



We've Scanned It, Now What?
Making NDT More Useful for Material Characterization

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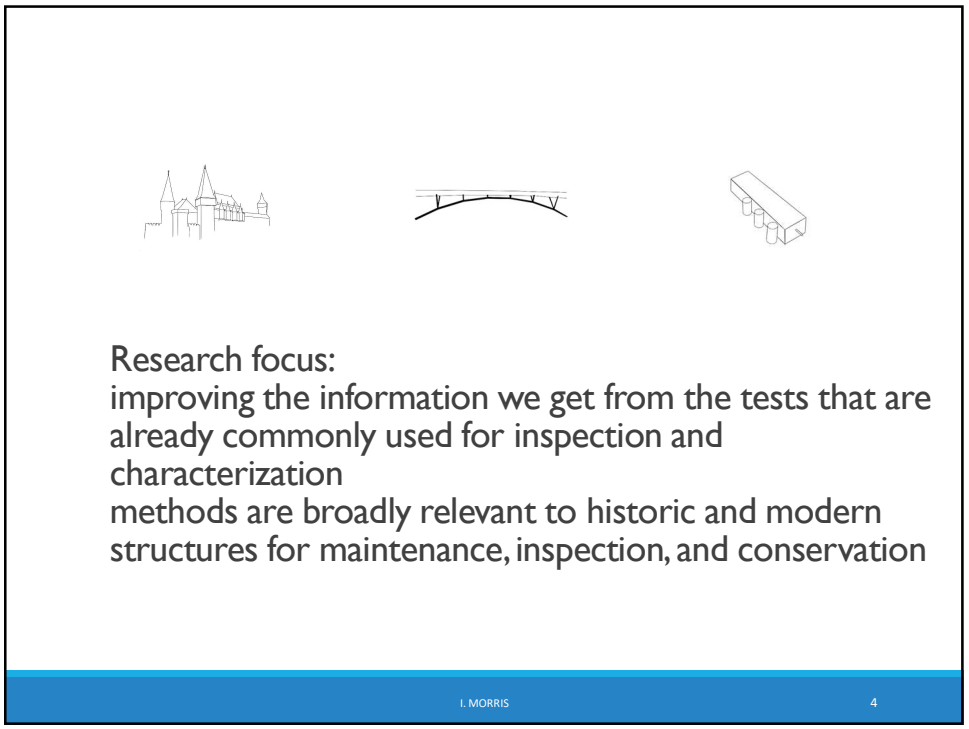


Research focus:
improving the information we get from the tests that are already commonly used for inspection and characterization
methods are broadly relevant to historic and modern structures for maintenance, inspection, and conservation

2


Hope
COLLEGE
PRINCETON
UNIVERSITY
ArchaeoTek
Archaeology
Luchini Trujillo
Structural Engineers
NEW MEXICO TECH

3

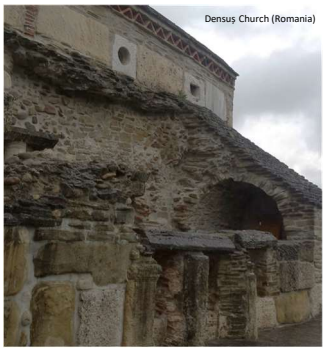

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I. MORRIS
4

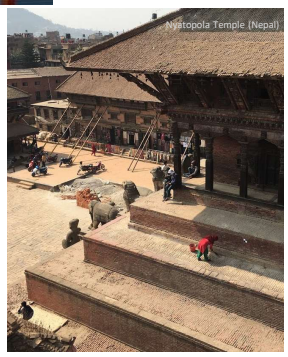
4



Motivation

Material properties are crucial parameters to know in many fields





5







Motivation

In situ methods aren't perfect:

ad hoc data collection

Invasive or permanent effect on structure

Accuracy costs time, experience, and money

Discrete vs. continuous coverage

6



Ongoing Projects:

GPR for feature detection: Corvin Castle



GPR attribute analysis and material sensitivity: Streicker Bridge



Prediction models for concrete samples

Can a model be trained on GPR attributes to predict properties?



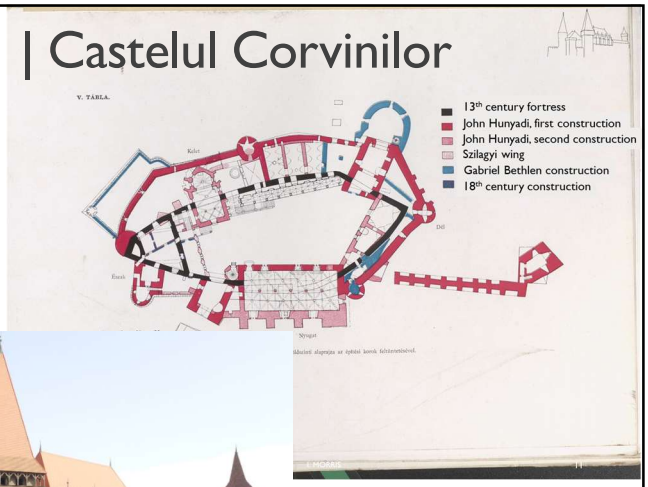
New Projects:

Correlating attributes and properties with additional NDT and for other material classes

Autonomous NDT surveys

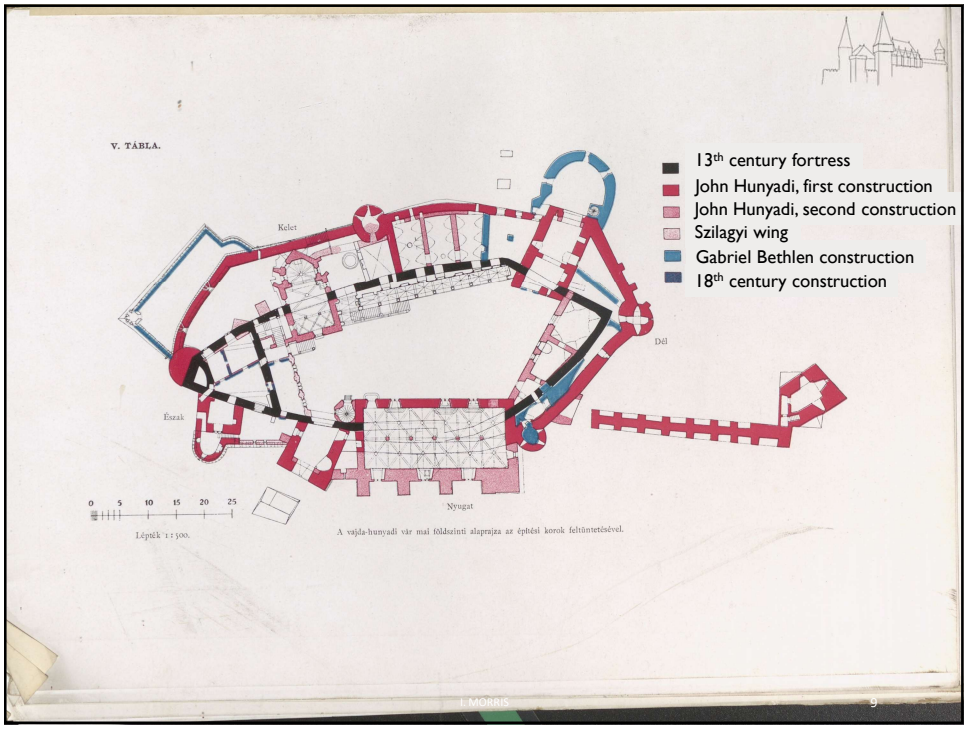
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Corvin Castle | Castelul Corvinilor

