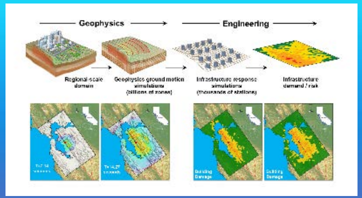

PEER International Pacific Rim Forum
June 16-17, 2021

Integration of Earth Science, Earthquake Engineering and Social Science Simulations for Earthquake Hazard, Disaster and Response Estimation

M. HORI
VAiG, JAMSTEC
The University of Tokyo and RIKEN
T. HORI (JAMSTEC), T. IRYO (Kobe Univ.), Y. SEKIMOTO (UTokyo),
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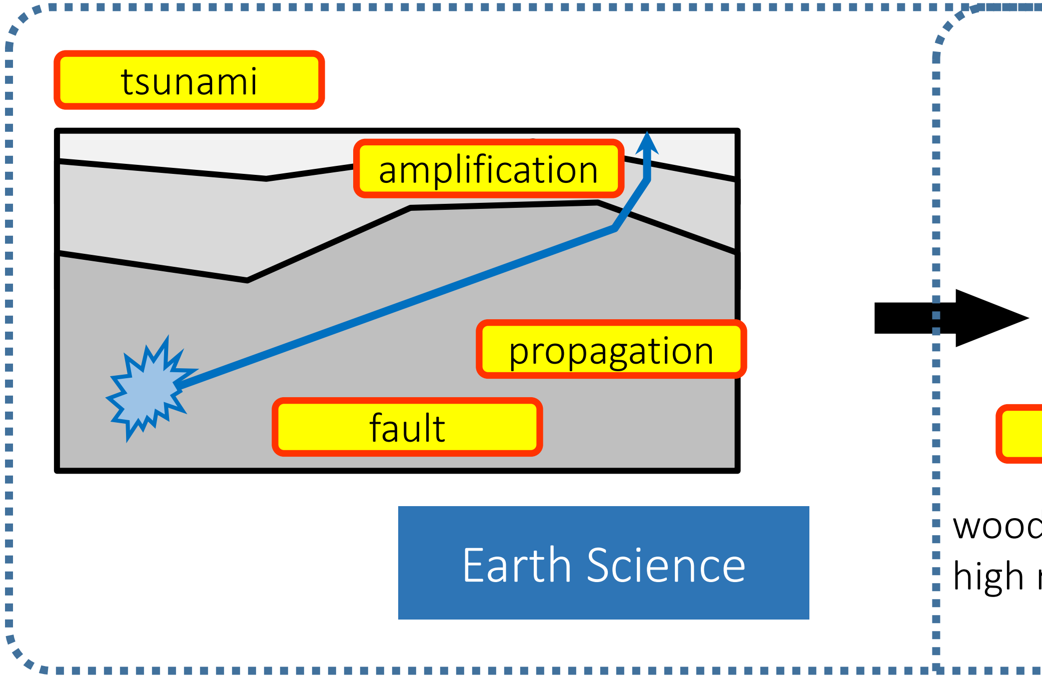
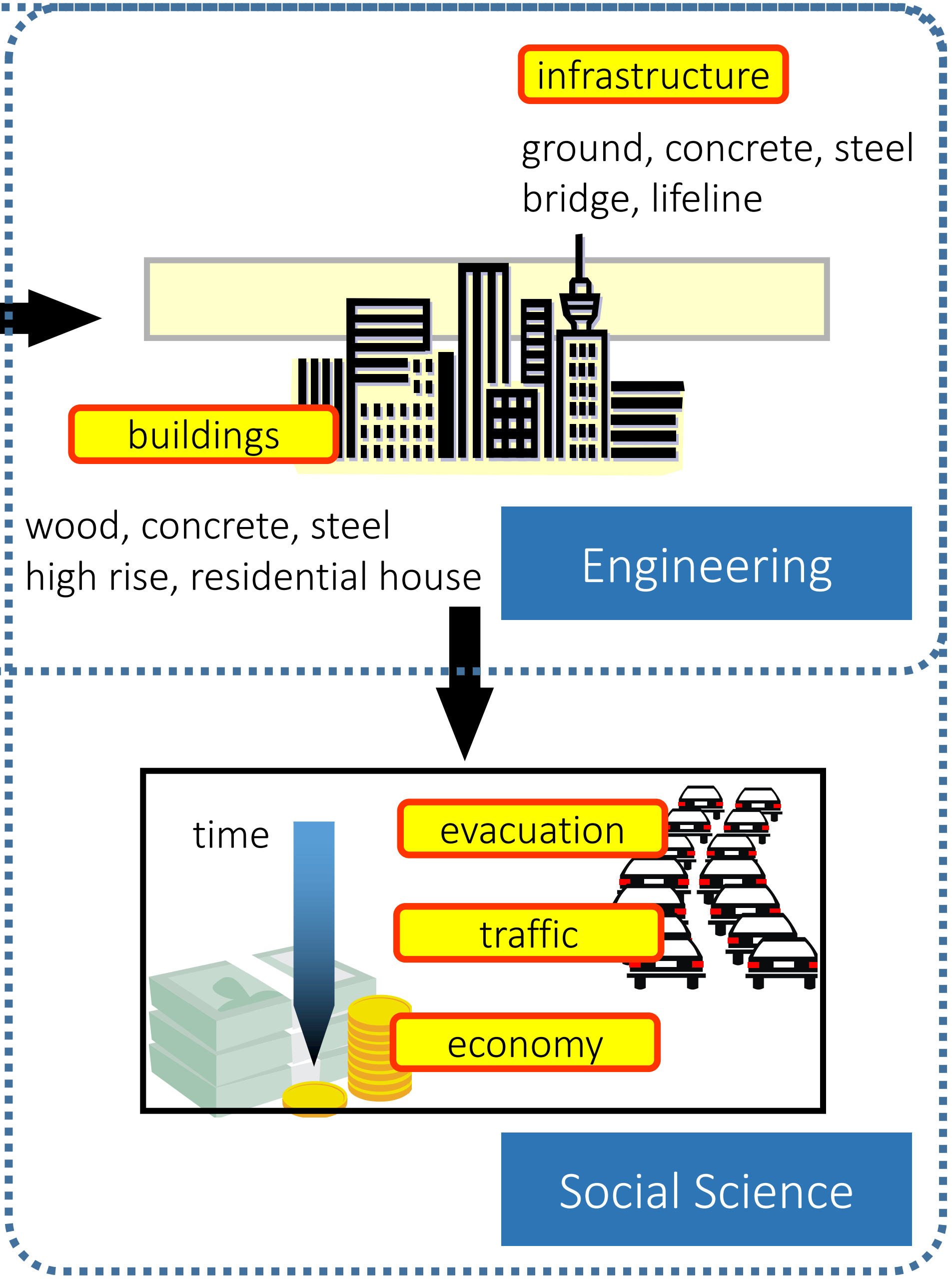
JAMSTEC
RIKEN
THE UNIVERSITY OF TOKYO
PEER

INTEGRATED EARTHQUAKE HAZARD AND DISASTER ESTIMATION





Integration of various numerical analysis methods that use HPC

- Earth Science Simulation
- Earthquake Engineering Simulation
- Social Science Simulation

MEXT HPC Research Project 3

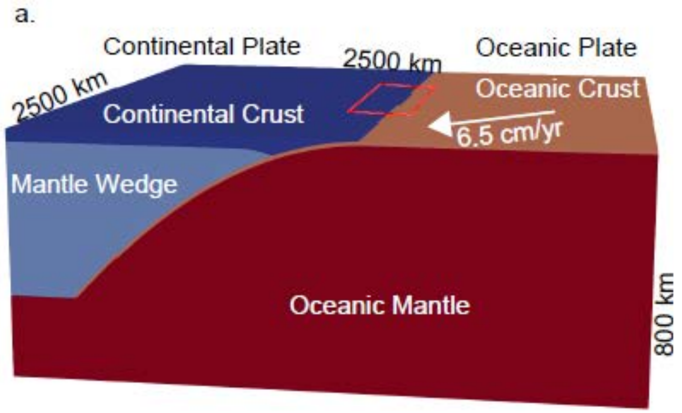
ELEMENTS OF INTEGRATED EARTHQUAKE SIMULATION

- Earth Science and Earthquake Engineering Simulation
  - FEM for Seismic Wave Propagation in Crust and Seismic Wave Application in Ground
  - DEM (Distinct Element Method) for Long-Term Crust Deformation
  - SPH (Smoothed Particle Hydrodynamics) for Tsunami Simulation
- Social Science Simulation
  - MAS for Mass Evacuation Simulation for Pedestrian and Vehicle
  - Traffic Simulation Combining Traffic Demand and Traffic Flow in Post-Earthquake Disaster Period
  - Economic Activity Simulation for Evaluation of Recovery Plan
- Integration of Simulation on Platform
  - Tokyo Metropolis Earthquake
  - Nankai Trough Earthquake

EARTH SCIENCE AND EARTHEQUAKE ENGINNERING SIMUALTION

◆ FEM

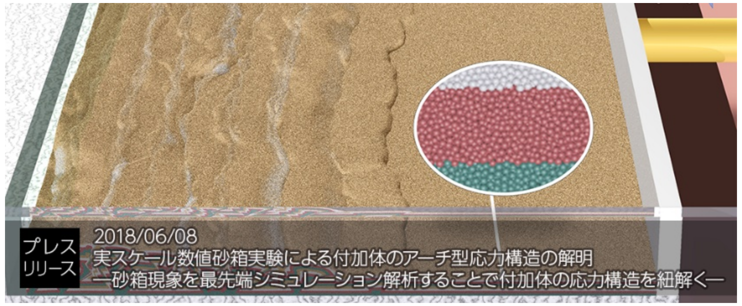
- Crust scale simulation of Nankai Trough Earthquake
- K: construction of analysis model partially based on observed data of curst structures
- Fugaku: construction of analysis model fully based on observed data of crust structure



analysis model of crust structure for Nankai Trough Earthquake

◆ DEM

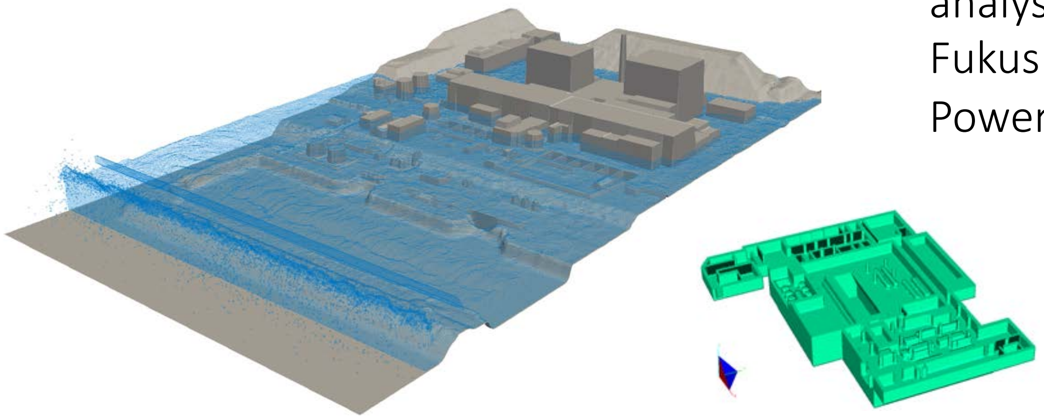
- Reproduction of sand box experiment using 2,400,000,000 particles
- Clarification of mechanism of forming accretionary prism



