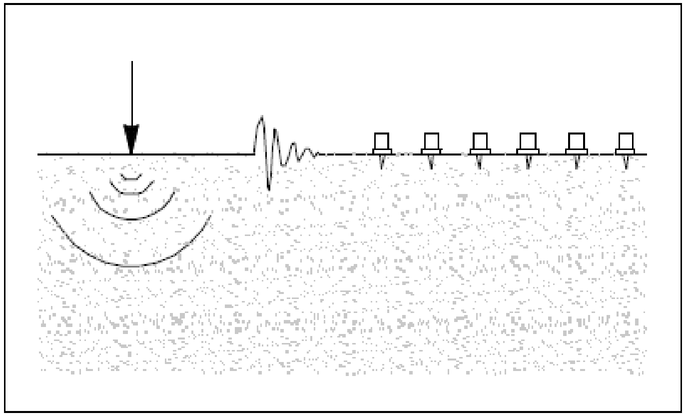
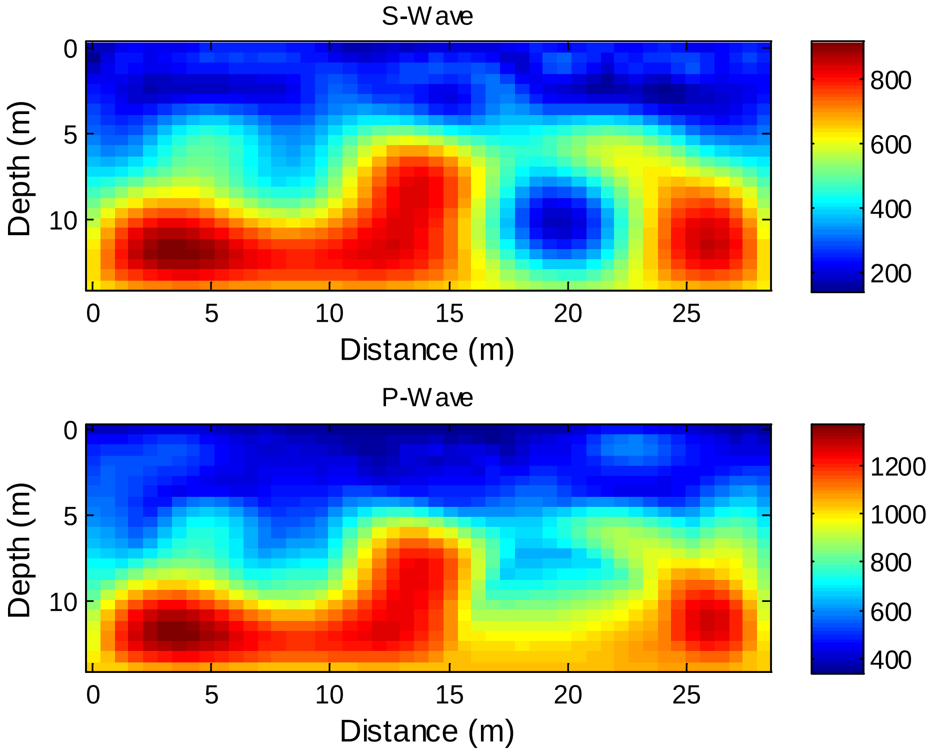
Seismic Full Waveform Inversion and Tomography

TRB Webinar 2015





By:

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Florida DOT
Ohio DOT

Outline

- Need and Motivation
- Overview of FWI
  - Concepts
  - Data acquisition and analysis
- Synthetic study
- Field data application
  - Florida sinkholes
  - Ohio Abandoned mines
- Conclusion

Need of site investigation

- Problems and disputations during and after construction
- Structural damage/collapse
- Long-term affects on structures

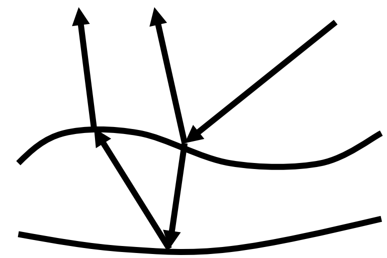
Sinkhole Collapse

Goals of site investigation

- Soil/rock stratigraphy
- Embedded Sinkholes/Anomalies

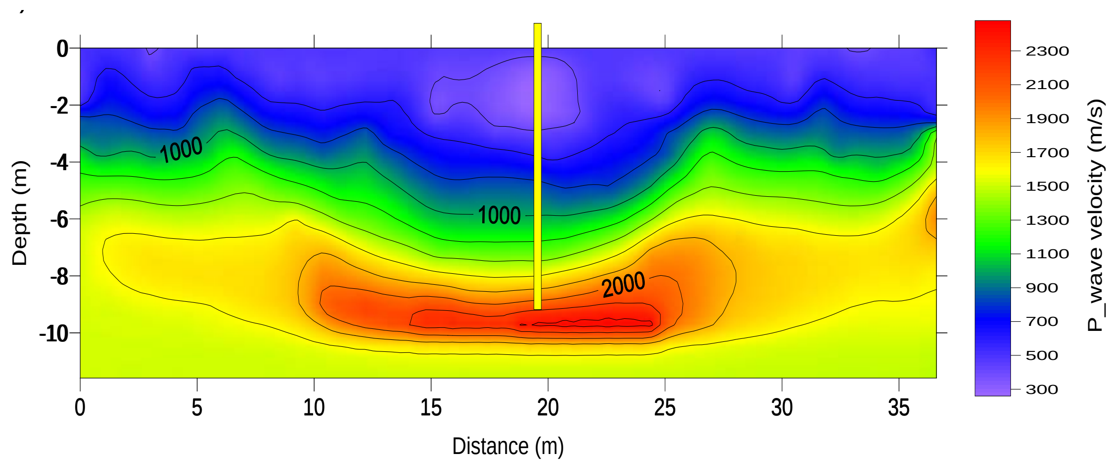
Seismic techniques

1) Imaging: localisation of interfaces (migration)



2) Material parameter (tomography)

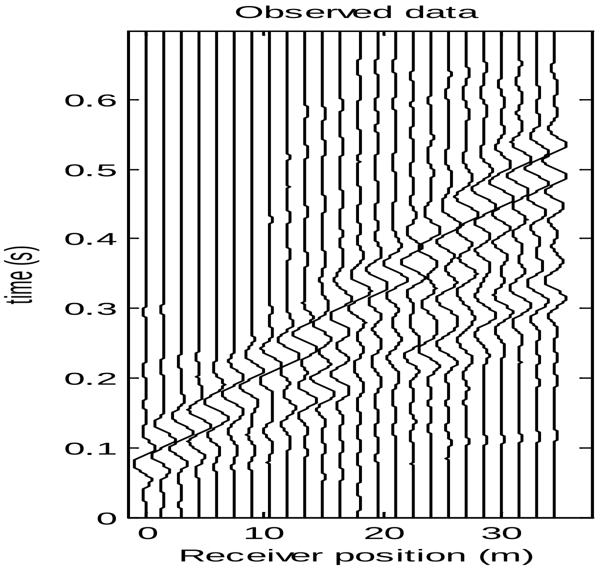
P-wave velocity
S-wave velocity
Poisson’s ratio
Density
Attenuation
Anisotropy

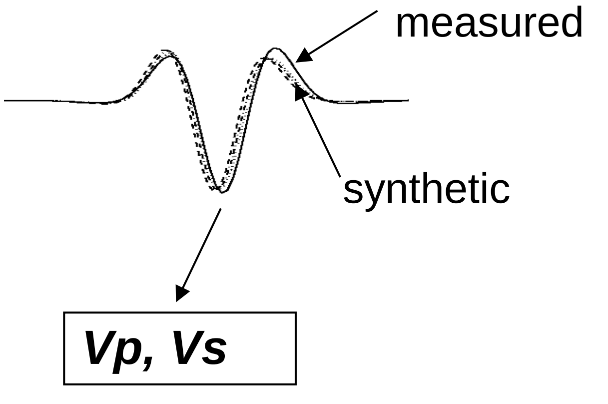


Full waveform inversion (FWI) motivation

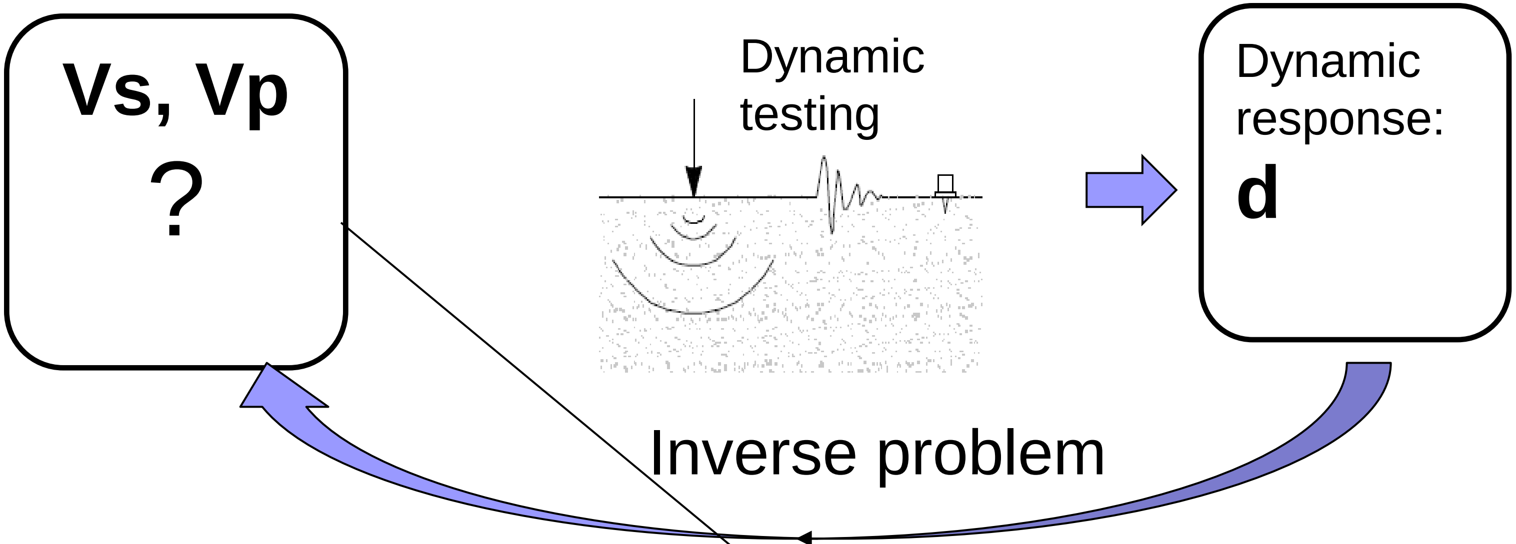
- Most conventional seismic inverse methods analyse travel times of specific wave types only, e.g.
  - travel time tomography
  - inversion of surface wave dispersion
  - migration

- FWI is <u>wave-equation based</u> and has the potential to
  - use full information content (waveforms)
  - consider all elastic wave-phenomena
  - infer multi-parameter images with high resolution



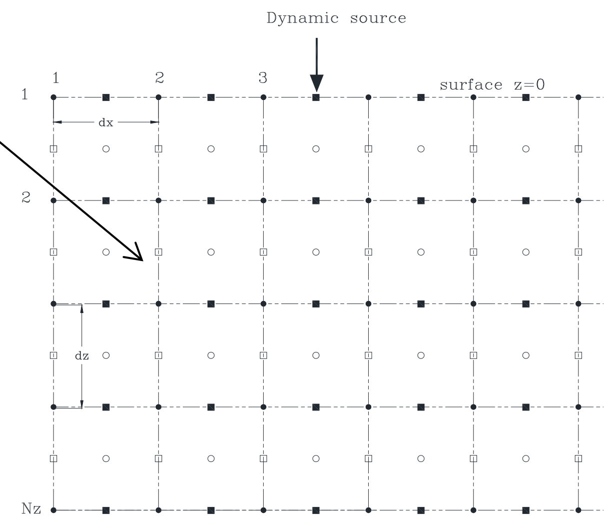


Overview of FWI



Inversion method:

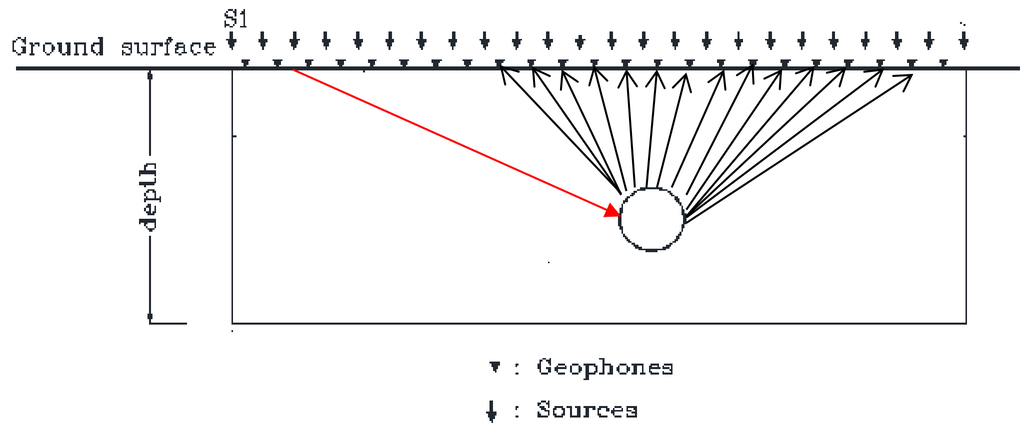
1. Forward modeling **d** = f(**Vs, Vp**)
   - 2-D elastic wave equations
   - $\mathbf{d}_{est} = f(\mathbf{Vs}_{est}, \mathbf{Vp}_{est})$

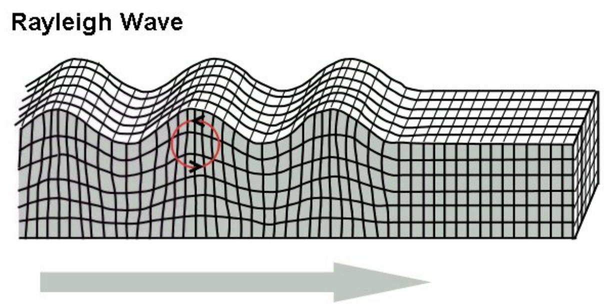


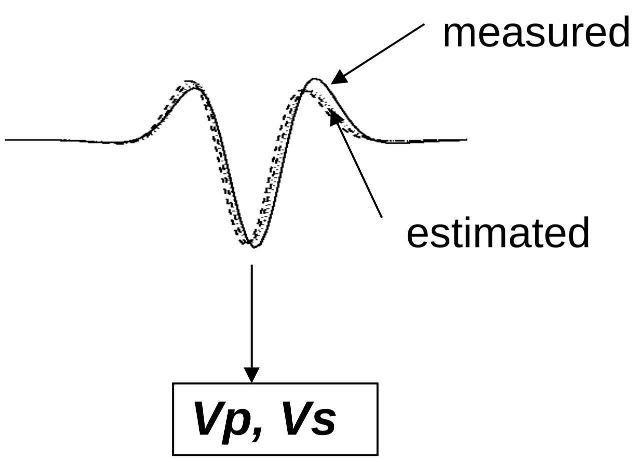
2. Model updating to get $\mathbf{d}_{est} \approx \mathbf{d}$
   - Gauss-Newton method
   - Converge when $\mathbf{d}_{est} - \mathbf{d} \sim 0$

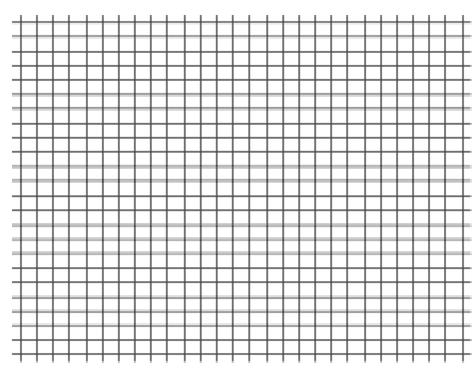
Data Acquisition and Analysis

- Data Acquisition
  - Multiple geophones at 1 to 3 m spacing
  - Multiple sources (strikes of hammer) at 1 to 3 m spacing
- Analysis
  - Use all measured waveforms (Rayleigh, S and P waves)

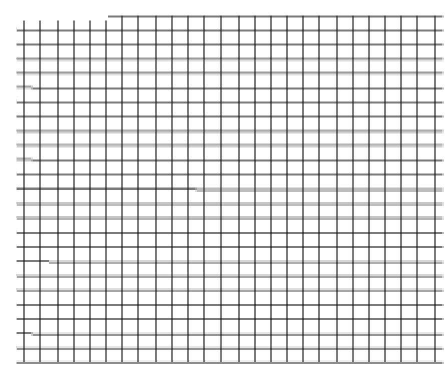






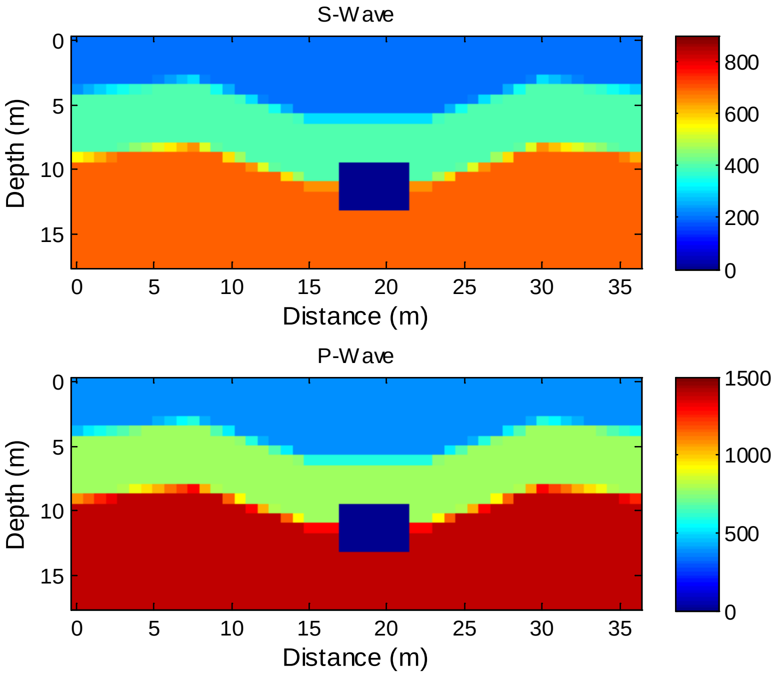


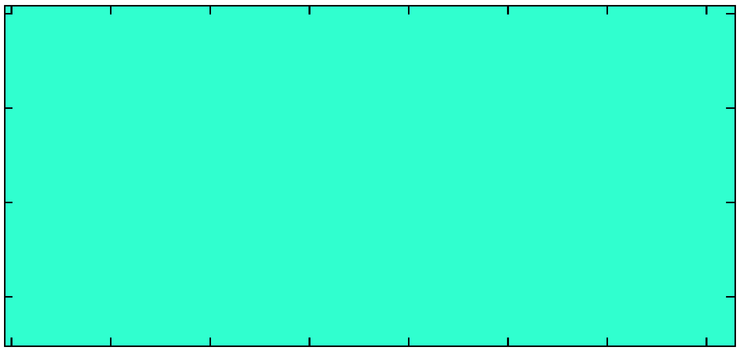
Compression wave



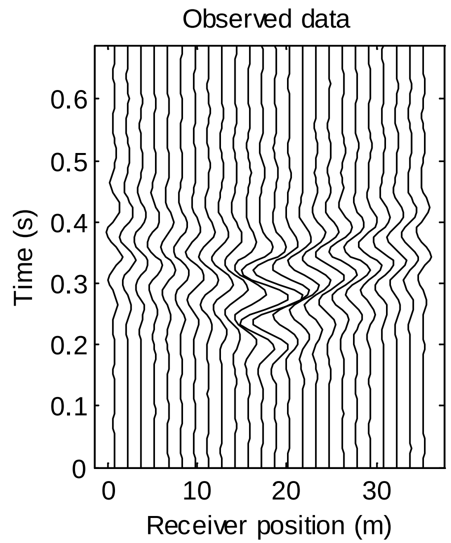
Shear wave

Synthetic test on an embedded void





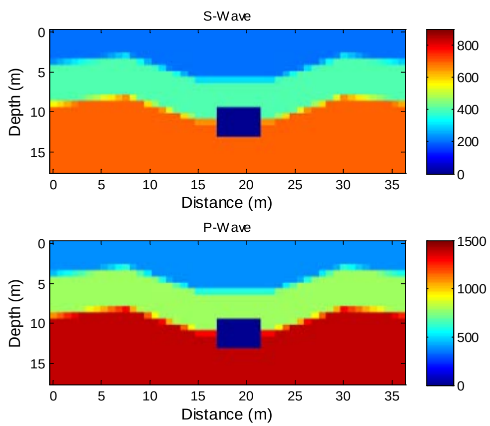
- Shot 13



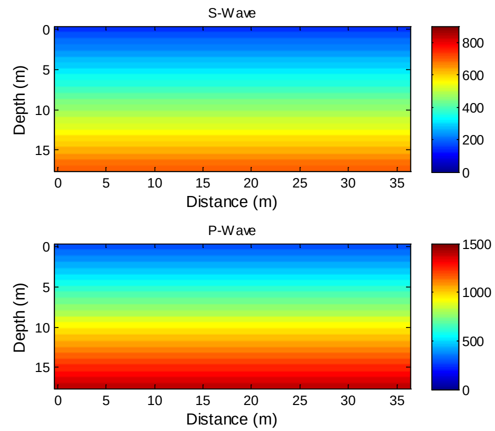
➢ Test configuration

- 24 receivers at 1.5 m spacing
- 25 shots at 1.5 m spacing

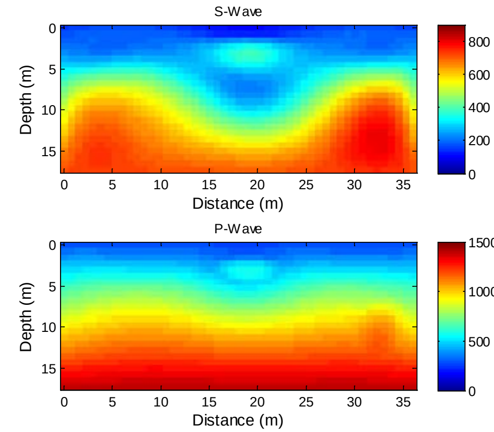
Embedded void



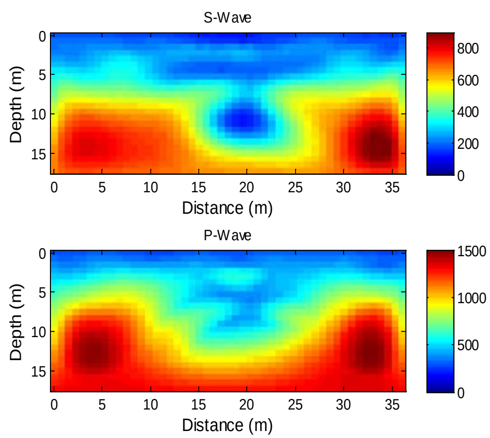
True model



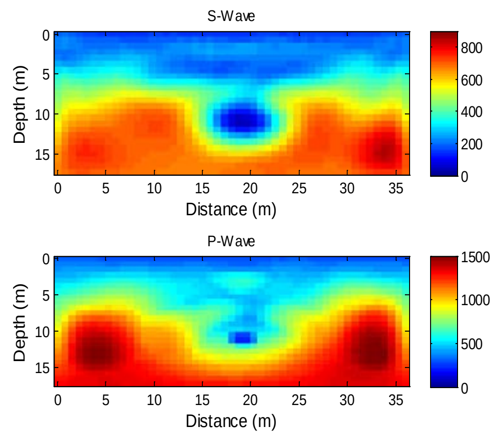
Initial model



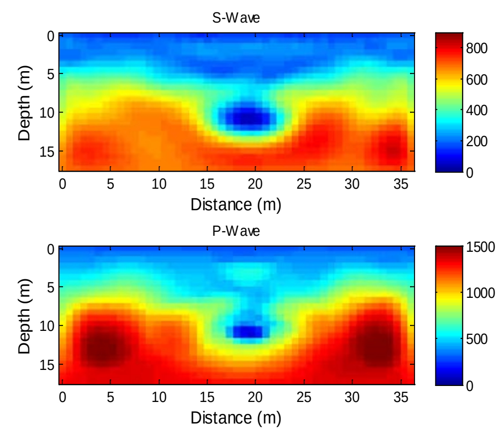
5 Hz



10 Hz



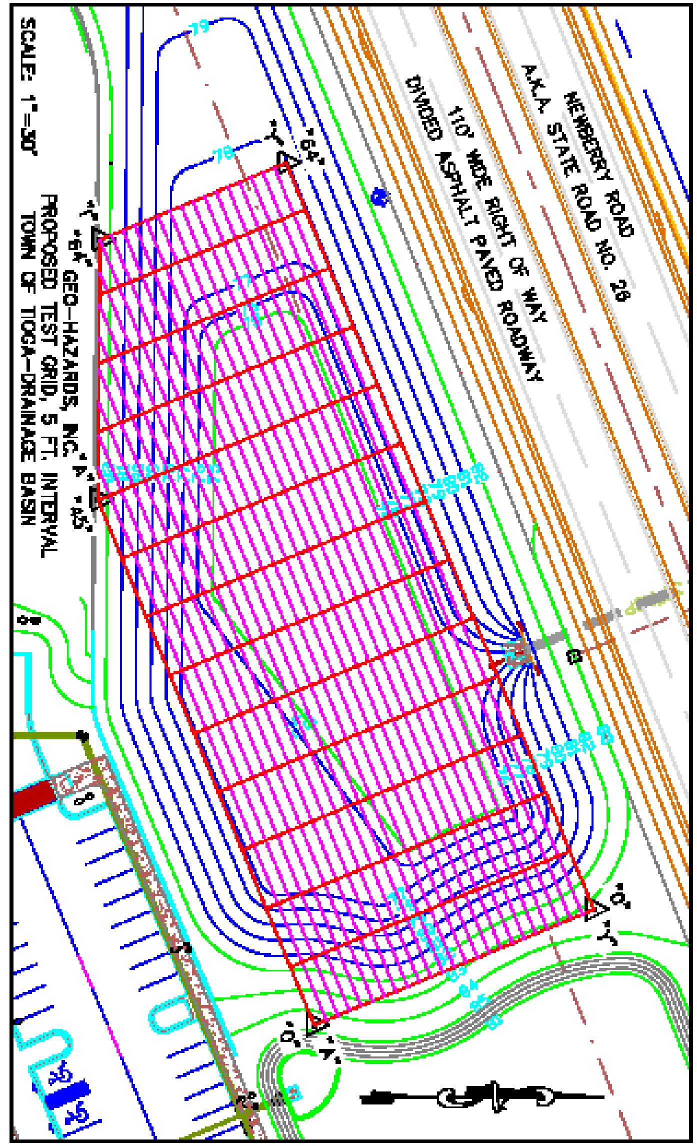
15 Hz



20 Hz

Florida sinkholes

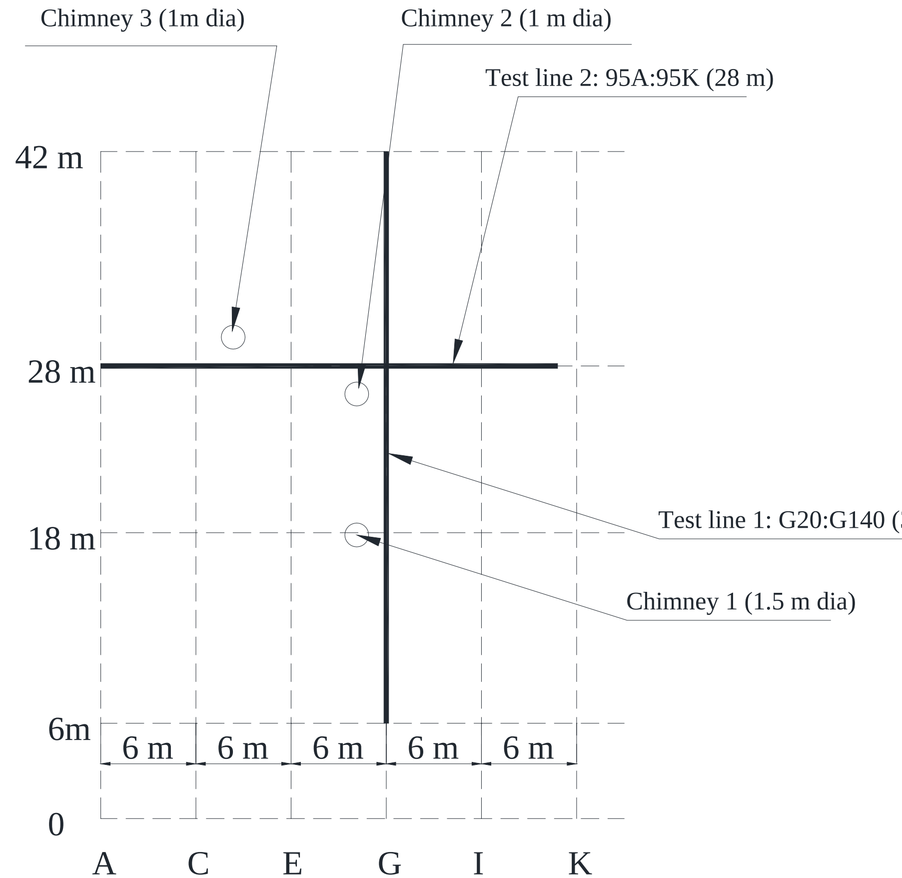
- Dry retention pond in Newberry, Florida
- fine sand and silt of a few meters thick, underlain by highly variable limestone
- top of limestone varies from 2 m to 10 m in depth
- 26 lines (A to Z) at 3 m spacing, 200 m long each line
- open chimneys in the southern portion
- flat open area in the northern portion with an unknown void



