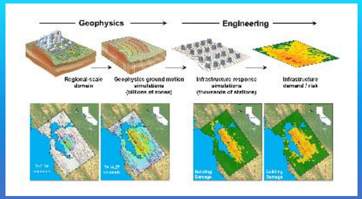

A Fast Scalable Implicit Solver for Nonlinear Wave Simulation on Low-Ordered Unstructured Finite Elements to Enhance Comprehensive Earthquake Simulation

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THE UNIVERSITY OF TOKYO

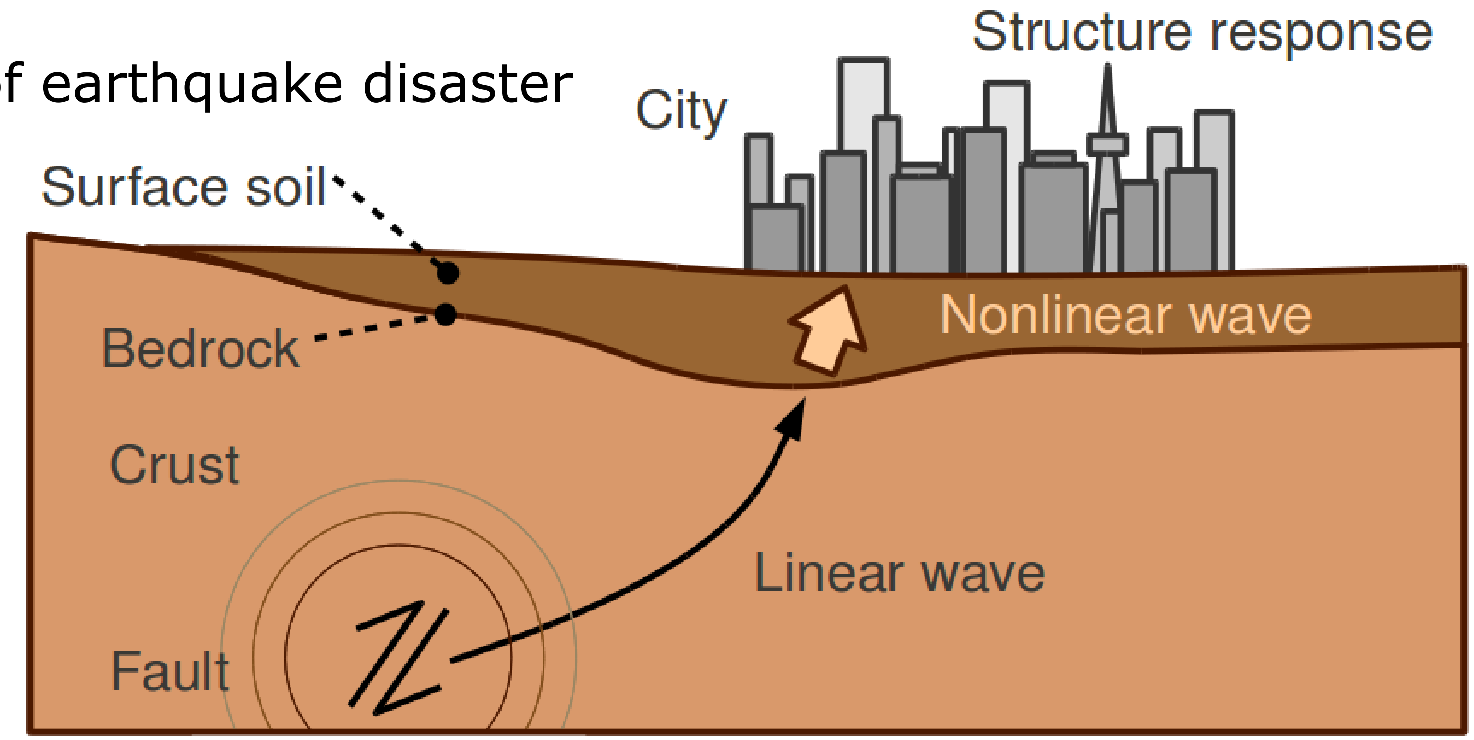
PEER

Compute whole process of earthquake disaster!

Enhancement of Comprehensive Earthquake Simulation from fault to city (more complex and higher frequency components)

huge computational cost: great leap is needed!

Process of earthquake disaster

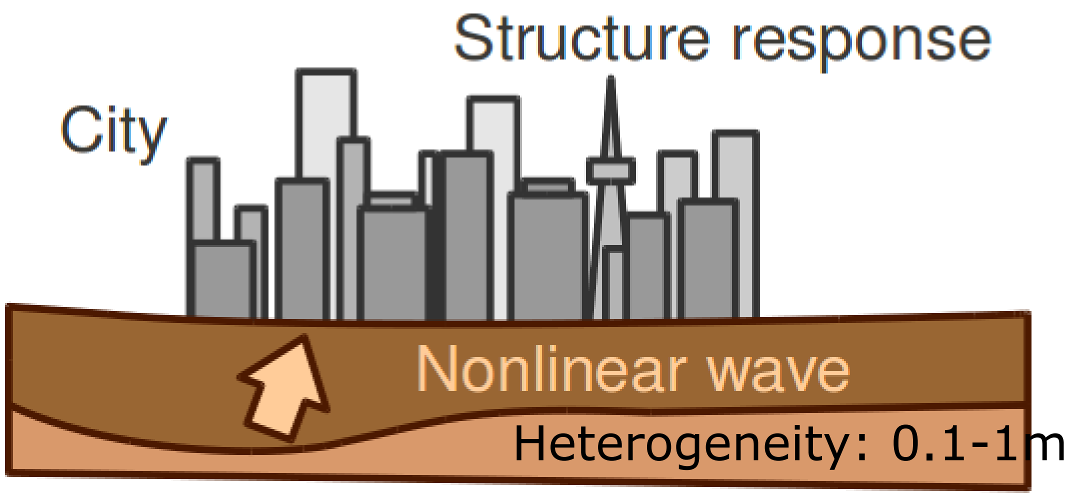


Earthquake simulation with supercomputing

- Tsuyoshi Ichimura, Kohei Fujita, Seizo Tanaka, Muneo Hori, Maddegedara Lalith, Yoshihisa Shizawa, and Hiroshi Kobayashi, Physics-based urban earthquake simulation enhanced by 10.7 BlnDOF x 30 K time-step unstructured FE non-linear seismic wave simulation, SC14: International Conference for High Performance Computing, Networking, Storage and Analysis, 15-26, 2014.

- Tsuyoshi Ichimura, Kohei Fujita, Pher Errol Balde Quinay, Lalith Maddegedara, Muneo Hori, Seizo Tanaka, Yoshihisa Shizawa, Hiroshi Kobayashi and Kazuo Minami, Implicit Nonlinear Wave Simulation with 1.08T DOF and 0.270T Unstructured Finite Elements to Enhance Comprehensive Earthquake Simulation, SC15: International Conference for High Performance Computing, Networking, Storage and Analysis, Article No. 4, 2015.

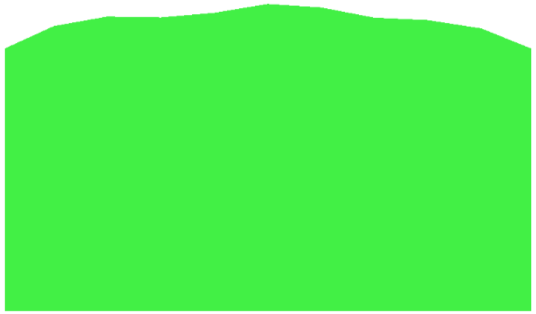
Major computational cost: Great leap is needed!



Earthquake simulation of city

- There is high fidelity soil structure dataset (digital twin city).
- If we can use this, dramatically improves the reliability of earthquake disaster estimates
- This simulation (**nonlinear wave propagation modeling in soft soil**) leads huge computational cost**.** This is Key for city simulation

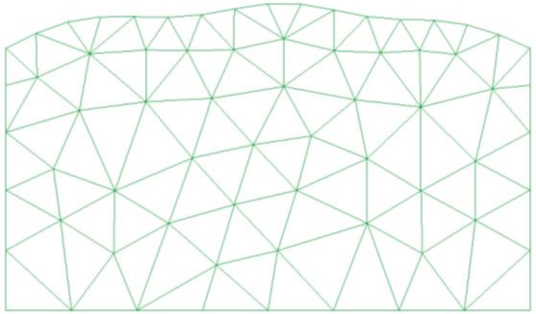
Numerical modeling of nonlinear wave propagation



Target
- complex domain with local complex geometry

Finite element model generator

geometry correctly modeled



Finite Element model
- Low-order Unstructured Finite Element (< 1m)

Matrix (components changes every time step)

Unknown vector (**10 $^{9\text{-}12}$ DOF**) !!!Huge DOF due to discretization with small elements!!

$$\underline{\left(\frac{4}{dt^2}\mathbf{M} + \frac{2}{dt}\mathbf{C}^n + \mathbf{K}^n\right)}\ \underline{\delta\mathbf{u}^n} = \mathbf{F}^n - \mathbf{Q}^{n-1} + \mathbf{C}^n\mathbf{v}^{n-1} + \mathbf{M}\left(\mathbf{a}^{n-1} + \frac{4}{dt}\mathbf{v}^{n-1}\right)$$

