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for CONSTRUCTION ENGINEERING
and TECHNOLOGY

Physics-Informed Machine Learning for Geotechnics: Integrating Theory, Data, and Computation



Royal Academy
of Engineering



Cambridge Centre for
Smart Infrastructure
& Construction



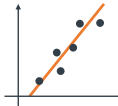
UK Research
and Innovation

The Evolution of Geotechnics: Models & Data

Empirical Era

Pre-1960s

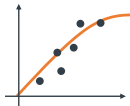
Data used to *fit* equations



Mechanistic Era

1960s-

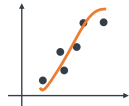
Data used to *calibrate* models



Physics-informed
Data-Driven Era

2010-

Data used to *replace* models?
augment





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The Opportunity

Explosion in sensing technologies: offer rich but underutilised data

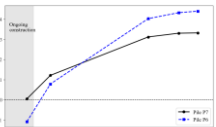
LiDAR



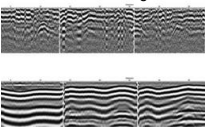
Imaging



Fibre Optics



Ground Penetrating Radar



Manual processing intractable!
Need automated methods to:

✓ Understand the data

✓ Detect problems early

✓ Inform “better” designs and processes



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The Promise (& Problems!) of AI



Computers and Geotechnics
journal homepage: www.elsevier.com/locate/compgeo

Review

Artificial intelligence transformations in geotechnics: progress, challenges and future enablers

Brian Sheil^{a,*}, Christos Anagnostopoulos^a, Róisín Buckley^a, Matteo Oryem Ciantia^{a,b}, Eky Febrianto^a, Jialong Fu^a, Zhiwei Gao^a, Xueyu Geng^a, Bin Gong^a, Kevin Hanley^a, Pengpeng He^a, Kostas Kolonitsos^a, Bruna de C.F.L. Lopes^a, Jelena Wink^a, Marco Previtali^a, Mohammad Rezaei^a, Agustín Ruiz-López^{a,c}, Jin Sun^a, Stephen Suryasentana^a, David Taborda^a, Stefano Utlir^a, Scott Whyte^a, Pin Zhang^a

AI training:
Need data

Blackbox uncertainty:
Need explainability

Real-world diversity:
Need generalisation

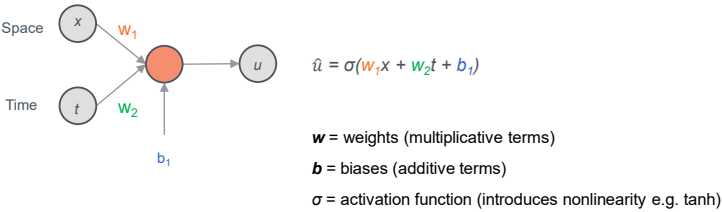


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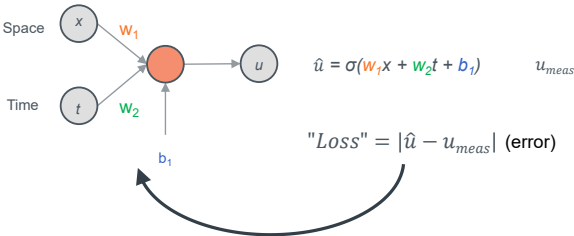


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An Introduction to Neural Networks