Southern portion

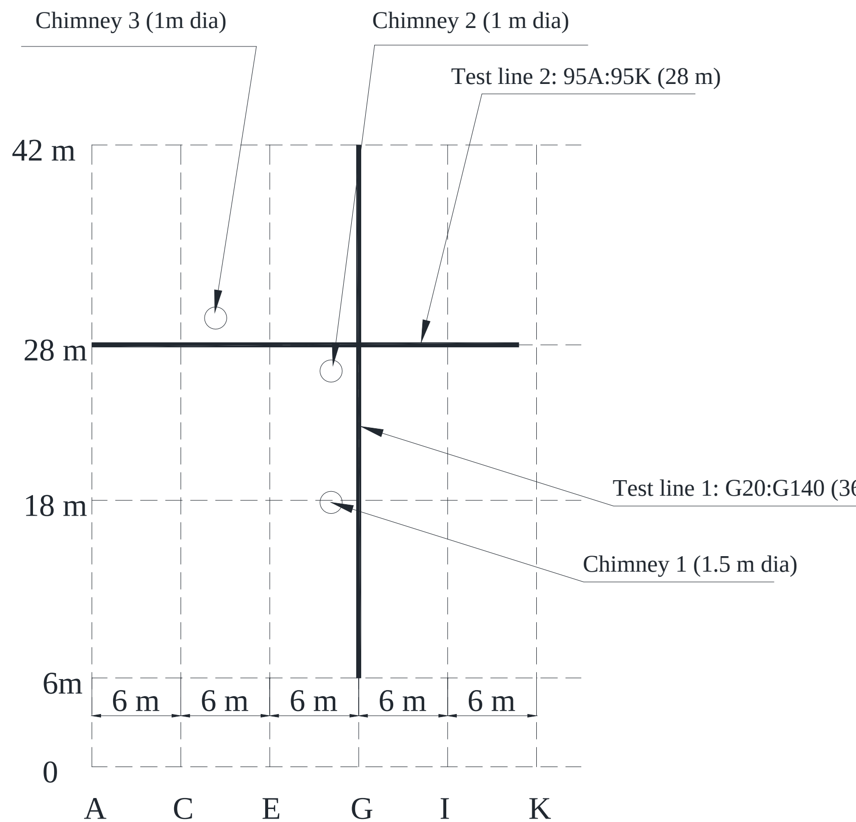
- ➢ Test configuration
- 2 test lines next to next to open chimneys
- 24 geophones, 25 shots

Chimney 1

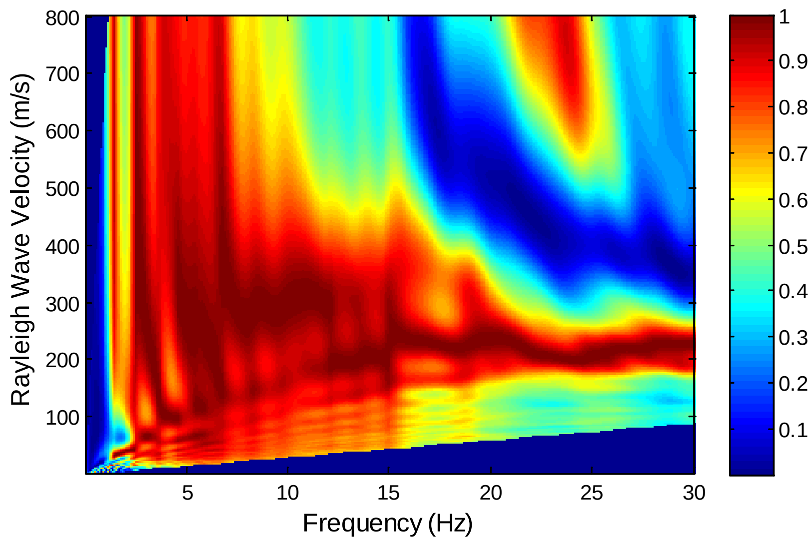


Chimney 2

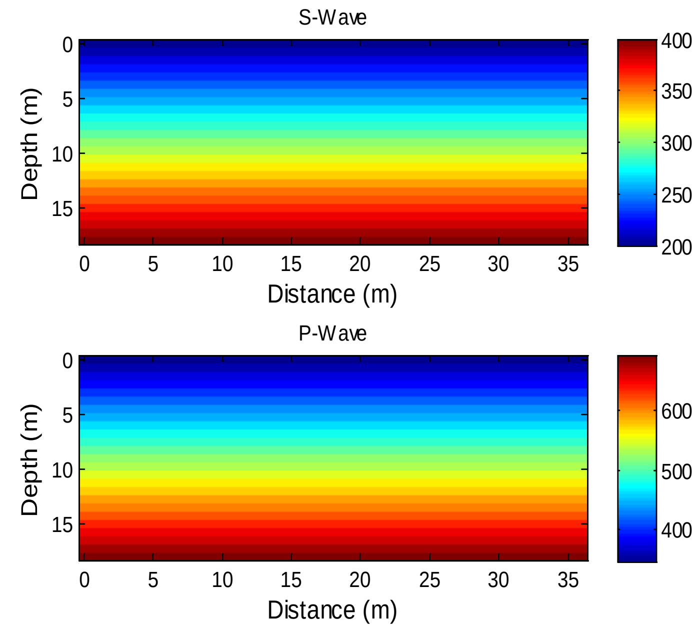
Chimney 3



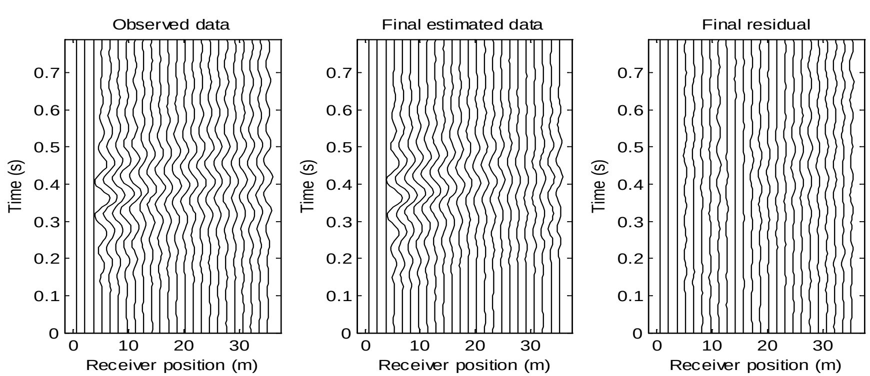
Data Analysis



- Power spectrum



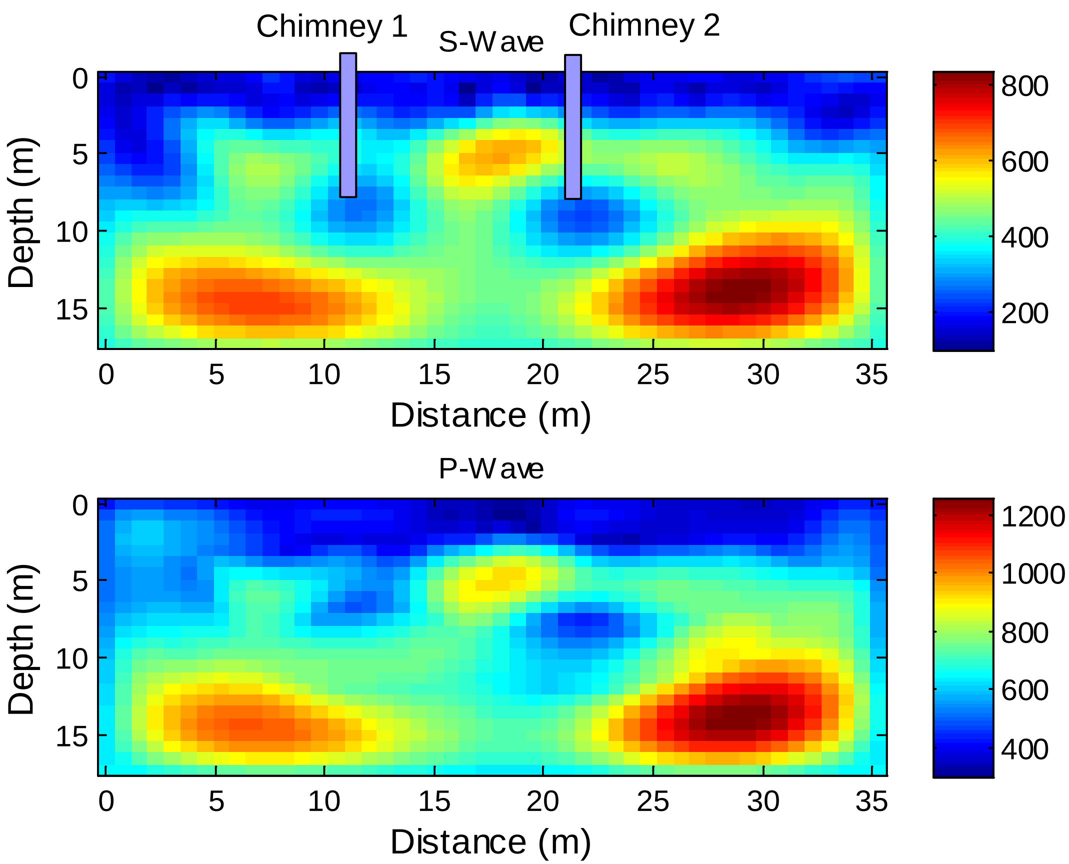
- Initial model



- Data comparison

Results

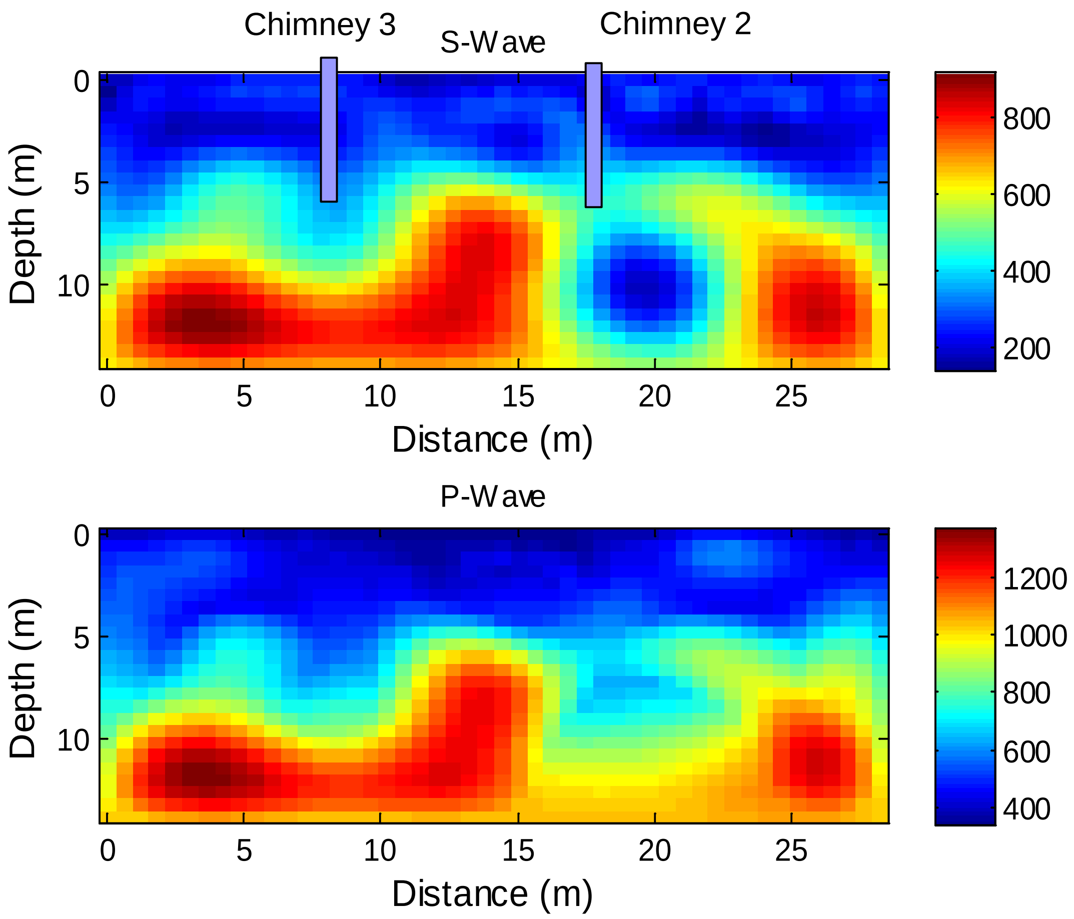
- ➢ Result of Line 1
- 2 anomalies near chimneys 1 and 2 at locations 12 m and 21 m



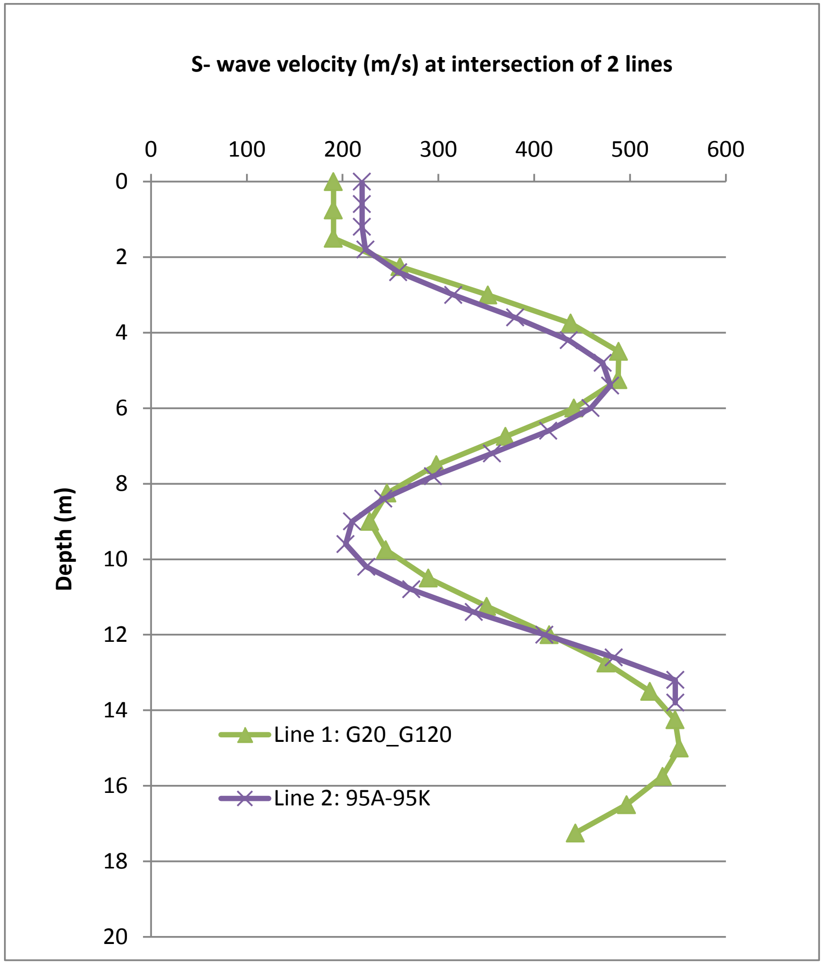
Results

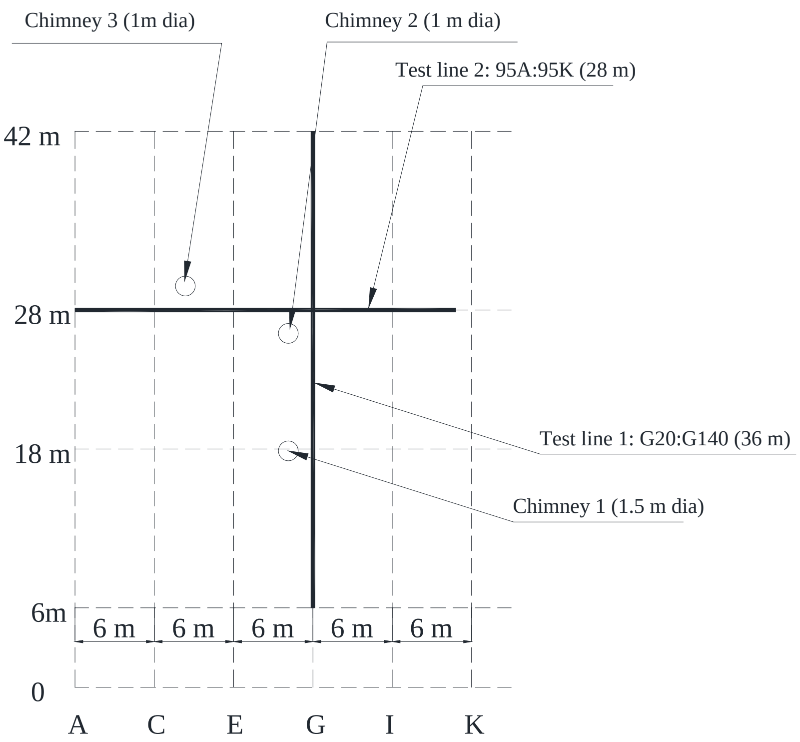
➢ Result of Line 2

- Low-velocity soil near chimney 3 at location of 8 m
- Anomaly near the chimney 2 at location of 17 m



Results



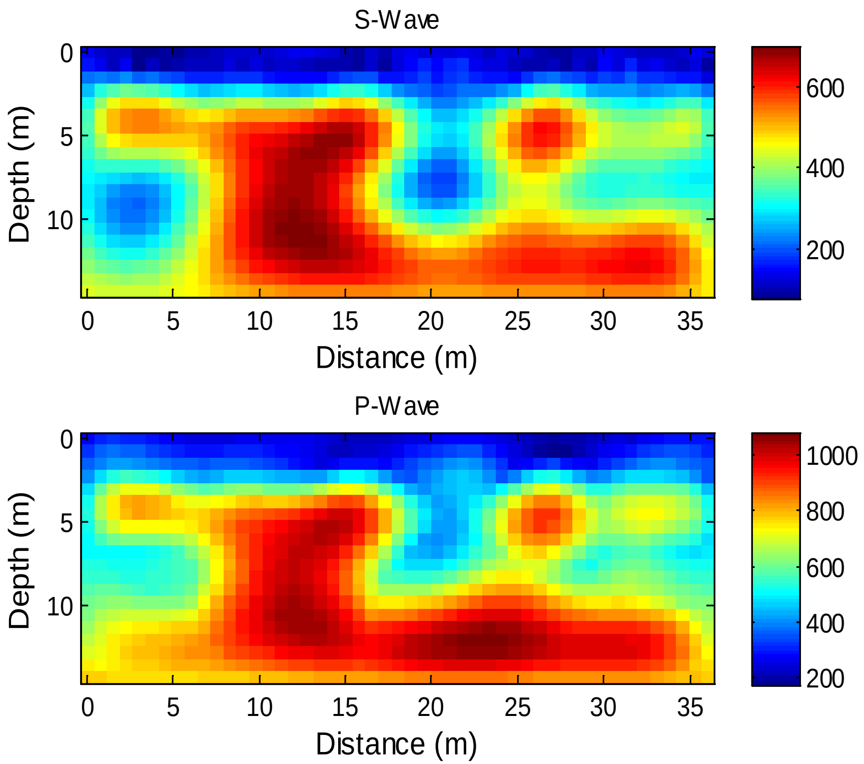


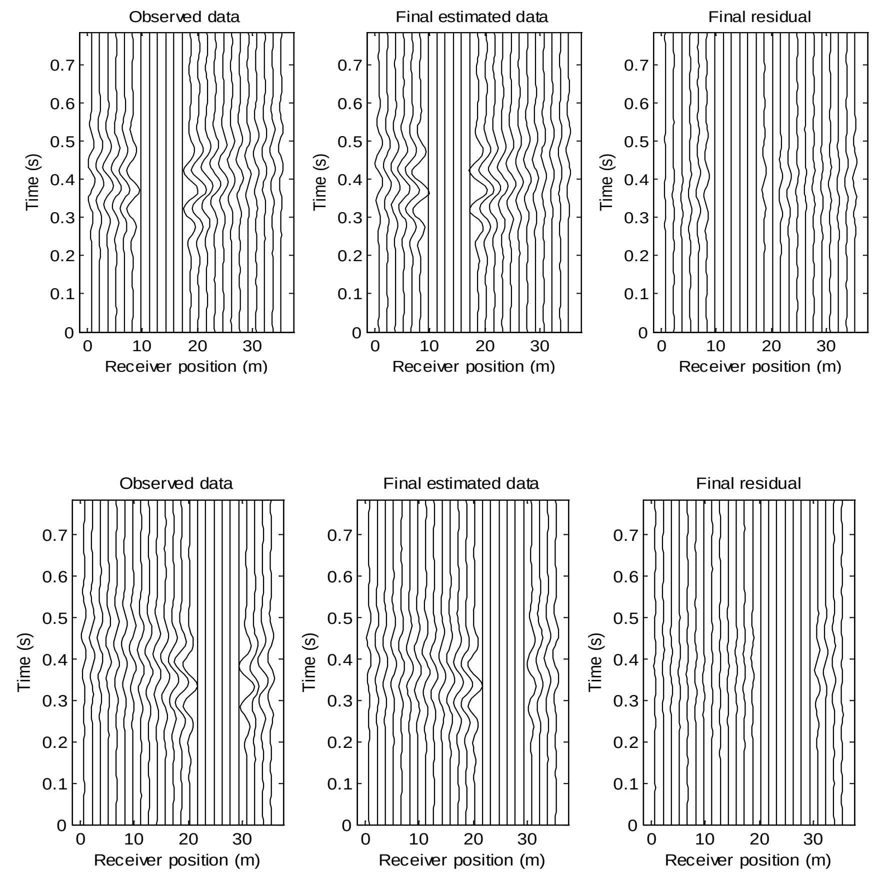
- Comparison of inverted S-wave velocity profiles at the intersection of 2 lines (22 m of line 1 and 18 m of line 2)

Northern portion

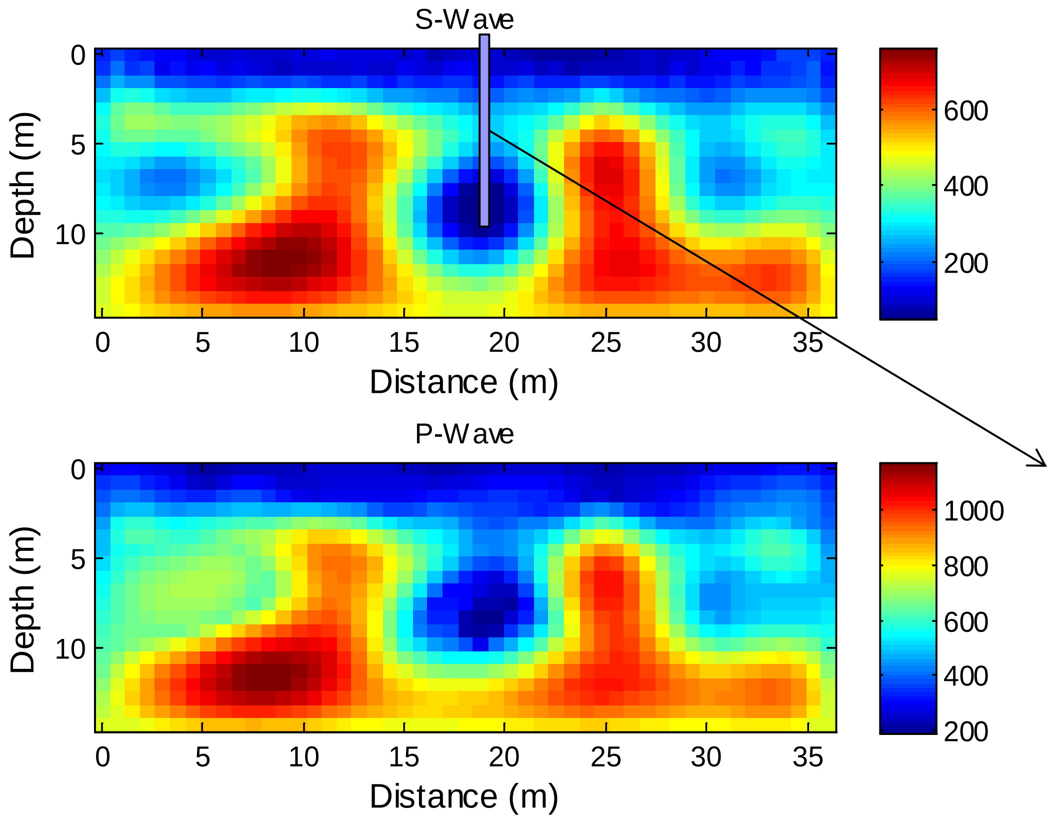
- Test configuration
- No indication of voids on the ground surface
- 10 testing lines at 3 m spacing (line K, L, M, N, O, P, Q, R, S, and T)
- each line 36 m long
- 24 geophones at 1.5 m spacing
- 25 shots at 1.5 m spacing

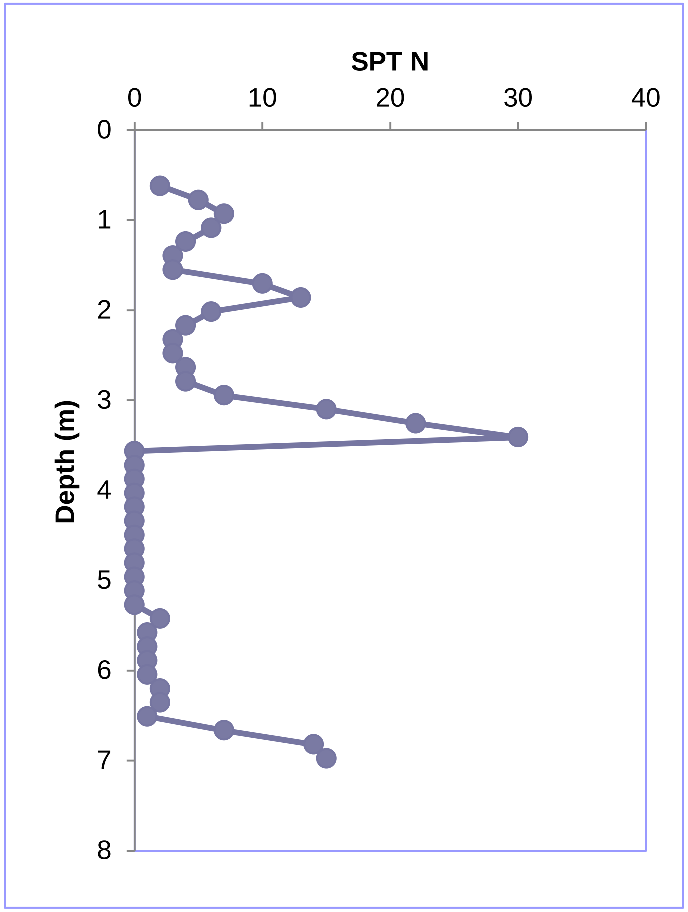
Results of line P





Results of line Q



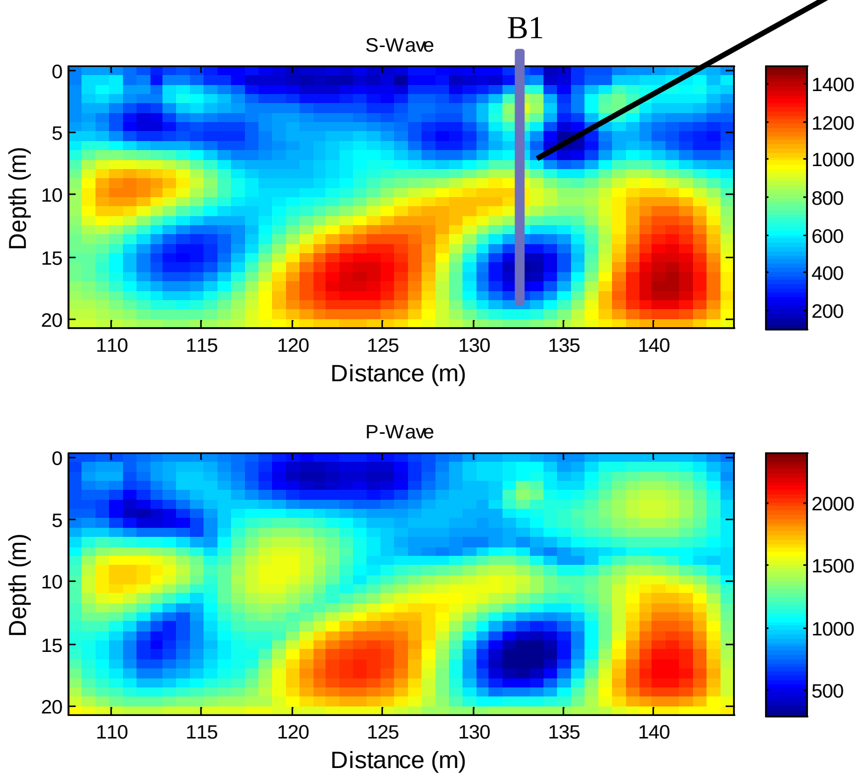


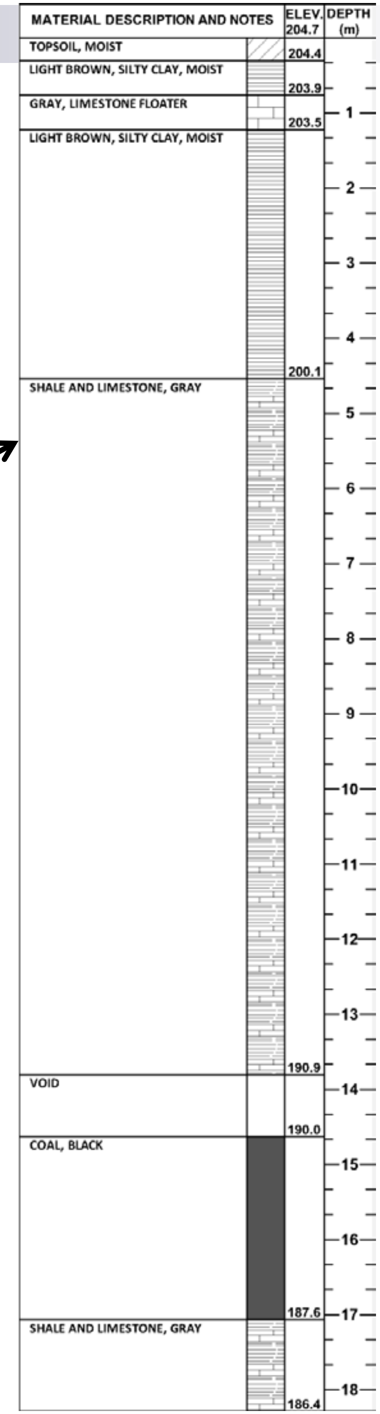
Ohio abandoned mine void

- Data collected on the shoulder of US33, Athens, Ohio
- 16 test segments at 36m/segment
- Land-streamer system of 24 geophones at 1.5m spacing
- 25 shots at 1.5m spacing
- 15 lb sledgehammer