analysis model of sand box

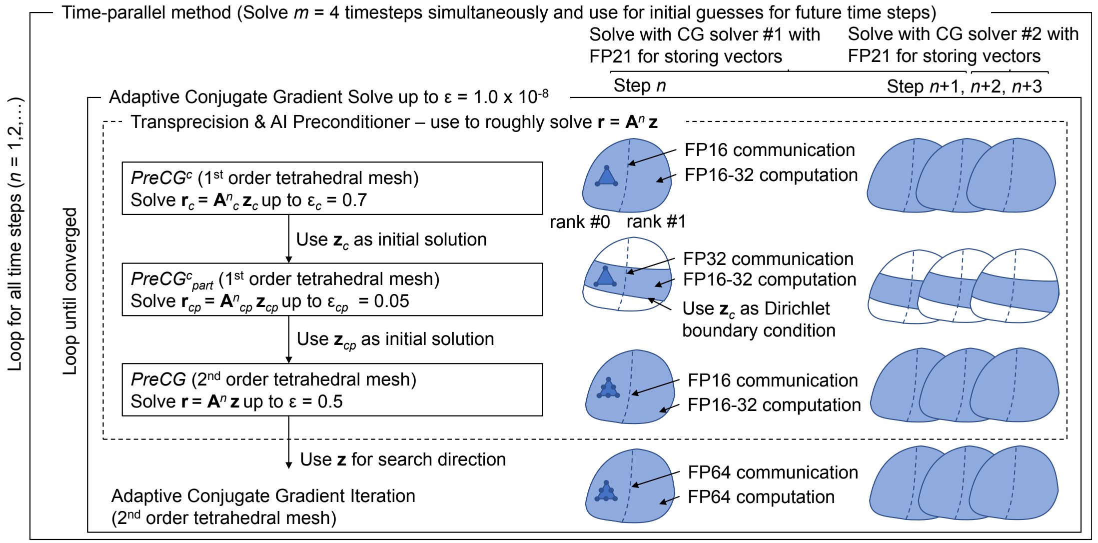
◆ SPH

- Tsunami inundation simulation
- Kochi City
- Fukushima nuclear power plant

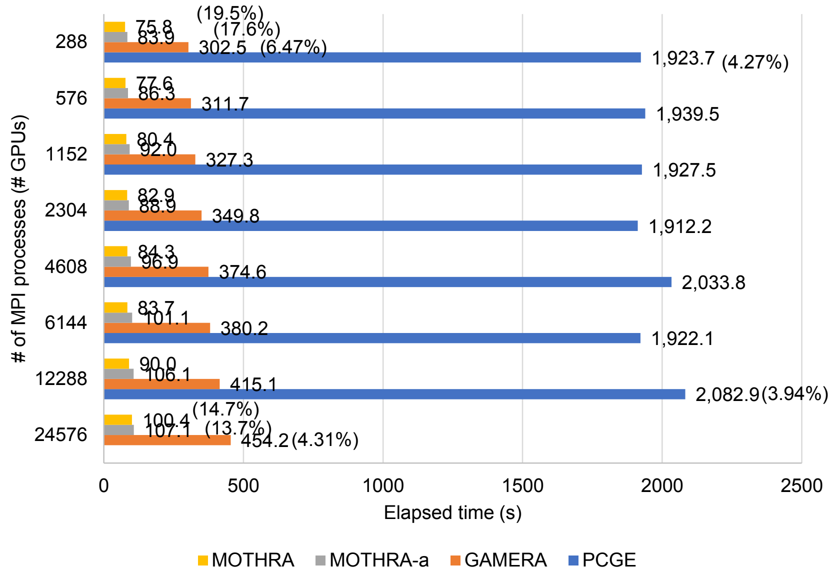


analysis model of Fukushima 1st Nuclear Power Plant

EARTH SCIENCE AND ENGINEERING: FINITE ELEMENT METHOD

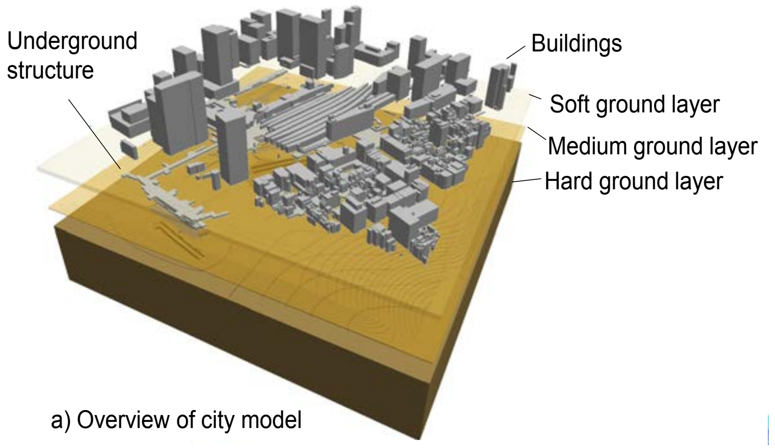


algorithm of solver



weak scaling on Summit

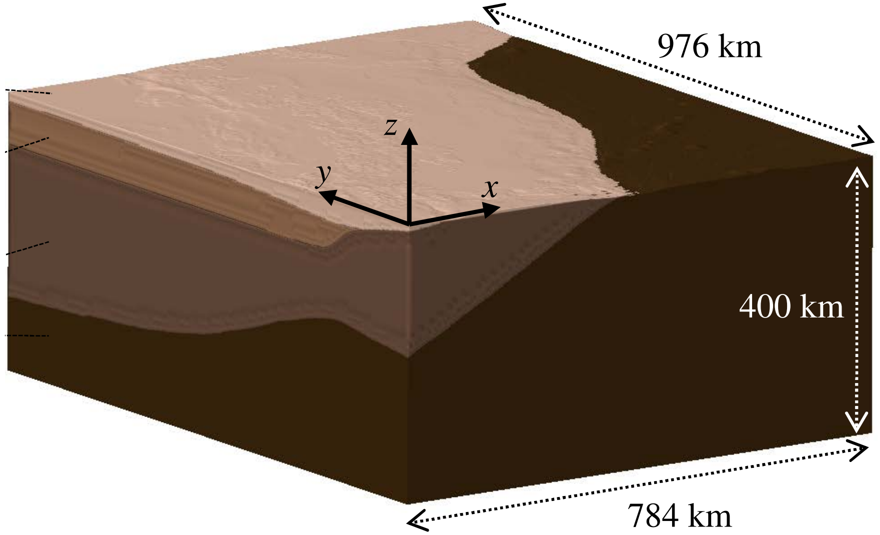
- Continuous improvement of CG
- Achievement of good scalability in parallel computer and GP-GPU computer
- Automated model construction of urban area
    - ground
    - structures

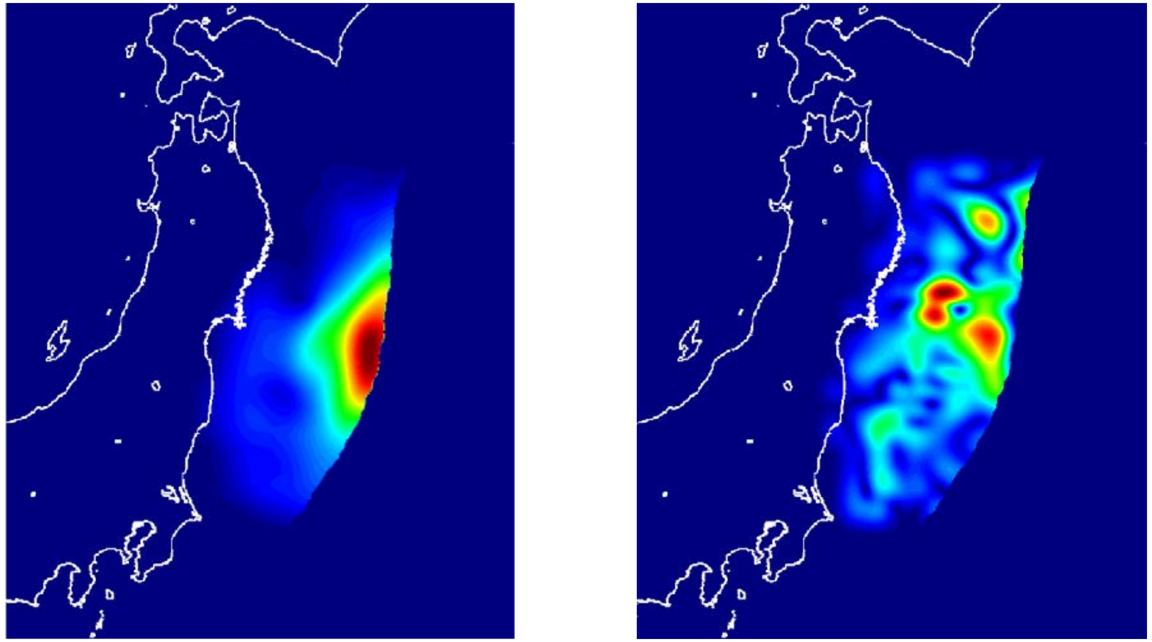


urban area model

EARTH SCIENCE: CRUST DEFORMATION ANALYSIS

- Fast Computation
  - FEM model of 8,219,600,000 DOF
  - Numerical Green functions of 360 source x 1,000 uncertainty
- Ensemble Computing
  - 1,000 models of different (Vp, Vs, ρ)
  - Difference in crust displacement is a few の meter
- Updated Lagrangian Analysis
  - Development of fast automated remeshing
  - Analysis of finite and large deformation of fault and subduction zone in geological time scale





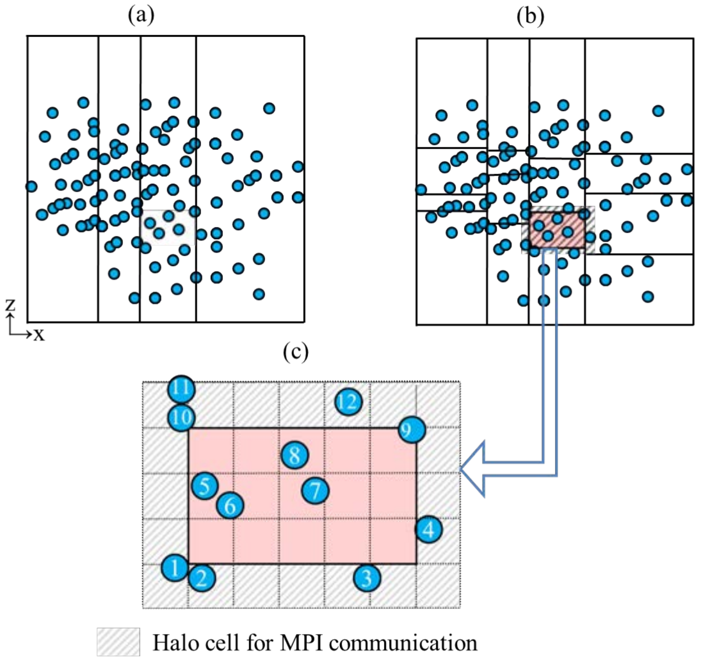
(a) original case

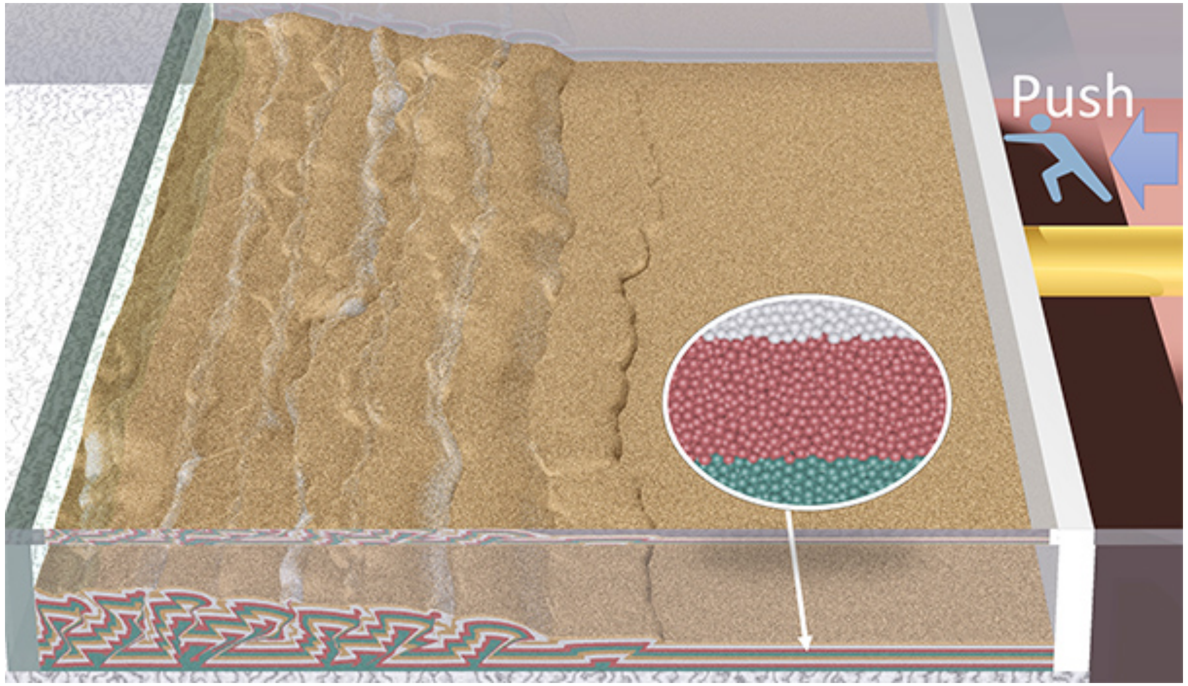
(b) difference

EARTH SCIENCE: DISTINCT ELEMENT METHOD

DEM: Particle Analysis Method for Contacting/Detaching of Spherical Particles

- 2.5 billion particles
- dynamic load balance for moving particles
- reproduction of sand box experiments





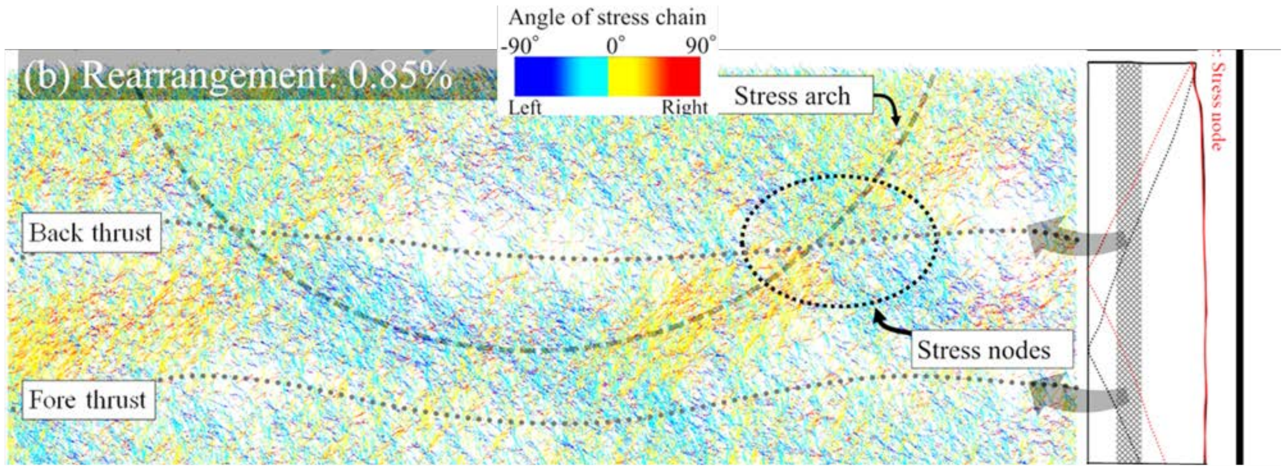
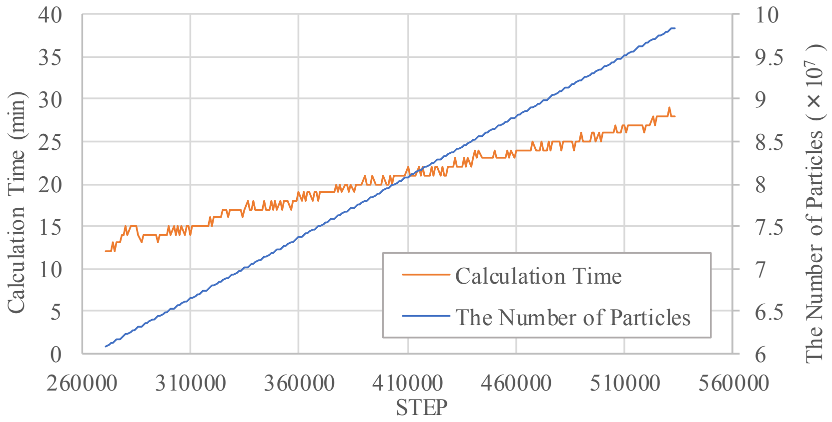


