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Non-Contact Air-Coupled Sensing for Rapid Evaluation of Bridge Decks

Jinying Zhu
University of Nebraska - Lincoln

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INSPECTING AND PRESERVING INFRASTRUCTURE THROUGH ROBOTIC EXPLORATION

INSPIRE University Transportation Center Webinar

Non-contact Air-coupled Sensing for Rapid Evaluation of Bridge Decks

March 12, 2020



Jinying Zhu

Associate Professor
Civil and Environmental Engineering
University of Nebraska-Lincoln

Ph.D.: University of Illinois at Urbana-Champaign

Research Interest

Nondestructive Testing and Evaluation (NDT/NDE)

Wave propagation

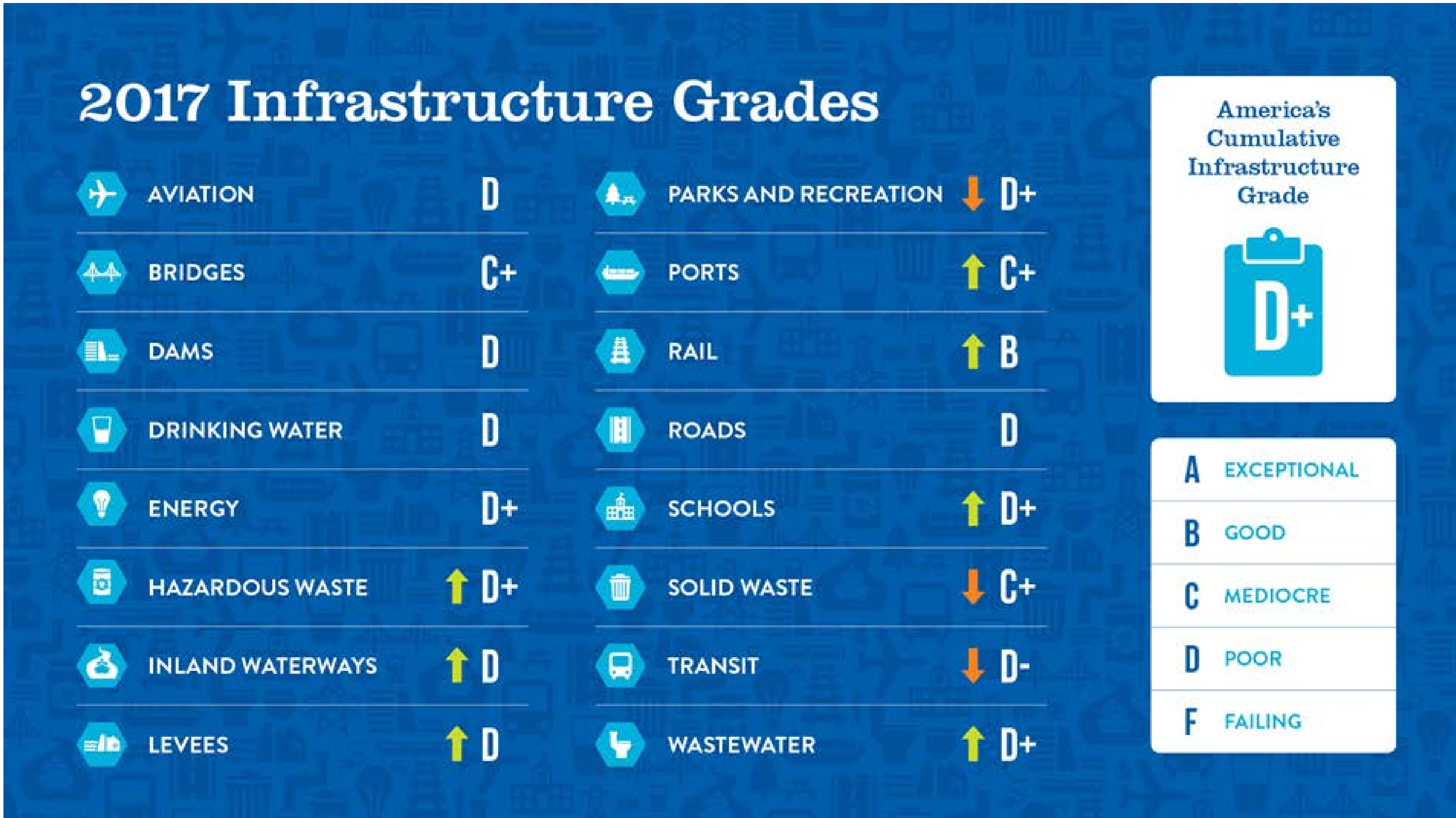
Sensor development and sensing technologies

Material characterization using ultrasonic waves

Nonlinear ultrasonics

Infrastructure in America

ASCE 2017 report card gives GPA of America's infrastructure– D+



Bridge deck delamination

- 6.3% of total bridge area belonged to structurally deficient bridges in 2016, improved from 9.5% of 2007 (old definition).
- 178 million trips across a structurally deficient bridge each day in 2018
- More than 50% bridge maintenance funds went to repair or replacement of bridge decks

Solutions?

Investment

- Challenging funding situation

Technical innovations

- New technologies and materials for long life bridges
- Prioritize maintenance needs based on reliable evaluation

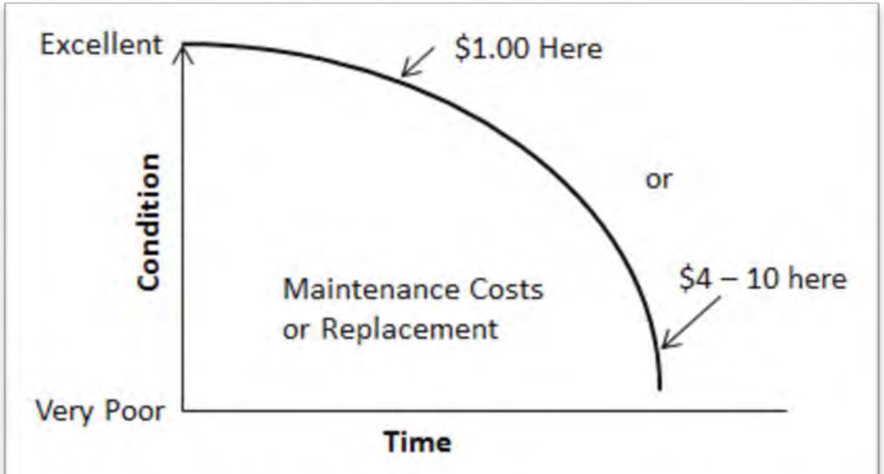


Figure 1. Cost of deferring maintenance.

Haas, R., W.R. Hudson, and L.C. Falls, *Pavement Asset Management*, Wiley Publishing, 2015.

Flexural vibration of shallow delamination

Shallow delaminations

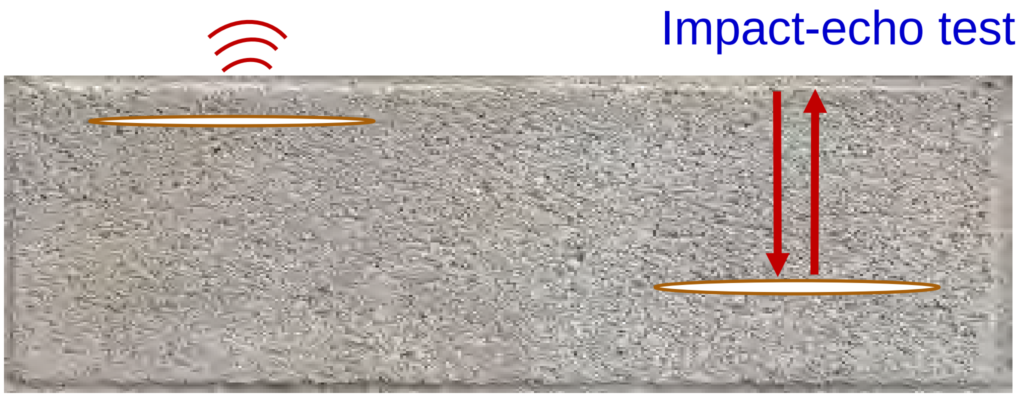
- Typically occur within the top 2 inch depth over the first layer rebars
- Flexural mode (drum vibration) is easy to excite – hollow sound
- Frequency depends on size and depth of delamination, usually low frequency (0.5~5kHz), within human hearing range

