HPC in Earthquake Simulation

The Evolution of Earthquake Simulation: From HPC Foundations to AI Frontiers

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Why Simulate Earthquakes?

CRUCIAL FOR UNDERSTANDING SEISMIC HAZARDS AND DISASTER MITIGATION.

EARLY METHODS LIMITED BY COMPUTATIONAL POWER -> ACCURACY ISSUES.

HIGH-PERFORMANCE COMPUTING (HPC) REVOLUTIONIZED THE FIELD.

TODAY: INTEGRATING HPC WITH ARTIFICIAL INTELLIGENCE (AI).

The Early Years (1990s): Overcoming Constraints

Challenges	Solutions
Severe computational limits restricted model complexity (3D basins)	Adoption of parallel computing
Complex geology (Unstructured meshes)	Development of toolsets (e.g., Archimedes) for parallel FEM on unstructured meshes

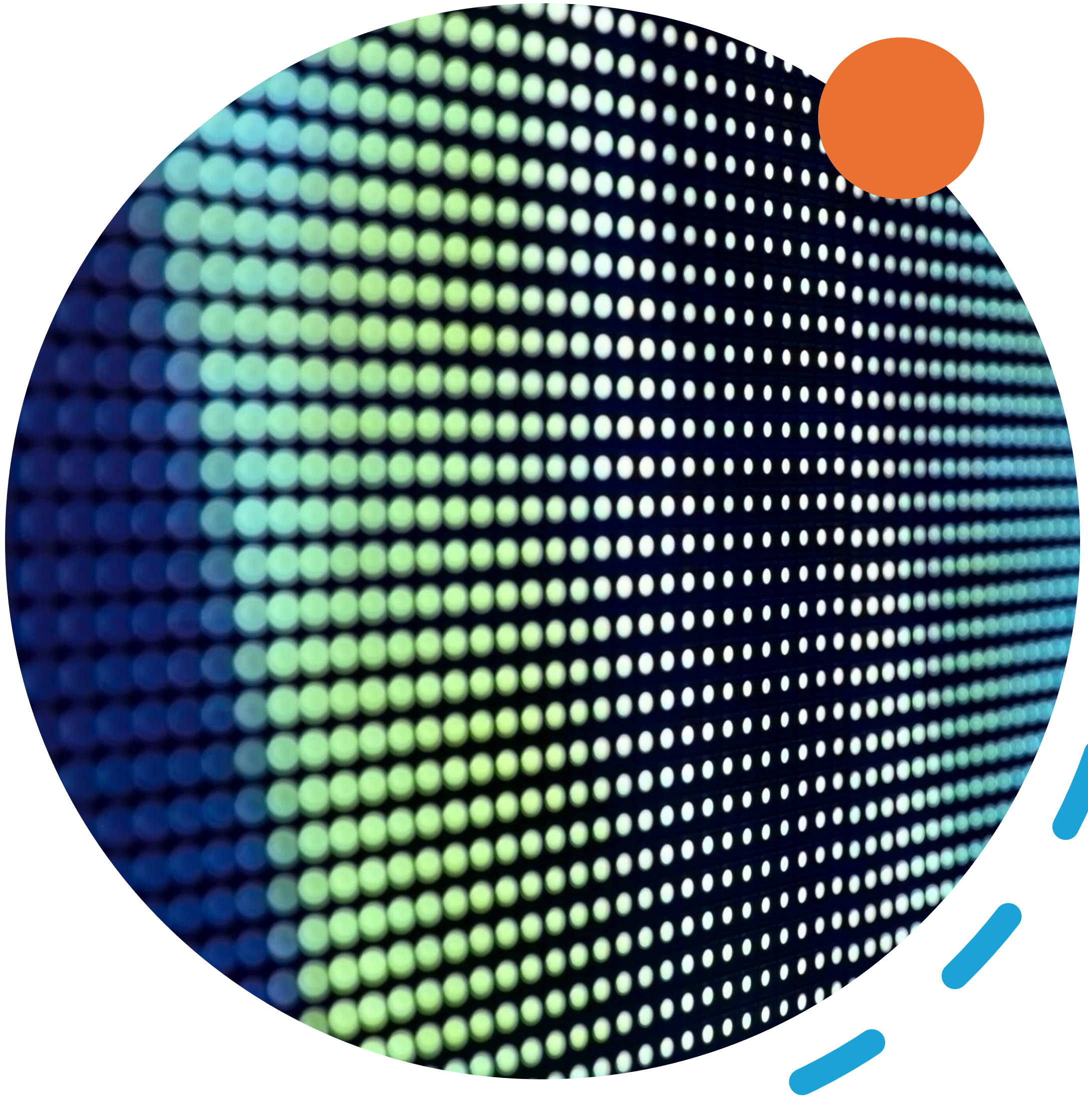
Archimedes

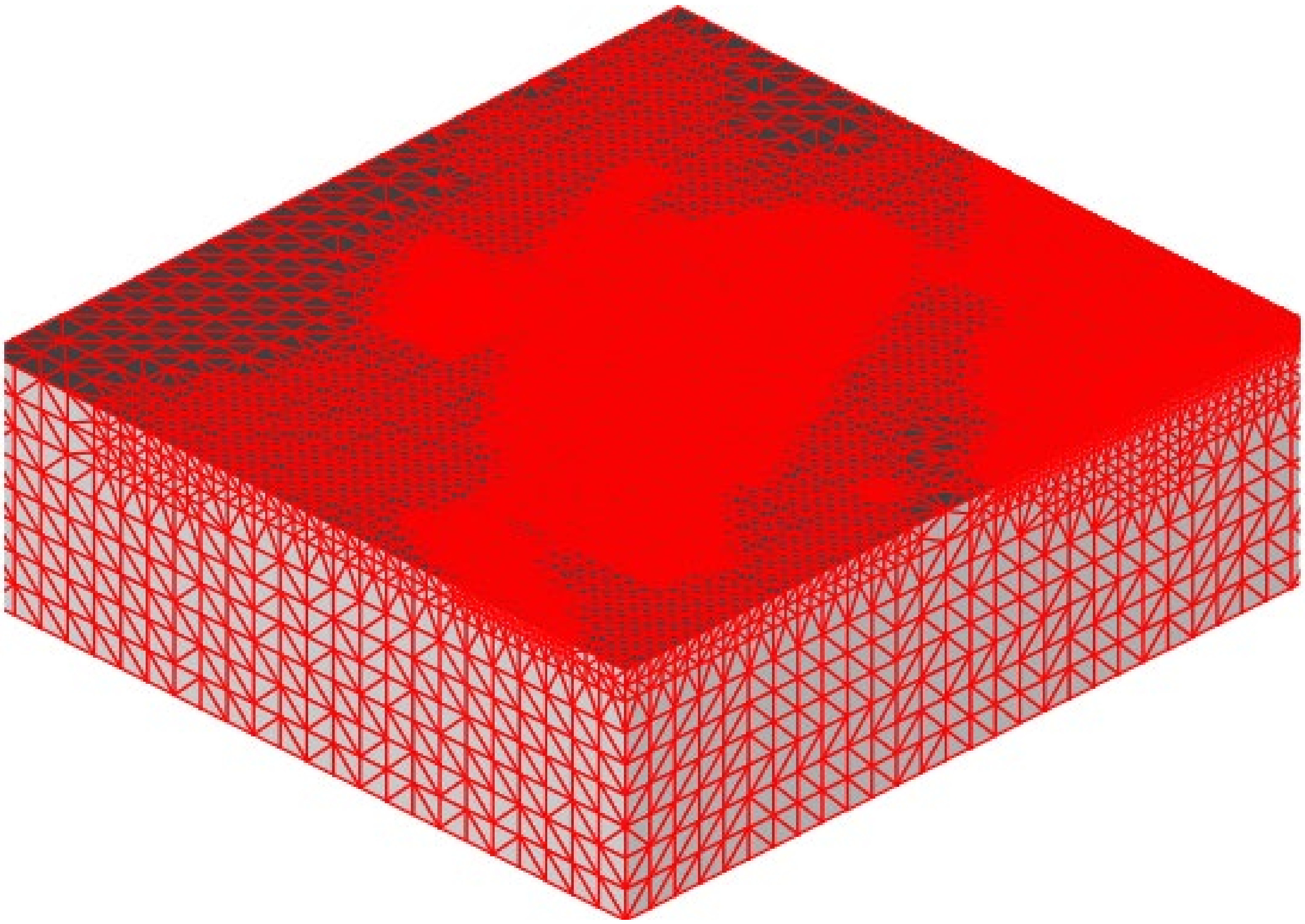
Included:

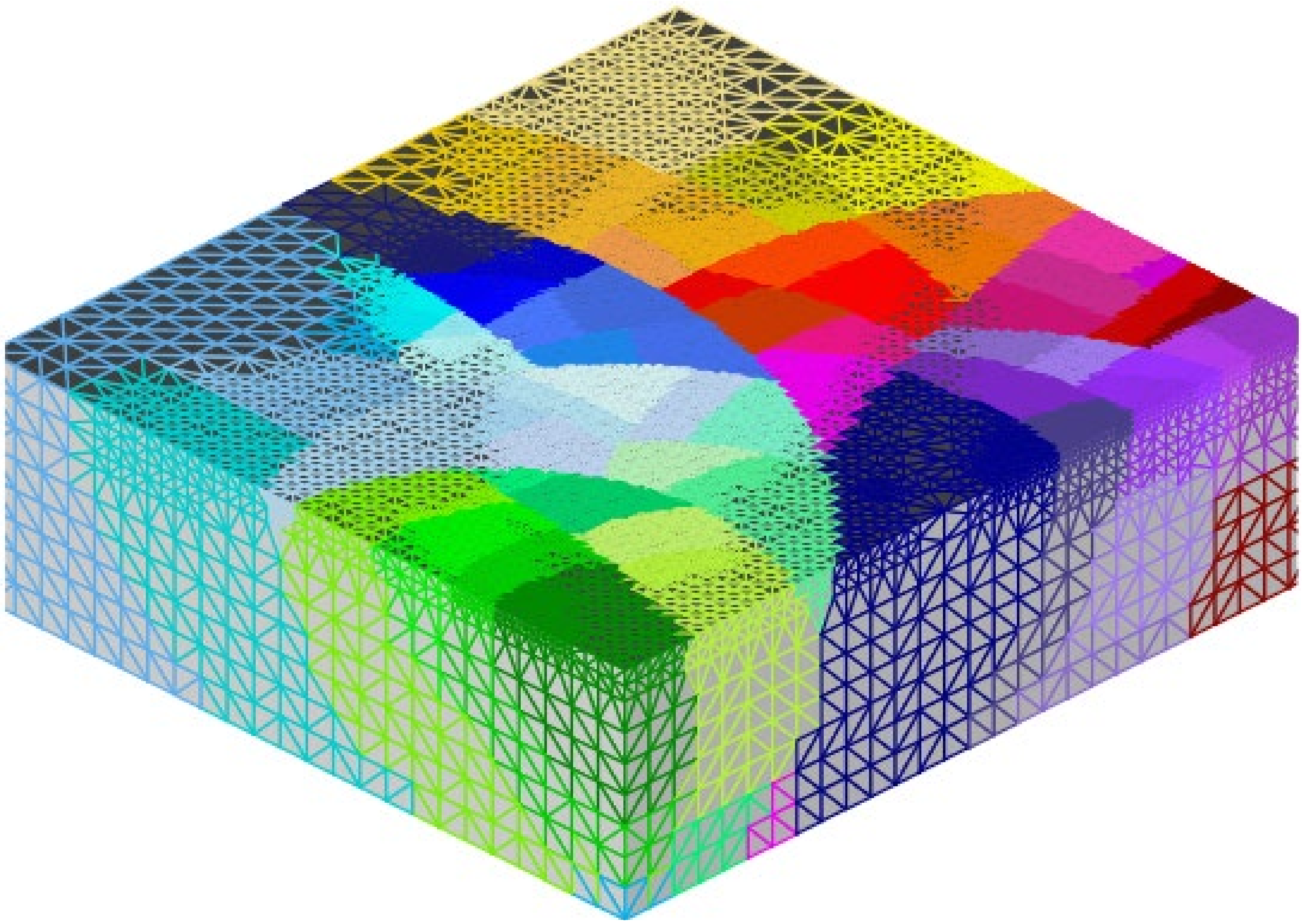
Mesh generation	Partitioning	Parceling

Compiler generated portable code (C/MPI) for various systems.

'Show Me' visualizer for 3D analysis of meshes, partitions, results.

