Collaborative Research: Development of Realistic Seismic Input Motions for Improving the Resilience of Infrastructures to Earthquakes

[1]**Chanseok Jeong** and [2]**Boris Jeremic**

[1]School of Engineering and Technology, Central Michigan University, Mount Pleasant, 48859, MI, USA

[2]Department of Civil and Environmental Engineering, University of California, Davis, 95616, CA, USA

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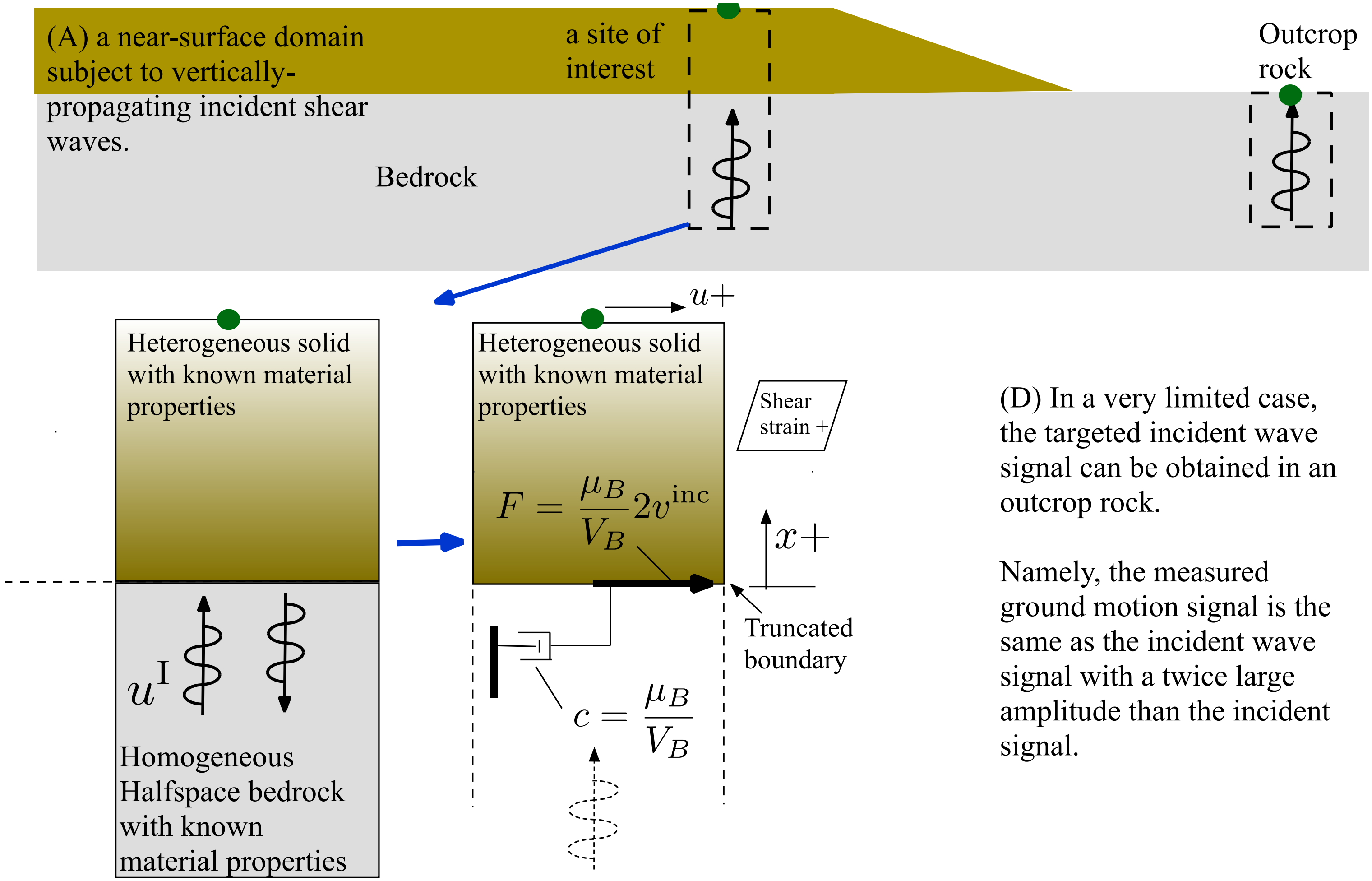
Motivation for this work

- Estimating incident seismic wavefields in a soil-structure system from seismic measurement allows engineers to pinpoint where large amplitudes of stress waves occur (or structural failures occur) in built environments during seismic events.
- It helps decision-makers to plan the budget and schedule of upgrades, *Improving the Resilience of Infrastructure to Earthquakes.*

Existing method: 1D Deconvolution



(B) a site of interest: we identify incoming vertically-propagating seismic wave signal at the soil-bedrock interface.

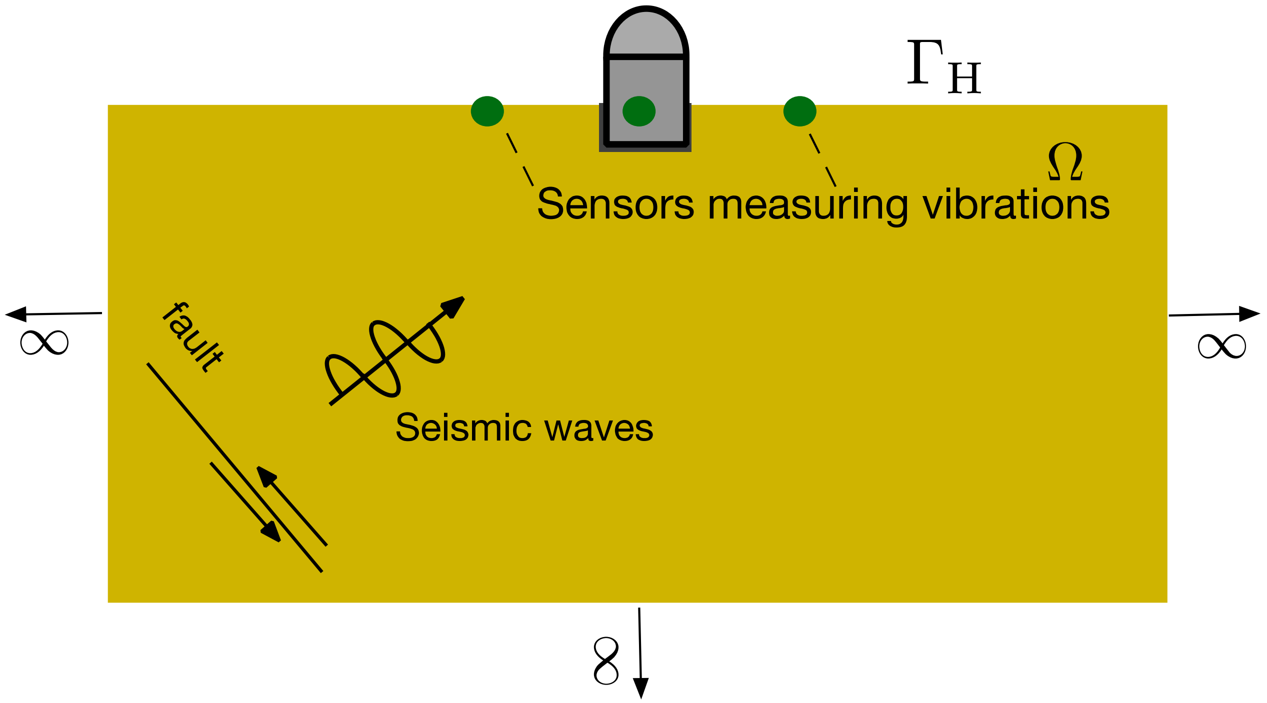
(C) a truncated, simplified model of the site of interest.

(D) In a very limited case, the targeted incident wave signal can be obtained in an outcrop rock.

Namely, the measured ground motion signal is the same as the incident wave signal with a twice large amplitude than the incident signal.

- The deconvolution method is useful in a 1D soil column only when geophysical property is horizontally layered, and incoming seismic waves vertically propagate.

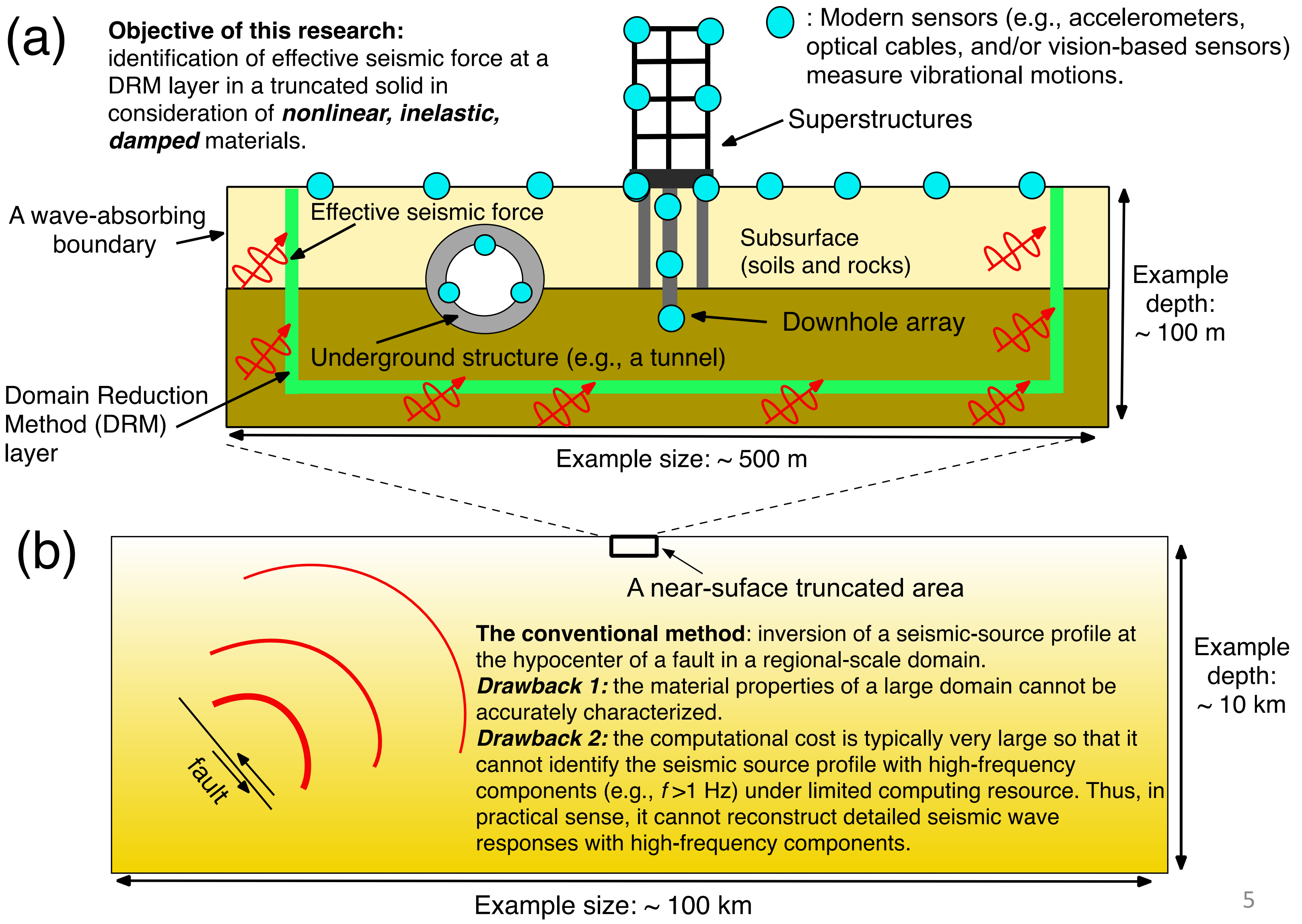
Existing method:
Large-scale seismic-source inversion approach



- It can identify the seismic source parameters at a hypocenter. Once they are characterized, a forward wave simulation reconstructs wave responses in structural and geomechanical systems of interest.
- Due to large computational cost and uncertainties of geophysical property data, it cannot be used in a practice.