Segment 4

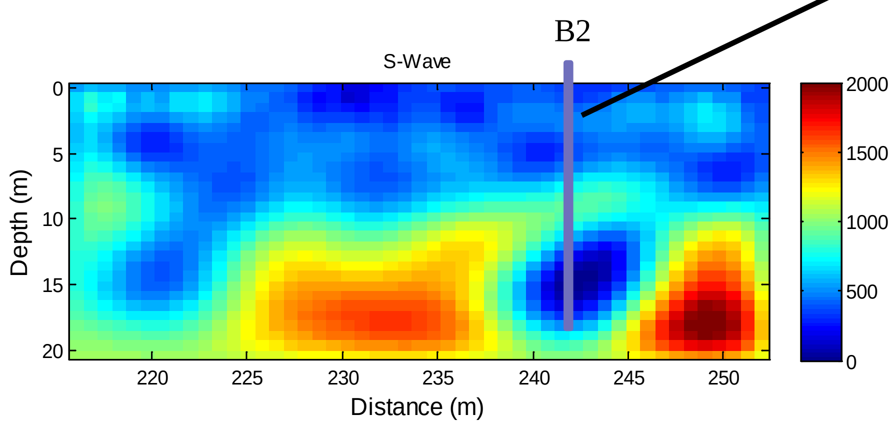
- 108 to 144 m
- Void located at 15 m in depth

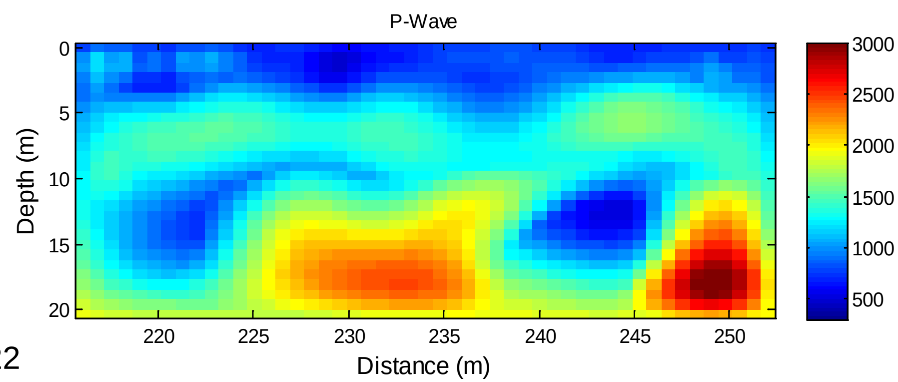


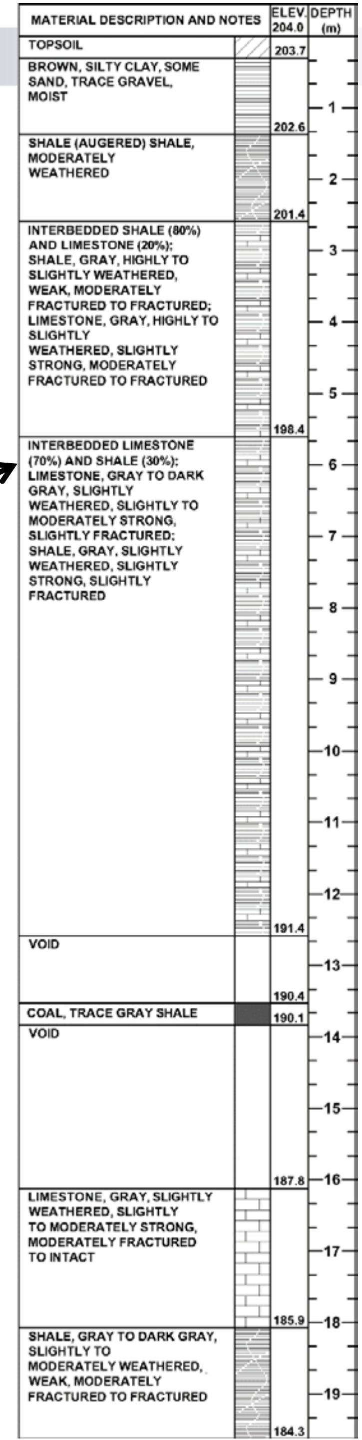


Segment 7

- 216 to 252 m
- Void located at 15m in depth







Conclusion

Advantage

- S-wave and P-wave velocities are determined independently to increase the credibility of characterized profiles
- Embedded low-velocity anomalies/voids are characterized without prior information of subsurface conditions
- Relatively easy implementation (no manual picking of travel times)

Limitation

- Test lines need to be on top of voids
- Offline voids may be seen due to 3-D effects

References

- Tran K.T., McVay M., Horhota D., Faraone M., and Sullivan B.W. (2014), “Seismic Waveform Tomography at a Site with Open Chimneys”, *Journal of Transportation Research Board*, Vol. 2433, pp 10-17

- Tran K.T., McVay M., Faraone M., and Horhota D. (2013) “Sinkhole Detection Using 2-D Full Waveform Tomography”, *Geophysics, Vol. 78 (5), pp. 1-9*

- Tran K.T. and McVay M. (2012). “Site Characterization Using Gauss-Newton Inversion of 2-D Full Seismic Waveform in Time Domain”, *Soil Dynamics and Earthquake Engineering*, Vol. 43, pp. 16-24.

Thank You!

???

Scour Monitoring of the Bonner Bridge, Oregon Inlet, Outer Banks, North Carolina

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State Location & Surveys Engineer

NC Dept. of Transportation

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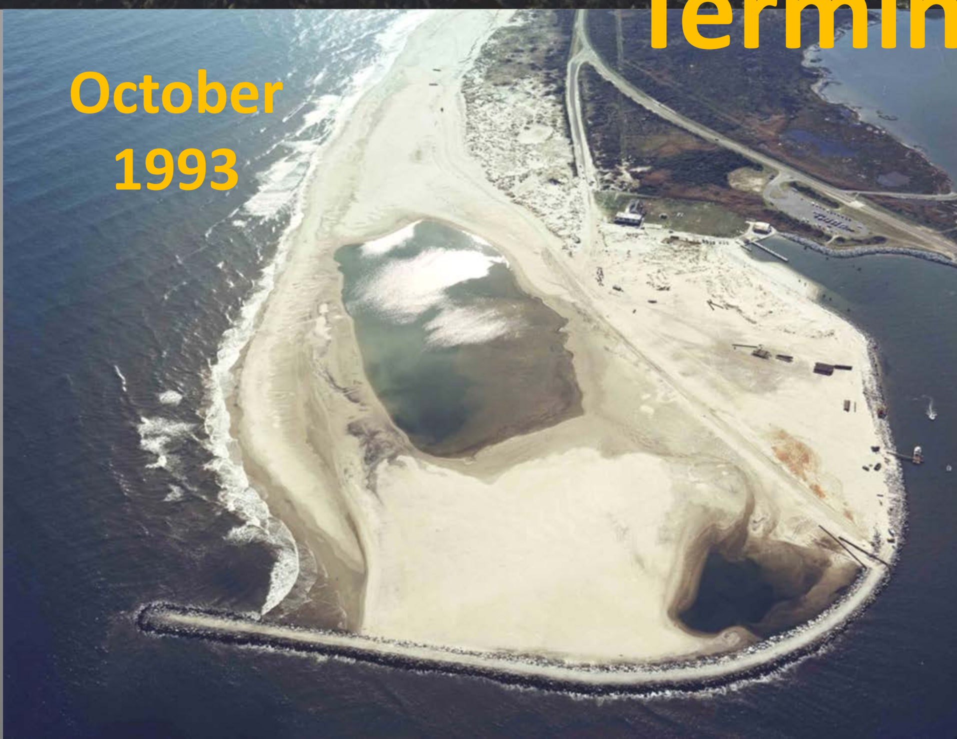
Bonner Bridge, Oregon Inlet, NC

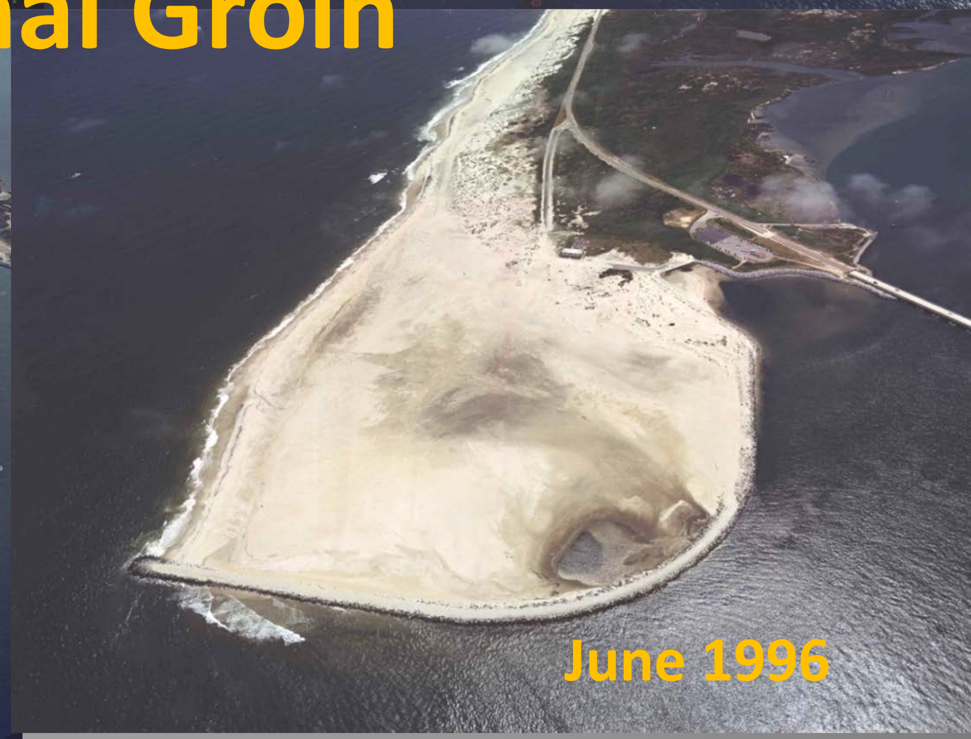
- Opened in 1964
- Total Bridge Length = 12,864.74’
- Post & Beam or Pile Bents

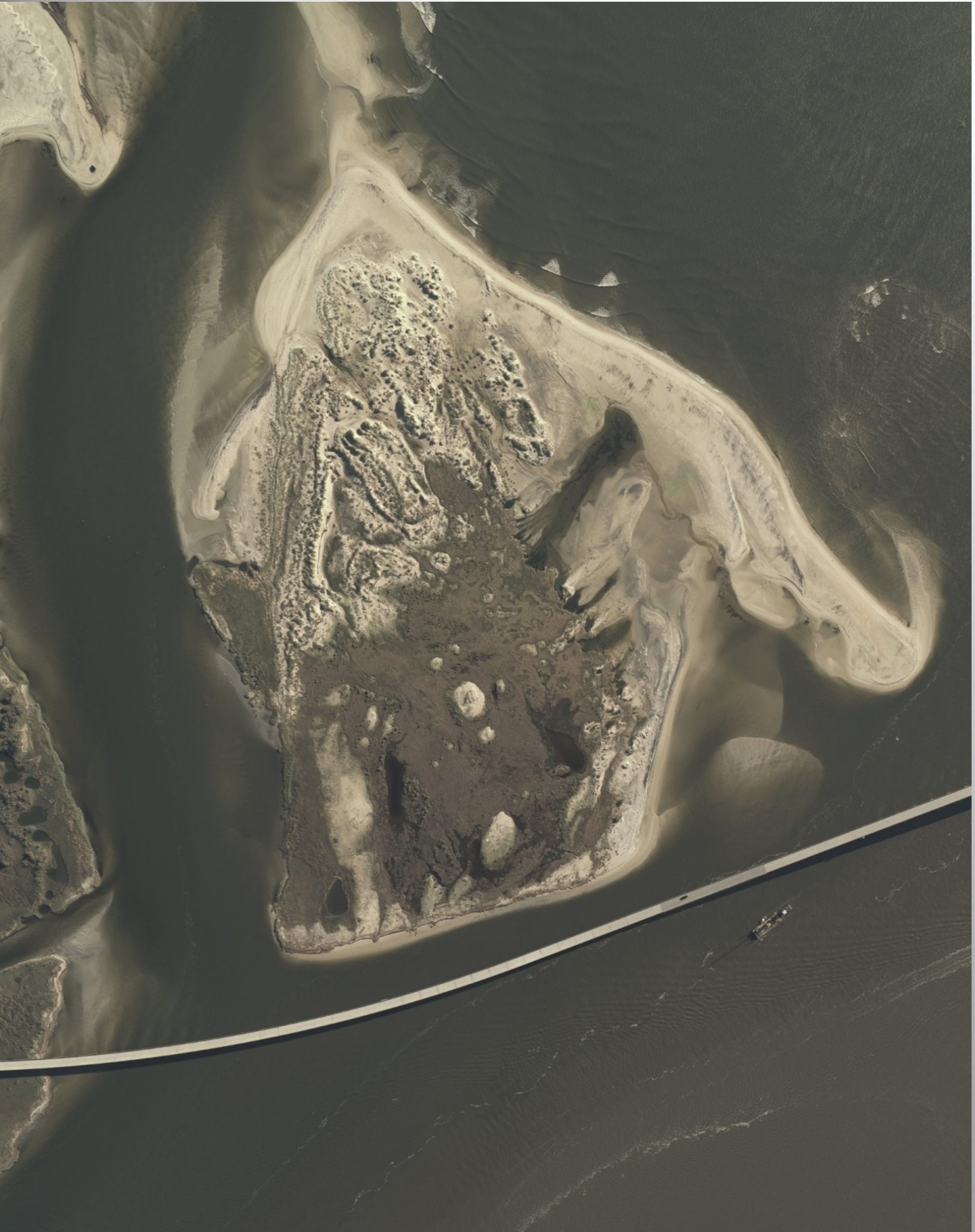
- 204 Spans - 201 @ 61’6”, 2 @ ~ 161’
- First large structure subject to direct ocean tidal currents

Beach Erosion to late 1980's

Terminal Groin







2011 - Hurricane Irene cuts 2nd channel at Oregon Inlet

Oregon Inlet
Spring 2015

Severe Beach Erosion – Severe Scour?

Monitoring by divers:

- Random
- Erratic
- Spot Visual Inspections
- Limited access due to Strong Currents

Scour Repairs

Bent 173-186 20” prestressed piles added in 1979

Bent 167-200 66” diameter cylinder piles added in 1981

Bent 108-123 Crutch bents installed in 1989-1991

Bent 159 pile footing reinforced in 2012

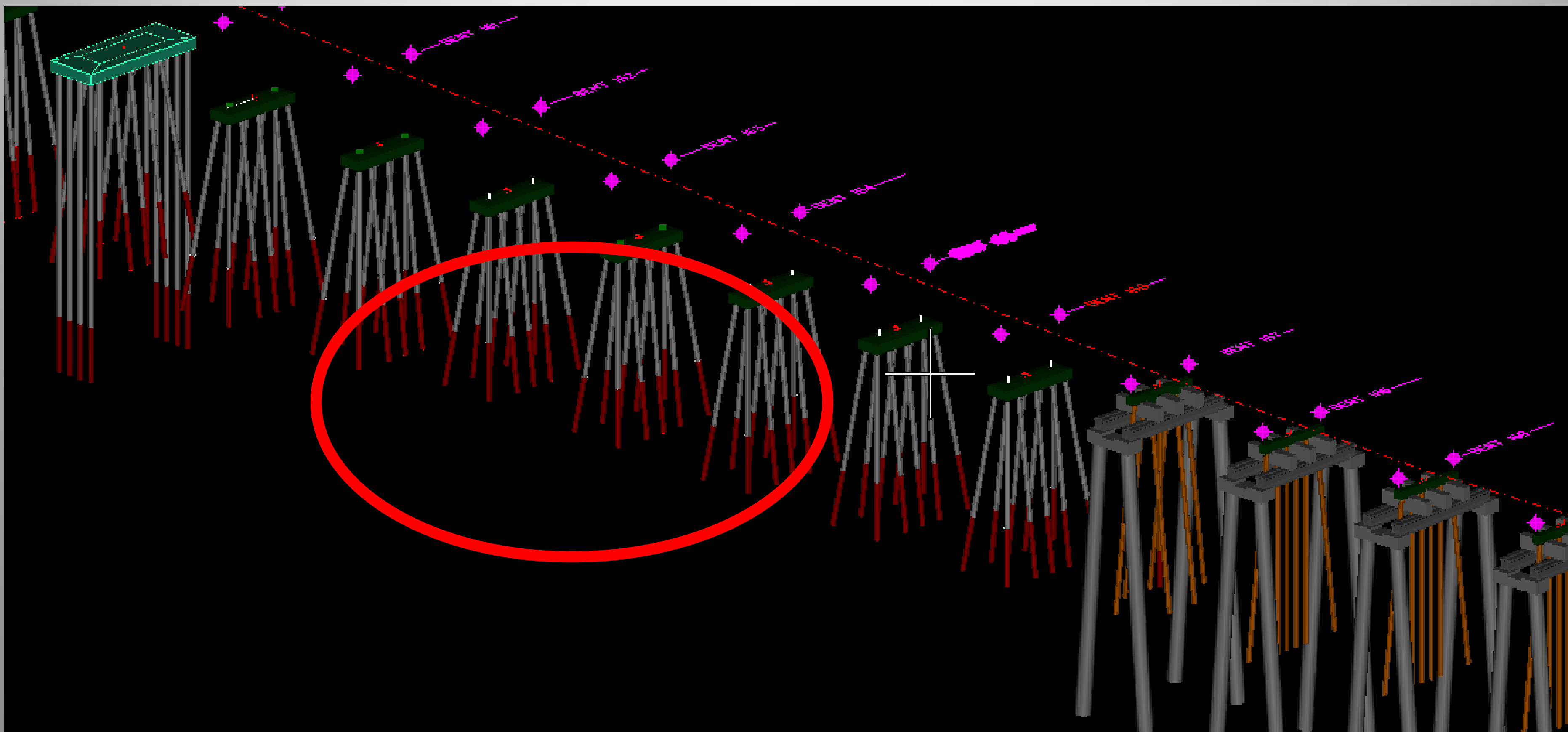
Crutch bents rehabbed in 2013-2015

Side Scan Sonar

2012 – NCDOT Purchased Side Scan Sonar for monitoring the Inlet floor along the bridge

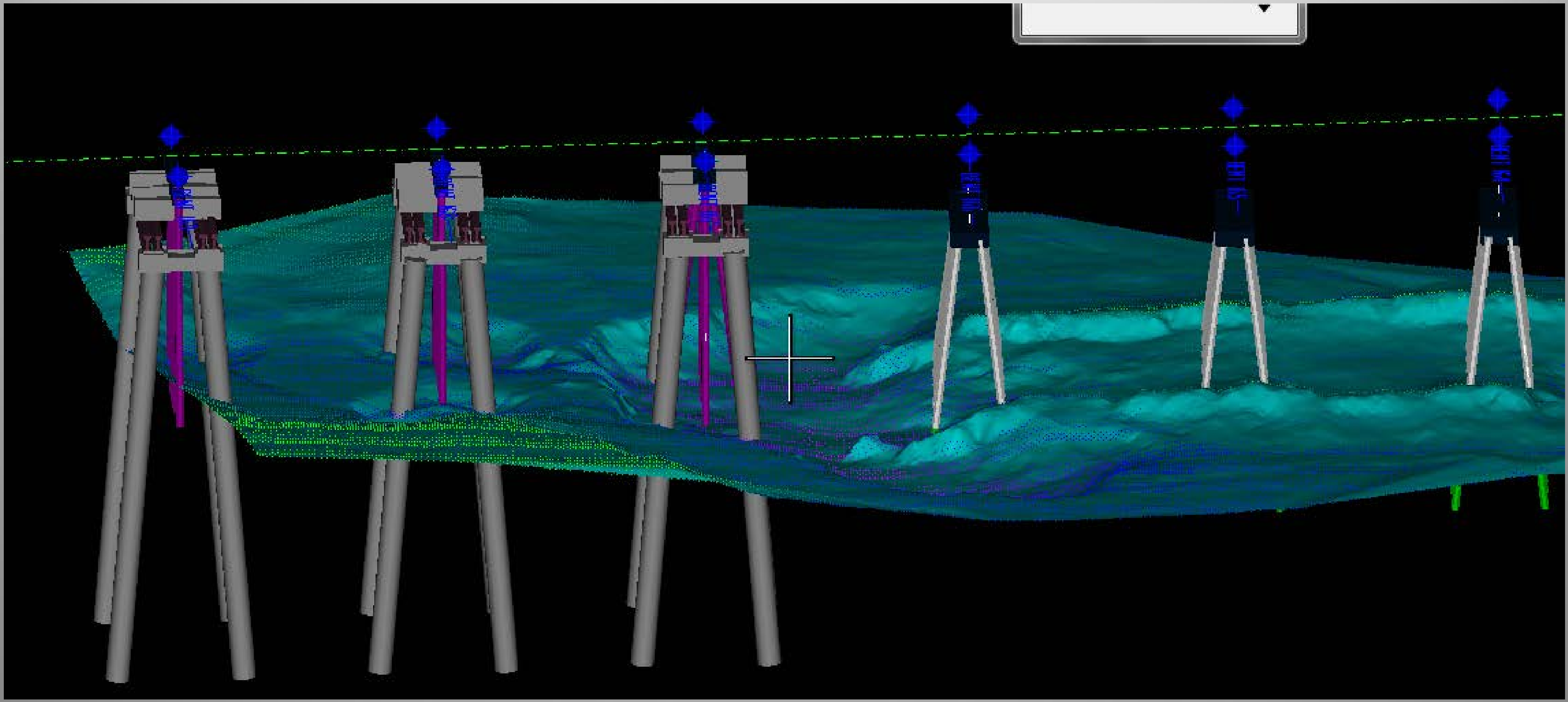
Side Scan Sonar

Bridge Model

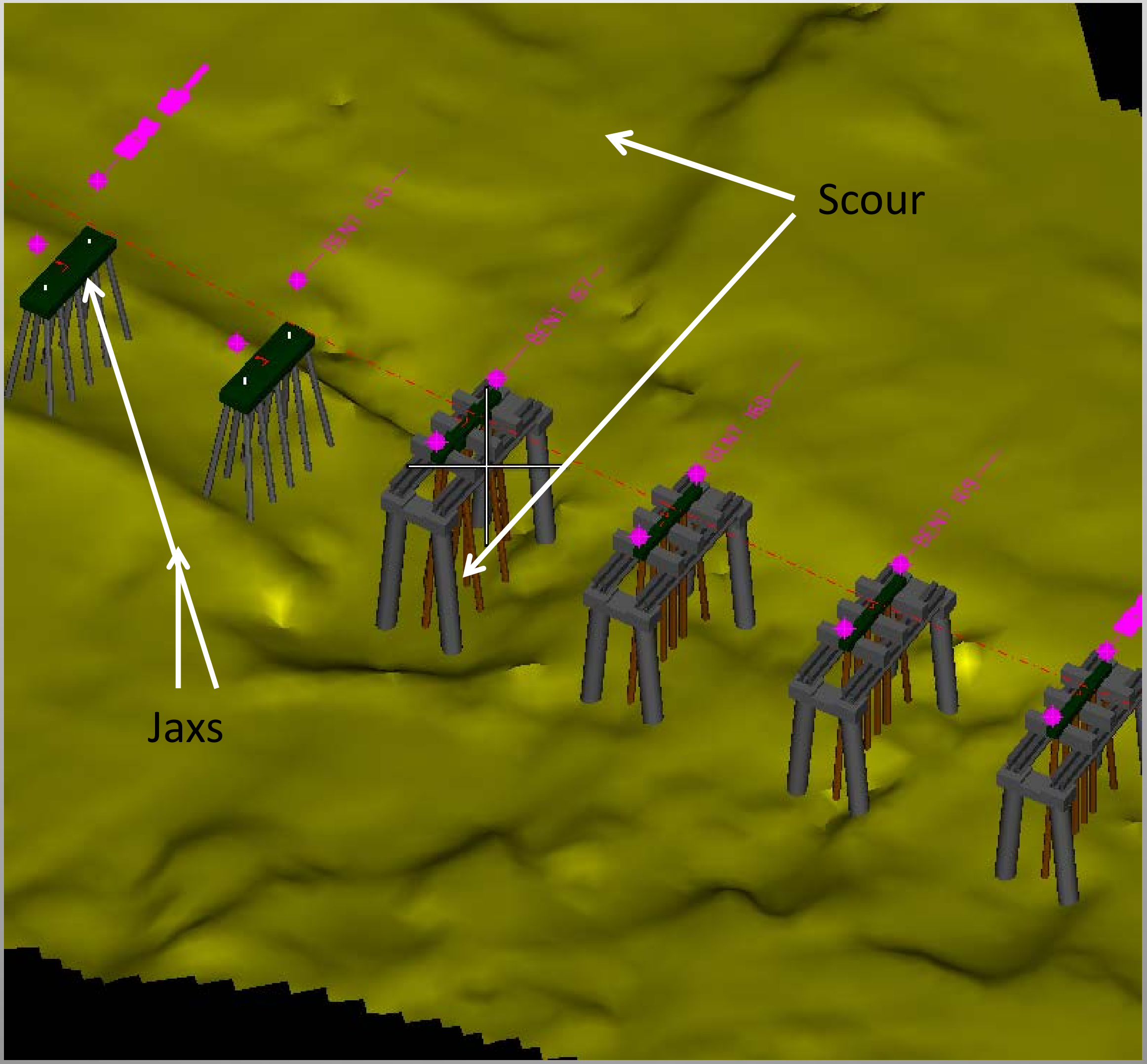


Red indicates Critical Scour Level
(~20’ above pile tip)