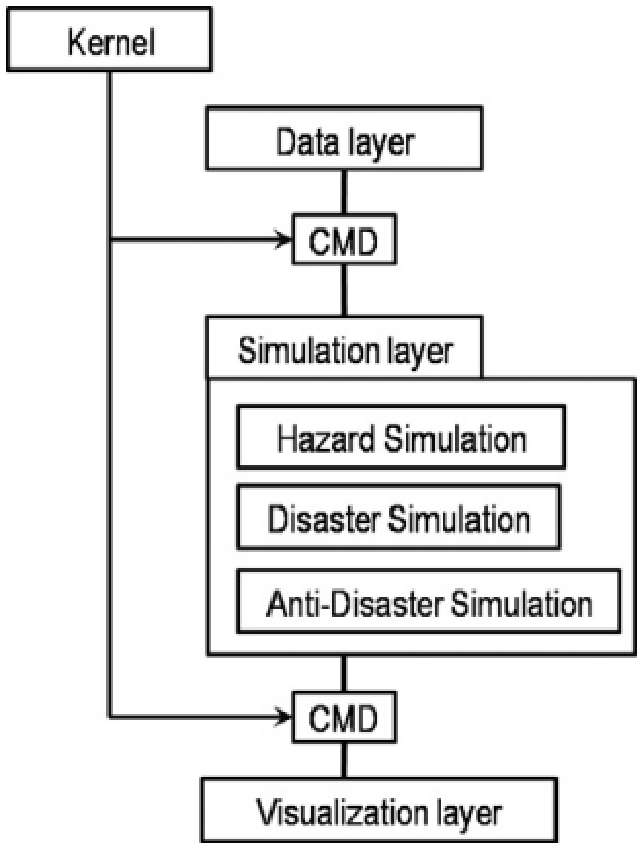


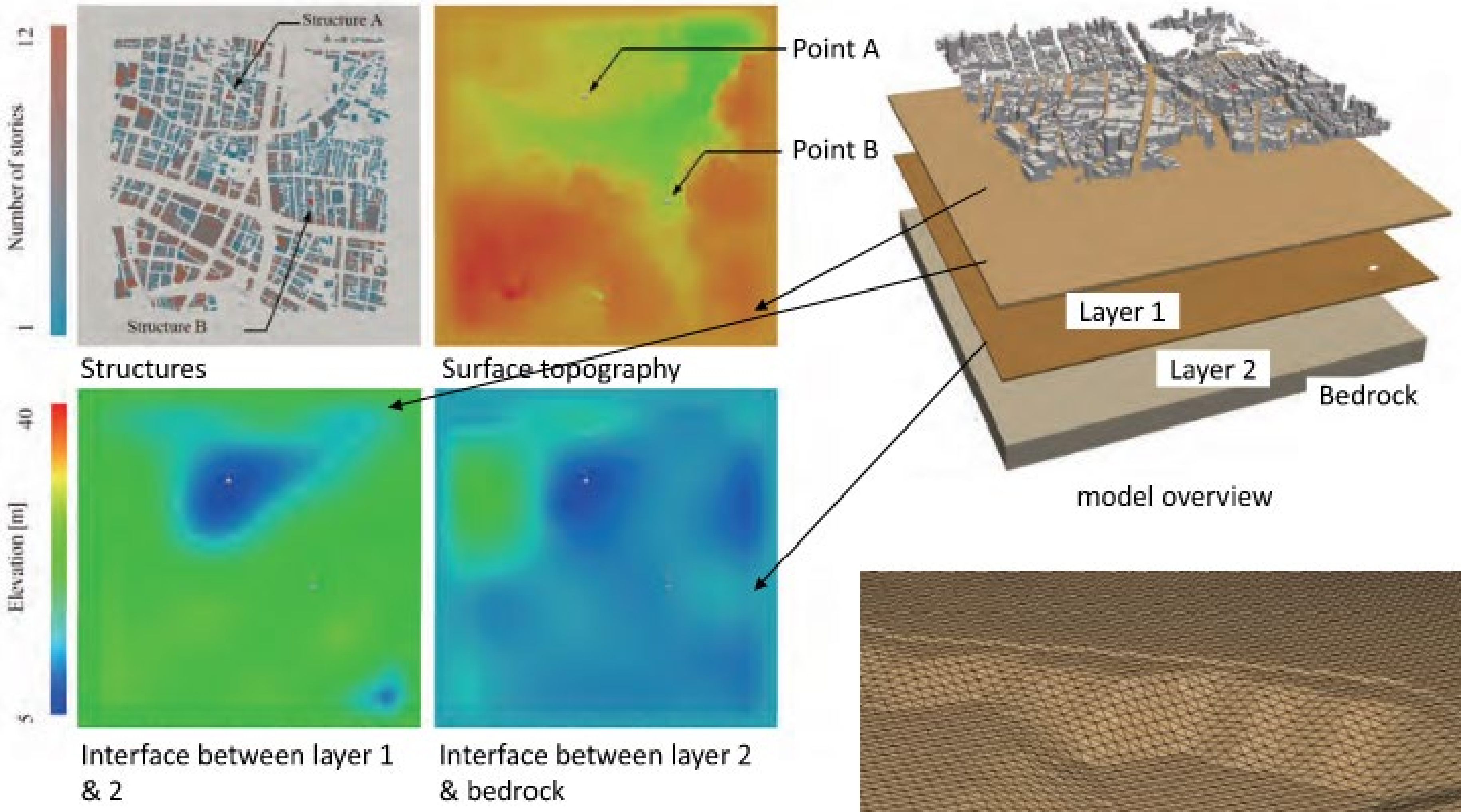


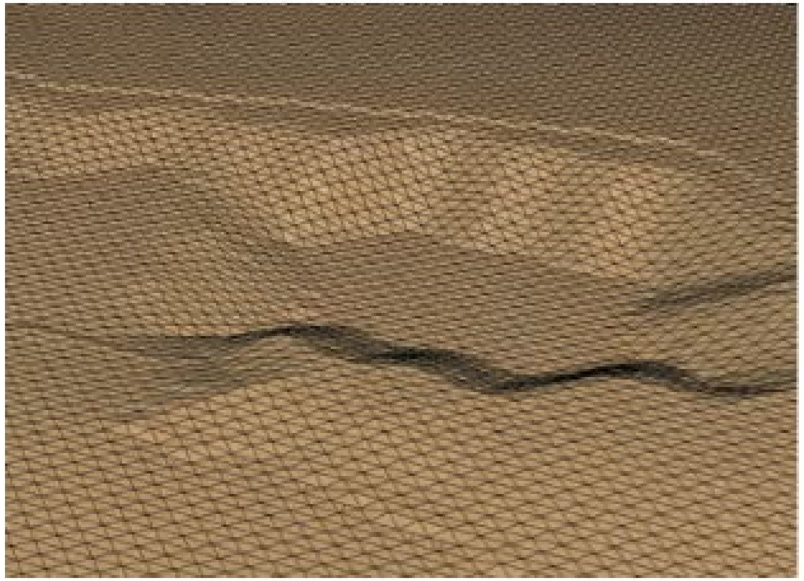


Scaling Up (2010s): HPC & Integrated Simulation (IES)

- Emergence of Integrated Earthquake Simulation (IES)
  - Hazard
  - Disaster
  - Response/Anti-Disaster
- Huge computational demand (Urban areas, Billions DOF).
- Integration of real-world data (GIS).