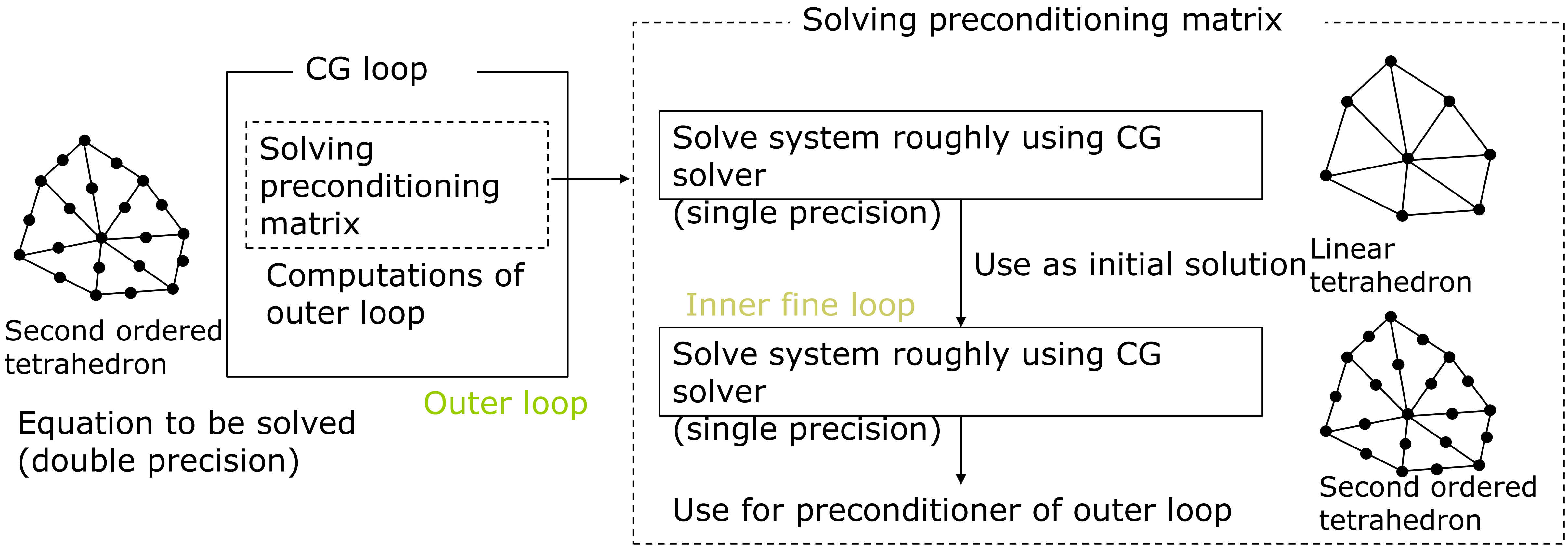
Discretized wave equation (**solve for each of $10^{4\text{-}5}$ time-steps**)

Now it’s time for supercomputing!

- Speeding up massive, implicit, unstructured, low-ordered, nonlinear finite-element solver

- Viewpoints for design of solver on supercomputer
  - Random access dominant kernel
  - Scalable: up to more than 10^6 parallel computation
  - Fast: good time-to-solution
  - Efficient use of memory: limitation of memory amount due to huge DOF

Key points of Proposed Algorithm



- Solve preconditioning matrix (=matrix of original problem) roughly to reduce number of CG loops
  - Use multi-grid method to reduce cost of preconditioner
  - Use single precision in preconditioner to reduce computation & communication

Performance of Proposed Solver: high-efficiency on K, Fugaku, Summit, Piz-daint, OFP

- Size-up scalability: **96.6% efficiency** from 9,216 cores to full K computer (663,552 cores) up to **1 trillion DOF**
  - Enables **18.6% of peak (=1.97 PFLOPS) on full K computer**
- Speed-up scalability: **76% efficiency** for 9,216 ➔ 294,912 cores
- Very good scaling considering non-uniform mesh is partitioned using METIS
  - Similar scalability can be attained for practical problem

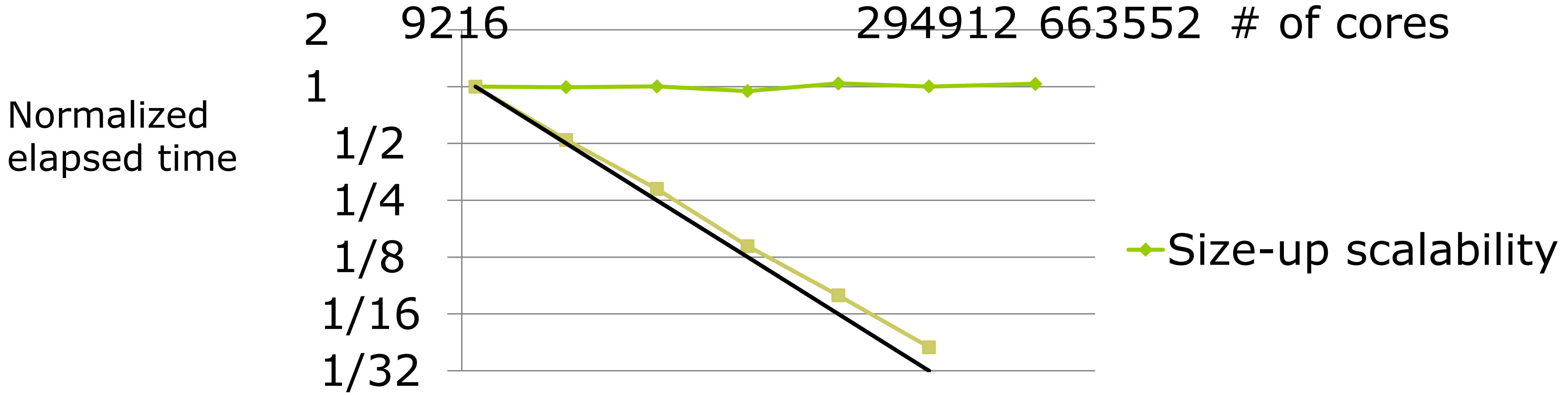
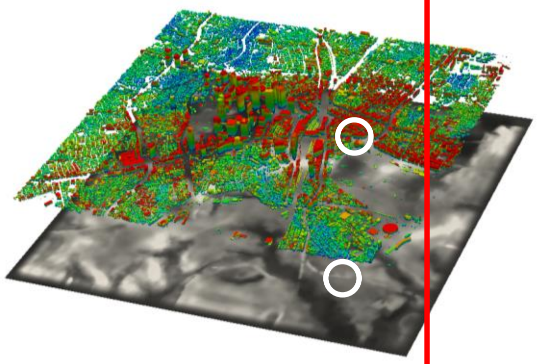
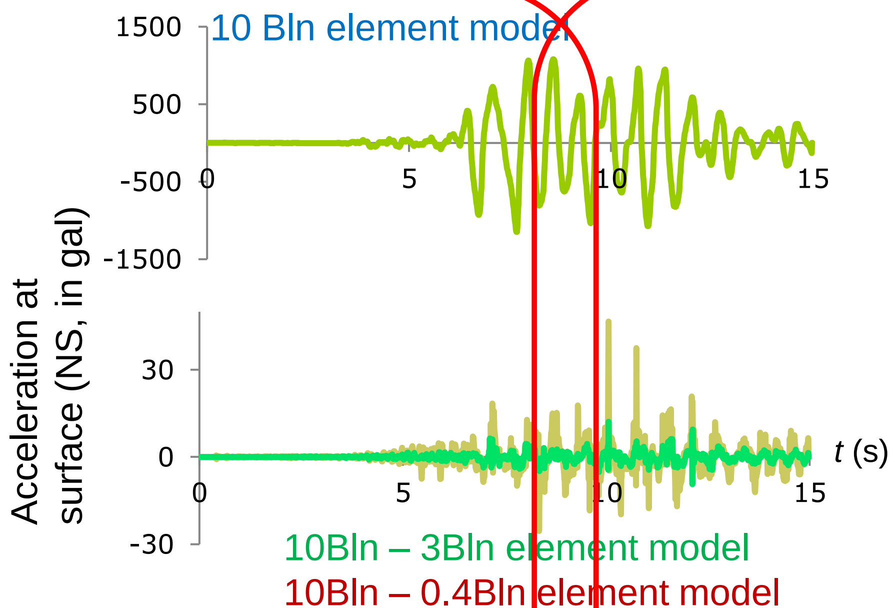



Image Landsat
Image IBCAO
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image U.S. Geological Survey

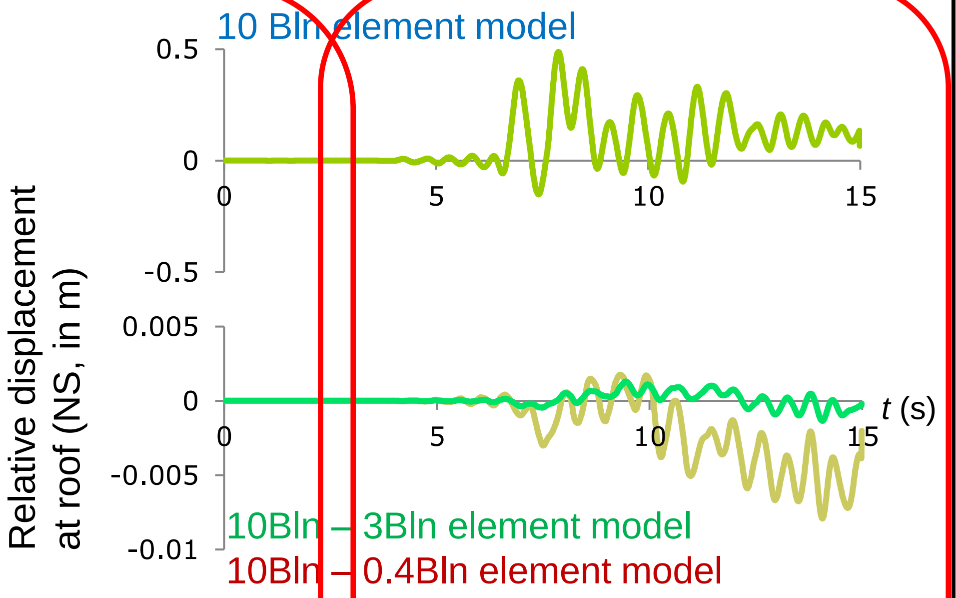
High quality simulation using proposed solver

