University of Pittsburgh | Swanson School of Engineering

Depth to Bedrock Seismic Research Project

April 11th, 2022

Steven Sachs, PhD

CENTER FOR Sustainable Transportation INFRASTRUCTURE

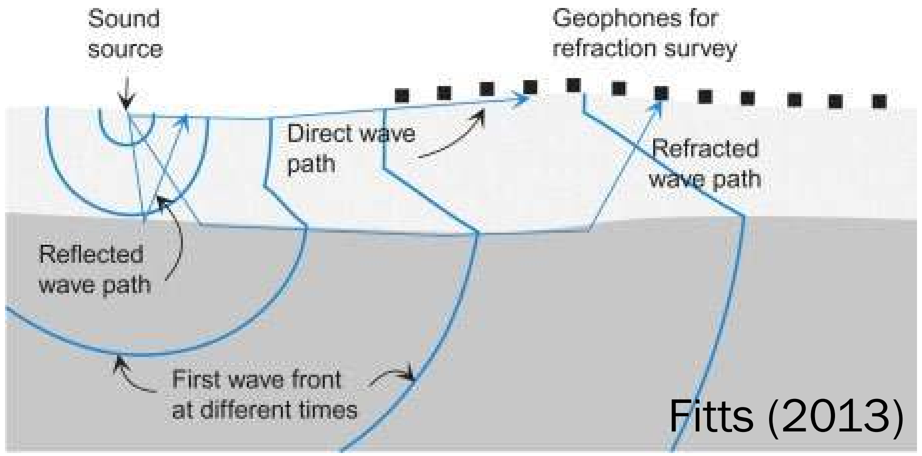
Background

- **Purpose**: evaluate the use of seismic methods to estimate the depth to bedrock

- **Goal**: establish the accuracy and efficacy of these methods as compared to current and historic core boring taken by PennDOT, with the goal being to eliminate a portion of the core borings currently being performed

What are seismic methods?

CENTER FOR SUSTAINABLE TRANSPORTATION INFRASTRUCTURE



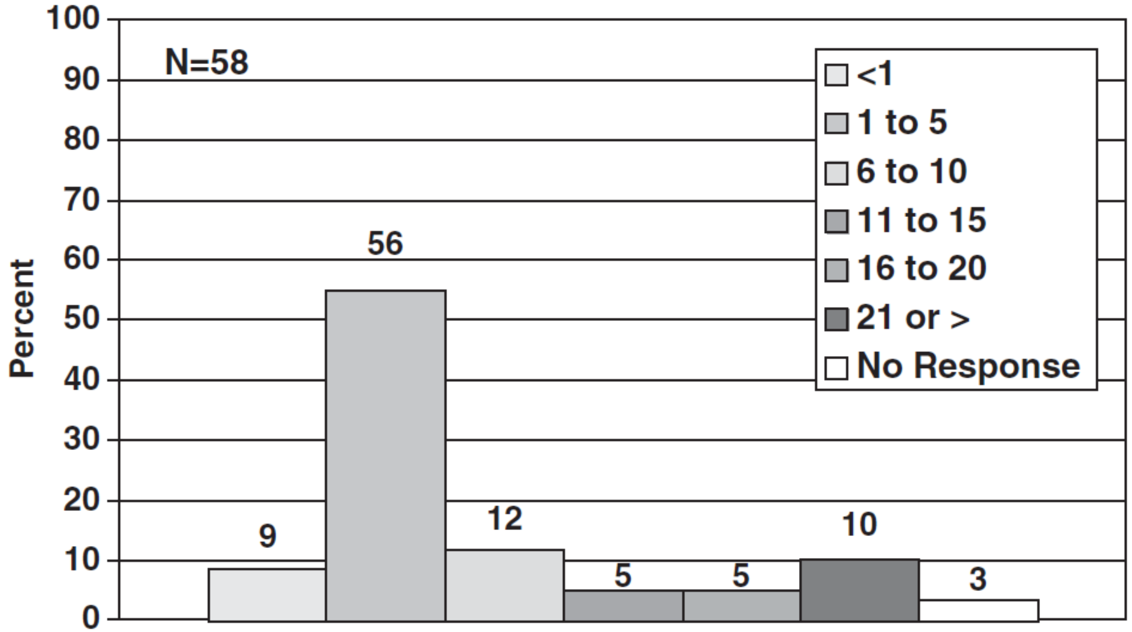
- Seismic methods are a branch of geophysical investigations that involve measuring the propagation of seismic waves through earth materials