Fig. 1: Map view of σ_1 of particles in the stress chain at the first thrust formation

ENGINEERING: SMOOTHED PARTICLE HYDRODYNAMICS

MScPHy: Particle Analysis Method for Solid-Fluid Interacting Problems

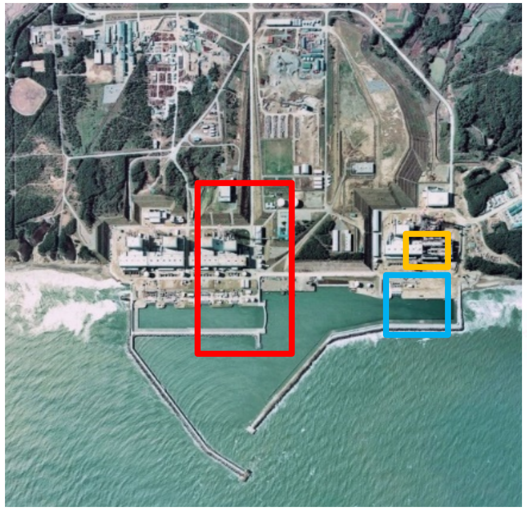
- Particles for tsunami and ground/structures
- Simple treatment of free boundary problem
- High performance of non-structured grid

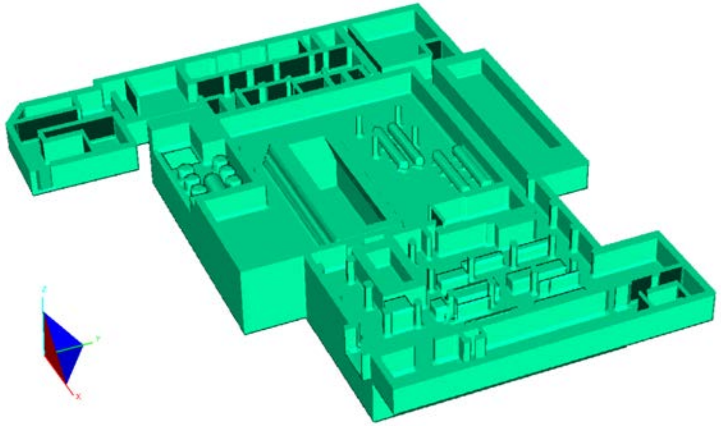


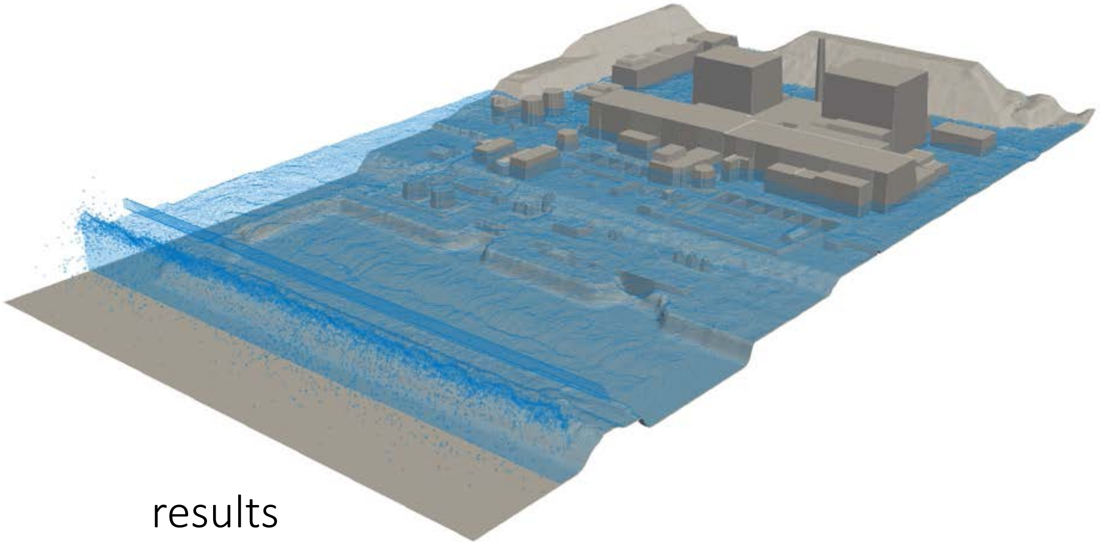
well-controlled load balance for many particles

analysis model

- exterior and interior of buildings
- particle radius of 30 cm
- use of 128 compute nodes in K





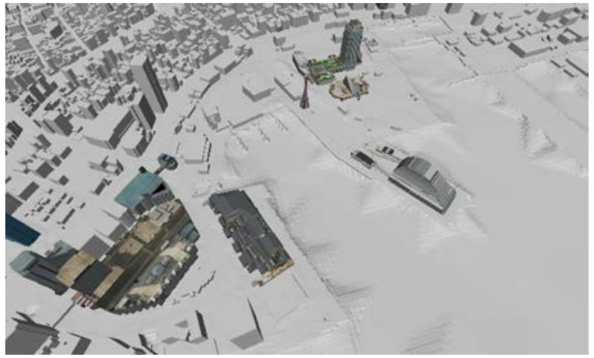


Tsunami Inundation of 1st Fukushima NPP

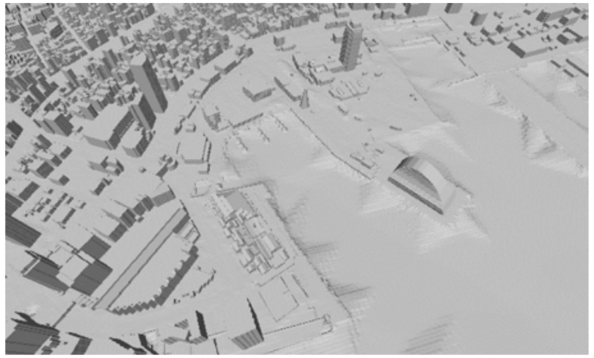
results

- fair agreement of observation
- practically acceptable computing time

ENGINEERING: AUTOMATED MODEL CONSTRUCTION FOR TSUNAMI

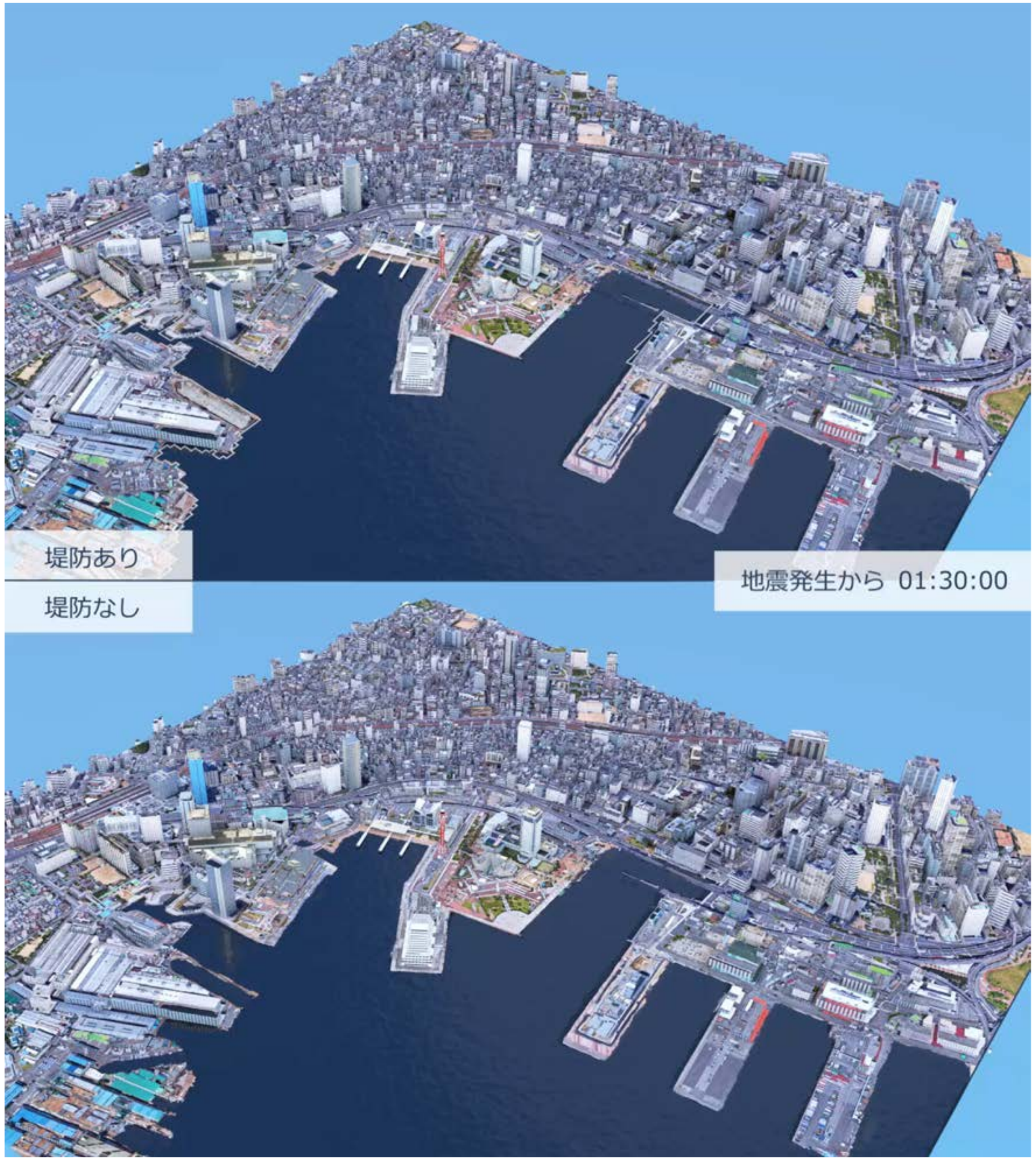


3D Geological Data of Low Resolution



2D Elevation Data of 1 m Resolution

- Analysis Model for JAGURS
- Combined Simulation of Ground Motion and Tsunami Inundation

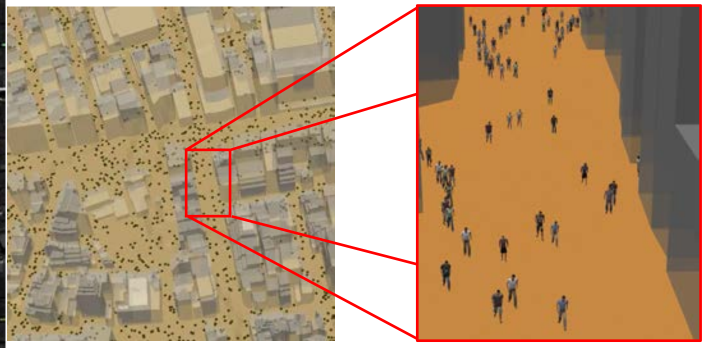


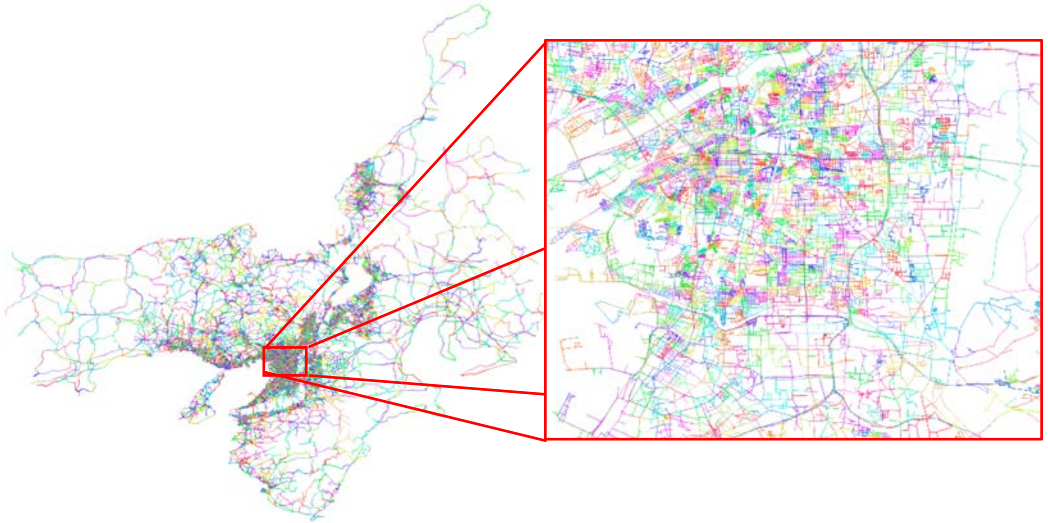
SOCIAL SCIENCE SIMULATION

- MAS
  - Development of agents for pedestrians and vehicles with functionalities of see, think, and move
  - Development of urban are model for mass evacuation

- Coupled Simulation of Traffic Demand and Traffic Flow
  - Development of traffic demand simulation for post-earthquake disaster
  - Enhancement of traffic demand simulation and traffic flow simulation with HPC capability

- Urban area of 900 km^2 and more than 10 million agents
- 2,056 compute nodes in K



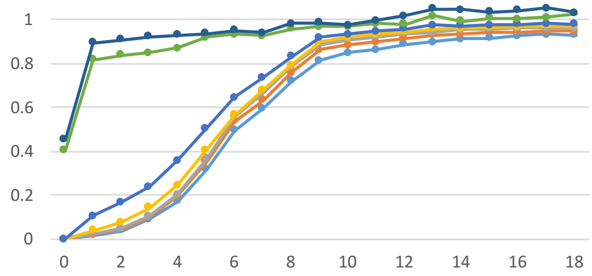


- large scale urban area traffic model of 400,000 links
- embarrassing parallel commuting of traffic demand and flow simulation