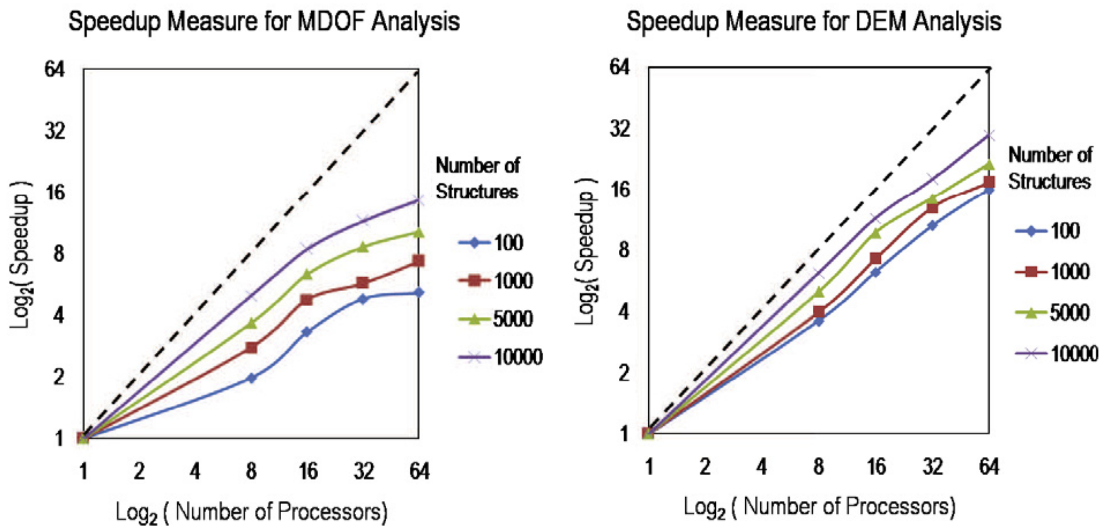
model details

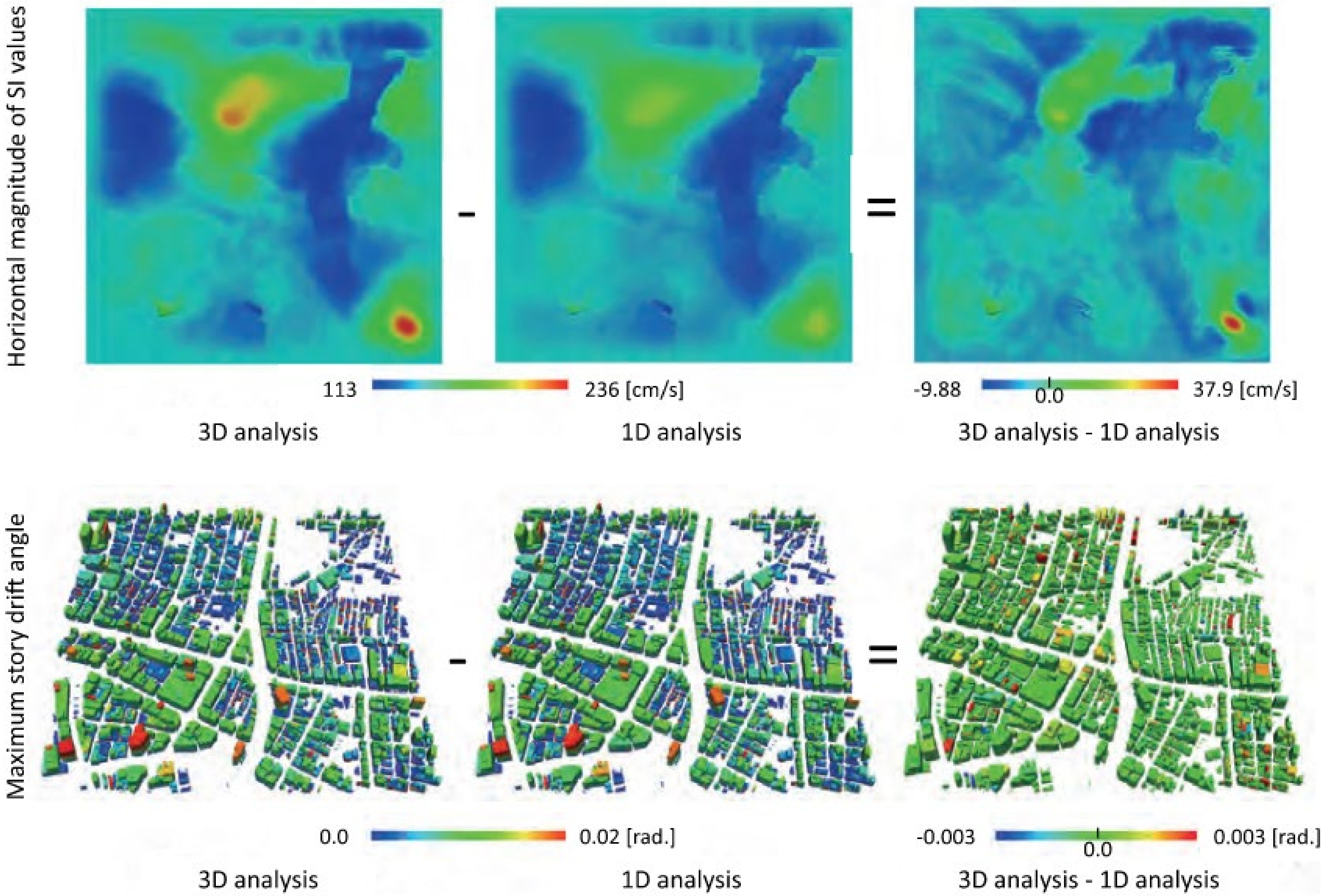
layer property

	V_p (m/s)	V_s (m/s)	ρ (kg/m^3)	$h_{\max}$ or h	γ_r
1st layer	1,210	150	1,500	0.25	0.005
2nd layer	1,380	255	1,800	0.05	∞
bedrock	1,770	490	1,900	0.005	∞