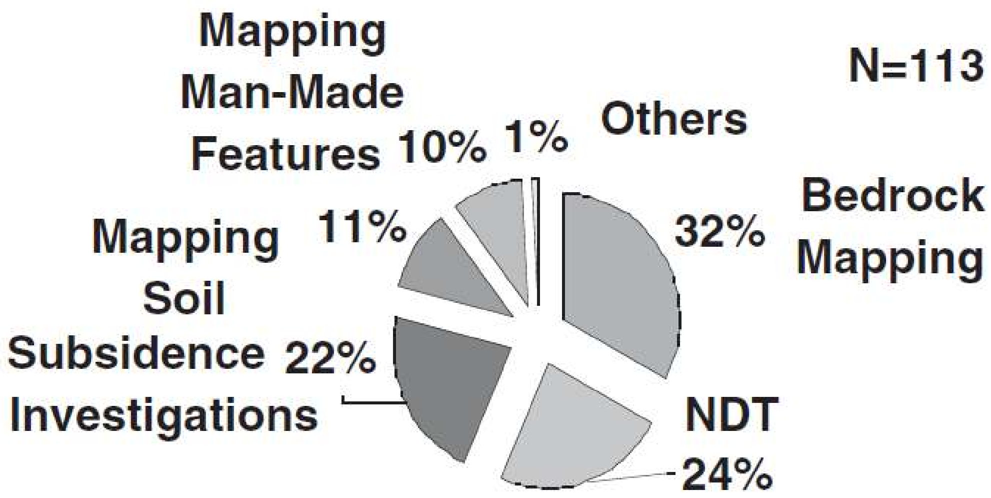
- In seismic surveys, seismic waves radiate outward from a sound source at the surface, which can be an explosive charge or a mechanical impact

DOT Experience

CENTER FOR SUSTAINABLE TRANSPORTATION INFRASTRUCTURE

NCHRP Synthesis 357





Objectives

- Identify locations with varied geologic conditions where borings have been performed
- Select common seismic methods to test and compare to ground truth boring
- Evaluate methods based upon accuracy, field effort, and processing effort
- Provide conclusions and recommendations

Testing Locations

CENTER FOR SUSTAINABLE TRANSPORTATION INFRASTRUCTURE

- Bedrock depths from 5.7 - 34.6 ft
- Two sites w/ no discernable bedrock
- Crawford, Erie, Forest, Mercer, Venango, and Warren counties
- Bedrock types: siltstone, sandstone, and shale
- Overburden material: silt, sand, gravel, and clay