- Checking quality of results: essential for real use of simulations
- Verify simulation method by convergence analysis
  - Discretize same mathematical problem with 3 different resolutions





Convergence of ground acceleration

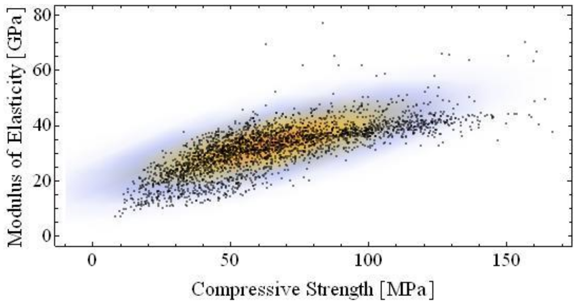


Convergence of structure response

- Ground acceleration & structure response converges **time-wise** within 1% tolerance
- **10 billion elements essential for spatio-temporal convergence & real use of simulation**

Proposed solver as a key component enhancing urban earthquake simulation

- Actual cities have large uncertainties



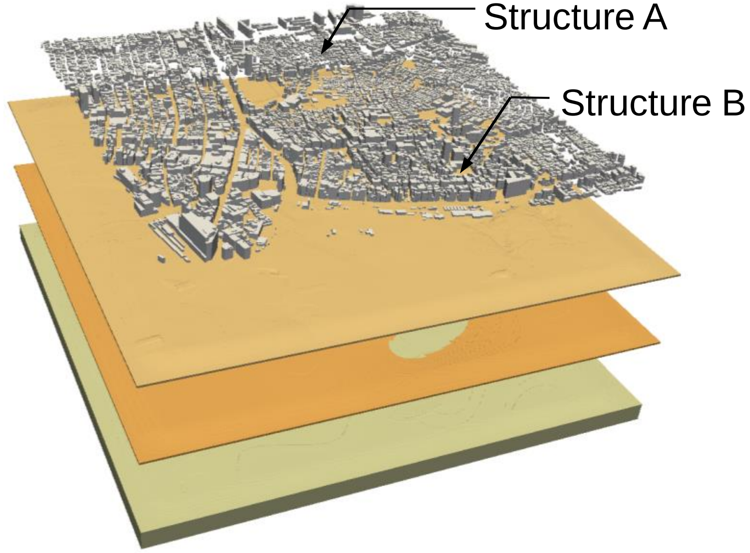
Input distribution

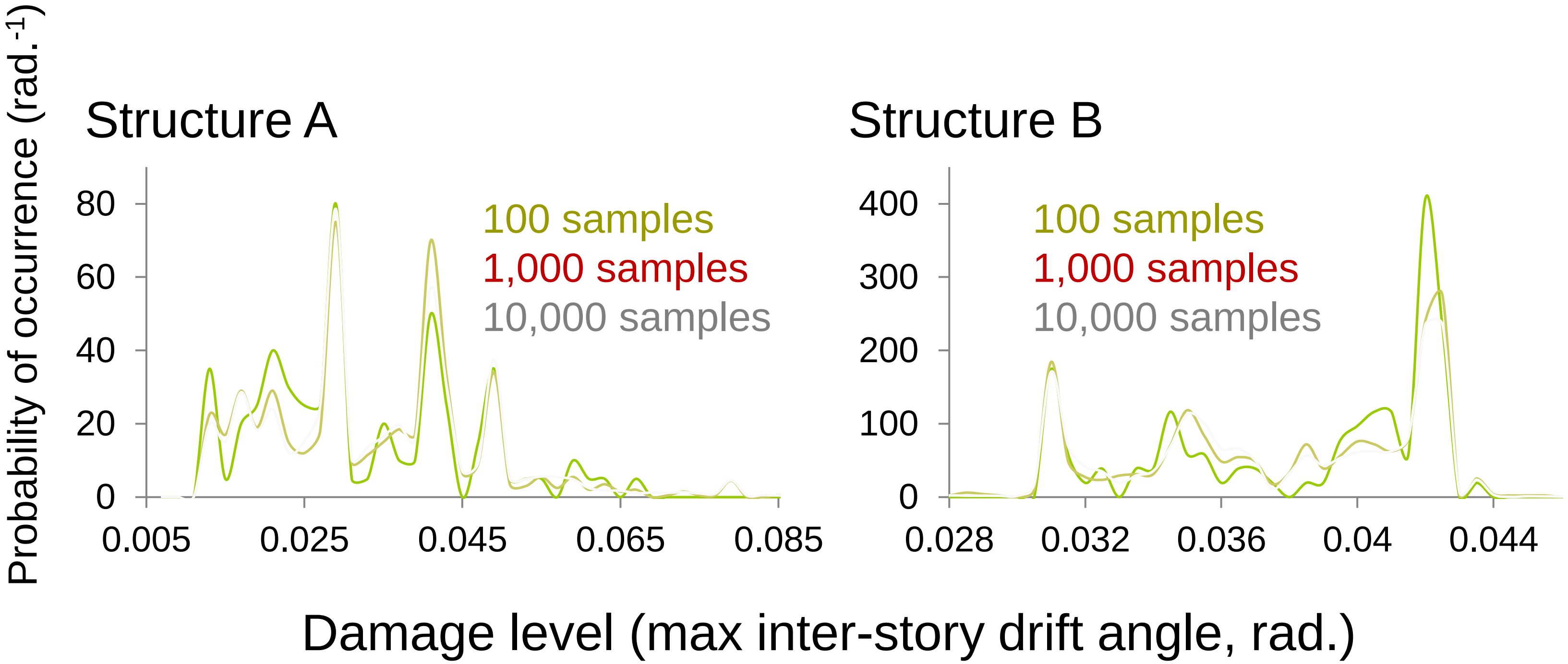
Do this for whole city (13,275 structures) using capacity computing on K computer

distribution

Proposed solver as a key component enhancing urban earthquake simulation

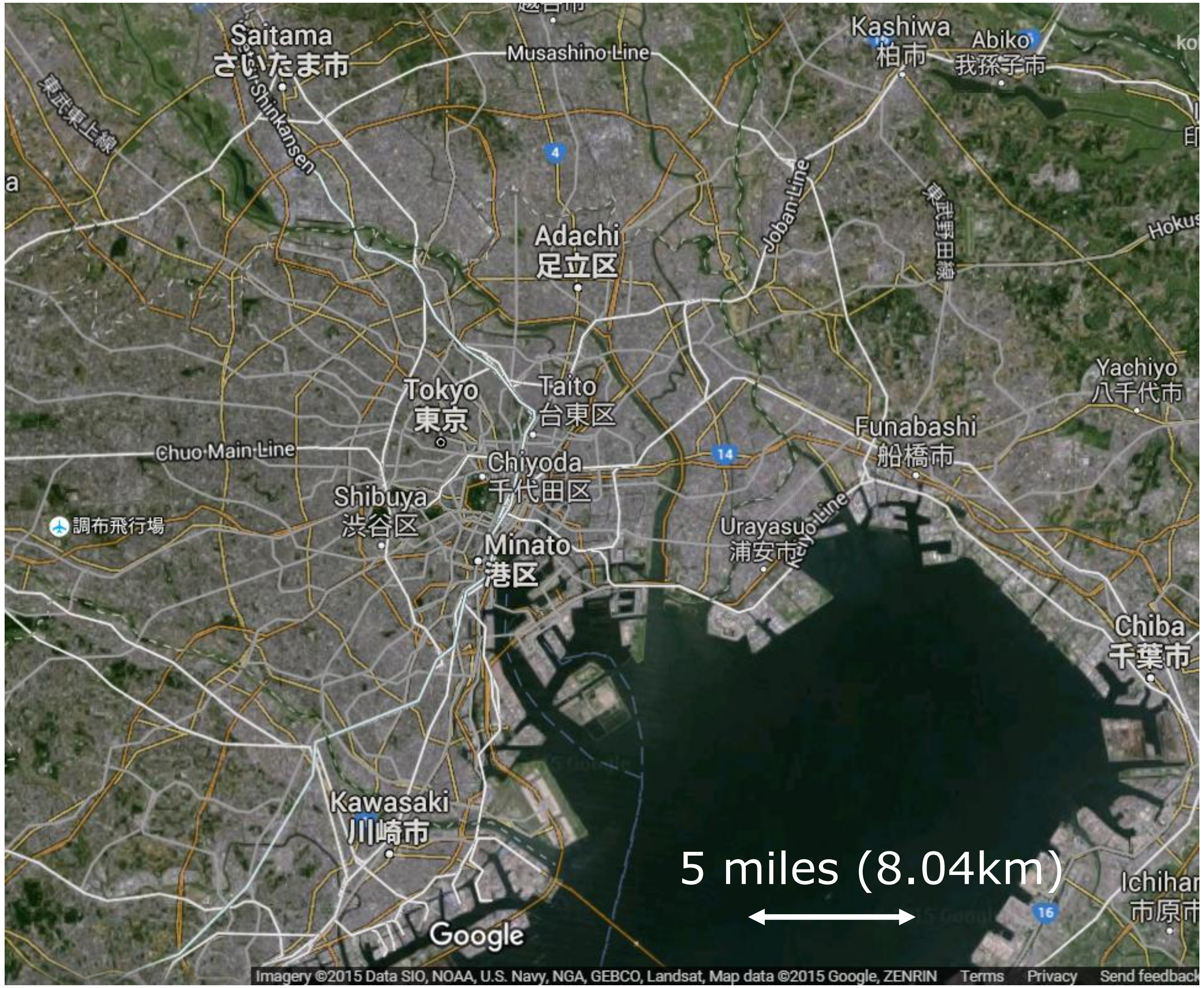
- Probability distribution of city converged with 10,000 samples
  - Computed in 3h 56min using 80,000 CPU cores of K computer
  - GAMERA combined with capacity computing improves reliability of disaster estimation



