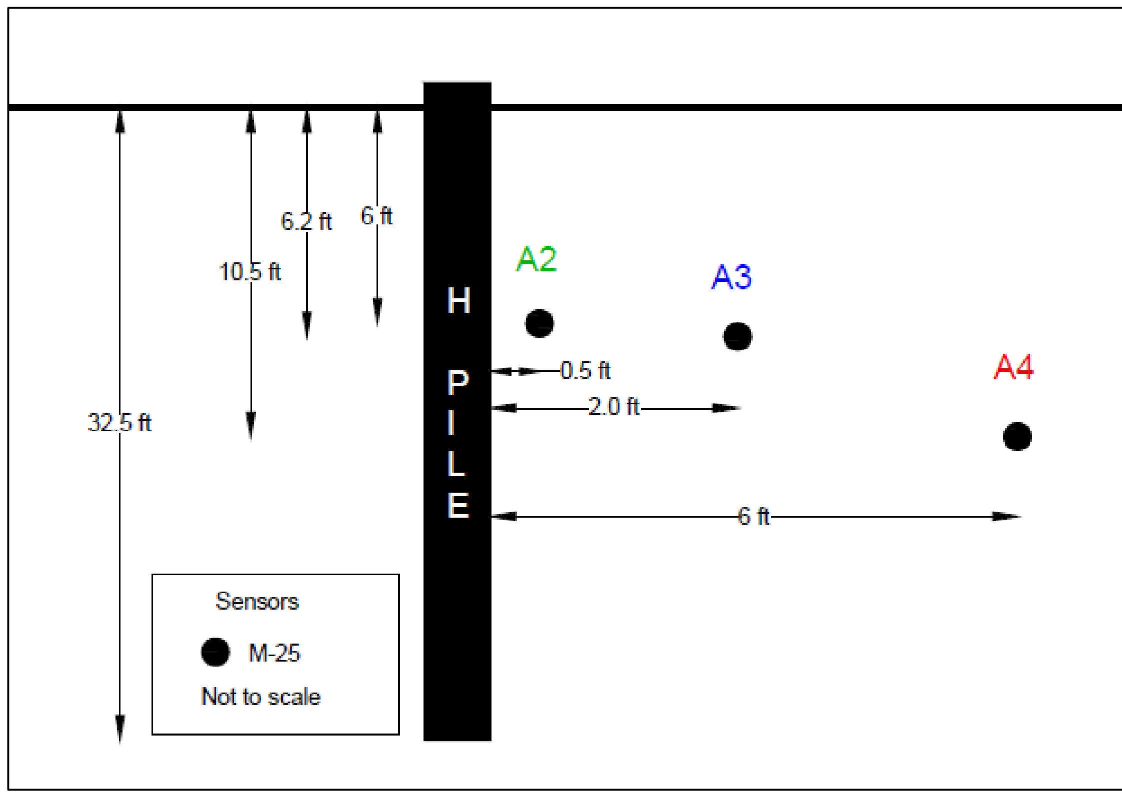


Site M-25 (Harbor Beach)

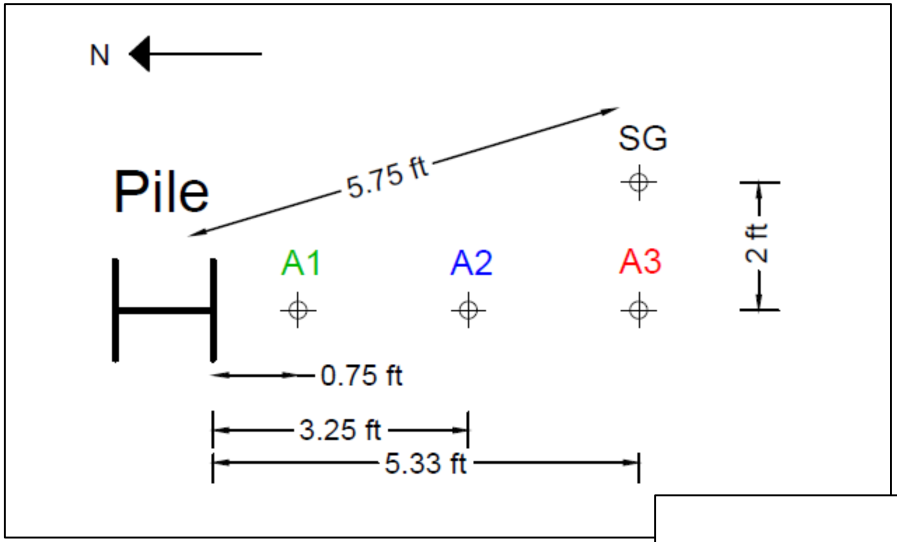


Plan view of sensor locations

Cross-Section of sensor locations

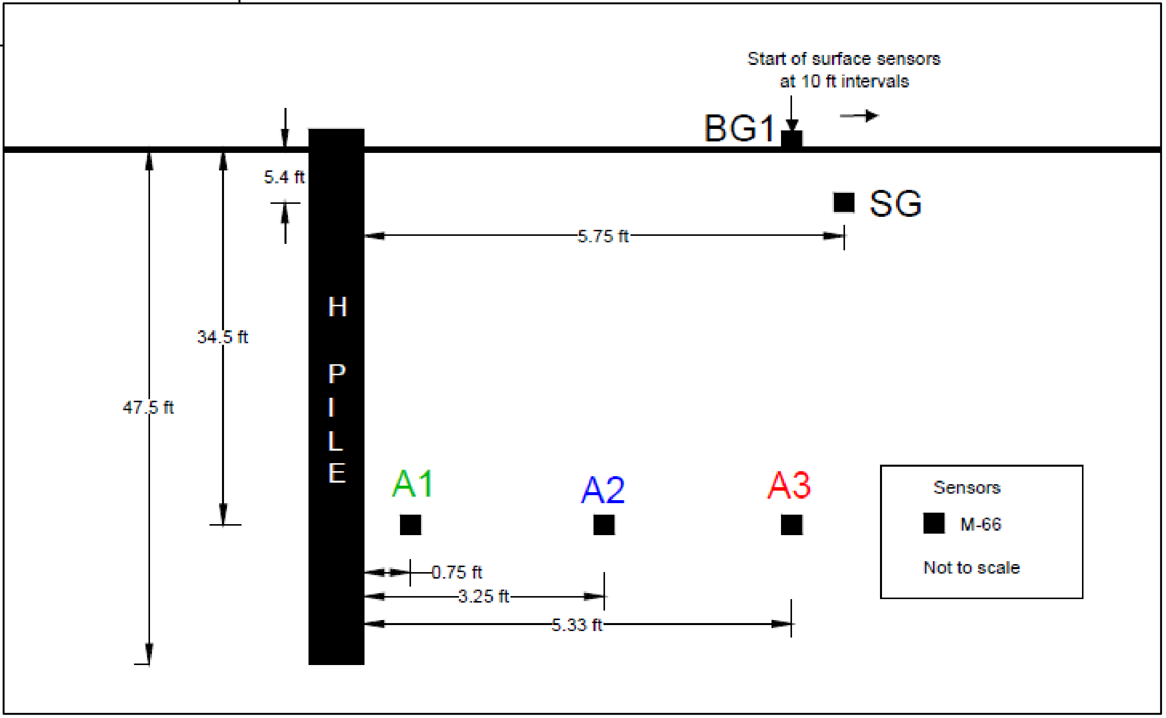


Site M-66 (Battle Creek)



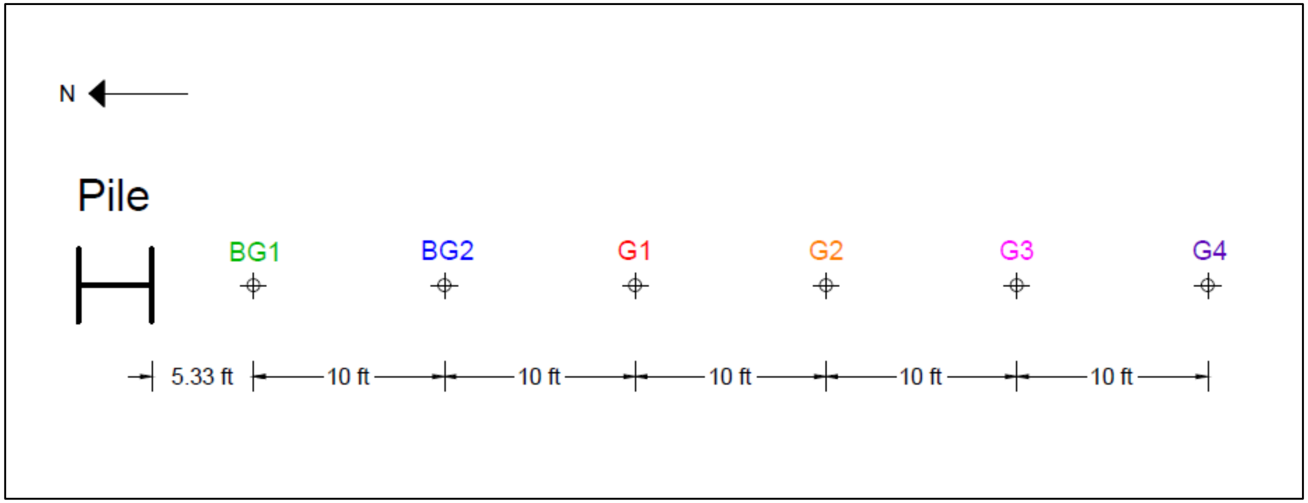
Plan view of sensor locations

Cross-Section of sensor locations



Site M-66 (Battle Creek)

Plan view of surface geophone sensor locations



Site M-66 (Battle Creek)