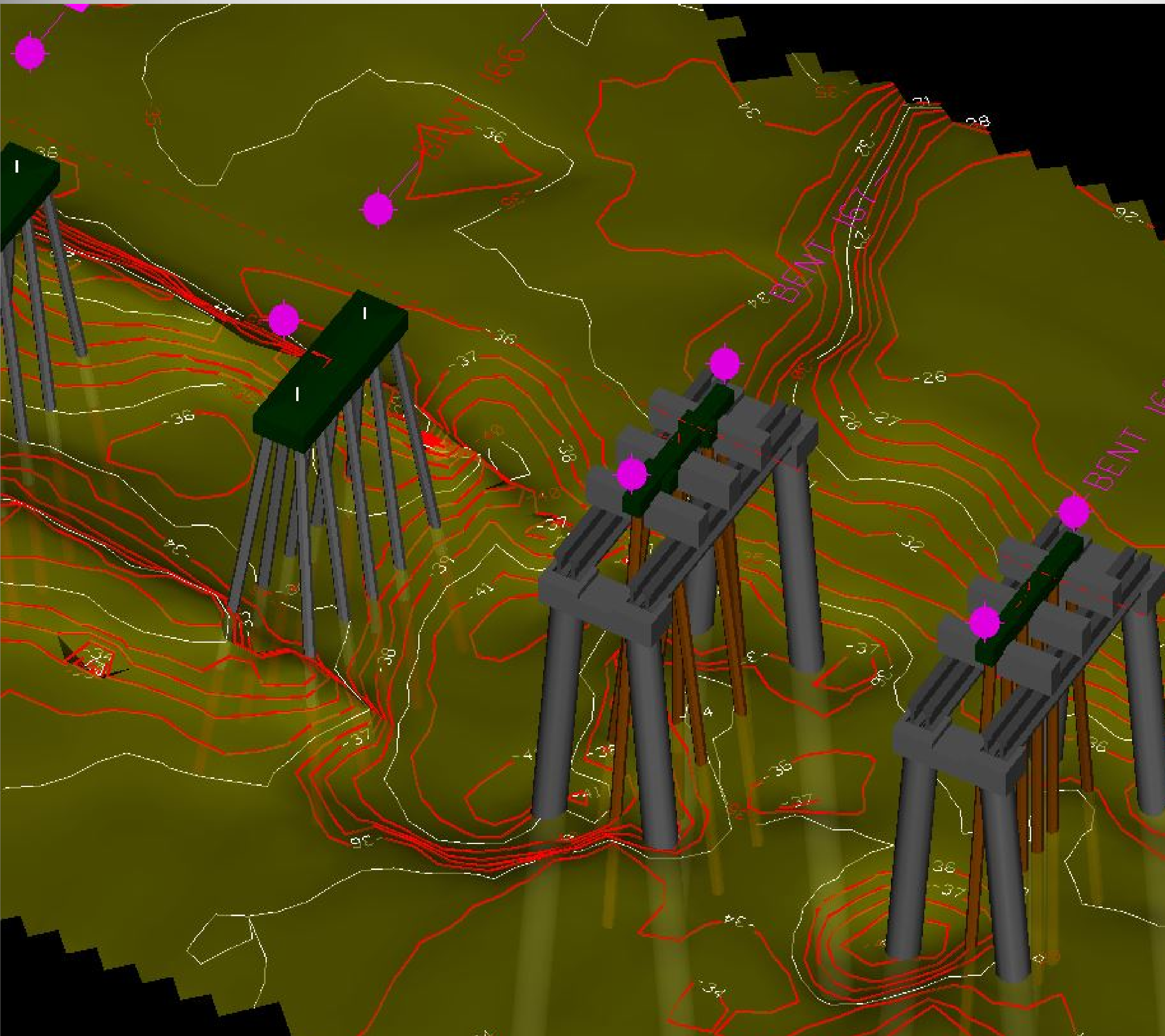
Bonner Bridge Mission



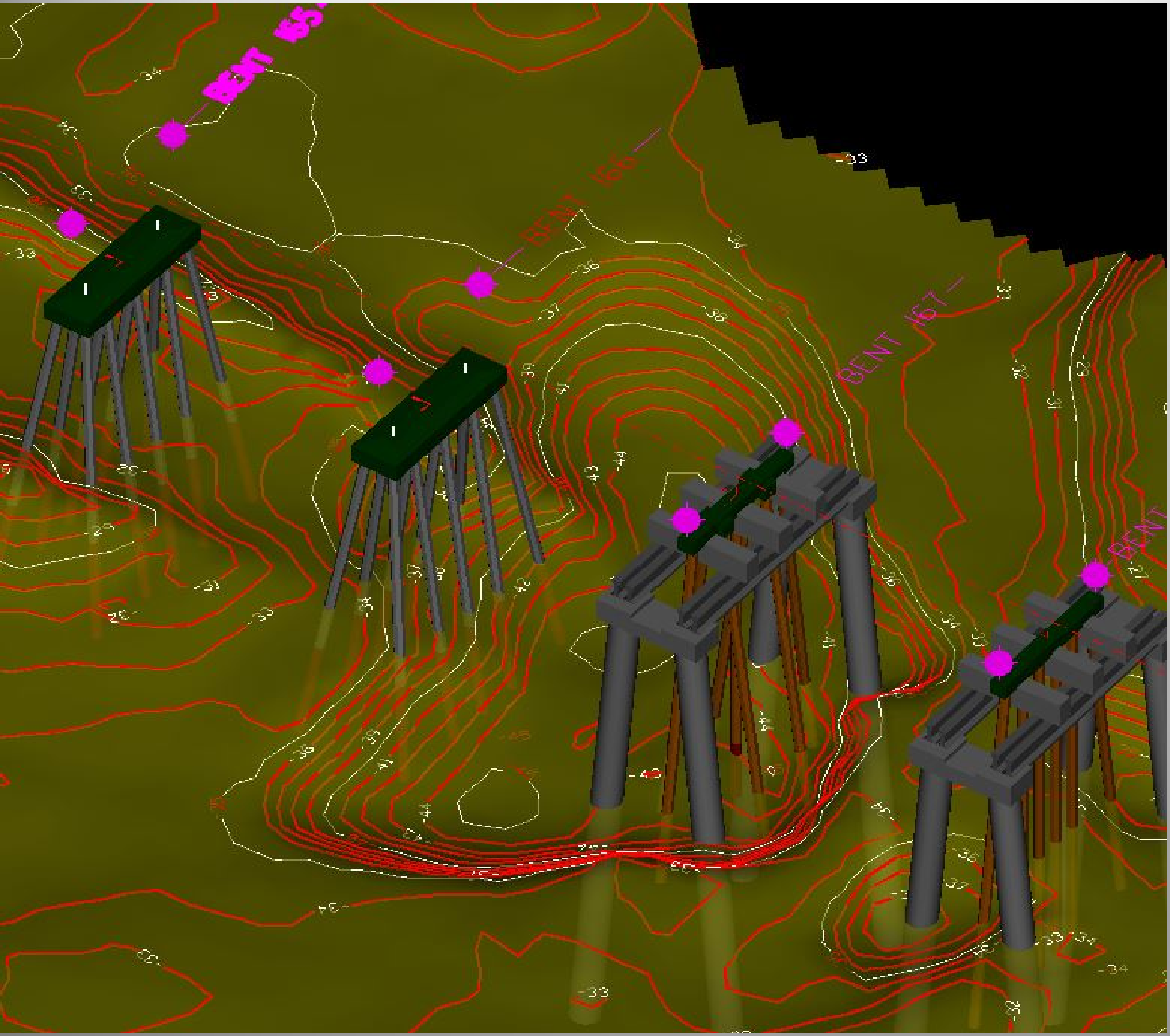
Bent 167



12/05/12

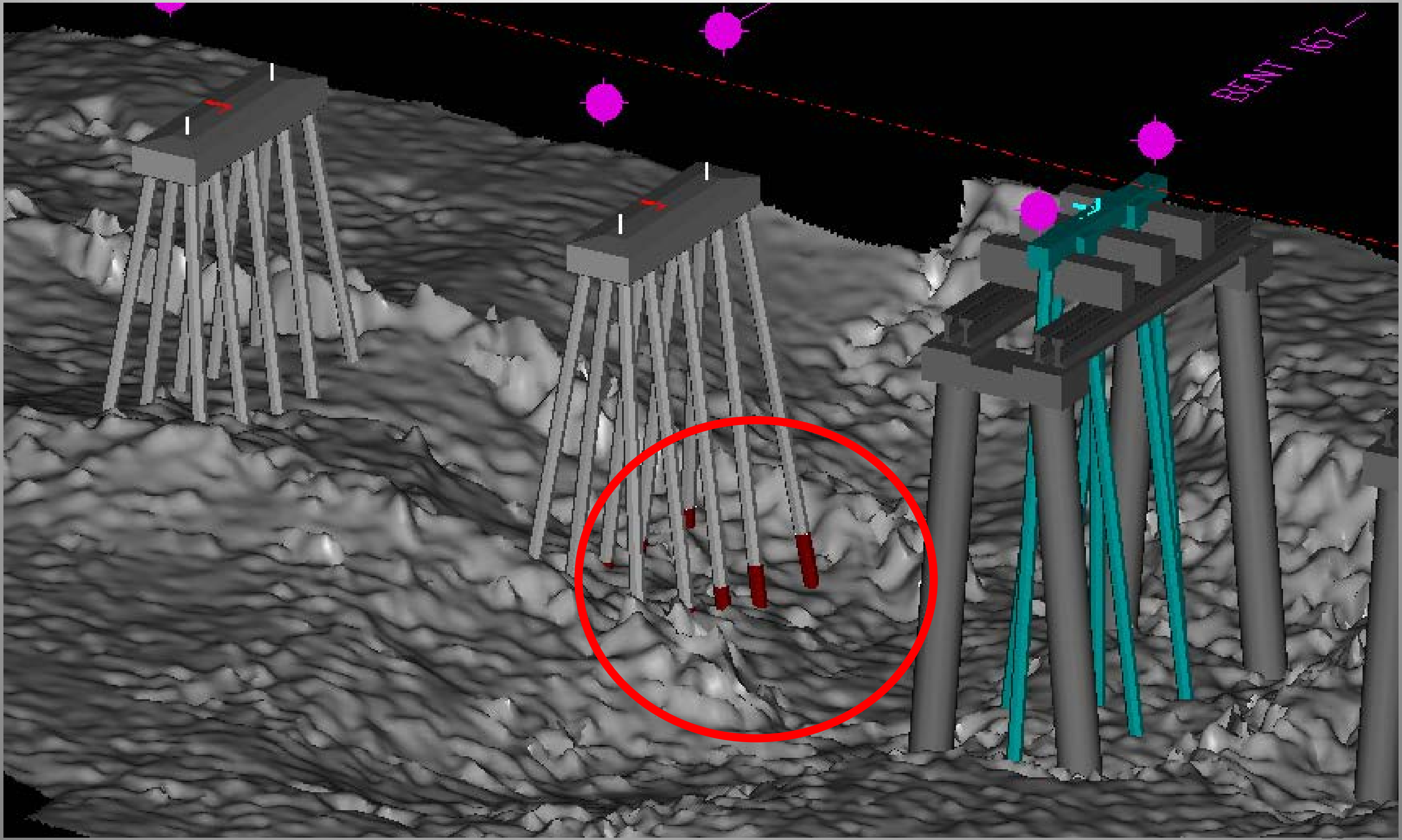


04/11/13

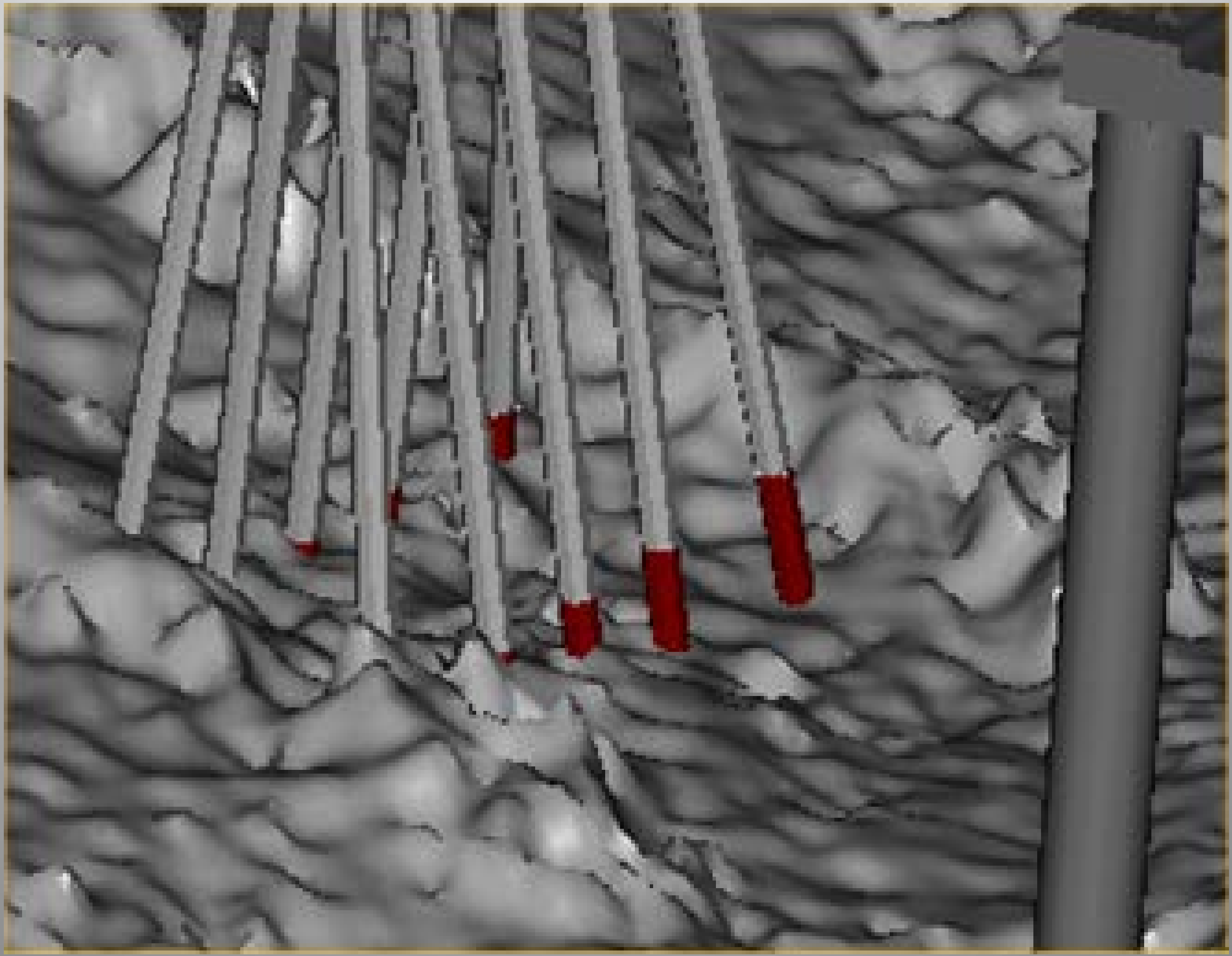


08/22/13

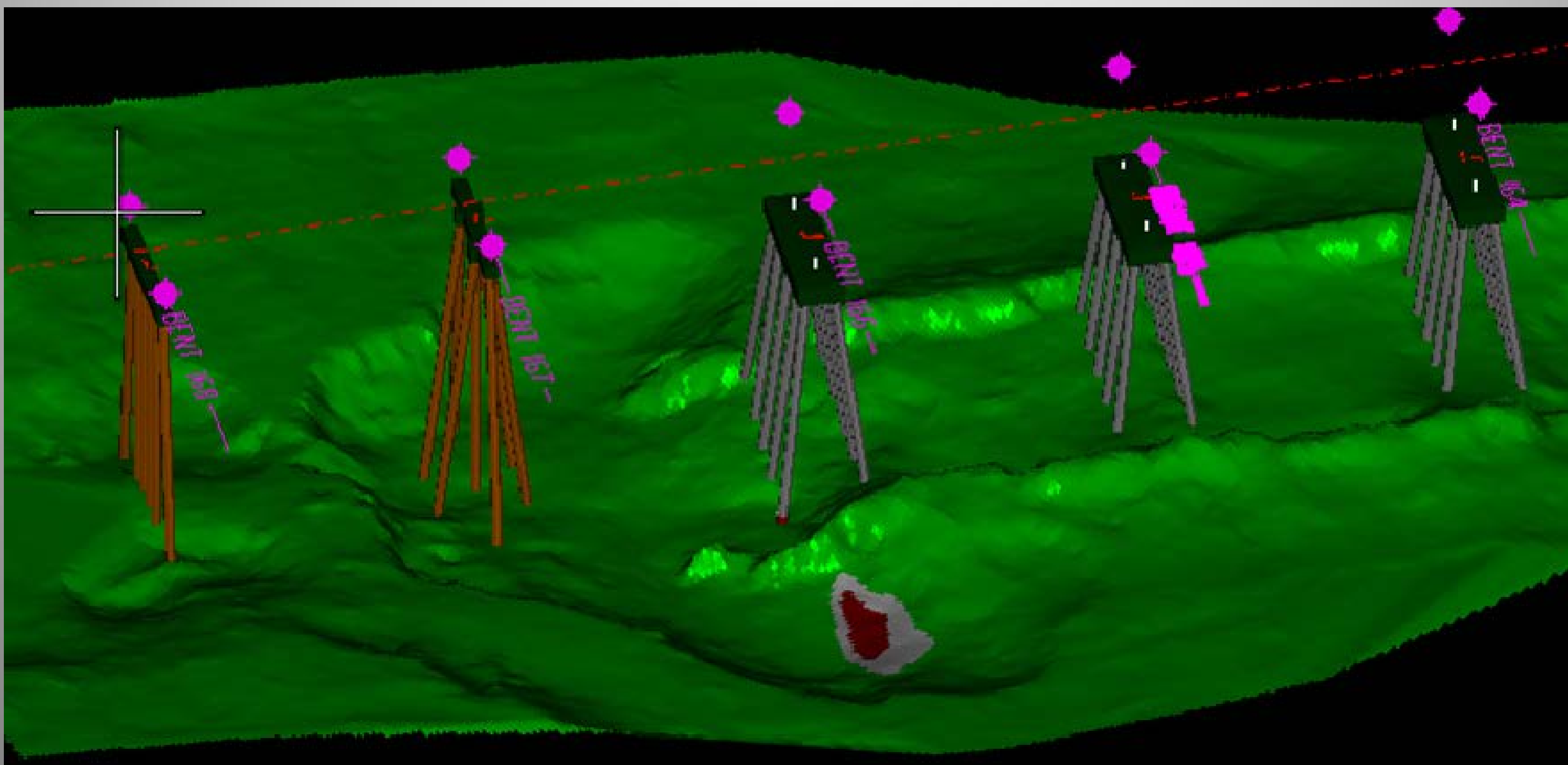
12/03/13, Following Thanksgiving Nor'Easter



12/03/13, Following Thanksgiving Nor'Easter



Bent 167



12/09/13, Following Dredging Operation

Lessons Learned

Sonar – Positives

- Very Accurate Information (0.5’)
- Complete picture of scour along area of concern
- Either entire bridge or specific areas

Sonar Negatives

- Repetitive trips
- Time to collect and process data - 8 -12 hours
- Weather dependent (cannot operate in high waves or in winds over 20 knots (Coast Guard small craft warning)

Questions

What happens when we start getting close to critical scour?

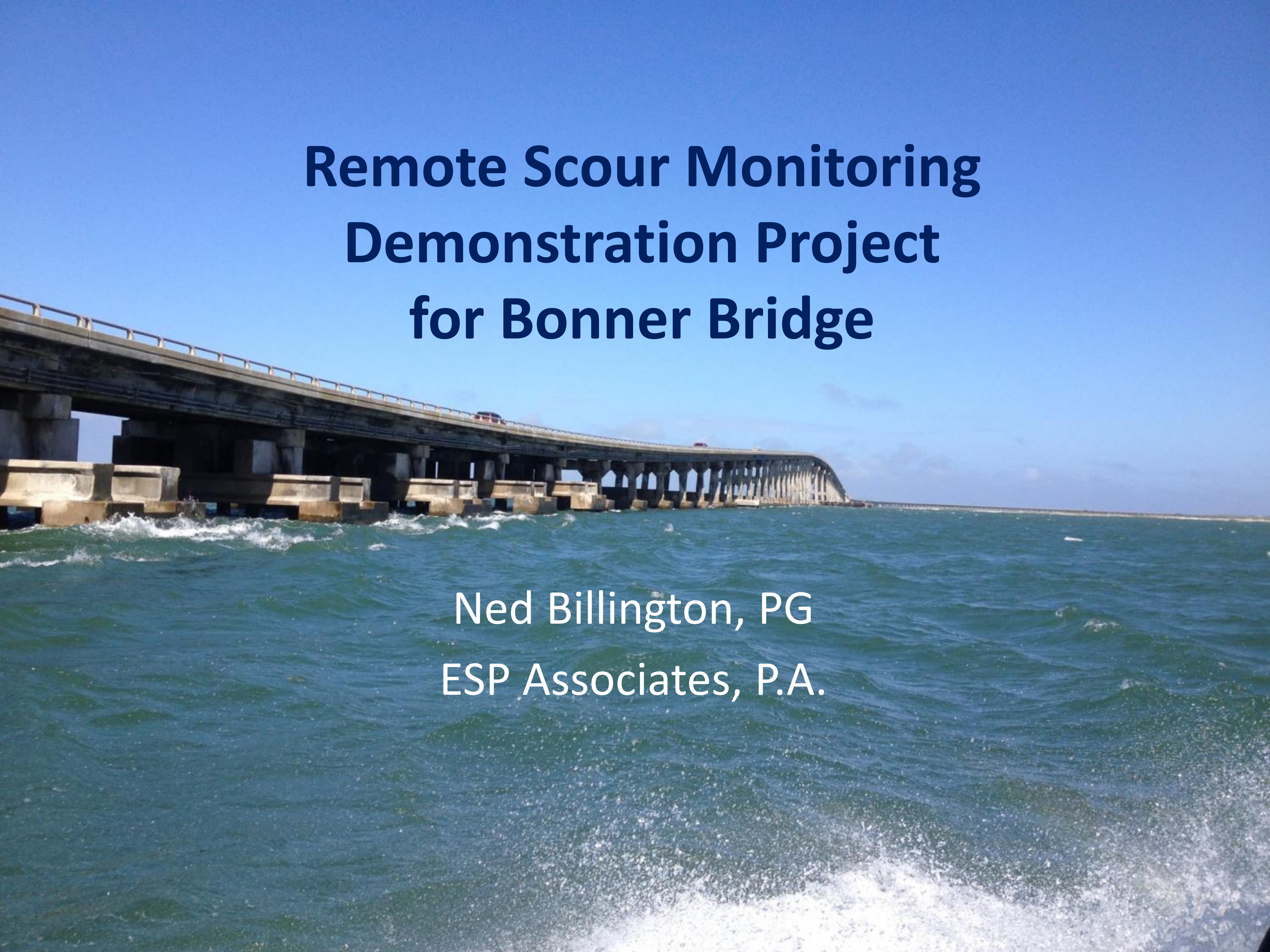
Can we monitor a specific area on shorter intervals

- **24 hours?**
- **12 hours**
- **1 hour?**

Can we determine the point of reaching critical scour and notify involved staff? (Alarm)

Remote Scour Monitoring Demonstration Project for Bonner Bridge

Ned Billington, PG
ESP Associates, P.A.



Project Goals

- To provide a remote scour monitoring system for a selected bent.
- Data to be displayed in real-time via a web site
- Considerations include cost and logistics for purchase, installation, removal, and re-installation.

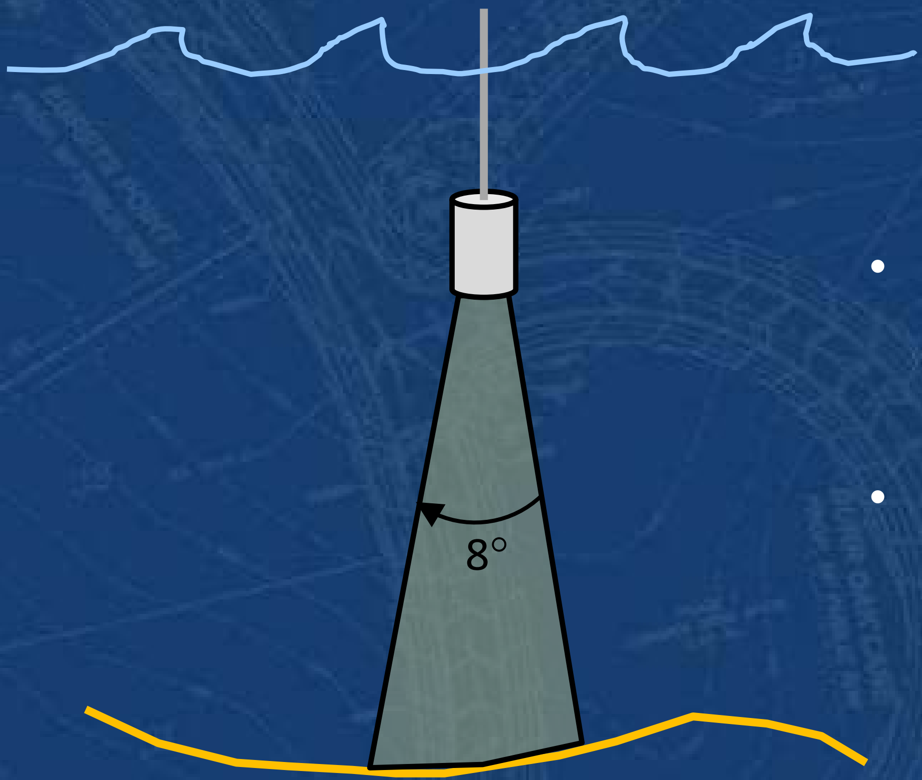
Selected System, ETI AS-3

- Master Controller
  - Data Collector, Cellular Modem, Radio, Solar Panel & Battery
  - Can handle multiple remotes
- Remote Controller
  - Four Transducers
  - Data Collector, Radio, Solar Panel & Battery
- Data Collection Software & Web Site

ETI Smart Sonar Transducer

- 235 KHz frequency
- 2 – 300 feet depth range
- Imbedded signal processing
- 8 degree beam width

Transducer Beam Width



- In 44 feet water depth, beam has footprint that is about 6 feet diameter (19 sq. ft. image area).
- Portion of reflected beam with shortest travel time will be the recorded depth.

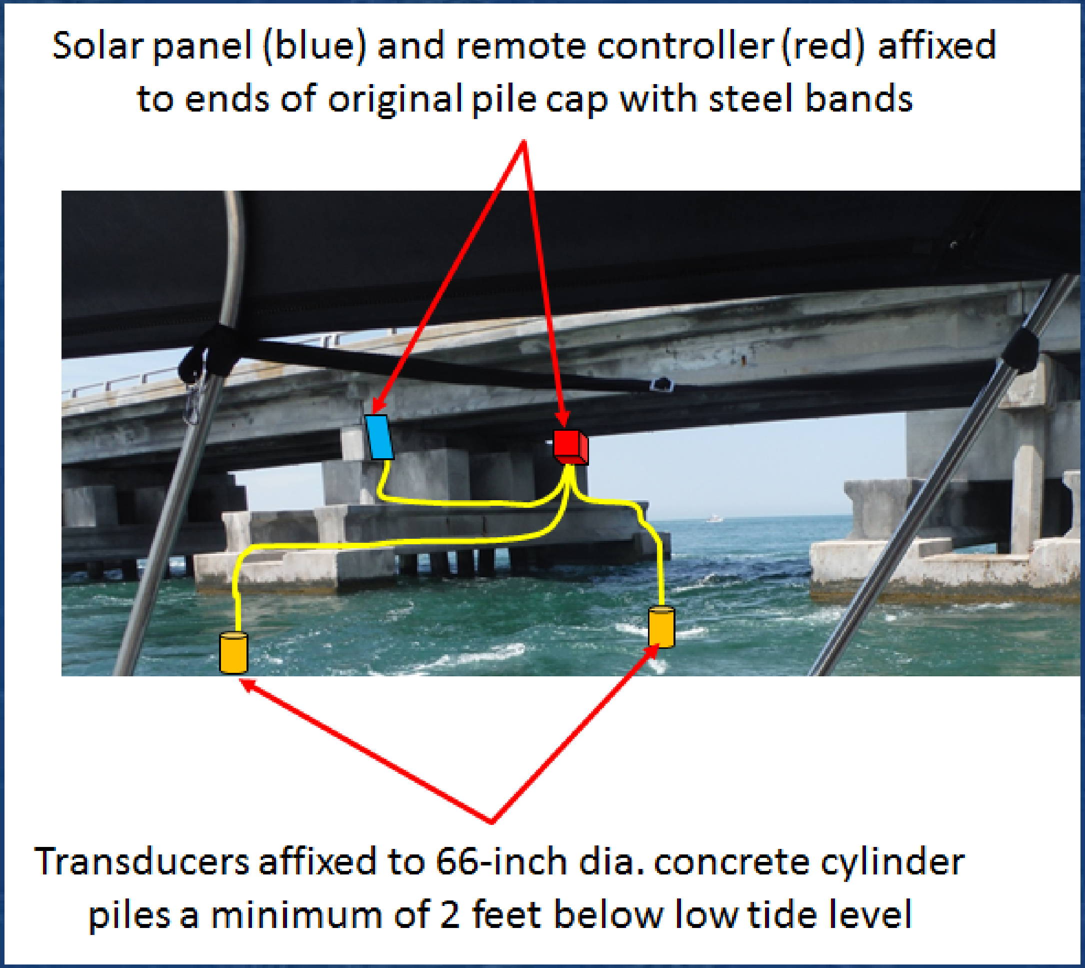
Master and Remote Locations

Master Controller Installation

Master Controller

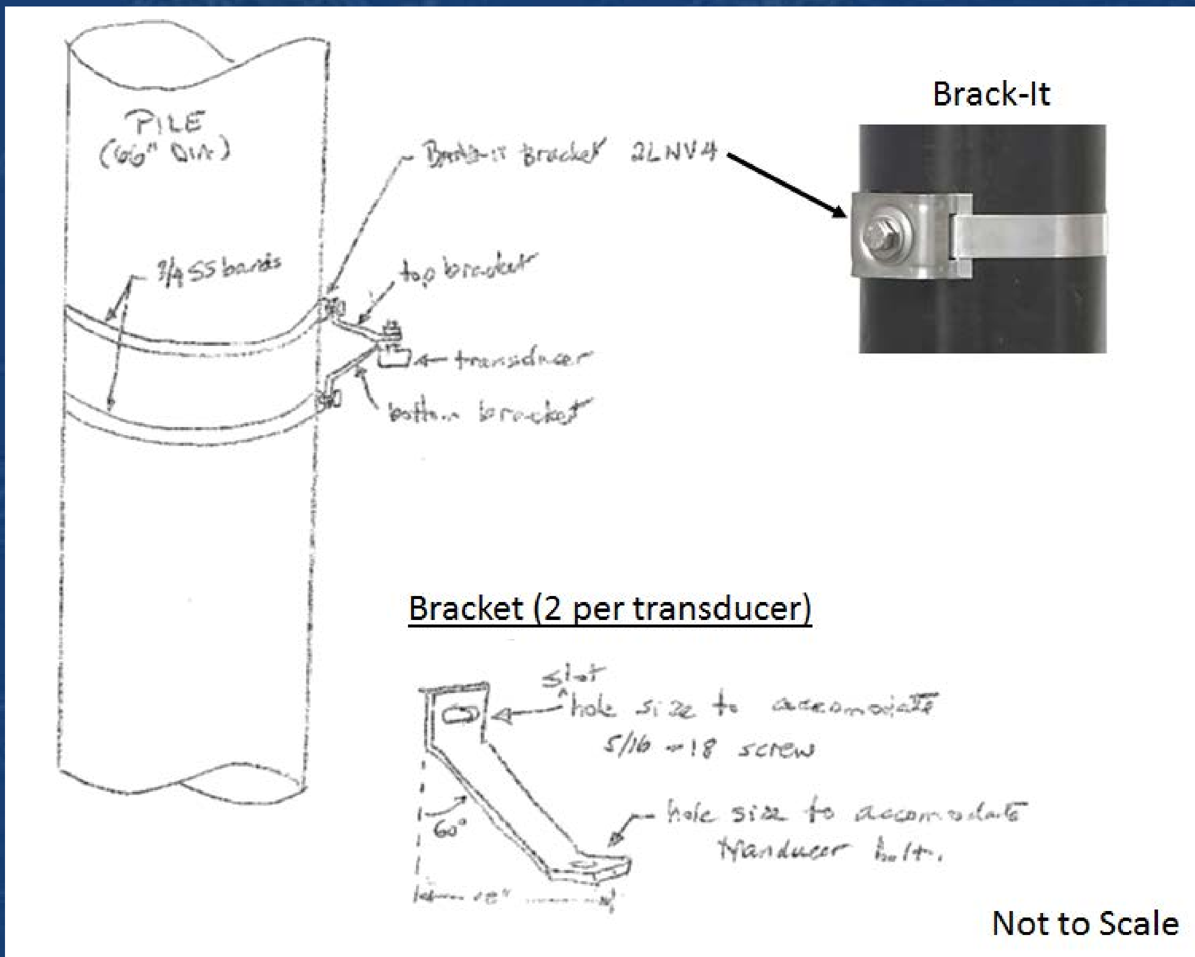
- CR1000 Data Logger
- Airlink Raven X Cellular Modem (Master only)
- RF401 Radio Modem
- 12V 18Ah Battery
- KS20 Solar Panel
  - 20W, 16.9V, 1.2A max
- Antennas