Scaling Up (2010s): HPC & Integrated Simulation (IES)

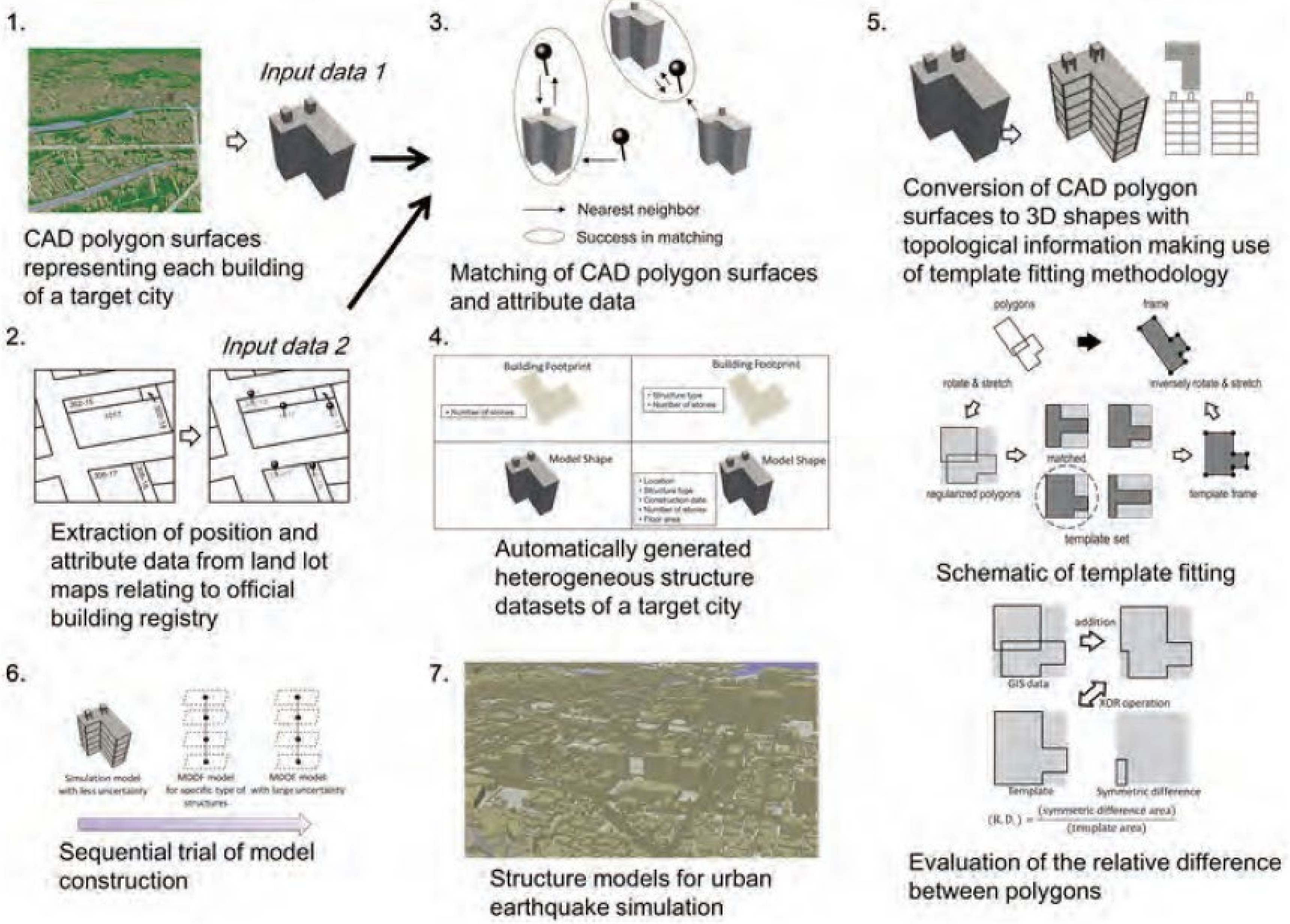
- HPC essential for IES feasibility, enabling:
  - Larger Scale & Higher Fidelity.
  - Simulation Acceleration.
- Results:
  - Detailed spatial maps
  - Identification of hazard/damage hotspots.