Objective

Investigate a new method for accurate reconstruction of **three component (3C) of incoming seismic wave field (i.e., 3D deconvolution)** in a 3D, truncated near-surface domain by using sparse seismic data in consideration of mildly nonlinear, inelastic materials.



Background:
Domain Reduction Method (DRM)

J. Bielak, K. Loukakis, Y. Hisada, C. Yoshimura, Domain reduction method for three-dimensional earthquake modeling in localized regions, Part I: Theory, **Bulletin of the Seismological Society of America,** 93, (2003).

- The original DRM theory converts incident waveforms into nodal forces within a DRM layer, allowing wave simulation in a truncated domain subject to seismic wave inputs.
- The theory has been used in numerous papers.

Research Goals

- Investigation of the novel inverse modeling (i.e., 3D deconvolution) coupled with the domain reduction method (DRM) in consideration of various measurement types.
- **Central Michigan U**: Theoretical investigation of the 3D deconvolution. Preliminary tests in 2D settings prior to the full 3D study.
- **UCDavis**: Investigation of the 3D deconvolution using the **Real-ESSI Simulator** in a 3D setting.

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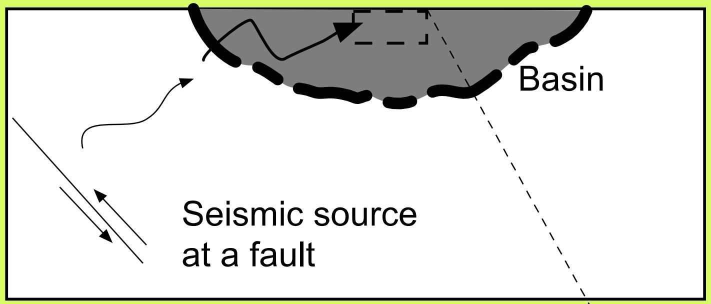
Overall algorithm of 3D deconvolution

Hypocenter-to-surface forward-only seismic wave simulation

e.g., kilometers



Production of synthetic measured data of Inverse DRM

Use a forward solver in an enlarged domain including a seismic source.

↓

Compute the wave motion at the sensor locations in the interior of the domain of interest.

Events generating real data (e.g., a real earthquake or experimental data from NHERI facilities)

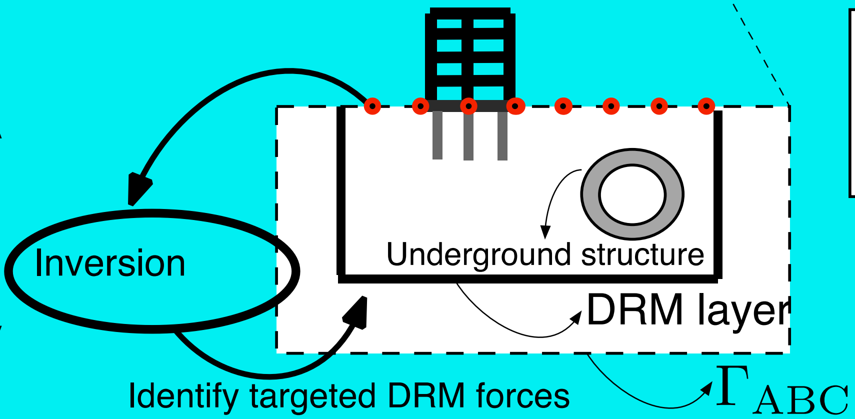
Real seismic event occurs.

↓

Record the wavefield at the sensor locations.

Proposed inversion method in a near-surface truncated domain of interest

Tens of meters



Identify targeted DRM forces on the DRM layer in the truncated domain.

Γ_{ABC}: an absorbing boundary condition (ABC)

Use the sensor data to perform the inverse simulation considering a near-surface truncated domain.

↓

Use the inverted DRM forces to reconstruct the wave responses within the truncated domain of interest.

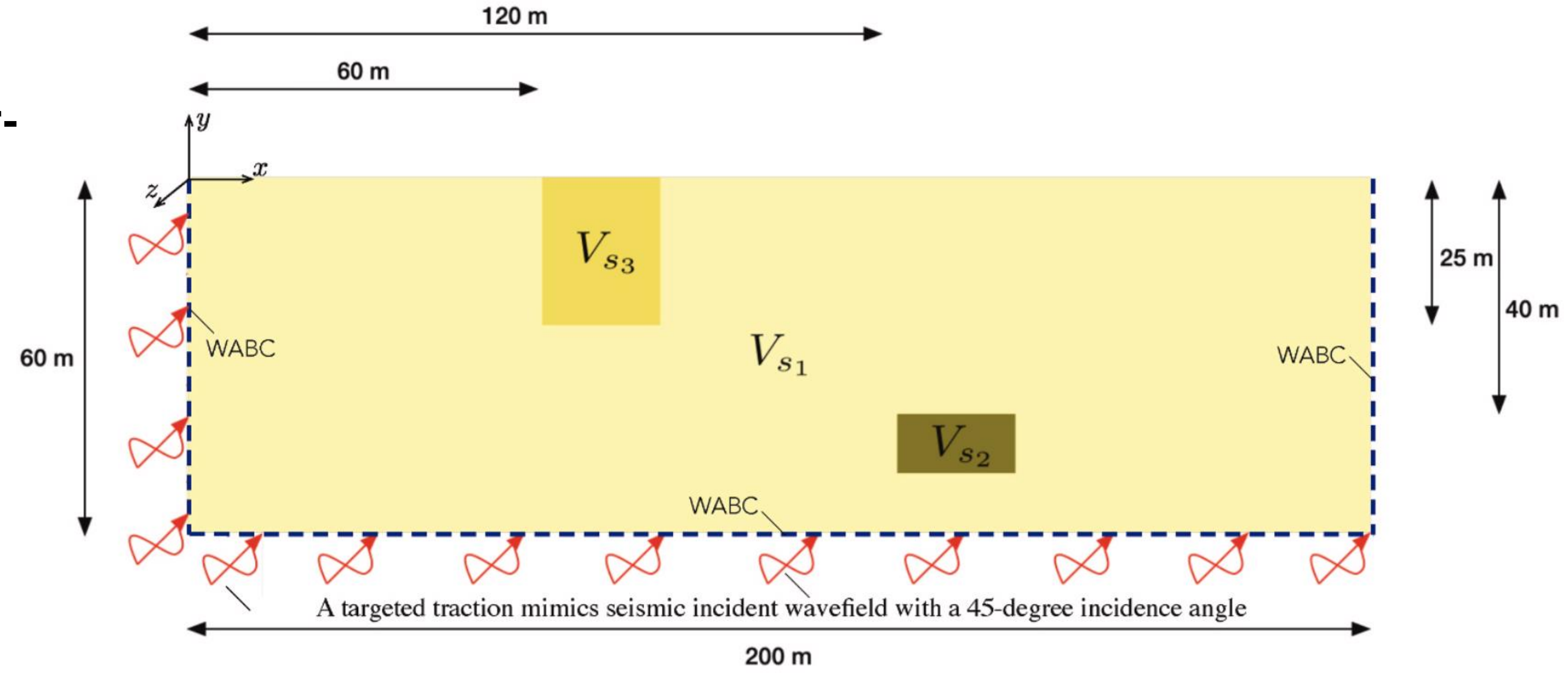
Overall algorithm of 3D deconvolution

- Iteratively estimates control parameters representing the DRM nodal forces at all the time steps during the observation period.
- Aims to minimize a misfit functional, which quantifies the mismatch between wave response signals measured at sensor locations and those computed based on estimated control parameters.
- PDE-constrained optimization is utilized.
    - Established methodology recognized within computational optimization communities.
    - Historically proven to exhibit robustness in material inversion for geotechnical site characterization problem.

Research Results: Guidio et al. SDEE (2022)

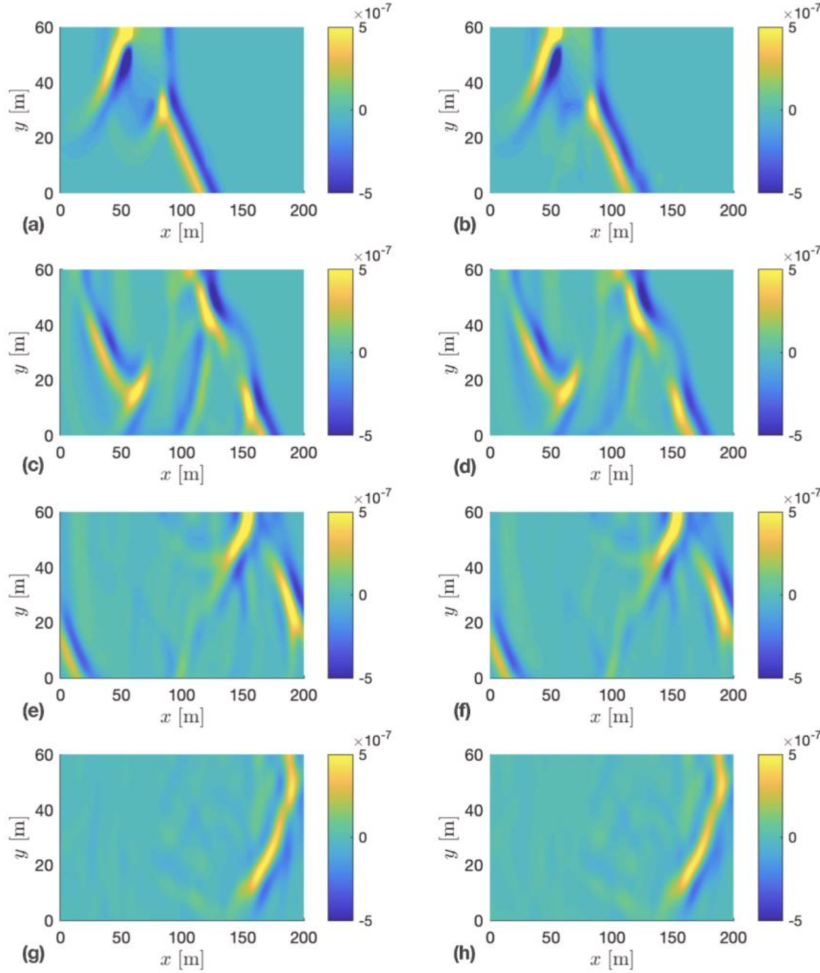
(2022) B. Guidio, B. Jeremic, L. Guidio, and C. Jeong, *Passive-seismic inversion of SH-wave input motions in a domain truncated by wave-absorbing boundary conditions*, **Soil Dynamics and Earthquake Engineering**, Vol. 158, Elsevier.