Original Remote Installation Plan

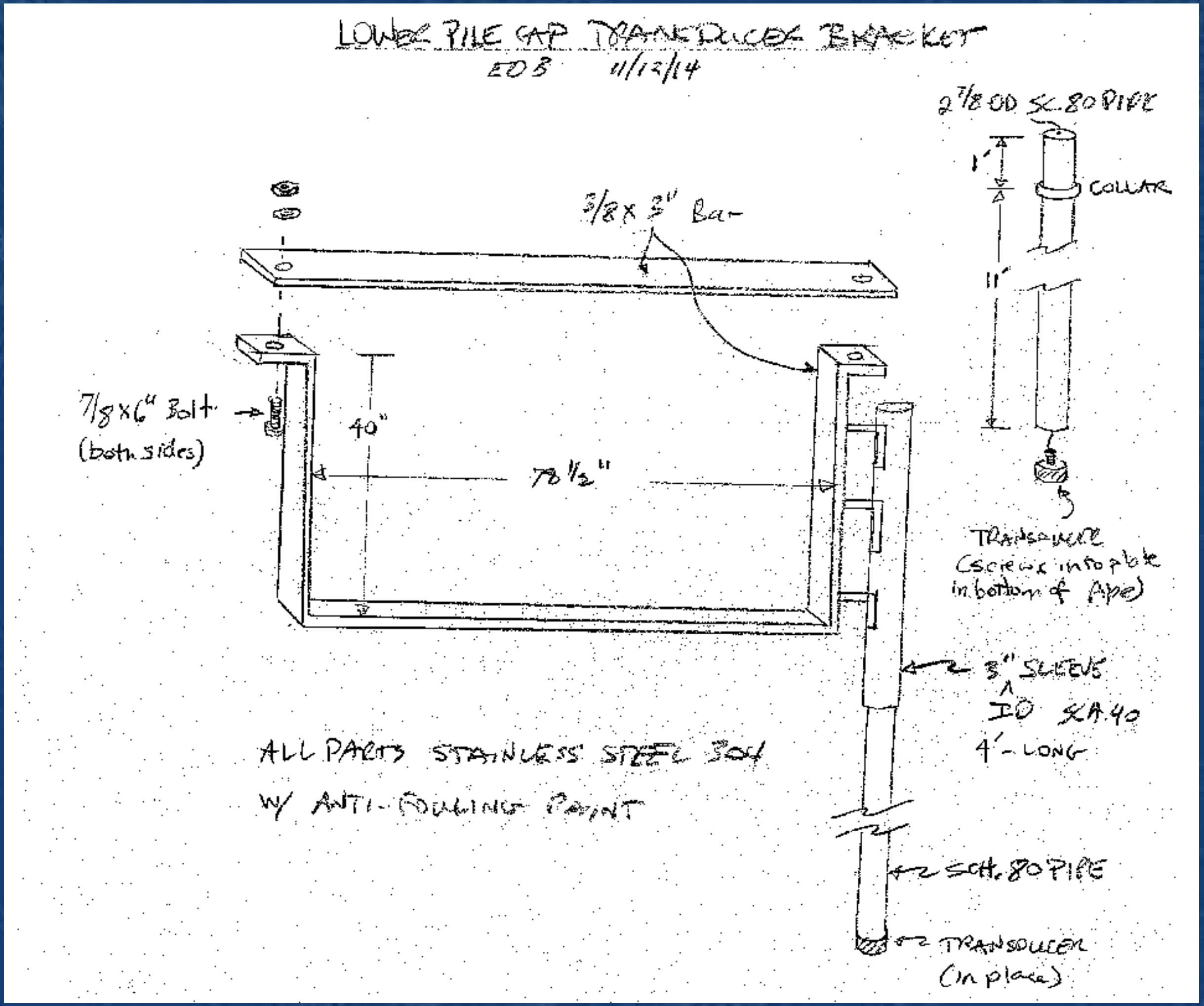


Remote Installation
Solar Panel and Controller

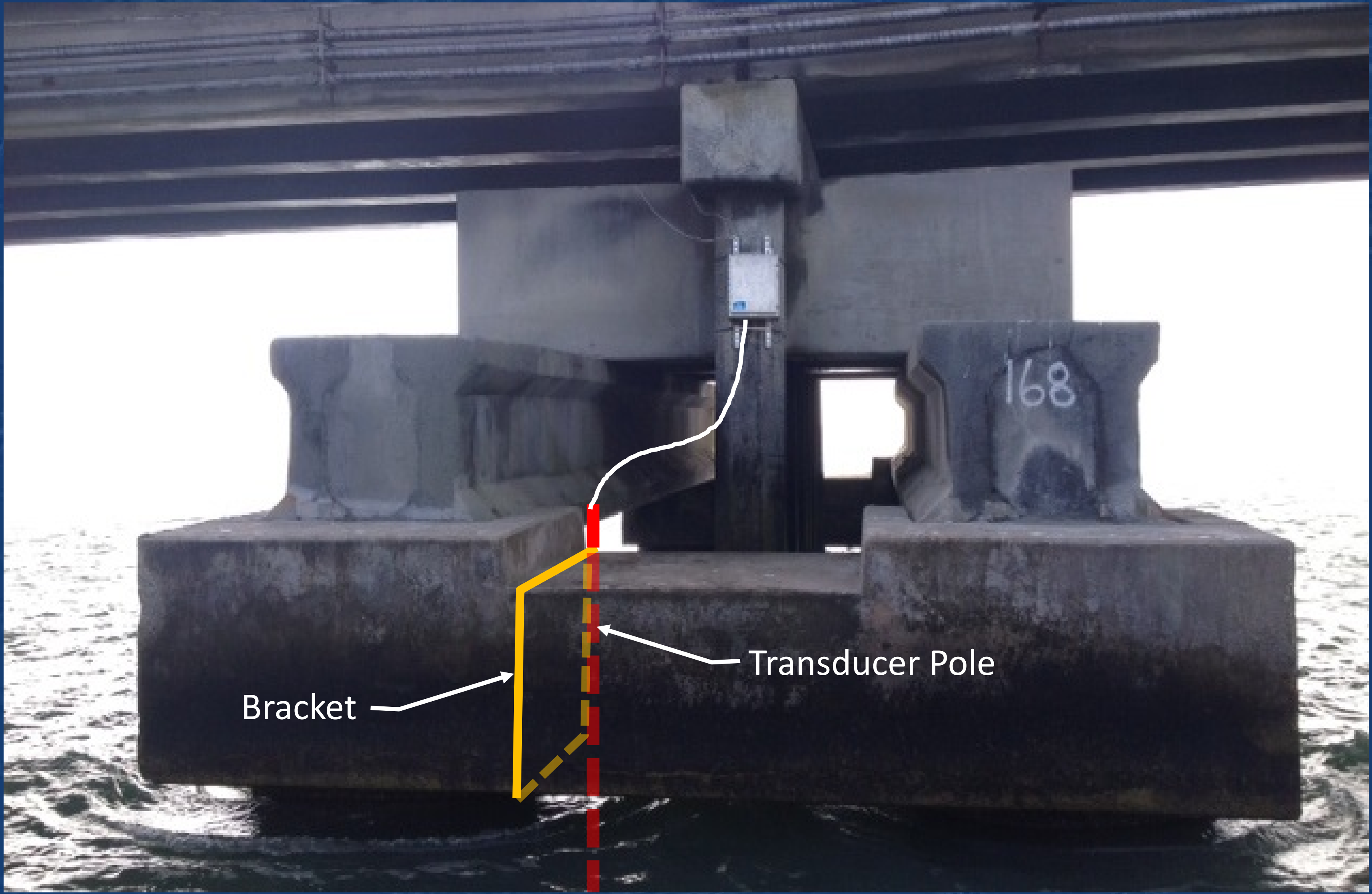
Original Transducer Mounting Plan



Revised Transducer Mounting Plan



Revised Transducer Mounting Plan



West Side Transducers and Solar Panel

East Side Remote Controller

Website

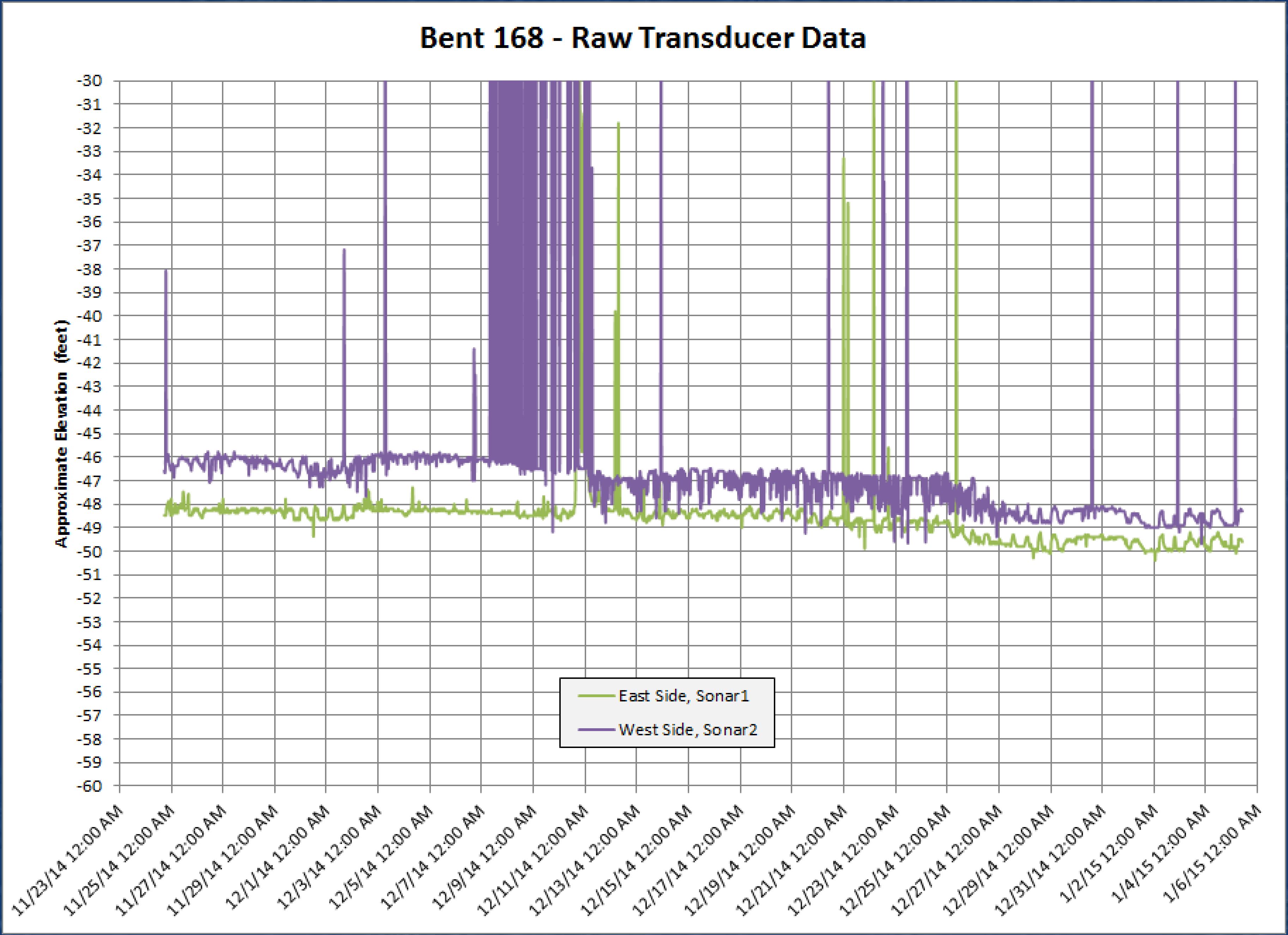
Bonner Bridge Scour Monitoring System

Sonar Data - 7 Days | Sonar Data - 30 Days

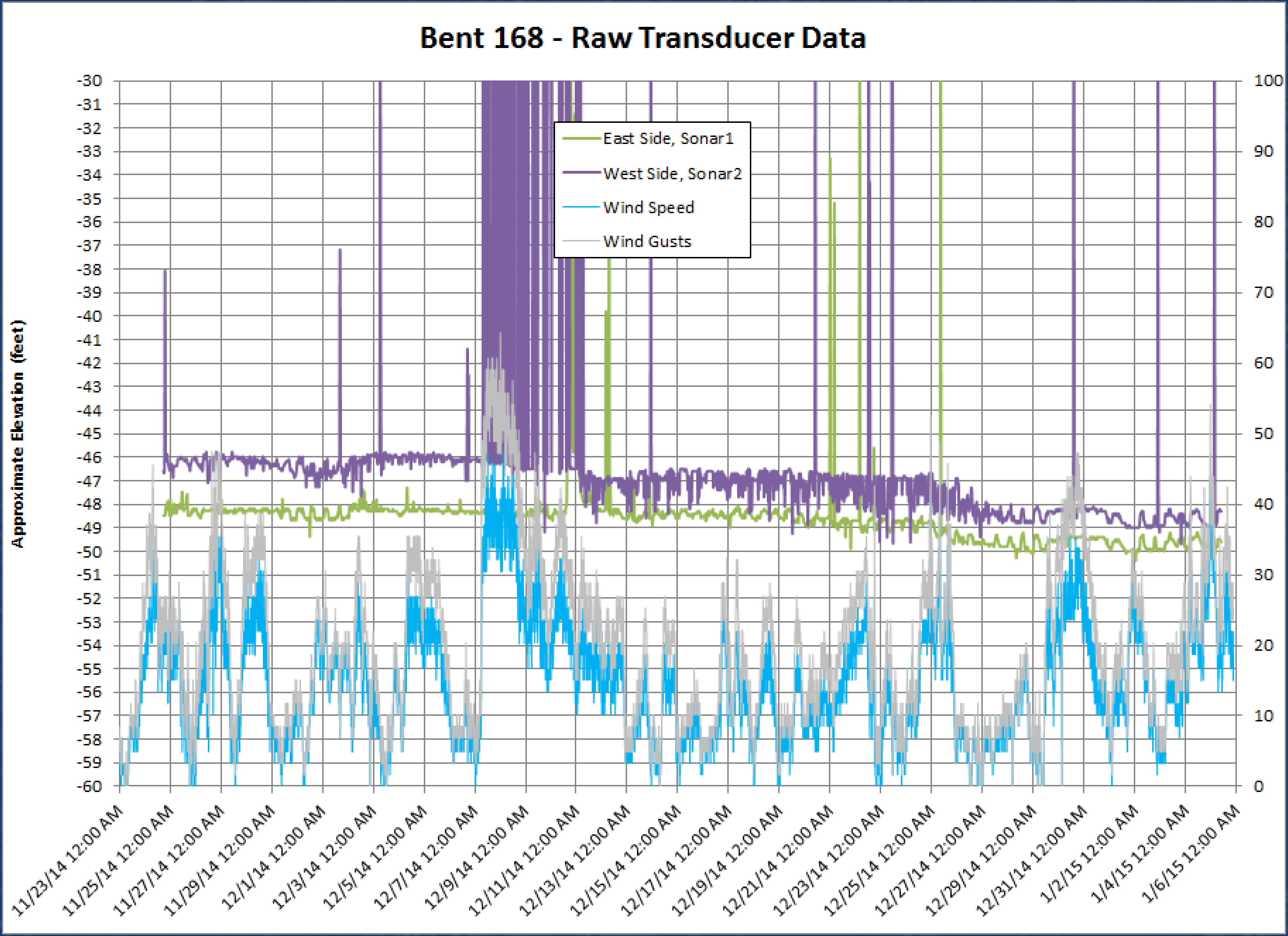
24 Hour Table | Cumulative Table | Battery Voltages

ESP
ESP Associates, P.A.

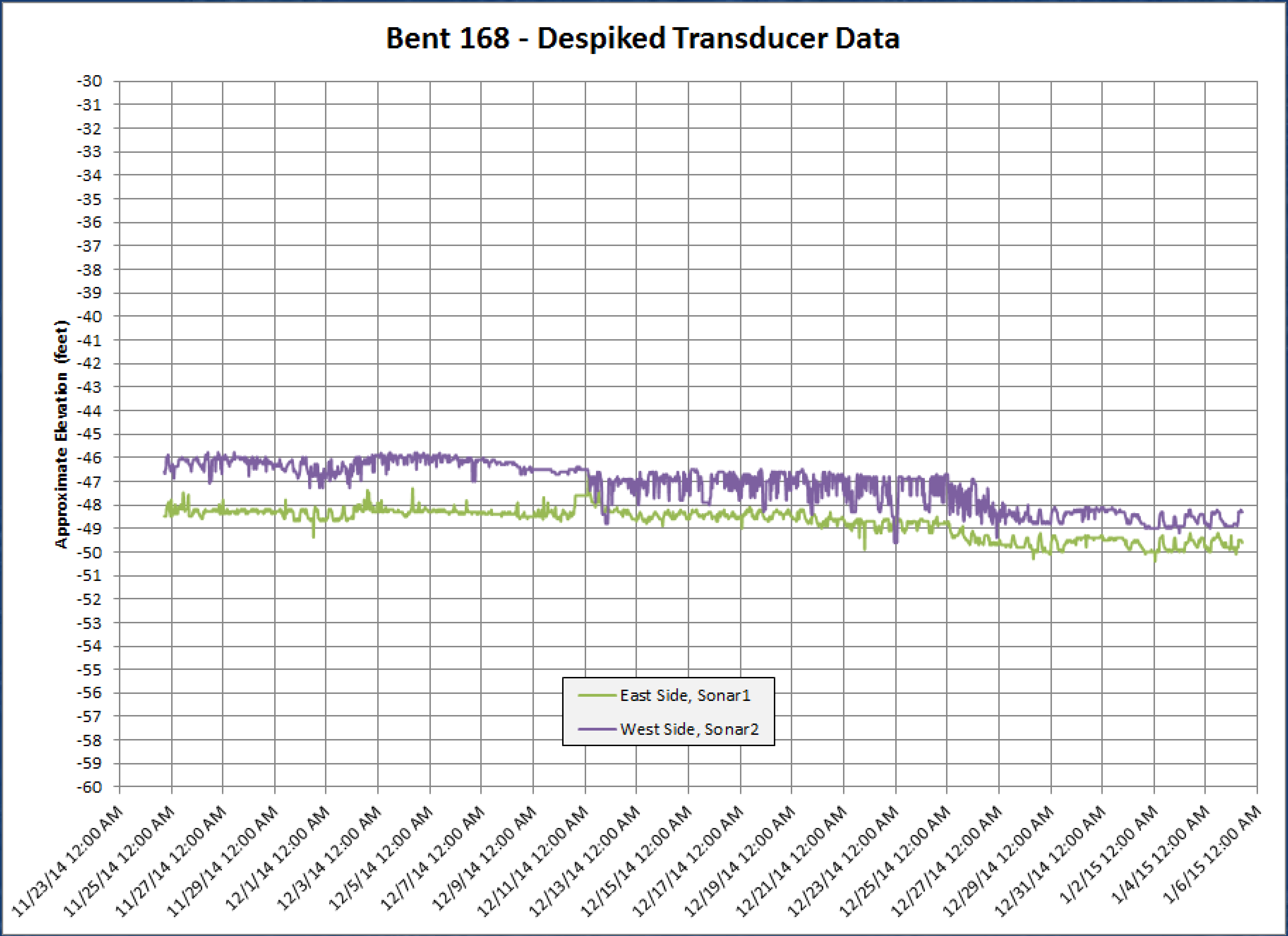
http://www.bonnerbridgesonar.com/index.html

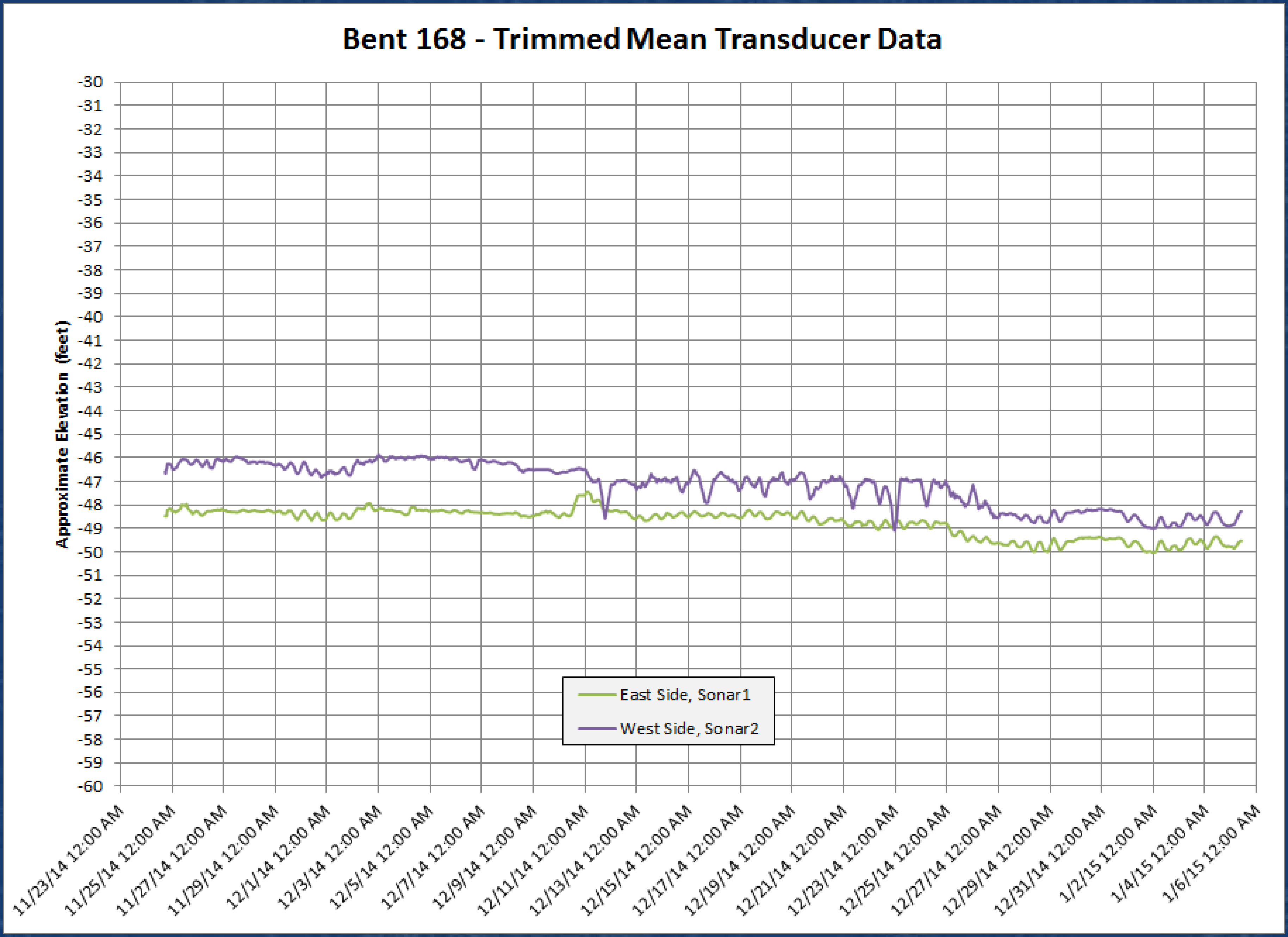


Bent 168 - Raw Transducer Data
Approximate Elevation (feet)
-30
-31
-32
-33
-34
-35
-36
-37
-38
-39
-40
-41
-42
-43
-44
-45
-46
-47
-48
-49
-50
-51
-52
-53
-54
-55
-56
-57
-58
-59
-60
11/23/14 12:00 AM
11/25/14 12:00 AM
11/27/14 12:00 AM
11/29/14 12:00 AM
12/1/14 12:00 AM
12/3/14 12:00 AM
12/5/14 12:00 AM
12/7/14 12:00 AM
12/9/14 12:00 AM
12/11/14 12:00 AM
12/13/14 12:00 AM
12/15/14 12:00 AM
12/17/14 12:00 AM
12/19/14 12:00 AM
12/21/14 12:00 AM
12/23/14 12:00 AM
12/25/14 12:00 AM
12/27/14 12:00 AM
12/29/14 12:00 AM
12/31/14 12:00 AM
1/2/15 12:00 AM
1/4/15 12:00 AM
1/6/15 12:00 AM
East Side, Sonar1
West Side, Sonar2



Bent 168 - Raw Transducer Data
East Side, Sonar1
West Side, Sonar2
Wind Speed
Wind Gusts
Approximate Elevation (feet)
-30
-35
-40
-45
-50
-55
-60
100
90
80
70
60
50
40
30
20
10
0
11/23/14 12:00 AM
11/25/14 12:00 AM
11/27/14 12:00 AM
11/29/14 12:00 AM
12/1/14 12:00 AM
12/3/14 12:00 AM
12/5/14 12:00 AM
12/7/14 12:00 AM
12/9/14 12:00 AM
12/11/14 12:00 AM
12/13/14 12:00 AM
12/15/14 12:00 AM
12/17/14 12:00 AM
12/19/14 12:00 AM
12/21/14 12:00 AM
12/23/14 12:00 AM
12/25/14 12:00 AM
12/27/14 12:00 AM
12/29/14 12:00 AM
12/31/14 12:00 AM
1/2/15 12:00 AM
1/4/15 12:00 AM
1/6/15 12:00 AM


Bent 168 - Despiked Transducer Data
Approximate Elevation (feet)
-30
-31
-32
-33
-34
-35
-36
-37
-38
-39
-40
-41
-42
-43
-44
-45
-46
-47
-48
-49
-50
-51
-52
-53
-54
-55
-56
-57
-58
-59
-60
East Side, Sonar1
West Side, Sonar2
11/23/14 12:00 AM
11/25/14 12:00 AM
11/27/14 12:00 AM
11/29/14 12:00 AM
12/1/14 12:00 AM
12/3/14 12:00 AM
12/5/14 12:00 AM
12/7/14 12:00 AM
12/9/14 12:00 AM
12/11/14 12:00 AM
12/13/14 12:00 AM
12/15/14 12:00 AM
12/17/14 12:00 AM
12/19/14 12:00 AM
12/21/14 12:00 AM
12/23/14 12:00 AM
12/25/14 12:00 AM
12/27/14 12:00 AM
12/29/14 12:00 AM
12/31/14 12:00 AM
1/2/15 12:00 AM
1/4/15 12:00 AM
1/6/15 12:00 AM