Chain drag works for shallow

IE test for deep delaminations

Deep delaminations

- Thickness mode (Impact-echo mode), Frequency depends on depth only (higher frequency than flexural mode)
- Chain drag does not work



$$D = \beta \frac{C_P}{2f}$$

$$\beta = 0.96 \text{ for plate}$$

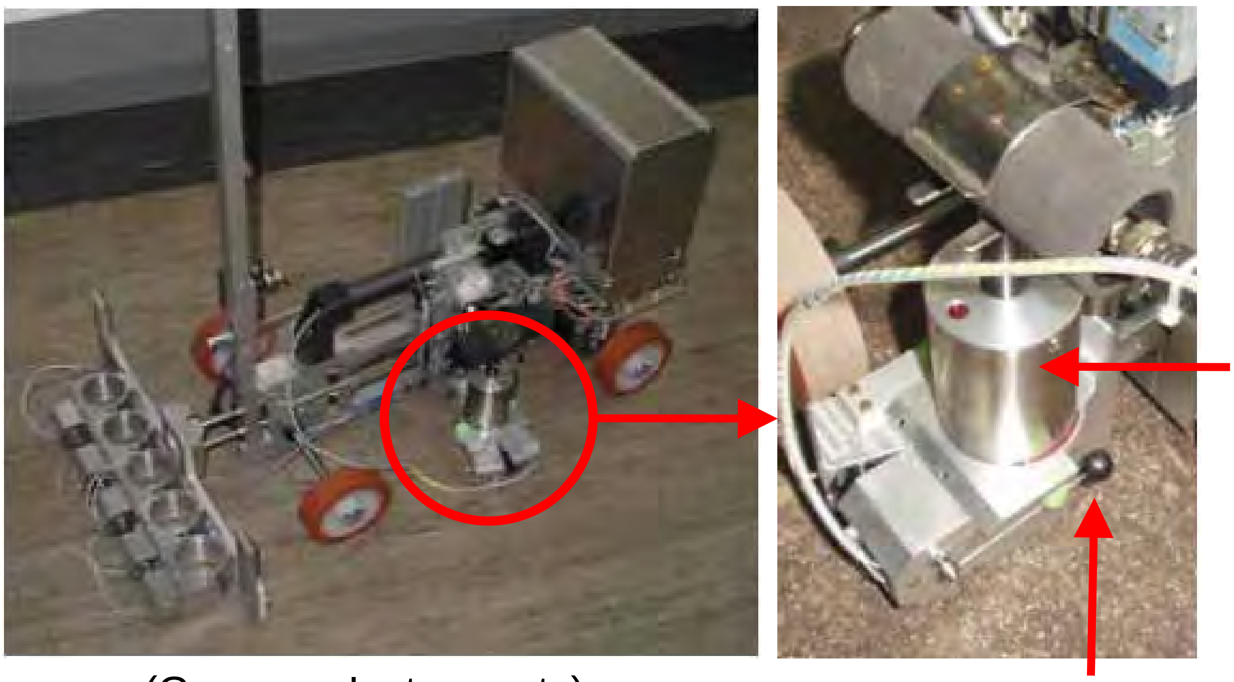
Challenges in current chain drag test

- Listen
  - Affected by traffic noise
  - Varies from person to person, day to day
- Make Decision
  - Subjective, depends on inspector's experience
  - No data saved for future reference and comparison
- Mark, measure and map defects
  - Slow, directly show results on deck

Improvement in impact-echo

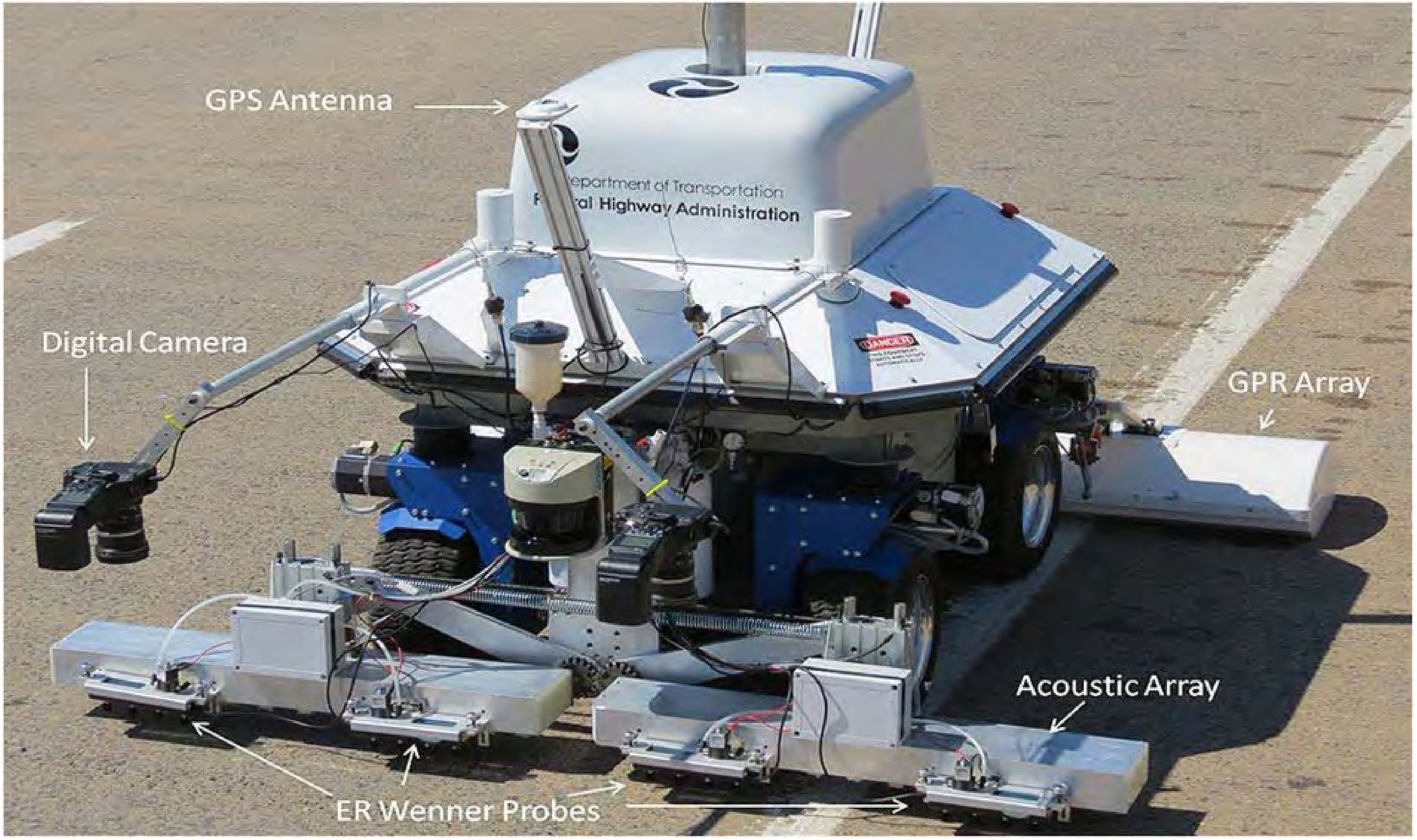
Stepper: an automated scanning device (2008)

Can only reach slow walking speed



(Germann Instruments)