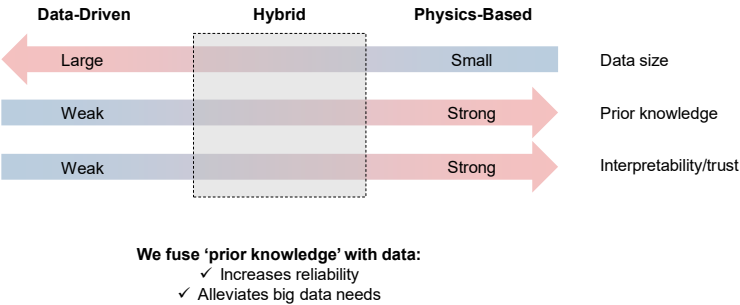


An Introduction to Neural Networks

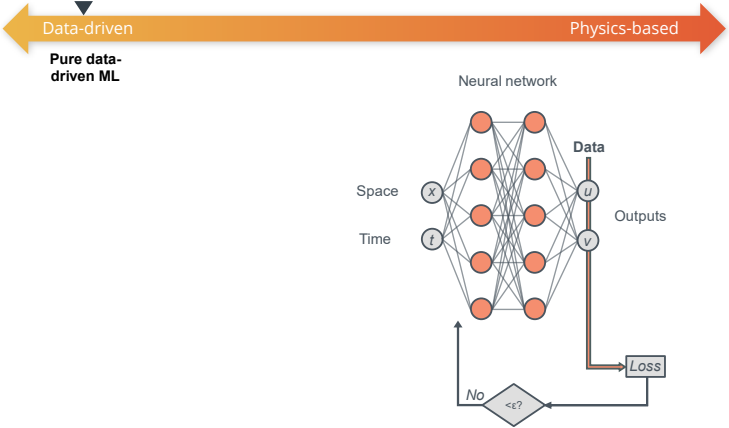


Universal approximation theorem: neural networks with a certain structure can approximate *any* continuous function to *any* desired degree of accuracy