SOCIAL SCIENCE SIMULATION

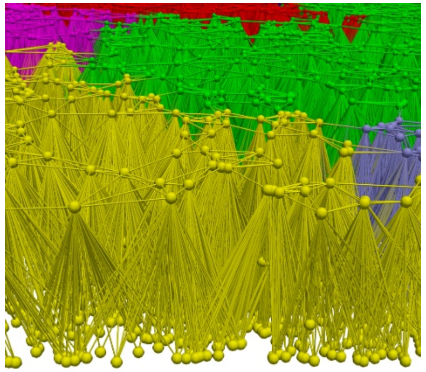
- Economic Simulation
  - Analysis method of solving dynamic problem for industrial activities of using damaged stocks
  - MAS for 1:1 scale economic model to analyze impact of earthquake damage

- Utilization of Urban Area Data
  - Preparation of detailed information for constructing analysis models of social science simulation
  - Development of sophisticated methods of inter/extra-polating scattered and fragmented urban area data



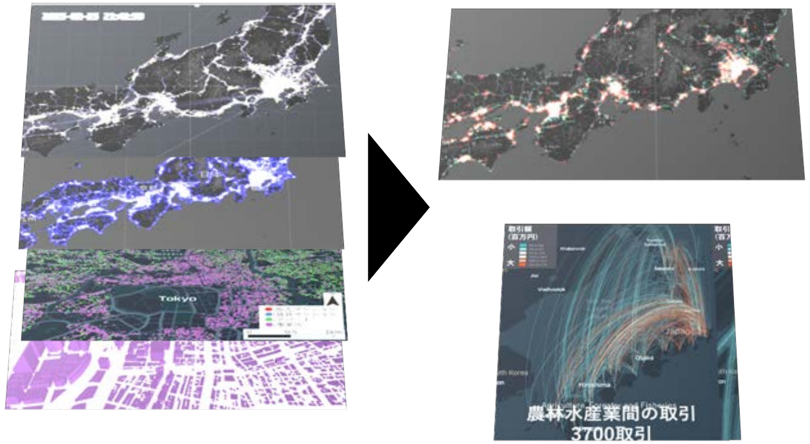
post-disaster recovery of production

analysis method of solving Bellman's equation for 3 regions and 36 industrial sectors over Japan



MAS for 150,000,000 agents
largest HPC computation in economics

dynamic load balance among agents of various size; from largest agent of national bank to smallest agent of household

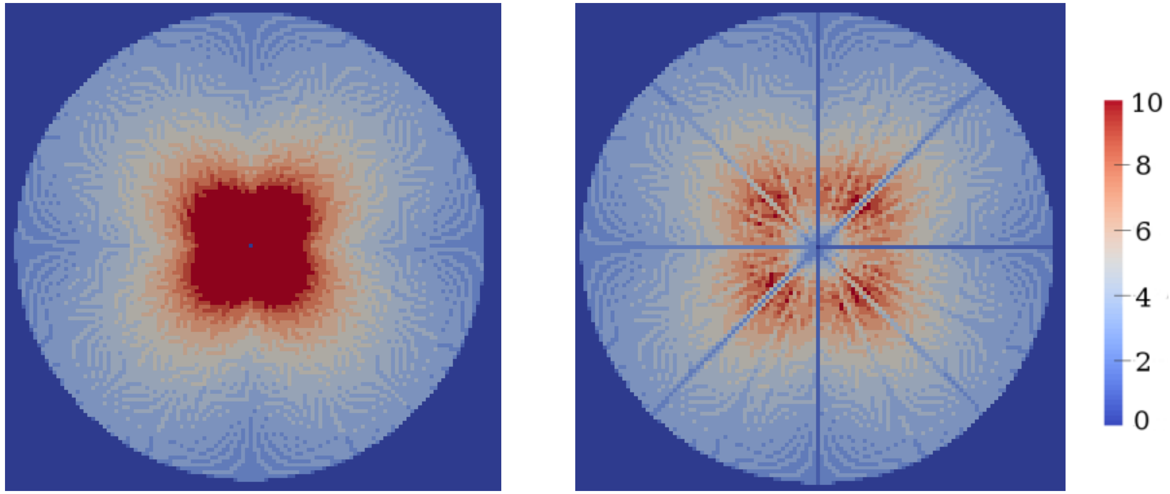


various data set of urban area information about economic activities

SOCIAL SCIENCE SIMULATION: MAS FOR MASS EVACUATION

- Development of Autonomous Agent with Different Attribute
  - Pedestrian and vehicle agent with functionalities of see, think and move, moving in urban area model in non harmonious manner
  - Urban area model of road network with interactions and buildings producing derbis

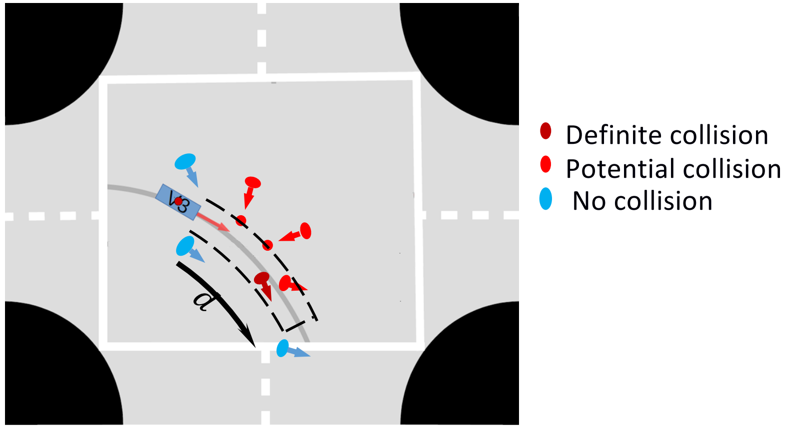
- Good Scalability
  - Gradual concentration of agents in shelters
  - Dynamic load balance in assigning compute nodes to agents



Before

(b) After

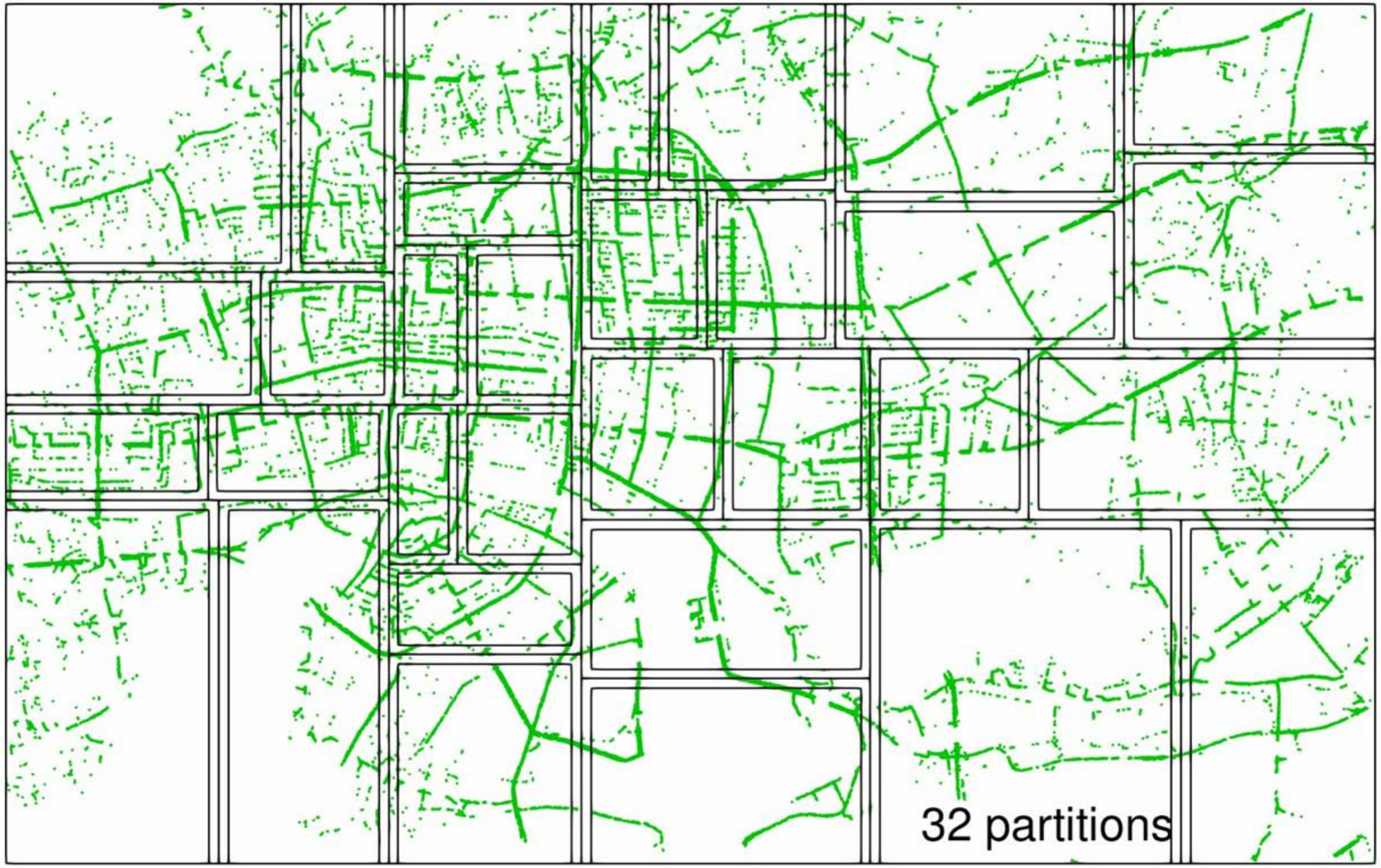
functionality of see: efficient scanning



d =Distance required for car to decelerate to stop

functionality of move: smooth in and out at intersection

SOCIAL SCIENCE SIMULATION: MAS FOR MASS EVACUATION



Load Balance - Compute Node Allocation -

Strong Scalability

Number of nodes	Runtime (s)	Strong scalability
256	5016	
512	2516	99%
1024	1400	89%
2048	842	83%

Key Features

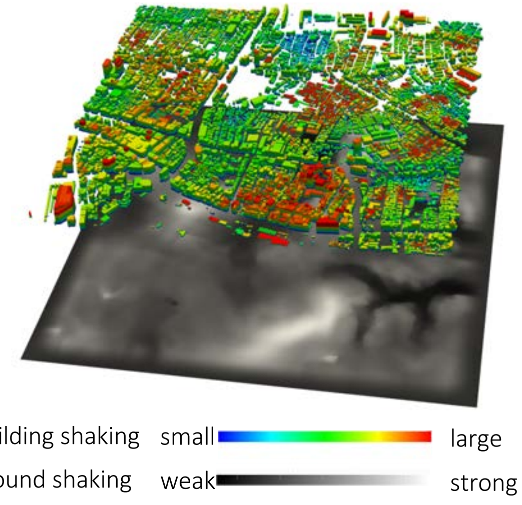
- Resolution: 1 x 1 m, 0.1 sec
- Domain: 900 km^2
- Number: more than 10,000,000
- Scalability: up to 2048 compute nodes

Automated Model Construction

- Use of various urban area data
- Grid model for agent movement
- Node-link model for agent memory

SOCIAL SCIENCE SIMULATION: TRAFFIC DEMAND AND FLOW

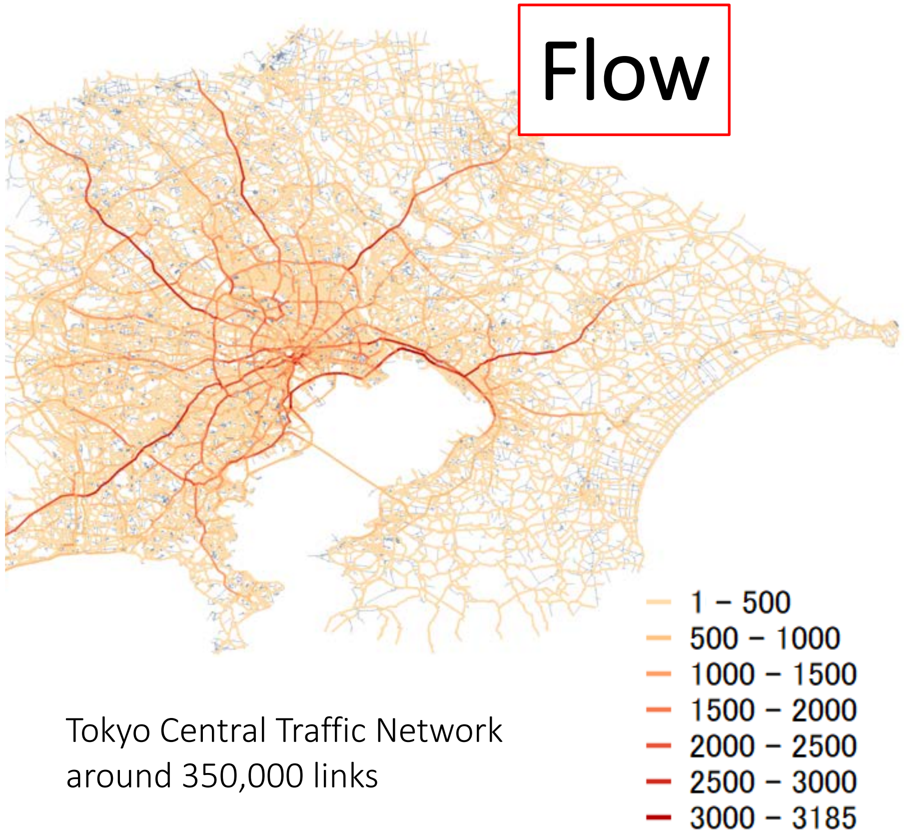
Earthquake Disaster Simulation



road network damage

Traffic Flow Simulation

- Computation of stable state of traffic flow considering network damage and reduced/increased traffic demand
- Estimation of trip time delay for all traffic links