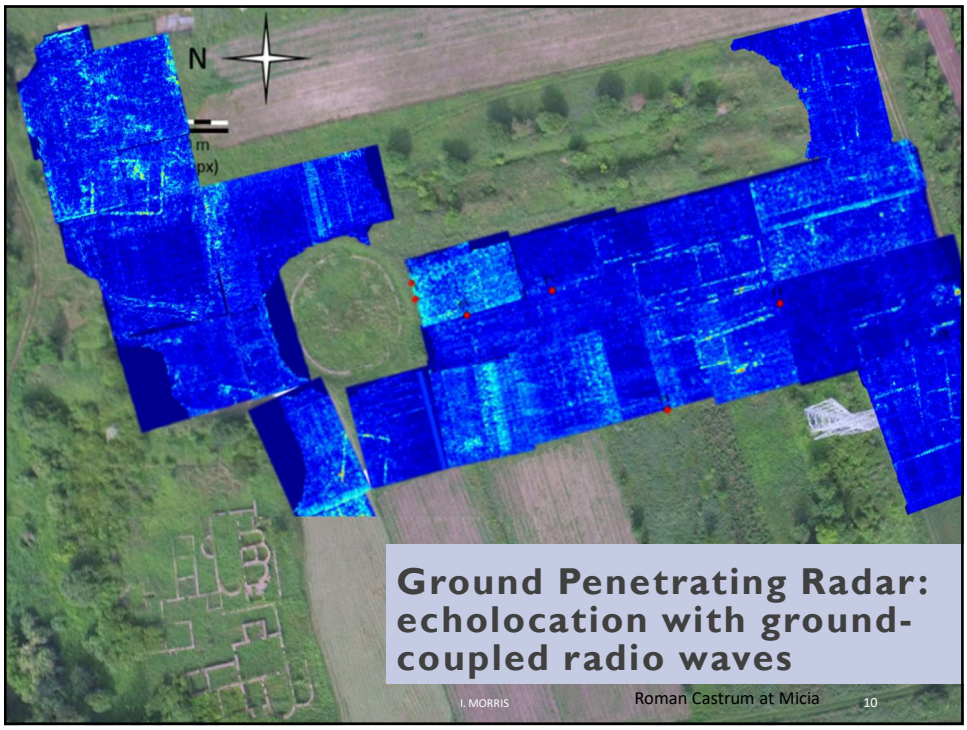




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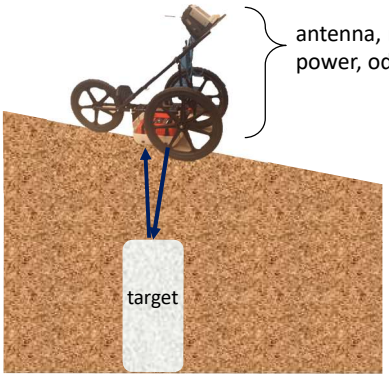

V. TÁBLA.
13th century fortress
John Hunyadi, first construction
John Hunyadi, second construction
Szilagyi wing
Gabriel Bethlen construction
18th century construction
Kelet
Dél
Észak
Nyugat
0 5 10 15 20 25
Léptékː 1:1500.
A vajda-hunyadi vár mai földszinti alaprajza az épitési korok feltüntetésével.
I. MORRIS
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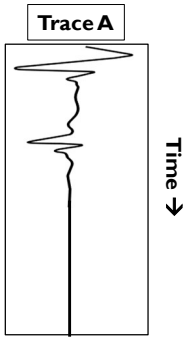
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N
Ground Penetrating Radar: echolocation with ground-coupled radio waves
I. MORRIS
Roman Castrum at Micia
10

10

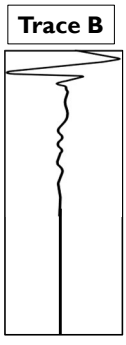
GPR Basics: Traces

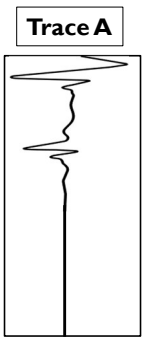


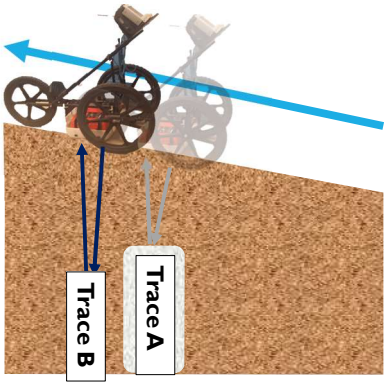


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GPR Basics: Traces

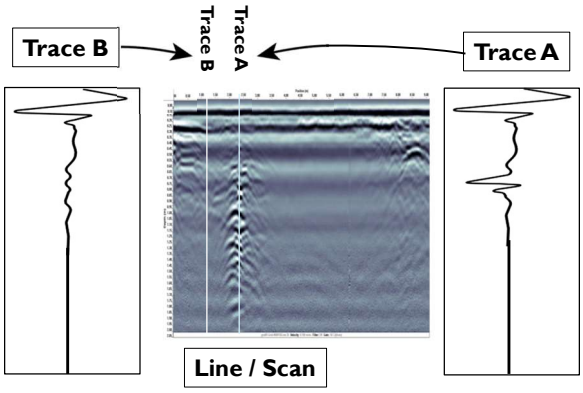






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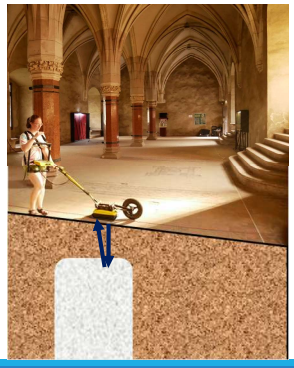
GPR Basics: Traces to Scans

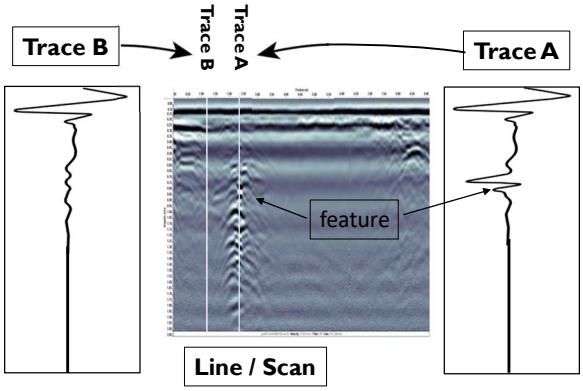


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GPR Basics: Traces to Scans

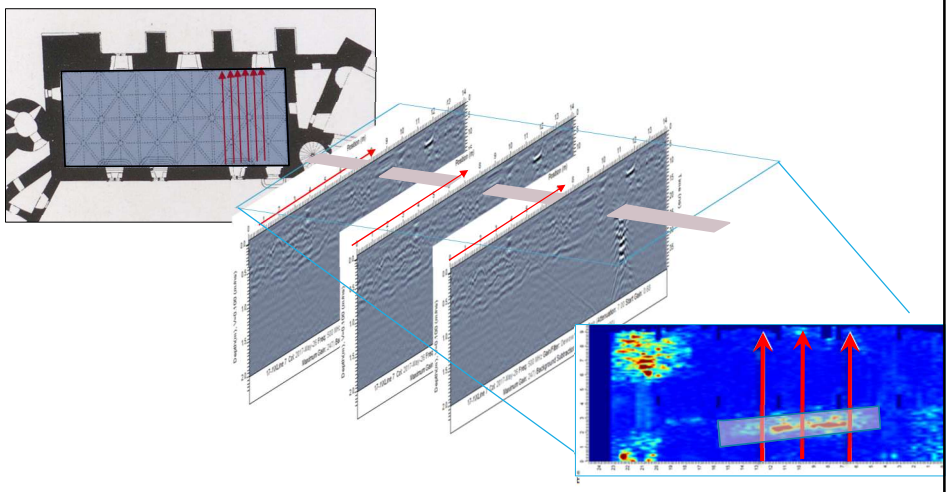
Qualitative, visual interpretation of features with amplitude profiles