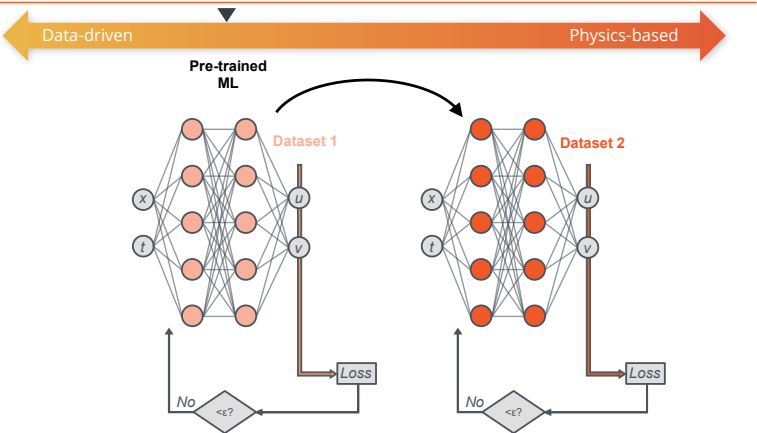
Data-Physics Spectrum



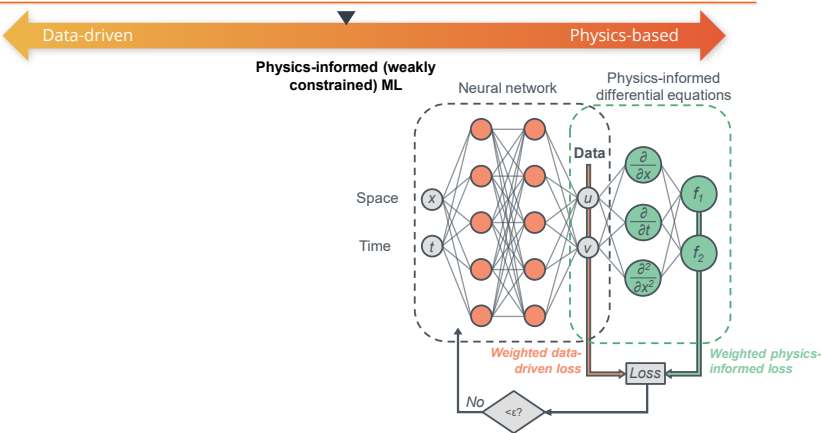
Data-Physics Spectrum



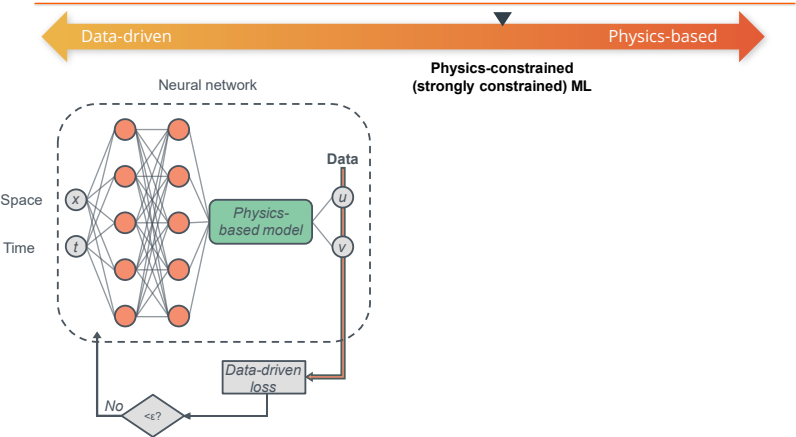
Data-Physics Spectrum



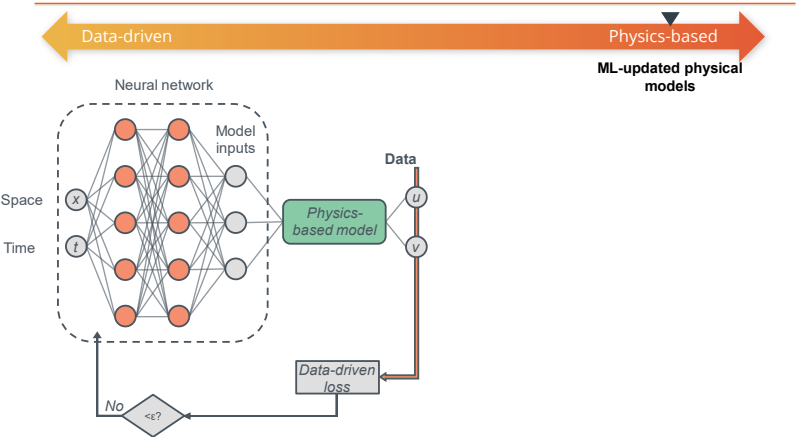
Data-Physics Spectrum



Data-Physics Spectrum



Data-Physics Spectrum



Tunnel Asset Management as a Use Case



Motivation



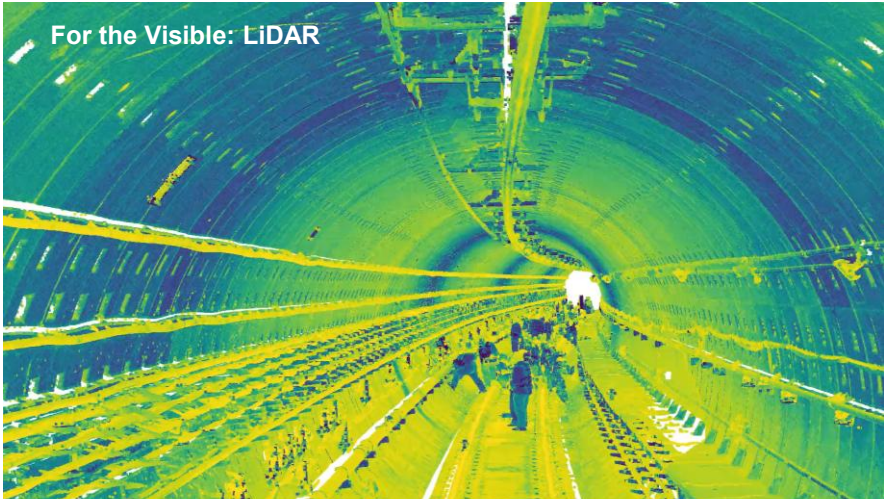
Islington Tunnel

Critical part of UK infrastructure network

Over 200 years old & visibly deteriorating

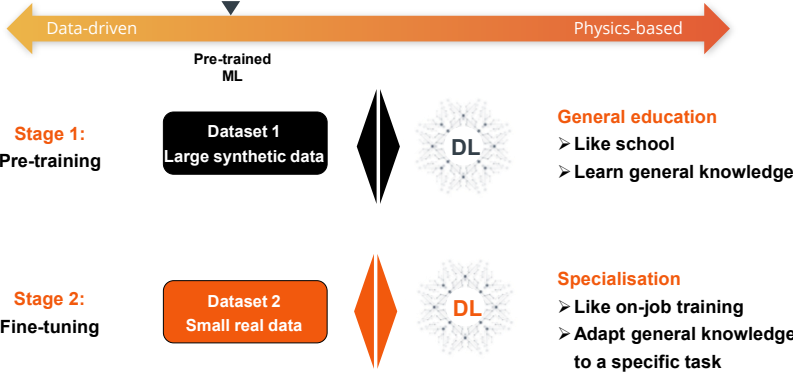
Current inspection & reporting processes are manual