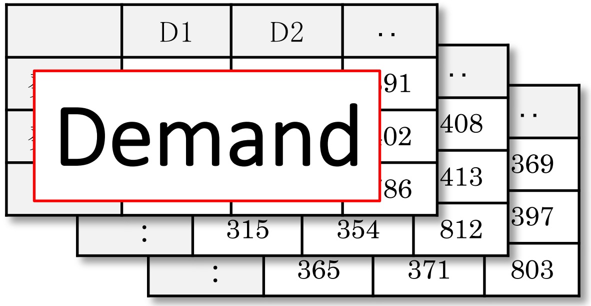
Tokyo Central Traffic Network
around 350,000 links

trip time

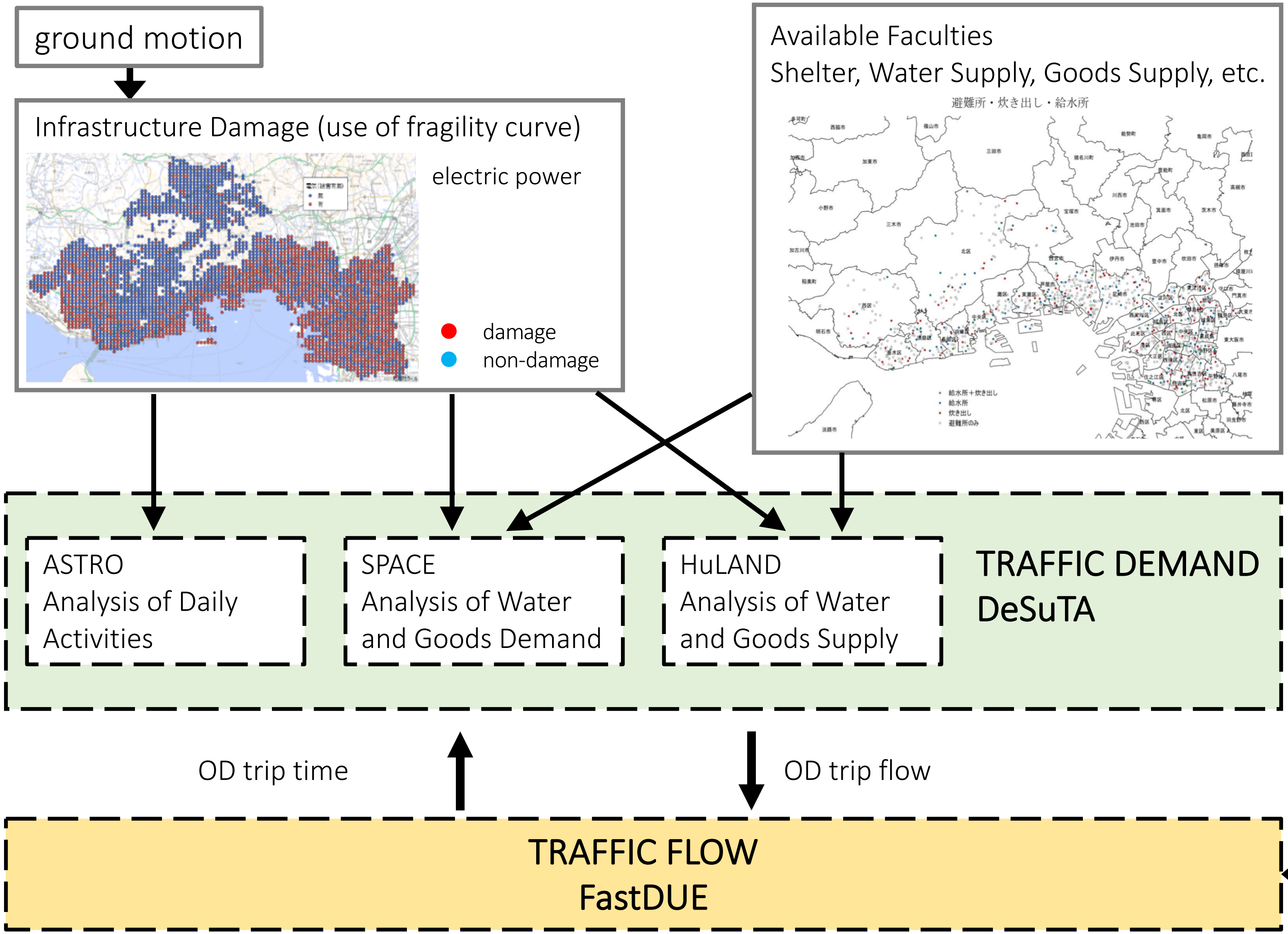
trip demand

Traffic Demand Simulation

OD traffic pattern and its change



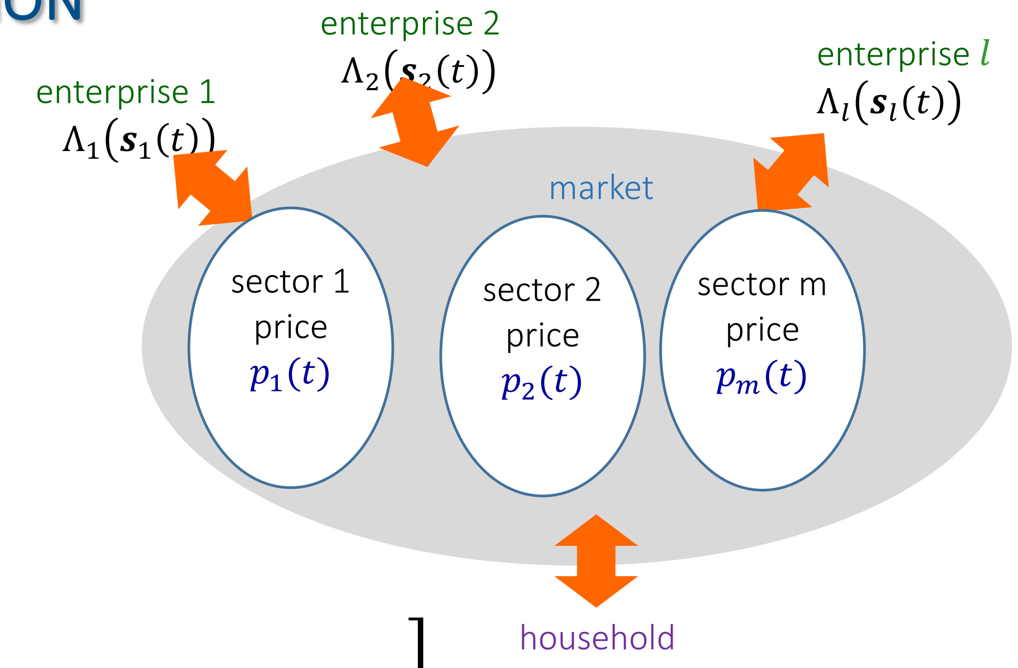
SOCIAL SCIENCE SIMULATION: COUPLING OF DEMAND AND FLOW SIMULATION



Graph Model of Road Network

- Node is used to specify OD
- (Origin and Destination of trip)
- Link is used to specify route between OD

BELLMAN'S EQUATION



Λ_i: value of i-th enterprise

value at term t (stock value)

reduction factor

$$\Lambda_i(\boldsymbol{s}_i(t)) = \max_{\boldsymbol{d}_i(t)} \left[E_\varepsilon[\Pi(\boldsymbol{s}_i(t), \boldsymbol{d}_i(t))] + \psi \sum_{\{q', \Delta\theta_i\}}^{Q} \phi_i(q', \Delta\theta_i) \cdot \Lambda_i(\boldsymbol{s}_i{}'(\boldsymbol{s}_i(t), \boldsymbol{d}_i(t))) \right]$$

expected profit at t
income – outcome

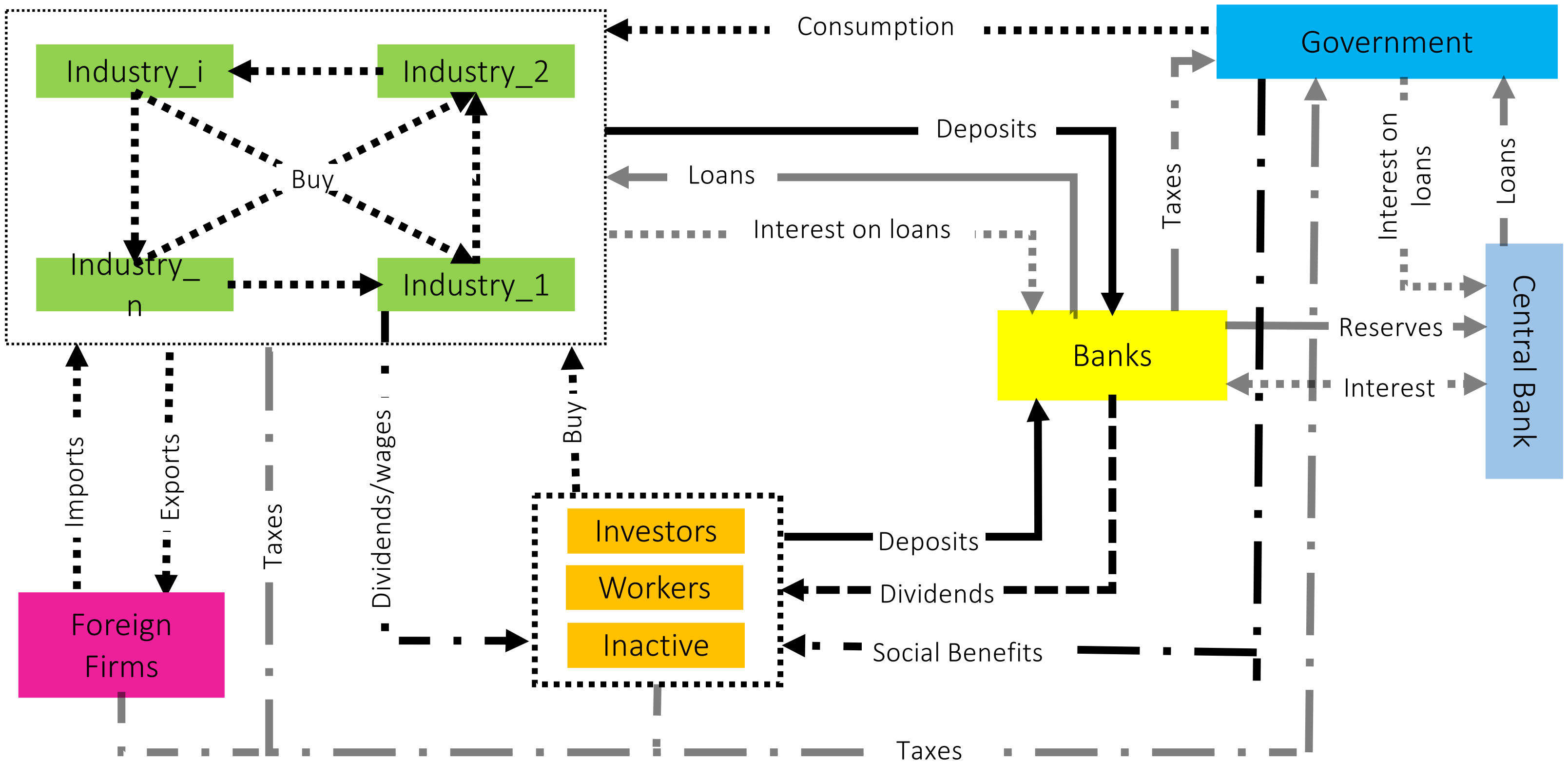
probability of state
at t+1 term

value at t+1

variables

$\boldsymbol{s}_i(t)$	state variable vector capital, labor, infrastructure, {price}, {lifeline}, supply chain
$\{\phi_i(q', \Delta\theta_i)\}$	probability of price vector at next term q' and lifeline and supply chain operation $\Delta\theta_i$
$\boldsymbol{d}_i(t)$	control variable vector
$\boldsymbol{s}_i{}'(\boldsymbol{s}_i(t), \boldsymbol{d}_i(t))$	state variable vector at next term determined by $\boldsymbol{s}_i(t)$ and $\boldsymbol{d}_i(t)$

SOCIAL SCIENCE SIMULATION: MAS FOR ECONOMIC SIMULATION

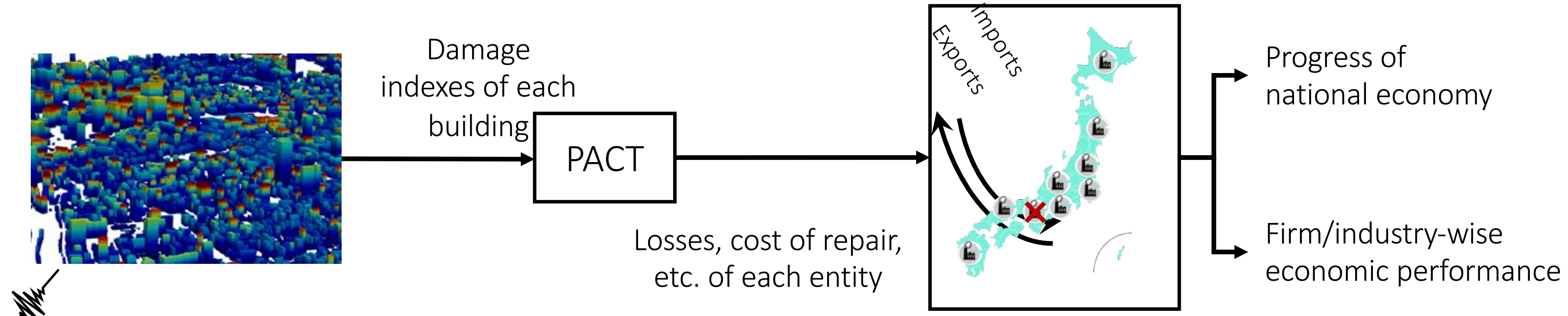


Number of MPI processes	Runtime per period (s)	Scalability (%)
16	492.00	
32	294.13	83.64
64	187.04	78.63
128	129.00	72.50
256	107.32	60.10