Horizontal magnitude of SI values
-
=
113
236 [cm/s]
-9.88
0.0
37.9 [cm/s]
3D analysis
1D analysis
3D analysis - 1D analysis
Maximum story drift angle
-
=
0.0
0.02 [rad.]
-0.003
0.0
0.003 [rad.]
3D analysis
1D analysis
3D analysis - 1D analysis

Tackling Uncertainty with High-Fidelity Models

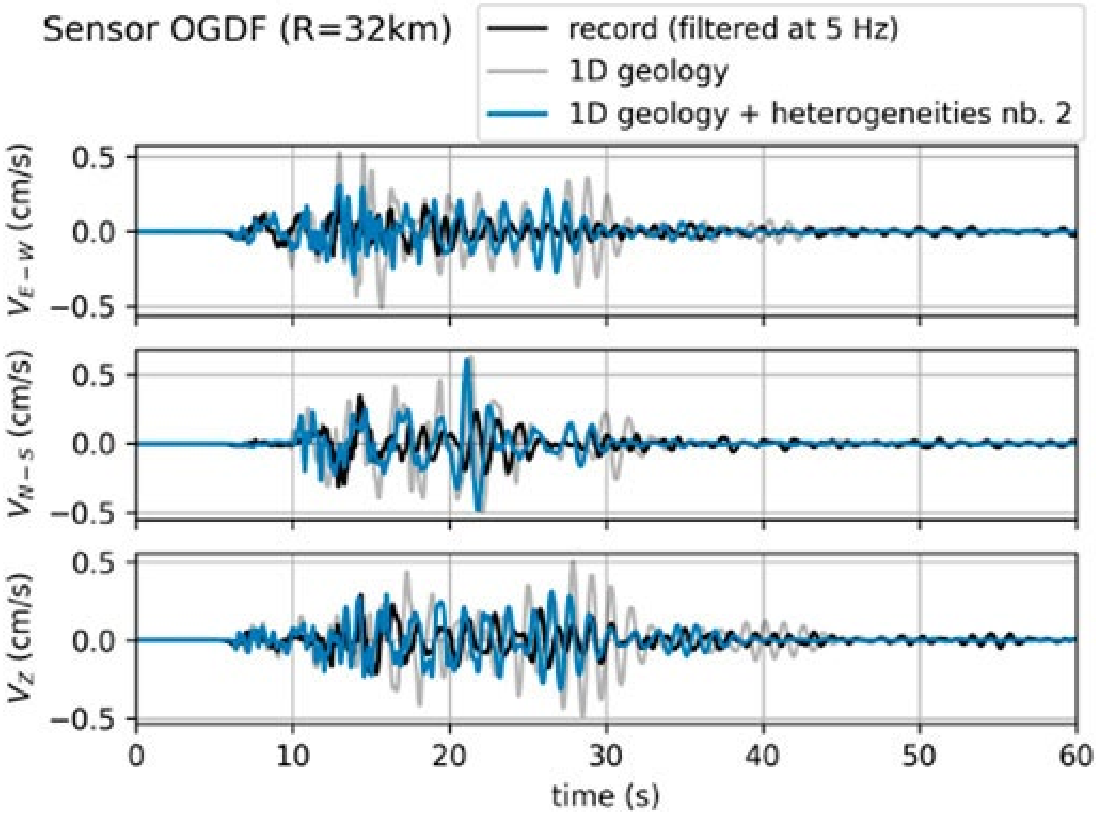
- Challenge: Significant uncertainties (source, geology, structures).
- HPC enables Uncertainty Quantification (UQ) via large-scale ensemble simulations.