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Basic Survey Idea

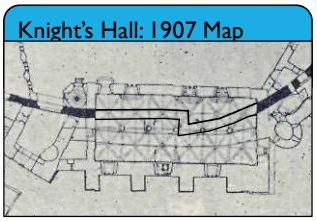


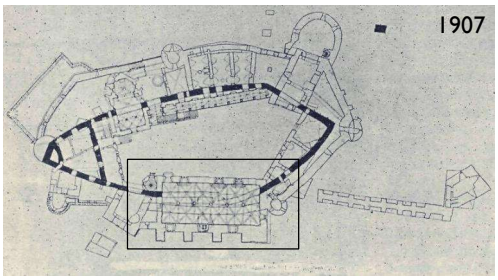
Grid of parallel transects → 3-d data cube → depth slice

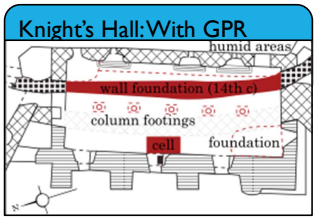
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Strengths

Build verified map of features
Improve existing knowledge of site
Produce new evidence and insight



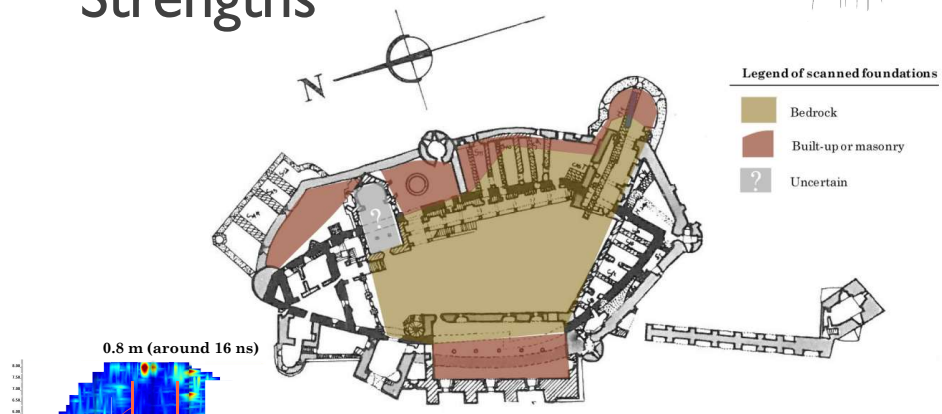


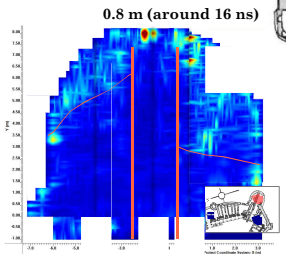


Vatasianu, 1933 Morris, 2019a

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Strengths



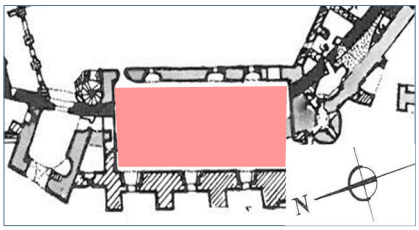


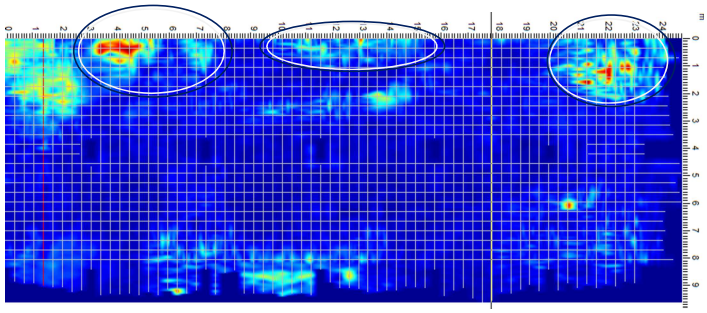
Morris, 2019a

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Strengths

Extent of subsurface humidity: drainage from courtyard





Morris, 2019a

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Challenges

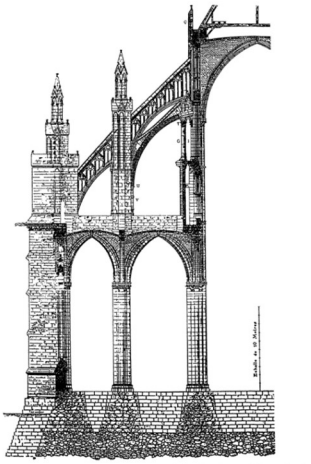
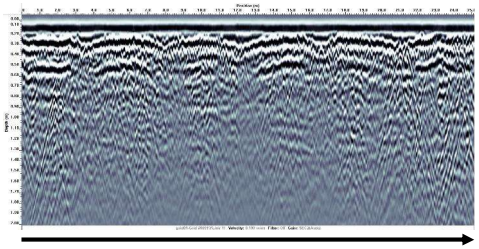
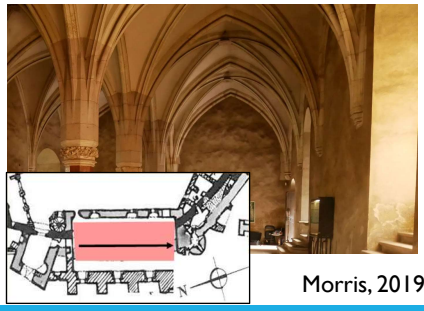


Fig. 5 Amiens Cathedral. Section of the choir including foundations. This section is pastiche created from two separate section drawings originally published by Durand.

Bonde 1989



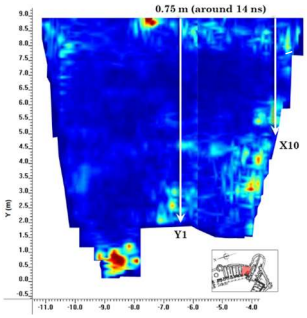


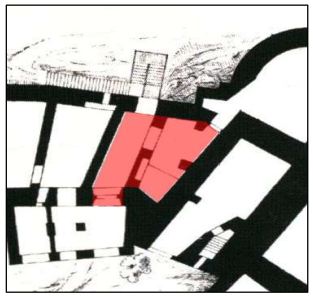
Morris, 2019a

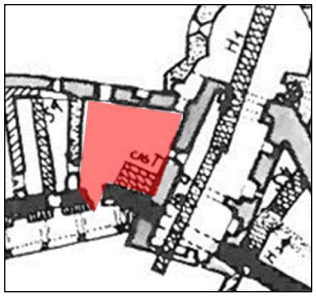
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Challenges

Differentiate between materials and determine the identity of reflections
Visual anlaysis based on maps



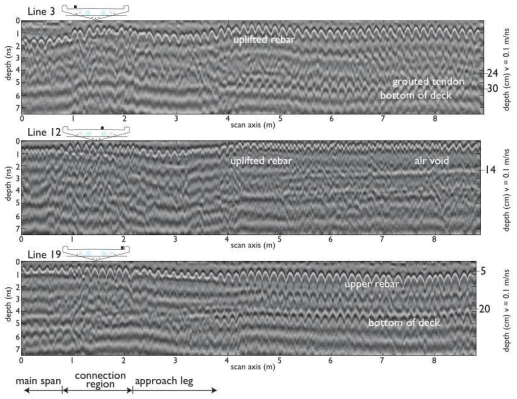




Morris, 2019a

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GPR in Civil Engineering

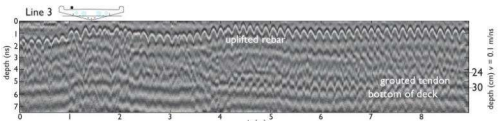


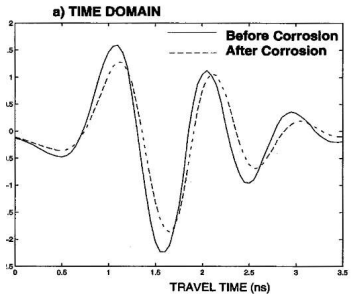
Can infer some variation in material condition or identity (e.g., rebar corrosion)
Still relies on visual analysis

Morris, 2019b

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GPR in Civil Engineering



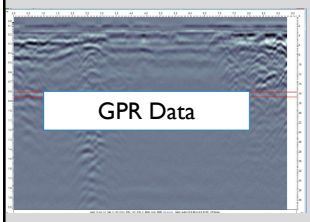


Can infer some variation in material condition or identity (e.g., rebar corrosion)
Still rely on visual analysis

Morris, 2019b Hubbard, 2003

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Can we use ground penetrating radar to estimate material properties?