- We consider 2D **scalar-waves** (SH-wave) in a linear elastic solid.
- Control parameters are the nodal forces of traction, representing a plane wave, on ABC.

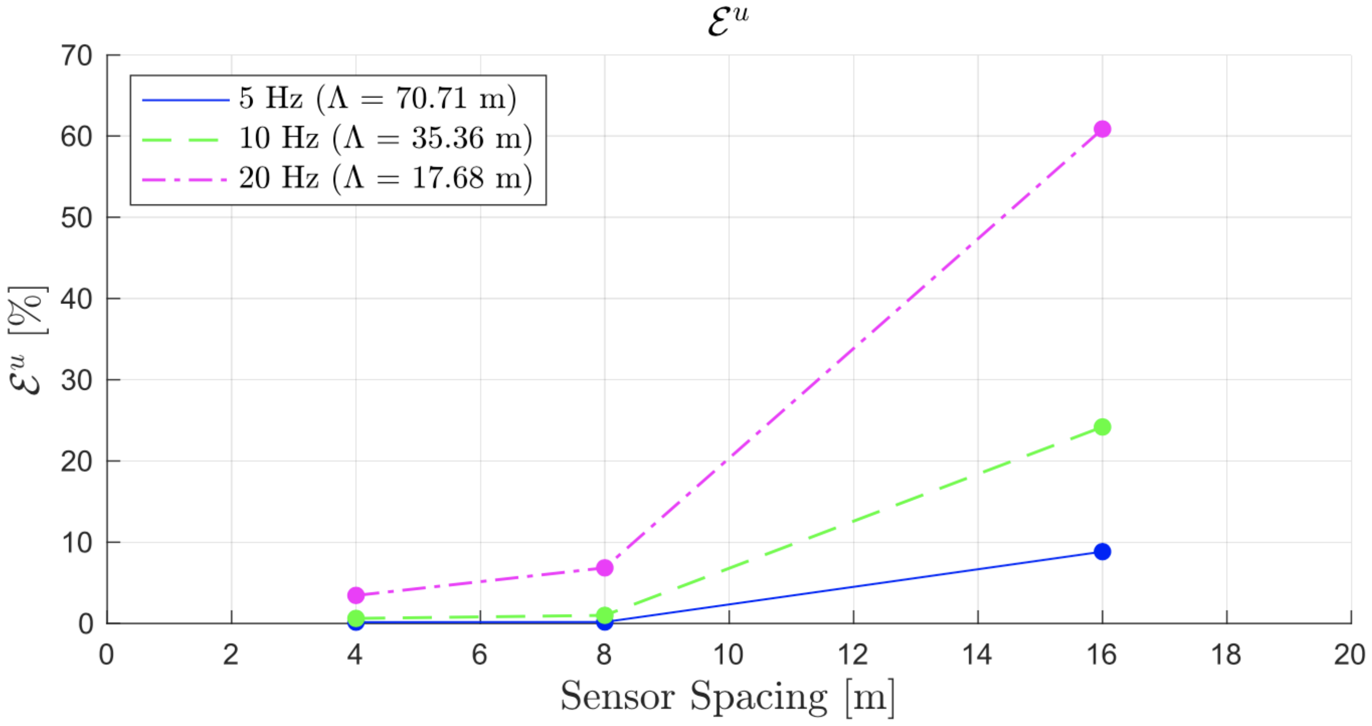


Research Results:
Guidio et al. SDEE (2022)

Target Estimation



$$\mathcal{E}^u = \sum_{j=1}^{N-timestep} \frac{|\mathbf{u}_j^{\text{target}} - \mathbf{u}_j^{\text{reconstructed}}|^2}{|\mathbf{u}_j^{\text{target}}|^2} \times 100[\%]$$



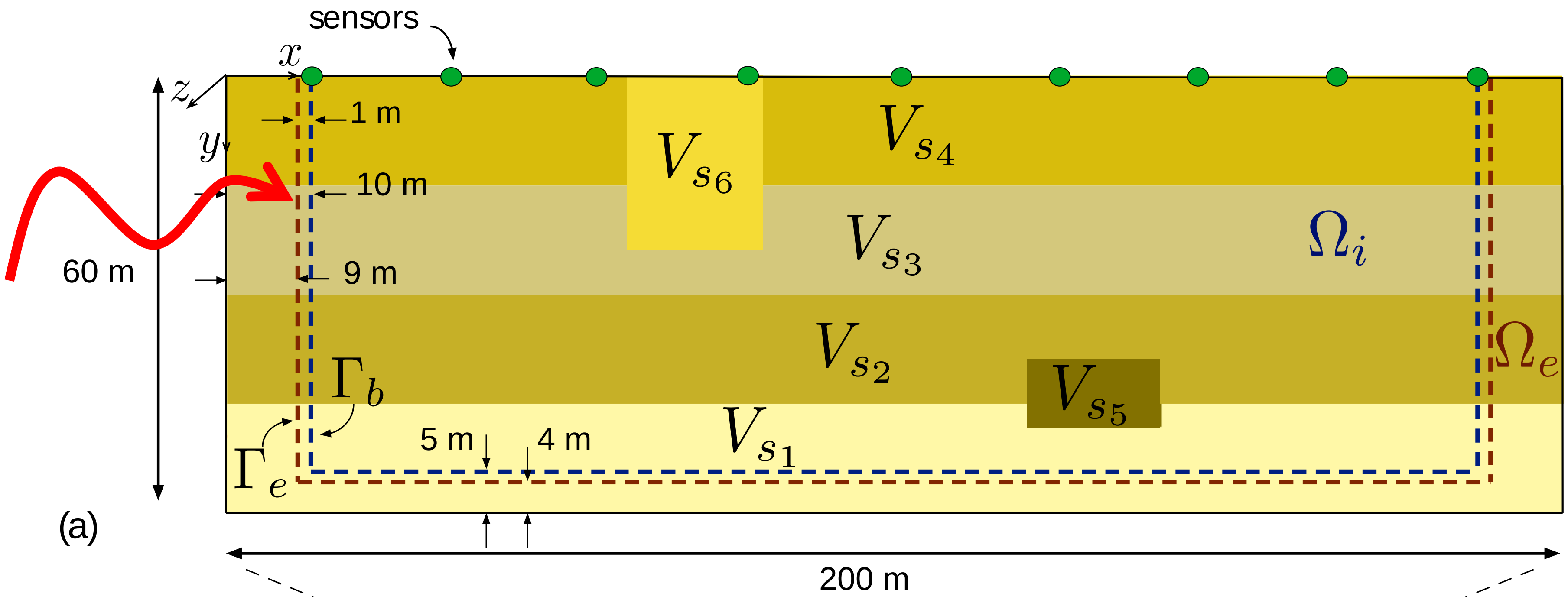
Waves of a dominant frequency of 20 Hz are considered with a sensor spacing of 8 m.

To increase the accuracy of the presented algorithm, **the number of sensors per unit length should increase as the frequency content of an incident wave increases**.

Research Results: Guidio et al. SDEE (2023)

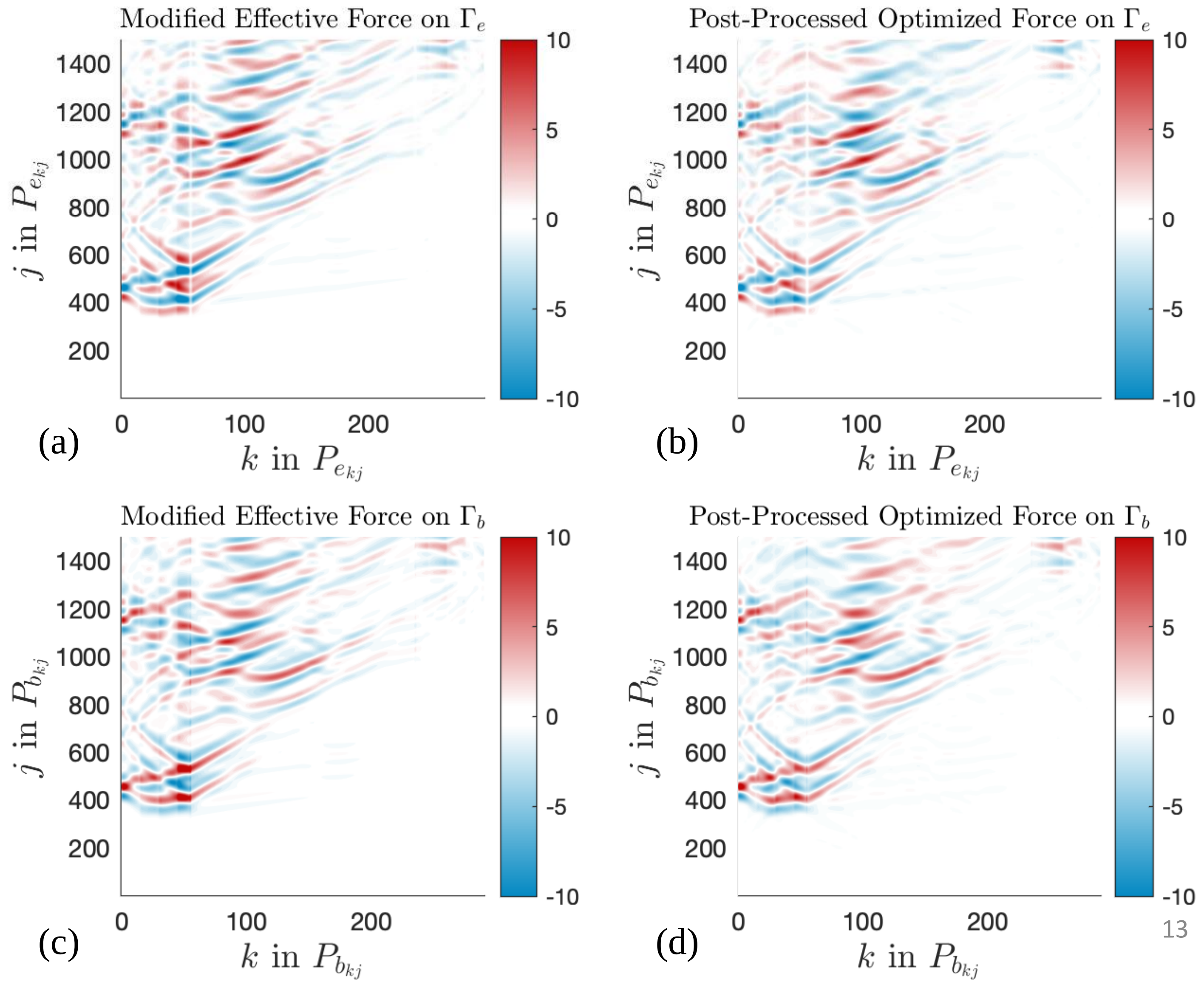
(2023) B. Guidio, H. Goh, and C. Jeong, *Effective seismic force retrieval from surface measurement for SH-wave reconstruction*, **Soil Dynamics and Earthquake Engineering**, Vol. 165, 2023.