Robotic Bridge Deck Assessment Tool - RABIT



FHWA Long-Term Bridge Performance (LTBP) Program

Stress wave based NDT methods

CHALLENGES

- Contact sensor
- Marking grid before testing
- Contact source

Slow

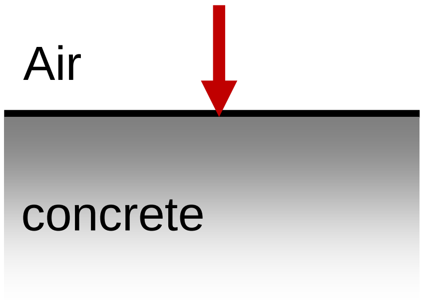
SOLUTIONS

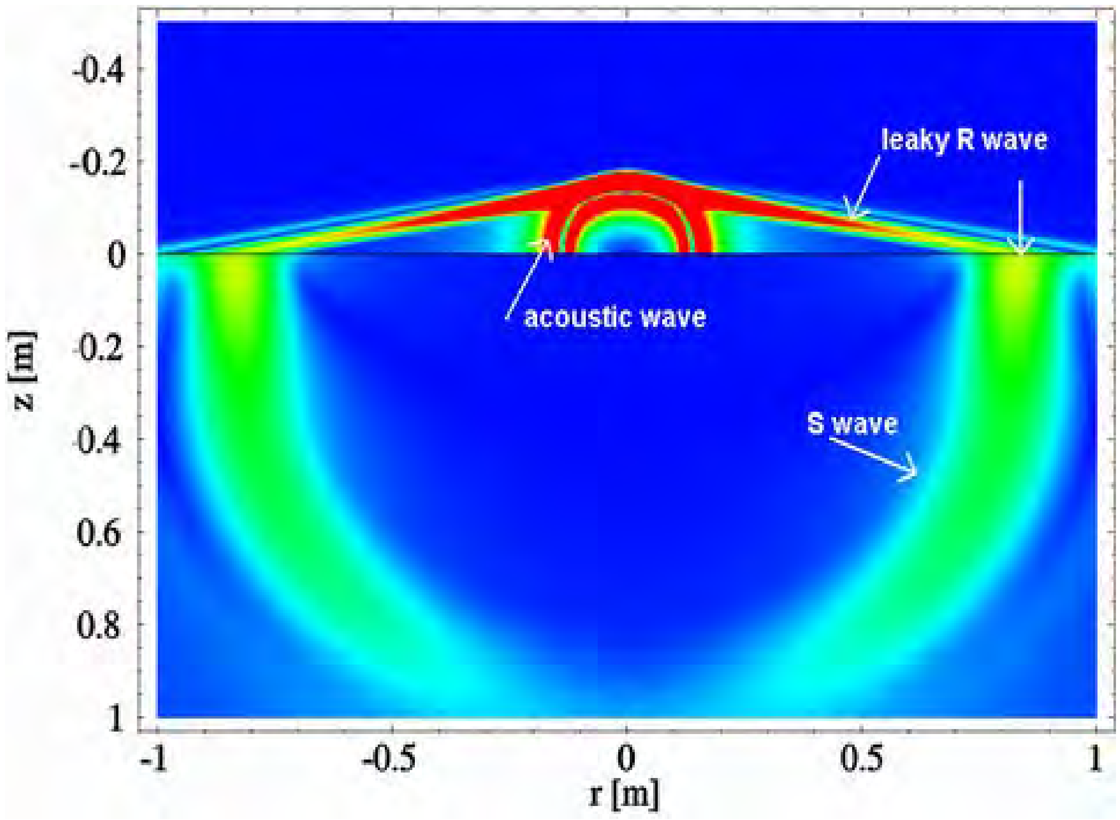
- Non-contact sensor (air-coupled sensing)
- Auto positioning system (GPS/Lidar)
- Continuous excitation

Rapid

Air-coupled Sensing

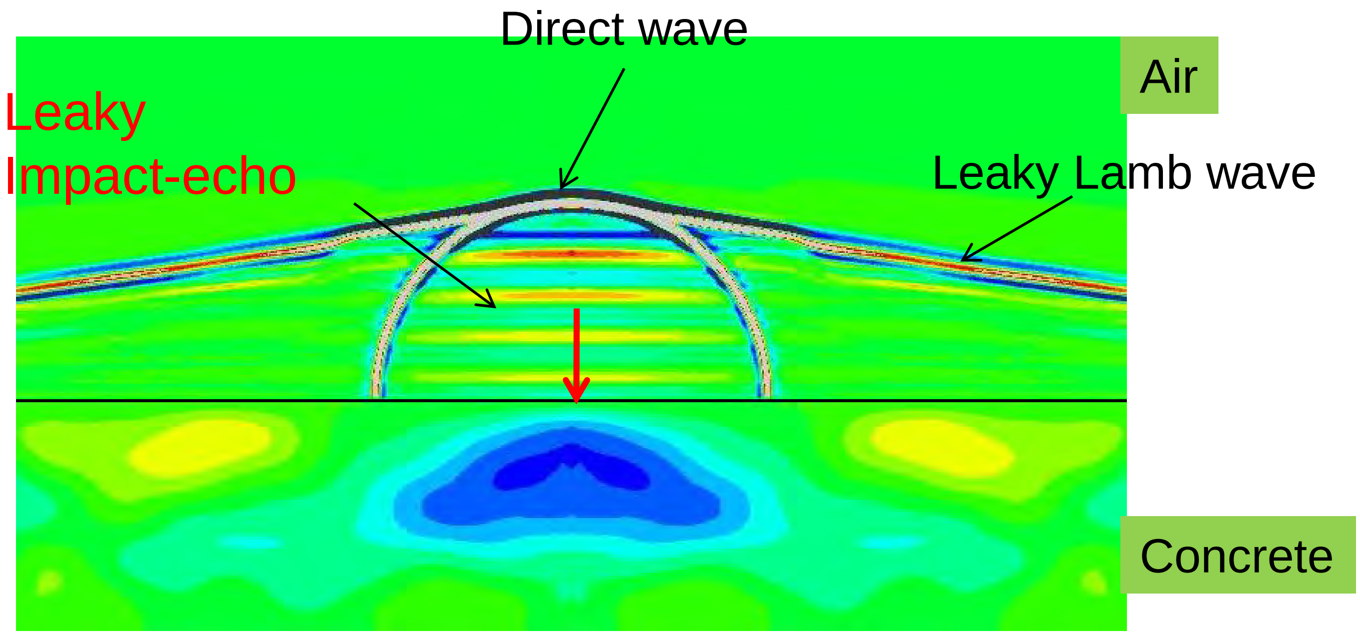
Wave field in Air/Concrete





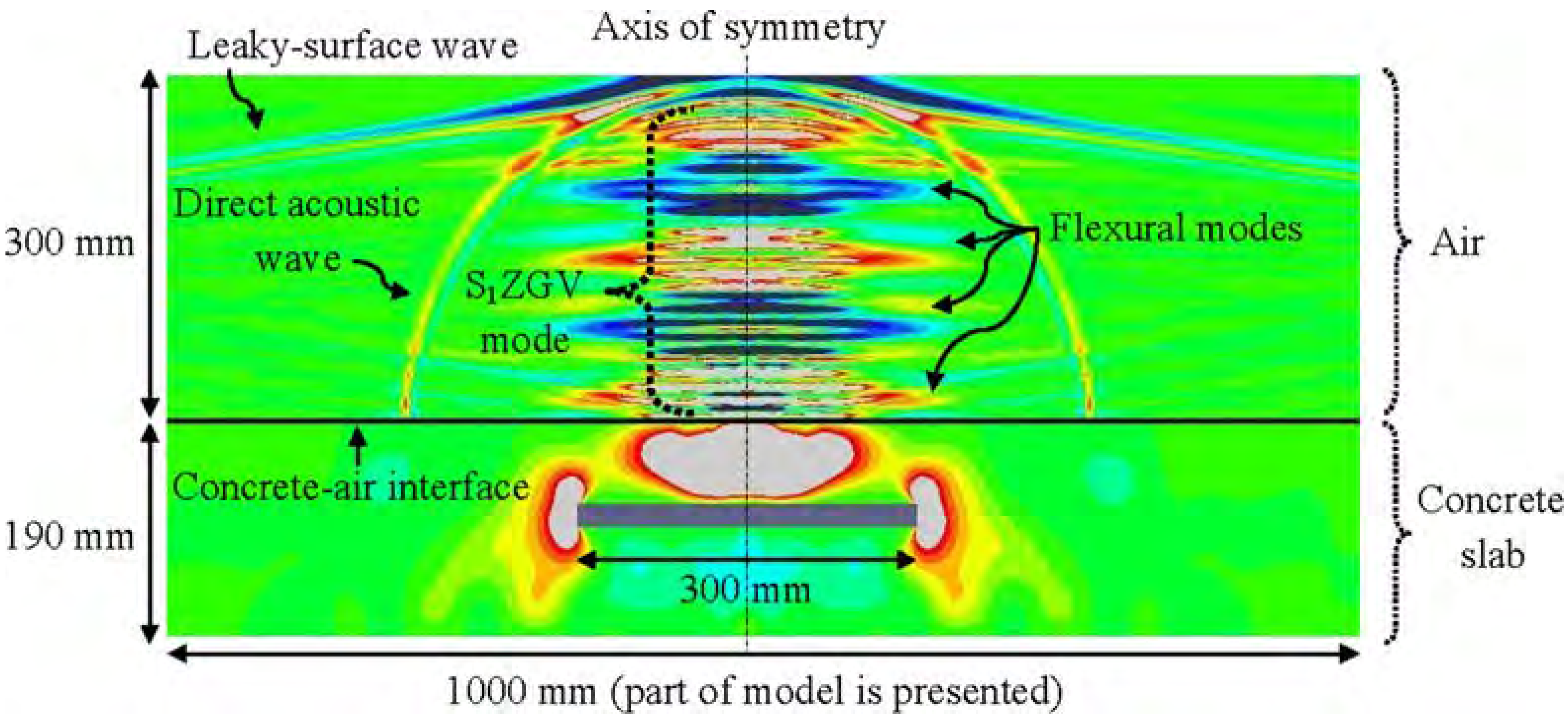
Numerical Simulation of IE test on a plate

Numerical simulation verifies that the IE vibration in a plate radiates quasi-plane wave in air.