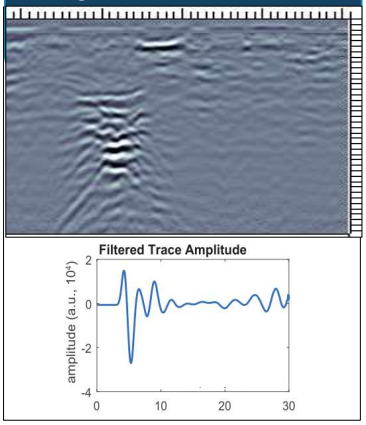


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GPR Basics: Traces to Attributes



Radargrams and Traces

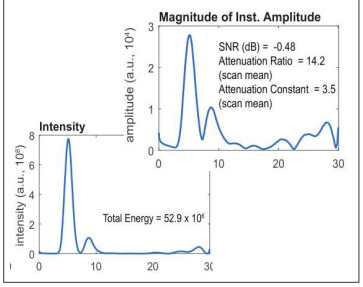


Transient and Composite Attributes

Summary or Propagation Attributes

Amplitude Attributes

e.g., instantaneous amplitude



Morris, 2019b

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GPR Basics: Trace Amplitudes to Attributes

Amplitude Attributes

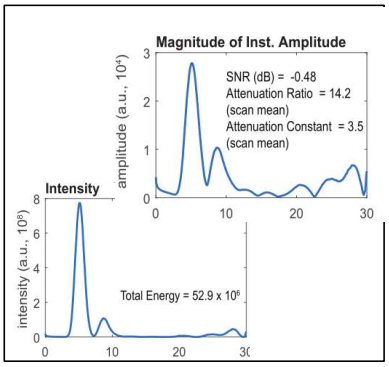
Capture extremes, ranges:
e.g., intensity

Summary Attributes:

Capture trends in an entire trace:
e.g., energy, attenuation ratio

Transient and Composite Attributes:

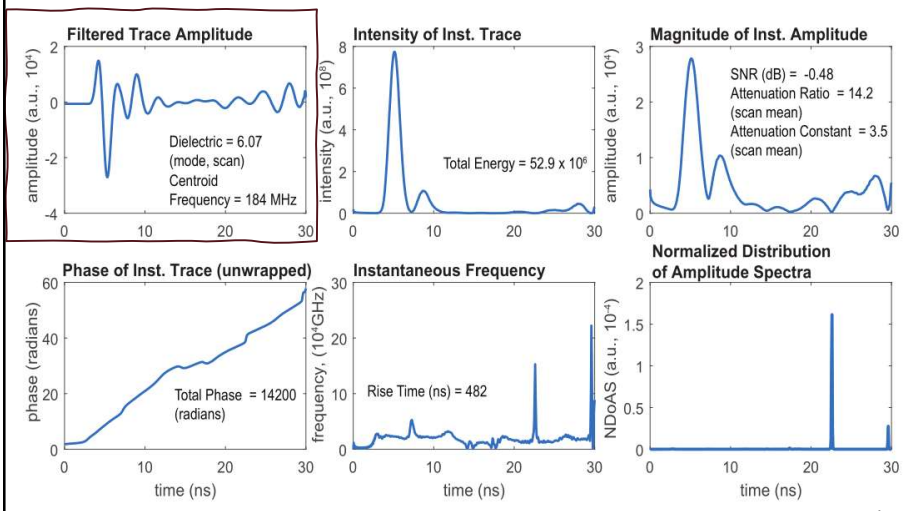
Capture structure, overall changes, character of whole scans:
e.g., similarity, coherence



Morris, 2020

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GPR Basics: Trace Amplitudes to Attributes

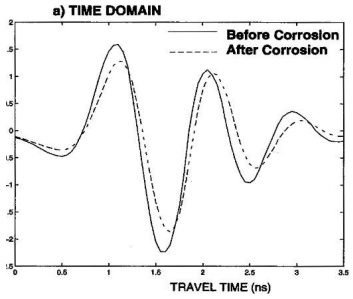


Morris, 2020

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Why Attributes?





Quantitative measure of different phenomena

Attributes:

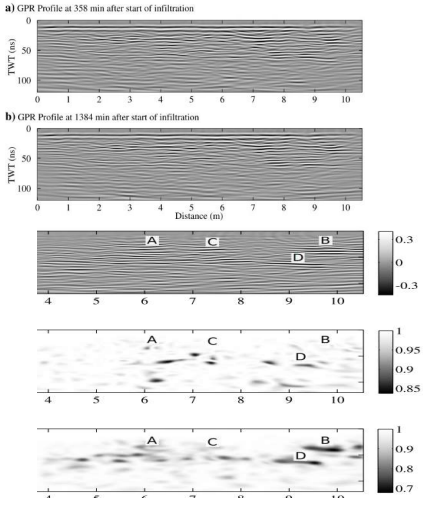
Corroded values less than uncorroded

Hubbard 2003

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Why Attributes?





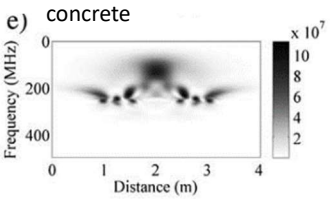
Quantitative measure of different phenomena

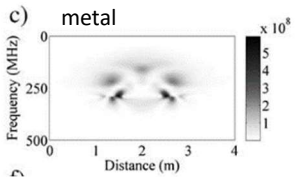
Highlight subtle spatiotemporal changes

Allroggen 2016

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Why Attributes?





Quantitative measure of different phenomena

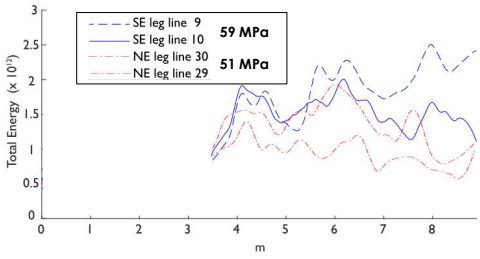
Highlight subtle spatiotemporal changes

Describe reflections from different materials

dos Santos 2014

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Why Attributes?



Quantitative measure of different phenomena

Highlight subtle spatiotemporal changes

Describe reflections from different materials

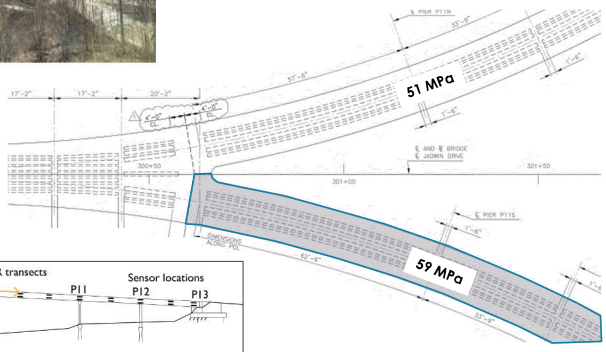
Differentiate between different strength concre