Problem settings: 20 periods with 331million agents in reedbush computer (The Univ. of Tokyo)

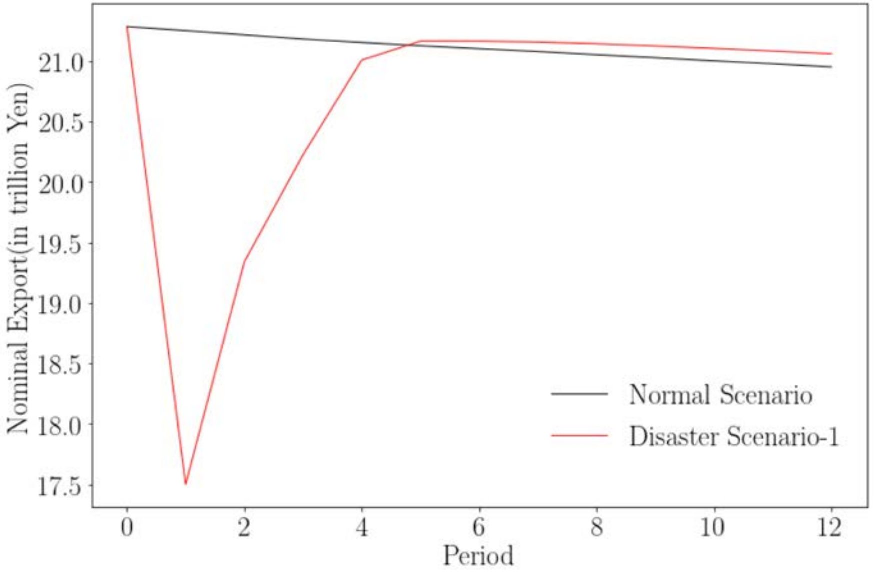
- Macro Economic Agent Based MAS of Poledna et al.
  - Verified by comparing general economics model
- First Enhancement of MAS with HPC Capability
  - 1:1 Scale of Japanese Economy (100,000,000 human agents + 4,000,000 non-human agents)
  - Ensemble computing for uncertainty quantification

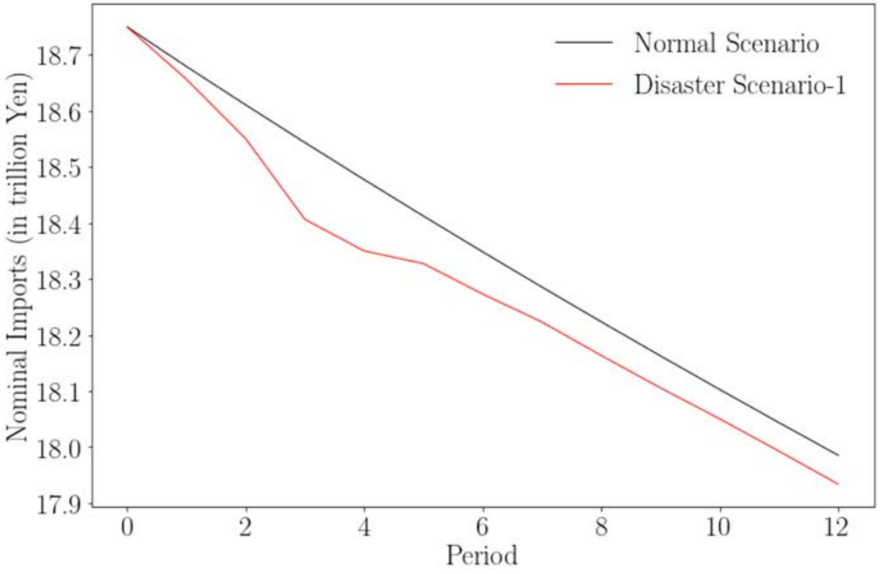
SOCIAL SCIENCE SIMULATION: MAS FOR ECONOMIC SIMULATION RESULTS



Physics based natural disaster simulations

1:1 scale model of Japanese economy

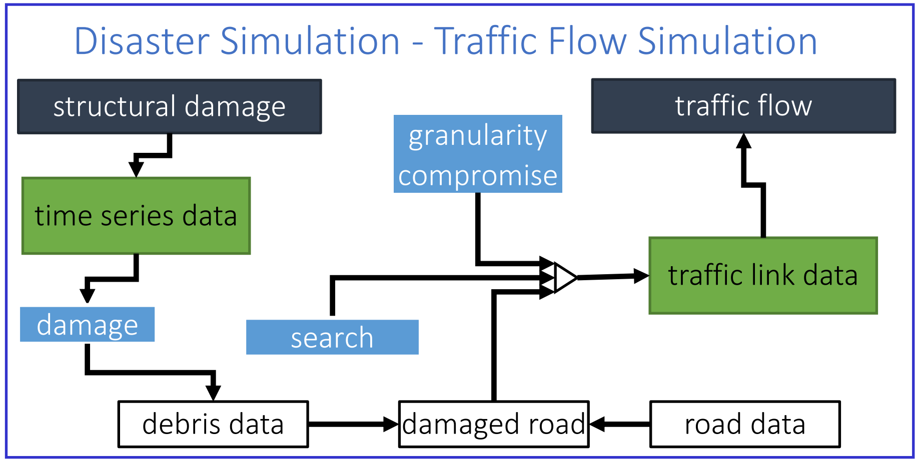


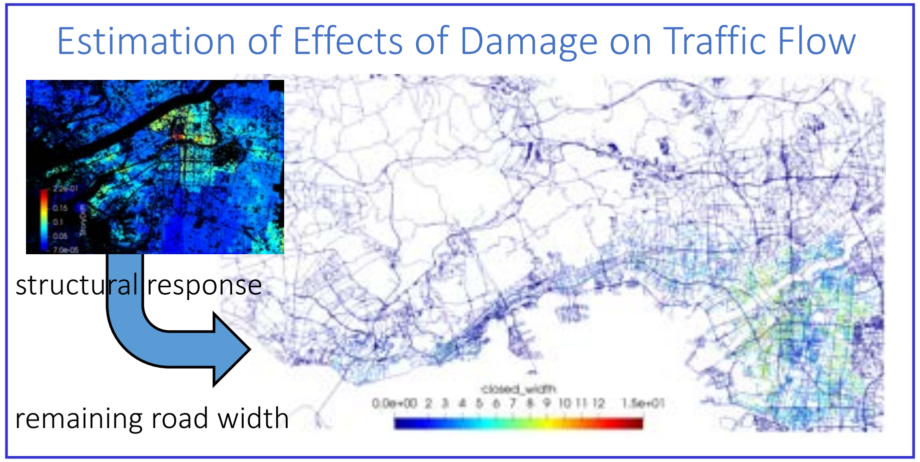


Comparison of Recovery Plan

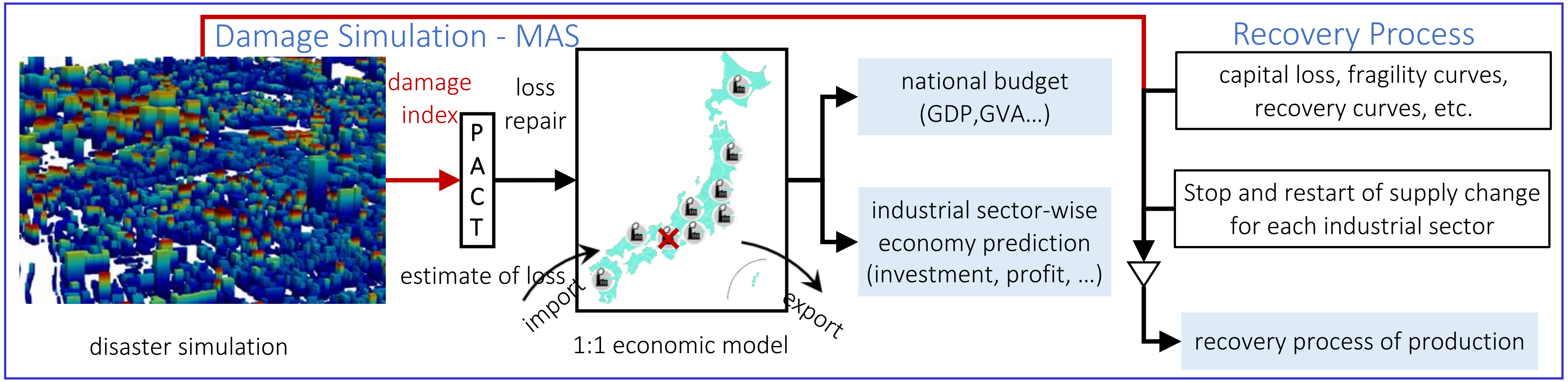
INTEGRATION OF SICAL SCIENCE SIMULATION

◆ Traffic Simulation





◆ Economic Simulation



INTEGRATION: AUTOMATED MODEL CONSTRUCTION

- Bridge Model in Road Network
  - Use of intermediate data
  - Inter/extra-polation based on derivatives

Data (direct use)
Design Documents of Target Structure
- digital document
- printed document

Data (in-direct use)
National Database
- road information
- regional information
- DEM
- ground
- intersection

Derivatives
- location coordinate
- span
- height (road)
- height (ground)
- ground conditions

Data (in-direct use)
Design Standards for Interpolation
- design standard
- design guidelines (bridge)
- design guidelines (road)

Derivatives
- empirical relations
- ordinary approximations

Bridge Information
Configuration
- height, span , …

Construction Types
- truss, suspension, …

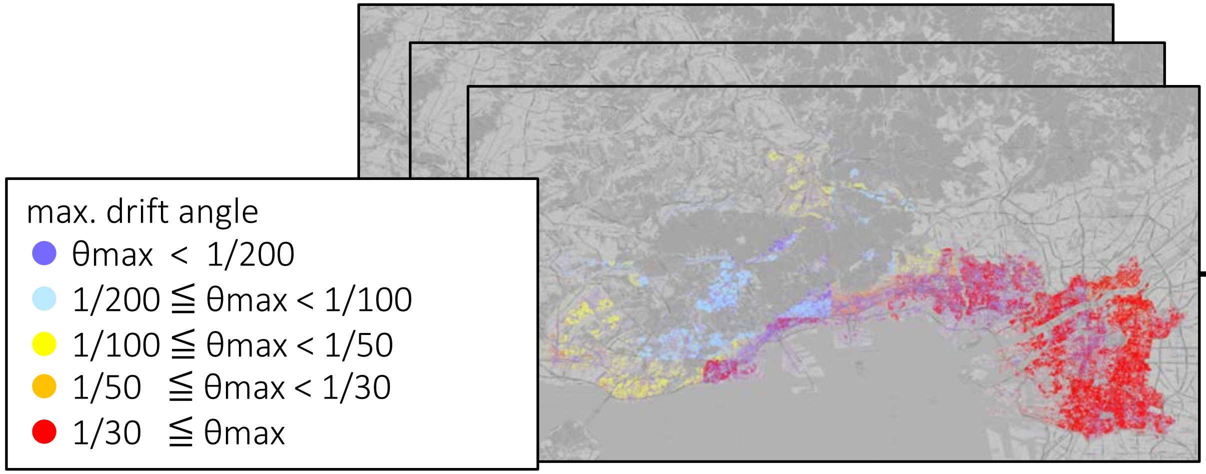
Material Properties
- elasticity, strength , …