Welding the second piece after completion of pile driving and monitoring again

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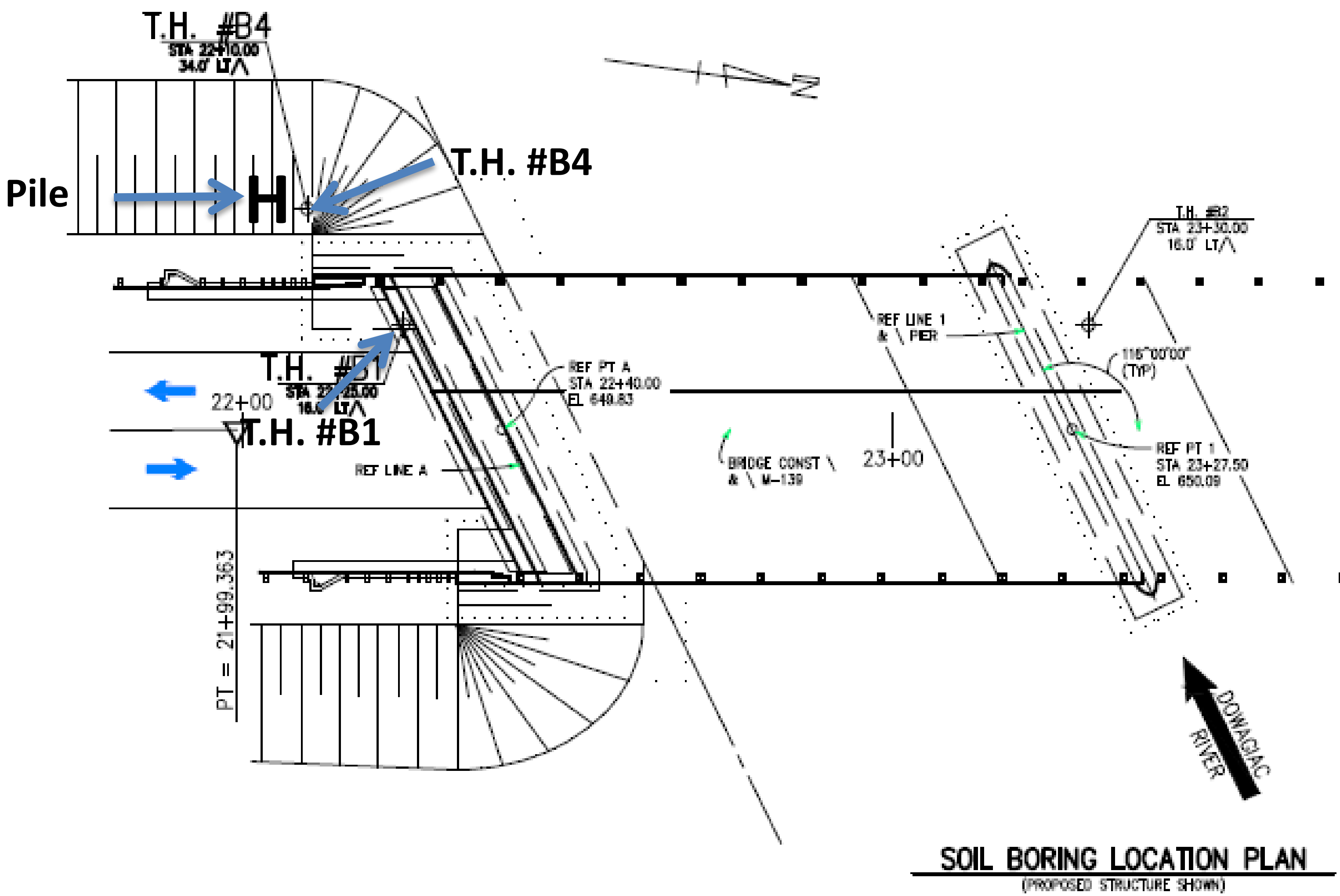
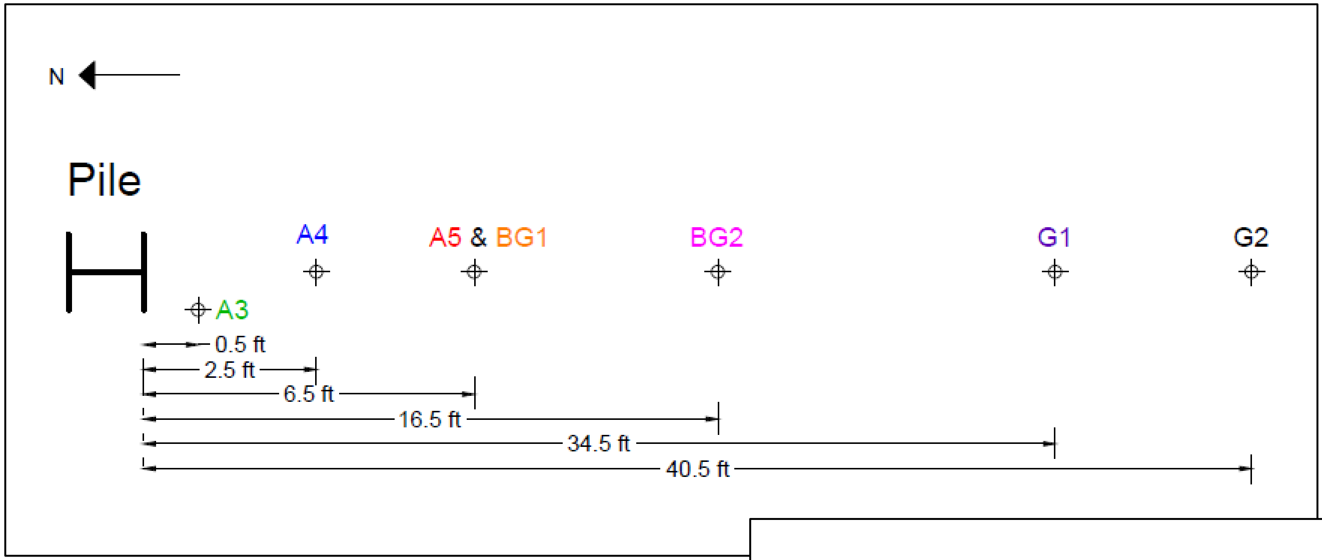
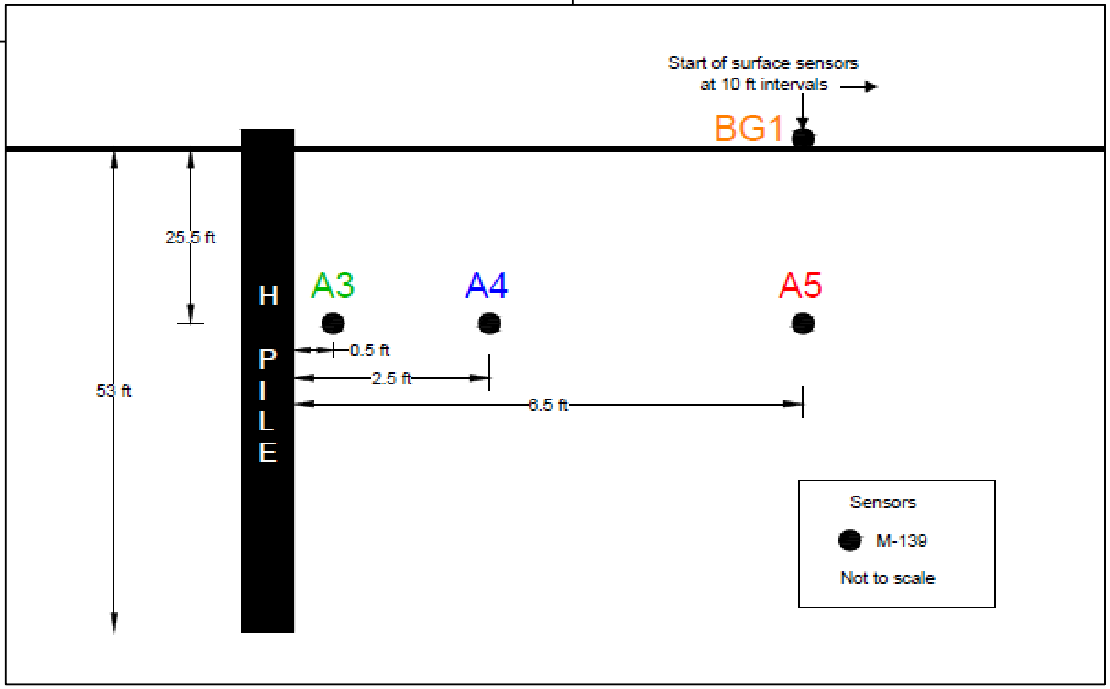
Site M-139



T.H. #B4
STA 22+10.00
34.0' LT/\
Pile
H
T.H. #B4
T.H. #B1
22+00
T.H. #B1
REF LINE A
PT = 21+99.363
REF PT A
STA 22+40.00
EL 649.83
BRIDGE CONST \
& \ M-139
23+00
REF LINE 1
& \ PIER
T.H. #B2
STA 23+30.00
16.0' LT/\
116°00'00"
(TYP)
REF PT 1
STA 23+27.50
EL 650.09
DOWAGIAC
RIVER
SOIL BORING LOCATION PLAN
(PROPOSED STRUCTURE SHOWN)

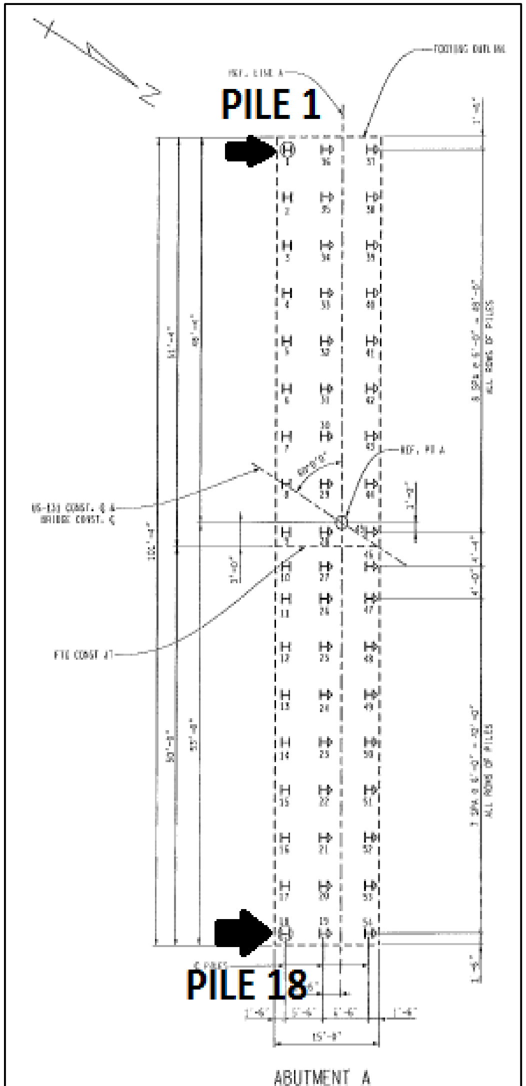
Site M-139

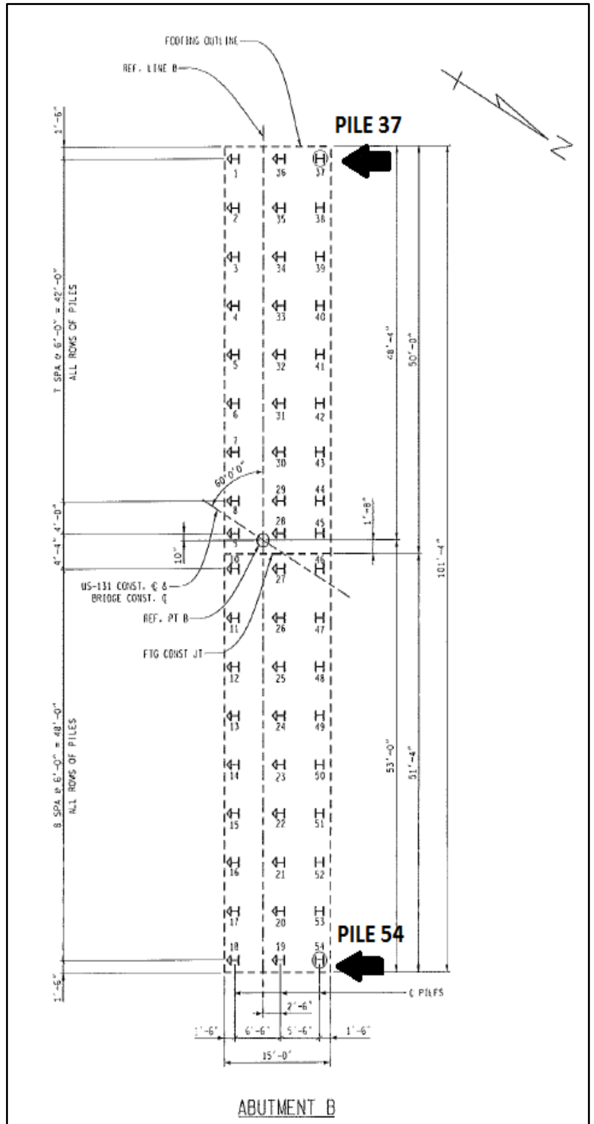

N
Pile
A4
A5 & BG1
BG2
G1
G2
A3
0.5 ft
2.5 ft
6.5 ft
16.5 ft
34.5 ft
40.5 ft

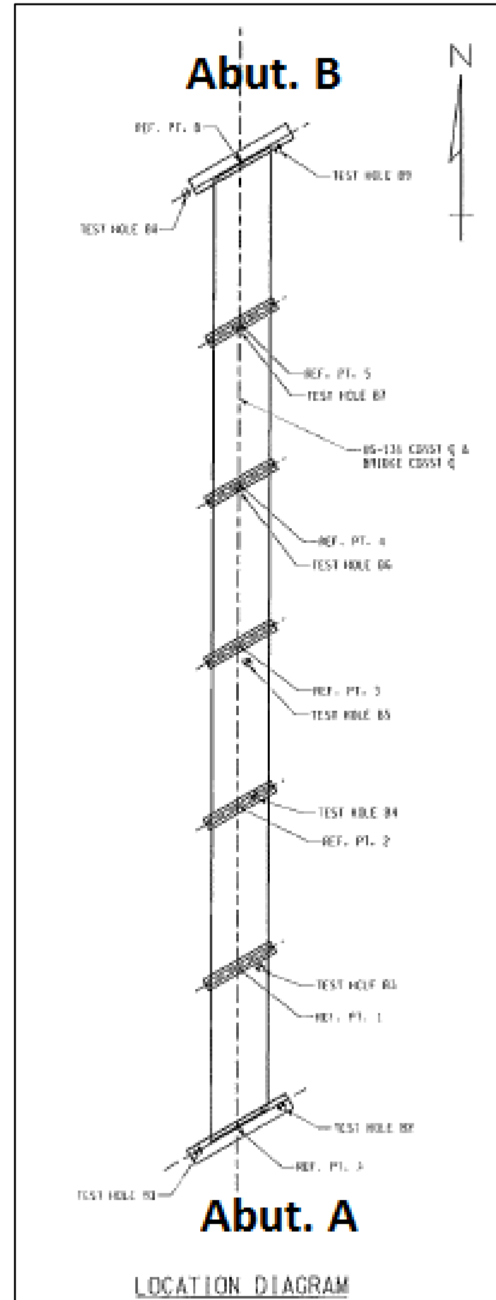

Start of surface sensors
at 10 ft intervals
BG1
25.5 ft
H PILE
A3
A4
A5
0.5 ft
2.5 ft
6.5 ft
53 ft
Sensors
M-139
Not to scale