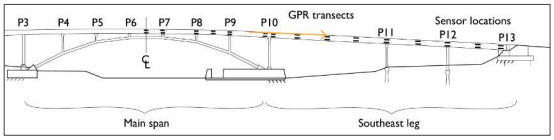
Morris 2019b

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Streicker Bridge





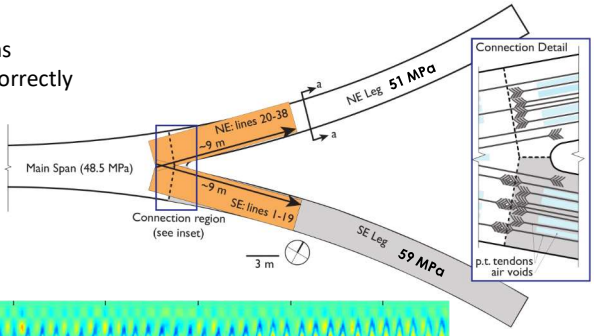


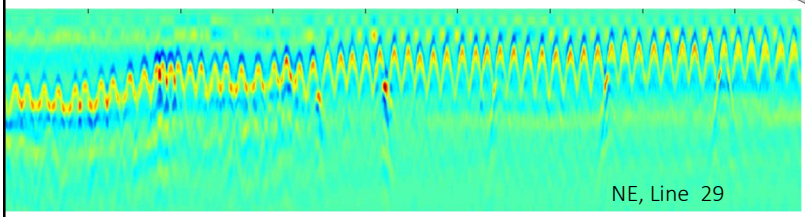
Morris 2019b

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Streicker Bridge: GPR Visual Analysis

Identify deviations from plans
Describe internal structure correctly

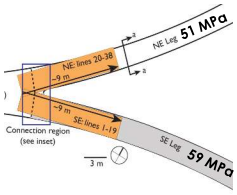




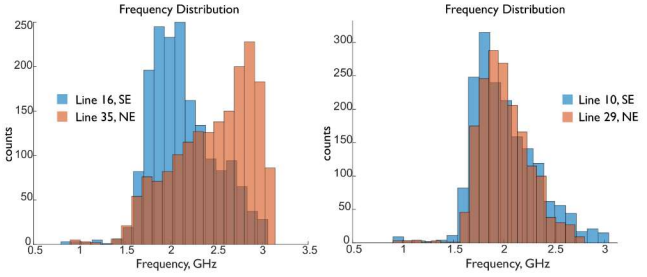
Morris 2019b

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Streicker Bridge: GPR Attribute Analysis



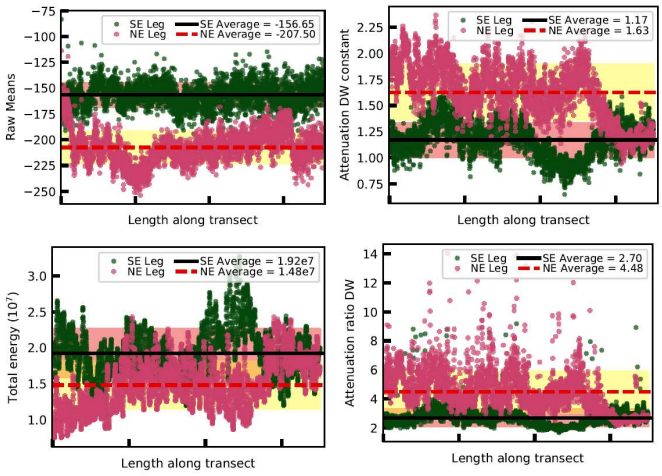
Consistent relative trends between stronger and weaker leg:
stronger concrete (SE) has more attenuation and stronger reflections



Morris 2019b

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Streicker Bridge: GPR Attribute Analysis



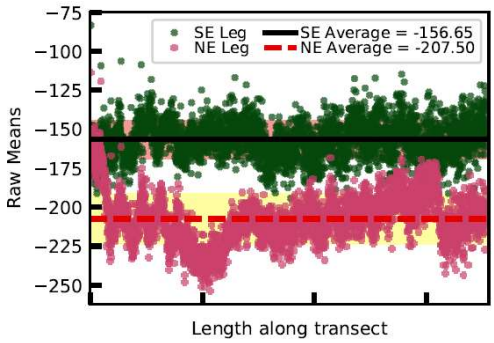
-Statistically different means
-Each value comes from a different population

Welch's t-score and Mann-Whitney U-score

Kumar 2021

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Streicker Bridge: GPR Attribute Analysis



Even simple amplitude attributes can differentiate phases and features

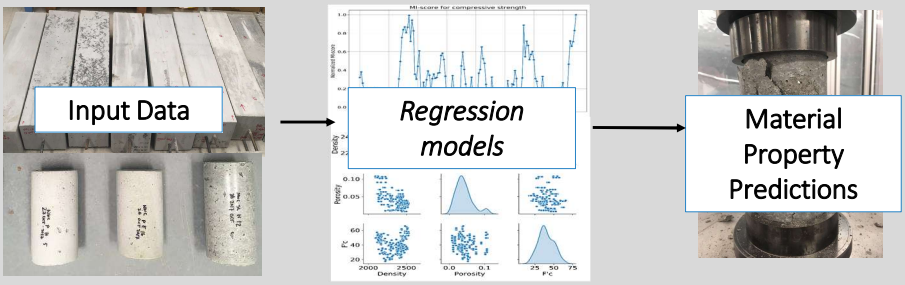
Makes novel connection between fundamental physical properties and GPR phenomena

Establishes that GPR could be used to assess uniformity and variability in situ (while also collecting data about physical features in the concrete)

Morris 2019b, Kumar 2021

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Prediction models for concrete samples:
Can a model be trained on GPR attributes to predict properties?



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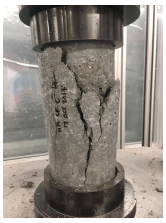
Is there a model that describes the relationship between physical properties and GPR attributes?

Can a model be trained on GPR attributes to predict properties?

Approach

1) Create a labeled data set of concrete properties (density, porosity, and compressive strength) and GPR attributes: input data
2) Use supervised learning to model relationship between attributes and material properties: regression modeling







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Experimental Data Set:



Direct tests (cylinder)

Indirect Tests (beams)

Θ ρ | f'c ρ | f'c ρ

GPR scan, 900 Mhz (longit. x2, transv. x1)

Scan Key

I

Sample Id, Mix etc

Label Vectors

ρ θ f'_c n = 219

Features

GPR Attribute

n = 150 (energy)
n = 512 (others)

n = 219

Morris 2020

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Outline of Final Modeling Workflow

Impute Θ and f'c

y
X

Match corresponding labels (properties y) to features (attributes X)
$D = (X, y)$

Segregate data using stratified approach
D_{train} D_{test}

Compute attributes

Preprocess:
Time zero
Truncate
Resample
Dewow

GPR radargrams

Physical Properties (label vectors y):
Density (ρ)
Porosity (fractional, θ)
Compressive Strength (f'c)

Included Models:
KNN: K-nearest neighbors
SVR: Support Vector Regression
RR: Ridge Regression
RF: Random Forest Regression
ADA: AdaBoost Regression

Train Models
Learn function $f(\mathbf{x}; \boldsymbol{\theta})$,
such that $f: \boldsymbol{x} \rightarrow \boldsymbol{y}$

KNN, SVR, RR, RF, ADA

1. Heuristic feature selection from D_{train} by f_1 score
2. Normalize features
3. Learn model parameters
4. Cross-validation for each model's hyper-parameters
5. Predict test set labels (properties)

Baseline Model

Random Search
Grid Search

Final model

Final prediction

Morris 2020

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Modeling Workflow

85% Training
15% Testing

GPR Attribute Label Vectors

Training

Testing

Model Creation

Model Validation

Impute ρ and f'c

y
X

Match corresponding labels (properties y) to features (attributes X)
$D = (X, y)$

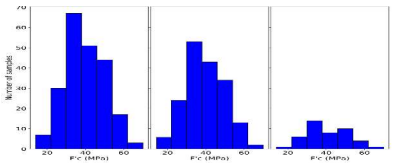
Segregate data using stratified approach
D_{train} D_{test}