- We consider 2D **scalar-waves** (SH-wave) in a linear elastic solid.
- Unknown control parameters are the nodal forces in the DRM layer.
- Four-node elements are used for structural mesh.
- Region of interest (ROI) is subject to incoherent incident waves.



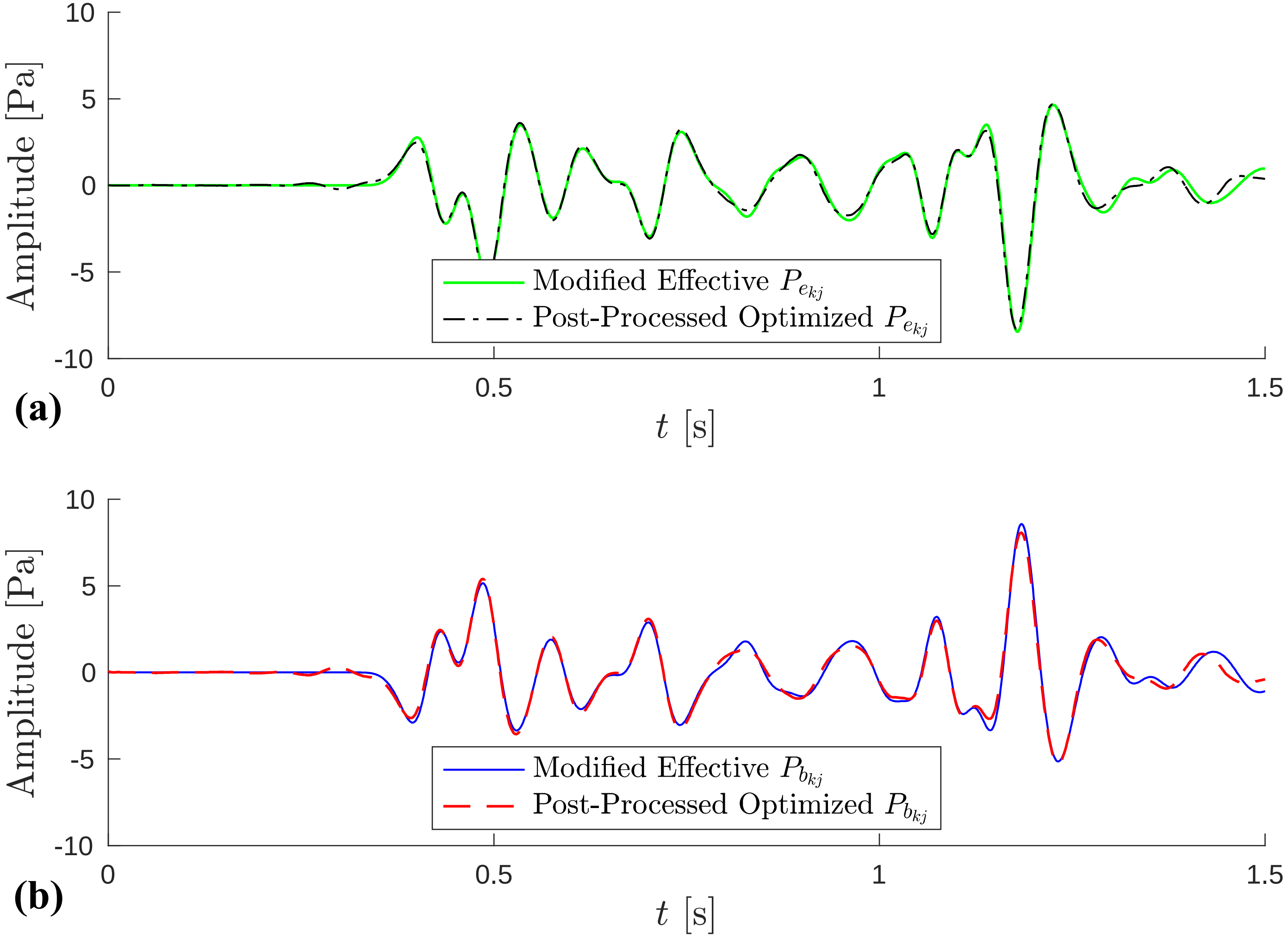
Research Results:
Guidio et al. SDEE (2023)

- Excellent agreement between the targeted and inverted DRM forces.
- An incident wave of a dominant frequency of 10 Hz and a sensor spacing of 1 m are used.
- A very large number of control parameters are inverted.
  - 1500 timesteps
  - 586 nodes in a DRM layer
  - 1500 x 586 = 0.9 M control parameters.



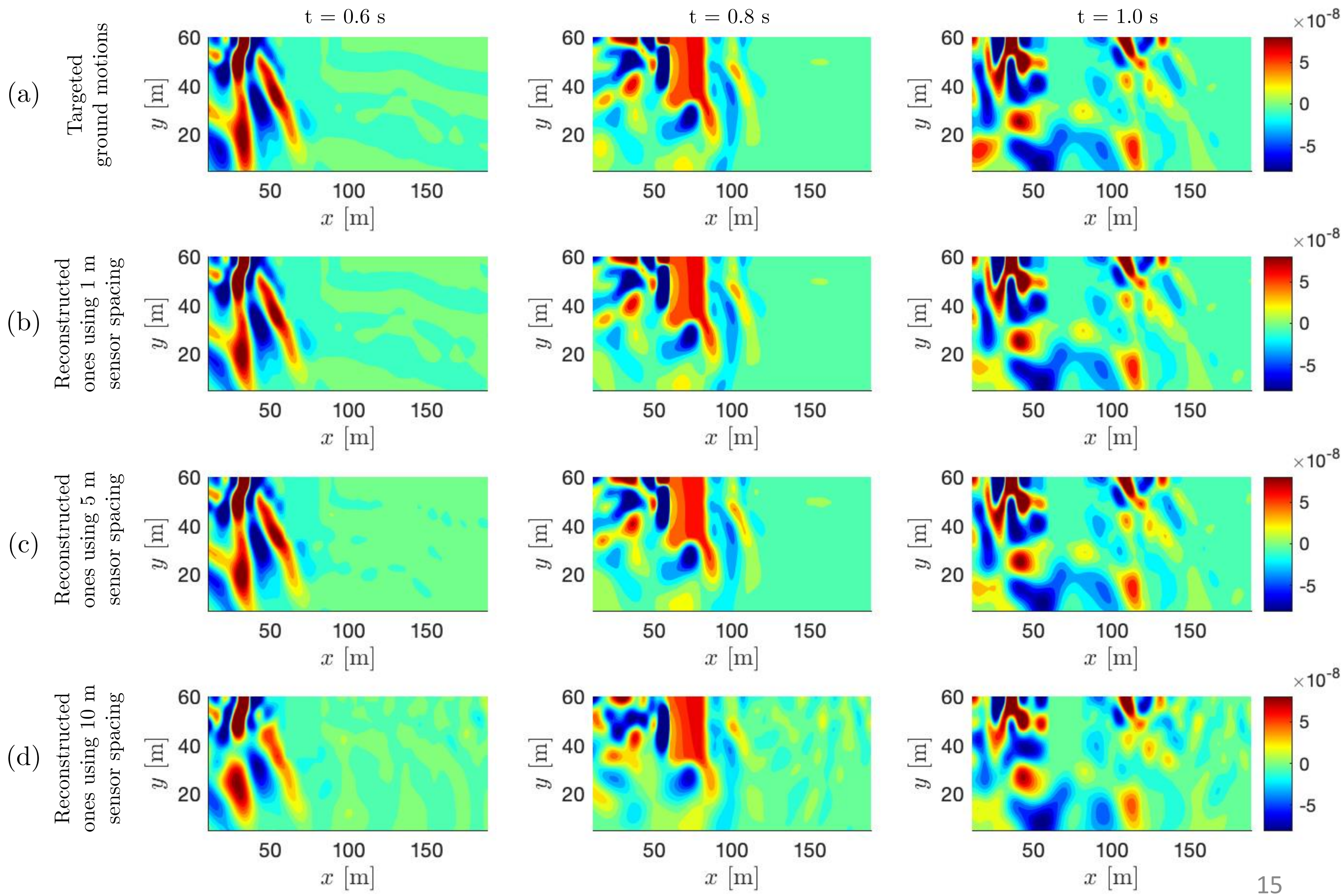
Research Results:
Guidio et al. SDEE (2023)

- Time signals of targeted and inverted DRM forces at randomly selected two nodes at a DRM layer.
- The disagreement between them is relatively large at the later time steps (e.g., 1.2 to 1.5 s).
- Such a relatively large error at the later time is due to the fact that we cannot identify the part of the target DRM force signal that is attributed to the incident waves in the later time, which do not arrive at the sensors before the end of the observation duration.