Site US-131

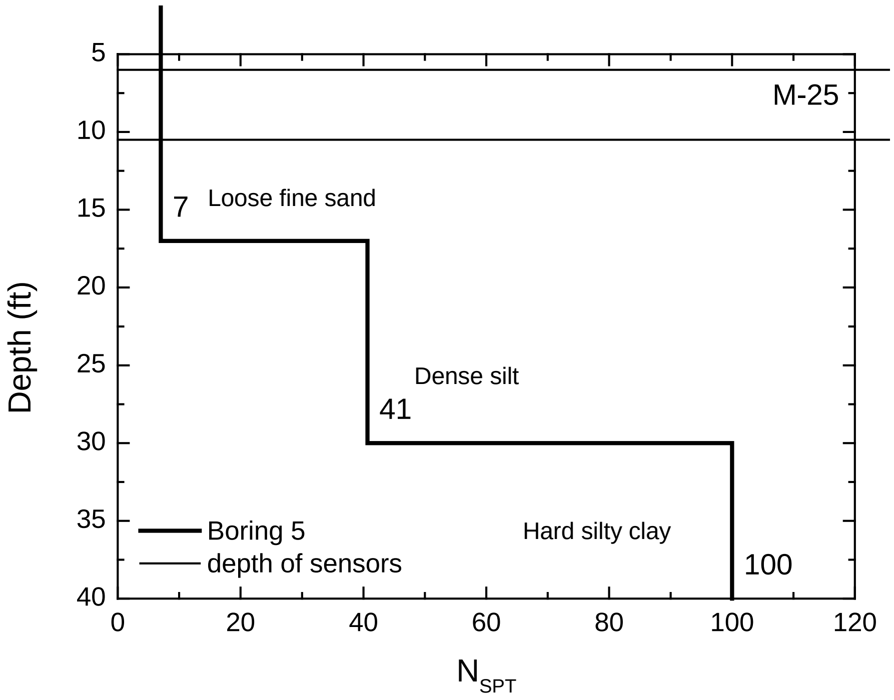
Tested at both abutments

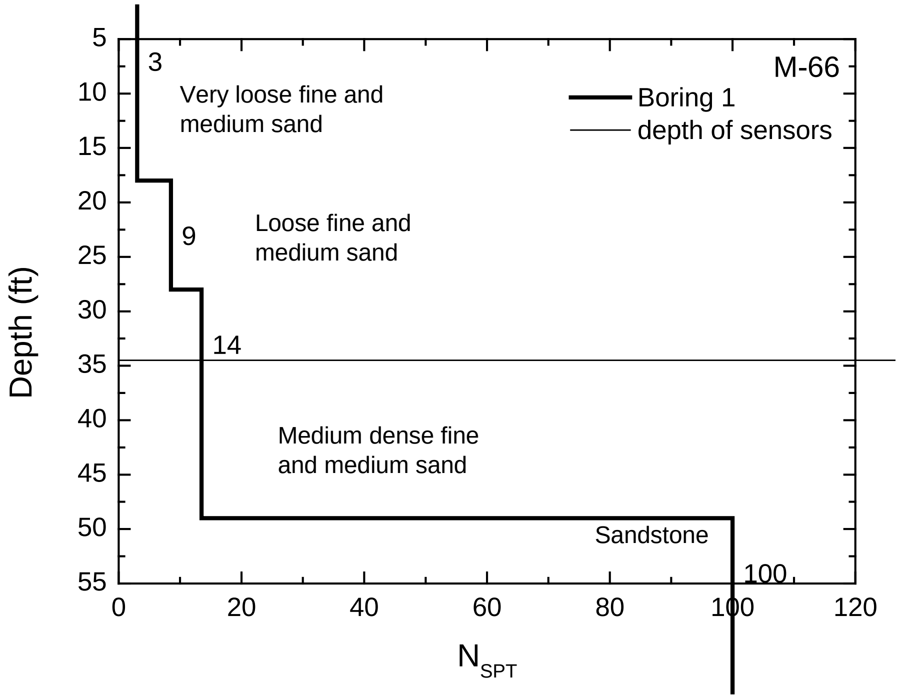




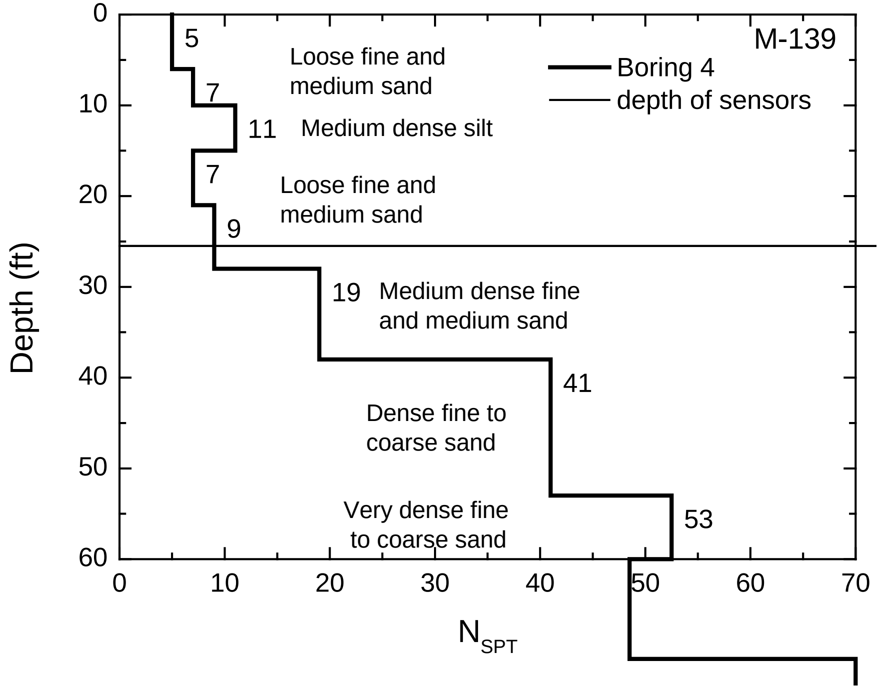


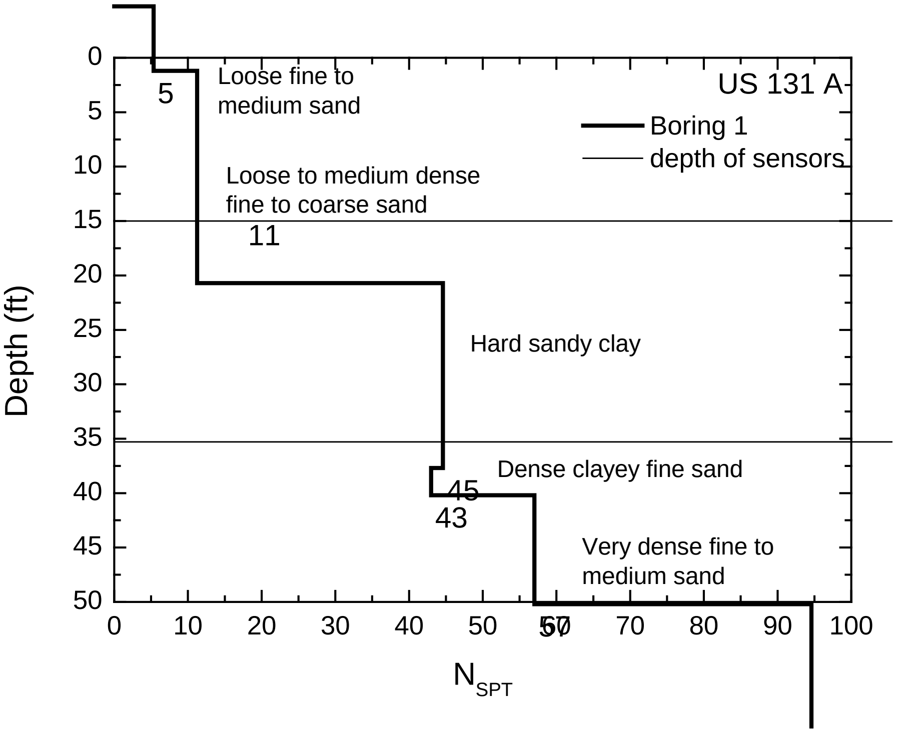
Site Conditions



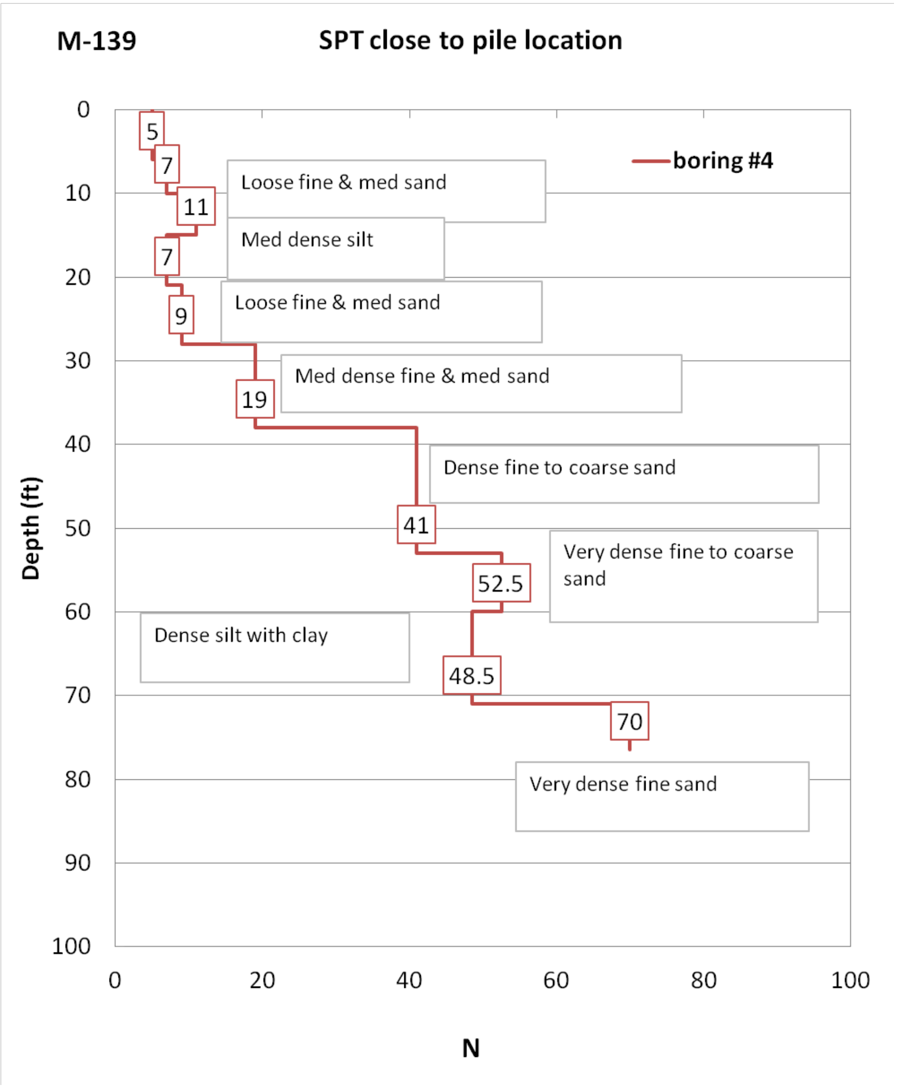


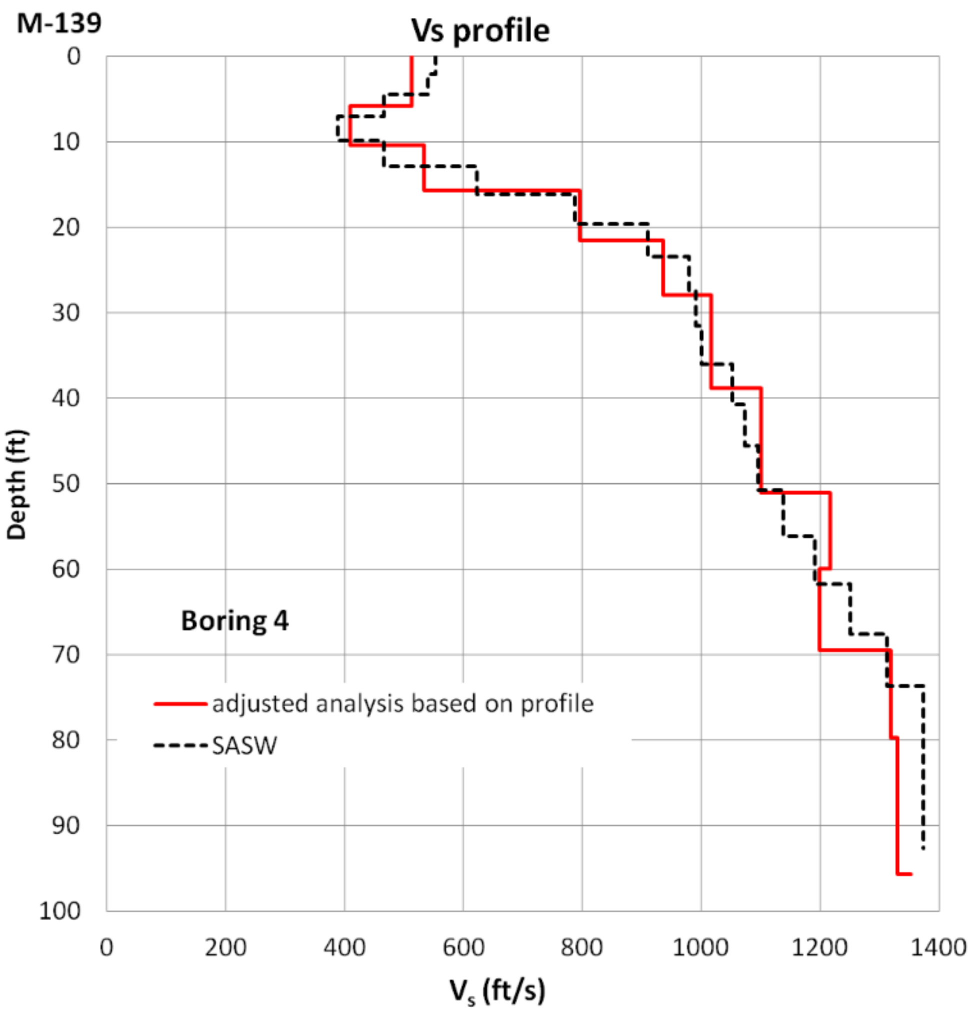
Site Conditions





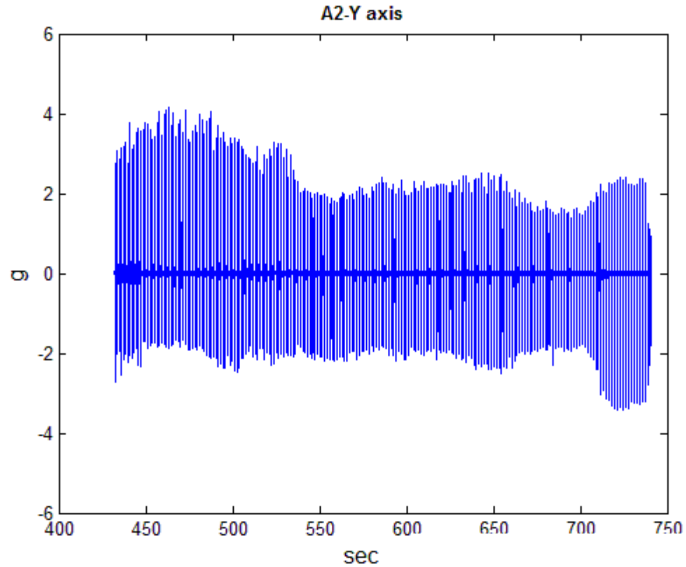