Compute attributes

Preprocess:
Time zero
Truncate
Resample
Dewow

GPR scans

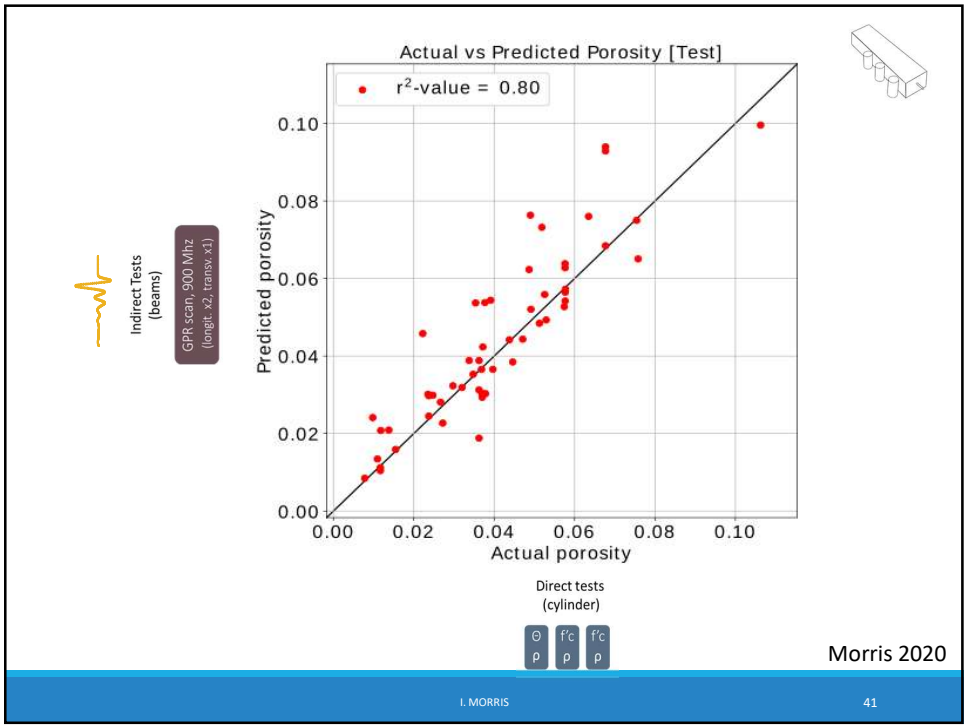
Divide testing/training data so that each mix and cure is represented



complete training testing

f'c

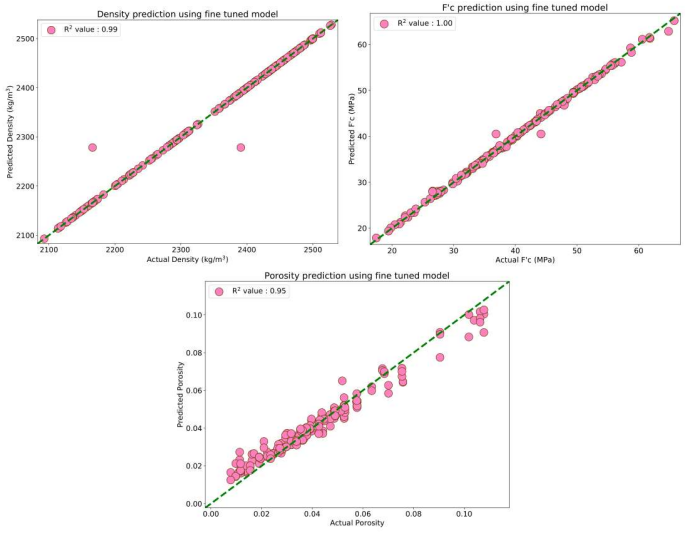
40



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Does a relationship exist?

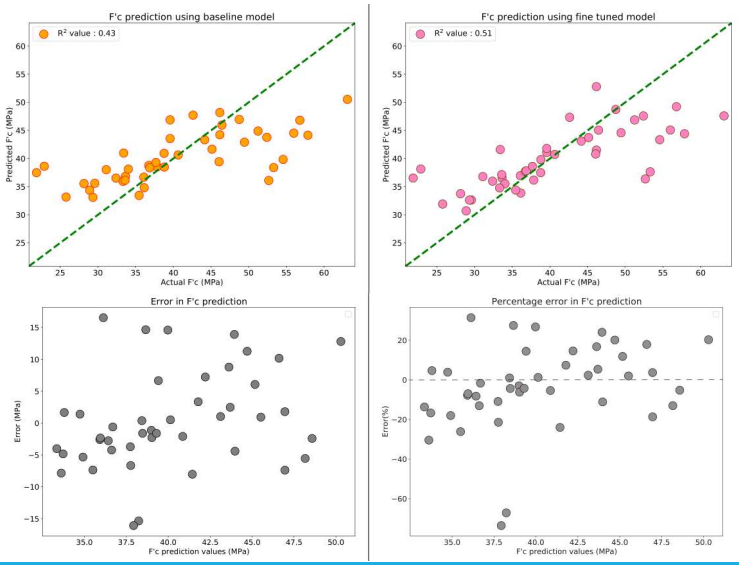


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Final Predictions: Compressive Strength





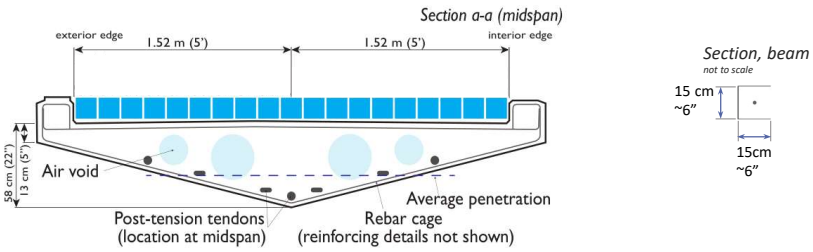
Morris 2020

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Streicker Bridge Predictions



Data Set	SE leg (59.7 MPa), Relative Error (%)	NE leg (48.5 MPa), Relative Error (%)
Summary attributes	46.2, 23%	46.4, 4%
Full instantaneous amplitudes	40.1, 33%	36.7, 24%
Truncated (200) instantaneous amplitudes	42.8, 28%	41.0, 15%
Truncated (150) instantaneous amplitudes	41.7, 30%	40.9, 16%
Truncated (150), normalized instantaneous amplitudes	39.0, 34%	38.6, 20%
Truncated (200) instantaneous amplitudes, NWC and HPC only	46.3, 22%	46.4, 4%

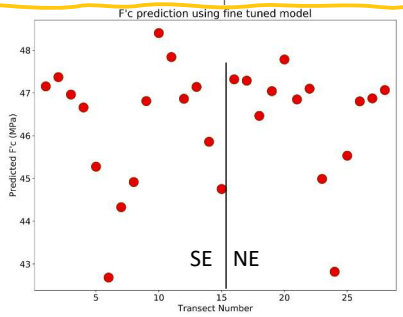


Morris 2020b

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Streicker Bridge: Strength

Data Set	SE leg (59.7 MPa), Relative Error (%)		NE leg (48.5 MPa), Relative Error (%)	
Summary attributes	46.2,	23%	46.4,	4%
Full instantaneous amplitudes	40.1,	33%	36.7,	24%
Truncated (200) instantaneous amplitudes	42.8,	28%	41.0,	15%
Truncated (150) instantaneous amplitudes	41.7,	30%	40.9,	16%
Truncated (150), normalized instantaneous amplitudes	39.0,	34%	38.6,	20%
Truncated (200) instantaneous amplitudes, NWC and HPC only	46.3,	22%	46.4,	4%



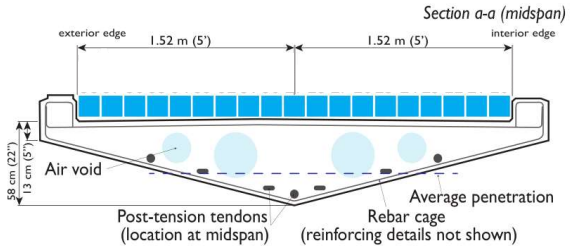
Morris 2020b

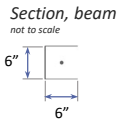
45

Streicker Bridge Predictions

While the models perform well on the lab data, where the GPR reflections are in a single configuration, they do not perform as well on GPR data from Streicker bridge because of the different reflection configuration

Experimental Limitations: reflection patterns, assumes that the 28 day cylinder tests reflect present values (over 10 years later)