Numerical Simulation of IE test

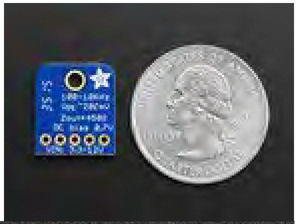
Strong flexural mode in delaminated plate (75mm depth).

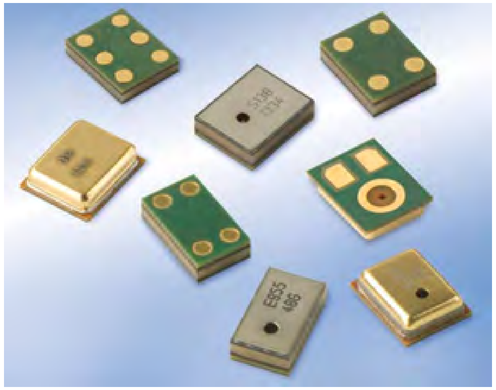


Problem: how do we sense the waves in air?

Air-coupled Sensors - Microphones

High precision condenser microphone
- frequency range (4Hz – 80kHz)
- expensive (>$1000)

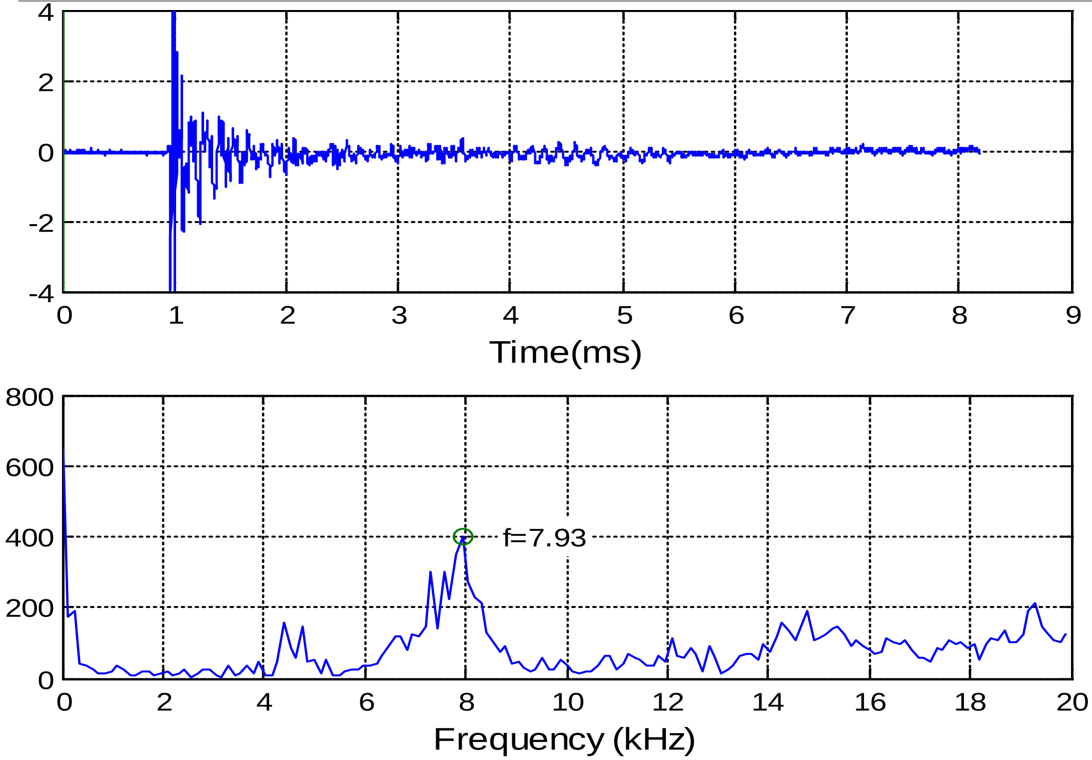


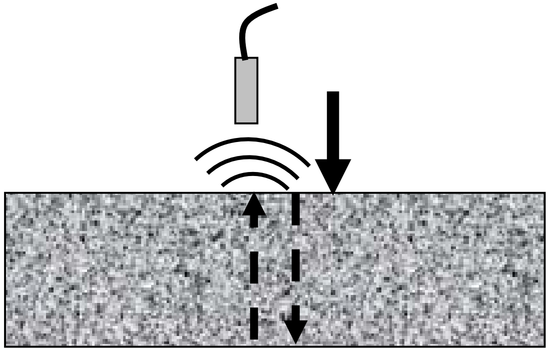


Audio Microphone
Freq range: 0-25kHz

MEMs Microphone
Freq range: 0-10kHz
Very cheap

Air-Coupled Impact-Echo– Typical Signal



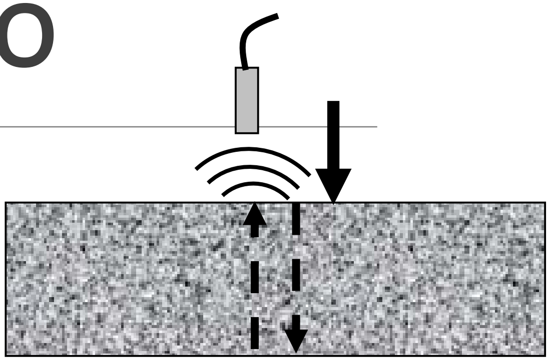


Tested on a concrete slab of h=250mm, Cp=4100m/s.