Bent 168 - Trimmed Mean Transducer Data
Approximate Elevation (feet)
-30
-31
-32
-33
-34
-35
-36
-37
-38
-39
-40
-41
-42
-43
-44
-45
-46
-47
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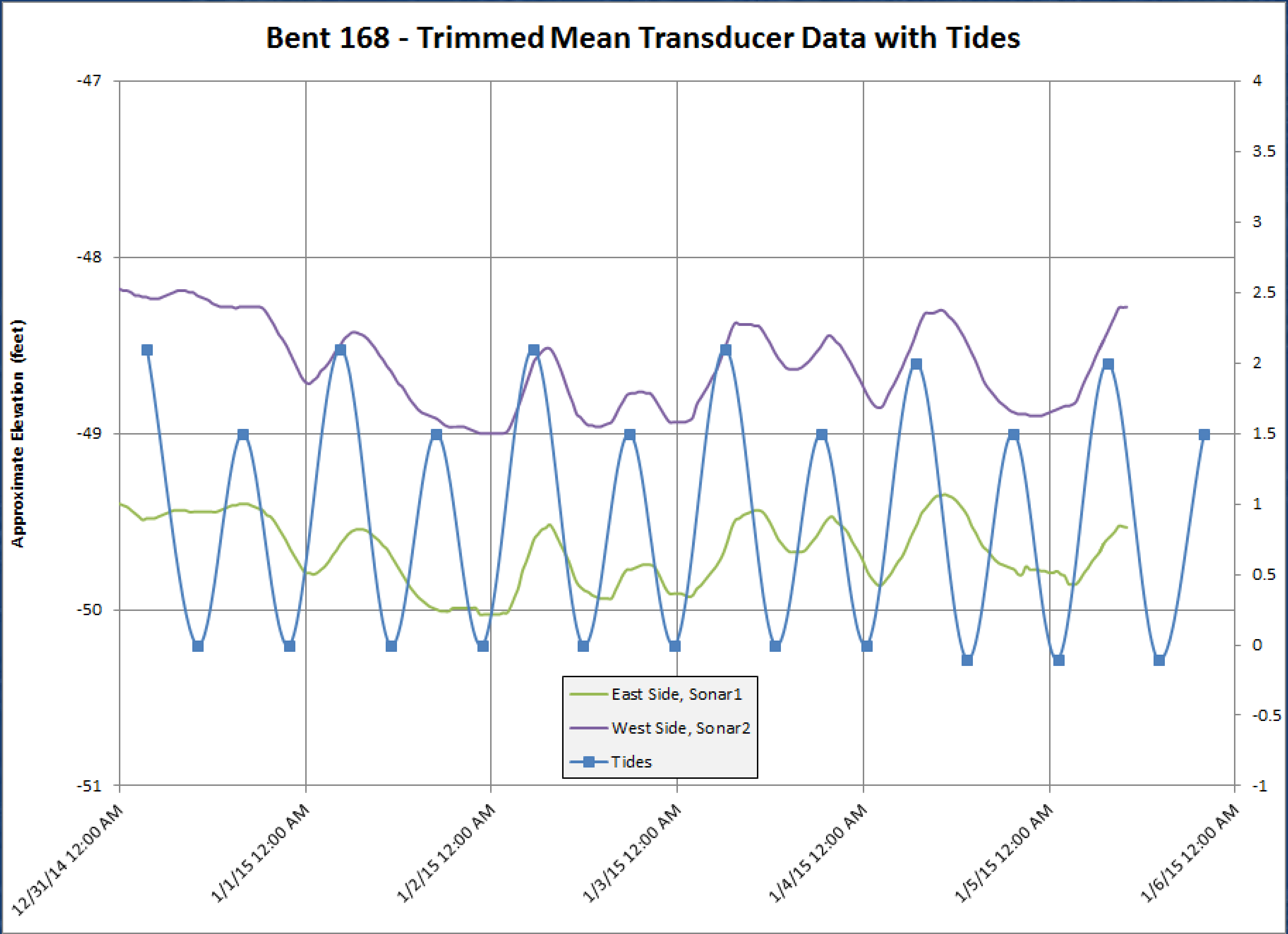
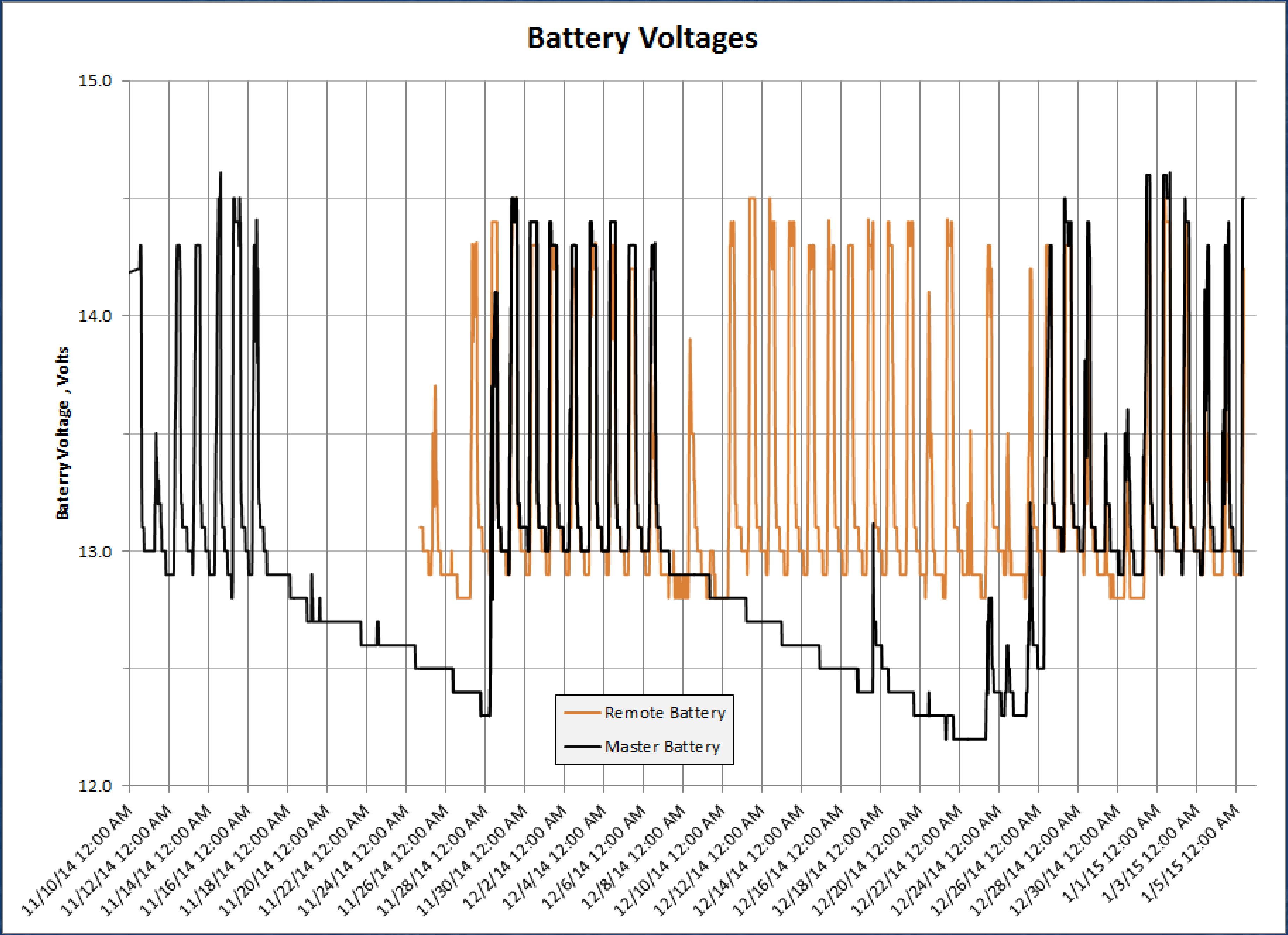
-60
11/23/14 12:00 AM
11/25/14 12:00 AM
11/27/14 12:00 AM
11/29/14 12:00 AM
12/1/14 12:00 AM
12/3/14 12:00 AM
12/5/14 12:00 AM
12/7/14 12:00 AM
12/9/14 12:00 AM
12/11/14 12:00 AM
12/13/14 12:00 AM
12/15/14 12:00 AM
12/17/14 12:00 AM
12/19/14 12:00 AM
12/21/14 12:00 AM
12/23/14 12:00 AM
12/25/14 12:00 AM
12/27/14 12:00 AM
12/29/14 12:00 AM
12/31/14 12:00 AM
1/2/15 12:00 AM
1/4/15 12:00 AM
1/6/15 12:00 AM
East Side, Sonar1
West Side, Sonar2



Bent 168 - Trimmed Mean Transducer Data with Tides
Approximate Elevation (feet)
-47
-48
-49
-50
-51
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
12/31/14 12:00 AM
1/1/15 12:00 AM
1/2/15 12:00 AM
1/3/15 12:00 AM
1/4/15 12:00 AM
1/5/15 12:00 AM
1/6/15 12:00 AM
East Side, Sonar1
West Side, Sonar2
Tides


Battery Voltages
Baterry Voltage , Volts
15.0
14.0
13.0
12.0
Remote Battery
Master Battery
11/10/14 12:00 AM
11/12/14 12:00 AM
11/14/14 12:00 AM
11/16/14 12:00 AM
11/18/14 12:00 AM
11/20/14 12:00 AM
11/22/14 12:00 AM
11/24/14 12:00 AM
11/26/14 12:00 AM
11/28/14 12:00 AM
11/30/14 12:00 AM
12/2/14 12:00 AM
12/4/14 12:00 AM
12/6/14 12:00 AM
12/8/14 12:00 AM
12/10/14 12:00 AM
12/12/14 12:00 AM
12/14/14 12:00 AM
12/16/14 12:00 AM
12/18/14 12:00 AM
12/20/14 12:00 AM
12/22/14 12:00 AM
12/24/14 12:00 AM
12/26/14 12:00 AM
12/28/14 12:00 AM
12/30/14 12:00 AM
1/1/15 12:00 AM
1/3/15 12:00 AM
1/5/15 12:00 AM

Comparisons with Multi-beam Data

- Multi-beam data indicated a difference of 0.1 foot at Sonar 1 and 0.5 foot at Sonar 2.
- Transducer footprint is about 6 feet diameter
- Multi-beam bin size is 3 feet x 3 feet.

Lessons Learned

- Diving conditions are too unpredictable
  - Transducer mounts should be installed above water
- Mounting with steel bands limits locations, complicating logistics and increasing effort
  - Epoxy bolts should be used for mounting the equipment
- Boat type limited access to bents
  - Use vessel with push knees, e.g.

Conclusions

- System is robust and effective in providing real-time water depth elevations for scour monitoring.
- Experience gained on this demonstration project will allow NCDOT to install the remote system relatively quickly as needed.
- Estimate minimum 2 days needed for installation, depending on weather.

With thanks to the North Carolina Department of Transportation Locations and Surveys Unit

Utilizing Near-Surface Geophysics for Large-Scale Transportation Project on the Island of Oahu

Phil Sirles & Jacob Sheehan*, Olson Engineering
Khamis Haramy, P.E., FHWA/Central Federal Lands
Robin Lim, Ph.D. P.E., Geolabs
Zoran Batchko, P.E., PB Americas

1st Case History – Mapping Soft Soils Beneath Highways

Project example of using **unique** applications of "near-surface geophysics" to solve difficult geologic and geotechnical problems encountered in Hawaii on a very large transportation project:

- Honolulu High Capacity Transit Corridor Project (HHCTCP), Oahu

Honolulu High-Capacity Transit Corridor Project

- The local population of Honolulu (approximately 500,000) combined with the large number of tourists causes daunting heavy traffic.
  - Particularly, for commuters with the planned expansion of the University of Hawaii (UH) campus in Waipahu west of Honolulu.
- To help the commute between the tourist beaches of Waikiki to the proposed UH campus, construction the HHCTCP light-rail project has begun.
- **The light rail system, as voted on, was dictated by law to utilize existing right-of-ways (i.e., roadways).**
  - **This mandate creates a unique engineering challenge. Elevated sections of Phase 1 parallel or are directly overhead the Farrington and King Kamehameha highways.**

HHCTCP will link West (Waipahu) to East Honolulu (Waikiki)

Geophysics HHCTCP Project Objectives:

- Map top-of-bedrock
- Map lateral variation of '*soft soils*'

Engineering Purpose for PB Geotecch Team:

"Aid our design team with subsurface information … between [below and beyond] drill holes"

"Identify 'anomalous' areas for further geotech [drilling] investigations"

GEOLOGIC and CULTURAL SETTING

- ✓ Bedrock: basaltic / volcanic mix of tuffs
- ✓ Soft soils: Defined using IBC Vs at <600 ft/s
- ✓ Est'd depth to bedrock: 5 to 175* feet (**initial estimate*)
- ✓ Water table: in the upper 10-15 feet (*often saline*)
- ✓ Cultural setting: URBAN (*Industrial & Retail*)
- ✓ *HEAVY TRAFFIC*: had to work on median/curb/sidewalk
- ✓ Need for city/state traffic control plans

Geophysical Method?

Electrical

2D Refraction Microtremor (ReMi)

1D IBC Vs30 → 2D Profiles

FIELD METHOD

- ❑ Laptop/Toughbook
- ❑ 4.5 Hz vertical geophones (spikes & plates)
- ❑ 24-ch seismograph, 24 ‘*live*’ channels with 48 laid out
- ❑ Roll-along box (std. for reflection data acquisition)

HHCTCP PROGRAM

- Blind Test Phase: acquire 2 short lines at boring locations with soft soil and shallow bedrock.
- Process, Interpret & Present results to PB design team
- Make a team GO or NO GO decision

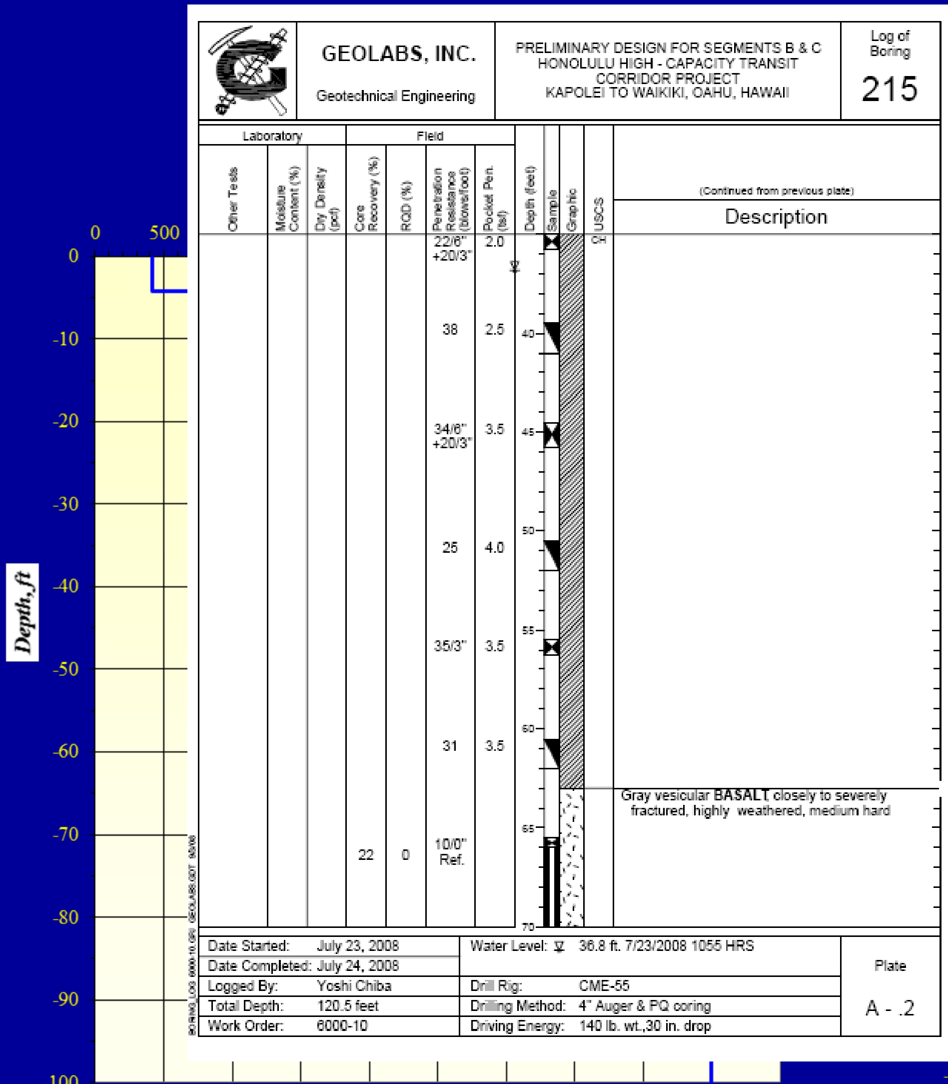
TEST LINE #1: DEEP "SOFT SOIL" SITE

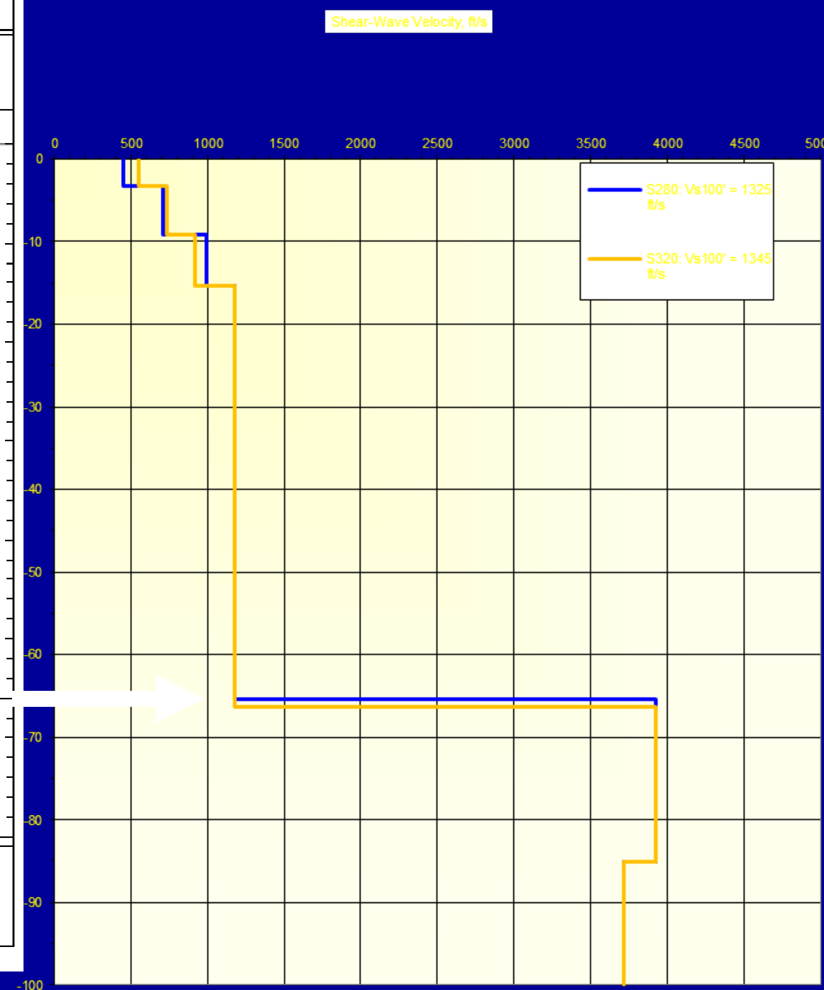
TEST LINE #1: DEEP “SOFT SOIL” SITE

*Working in **Paradise** is not in th*

TEST LINE 1

1D Vs100 'Blind' Results at Boring locations





S0 (B107)

S280 & S320 (B215)

HHCTCP PROGRAM

• Blind Test Phase: acquire 2 lines at TH locations – **BOTH SUCCESSFULLY DETECTED BEDROCK AND SOFT SOILS**

• Process, Interpret & Present results to design team

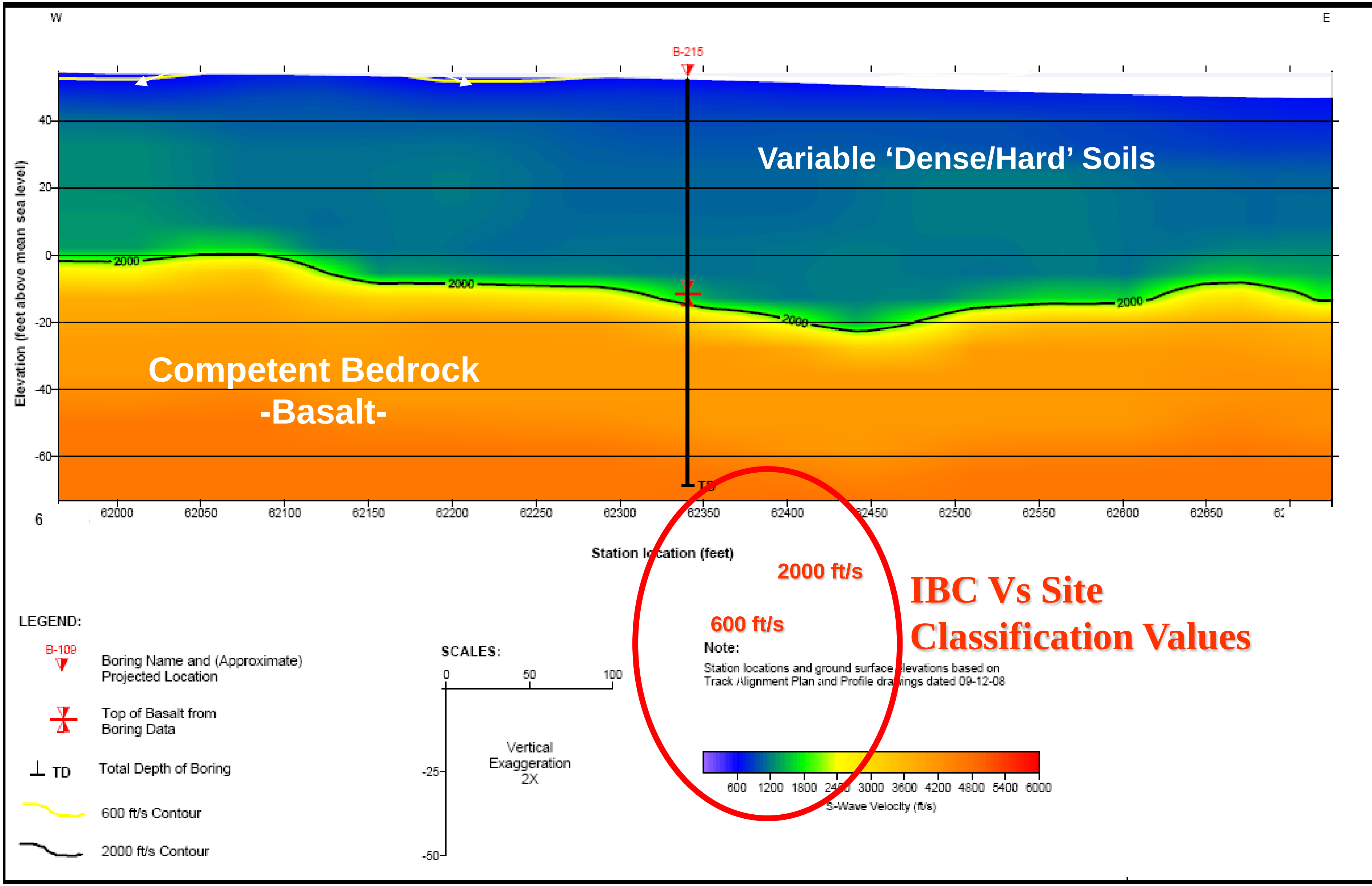
→**"GO"** ~~or NO GO DECISION~~

• Production Phase: acquire ~2.5 miles of data (used backhoe)