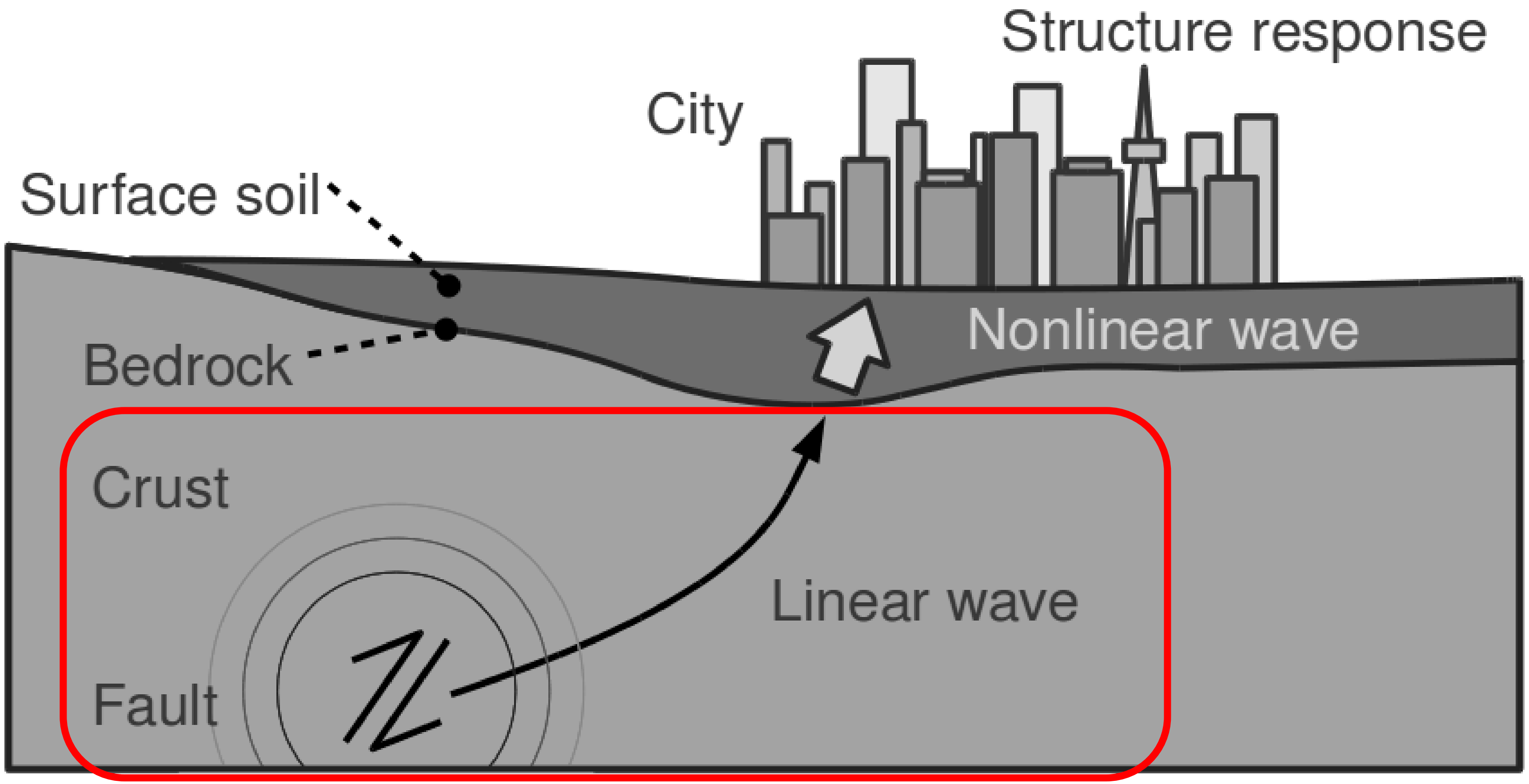


High-fidelity fault-to-city-to-society simulation using full power of K computer

- Target Tokyo metropolis
  - One of world's largest metropolitan areas
  - Enabling of this area leads to application to nearly all cities

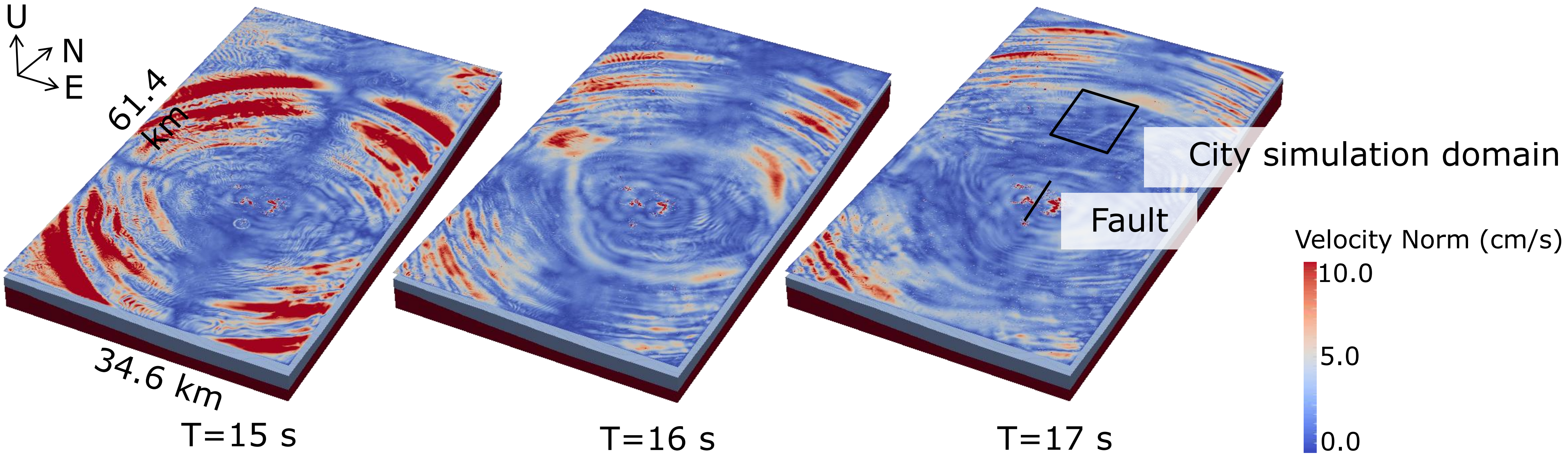


Fault-to-city simulation



Fault-to-city simulation

- Earthquake linear wave propagation simulation @ 10Hz target frequency
  - Use 18 billion unstructured low ordered finite elements & 56 billion DOF model with implicit time integration