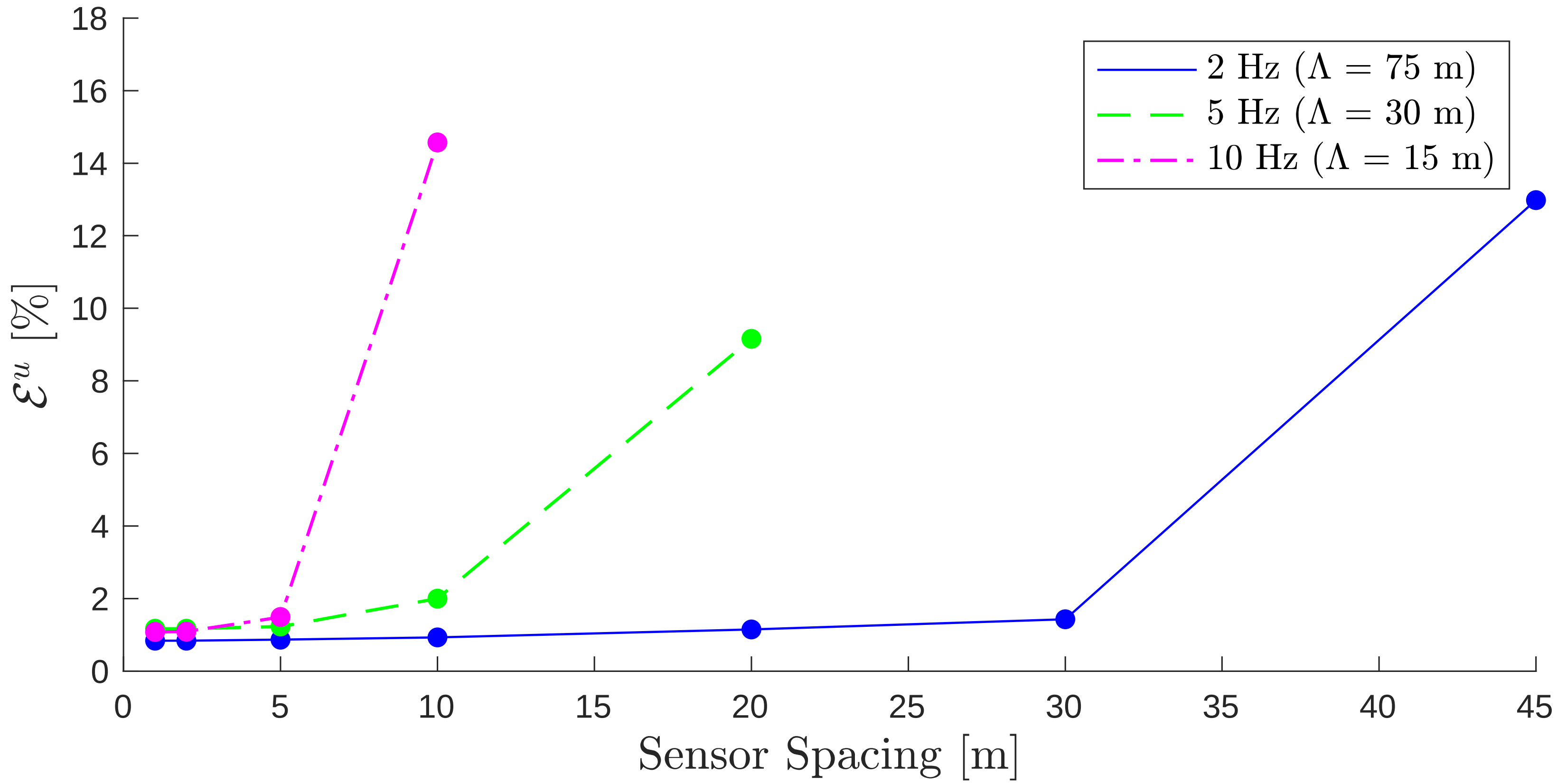
Research Results:
Guidio et al. SDEE (2023)

- (a) Targeted wave responses in the ROI,
- (b-d) their reconstructed counterparts, induced by the inverted DRM forces, using 1 m, 5 m, and 10 m sensor spacing.
- As the spacing of the sensors is increased, the agreement between the targeted and reconstructed motions in ROI diminishes.



Research Results: Guidio et al. SDEE (2023)

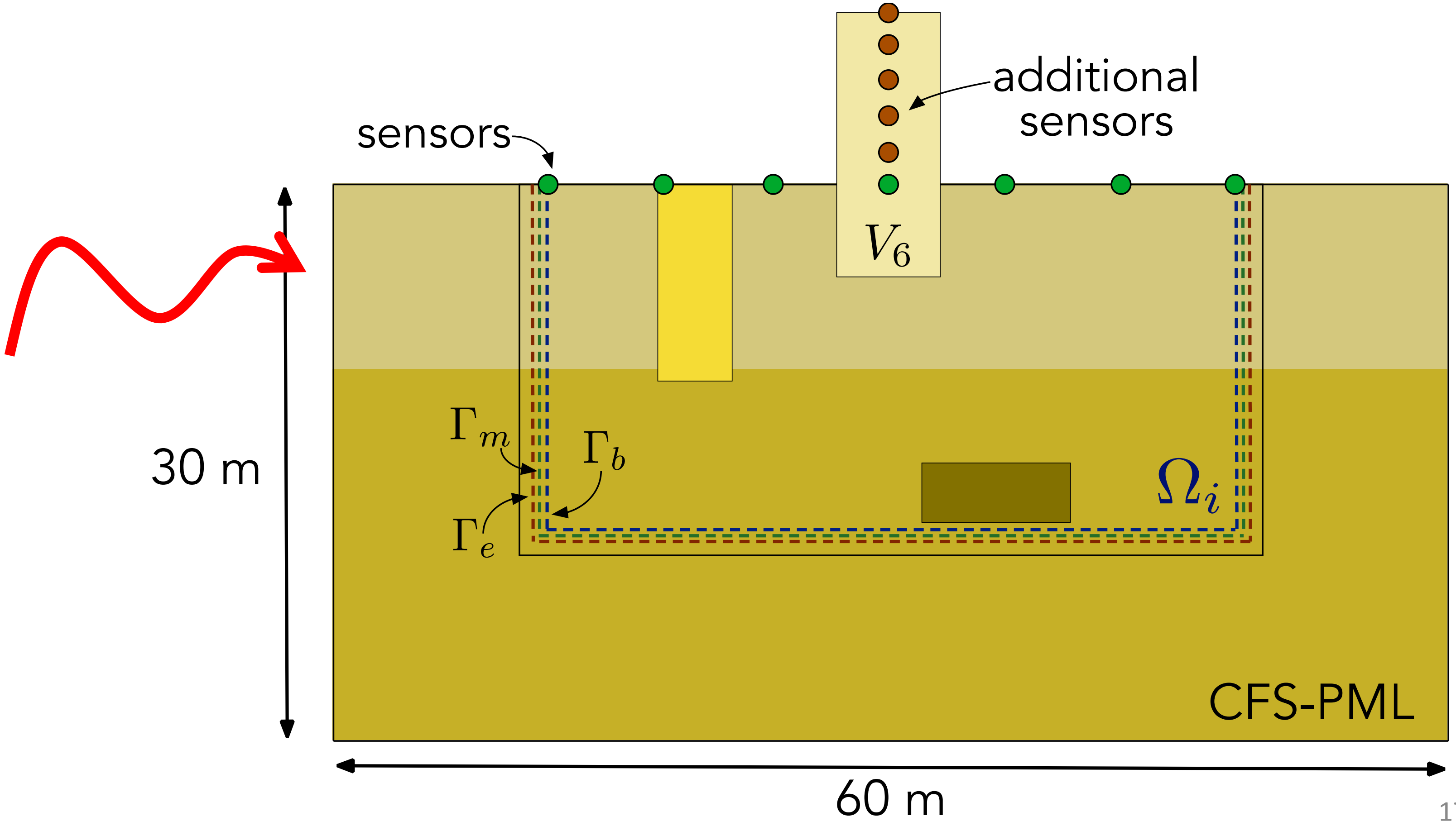
- Relation between the sensor spacing and the dominant frequency (or reference wavelength) of the surface wave-dominant incident waves.
- The minimally required sensor spacing decreases as the dominant frequency increases.
- The minimally required sensor spacing can be 1/3 of the wavelength of the top soil layer.



Research Results: Guidio et al. SDEE (202x)

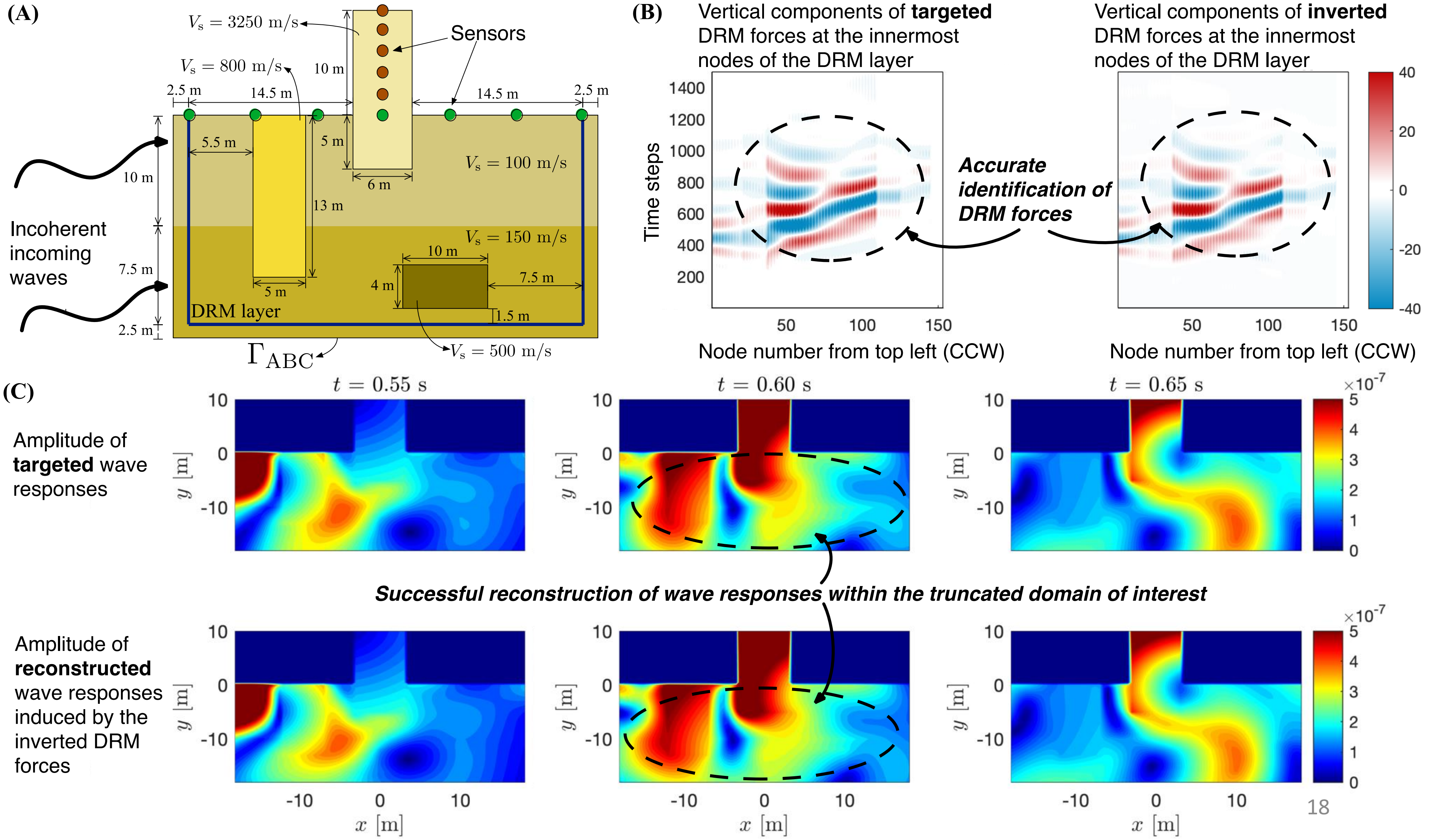
(202x) B. Guidio, H. Goh, L. F. Kallivokas, C. Jeong, *On the reconstruction of the near-surface seismic motion*, **Soil Dynamics and Earthquake Engineering** (under review).