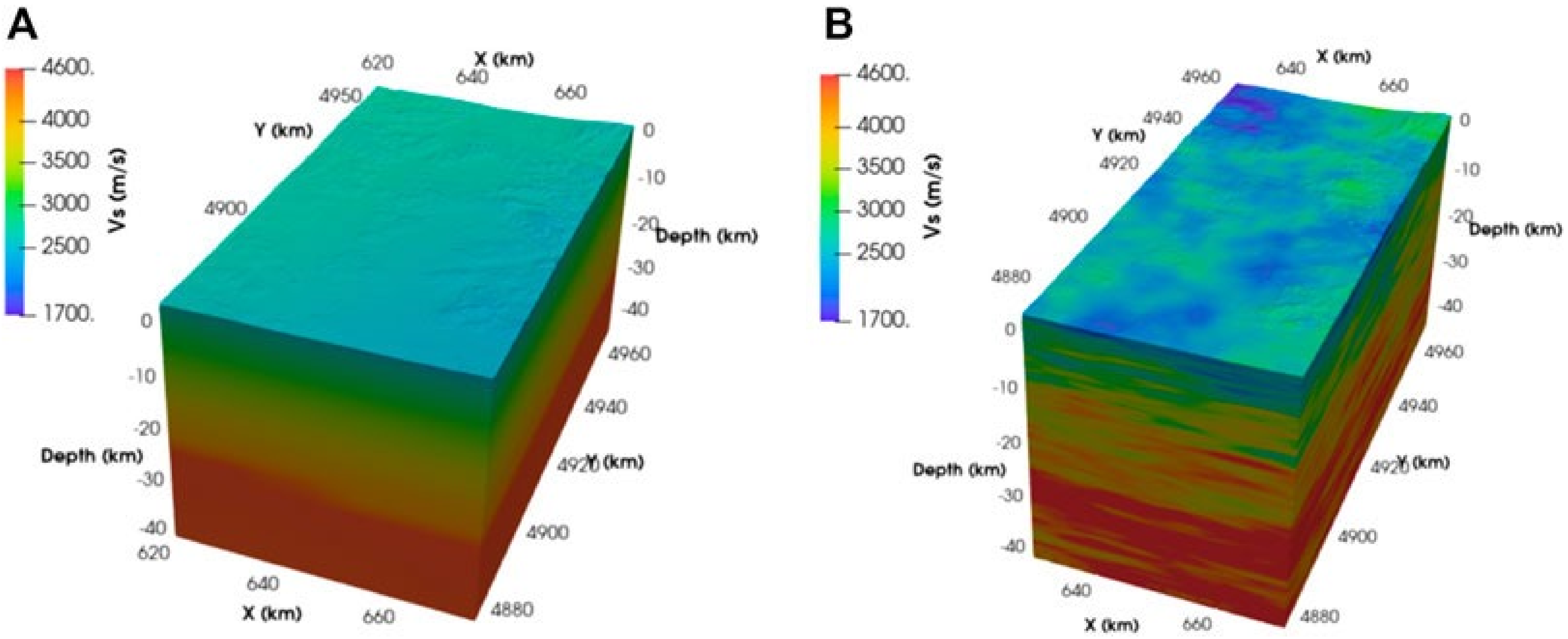


1.
Input data 1
CAD polygon surfaces representing each building of a target city
2.
Input data 2
Extraction of position and attribute data from land lot maps relating to official building registry
3.
Nearest neighbor
Success in matching
Matching of CAD polygon surfaces and attribute data
4.
Building Footprint
Model Shape
Automatically generated heterogeneous structure datasets of a target city
5.
Conversion of CAD polygon surfaces to 3D shapes with topological information making use of template fitting methodology
polygons
frame
rotate & stretch
inversely rotate & stretch
matched
regularized polygons
template set
template frame
Schematic of template fitting
addition
GIS data
XOR operation
Template
Symmetric difference
(R. D.) = (symmetric difference area) / (template area)
Evaluation of the relative difference between polygons
6.
Simulation model with less uncertainty
MDOF model for specific type of structures
MDOF model with large uncertainty
Sequential trial of model construction
7.
Structure models for urban earthquake simulation

Tackling Uncertainty with High-Fidelity Models

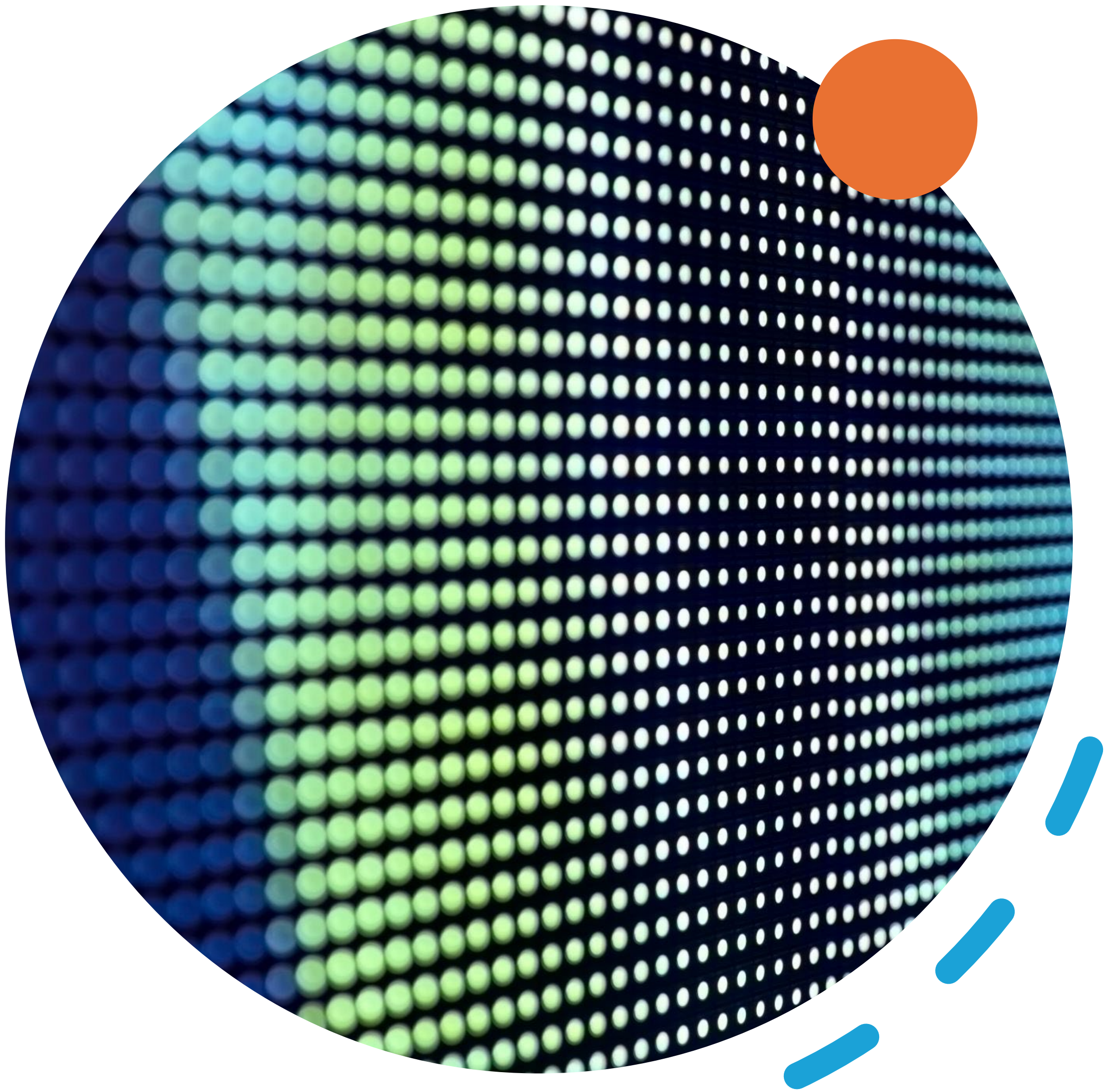
- Addressing geological complexity: Incorporating heterogeneity (e.g., random fields).
- Requires advanced HPC simulation frameworks (e.g., SEM3D - Spectral Element Method code with excellent scalability).
- Need for improved model validation against observations.