City simulation

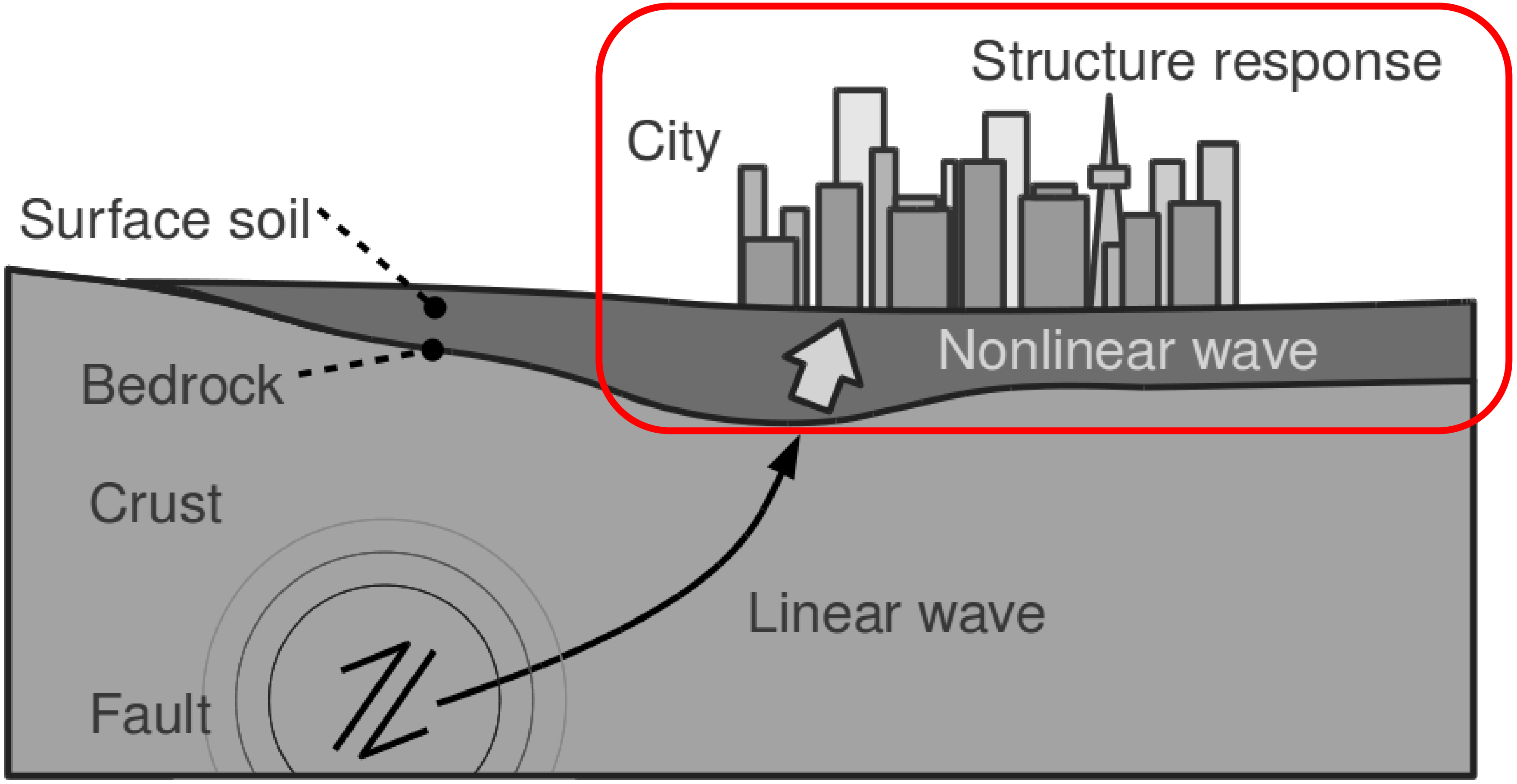
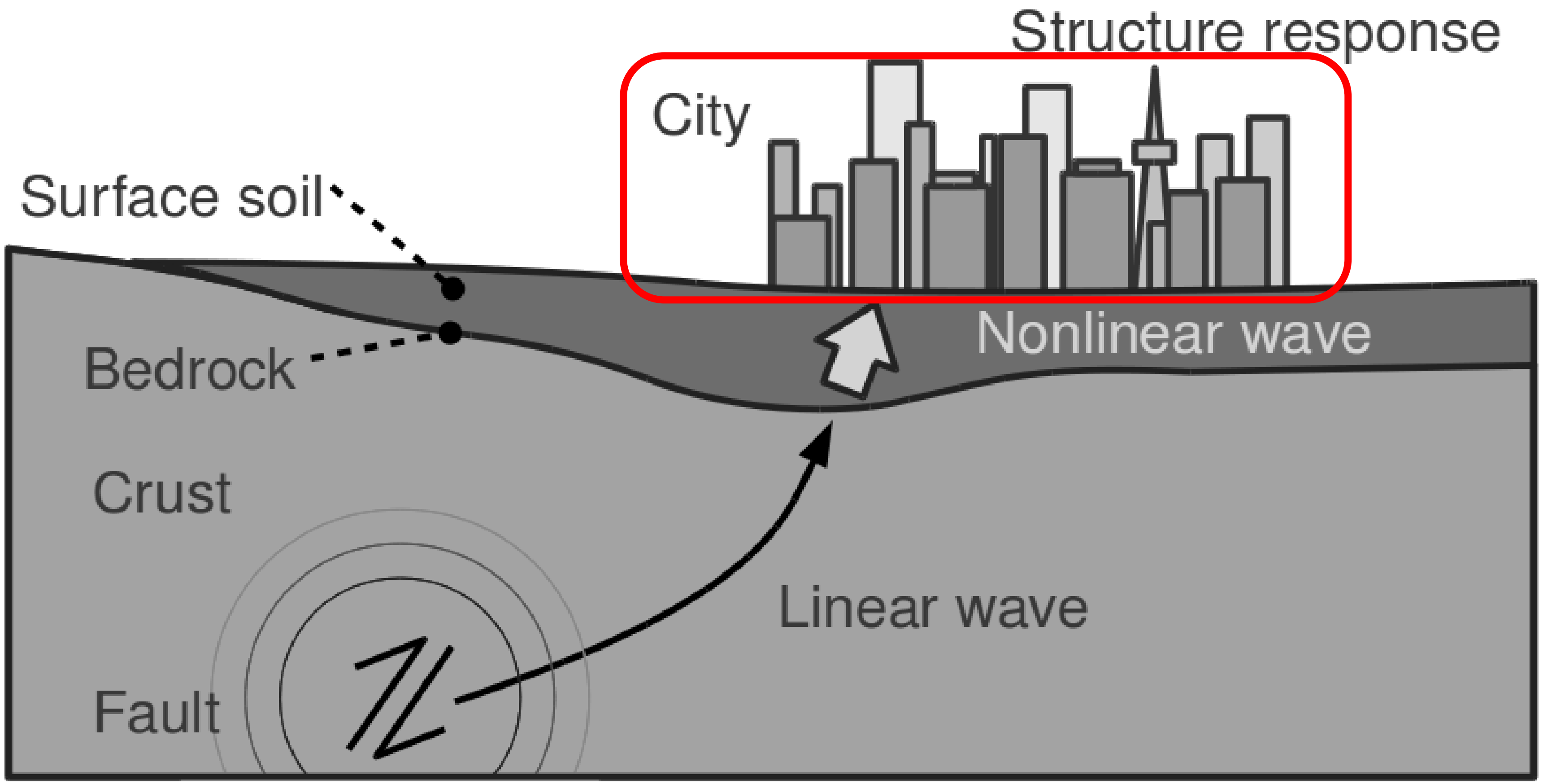


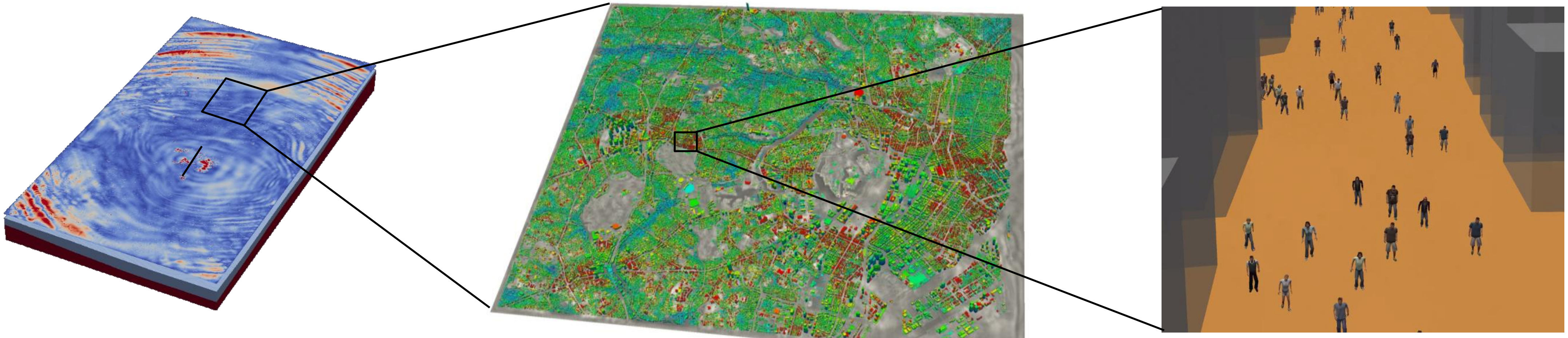

Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
Google earth

Social simulation



High-fidelity fault-to-city-to-social simulation accomplished

- All phases of earthquake fault-to-city-to-social simulation simulated at state-of-art level
- Enables huge leap in improving reliability of earthquake response estimation
  - HPC can play an essential role for saving lives and society



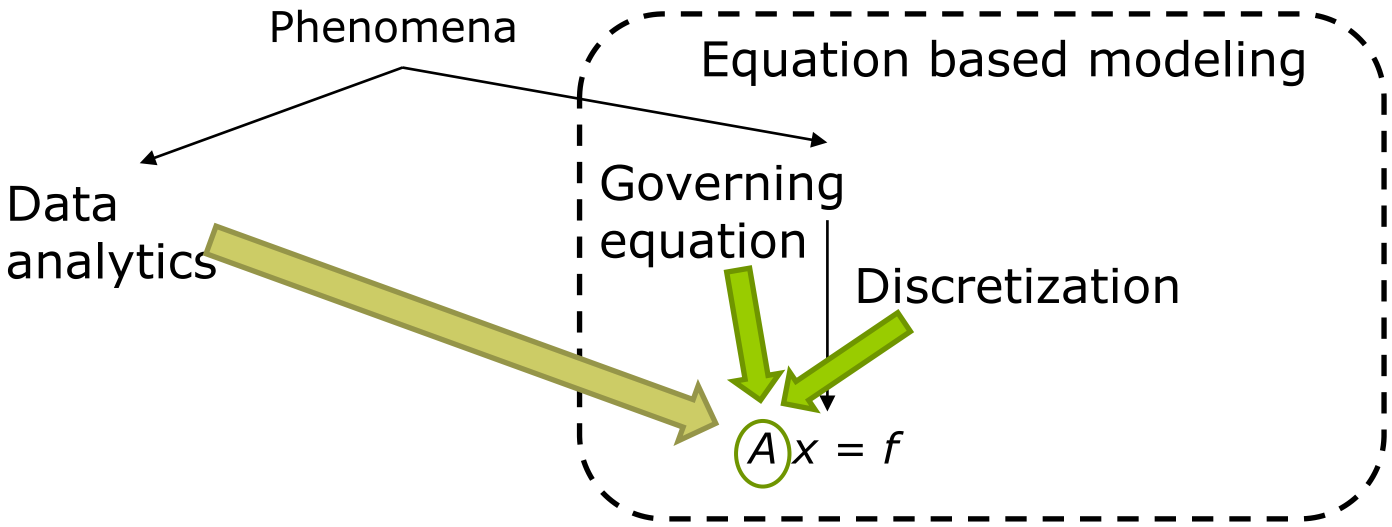
Fault-to-city simulation City simulation Social simulation

Supercomputing with data-learning

- Tsuyoshi Ichimura, Kohei Fujita, Takuma Yamaguchi, Akira Naruse, Jack C. Wells, Thomas C. Schulthess, Tjerk P. Straatsma, Christopher J. Zimmer, Maxime Martinasso, Kengo Nakajima, Muneo Hori, Lalith Maddegedara, A Fast Scalable Implicit Solver for Nonlinear Time-Evolution Earthquake City Problem on Low-Ordered Unstructured Finite Elements with Artificial Intelligence and Transprecision Computing, SC18: International Conference for High Performance Computing, Networking, Storage and Analysis, Article No. 49, 2018.