- 2D **vector-wave** setting in a linear elastic solid.
- PML is applied as ABC.
- Nine-node elements.
- ROI is subject to incoherent incident waves.



Research Results:
Guidio et al. SDEE (202x)

- Excellent agreement between the targeted and inverted DRM forces.
- An incident wave of a dominant frequency of 5 Hz and a sensor spacing of 2 m are used.
- A very large number of control parameters are inverted.
    - 1500 timesteps
    - 222 nodes in a DRM layer
    - 1500 x 222 = 0.33 M control parameters.



Summary of the preliminary tests on the 3D deconvolution.

- The presented inversion solver can identify effective seismic forces at all the nodes within a DRM layer and all the time steps during the observation time.
- The targeted wave responses induced by the targeted incident waves can be accurately reconstructed within the interior domain by using the presented method.
- The presented inversion method is effective in both scalar wave and vector wave cases.

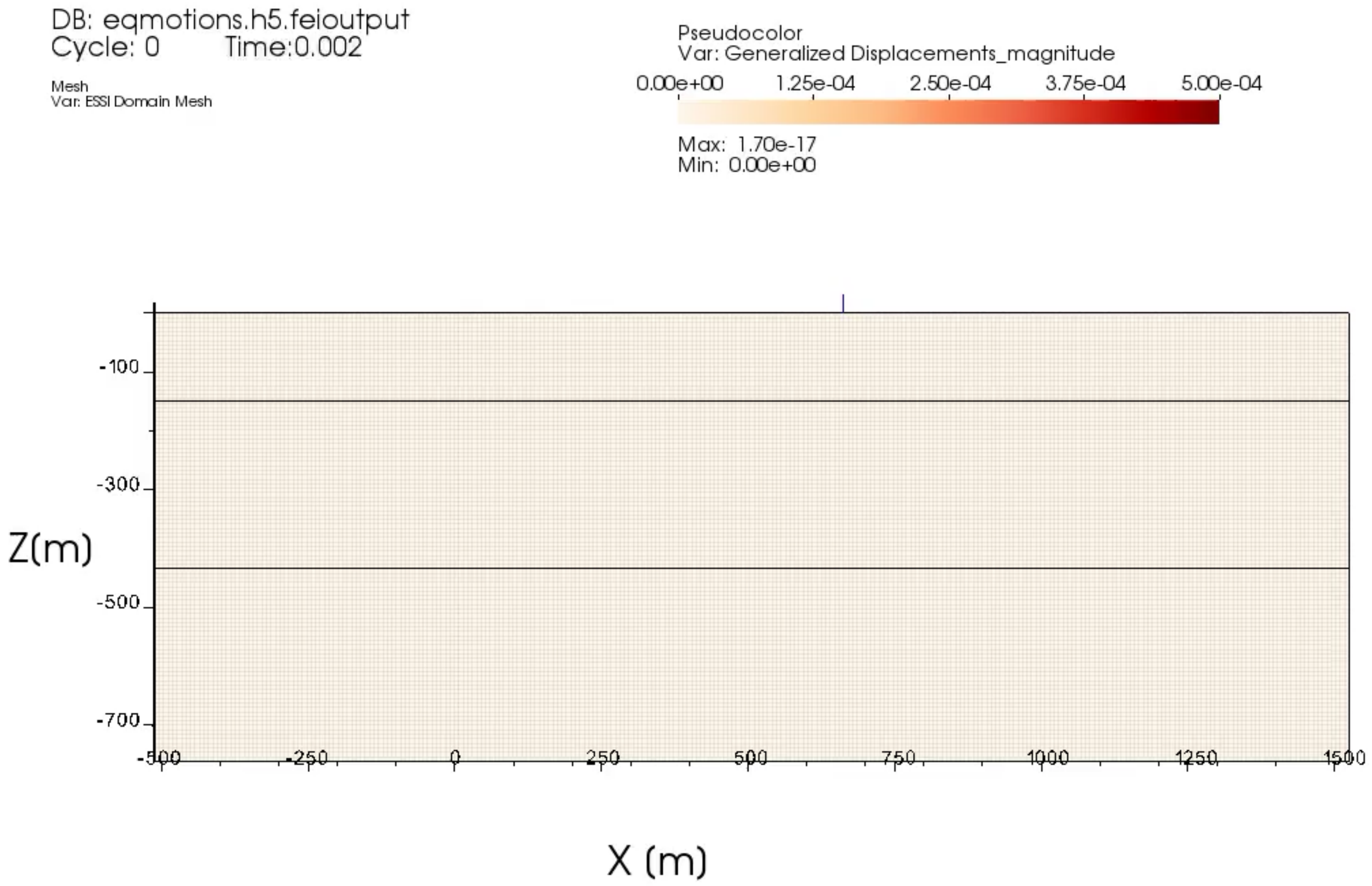
Advantages of 3D deconvolution over the existing methods.

- 3D deconvolution can be applicable to any arbitrarily-incoherent incident seismic waves.
  - 1D deconvolution is applicable only for a vertically-propagating incident wave.
- Due to the small size of the truncated domain, the computational cost of 3D deconvolution is relatively low, even in 3D settings.
  - Large-scale seismic-source inversion's computational cost is significantly high so that it is infeasible.
- Additionally, 3D deconvolution requires only wave speed information of the near-surface ROI, which can be readily obtained through site characterization methods.
  - Large-scale seismic-source inversion require wave speed information in a large domain that should include a source.