• Process Vs profiles, integrate geologic& geotechnical data

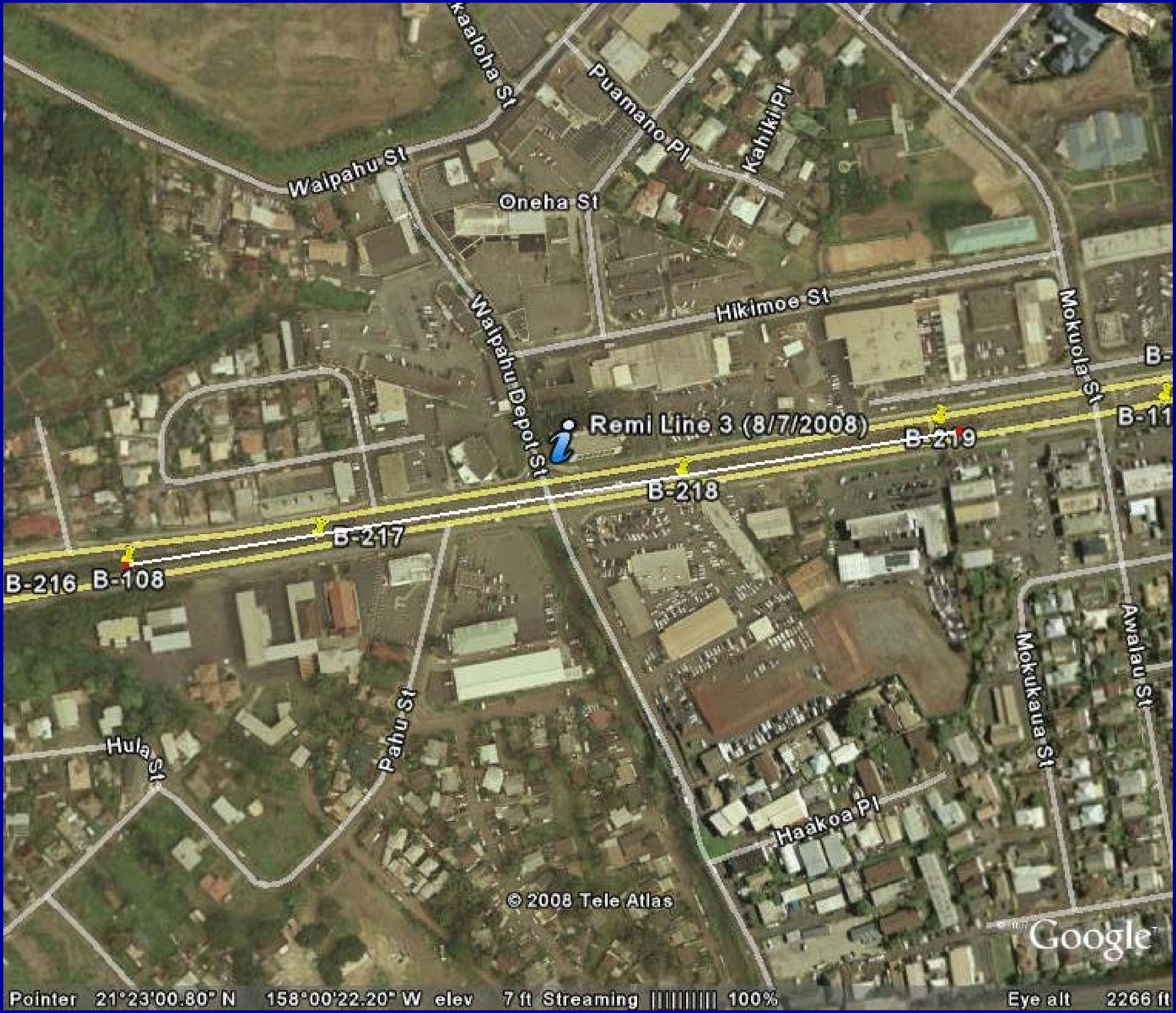
• Prepare Geophysical Report

• Export Vs results for PB GIS team to give geotech engineers

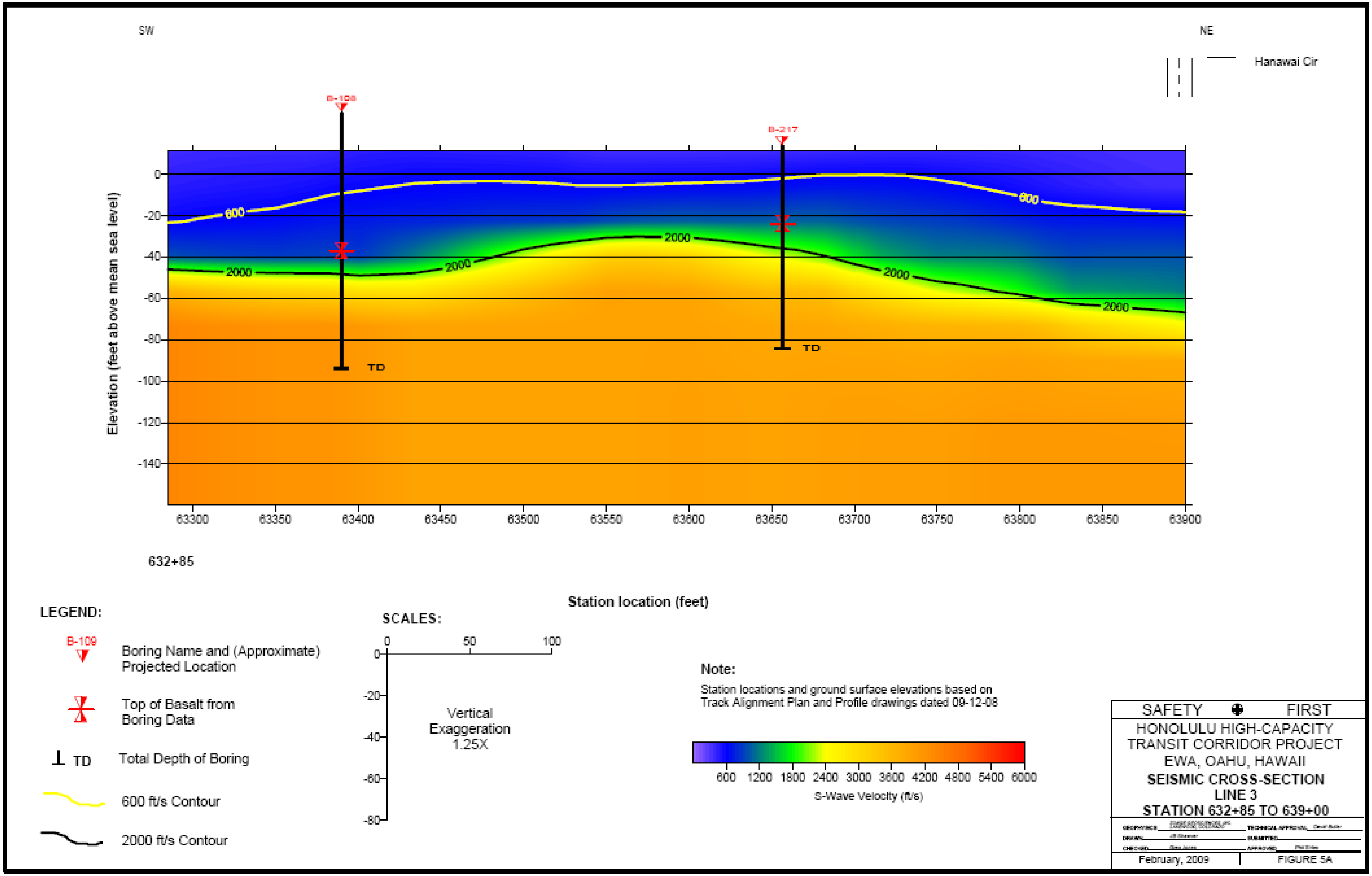


TEST LINE 1 → *Finalized Vs Section with Seismic Interpretation and Geology*

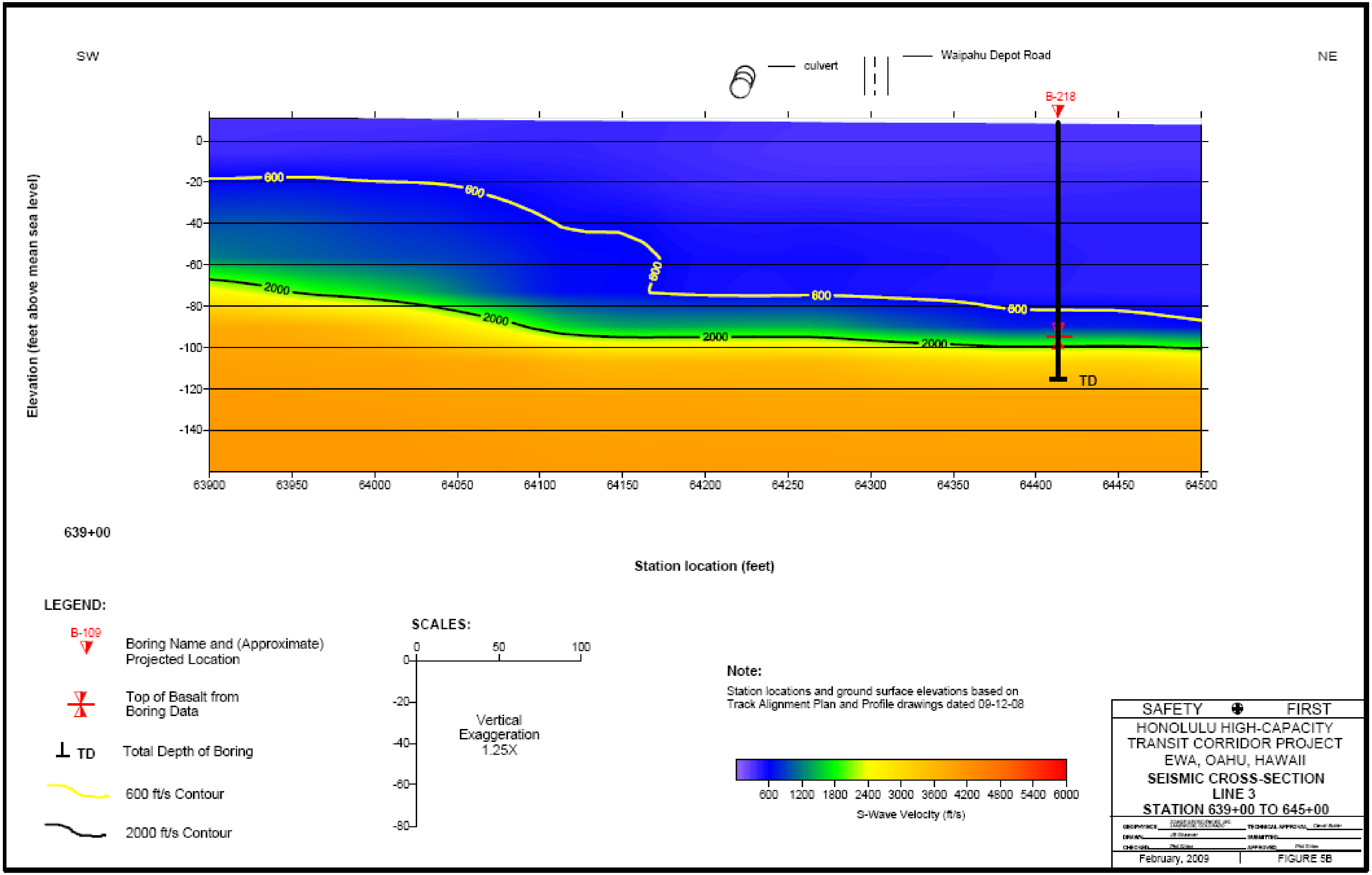

KANUKU
08/06/2008



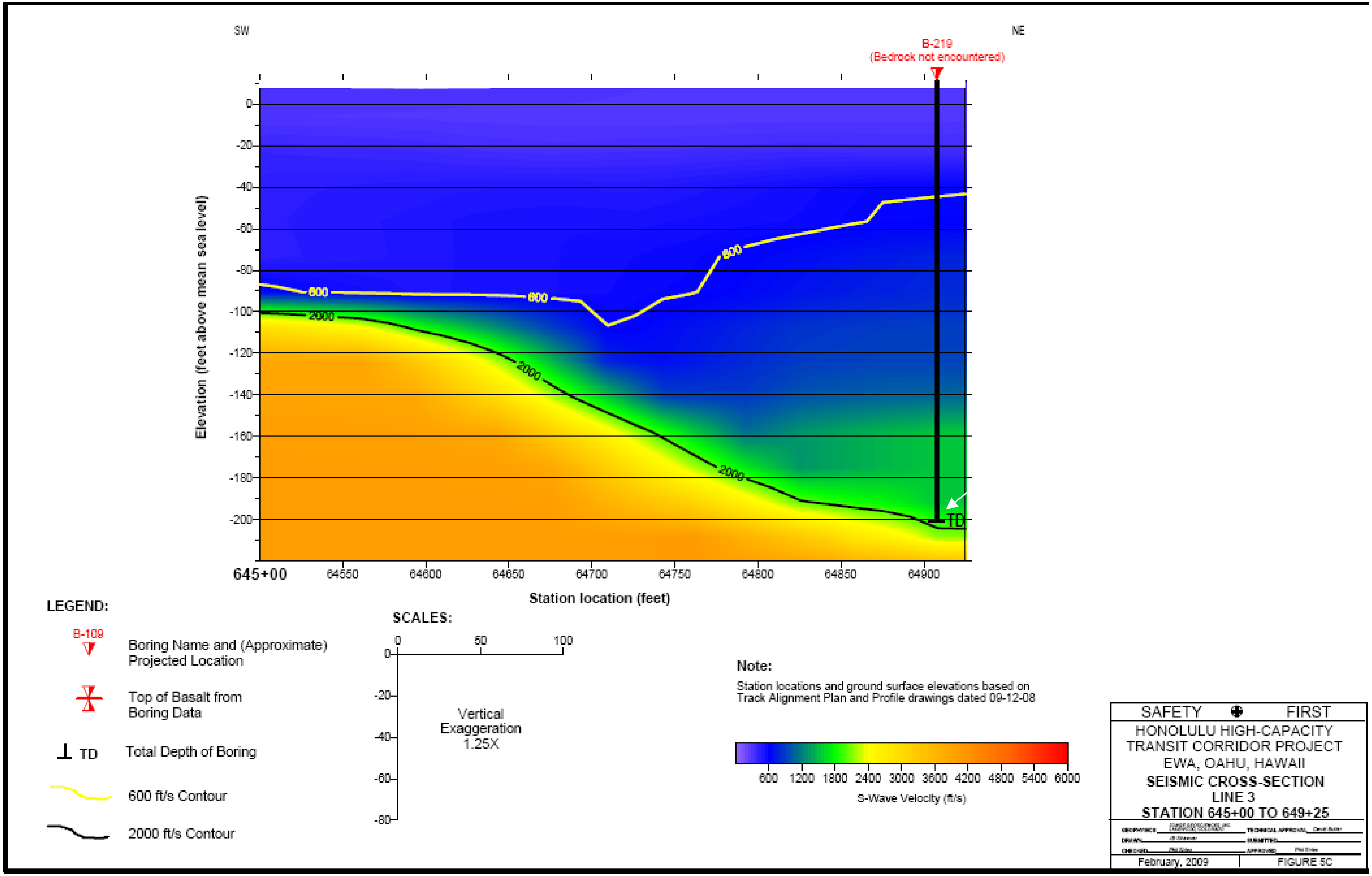
LINE 3 – *PRODUCTION PHASE*



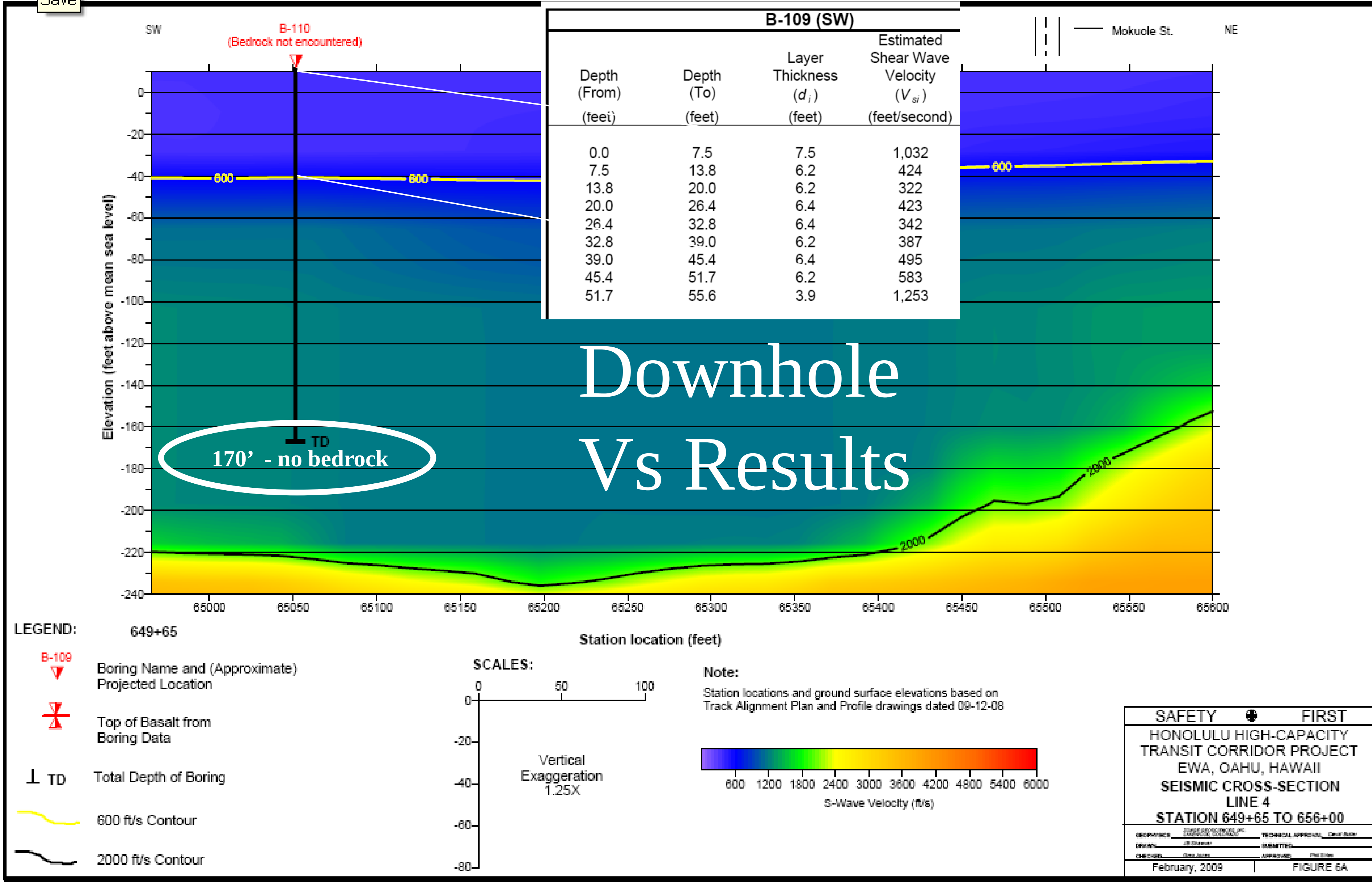
LINE 3 – *PRODUCTION PHASE*



LINE 3 (Continued)



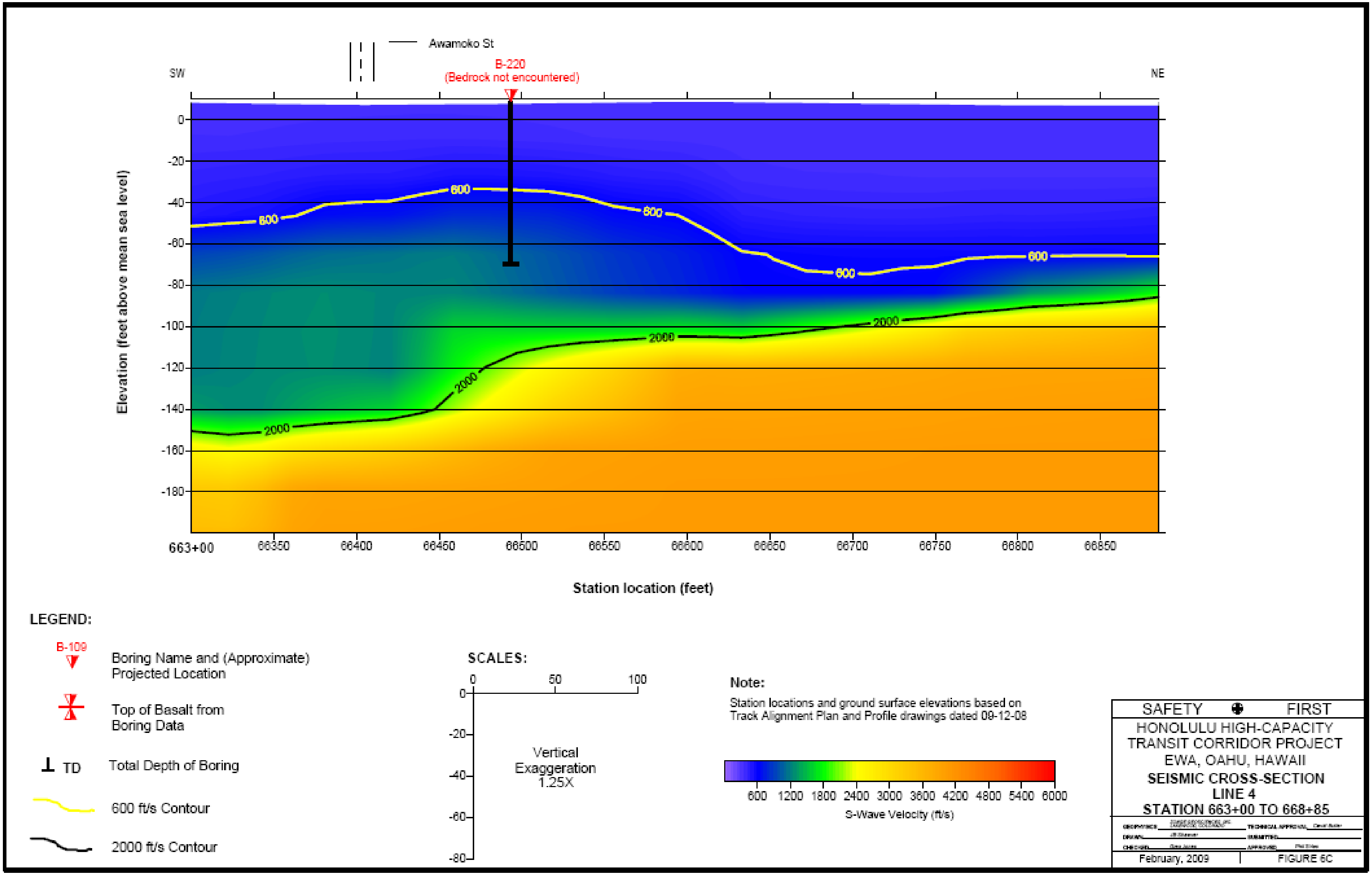
LINE 3 (Continued)



B-109 (SW)

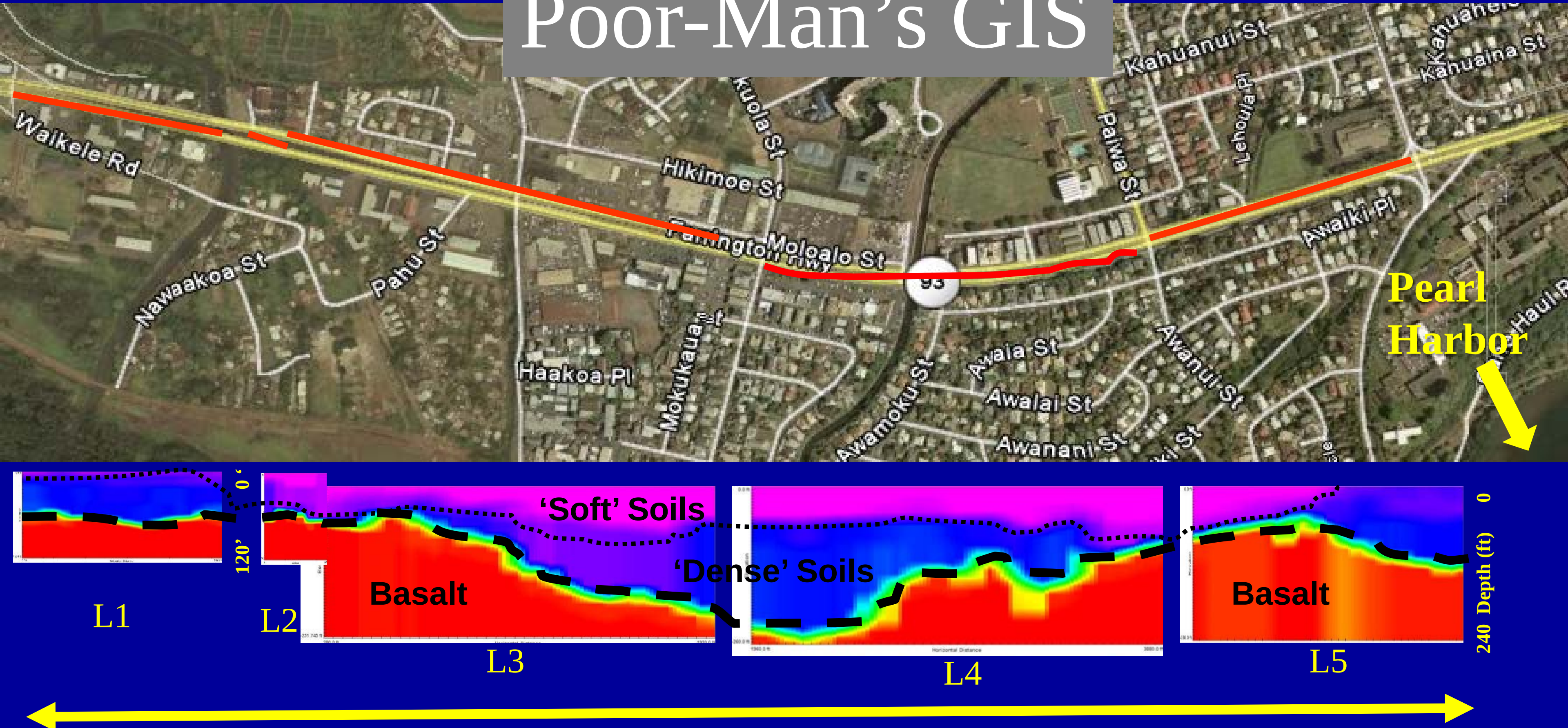
Depth (From) (feet)	Depth (To) (feet)	Layer Thickness (d_i) (feet)	Estimated Shear Wave Velocity (V_{si}) (feet/second)
0.0	7.5	7.5	1,032
7.5	13.8	6.2	424
13.8	20.0	6.2	322
20.0	26.4	6.4	423
26.4	32.8	6.4	342
32.8	39.0	6.2	387
39.0	45.4	6.4	495
45.4	51.7	6.2	583
51.7	55.6	3.9	1,253

LINE 4

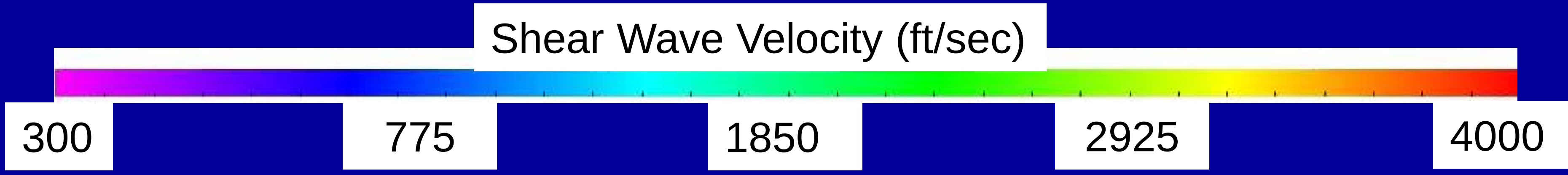

Awamoko St
B-220
(Bedrock not encountered)
SW
NE
Elevation (feet above mean sea level)
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
600
2000
663+00
66350
66400
66450
66500
66550
66600
66650
66700
66750
66800
66850
Station location (feet)
LEGEND:
B-109
Boring Name and (Approximate) Projected Location
Top of Basalt from Boring Data
TD Total Depth of Boring
600 ft/s Contour
2000 ft/s Contour
SCALES:
0 50 100
Vertical Exaggeration 1.25X
Note:
Station locations and ground surface elevations based on Track Alignment Plan and Profile drawings dated 09-12-08
600 1200 1800 2400 3000 3600 4200 4800 5400 6000
S-Wave Velocity (ft/s)
SAFETY FIRST
HONOLULU HIGH-CAPACITY TRANSIT CORRIDOR PROJECT
EWA, OAHU, HAWAII
SEISMIC CROSS-SECTION
LINE 4
STATION 663+00 TO 668+85
February, 2009
FIGURE 6C

LINE 4 (End)

Poor-Man's GIS



6,800 feet (~1.25 mi) or 170 Sounding



CONCLUSIONS

- 2D PSW was an effective method to map
  - Top-of-Bedrock (Basalt)
  - Vertical & Lateral changes in soft-to-dense soils
- Quick field procedures to acquire ~1500-2200 ft/day
- Correlation with test borings was excellent
- Use caution when applying an ‘averaging’ or ‘bulk’ geophysical measurement technique … very difficult to *adjust* geologists and engineers to VOLUMES of material properties, not **lenses or layers** like at the drill hole scale.

RECOMMENDATIONS

- Understand the geologic and cultural setting!
- Select an appropriate NS geophysical method!
- Conduct a ‘test phase’ (*if practical*)!
- Correlate data with known conditions (*ground truth*)!

➡ GO or NO GO DECISION ***WITH ENGINEERS INPUT***!

- Find ways to quickly acquire data
- Follow FHWA’s mantra: “**Get in… Get out… Stay Out**”
- Export results GIS staff to present results to design team

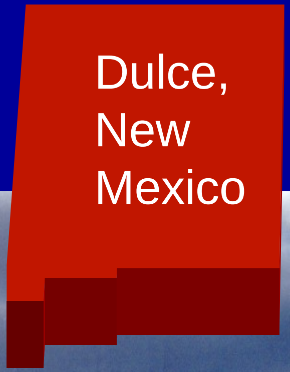
Test Line 3 (I-1 overpass on Farrington Hwy)

Ongoing HHCTCP Construction Activities

Mapping Clay in the Subgrade Case ~~Studies~~ Study

FHWA, EFLHD

FHWA, CFLHD



Mapping Clay in the Subgrade

Given the site-specific setting and a max. depth of interest of <10 feet, which geophysical method(s) would you choose?

Geologic Setting

- Interbedded sandstones
- Shales
- Conglomerates
- Clays
- Silts
- Sands
- Gravels

Other Site Conditions

- Flat to gently rolling hills
- Open brush to sparse trees

Geophysical Methods (tools)

- Seismic Refraction
- Seismic Reflection
- Crosshole Seismic
- Ground Penetrating Radar
- Electrical Resistivity
- TDEM
- FDEM
- Magnetics
- SASW / MASW

Mapping Clay in the Road Base

These combined geophysical methods were chosen for these site conditions

Geologic Setting

- Interbedded sandstones
- Shales
- Conglomerates
- Clays
- Silts
- Sands
- Gravels

Other Site Conditions

- Flat to gently rolling hills
- Open brush to sparse trees

Geophysical Method

- Electrical Resistivity Imaging
- Frequency Domain Electromagnetics

Clay Mapping Exercise

Would you choose both of these geophysical methods if the survey length was over a long stretch of highway (> 2 miles) ?

Geophysical Method Options:

Electrical Resistivity Imaging (ERI)

Frequency Domain Electromagnetics (FDEM)

Engineering Problem

Presence of swelling clay beneath roadway poses problems to roadway rehabilitation design and construction…..

Engineering Problem

Roads constructed over clay areas are subject to potential deformation due to:

- Low shear strength
- High moisture content
- Clay structure (dipping or horizontal bedding)

Soil borings are taken at 0.5 to 0.25 mile intervals for geotechnical verification:

- Set boring intervals may miss critical clay-rich zones
- Geologic interpolation may not be representative
- Great potential to miss large expanses of clay

Engineering Problem

Bottom Line is Cost!

Unexpected clay may result in:

- Project overrun costs
- Construction delays
- Rehabilitation cost increase

Geophysical Demonstrations Effort (Phase I)

Objectives

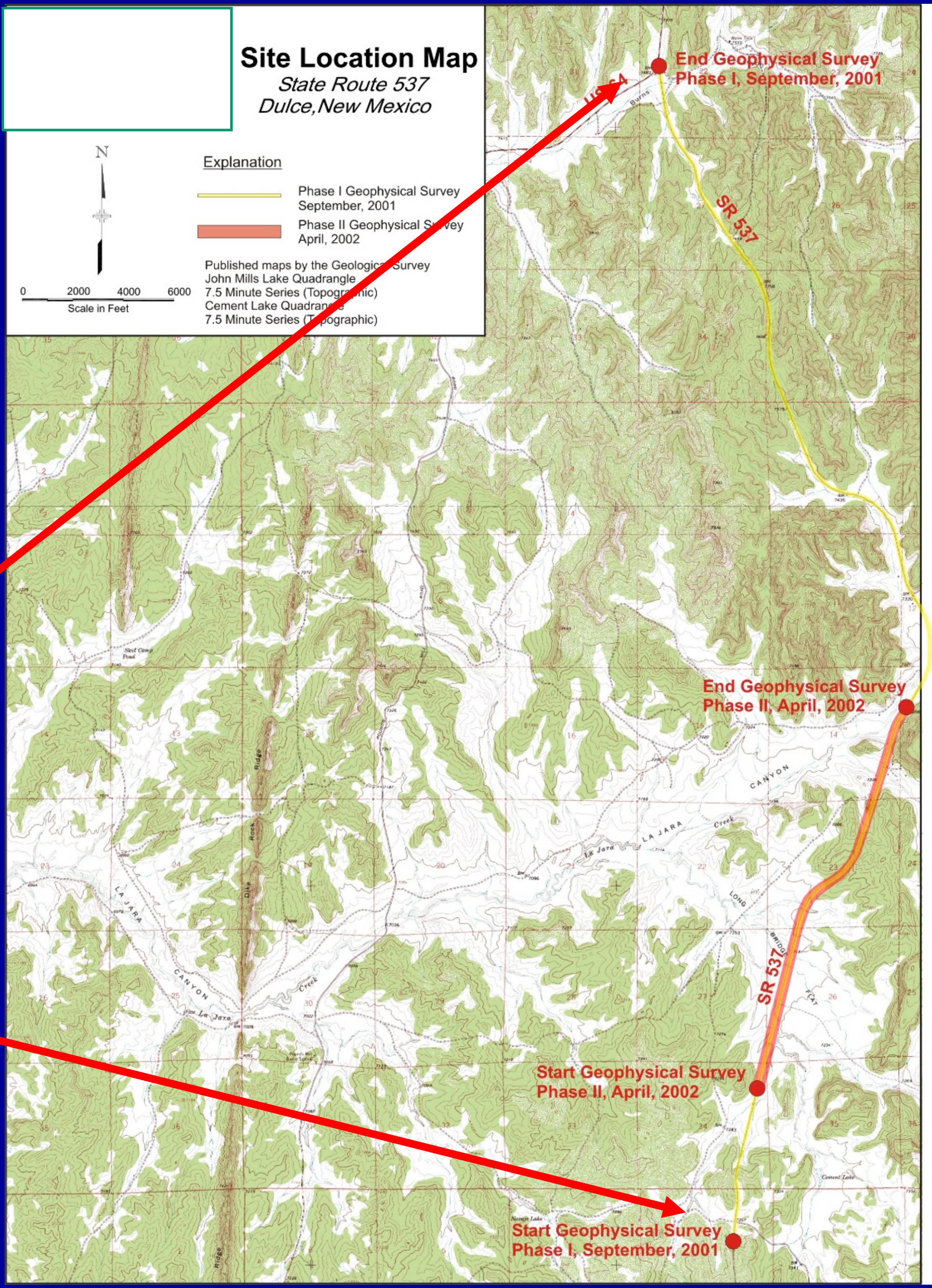
- Locate and map the ***spatial distribution*** of clay beneath the roadway
- Determine the ***depth and thickness*** of the clay
- ***Integrate geophysical data*** or cross-section into FHWA P & P format

CFLHD Approach

Multi-Phase Demonstrations

Production

Jicarilla Apache
Indian Reservation
New Mexico



Phase I
Survey Area

Approximately
10 miles of SR537

Selected Geophysical Method
FDEM

- Frequency Domain Electromagnetic (FDEM): Geonics EM38, and EM31

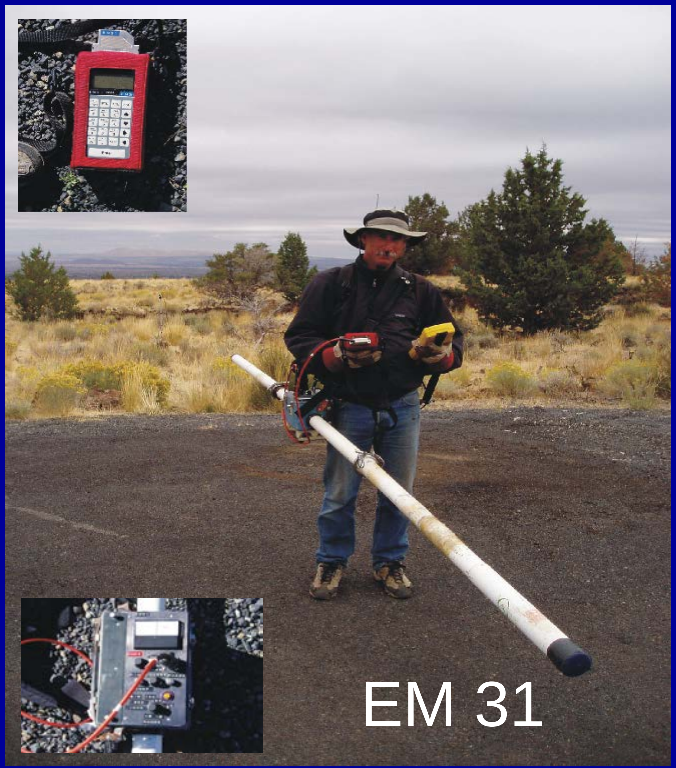
- Frequency Domain Electromagnetic (FDEM): Geonics EM31-3