Our Aim: to Build a “Digital Inspector”

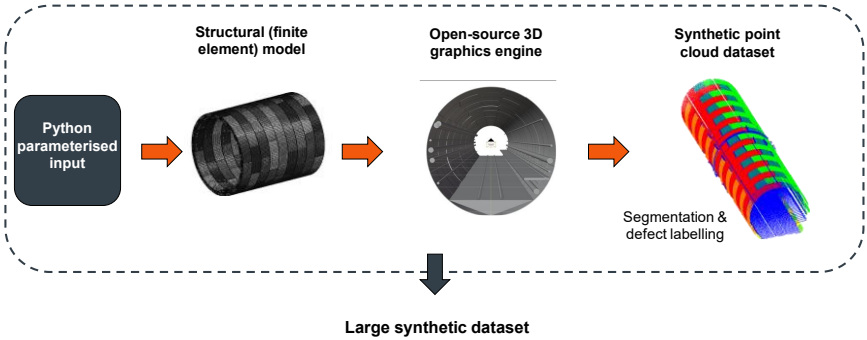


For the Visible: LiDAR

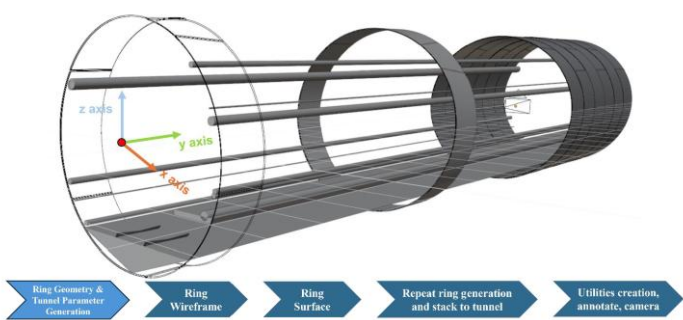
Combining Prior Knowledge with Data



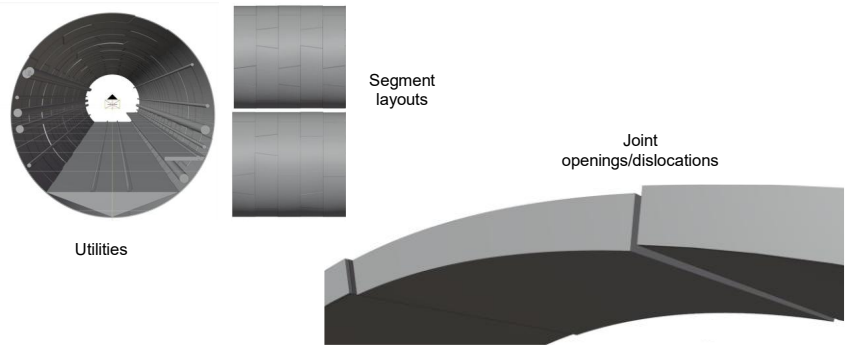
Dataset 1: Physics-Informed LiDAR Simulators



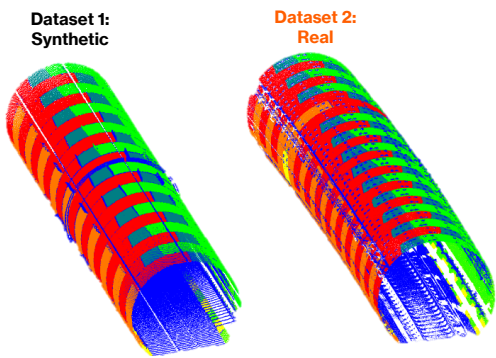
Graphics Engine: "Tunnel Scanner"