The tested thickness D= 0.96*4100/(2*7.93)=248mm

$$D = \frac{0.96 C_P}{2f}$$

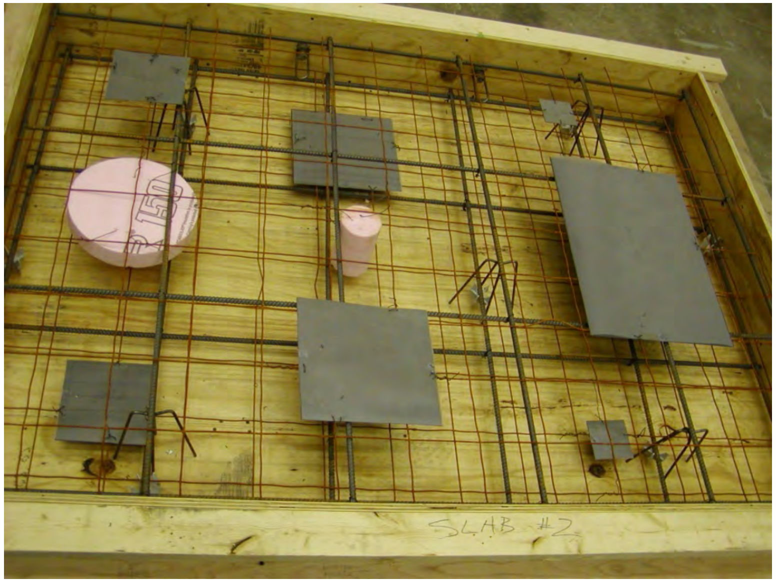
Air-Coupled Impact-Echo

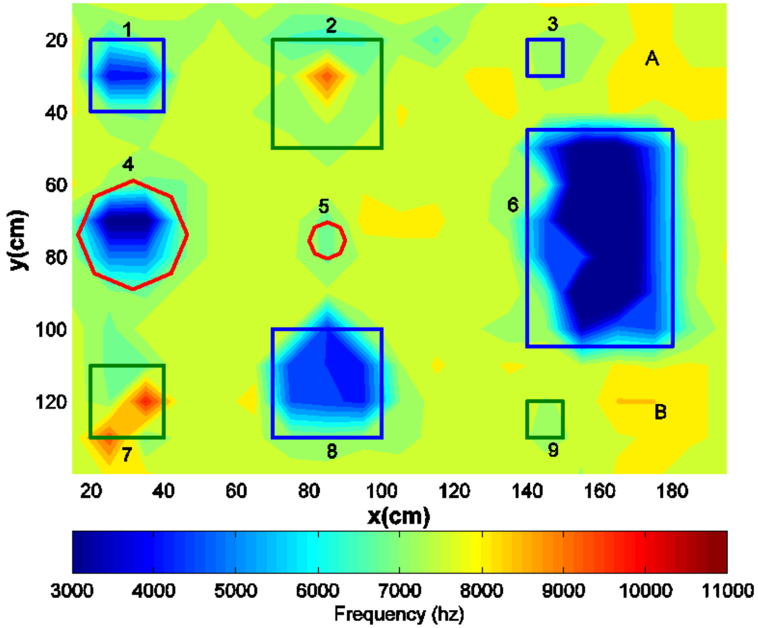


Preliminary laboratory experiment showed the feasibility of air-coupled IE test

Using a microphone

Shallow delaminations are easy to detect



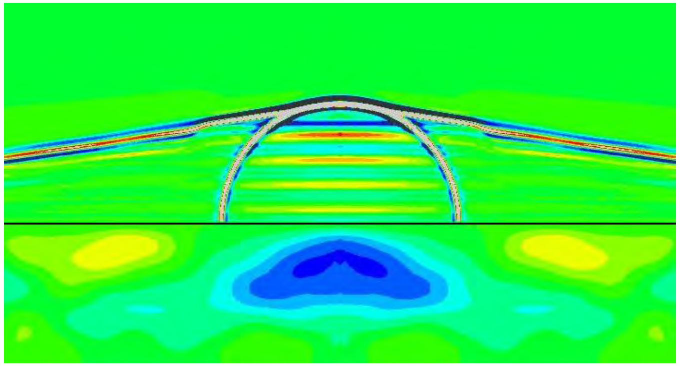


Problem: What about noise?

Parabolic reflector

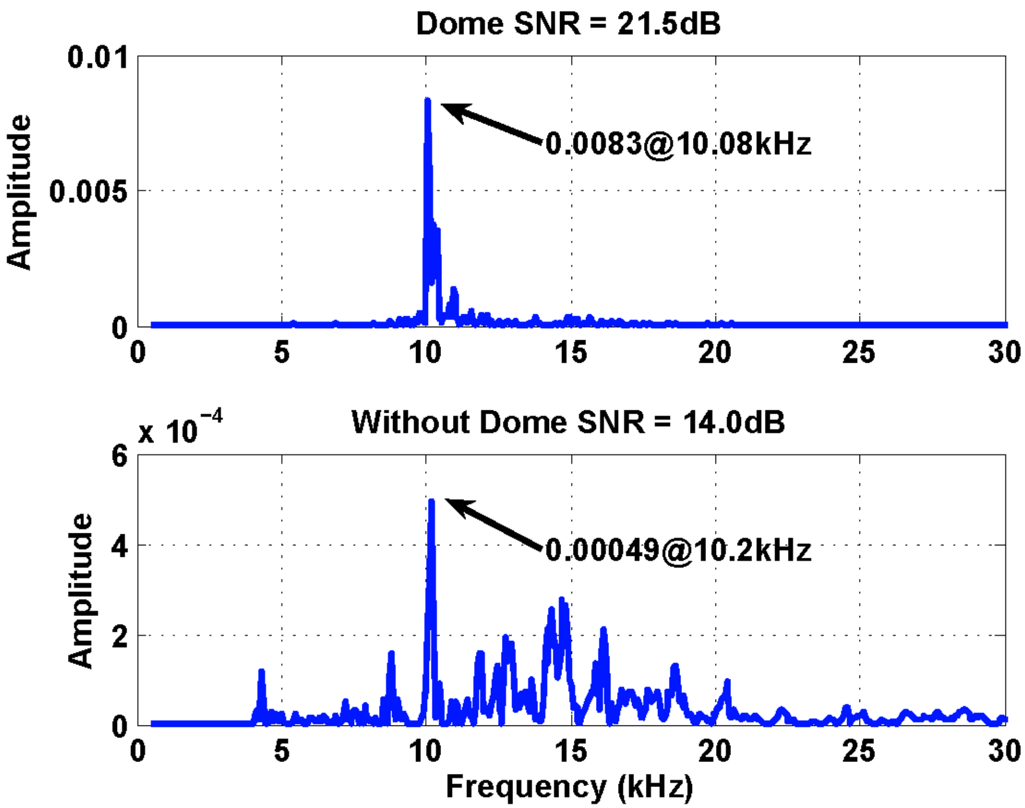
A parabolic reflector converges incident plane waves to the focal point.

Applications: microphone amplifier, antenna, flash light

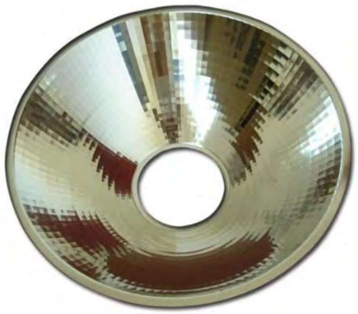


Experimental verification

Air-Coupled IE test on 190 mm (7.5 in) thick concrete slab with a 15 cm (4 in) diameter reflector

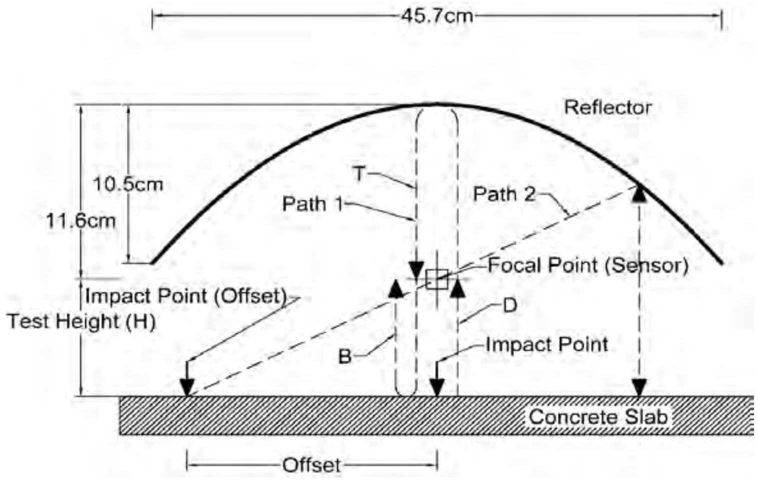


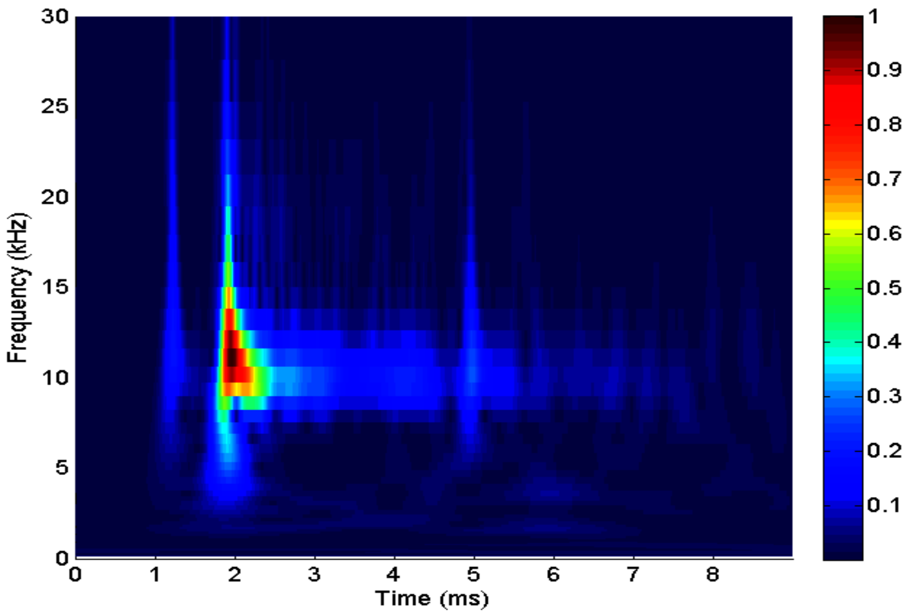
- Reflector brings **7.5dB** SNR gain on IE frequency
- IE frequency gain of **24.5 dB**