Site Conditions: V_s measurements

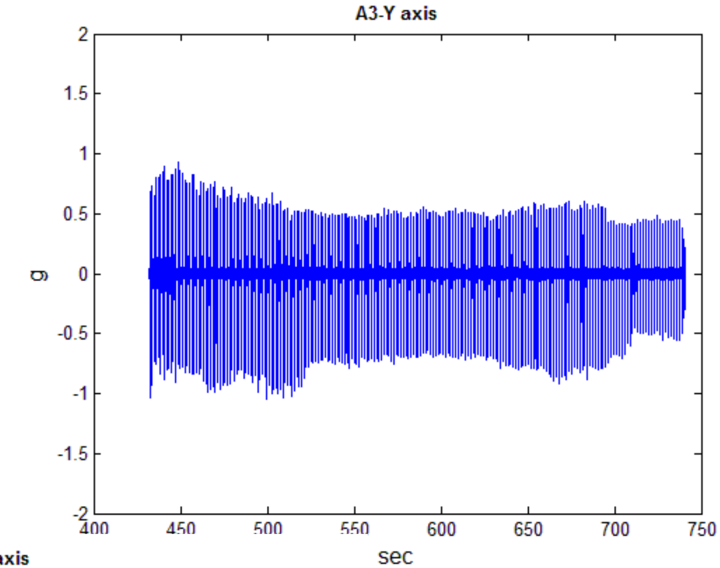


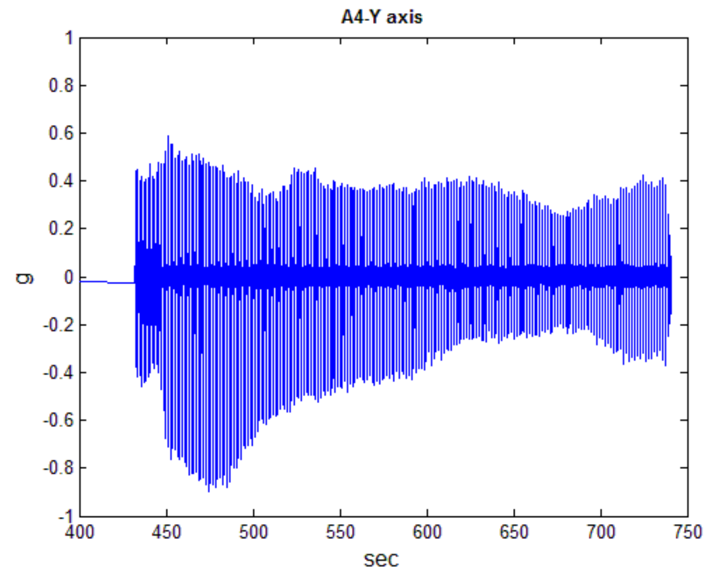


Field Testing Data

Site M-25 (Harbor Beach)

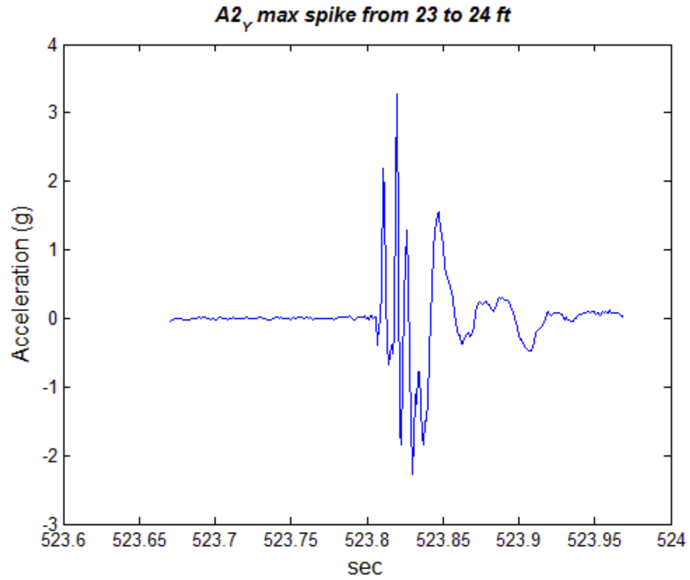


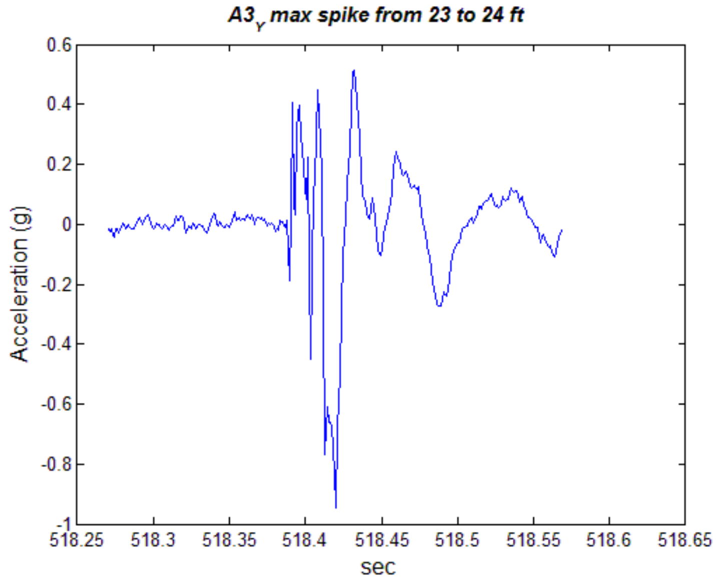


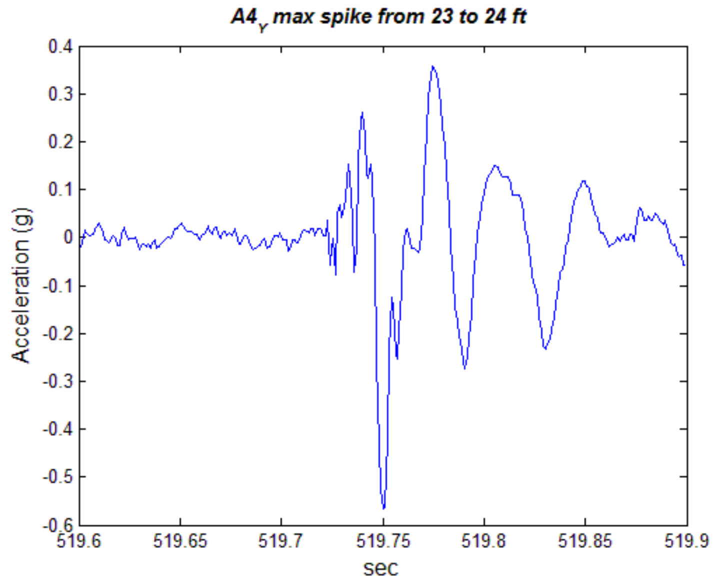


Record of accelerometers (vertical axis)

Site M-25 (Harbor Beach)