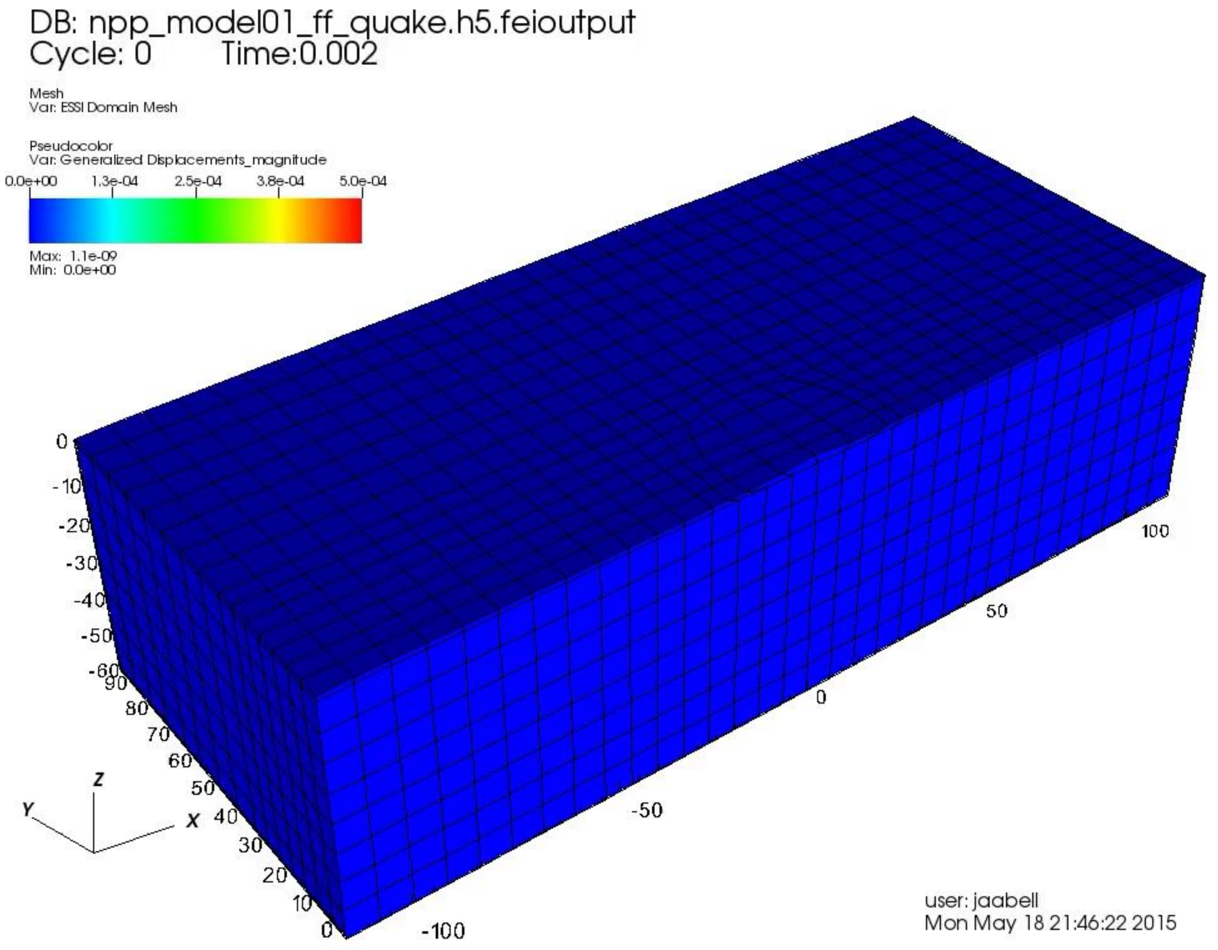
Real-ESSI Simulator

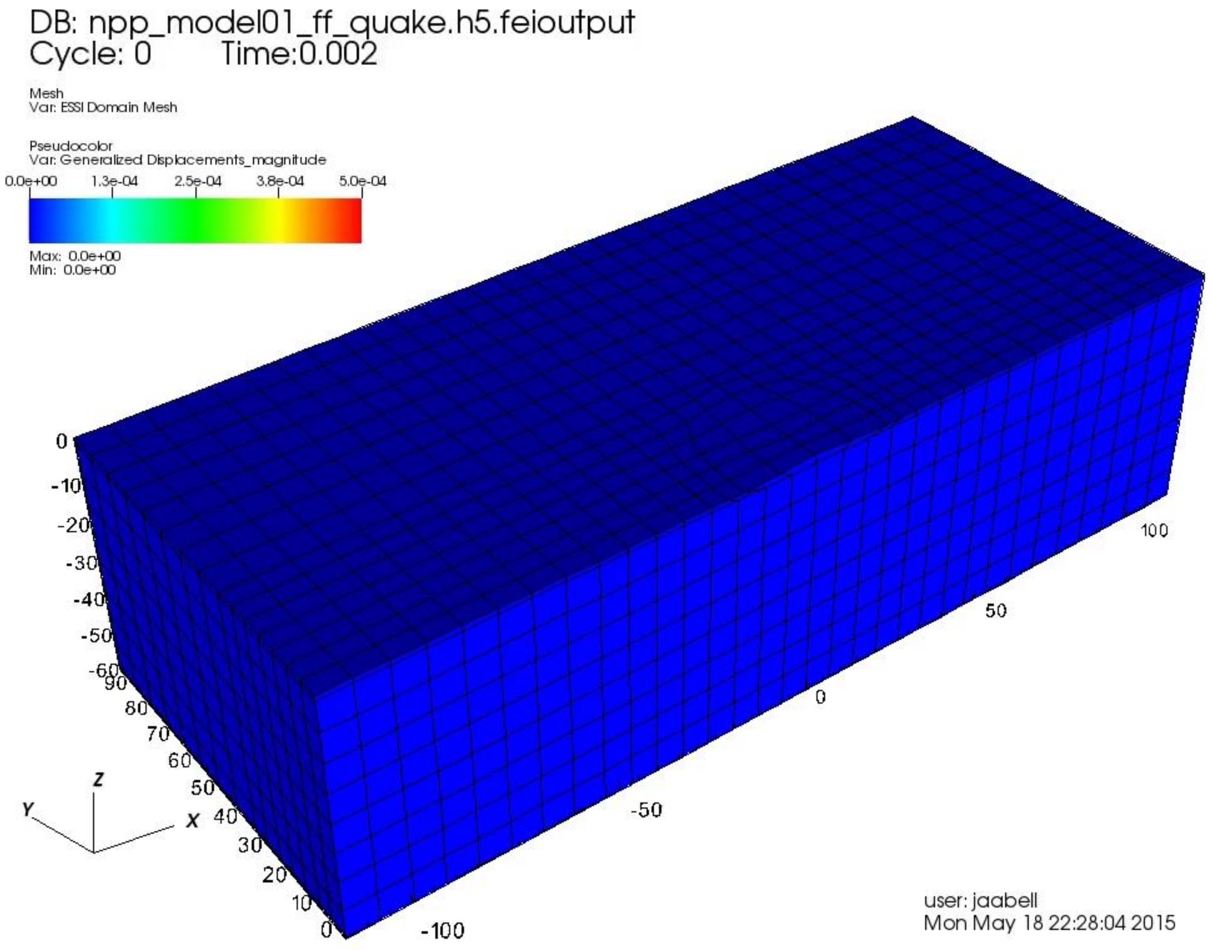
- Implementation of the Inverse Modeling Method in the **Real-ESSI Simulator**
  - **Real**istic Modeling and Simulation of **E**arthquakes and/or **S**oils and/or **S**tructures, and their **I**nteraction
  - Accurate and efficient reconstruction of full three component (3C) seismic wave field in 3D
  - Accuracy → High fidelity finite element method (FEM) modeling techniques
  - Efficiency → High performance parallel computing techniques
  - Extensive Verification and Validation
- Real-ESSI Simulator Features
  - Large library of models for elastic/inelastic materials, soil/structure/interface elements...
  - Domain Reduction Method (DRM) for seismic wave input
  - Hardware Aware Plastic Domain Decomposition method for parallel computing
  - Small-Tensor library for tensor, matrix calculations
  - Prep- and Post-Processing and Visualization
  - Available for public use (USA, CH, RS, M, EU, PRC, K…)
- http://real-essi.us

3C/3D Seismic Wave Field

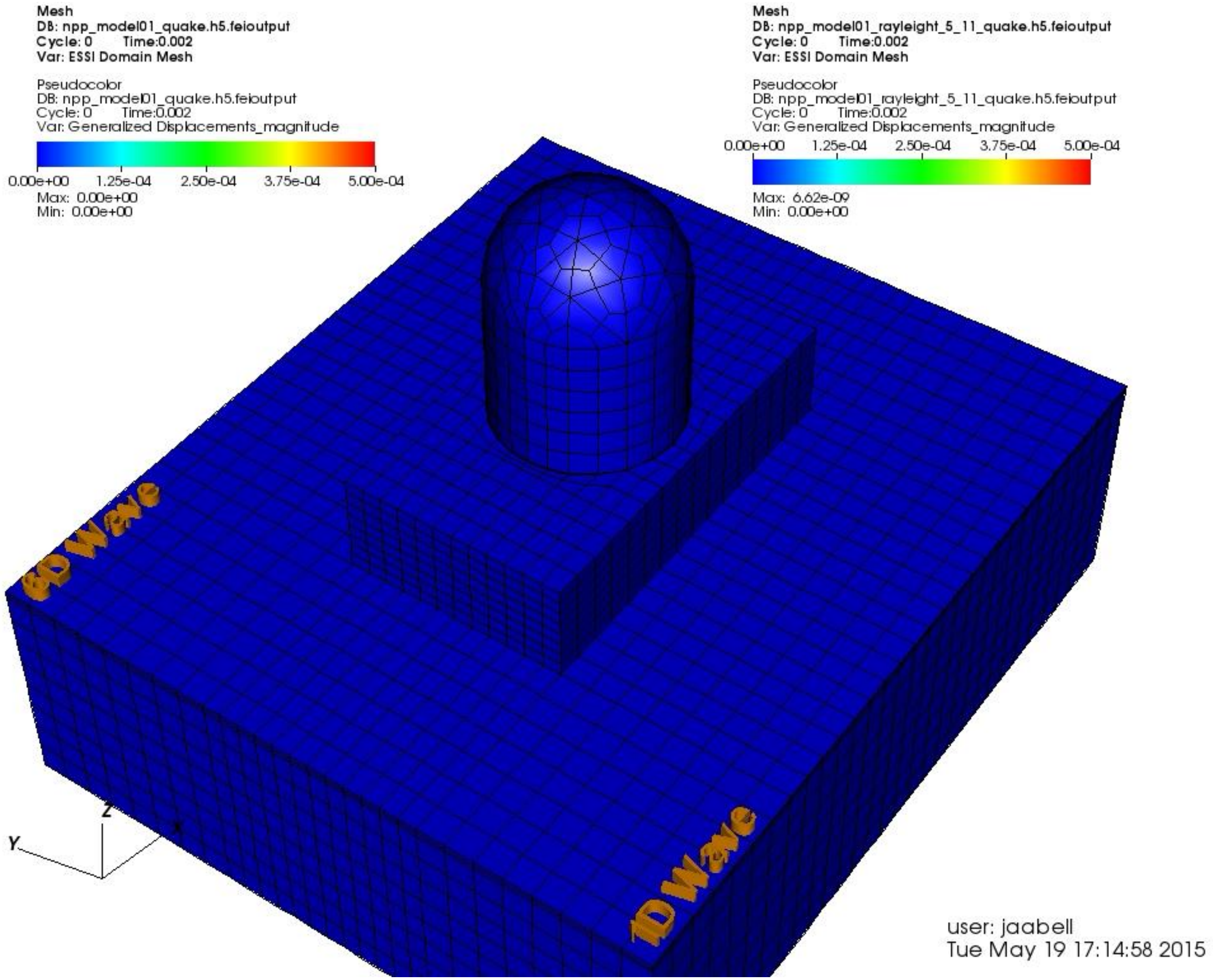


3C/3D Seismic Wave Field



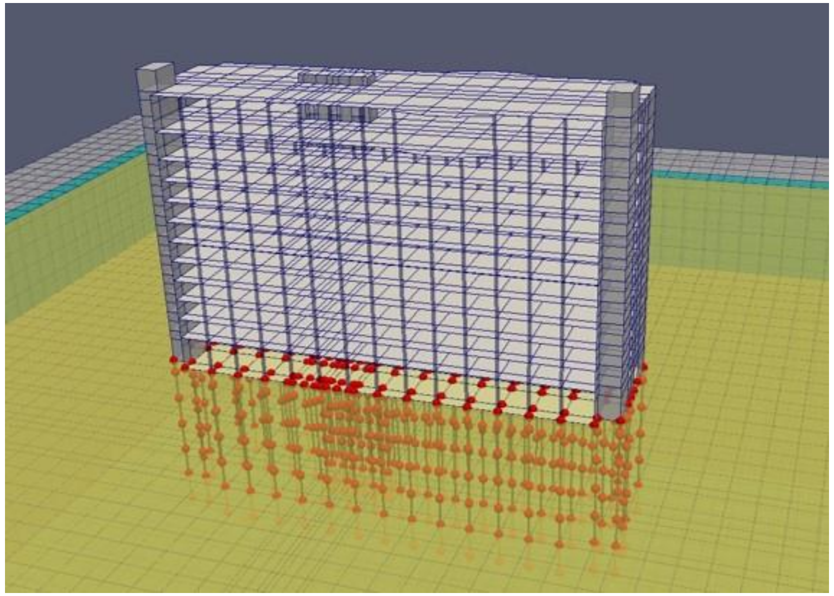


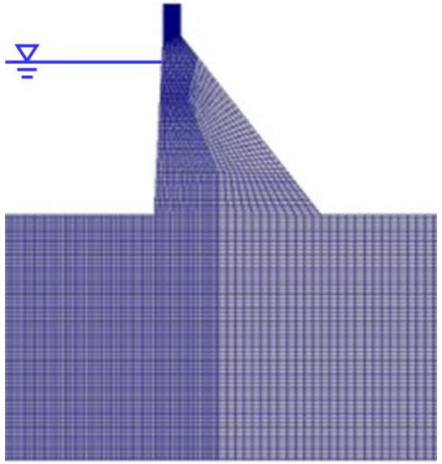
3C/3D Seismic Wave Field



Real-ESSI Modeling

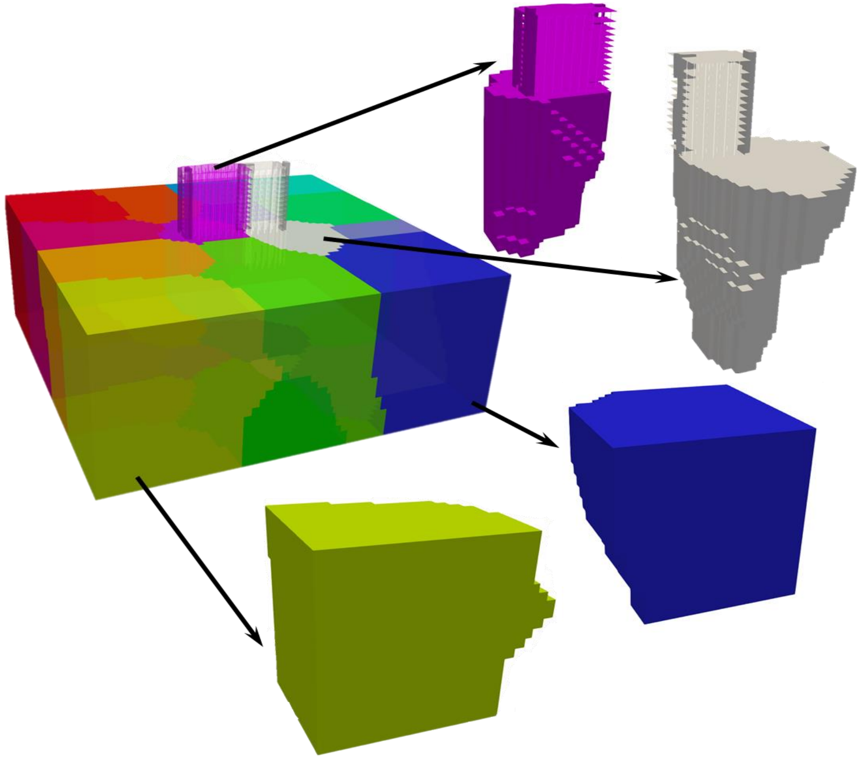
- Wave propagation (Thomson/Haskel. 3C/6C. 1C...)
- Dry Soil, solids
- Un-Saturated Soil, solids
- Saturated Soil, Solids
- Concrete, regular, ASR, 3D, 2D, 1D
- Steel, 3D, 2D, 1D
- Interfaces/contacts, 3D
- External and internal fluids
- ESSI energy calculations