Amplification mechanisms

1. Parabolic focusing
2. Multiple reflections



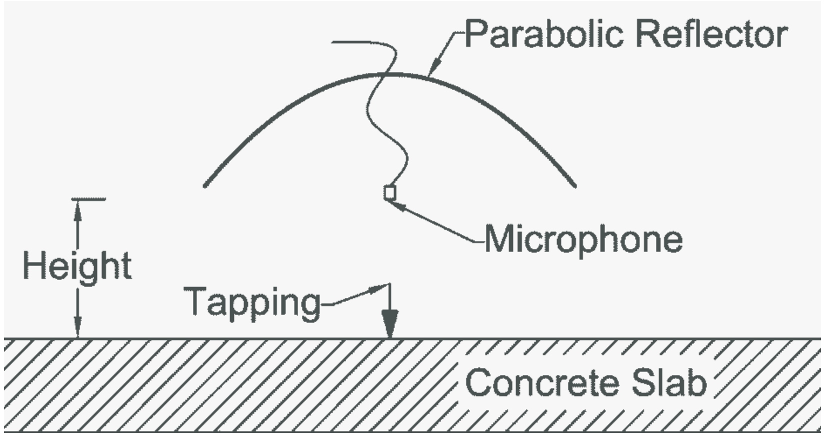


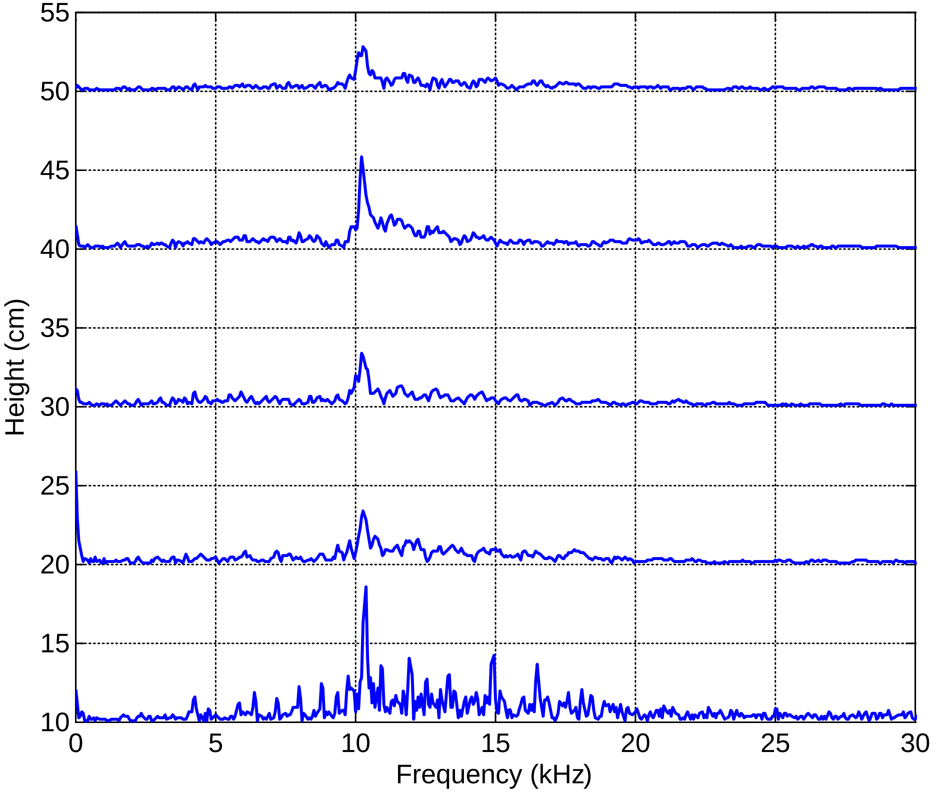
(Dai, Zhu, Haberman, JASA, 2011)

Effect of sensor height

The IE frequency is not affected by sensor height (with reflector)

Useful feature for field testing





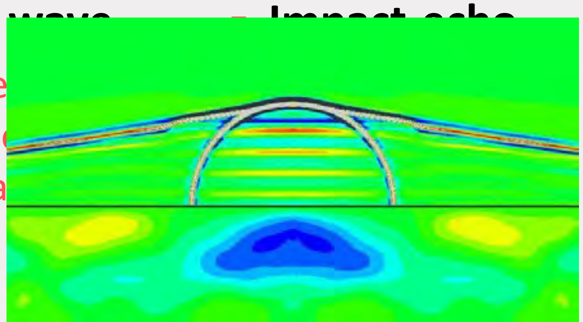
Frequency spectra for different sensor height (with parabolic reflector)

Air-coupled Sensing for Concrete – development timeline

Measuring Leaky surface wave 20..

Show fe... air-coupl... of surfa... concrete

Air-coupled Impact-echo 20..



Parabolic reflector for Impact-echo 2011

(JASA-EL)

Acoustic source 2013

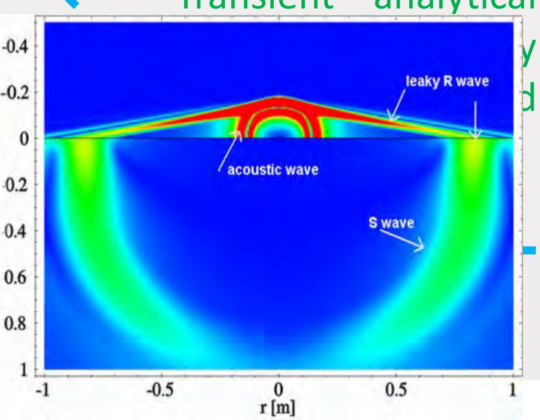
Spark source for non-contact excitation (JASA-EL)

Automated system 2017

Low cost acoustic scanning system

Analysis of leaky surface wave 2004

Transient analytical ...



Crack depth 2007

Use air-coupled surface wave to measure crack depth (JASA)

Analysis of reflector 2013

Optimize geometry of parabolic reflector (JASA)

Demonstration 2013-14

Air-coupled sensors on robot for Field

Air-coupled Sensing for Concrete – development timeline

2001 – Measuring Leaky surface wave
Show feasibility of air-coupled sensing of surface wave in concrete (QNDE)

2004 – Analysis of leaky surface wave
Transient analytical solution of leaky wave in fluid-solid system (JASA)

2005 – Air-coupled Impact-echo
Measured IE mode using mic. (Zhu thesis, ASCE)

2007 – Crack depth
Use air-coupled surface wave to measure crack depth (JASA)

2011 – Parabolic reflector for Impact-echo
(JASA-EL)

2013 – Analysis of reflector
Optimize geometry of parabolic reflector (JASA)

2013 – Acoustic source
Spark source for non-contact excitation (JASA-EL)