Structural Properties
- capacity , …

model

INTEGRATION: STRUCTURAL DAMAGE AND ROAD NETWORK

structural seismic response simulation



data conversion

polygon of road shut-down by debris

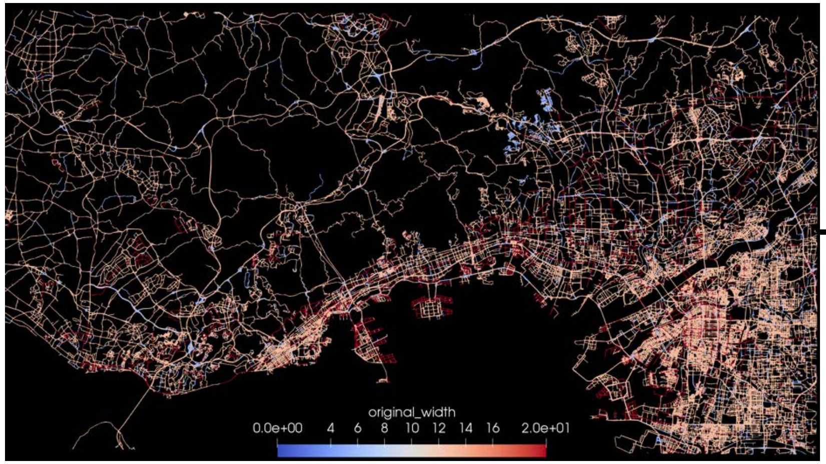
computation

shut-down length of link

data conversion

data merging

road network information



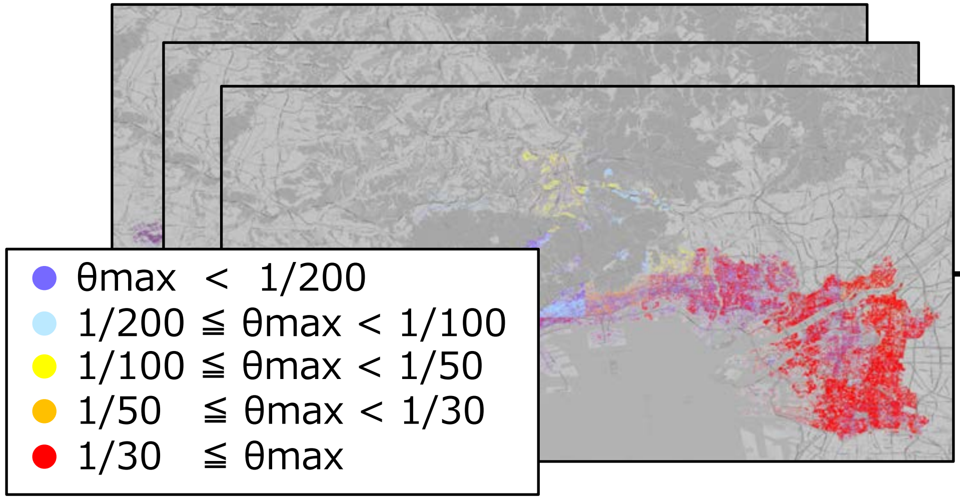
Road
- node: coordinates
- link
- width

Data source
- DRM

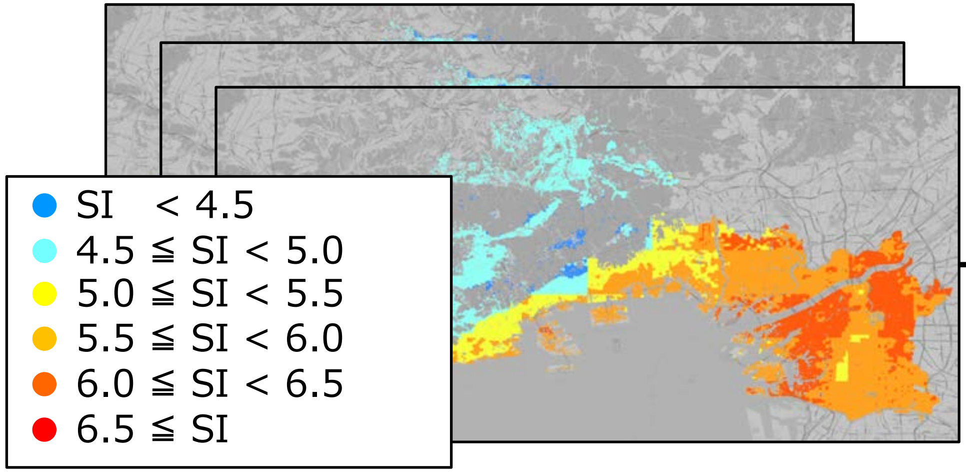
Difficulties
- Difference in coordinate system
- Errors in data merging
- Computation of shut-down length

INTEGRATION: STRUCTURAL DAMAGE AND ECONOMIC SIMULATION

seismic response simulation



ground motion amplification simulation



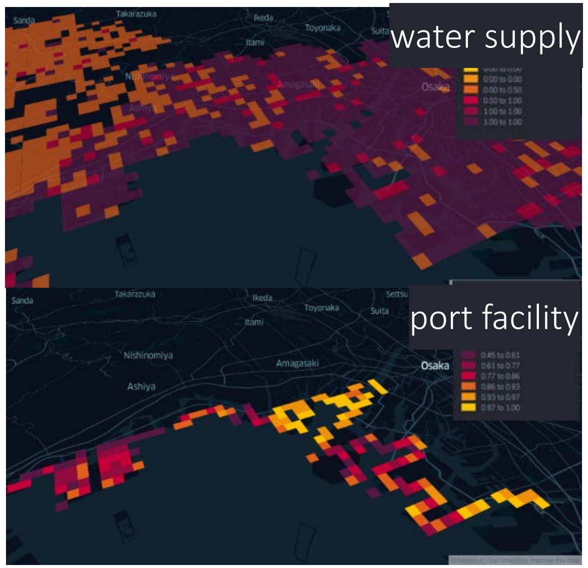
data conversion

Damage Index
degree of damage
small, middle, severe

data conversion

data conversion

Grid Data
- structural damage
- ground motion index



use of fragility curves and recovery curves for infrastructures

Difficulties
- Difference in coordinate system
- Errors in data conversion
- Lack of physical simulation of infrastructures

TOKYO METROPOLIS EARTHQUAKE

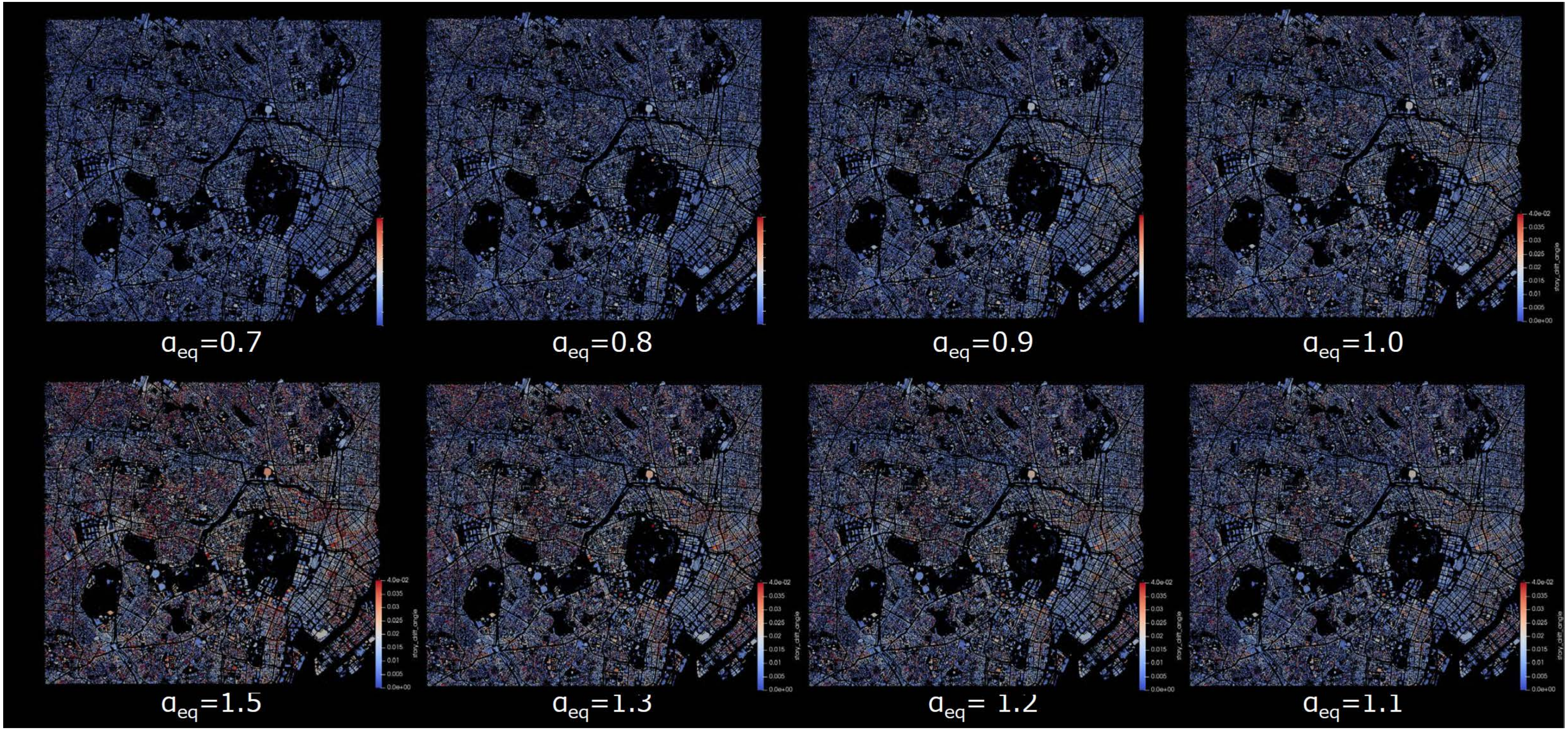
- **Earthquake Scenario** — Cabinet Office Prediction
  Input of synthesized seismic wave propagating from fault

- **Ground** — FEM 3-layer model (bedrock + 2 layers)
  non-linear RO

- **Residential Building** — number: 243,132
  linear MDOF

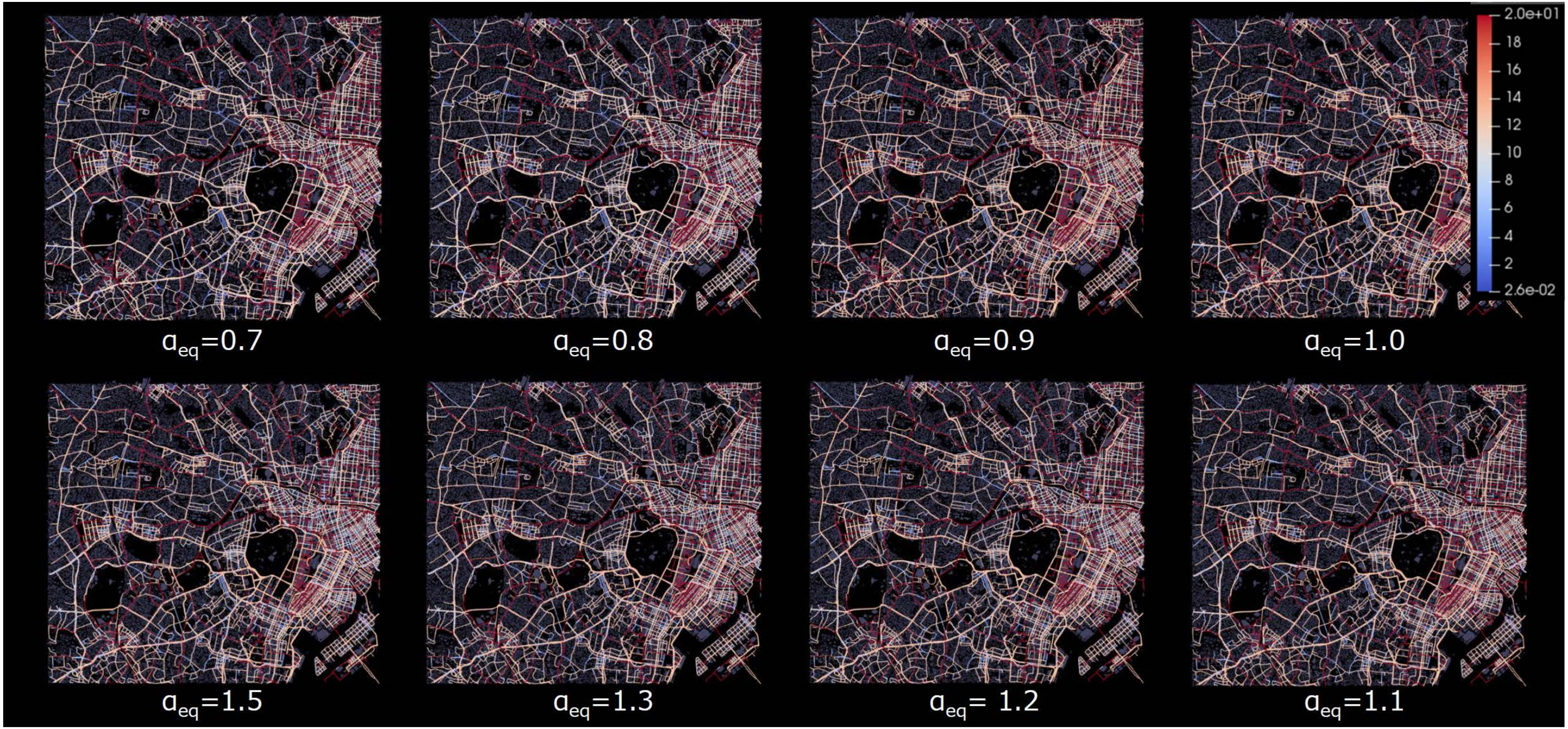
- **Road Network**
  - Central Tokyo — link: 347,691
  - Vehicle — number: standard size 5,000,000 + large size 250,000
    (558,572 packets, 1 packet = standard size 10 + large size 5)
    time: 4 - 10

BUILDING DAMAGE CONSIDERING UNCERTAINITY OF SURFACE LAYERS



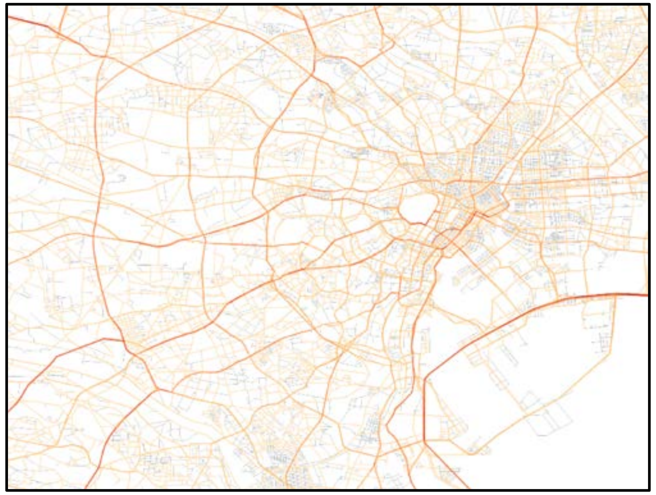
a_{eq}: parameter of ground motion amplification