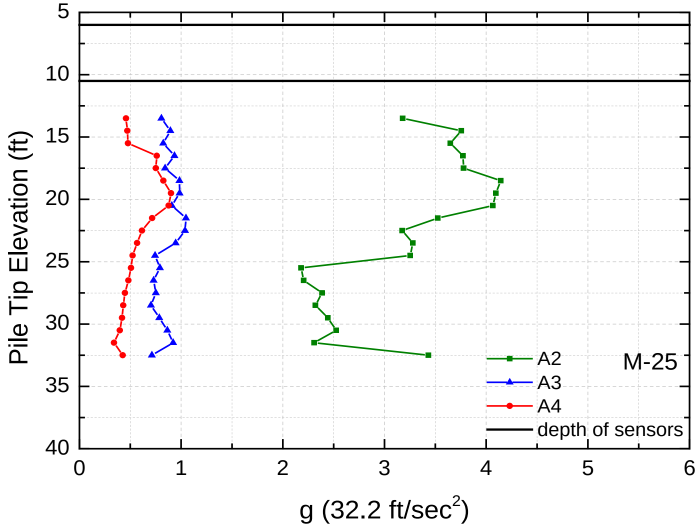


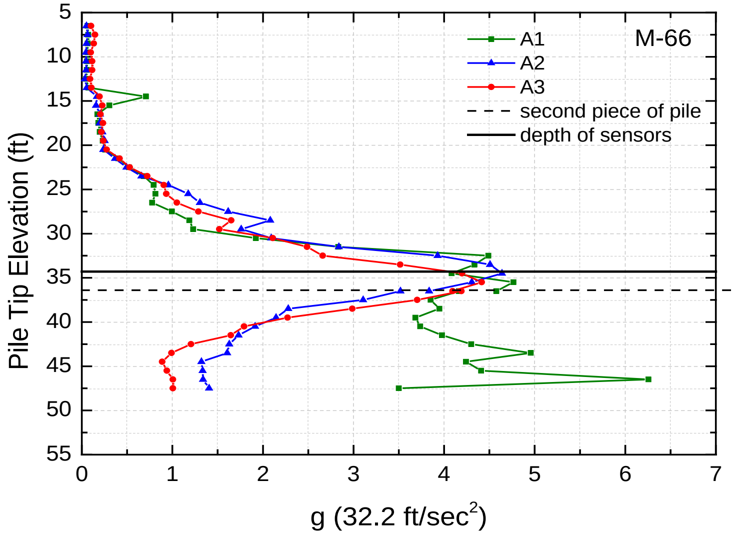


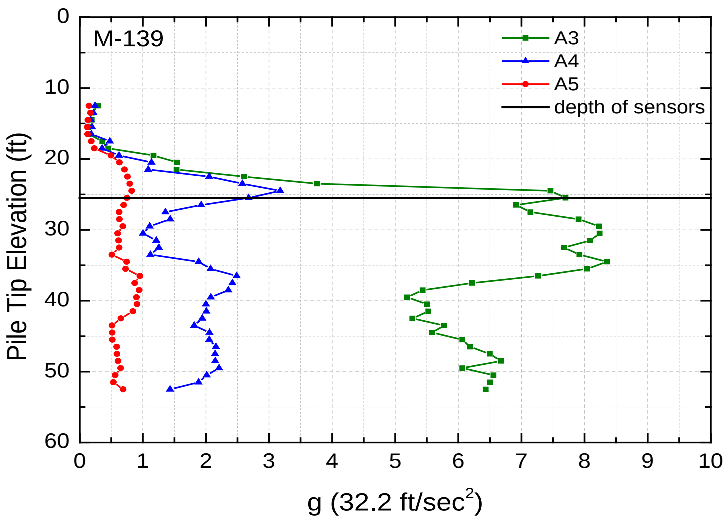


Max spike for pile tip elevation 23-24 ft

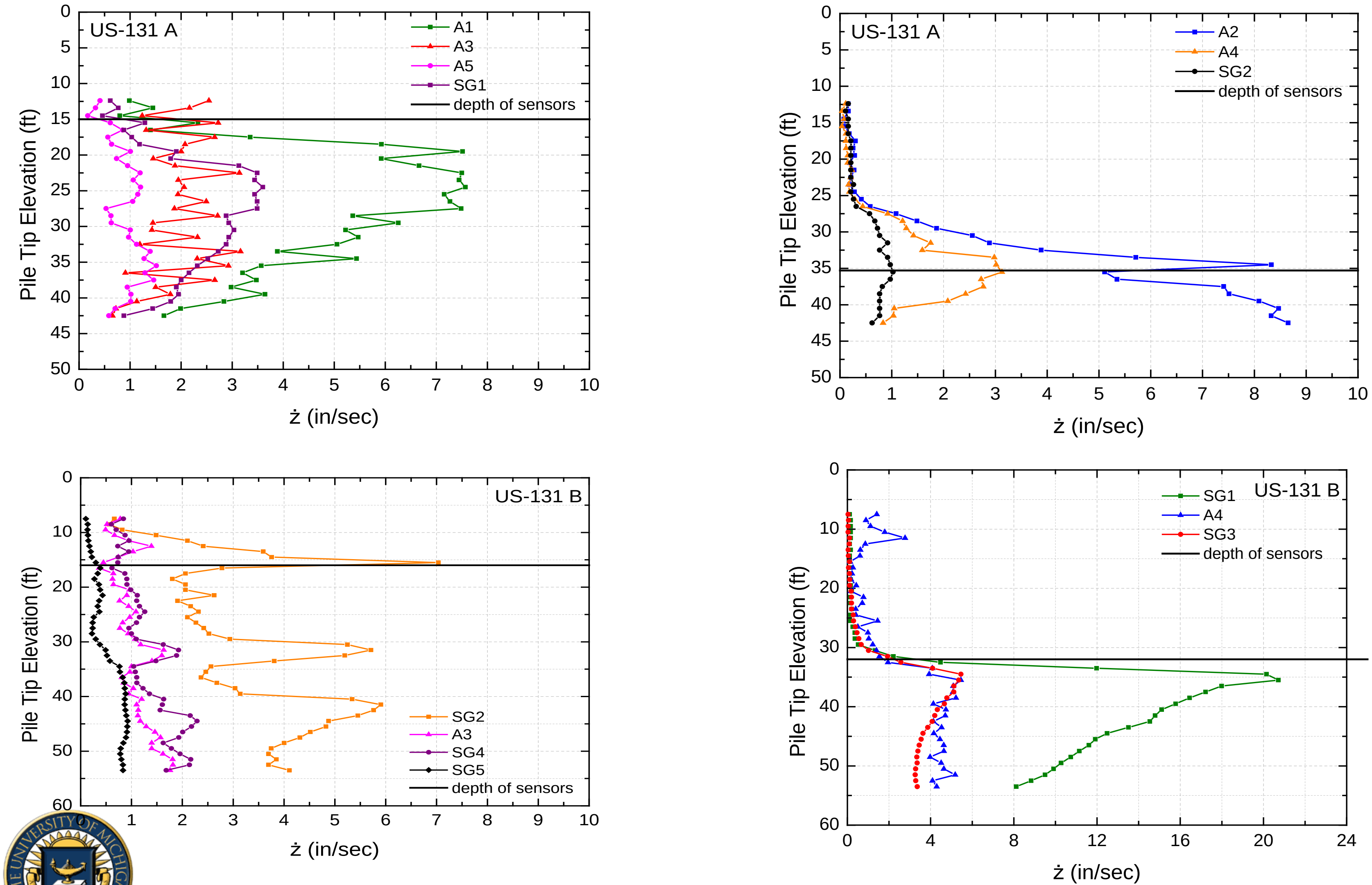
Acceleration Results



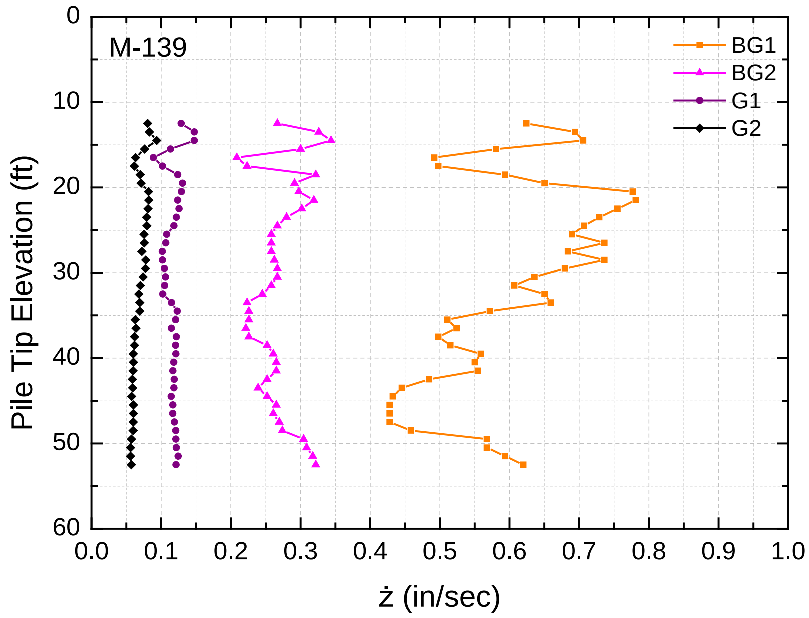


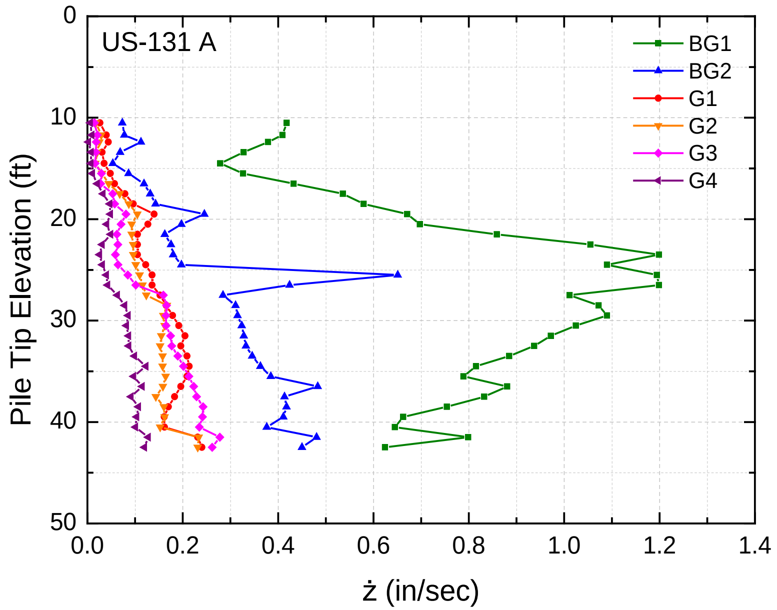


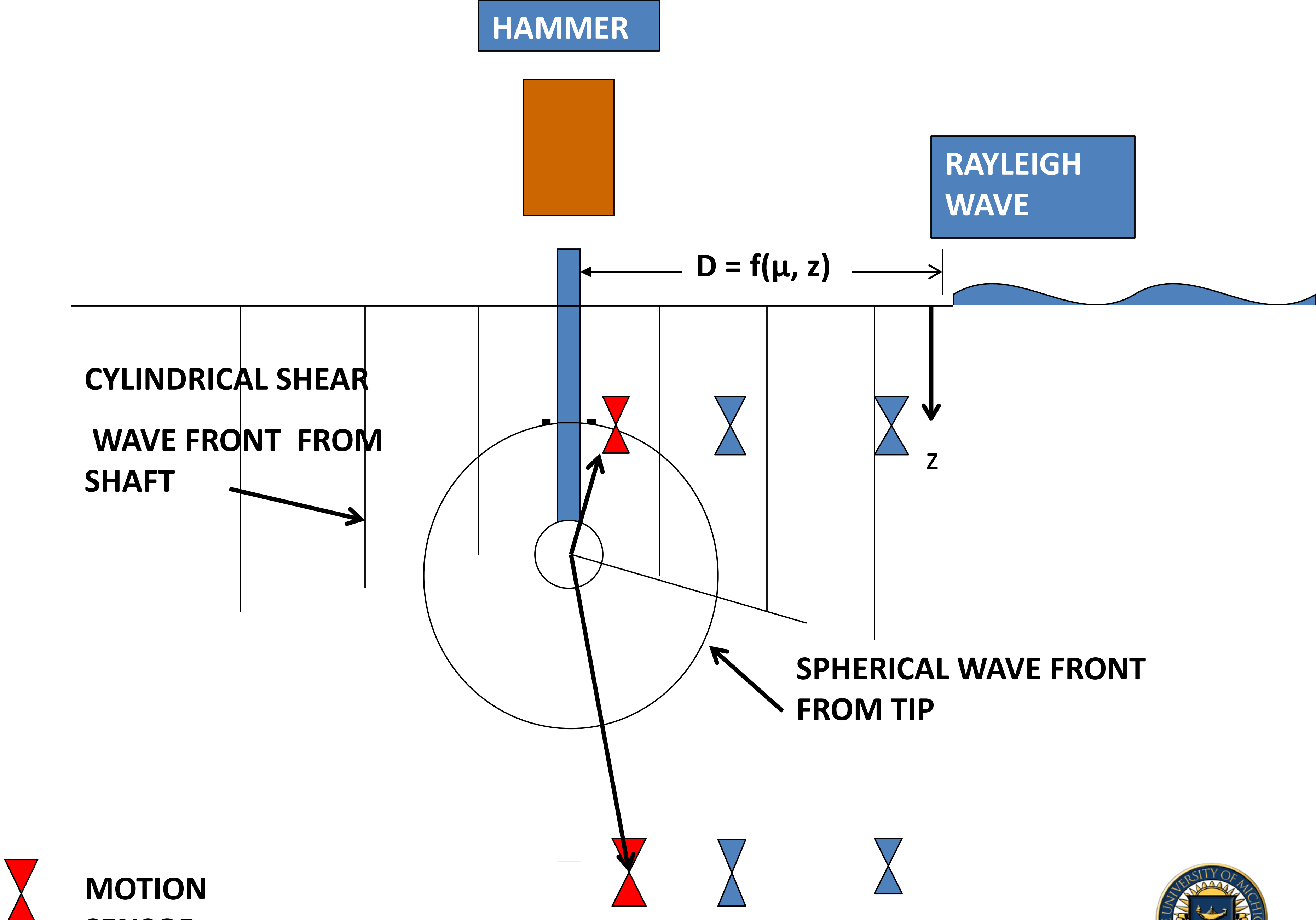
Peak Particle Velocity (PPV) Results



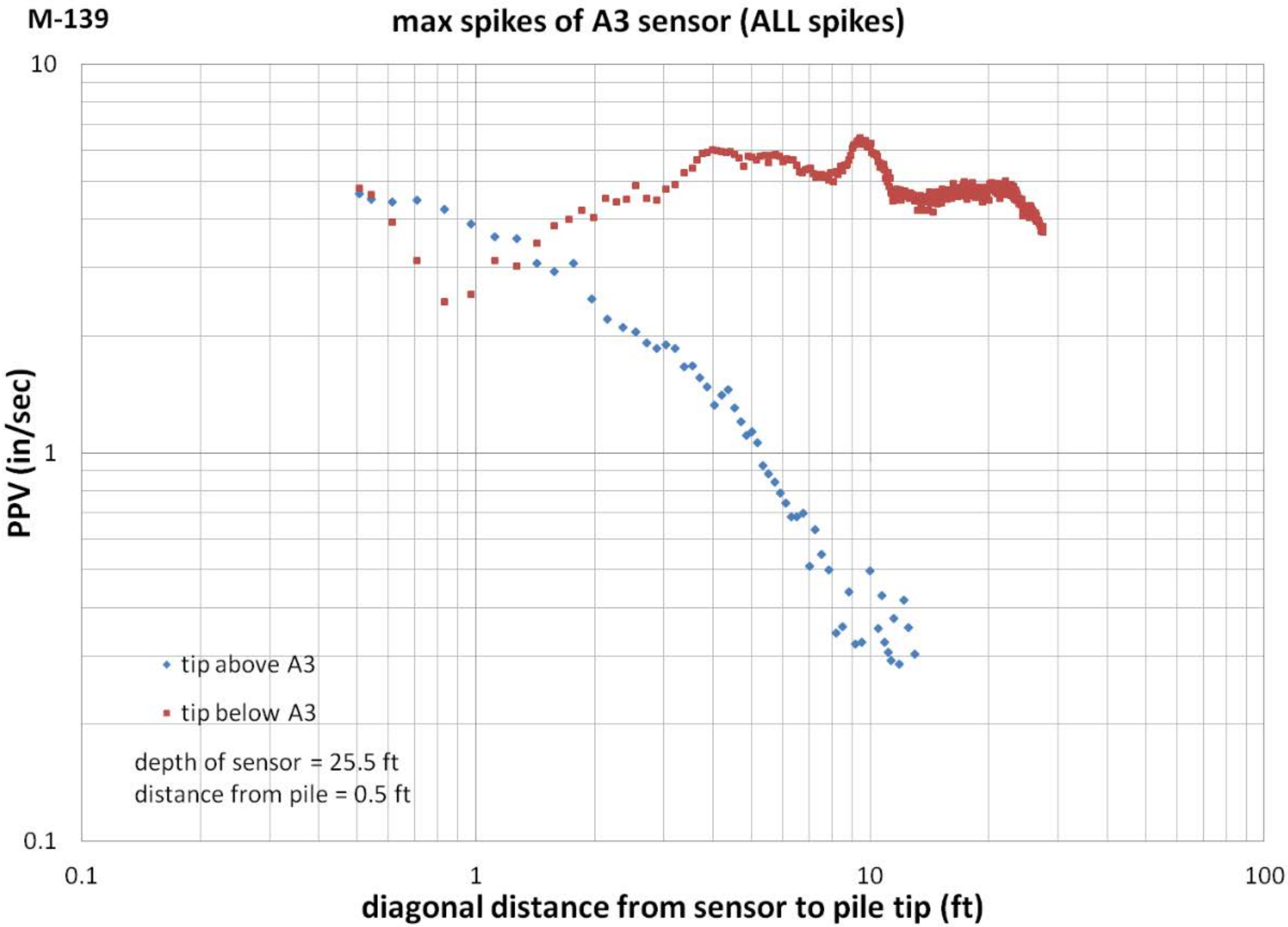
Peak Particle Velocity (PPV) Results (Surface geophones)

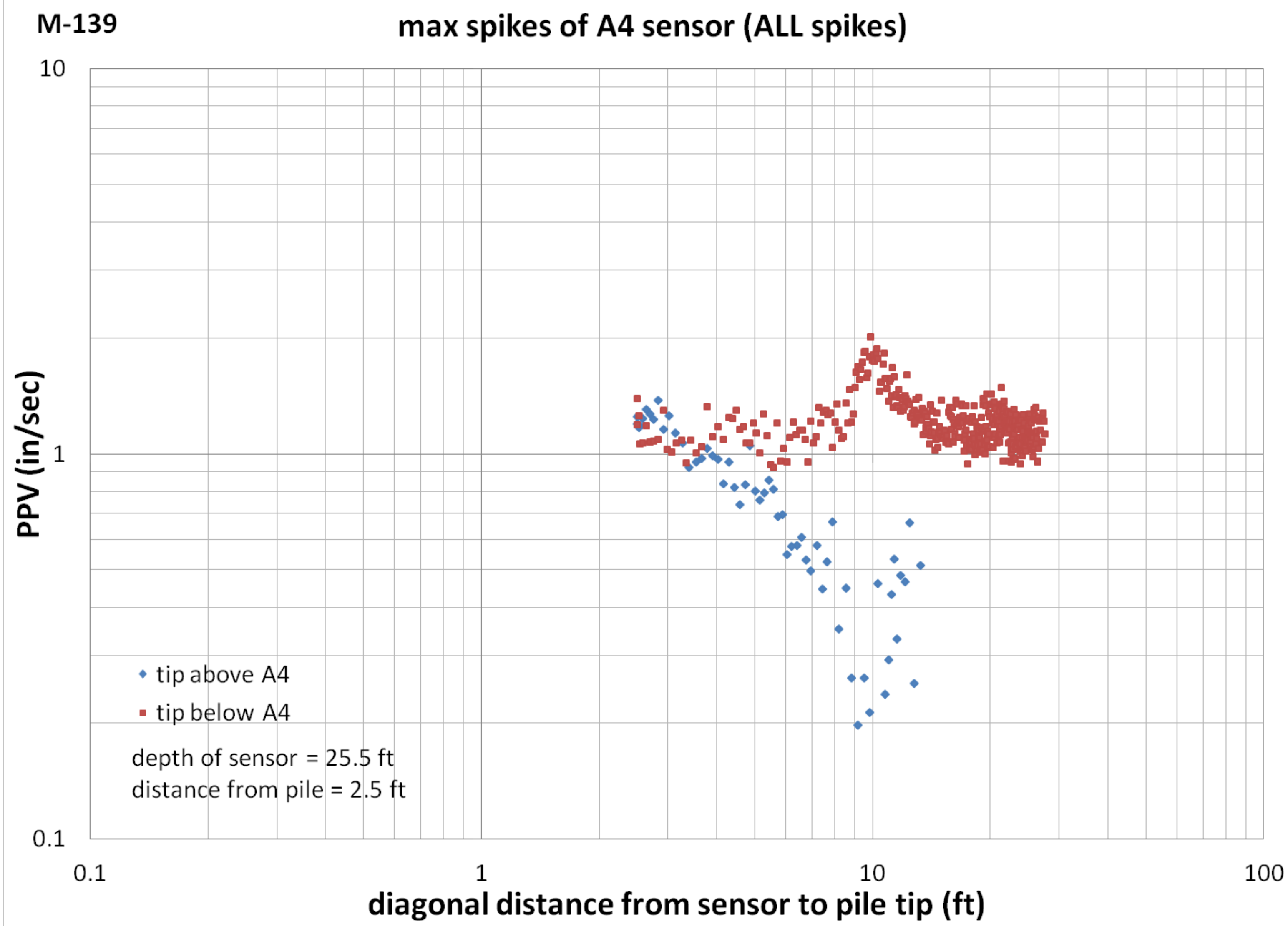





HAMMER
RAYLEIGH WAVE
D = f(μ, z)
z