Frequency Domain Electromagnetics

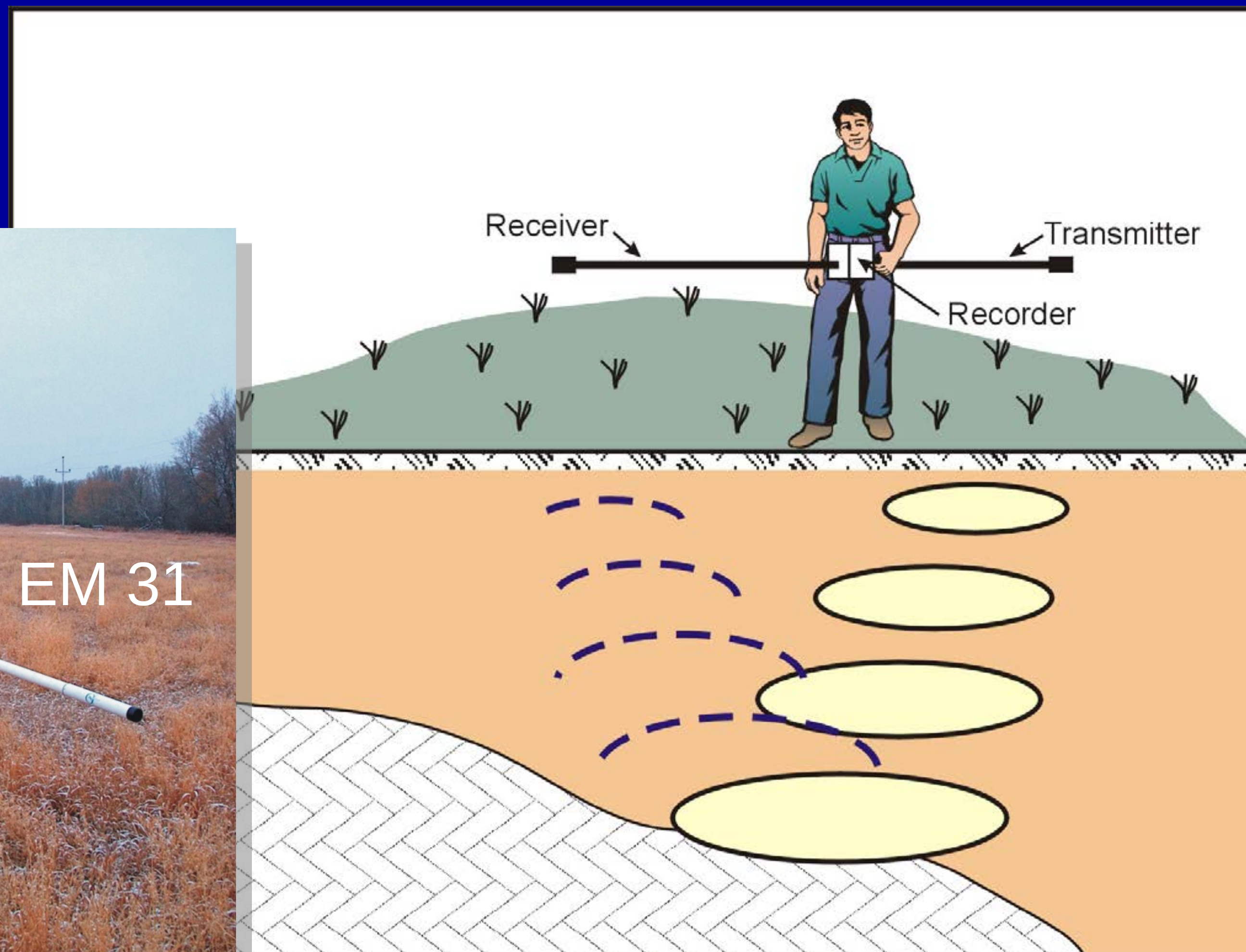
Phase I & II: Geonics EM38 and EM31

Phase III: Geonics EM31-3

Lateral Extent & Depth (may require multiple passes)



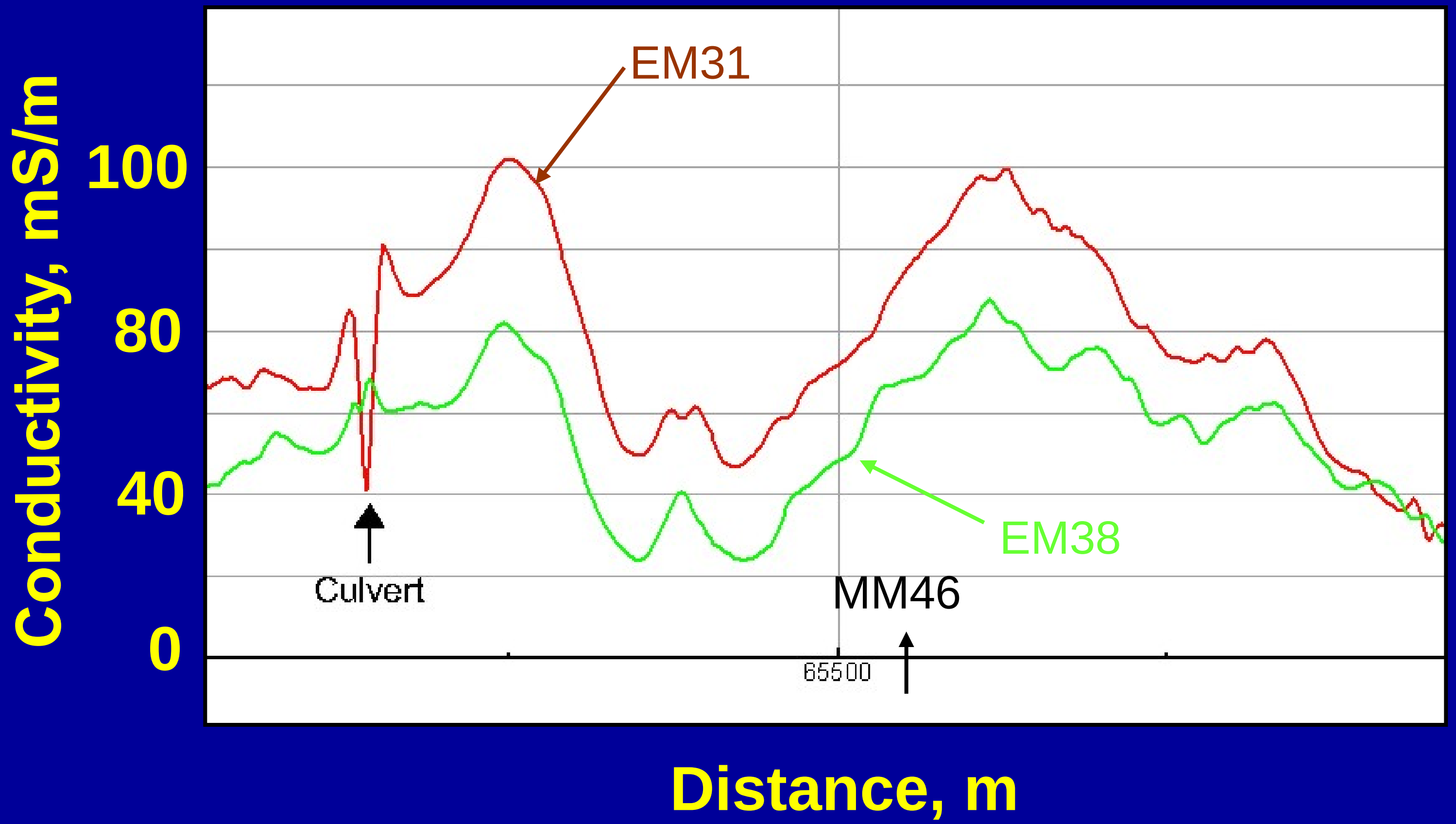
EM31 Wave Propagation



EM Data Acquisition - Field Setup

- EM31 data acquired along both lanes
- 0.5 second sample rate
- Drove at ~5 mph
- **continuous / streaming GPS!**

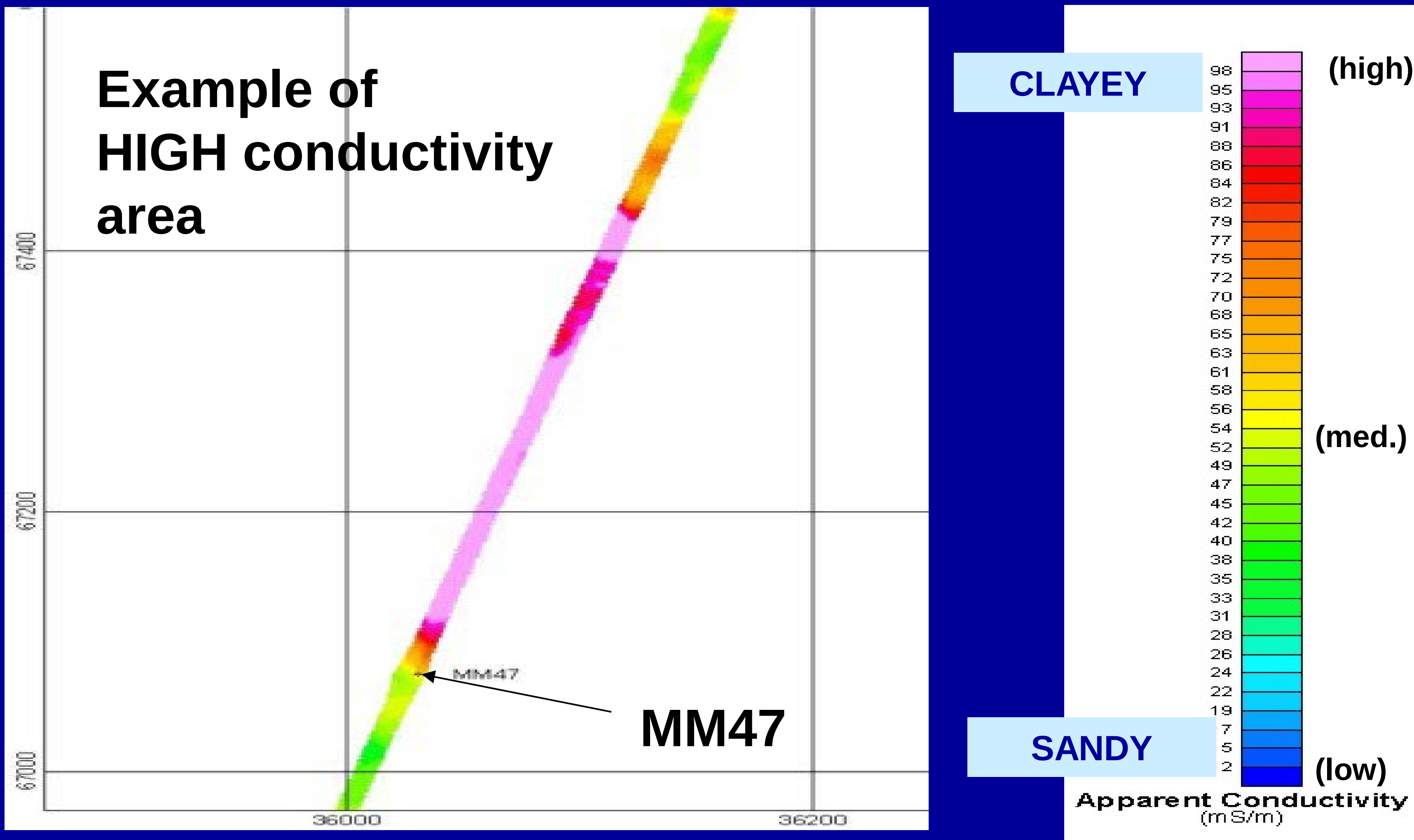
EM31 & EM38 Data Profiles



EM Profiles of raw data for one lane of SR537 near MM46

EM31 “Data / Results”

Grid Northing, m



Grid Easting, m

Phase I
EM Lessons (*and Limitations*)

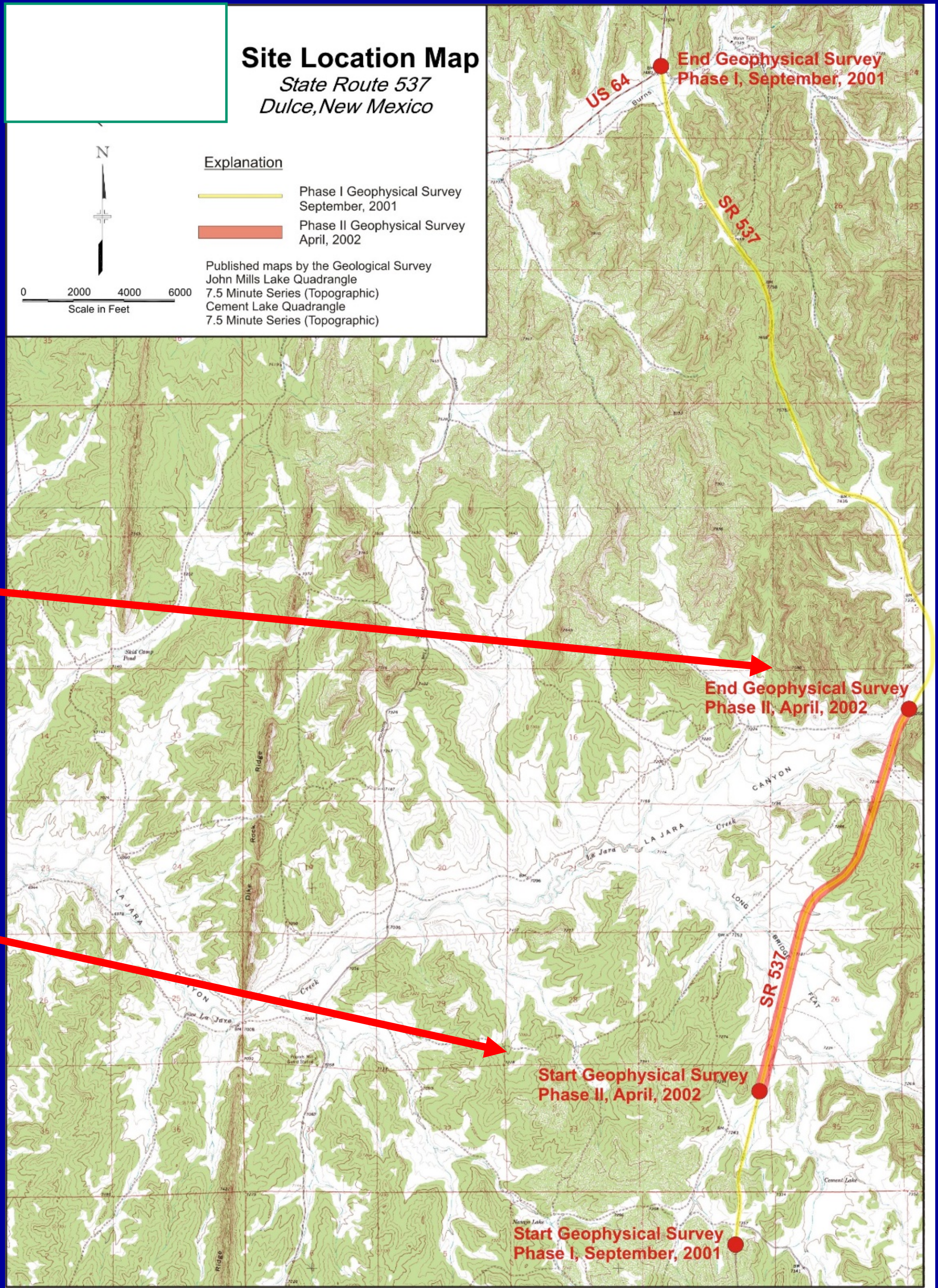
- Unique survey coordinate system (to FHWA and this highway)
- Unable to produce geo-electric depth models (i.e., earth sections)
- Unable to integrate the data onto FHWA P & P
- Needed additional geologic / geotechnical data to correlate with EM data
- Construction haul-truck traffic was ***DANGEROUS***!

Overcame Phase I Limitations with the Phase II Survey

- Detailed survey – MP47 to MP50
- Same instrumentation (EM31)
  different coil orientations and heights
- Coordinated to avoid haul-truck traffic
- Incorporated ALL available lab data and correlated them with geophysical data
- Delivered geo-electric section in FHWA P & P format

Phase II Survey Area

MP47 to MP50
3 miles of SR537



Phase II EM Surveys – Field Setup

Tow Vehicle and EM31 Array System

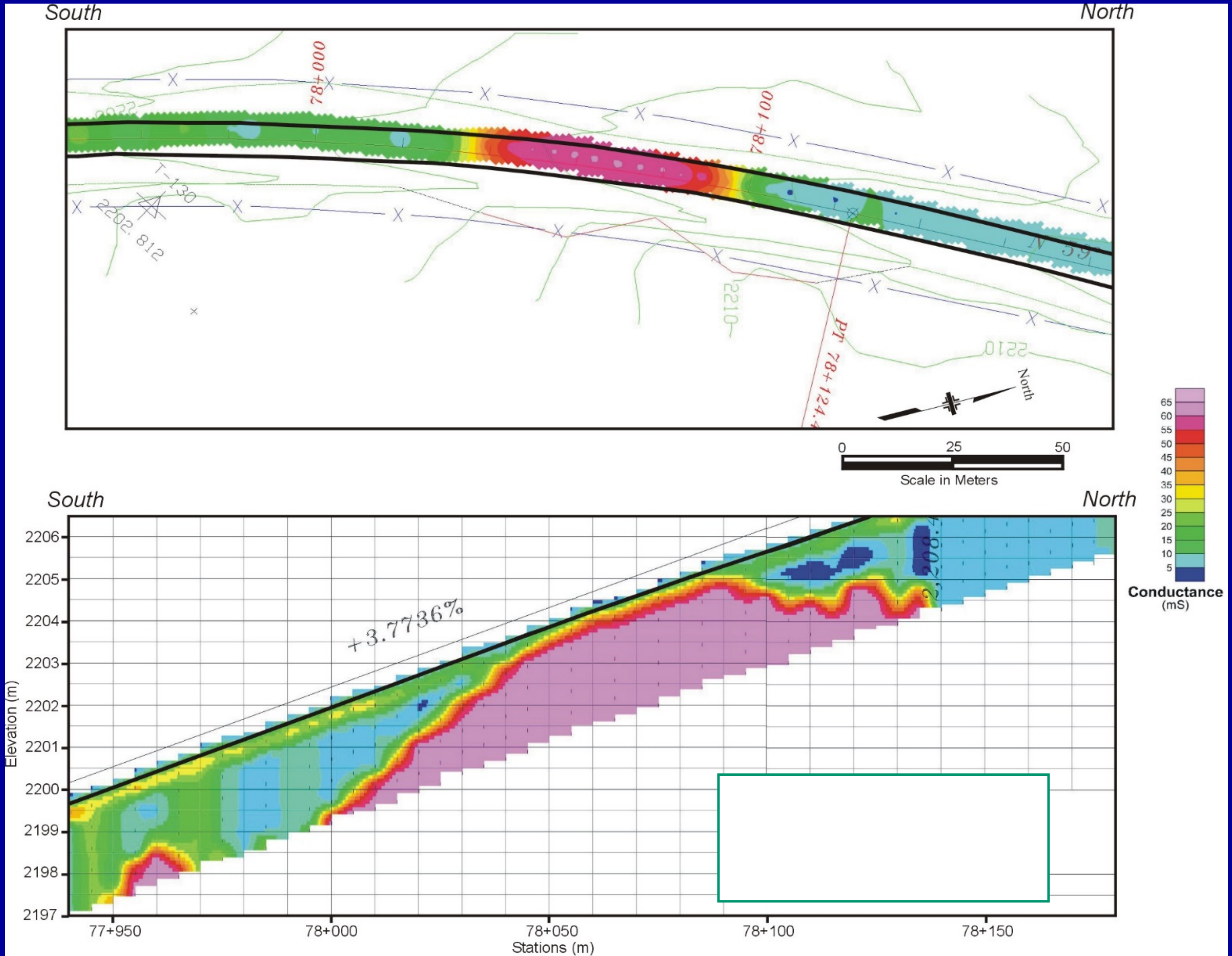
Different coil heights

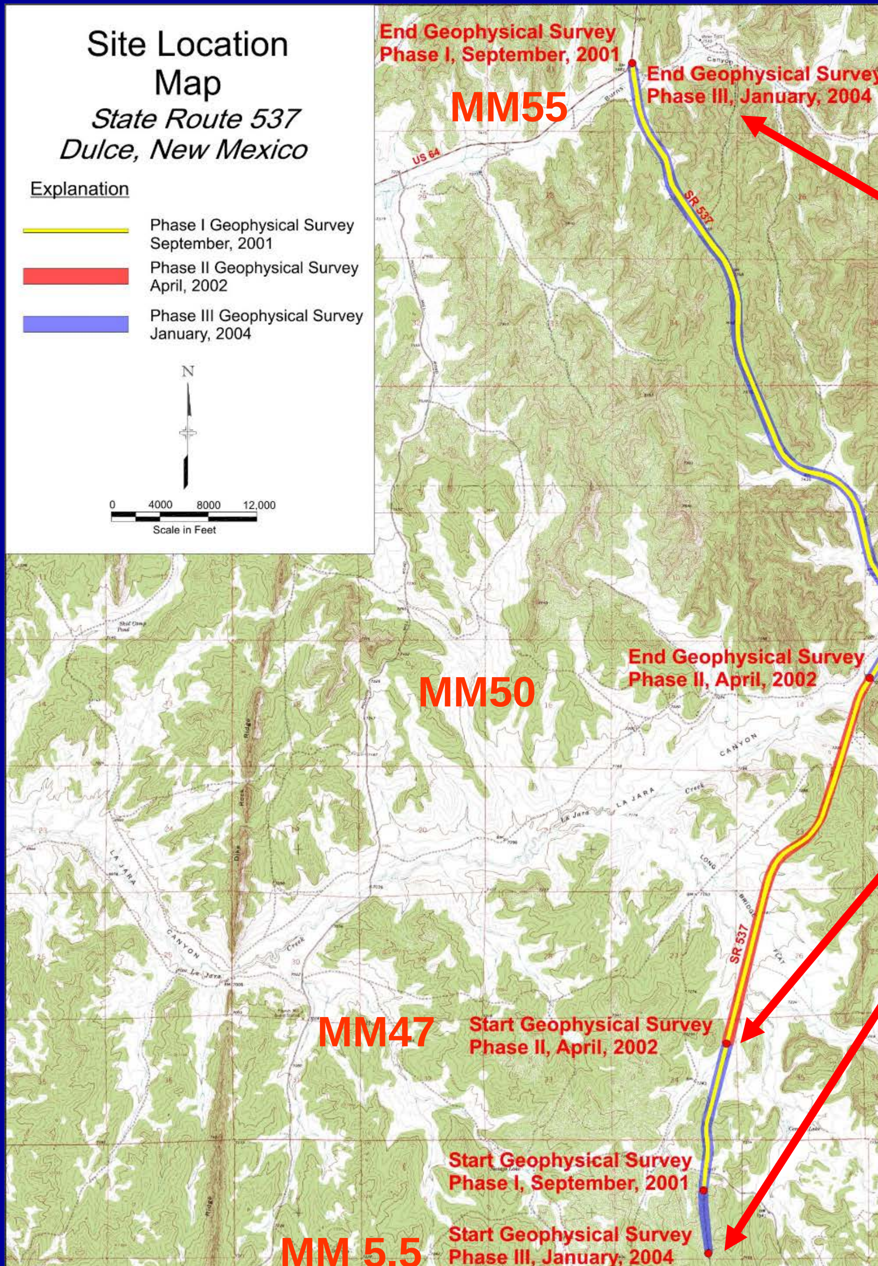
Phase II EM Results

Color Contoured ***Interval Conductance*** Overlain on Standard FHWA P & P Sheet

Plan View
2-foot depth

Profile View
(geo-electric section)
0 to 10-foot depth





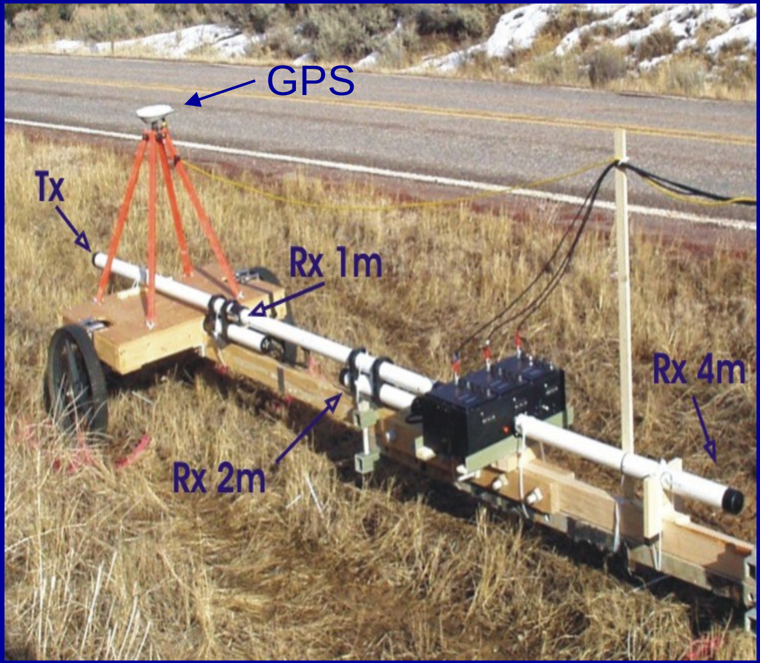
Phase III Survey Area

MM45.5 to MM47+
MM50 to MM55+
~ 8 miles of SR537

Phase III EM Surveys – Field Setup

- "**New**" EM31-3 instrument with 3 receiver coils
- Geophysical data integrated with GPS survey
- Data acquired more rapidly (e.g., ~10 MPH)
- New inversion code is used to handle the increased data for modeling vertical profile

Tow Vehicle and EM31-3 System

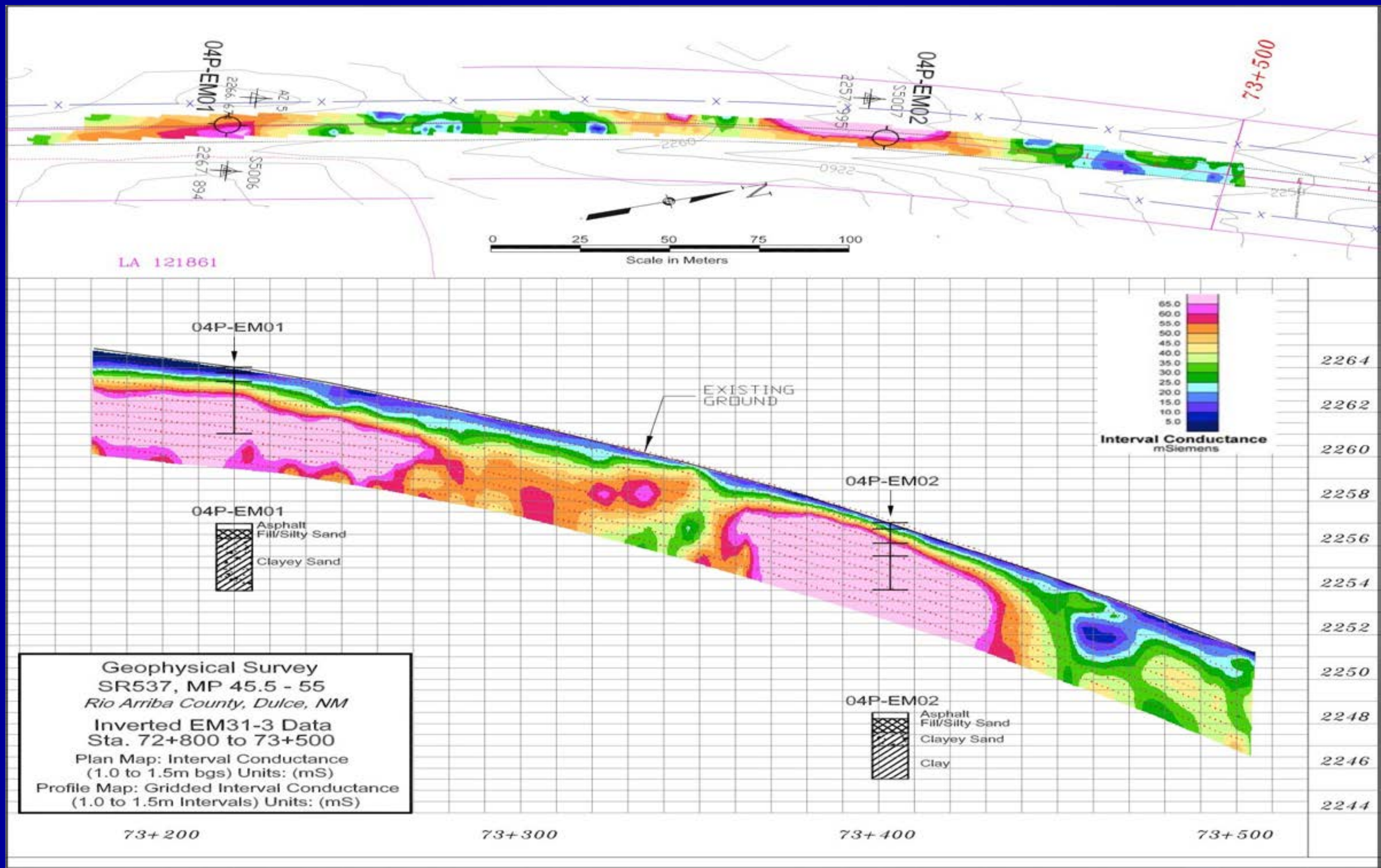


Phase III EM Results

Color Contoured **Interval Conductance** Overlain on Standard FHWA P & P Drawing with Soil Boring Information

Plan View
2-foot depth

Profile View
(geo-electric section)
0-15-foot depth



Lessons Learned from Clay Mapping Case Studies

- GPS and EM data acquisition systems need to be synchronized
- Data must be collected over roads without metallic reinforcement (e.g. asphalt, dirt, etc.)
- Areas with significant cultural features potentially affect the data (e.g. overhead or buried utilities, railroad crossings, metallic structures, etc.)
- Geophysical interpretation needs to be calibrated with site-specific geologic information (e.g. soil borings, lab analyses)

Benefits from Clay Mapping Case Studies

"A Practical Tool for Mapping Clay in Road Base"

- Fast, efficient, and co$t effective for mapping the lateral distribution, depth and thickness of clays
- Complements and focuses soil sampling programs during preliminary site investigations, road rehabilitation design, and construction projects
- Provides significant cost savings by reducing overruns for over-ex!