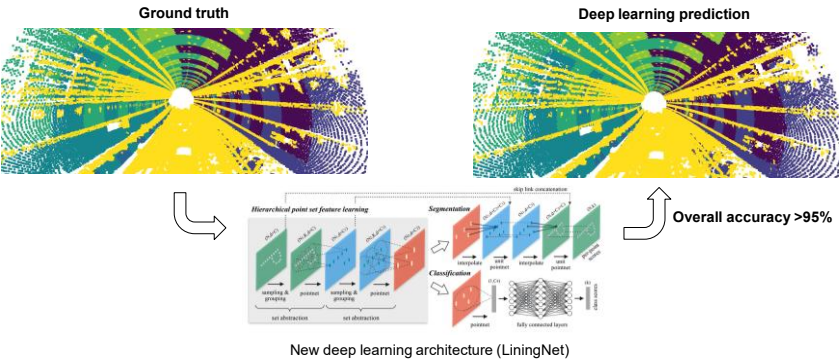
High-Fidelity Simulations



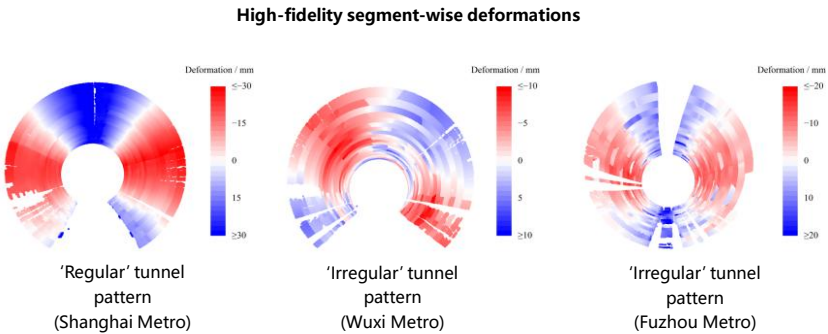
Synthetic Vs Real



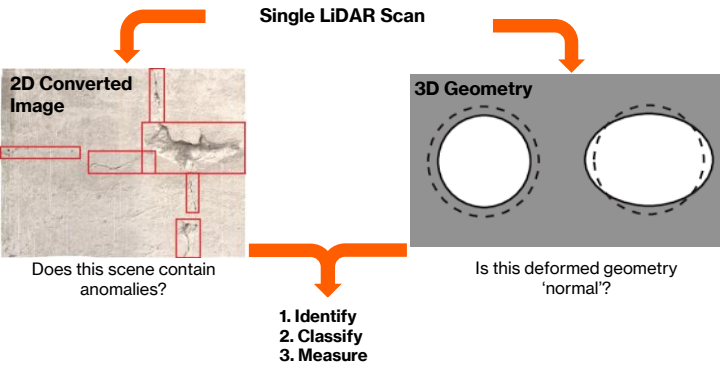
Step 1: Segmentation



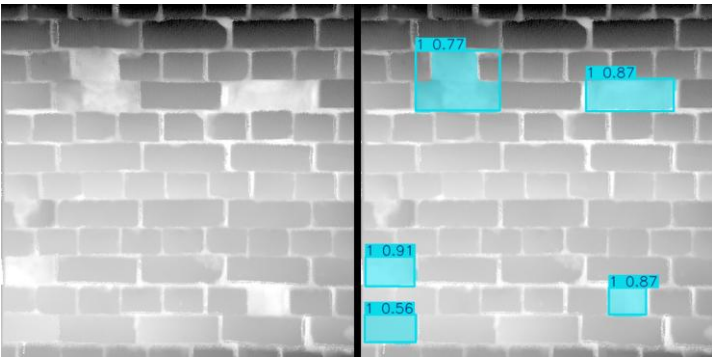
Step 2: Deformations



Step 3: Defect Analysis

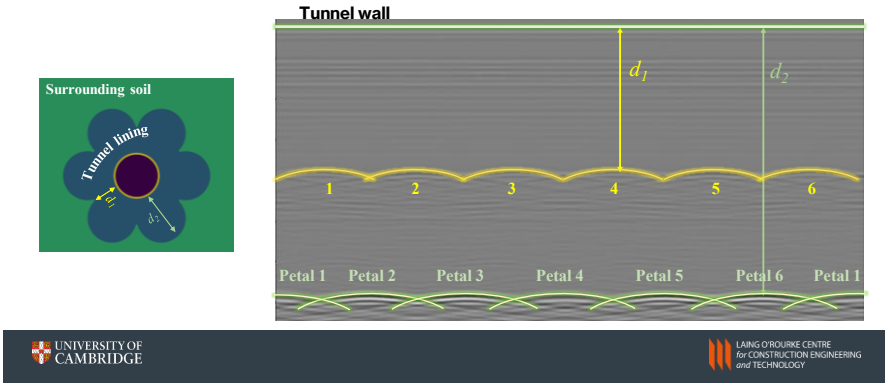


Predictions: Spalling

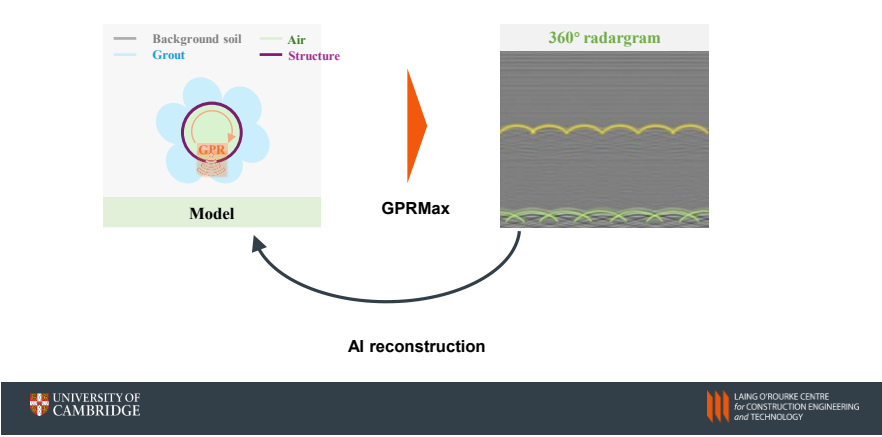