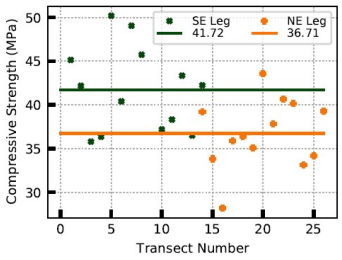


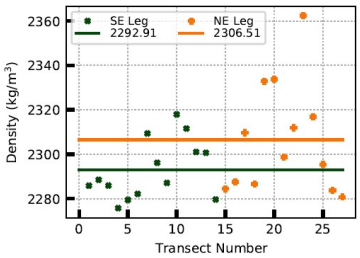
Morris 2020b

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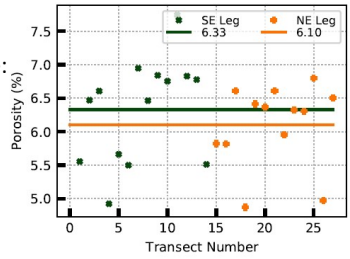
Streicker Bridge: Fine-Tuned Strength







28 Day strength difference: 13.6%
Attribute predicted strength difference: 12%



Attributes tell us that the concrete *is* different and estimate *how* different

Kumar 2021

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Some General Modeling Conclusions



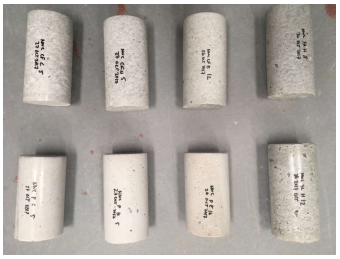
Porosity, density, and strength (to a limited degree), are captured by signal attenuation attributes.

Those attributes can be used to train models and make predictions of those *in situ* physical properties **without *a priori* information and completely noninvasively:** continuous spatial coverage, uses existing data, straightforward analysis

Modeling Limitations

Experimental measurements:

- Cold water saturation (porosity) does not measure unconnected pores, entrained air, or nanopores
- Strength measurements have high variability
- Variations and outliers in individual samples and tests
- Variations between each GPR scan

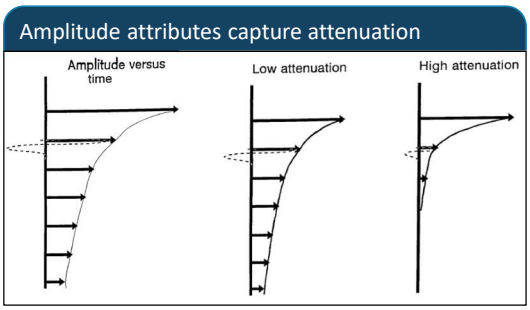


Morris 2020

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Why do amplitude attributes work?

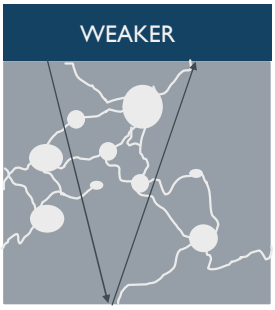


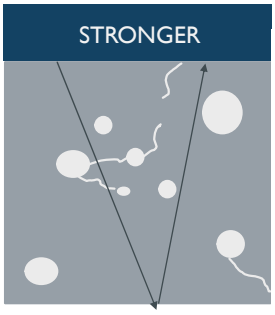


Morris 2020; c.f., Annan 2003, Neto 2006

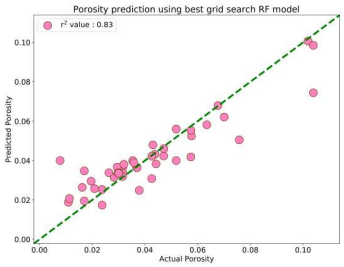
49

Why Porosity?





Porosity



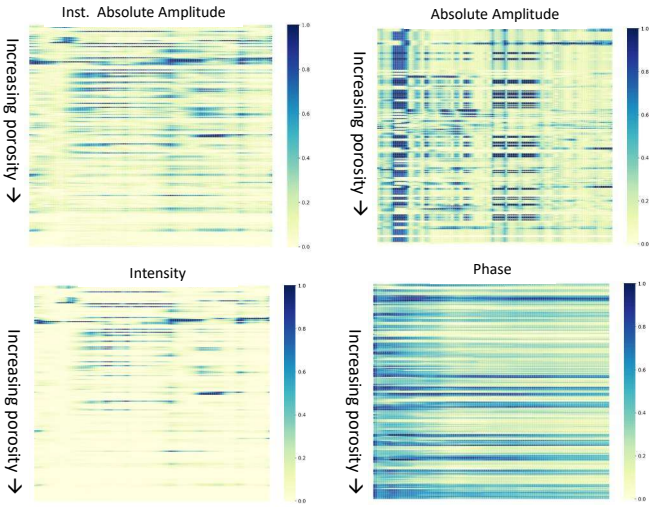
Best predictions for porosity
Density is second

see Lai 2009

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New Research: Improving models





- Add additional classes of attributes to models
- Not all attributes are useful or related to material properties of interest

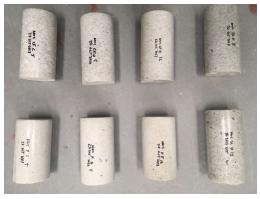
Morris 2020

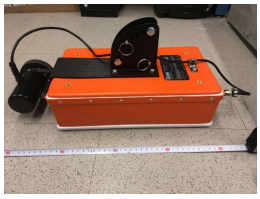
51

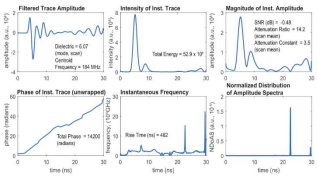


New Research: Improving models

- Improve dataset to move beyond preliminary models:
  - Gather GPR scans of concrete from other experiments (database creation or mining)
  - Denoising signals
  - Collect US and other NDT data on concrete samples
  - Collect more sophisticated porosity and strength data from cylinders
- Predicting strength directly from the predicted porosity
- Assess accuracy and error in the predictions
- Sensitivity study of antenna, material, and test settings on prediction models





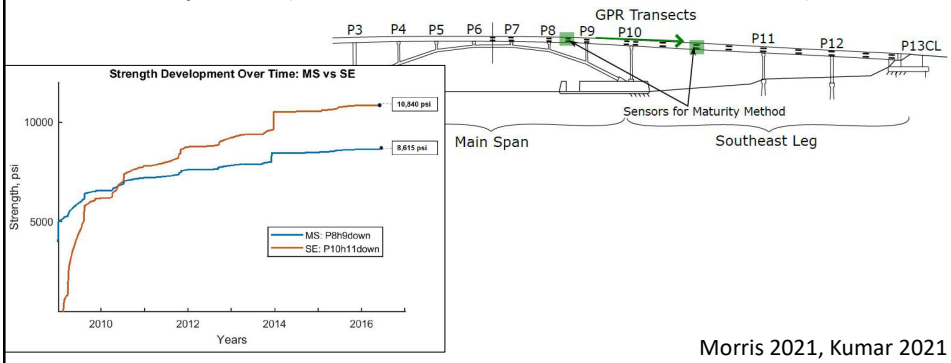


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New Research: Improving models

- Improve dataset to move beyond preliminary models:
  - Gather GPR scans of concrete from other experiments (database creation or mining)
  - Collect US and other NDT data on concrete samples:

Maturity Method (combined SHM data sources with NDT data sources)



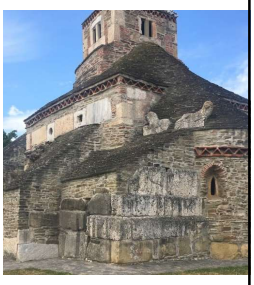
Morris 2021, Kumar 2021

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New Research: beyond concrete