Historical Boring Information

CENTER FOR SUSTAINABLE TRANSPORTATION INFRASTRUCTURE

Location	Project location					Boring Information			Bedrock Information			Predominate Overburden Material
	County	County code	SR	SEG	Offset	Boring ID	Station / Section	Offset	Depth to bedrock (ft)	Elevation	Lithology of bedrock	
1	Crawford	20	6	850	820	RB-1	725+79.0	9.0 FT. LT.	11.2	1180.2	Siltstone	SILT and fine to coarse SAND
2	Crawford	20	322	30	1919	RB-1	190+62.0	9.0 FT. RT.	16.2	1004.8	Sandstone	SILT and fine to coarse SAND
3	Crawford	20	1006	110	1250	B-1		From C.L 20' RT			No Bedrock	CLAY, gray with trace of SILT
4	Erie	25	226	10	576	B-1	5+78.0	7.0 ft. RT.	14.8	943.1	shale	SILT and fine to coarse GRAVEL
5	Erie	25	1006	110	2972	B-1	343+61.0	5.0 ft. LT.	34.6		shale	SILT and fine to coarse SAND
6	Erie	25	19	80	692	B-1	320+88.4	8.0 FT. LT.			No Bedrock	CLAY and SILT, little fine Sand
7	Forest	27	62	20	0	RB-1	B01		10.5/ 18.0	1022.7/ 1015.2	Sandstone/ SILTSTONE interbedded with SANDSTONE	UNSAMPLED
8	Forest	27	1003	60	1600	RB-2	141+15.0	6.0 FT. LT.	13.1	1390.8	Sandstone	SILT and fine and medium GRAVEL
9	Mercer	43	2001	50	1819	RB-1	124+29.0	6.0 FT. LT.	26.7	1120.9	SANDSTONE interbedded with SHALE	Fine to coarse SAND
10	Venango	60	38	110	0	B-1	337+11.0	7.0 FT. LT.	21.5/ 24.5	13013/ 1298.3	Sandstone/ shale	Fine to coarse SAND and SILT, ORGANICS (wood) at 7.5'
11	Venango	60	3006	30	1554	RB-1	B00	8.0 ft. RT.	15.8		SHALE interbedded with SANDSTONE	Fine to coarse SAND and SILT
12	Warren	61	27	490	2098	RB-1		8.0 FT. RT.	24.4	1266.9	Siltstone	Fine to coarse SAND, some fine to coarse Gravel, little Silt
13	Warren	61	1021	40	0	B-2	71+89.0	8.0 FT. RT.	5.7	1414.9	Sandstone	SAND and SILT
14	Warren	61	2010	20	1511	RB-2	9+10.0	6.0 ft. RT.	24		SILTSTONE interbedded with SANDSTONE	Sandstone boulder at 13.7, Fine to coarse SAND, little Silt, trace fine to coarse Gravel

Field Testing

- 3 Testing procedures
  - **Refraction Microtremor** (ReMi), **Multispectral Analysis of Surface Waves** (MASW), and **Horizontal-to-Vertical Spectral Ratio** (HVSR)
- Seismic data for all the three (3) methods will be collected along one (1) or two (2) sets of orthogonal profiles at each selected location (for ReMi and MASW) and at the intersection of the orthogonal profiles for HVSR. Geophones along each profile (for ReMi and MASW) will be spaced at 10 ft intervals, depending on site dimensions and depths of interest
- Geophone spacing is function of depth of interest
  - Closer spacing preferred for sites with shallow overburden, while greater spacing is better for anticipated deeper overburden
- These results will then be compared to the boring results
- Methods compared for field effort (time and expenses for equipment), processing effort (time and expenses for processing software and personnel), accuracy (how well each method matches the ground truth)

