Seismic Full Waveform Inversion and Tomography

TRB Webinar 2015

By:

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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

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 wave-equation based 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
   - $d_{est} = f(Vs_{est}, Vp_{est})$

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

![Diagram of data acquisition and analysis](image)

- Measured
- Estimated
- $V_p$, $V_s$

- Compression wave
- Shear wave

- $\uparrow$: Geophones
- $\downarrow$: Sources

- Ground surface

Rayleigh Wave
Synthetic test on an embedded void

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

Test line 1: G20:G140 (36 m)

Chimney 1 (1.5 m dia)

Test line 2: 95A:95K (28 m)

Chimney 2 (1 m dia)

Chimney 3 (1 m dia)
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
薯条

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


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
2011 - Hurricane Irene cuts 2\textsuperscript{nd} channel at Oregon Inlet
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 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

Jaxs

Scour
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

Solar panel (blue) and remote controller (red) affixed to ends of original pile cap with steel bands

Transducers affixed to 66-inch dia. concrete cylinder piles a minimum of 2 feet below low tide level
Remote Installation
Solar Panel and Controller
Original Transducer Mounting Plan

Bracket (2 per transducer)

Not to Scale
Revised Transducer Mounting Plan

Louver pile cap transducer bracket

7/8 x 6" bolt (both sides)

3/8 x 3" bar

78 1/2"

9/8" OD 3/8" pipe

1 1/3"

Collar

11"

Transducer (screw into pipe in bottom of pile)

2 5" sleeve

IO 5/8" 4'

Long

All parts stainless steel 304

W anti-fouling paint

O2 transducer (in place)
Revised Transducer Mounting Plan

Bracket

Transducer Pole
West Side Transducers and Solar Panel
East Side Remote Controller
Website

Bonner Bridge Scour Monitoring System

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

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 the
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
Variable ‘Dense/Hard’ Soils

Competent Bedrock
- Basalt -

LEGEND:
Boring Name and (Approximate) Projected Location
Top of Basalt from Boring Data
Total Depth of Boring
600 ft/s Contour
2000 ft/s Contour

Scales:
Vertical Exaggeration 2X
S-Wave Velocity (ft/s)

Station Location (feet)

Note:
Station locations and ground surface elevations based on Track Alignment Plan and Profile drawings dated 00-12-08

IBC Vs Site Classification Values

600 ft/s

2000 ft/s

TEST LINE 1 → Finalized Vs Section with Seismic Interpretation and Geology
LINE 3 – PRODUCTION PHASE
LINE 3 (Continued)
Stopped drilling at 200' (where's bedrock?)
Downhole Vs Results

170’ - no bedrock

LEGEND:

B-109
Boring Name and (Approximate) Projected Location

Top of Basalt from Boring Data

Total Depth of Boring

600 ft/s Contour

2000 ft/s Contour

SAFETY FIRST
HONOLULU HIGH-CAPACITY TRANSIT CORRIDOR PROJECT EWA, OAHU, HAWAII SEISMIC CROSS-SECTION LINE 4 STATION 649+06 TO 656+00

Note:
Station locations and ground surface elevations based on Track Alignment Plan and Profile drawings dated 09-12-08

Vertical Exaggeration 1.25X

Scales:

0 0 100
0 50 100

S-110 (Bedrock not encountered)

B-109 (SW)

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<th>Depth (To) (feet)</th>
<th>Layer Thickness (d) (feet)</th>
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LEGEND:

B-109

Projected Location

Top of Basalt from
Boring Data

Total Depth of Boring

600 ft/s Contour

2000 ft/s Contour

SAFETY FIRST
HONOLULU HIGH-CAPACITY
TRANSIT CORRIDOR PROJECT
EWA, OAHU, HAWAII
SEISMIC CROSS-SECTION
LINE 4
STATION 663+00 TO 668+85

Note:
Station locations and ground surface elevations based on
Track Alignment Plan and Profile drawings dated 9-12-08

Vertical Exaggeration 1.25X

LINE 4 (End)
Poor-Man’s GIS

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

Shear Wave Velocity (ft/sec)

- 300
- 775
- 1850
- 2925
- 4000

Basalt

‘Soft’ Soils

‘Dense’ Soils

Basalt

L1 L2 L3 L4 L5

300
4000

1850
2925

Shear Wave Velocity (ft/sec)
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)
Mapping Clay in the Subgrade Case Studies

FHWA, EFLHD

Natchez, Mississippi

Natchez Trace Parkway

FHWA, CFLHD

Dulce, New Mexico

SR 537
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
Bottom Line is Cost!
Unexpected clay may result in:

- Project overrun costs
- Construction delays
- Rehabilitation cost increase
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
Example of HIGH conductivity area

EM31 “Data / Results”

Grid Northing, m

Grid Easting, m

CLAYEY

SANDY

Apparent Conductivity (mS/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 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** Overlaid 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 cost 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!