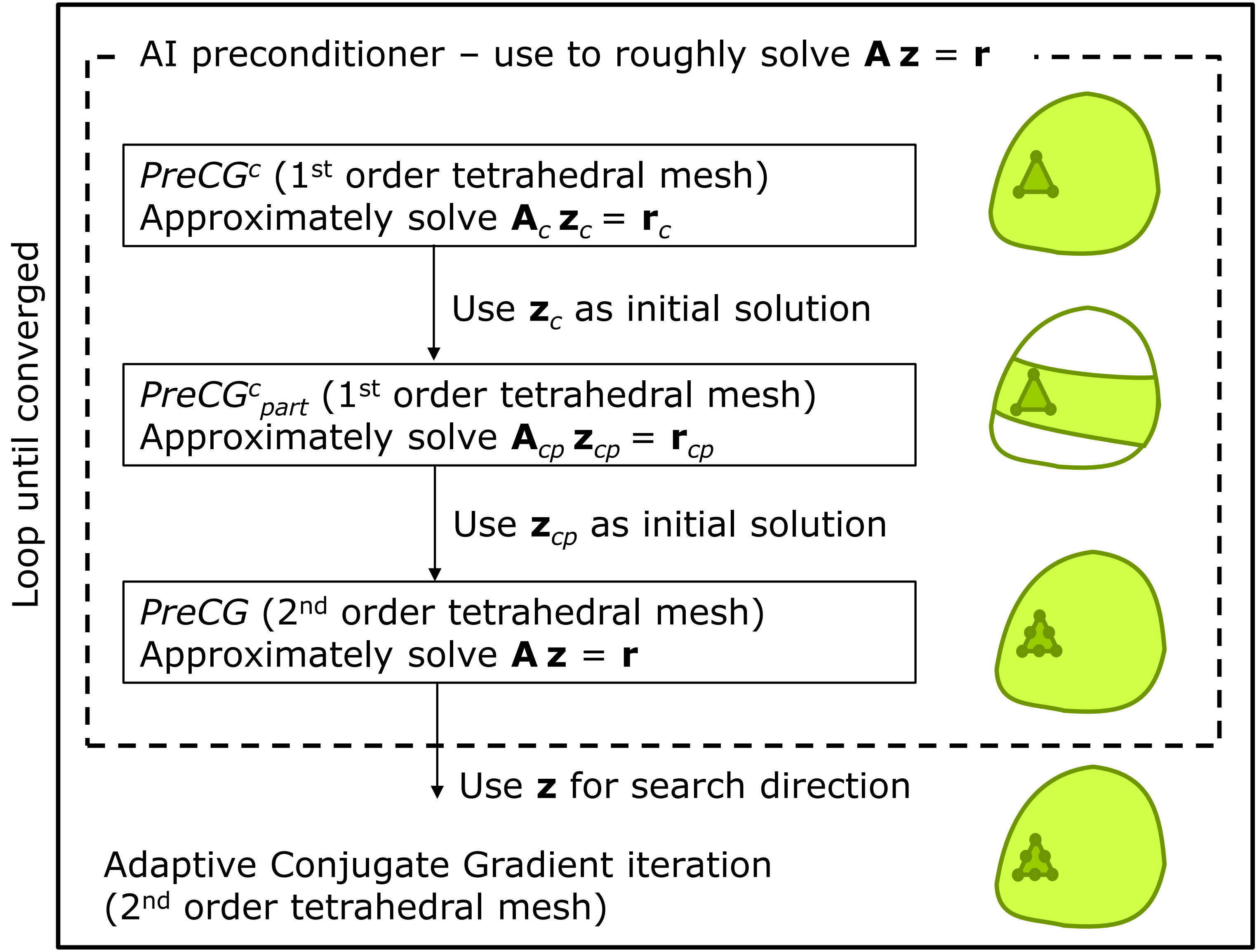
Fast scalable implicit solver with data learning

- Use information of underlying governing equation
  - Governing equation’s characteristics with discretization conditions should include information about the difficulty of convergence in solver
  - Extract parts with bad convergence via data learning and extensively solve extracted part ⇨ improve time-to-solution

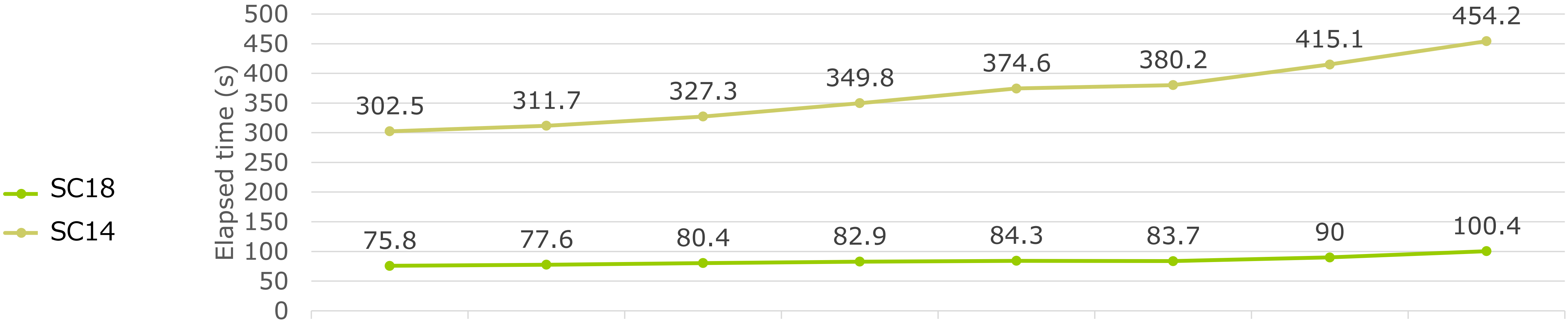


Solver suitable for use with data learning

- Transform solver such that data learning can be used robustly
  - Select part of domain to be extensively solved in adaptive conjugate gradient solver
  - Based on the governing equation’s properties, part of problem with bad convergence is selected with data learning

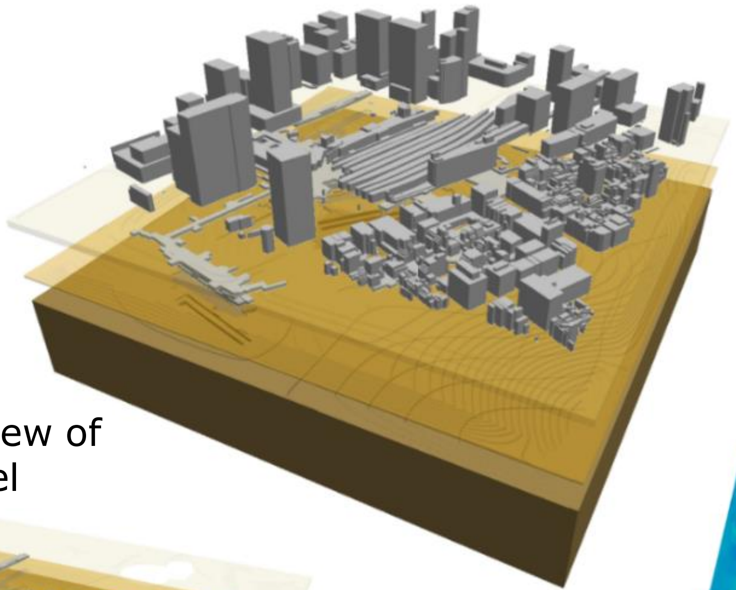


Weak scaling on Summit

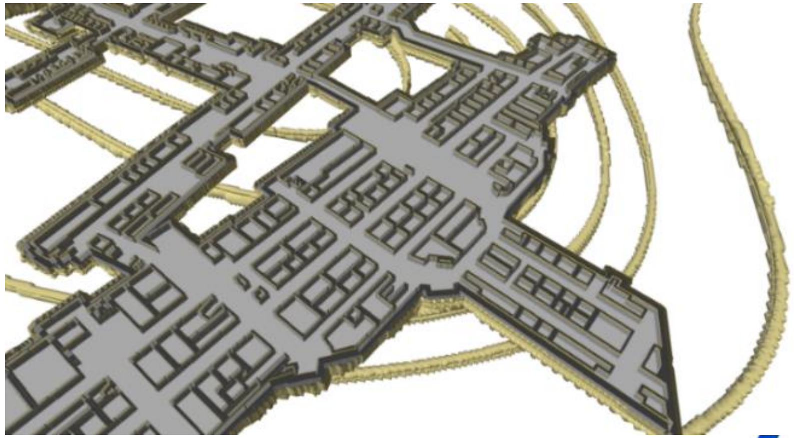


# of GPUs	288	576	1152	2304	4608	6144	12288	24576
# of node	48	96	192	384	768	1024	2048	4196
DOF	3.5×10^9	7×10^9	14×10^9	28×10^9	56×10^9	75×10^9	151×10^9	302×10^9
SC18's efficiency to FP64 peak	19.5%							14.7%