CYLINDRICAL SHEAR
WAVE FRONT FROM
SHAFT
SPHERICAL WAVE FRONT
FROM TIP
MOTION
SENSOR

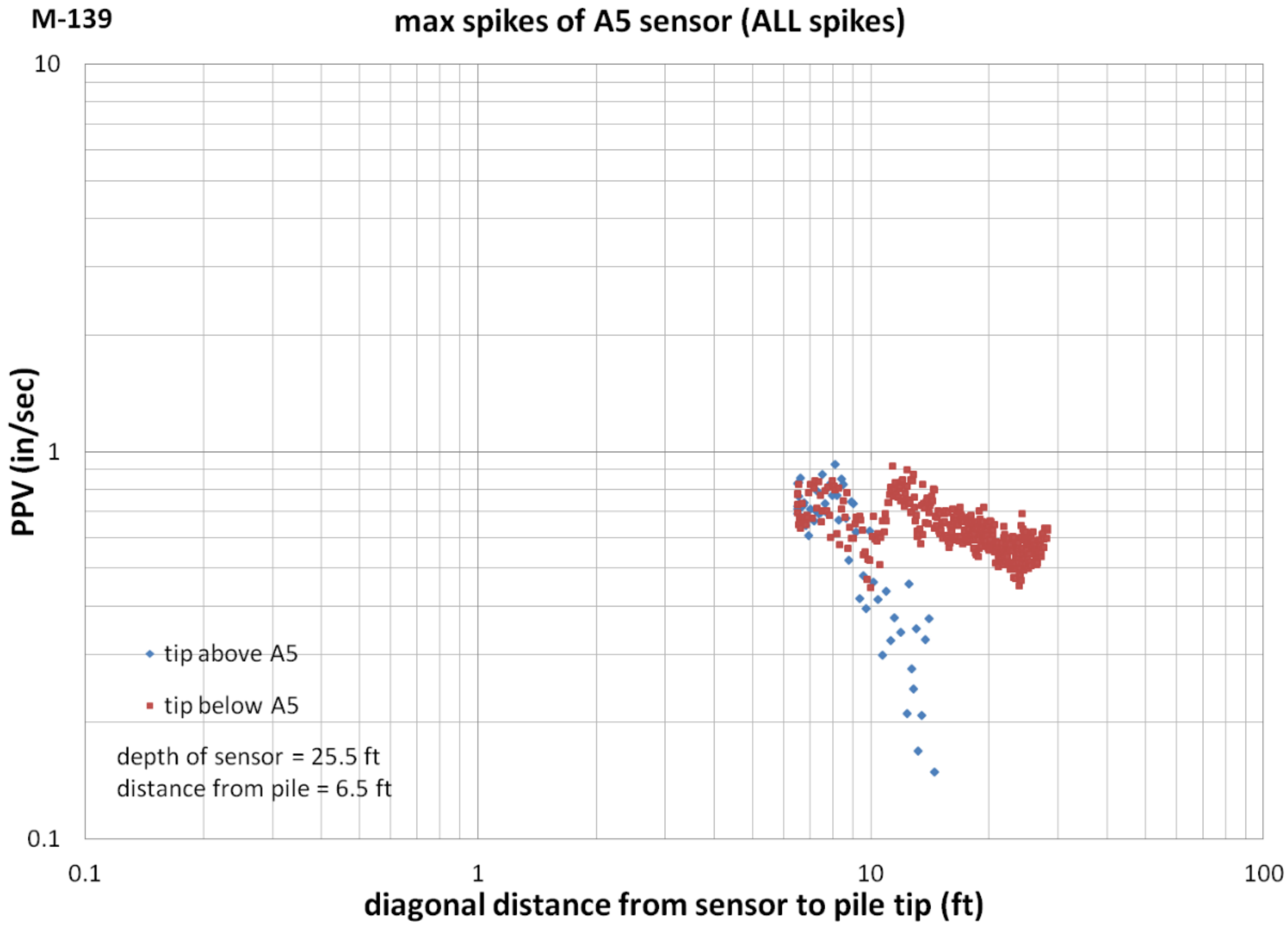
M-139


max spikes of A3 sensor (ALL spikes)
10
1
0.1
PPV (in/sec)
0.1
1
10
100
diagonal distance from sensor to pile tip (ft)
tip above A3
tip below A3
depth of sensor = 25.5 ft
distance from pile = 0.5 ft

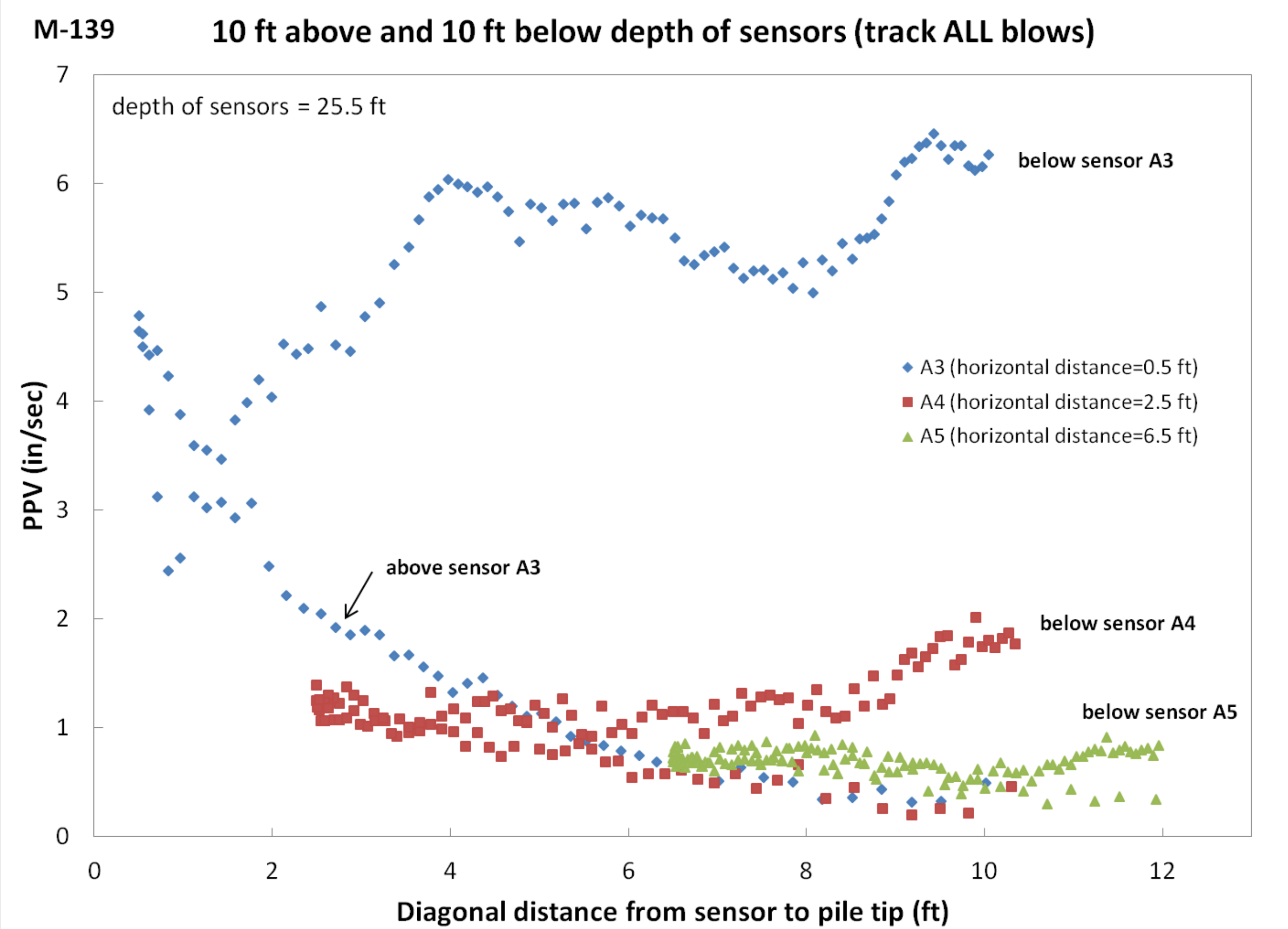


M-139
max spikes of A4 sensor (ALL spikes)
10
1
0.1
PPV (in/sec)
tip above A4
tip below A4
depth of sensor = 25.5 ft
distance from pile = 2.5 ft
0.1
1
10
100
diagonal distance from sensor to pile tip (ft)