2013-14 – Demonstration
Air-coupled sensors on robot for Field demonstration

2017 – Automated system
Low cost acoustic scanning system

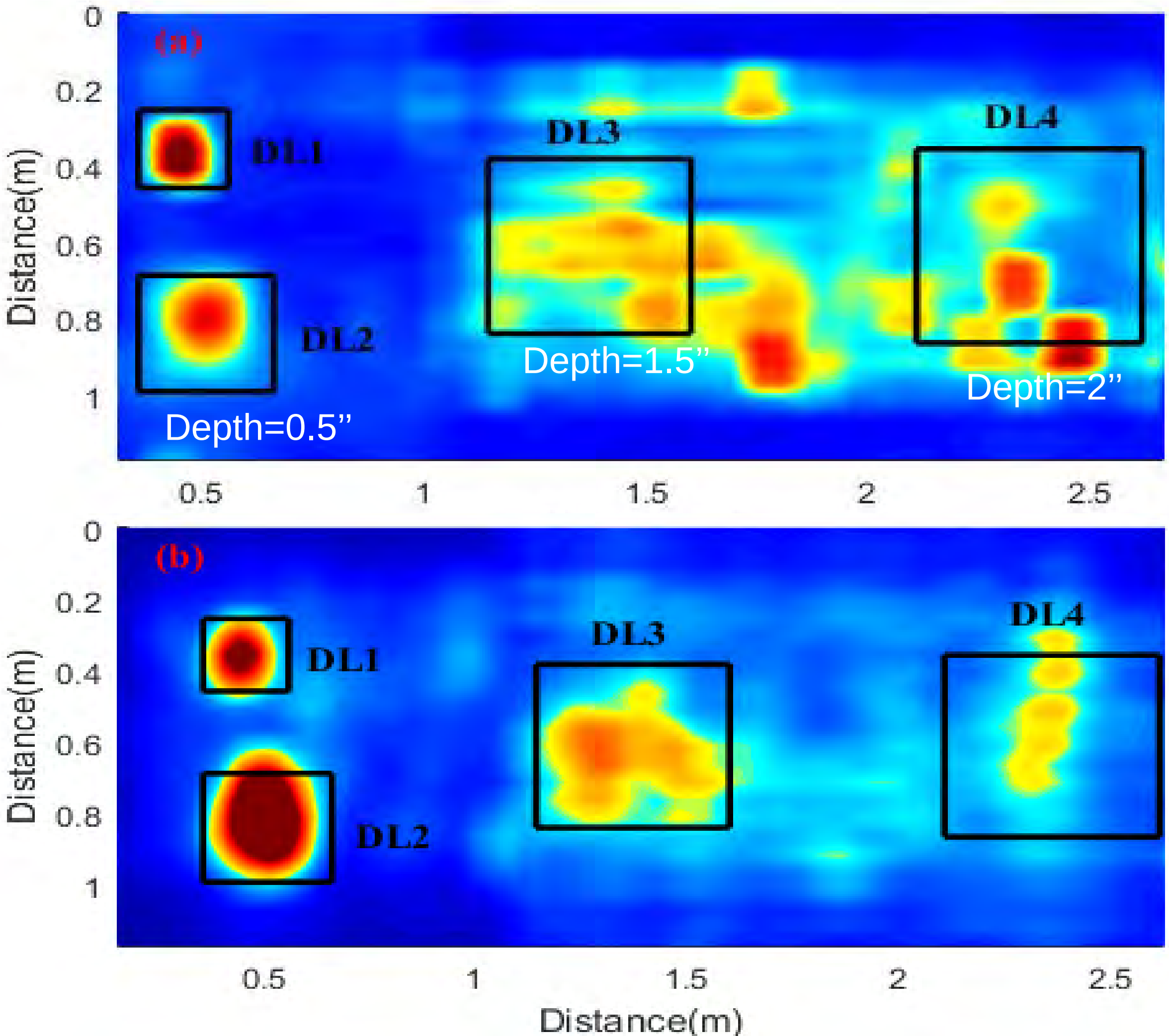
Applications to Bridge Evaluation

Problem: How to make it fast? What about source?

Resonance frequencies of delaminations

Delamination	Size	Depth	Resonant frequencies		
			1st	2nd	3rd
#1	8 x 8''	1''	**2.9 kHz**	--	--
#2	12 x 12''	1''	**1.7 kHz**	**3.1 kHz**	--
#3	18 x 18''	1.5''	0.85 kHz	**2.3 kHz**	--
#4	20 x 20''	2''	0.7 kHz	**1.4 kHz**	**2.6 kHz**

Scanning image of concrete slab



Steel-chain

Ball-chain

(Sun, Zhu, Ham 2018 ASCE JBE)

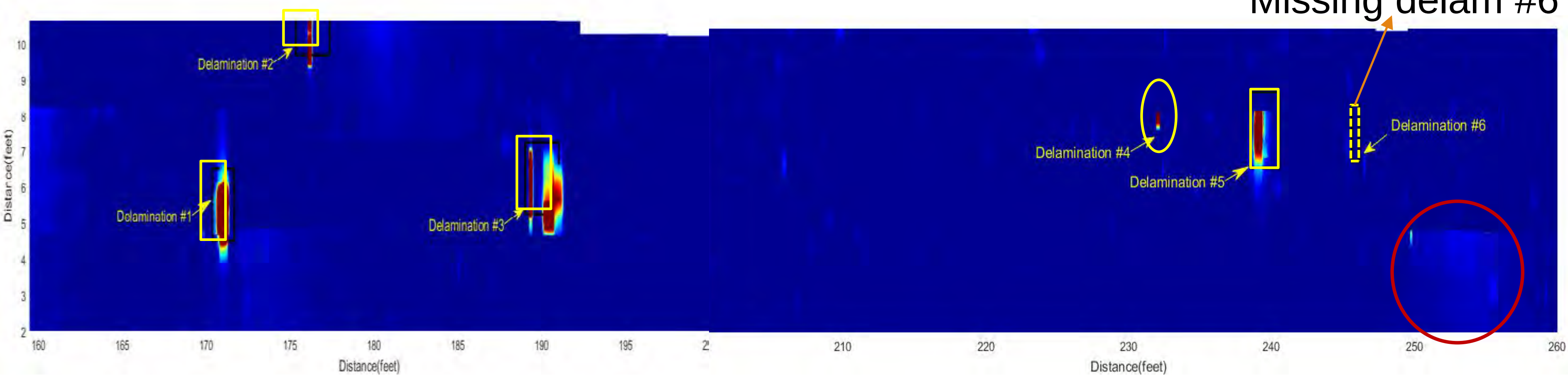
Automated Acoustic Scanning System

Automated Scanning system with 6 inch lateral resolution

Continuous data collection and analysis

RTK GPS gives spatial accuracy to 1cm (0.5 inch)

Missing delam #6



Traffic noise

Bridge deck with asphalt overlay

Name: S092 46635

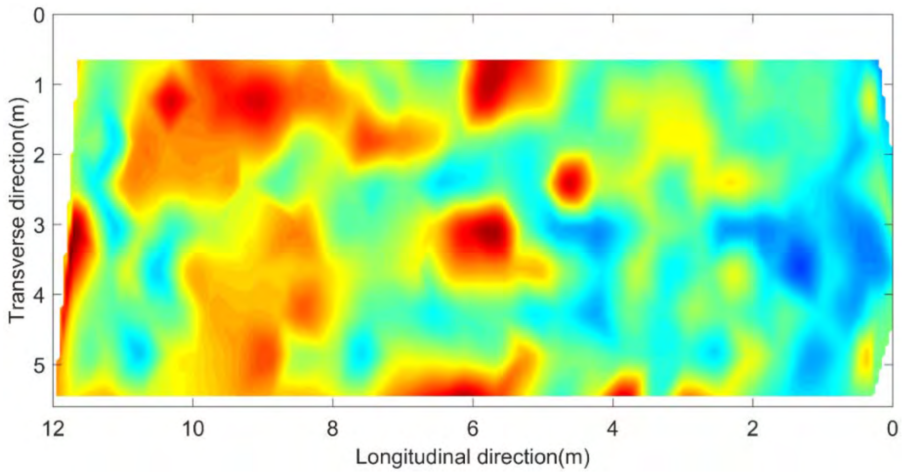
Location: N92 over Platte overflow

Length: 38 ft (13m)