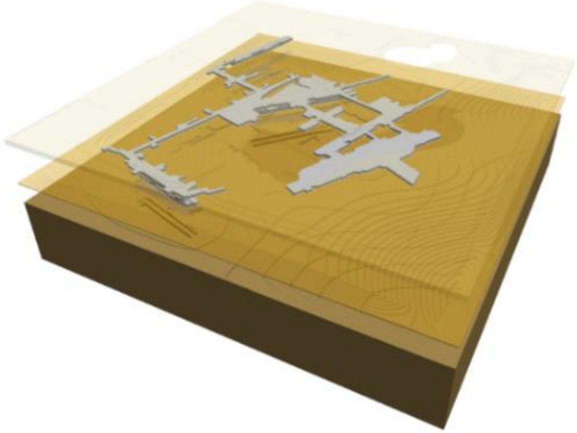
Urban earthquake simulation with data learning on Summit



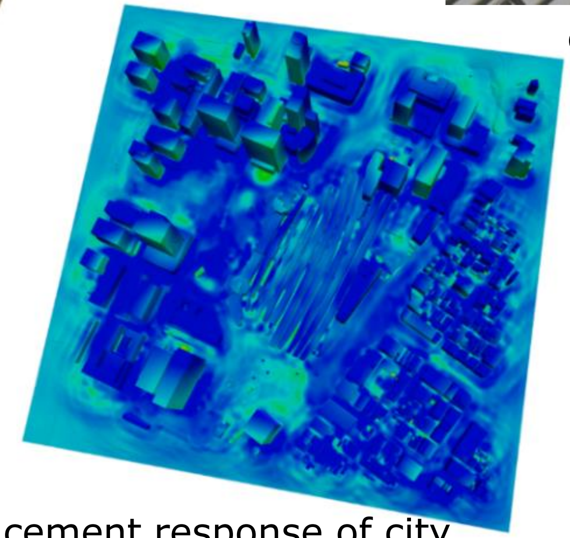
a) Overview of city model



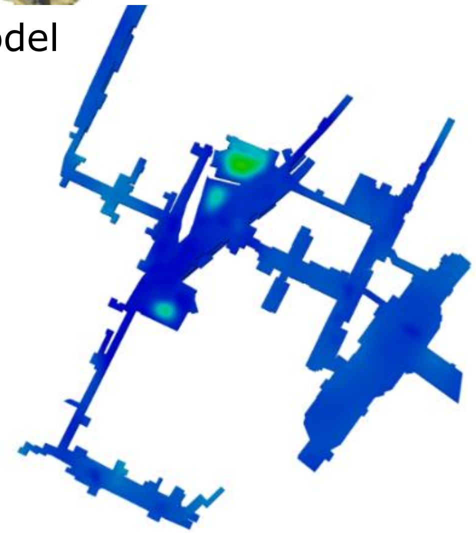
c) Close up view of city model



b) Location of underground structure



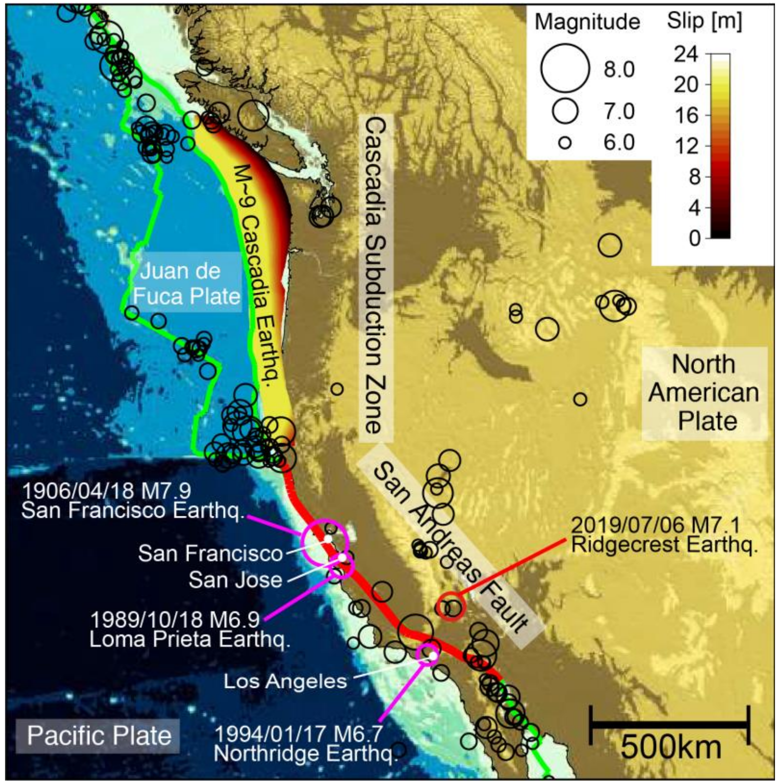
d) Displacement response of city

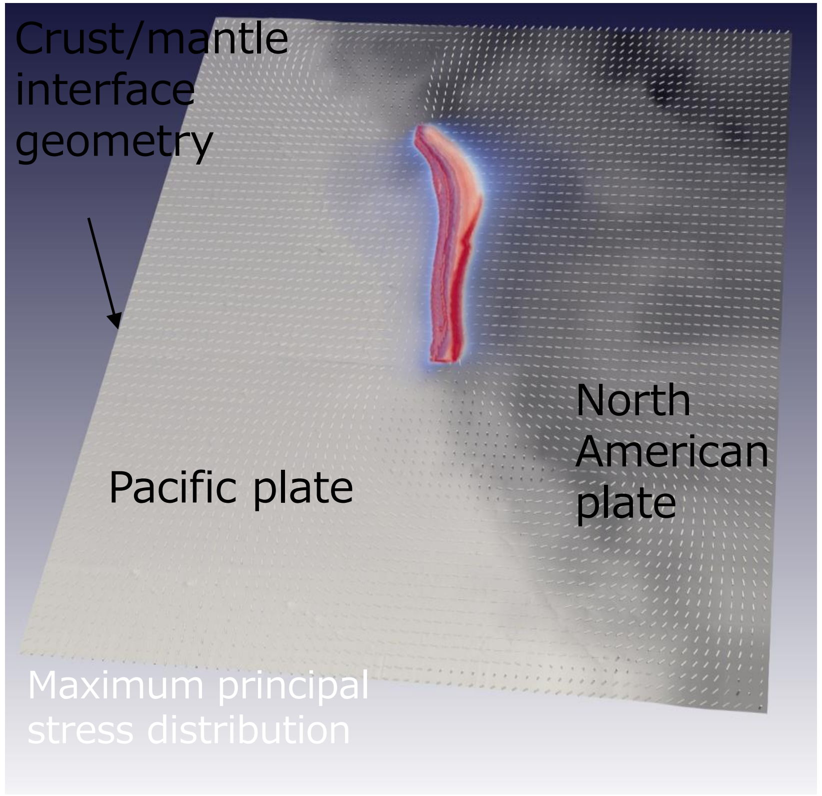


e) Displacement response of underground structure

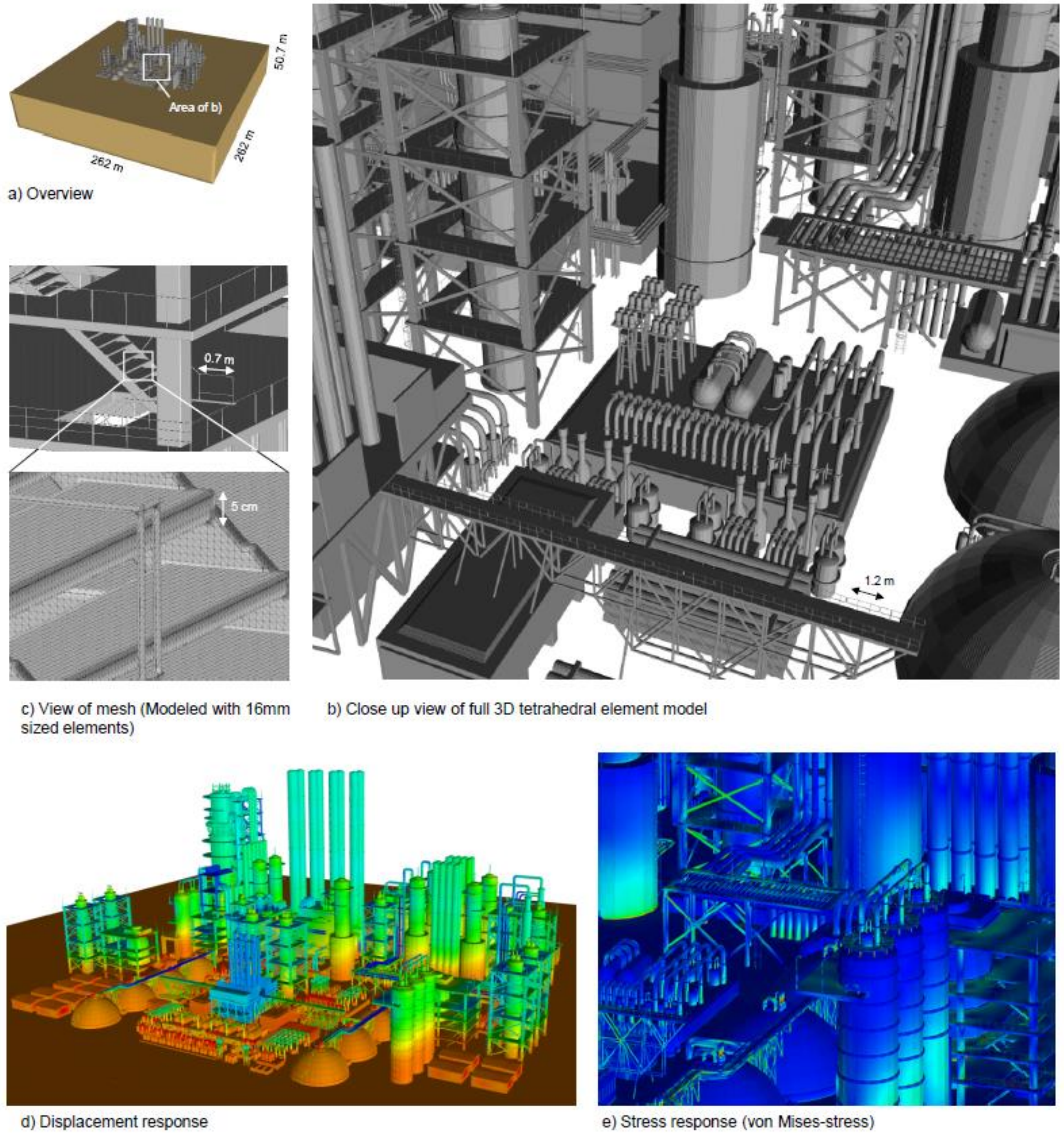
Crust deformation analysis in Cascadia subduction zone by 416-PFLOPS Fast Scalable Implicit Solver on Low-Ordered Unstructured Finite Elements Accelerated by 1.10-ExaFLOPS Kernel, SC19