M-139

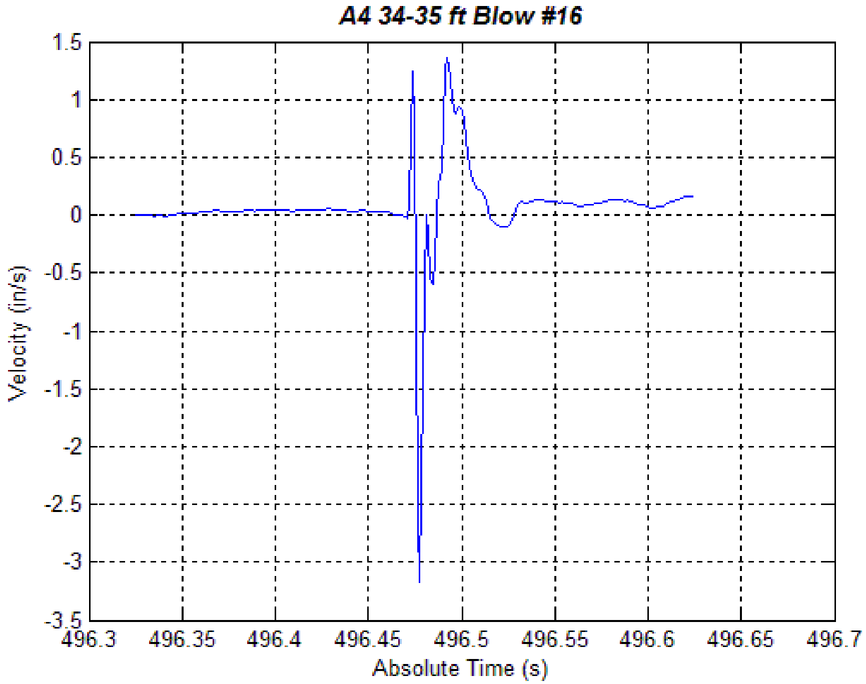


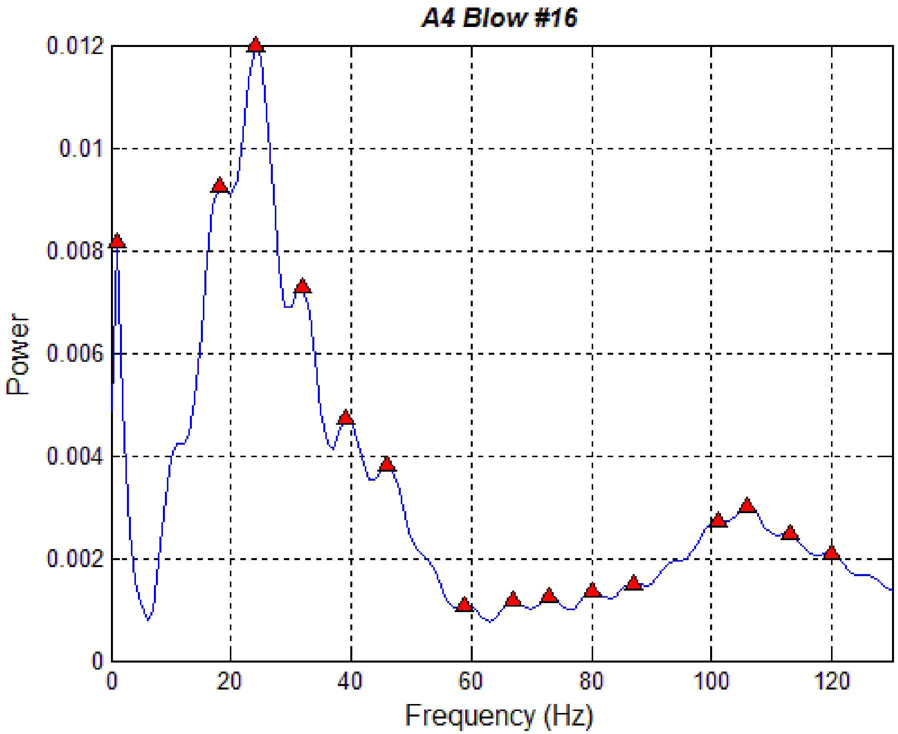
max spikes of A5 sensor (ALL spikes)
10
1
0.1
PPV (in/sec)
0.1
1
10
100
diagonal distance from sensor to pile tip (ft)
tip above A5
tip below A5
depth of sensor = 25.5 ft
distance from pile = 6.5 ft



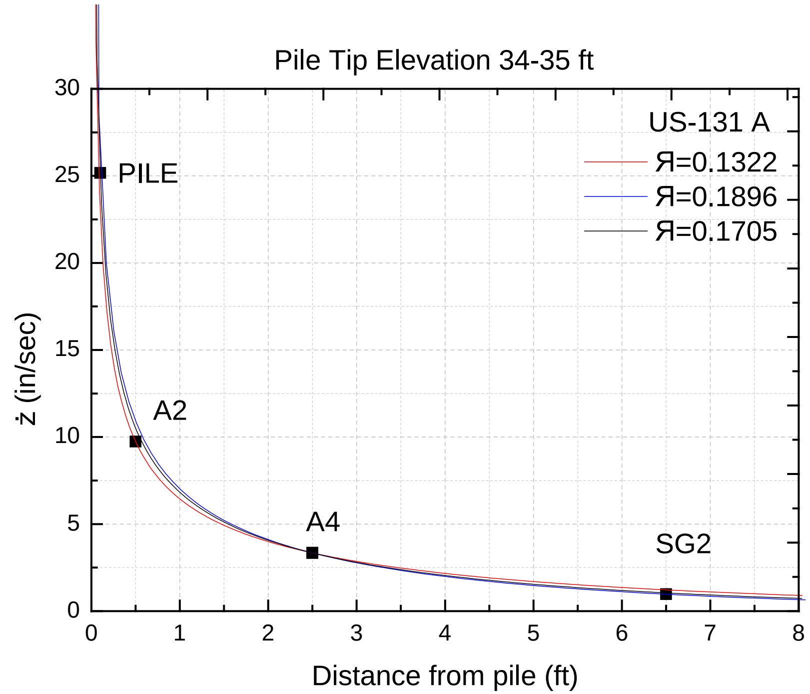
M-139
10 ft above and 10 ft below depth of sensors (track ALL blows)
depth of sensors = 25.5 ft
below sensor A3
above sensor A3
below sensor A4
below sensor A5
A3 (horizontal distance=0.5 ft)
A4 (horizontal distance=2.5 ft)
A5 (horizontal distance=6.5 ft)
PPV (in/sec)
Diagonal distance from sensor to pile tip (ft)
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12

Data Processing





Wave Attenuation Coefficients



Site US-131A

	Distance from pile (ft)	ż (in/sec)		я
PILE	0.1	23.80	Pile-A2	0.2220569
A2	0.5	9.74	A2-A4	0.1322479
A4	2.5	3.34	A4-SG2	0.1895872
SG2	6.5	0.97	A2-SG2	0.1704741
PILE	0.1	23.80	Pile-A4	0.1472161
PILE	0.1	23.80	Pile-SG2	0.1736980

ENERGY DISSIPATION

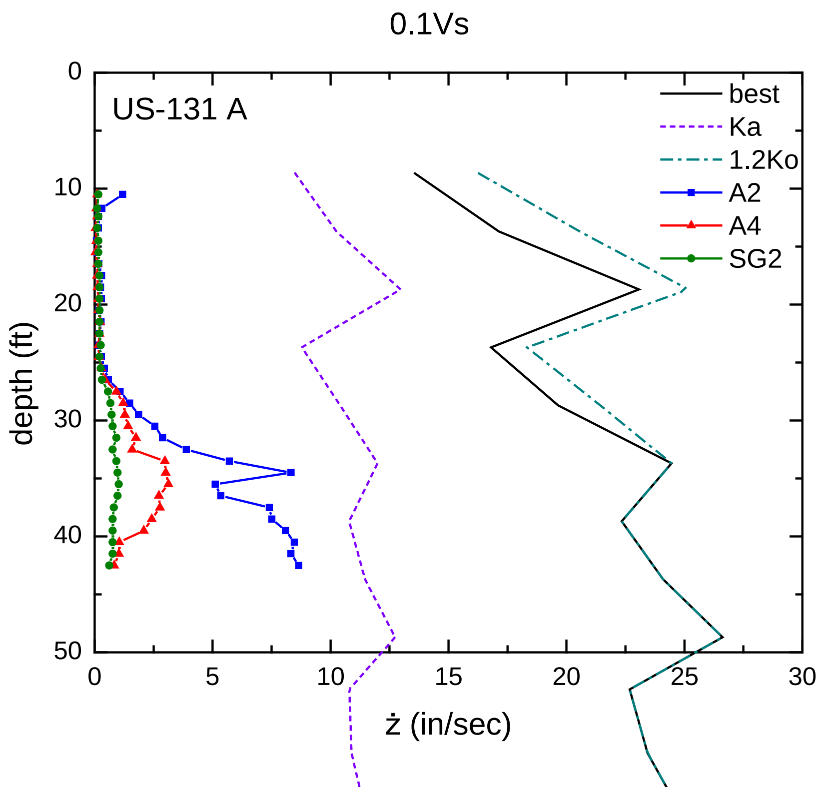
Bornitz Equation: $$A_2 = A_1 (r_1/r_2)^n \exp[-\alpha(r_2 - r_1)]$$

A_1 = amplitude at known distance r_1
A_2 = amplitude at any distance r_2
r_1 = distance from source to point of known amplitude
r_2 = distance from source to any point
n = coefficient depending on type of wave

- n = 1 for body waves in half-space
- n = 2 for body waves along surface
- n = 0.5 for Rayleigh waves

α = coefficient of attenuation replaced by: **Я** determined from this study

Shearing Strain Calculation



$\phi \approx \tan^{-1}[(N_{SPT}/(12.2+20.3\sigma_v'/Pa)]^{0.34}$

ϕ => K =>σ_h' => shear stress, τ

Best estimation based on using 3 layers with:

1st layer=>K_o

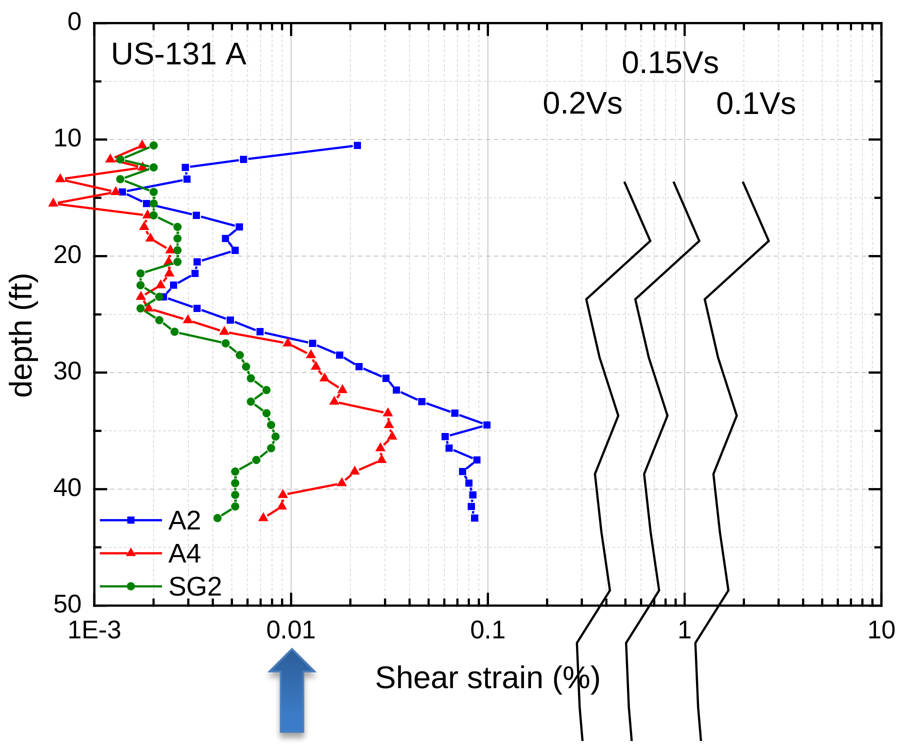
2nd layer=>1.1K_o

3rd layer=>1.2 K_o

maxPPV=$\tau_{max}/(V_s\rho)$ at pile face

(V_s reduced appropriately)

Shearing Strain Calculation



$\phi \approx \tan^{-1}[(N_{SPT}/(12.2+20.3\sigma_v'/Pa)]^{0.34}$

ϕ => K => σ_h' => shear stress, τ

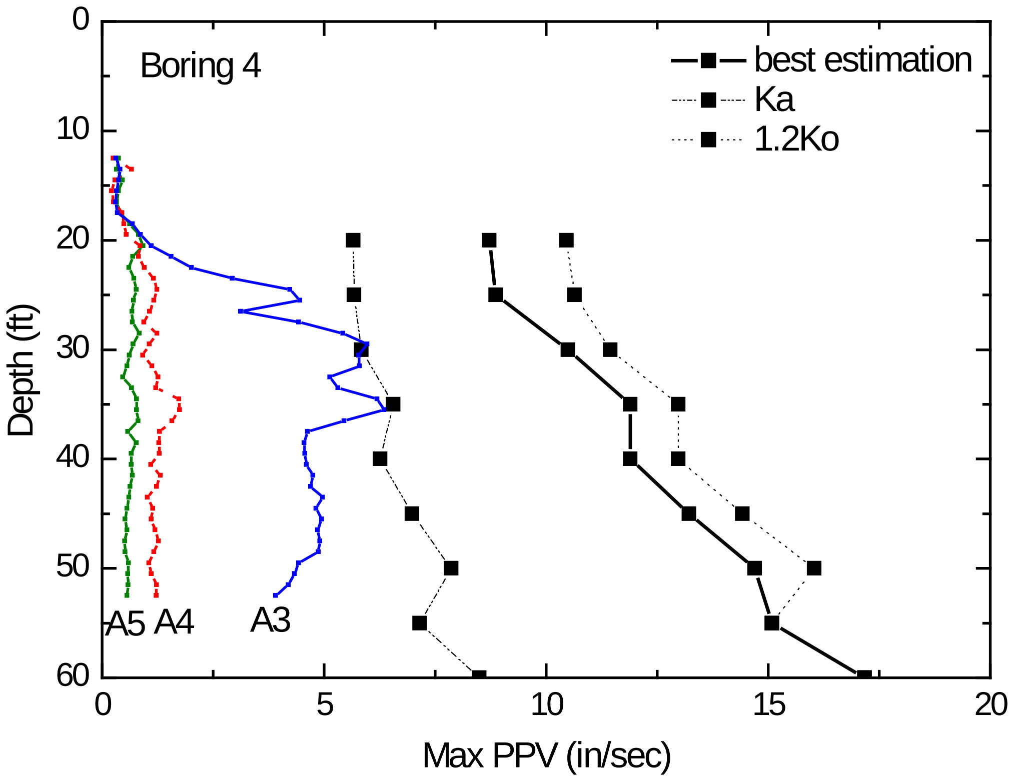
Best estimation based on using 3 layers with:

1st layer=>K_o
2nd layer=>$1.1K_o$
3rd layer=>$1.2\ K_o$

maxPPV=$\tau_{max}/(V_s\rho)$ at pile face

(V_s reduced appropriately)

Shearing Strain Calculation



$\phi \approx \tan^{-1}[(N_{SPT}/(12.2+20.3\sigma_v'/Pa)]^{0.34}$

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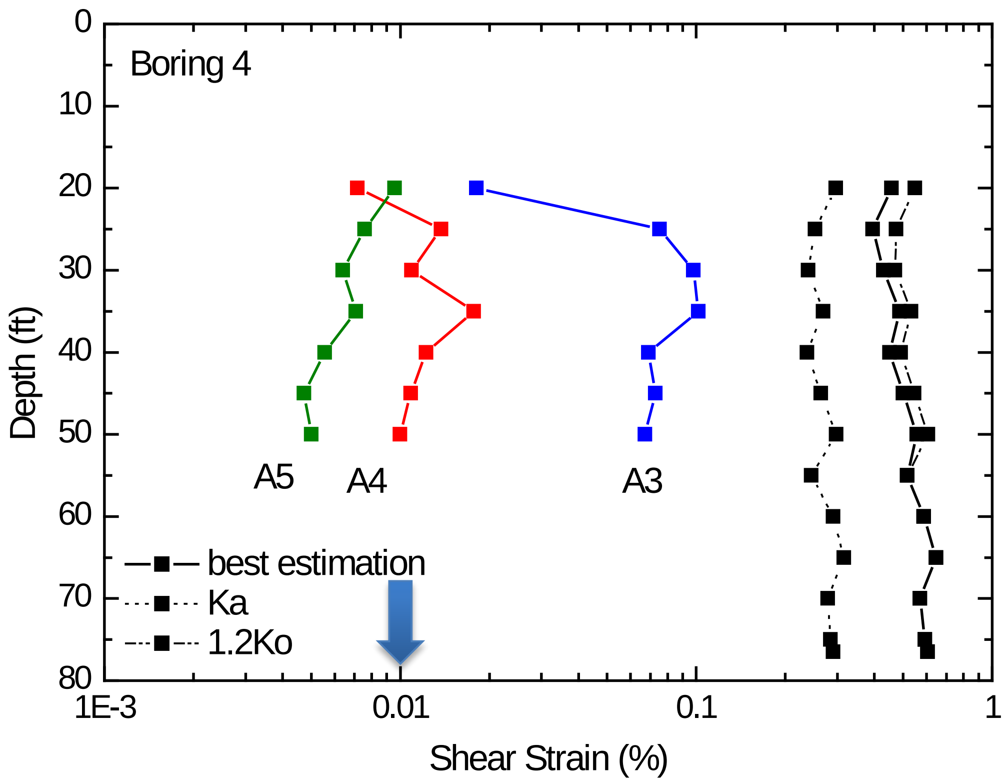
Shearing Strain Calculation



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Best estimation based on using 3 layers with:

1st layer=>K_o

2nd layer=>1.1K_o

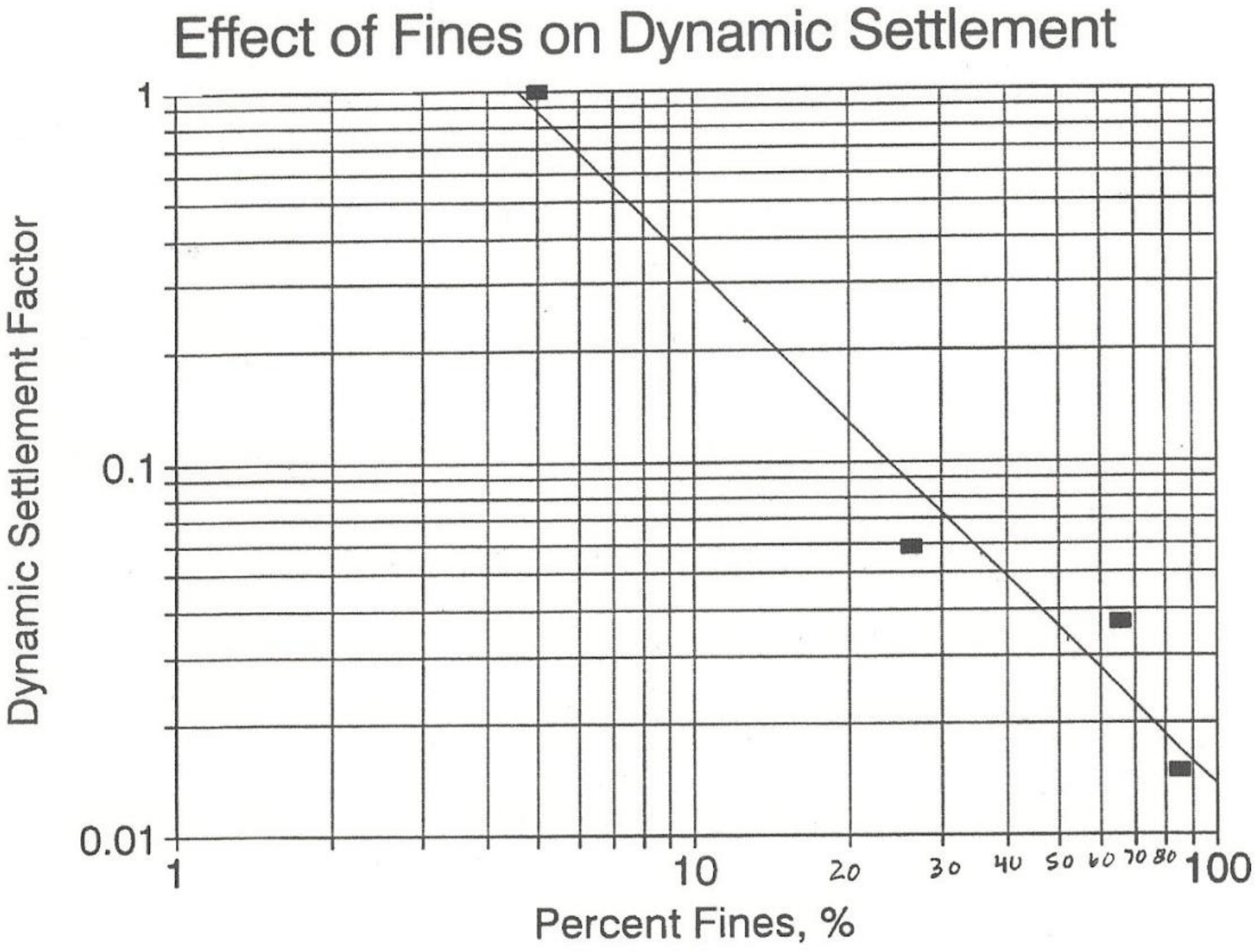
3rd layer=>1.2 K_o

maxPPV=$\tau_{max}/(V_s\rho)$ at pile face

(V_s reduced appropriately)

THRESHOLD STRAIN

- SILVER & SEED (1971) $\gamma_t \approx 0.01\%$
- YOUD (1972) $\gamma_t = 0.01\ \%$ (limit of his tests)
- DOBRY (1983) $\gamma_t = 0.01\%$ (for liquefaction)
- HSU & VUCETIC (2004) $\gamma_t < 0.01\%$ (10 cycles)
- MASSARSCH (2008) $\gamma_t = 0.001\ \%$ (many cycles)
- BRANDENBERG ET AL (2009) $\gamma_t < 0.01\%$



AFTER BORDEN & SHAO (1995)

Spreadsheet

- Input = Soil Profile, Pile Type and Size, Hammer
- Output = Yes or No to likelihood of shakedown settlement at selected distances from pile
- Not considered – number of piles or blows
- Not considered – amount of settlement

Conclusions

- In situ ground vibration measurements during pile driving extended our understanding and helped improve and refine the hypothetical model of energy transfer from pile to ground

- The Bornitz form of equation was determined to be the best way to most accurately represent attenuation. However, the conventional way of including material damping through the coefficient of attenuation, α, was determined to be too simple for driven piles as a source of energy, so a different symbol for coefficient of attenuation, я, has been chosen.

- A spreadsheet calculation tool was developed for identifying potentially troublesome sites. This tool requires input of only a basic soil stratigraphy, blow counts (N) for each strata, pile section and pile driver rated energy. Soil and attenuation properties are derived from correlations with blow count (N).

Acknowledgments

- Richard Endres (MDOT)
- Tony Pietrangelo (MDOT)
- Bob Fischer and Rick Burch (Technicians, Univ. of Michigan)
- Mohammad Kabalan, Adam Lobbestael, Zaher Hamzeh and Jane Gregg (graduate and undergraduate students, Univ. of Michigan)

THANK YOU!!!