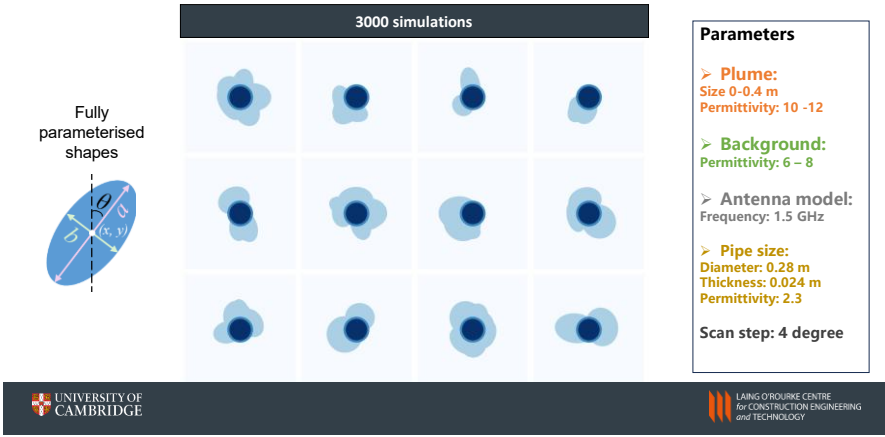
Problem Definition



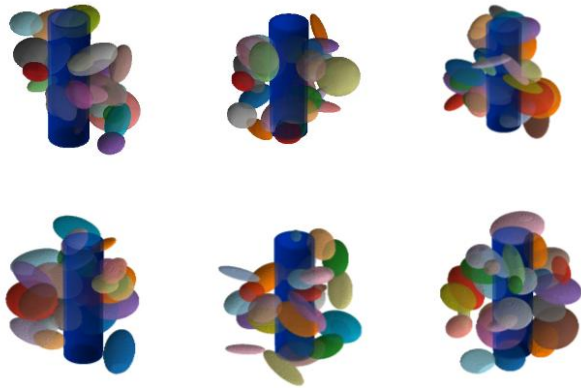
GPRMax: Electromagnetic Simulator



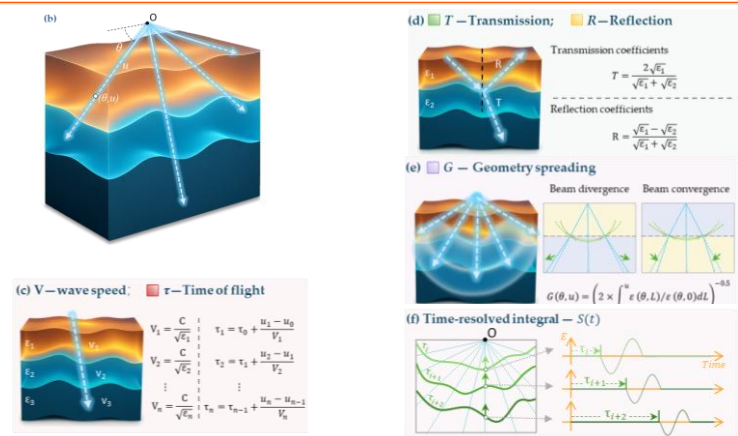
Synthetic Dataset



GPRMax Dataset



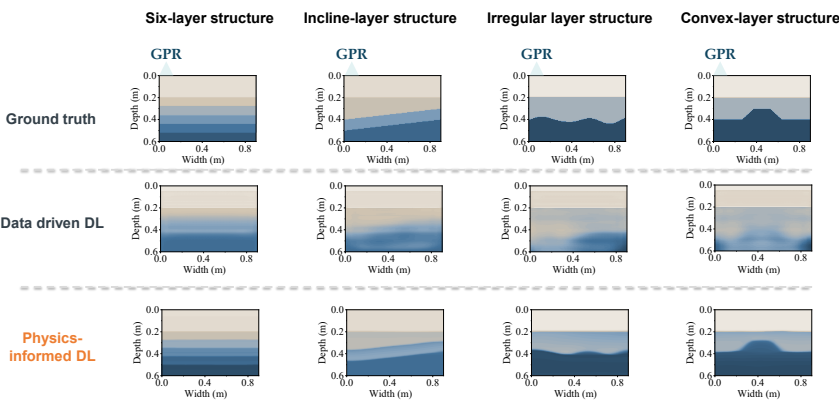
Encoding EM Wave Propagation Physics



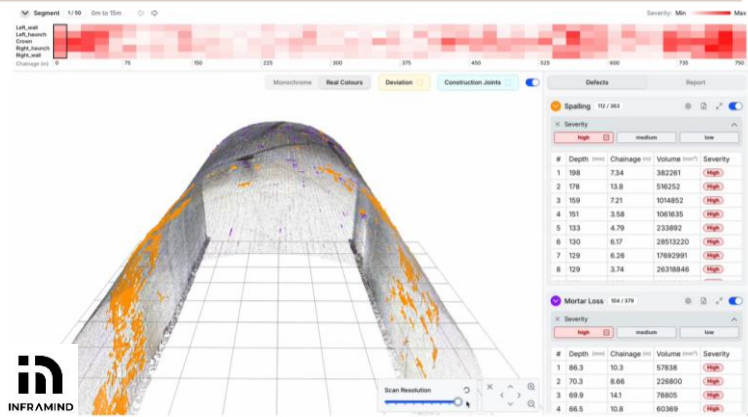
Results: DL-Predicted Reconstruction



Encoding EM Wave Propagation Physics



Online Platform: The Digital Inspector!



Summary

- ✓ **Data-driven era? Not quite!**
Combining established physics with data likely more fruitful
- ✓ **Physics-informed machine learning**
Significant potential for digital asset management
- ✓ **Ground penetrating radar**
AI offers unprecedented opportunity to reveal the unseen



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