- Target domain size (1944 km×2646 km×480 km) with 1.49×10^{10} DOF
- 23 sec with 162 computer nodes of Summit





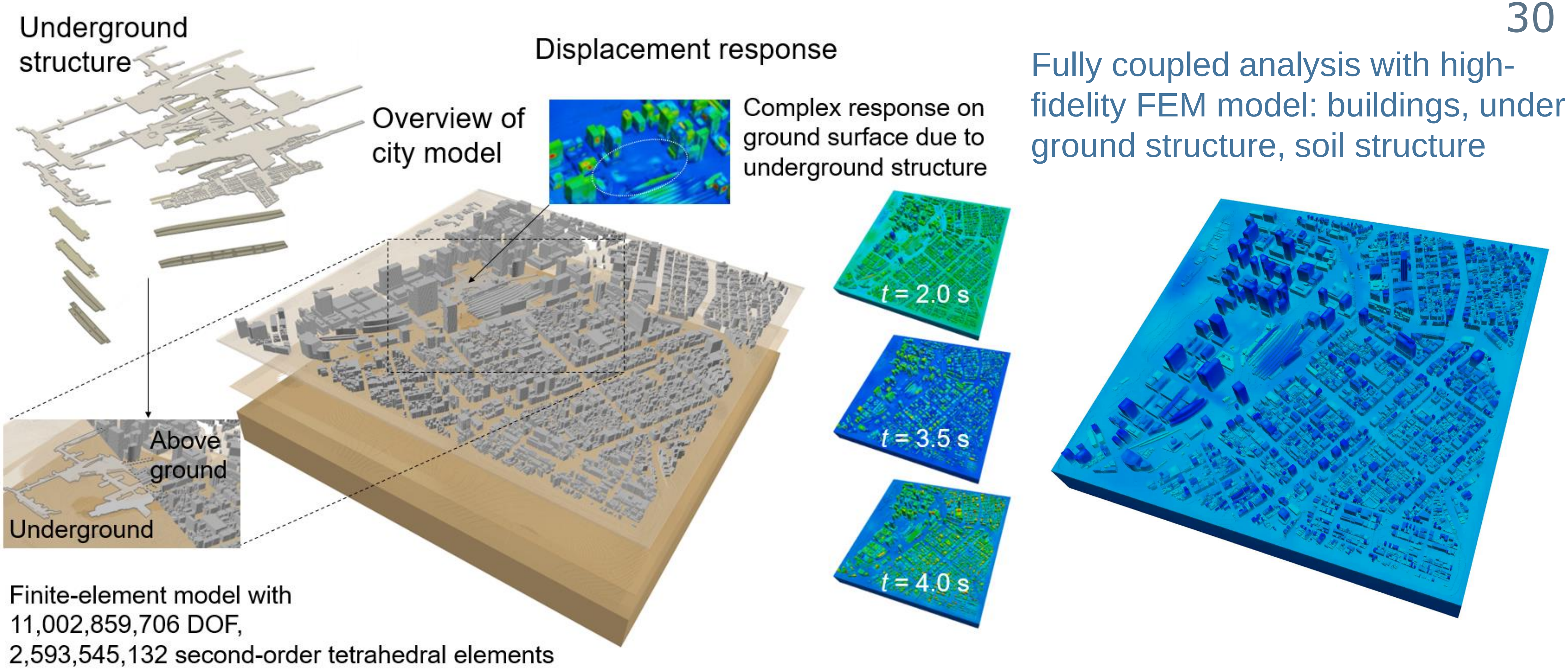
Seismic structural response analysis with high fidelity model



a) overview of the plant model with surrounding two-layered ground modeled with 11,321,249,889 elements and 49,064,764,344 degrees of freedom; b) close-up; c) complex geometry modeled with 16-mm sized second-order tetrahedral elements; d) displacement response to ground shaking; and e) stress concentration, which can be evaluated for all parts of the model at high-resolution for engineering purposes.

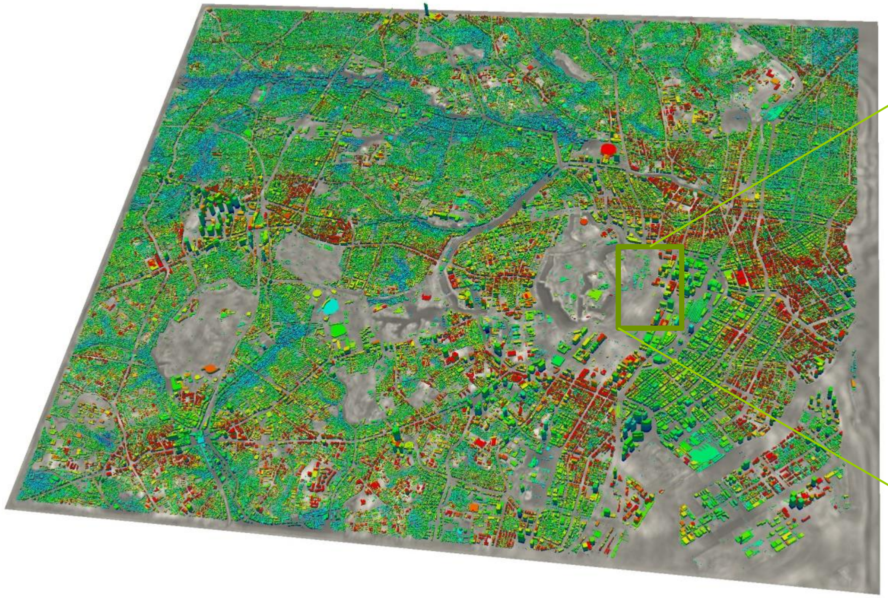
Tsuyoshi Ichimura, Kohei Fujita, Masashi Horikoshi, Larry Meadows, Kengo Nakajima, Takuma Yamaguchi, Kentaro Koyama, Hikaru Inoue, Akira Naruse, Keisuke Katsushima, Muneo Hori, Maddegedara Lalith, A Fast Scalable Implicit Solver with Concentrated Computation for Nonlinear Time-evolution Problems on Low-order Unstructured Finite Elements, IEEE International Parallel and Distributed Processing Symposium, 2018.

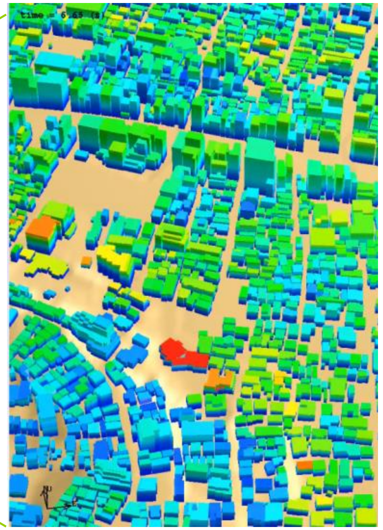
Fully coupled analysis with high-fidelity FEM model: buildings, under ground structure, soil structure



Computation example of 11,002,859,706 degrees of freedom; 2,593,545,132 element model of fully coupled ground and aboveground/underground structure earthquake shaking analysis using IRIS on 98,304 CPU cores (2,048 nodes) of Fugaku: The 2 x 2 km domain was modeled with 0.5-m tetrahedral elements with three soil layers; 9323 buildings; and an underground complex with 645 tenants.

Summary





Large-scale urban earthquake simulation in the Yamanote Line using huge urban data and K computer full-scale (large-scale nonlinear ground analysis with more than 130 billion DOF and seismic behavior analysis of 328,000 structures)

- **Developed a fast implicit matrix solver and realized large-scale high-fidelity urban earthquake simulation**
  - Awarded at Supercomputing Conference (SC)
    - Gordon Bell Prize Finalist (2014, 2015, 2018), Best Poster Award (2016, 2017)
  - HPC (& convergence of HPC and AI) can improve performance of earthquake simulation
  - Further improvement of reliability is expected on Fugaku Computer