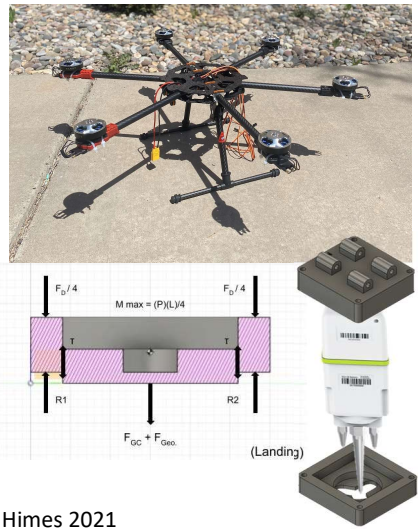
- Integrate GPR attributes into combined NDT approaches for historic sites and structures
- Adapt and create models for historic and natural materials (brick, stone)

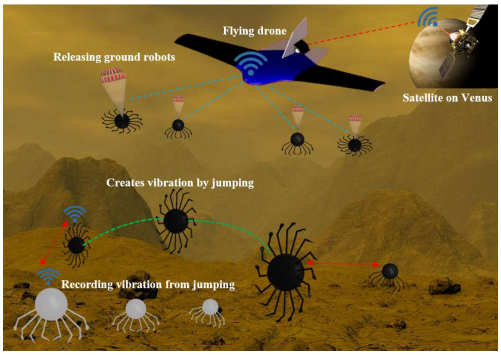




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New Research: Autonomous NDT surveys





- Drone-assisted civil-scale seismic reflection surveys
- Scalable and transferrable concept

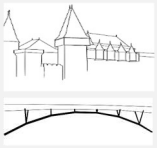
Himes 2021

Morris 2020

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Fundamentals: understanding how wave propagation (sound/pressure waves and EM waves) are controlled by physical properties of materials: aim is to use NDT for material characterization



Applications: leverage the relationships between wave propagation attributes and materials to improve survey and prediction of in situ properties, focused on existing structures

New Research

Contact me if anything is interesting: isabel.morris@nmt.edu

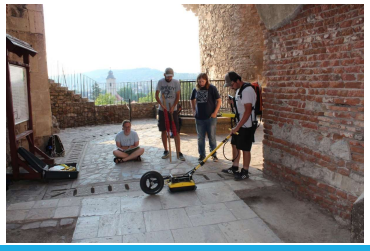
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Claire White, Maria Garlock, Sigrid Adriaenssens,
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Archaeotek + outside collaborators
Funding from NSF GRFP #1148900,
Princeton CST, CDH, CEE Dept
New Mexico Tech, NM AMP program







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Supplementary: Concrete Mixes



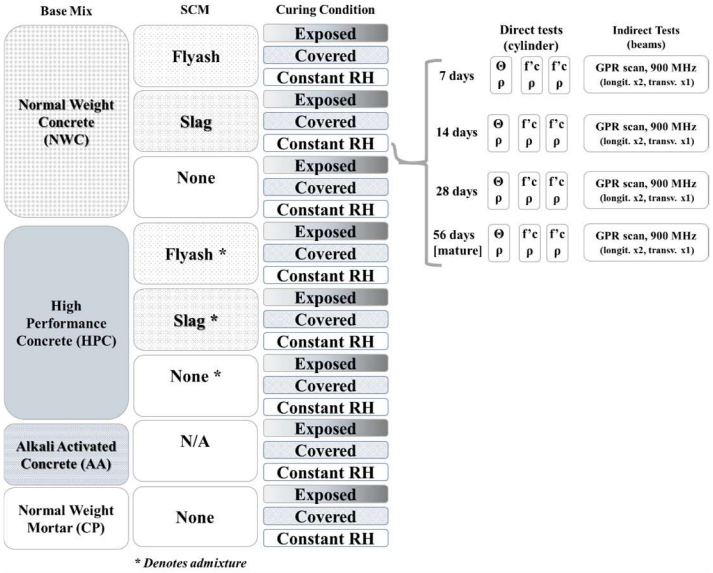
Table 5.1: Mix Design and water/cement ratios for included concrete and mortar

Material (percent by weight)	AA	HPC CF	HPC FA	HPC SL	NWC P	NWC CF	NWC FA	NWC SL
Sodium Hydroxide (NaOH)	0.61	–	–	–	–	–	–	–
PQ D Silicate Solution	3.35	–	–	–	–	–	–	–
Fine Aggregate (sand)	37.69	27.96	26.92	28.13	55.80	31.31	31.31	31.31
Coarse Aggregate (3/8)	28.26	44.06	43.66	45.76	–	43.89	43.89	43.89
Water	7.25	5.30	6.61	5.86	11.46	6.43	6.43	6.43
Granulated Blast Furnace Slag	11.42	–	–	5.07	–	–	–	4.59
Class F/C Flyash	11.42	–	2.43	–	–	–	3.67	–
Ordinary Portland Cement (OPC)	–	20.94	19.41	13.57	32.74	18.37	14.69	13.78
Silica Fume	–	1.74	0.97	1.61	–	–	–	–
HRWR type f (oz per 60 # batch)	–	3	3	3	–	1	1	1
WR type a/d (oz per 60 # batch)	–	1.2	1.2	1.2	–	–	–	–
W/C ratio (washed aggregates, w/o admixture)	*0.40*	*0.28*	*0.34*	*0.34*	*0.41*	*0.41*	*0.41*	*0.41*

Morris 2020

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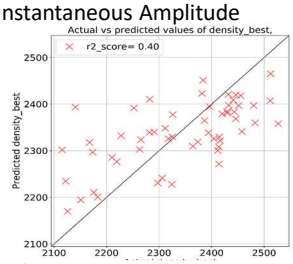
Supplementary: Experimental Overview



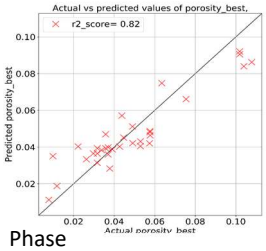
60

Supplementary: Without Stratified Data Segregation

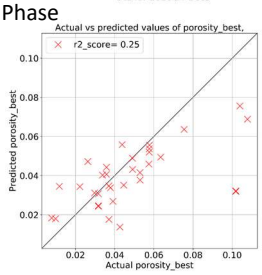
Instantaneous Amplitude



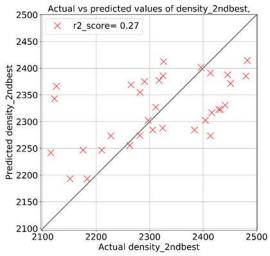
Intensity



Phase



Phase



Morris 2020

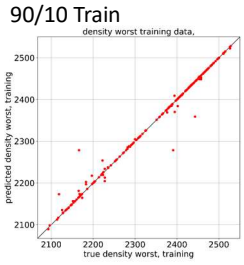
61

Supplementary: Overfitting

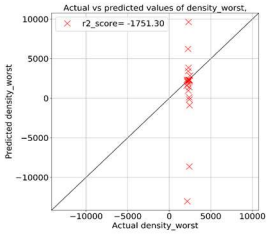
Between 90-75% Training, 10-25% Testing

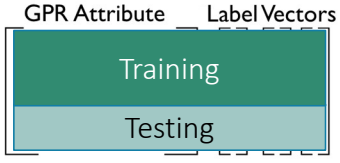
85/15 offers best performance (highest correlation, best testing performance)

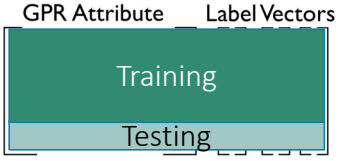
90/10 Train



90/10 Test







Morris 2020

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Supplementary:

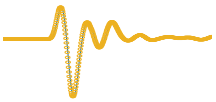
GPR Data Processing: Attributes

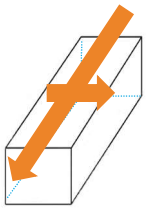


Preprocessing

1) Trim First break (STALTA)
2) Remove reflections after beam
3) Resample traces
4) Remove DC

Chose 150 traces from each scan
Transverse/transient
Longitudinal





Calculated Attributes

1) Instantaneous trace (Hilbert Transform)
2) Instantaneous amplitude envelope
3) Instantaneous phase
4) Intensity
5) Normalized cumulative trace energy