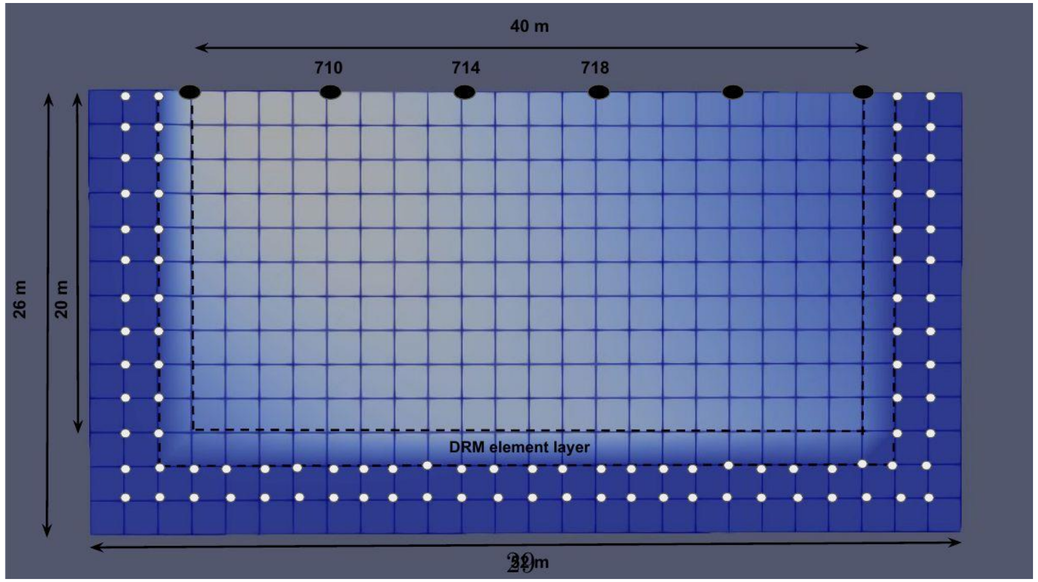
Real-ESSI HPC

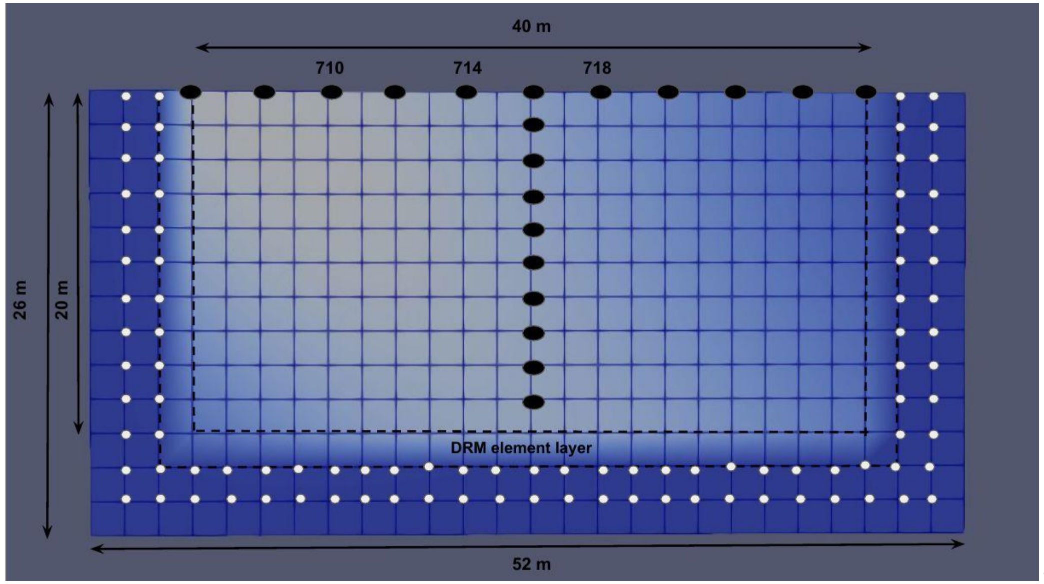
- Hardware Aware Plastic Domain Decomposition,
  Dynamic balancing of computational load for
  - Elastic and inelastic simulations
  - Multiple performance CPUs
  - Multiple performance networks
- Small-Tensor library, for tensor/matrix/vector computations
  - Template metaprograms



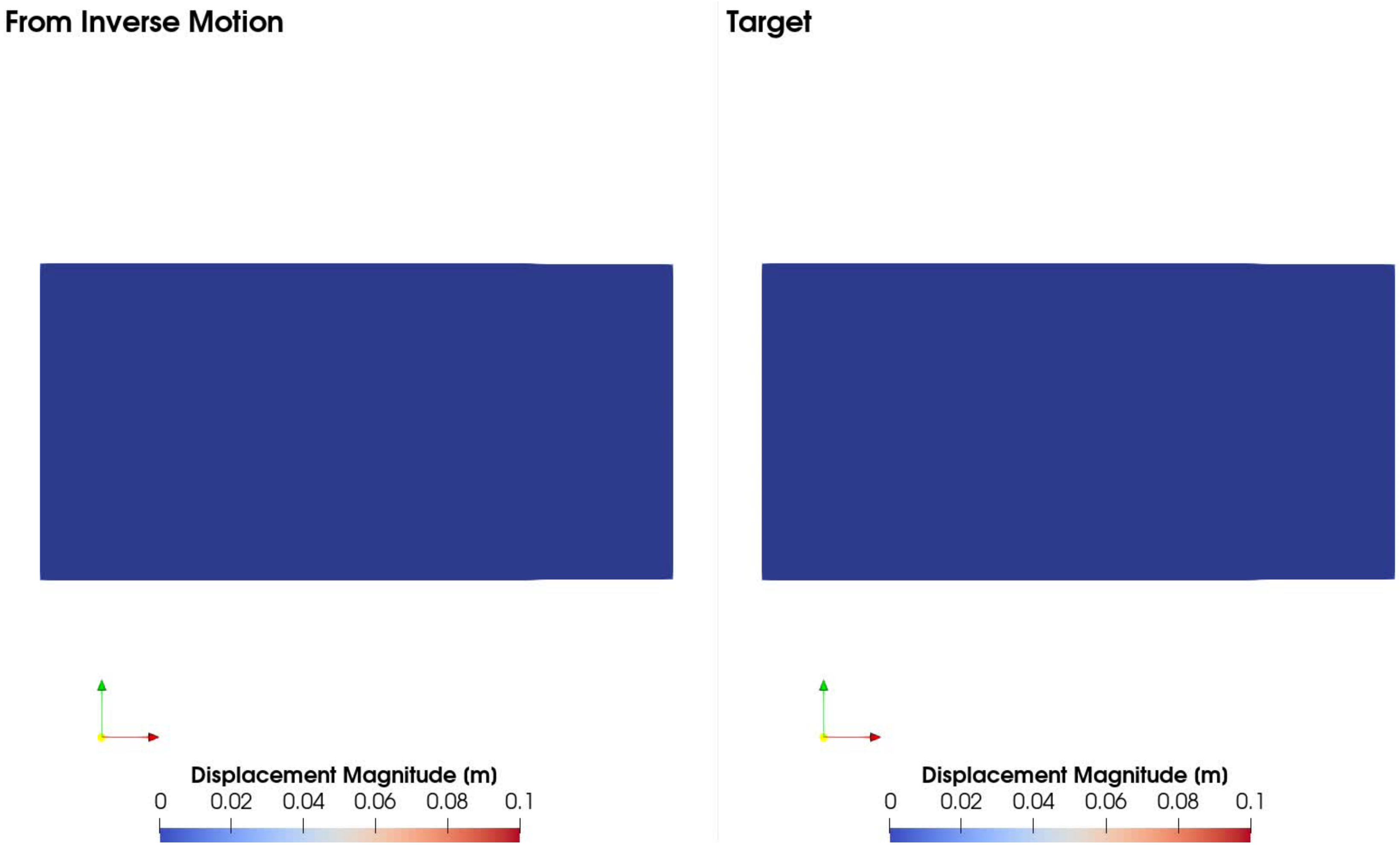
3D-Deconvolution

- 3D-Deconvolution implemented in Real-ESSI
- Method trials
  - Verification, using Thomson/Haskel solution
  - Effective number of observation points
  - Effective location of observation points





3D-Deconvolution Trials



3D Deconvolution for Energy Calculations

- Use developed seismic wave fields to calculate seismic energy input in ESSI system
  - Aki and Richards, state that small % of seismic energy that makes it to the surface
- Use accurate seismic field development to calculate:
  - Seismic energy input into ESSI model
  - Dissipation of seismic energy in soil and interfaces
  - Dissipation of seismic energy in structure

Seismic Energy for Design

- Use accurate seismic energy input and dissipation calculations for assessing and improving infrastructure

Link 1
Individual foundation

Link 2
Continuous foundation

Summary

- We investigate the 3D deconvolution for accurate reconstruction of 3C incoming seismic wave in a 3D, truncated near-surface domain by using seismic data in consideration of nonlinear, inelastic materials using Real-ESSI Simulator.
- Engineers can use the 3D deconvolution within Real-ESSI Simulator without ad-hoc programming.
- The 3D deconvolution is used to accurately calculate seismic energy input into a realistic infrastructure object under realistic seismic excitations for energy-based design.
- Acknowledgement: This material is based upon work supported by the National Science Foundation under Awards CMMI-2053694.