Field Testing

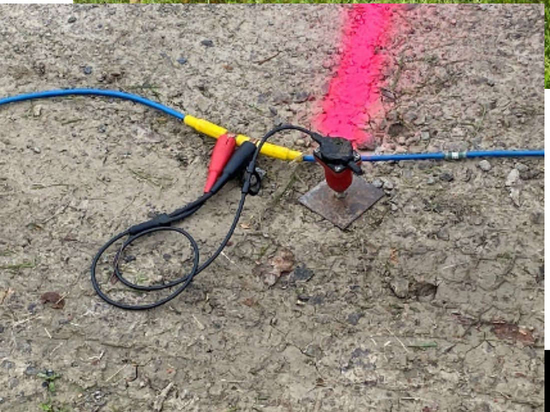
CENTER FOR SUSTAINABLE TRANSPORTATION INFRASTRUCTURE

Site Restrictions

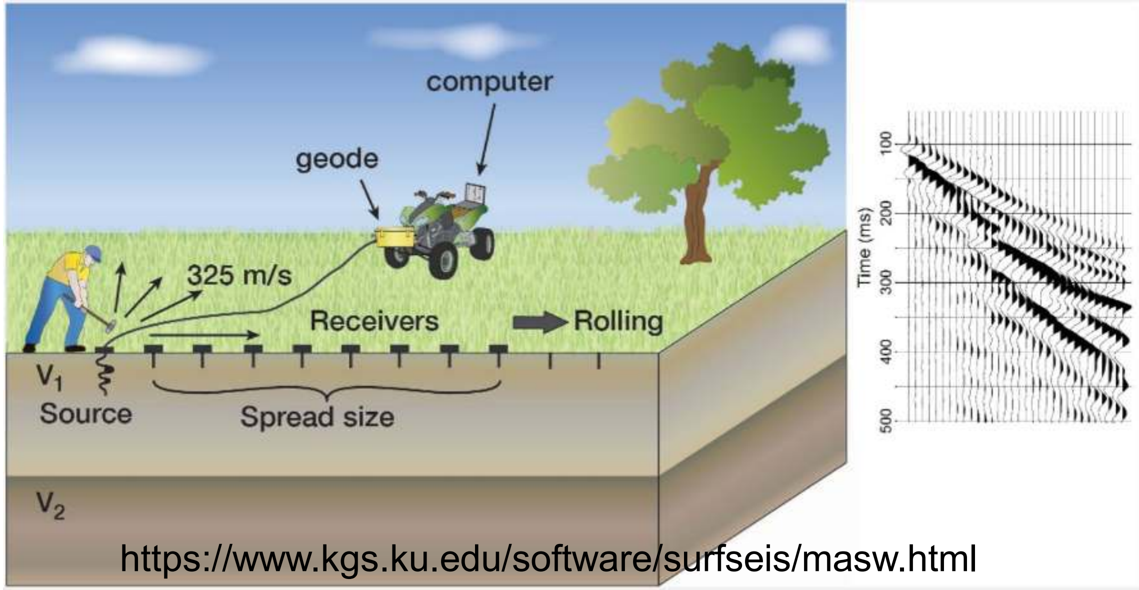
- Desired to collect data directly on top of boring locations but was not possible
- Every effort was made to perform the testing as close as possible to the location of the core
- Testing shifted out into the shoulder and moved along the road to avoid blind curves

- Additionally, desire to collect data in orthogonal directions for both the ReMi and MASW methods by laying geophones in an x pattern
- With ROW restrictions and testing performed in shoulder it was also not possible to obtain testing in orthogonal directions
- For ReMi and MASW testing, geophones laid out in a line to receive seismic wave data.
- Primarily interested in comparing the ground truth depth to a depth obtained from the passive testing, it is sufficient to test with geophones located along one line

Multispectral Analysis of Surface Waves (MASW)



- Geophones spaced at 10 ft interval in linear array
- Composite strike plate w/ 16-lb sledgehammer used to generate seismic surface waves for shear wave velocity and depth estimates
- Surface wave train recorded at each geophone Fourier-transformed, to provide shear-wave velocity as a function of frequency, which is in turn inverted to determine S-wave velocity as a function of depth at each geophone location



https://www.kgs.ku.edu/software/surfseis/masw.html

Refraction Microtremor (ReMi)

- Same setup as MASW testing
- Ambient seismic surface wave trains measured for fifteen 30-second records at a sampling interval of 2 milliseconds
- Data analyzed using Seis Opt ReMi by Optim
- Surface Wave Analysis makes use of the fact that much of the seismic noise at the ground surface consists of Rayleigh waves
- By decomposing the frequency content of a Rayleigh wave train and measuring the velocity at which each component passes through the geophone array, it is possible to calculate the shear-wave velocity as a function of depth beneath the geophone array

Horizontal/Vertical Seismic Ratio (HVSR)

- Non-invasive, uses single, broad-band three-component seismometer (Tromino) to record ambient seismic noise
- Measures two horizontal and vertical components of ambient seismic signals which occur everywhere in nature
- Ratio of avg horizontal-to-vertical frequency used to determine the fundamental site resonance frequency, where sediment thicknesses (bedrock depths) can be estimated
- Primary resonance frequency deduced from peaks on H/V which is interpreted as a significant stratigraphic boundary (typically the sediment-bedrock interface)
- Processing consists of estimating the ratio between the Fourier amplitude spectra of the horizontal-to-vertical components to determine resonance frequency and estimate shear-wave velocity to determine sediment thickness and bedrock depth estimates

Results

	Rock Depth (ft)				Error (%)		
Site	ReMi	MASW	HVSR	Boring	ReMi	MASW	HVSR
1	15.4	16.7	12.2	11.2	27.3	32.9	8.2
2	16.2	16.4	6.7	16.2	0.0	1.2	141.8*
3	45.2	43.7	46.8	Not Encountered			
4	17.8	17.4	11.1	14.8	16.9	14.9	33.3
5	35.6	36.5	37.5	34.6	2.8	5.2	7.7
6	56.5	NA	56	Not Encountered			
7	21.3	17.6	21.2	21.3	0.0	21.0	0.5
8	18.4	17.6	14.3	13.1	28.8	25.6	8.4
9	25.3	23.3	27.7	26.7	5.5	14.6	3.6
10	25.2	23.3	26.6	24.5	2.8	5.2	7.9
11	22.1	23.5	17.7	15.8	28.5	32.8	10.7
12	26.5	23.5	24.5	24.4	7.9	3.8	0.4
13	7.4	7.6	14.3	5.7	23.0	25.0	60.1
14	18.1	23.4	26.7	24	32.6	2.6	10.1