Year built: 1955

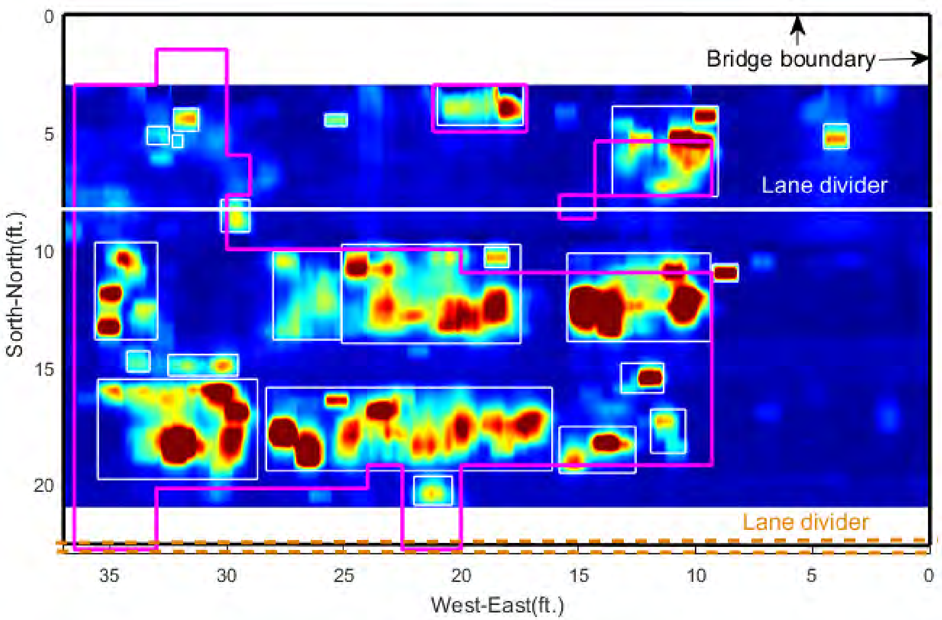
Condition: Poor *[4 out of 9], 2016*

GPR scan image

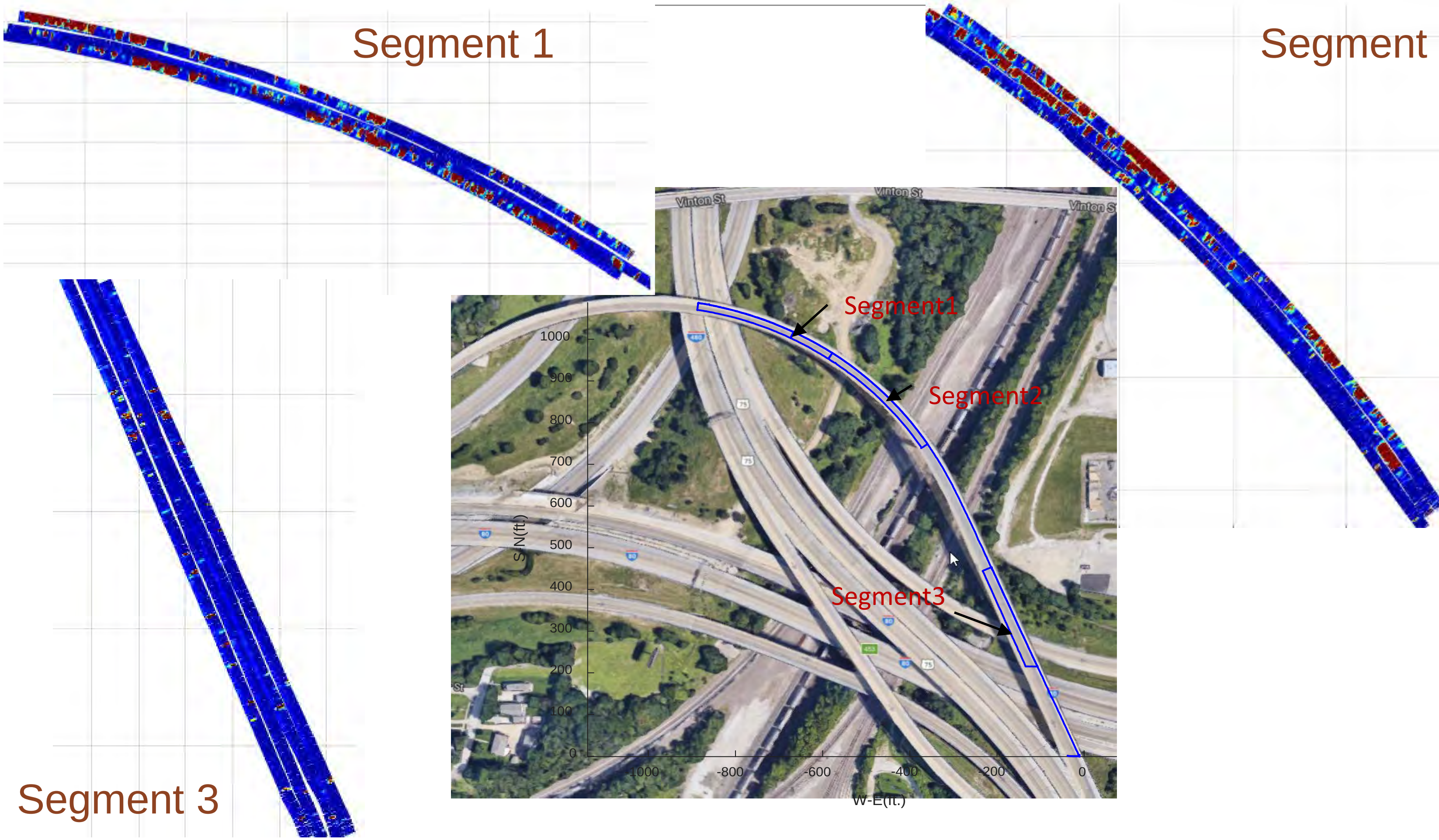


Removal of asphalt layer

Chain drag and acoustic scanning test results after removal of asphalt layer



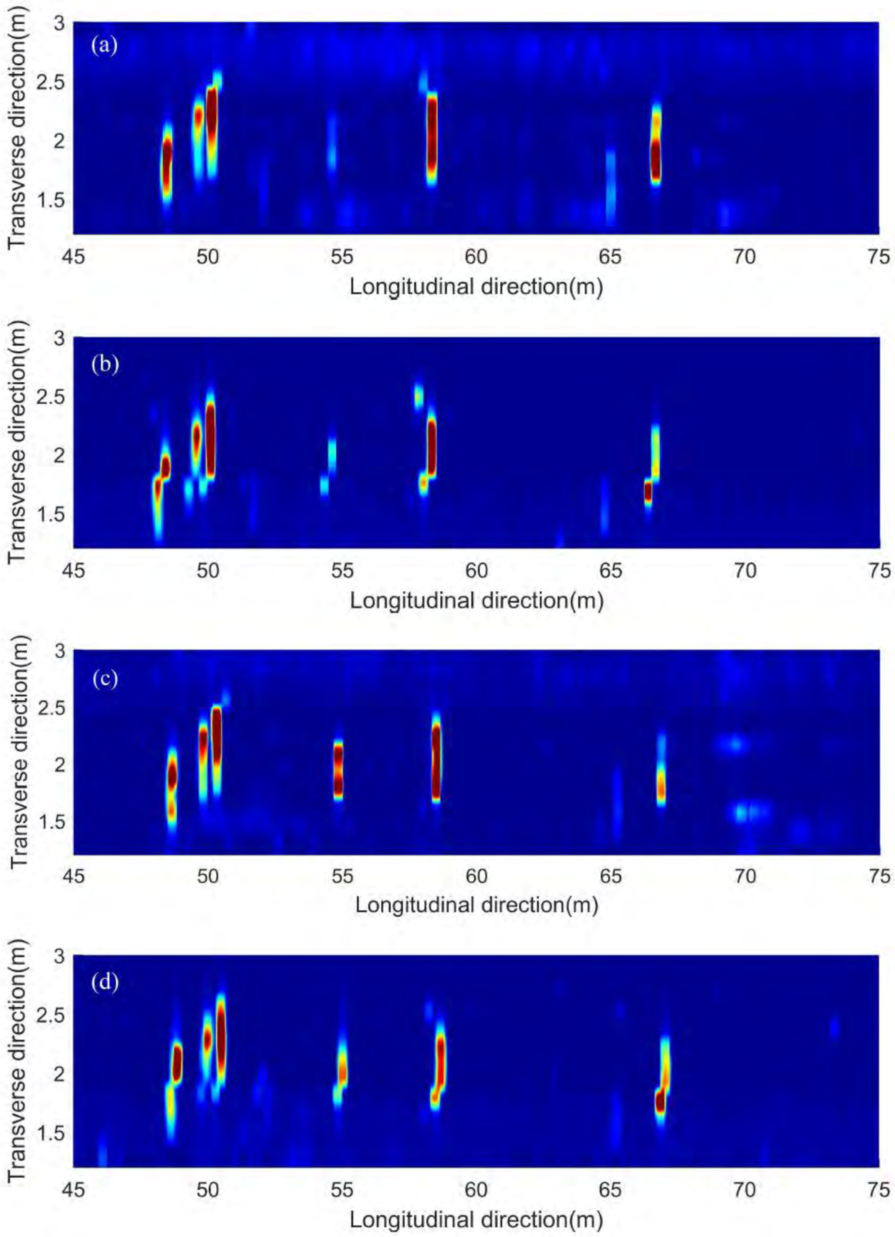
Hwy75 NB to I-80 NB flyover (Omaha, NE)



Tested on 07/06/2017

Repeatability

Acoustic scanning



Future for air-coupled sensing

- Robust acoustic test and analysis methods
- Non-contact or rapid source (traffic speed)
- Integrated scanning system with Automated data acquisition and positioning
- Big data and data analytics

Acknowledgements

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Rutgers University

Electric Power Research Institute (EPRI)

University of Nebraska System

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INSPIRE University Transportation Center Webinar

Mobile Manipulating Drones, Dr. Paul Oh

June 17, 2020