A
4600.
4000
3500
3000
2500
1700.
Vs (m/s)
X (km)
620
640
660
Y (km)
4950
4900
0
-10
-20
-30
-40
Depth (km)
4960
4940
4920
4900
4880
B
4600.
4000
3500
3000
2500
1700.
Vs (m/s)
X (km)
640
660
Y (km)
4960
4940
4920
4900
4880
0
-10
-20
-30
-40
Depth (km)

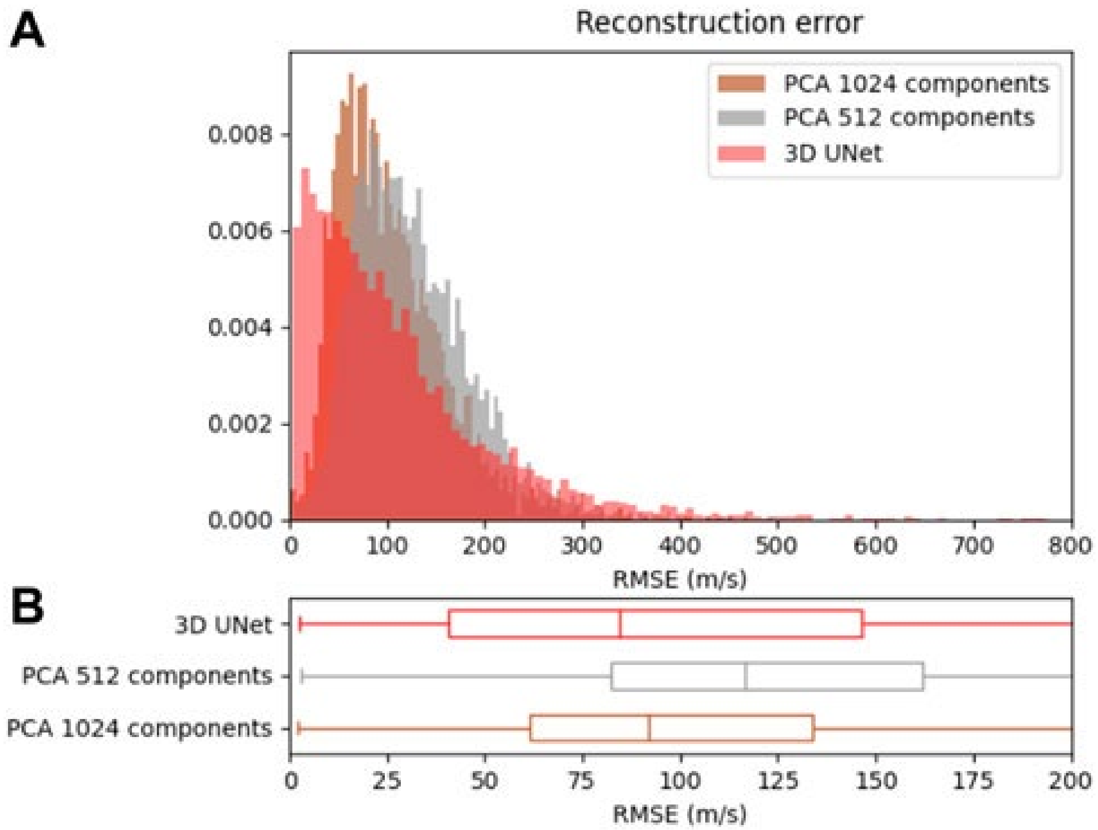
The AI Revolution (2020s-Present): Data & Adaptation

- AI for Real-Time Integration
- AI/ML excels at pattern recognition in large, complex datasets.
- Processing diverse, real-time data streams: Seismic networks, GNSS, InSAR, IoT.
- Adaptive Simulation: Using real-time data to update models dynamically.
- Potential for improved accuracy and reduced latency in predictions.



The AI Revolution: Efficiency & Complexity

- Models are too complex: AI for Dimensionality Reduction:
  - PCA
  - 3D UNet Autoencoders.
- Enables more efficient UQ and potentially faster surrogate models.



Persistent Challenges & Future Directions

- Current Problems:
  - High computational cost:
    - High frequencies (>10 Hz), and large scales are still demanding.
  - Data Fidelity & Integration:
    - Better, more complete input models are needed.
  - Uncertainty Management:
    - Robust characterization and propagation.
- Future:
  - Hybrid AI-HPC
  - Multi-scale modeling
  - Predictive analytics.

Our Journey Ends Here … for Now

- **From Code to Impact**
  Simulation tech is saving lives.
- **HPC + AI = Power & Precision**
  Together, they break old limits.
- **The Future Quakes Smarter**
  We're not done, just getting started.