*Conducted on windy day; HVSR sensitive to vibrations
error most likely reduced if conduced under calmer conditions

Method Comparison

- Data collection and processing times higher for ReMi and MASW due to more involved field setup and data processing
- Based upon cost, accuracy, and efficiency, HVSR method is preferred
- Both ReMi and MASW methods produce reasonable results

	ReMi	MASW	HVSR
Median % Error	12.4	14.8	8.3
Data Collection (hr)	16.6	21.3	5.8
Data Processing (hr)	10.3	10.9	4.9
Total Time (hr)	26.9	32.2	10.7

		ReMi	MASW	HVSR
accuracy based on median %Error	**Accuracy Rank**	3	2	1
efficiency based on Total Time	Efficiency Rank	2	3	1
cost = rate x total time + equipment	Cost Rank	2	3	1
	Accuracy/Efficiency/Cost Rank Sum	7	8	3
	OVERALL RANKING	2	3	1

Method Comparison

CENTER FOR SUSTAINABLE TRANSPORTATION INFRASTRUCTURE

- HVSR would be the easiest for PennDOT to adopt
- The self-contained device can be very quicky deployed by one person with minimal setup and testing time
- Interpretation of the data which ideally would be performed by a trained seismologist, but possible to interpret results with training
- ReMi and MASW valid and produce reasonable results but more difficult for PennDOT to employ as equipment and setup is more involved
- Testing time and data analysis are longer resulting in a larger overall cost

accuracy based on median %Error	Accuracy Rank	3	2	1
efficiency based on Total Time	Efficiency Rank	2	3	1
cost = rate x total time + equipment	Cost Rank	2	3	1
	Accuracy/Efficiency/Cost Rank Sum	7	8	3
	OVERALL RANKING	2	3	1

Discussion

- HVSR results at Site 2 and 14 produced the largest errors encountered across all three methodologies
- HVSR method is sensitive and ambient conditions can influence results
- Should be deployed in calm conditions with as little noise and background interference as possible
- Multiple measurements should always be taken and ideally cross referenced with ground truth borings or another methodology

Conclusions

- No discernable trend with different rock types encountered

- More important that there be a measurable difference in stiffness between the overburden and bedrock such that the technology can detect a difference in shear wave velocity at the layer boundary

- Seismic methods could be used across the state regardless of the geology with the caveat that similar material stiffness near the bedrock location will make the interpretation of the 'true' depth more difficult.

Conclusions

- Testing was not able to be carried out directly at the boring locations; good correlation still found reasonably close as possible to the actual locations

- All three methods tested (ReMi, MASW, and HVSR) can be used to predict the depth to bedrock

- A benefit of these technologies is that greater depths can be probed than were possible to obtain with the boring
  - Boring did not encounter bedrock at sites 3 and 6
  - Depths obtained from the procedures around 45 and 56 feet
  - If depth not obtained from boring, seismic methods would allow to approximate in instances where the depth to bedrock is critical

Recommendations

- While seismic methods can be exceedingly useful, it is still not a replacement for ground truth boring results
- By employing boring in conjunction with a seismic scan, one would be able to potentially map a much larger area with reasonable accuracy
- Recommended that seismic methods can be employed in areas where depth to bedrock is needed as a minimally important variable
- Borings should still be taken at critical locations for large projects
- Seismic methods can be employed in conjunction with borings at strategic locations to reduce the total number of borings needed

Acknowledgements

- PennDOT
- PennDOT District 1-0
- RETTEW Field Services Inc.
  - Felicia Bechtel, MS, PG
  - Tim Bechtel, PhD, PG
  - Corey Miller, MS
- Jason Daley, PE
- Micah Shinn
- Shelley Scott

University of Pittsburgh | Swanson School of Engineering

Questions?