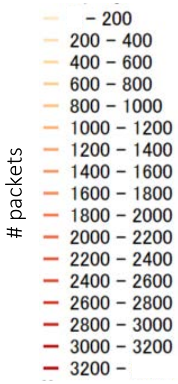
REMAINING ROAD WIDTH CONSIDERING UNCERTAINITY OF SURFACE LAYERS



road closed if remaining width ratio < 0.5

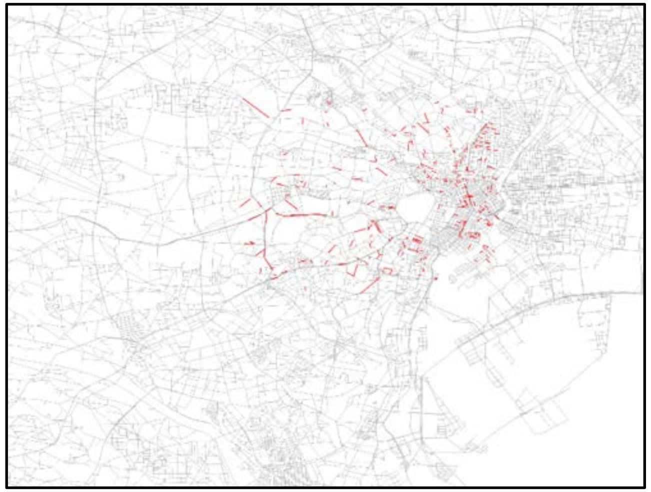
TRAFFIC SIMULATION: TRAFFIC DENSITY

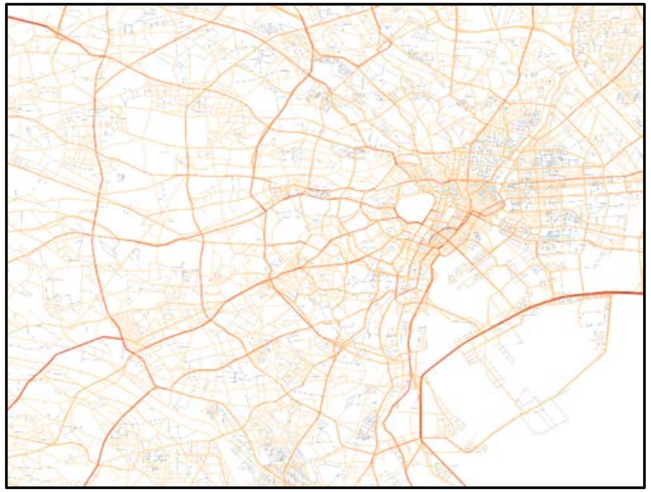




ordinary traffic density

Case 1





Case 2

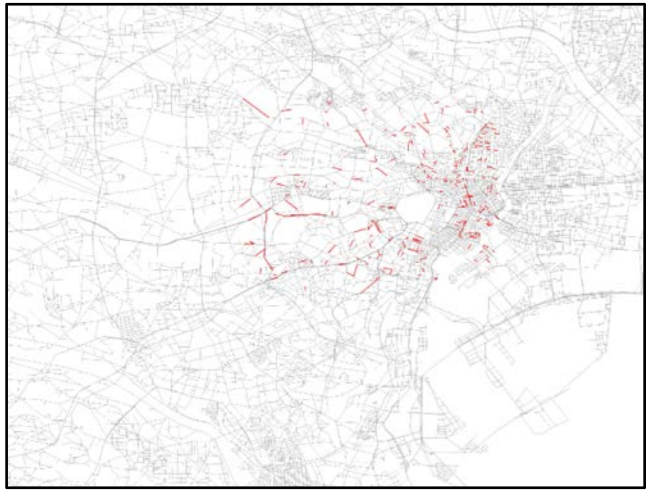
damaged sites

traffic density

TRAFFIC SIMULATION: DEGREE OF CONGESTION

ordinary traffic congestion

Case 1



Case 2

damaged sites

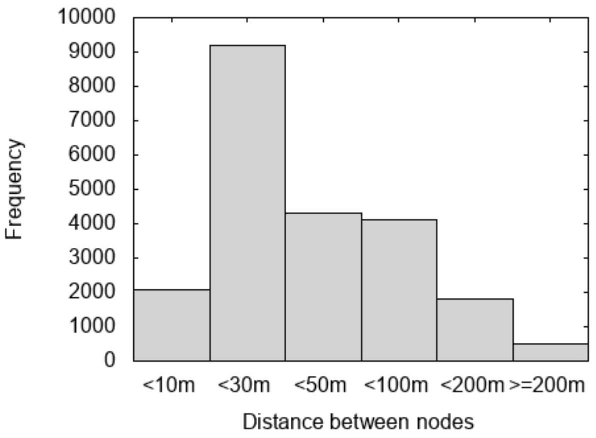
traffic congestion

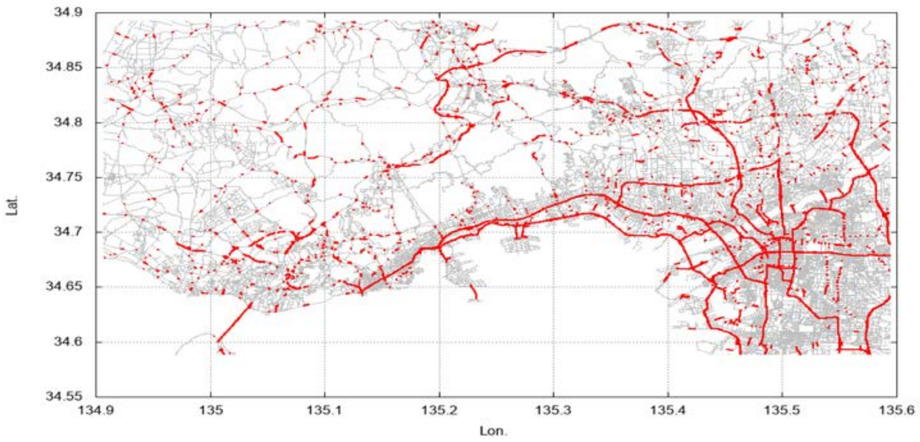
NANKAI TROUGH EARTHQUAKE

◆ Earthquake Scenario	Cabinet Office Estimation (basic, east-side, land-side) Osaka area synthesized Other area use of predicted seismic intensity
◆ Ground	2-layer model (bedrock + surface layer) non-linear RO
◆ Residential Building	number: 1,266,706 linear MDOF
◆ Road Network	
● Kansai	link: 495,595
● Vehicle	number: standard size 5,000,000 + large size 250,000 (558,572 packets, 1 packet = standard size 10 + large size 5) time: 4 – 10
● Demand	local government estimation (use of Kumamoto Earthquake data)

AUTOMATED MODEL CONSTRUCTION

Urban Area Information about Bridge Attributes
number of Links: 21,968





data resource

<u>Structures</u>
- residential building maps
- GIS of urban
- CAD data
- design guidelines
- design regulations, etc.

<u>Road</u>
- coordinates/links
- attributes
- specification
- width, etc.

<u>Ground</u>
- elevation
- boring data
- AVS30 etc.

identification of bridge location

↓ road & ground

setting of bridge type
width, span number, pier height, ground conditions, etc.

↓ structures

seismic response model (3D frame model)
nodes, elements, cross section properties, materials, connection

↓

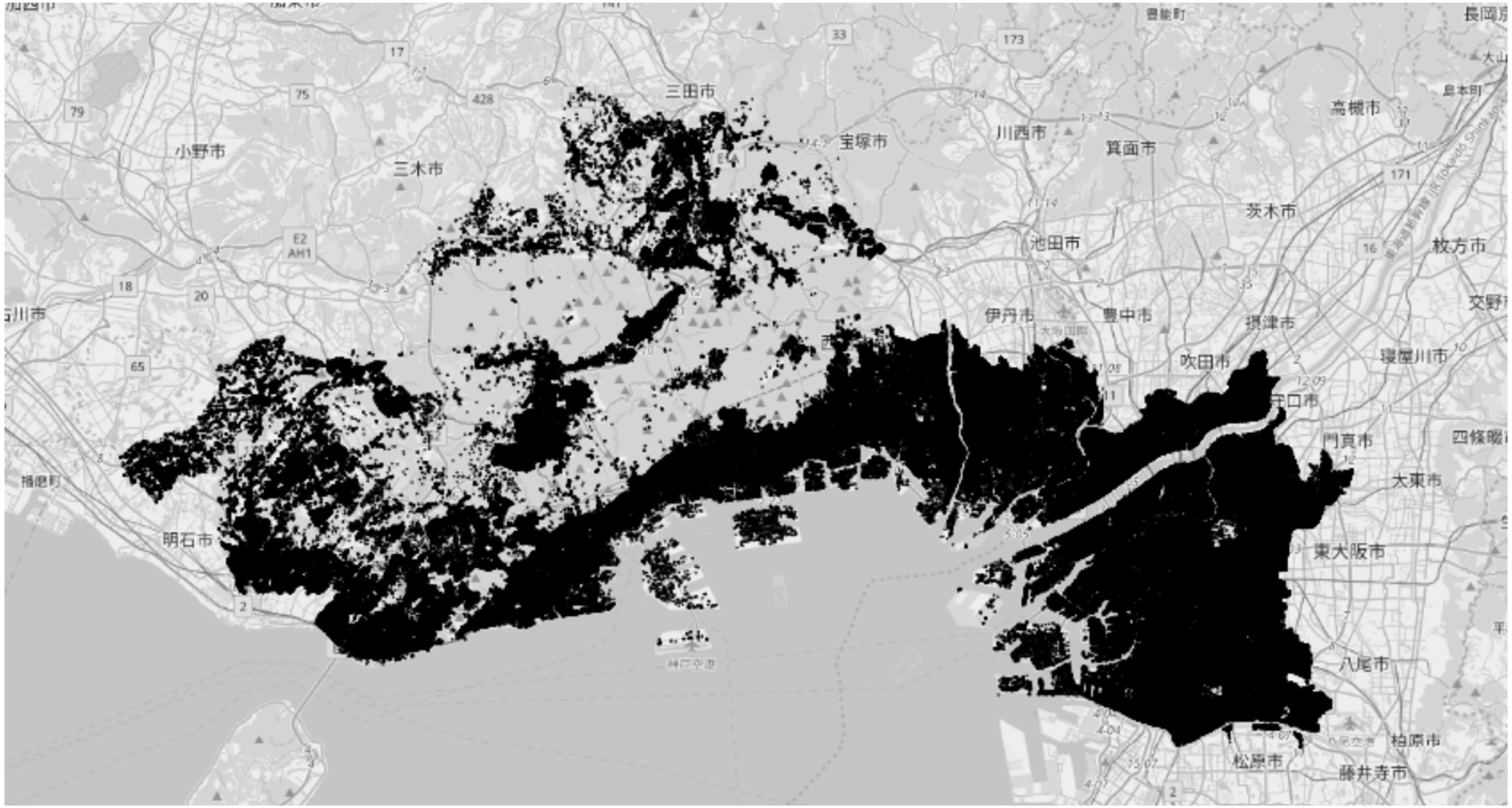
analysis method

BUILDING MODEL

1,266,706 Residential Buildings

wood	87
S	10
RC	3
SRC	less than 0.1

2 story	88
3 – 5 story	11
others	less than 1

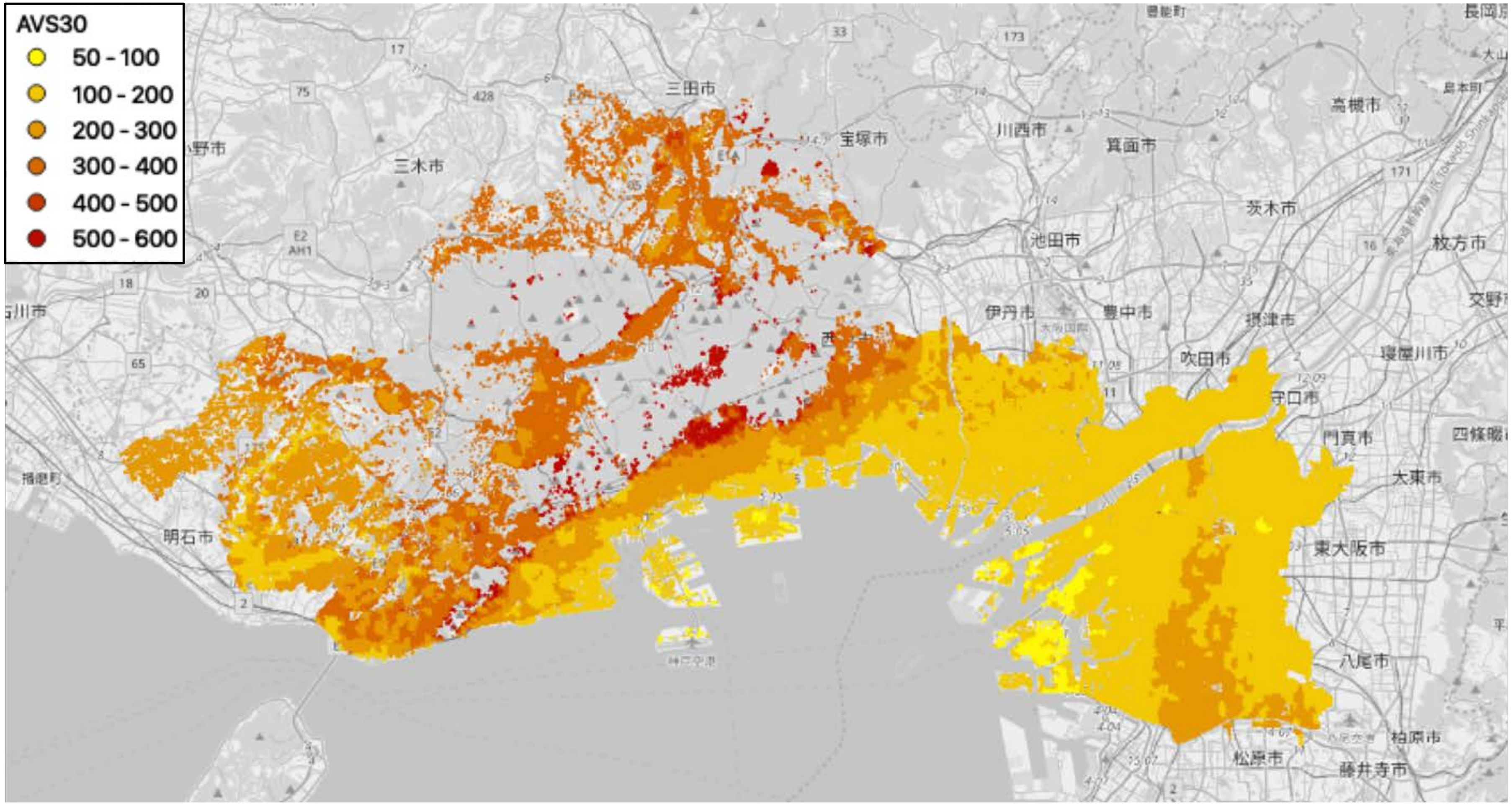


GROUND MODEL

Ground Data (AVS30)

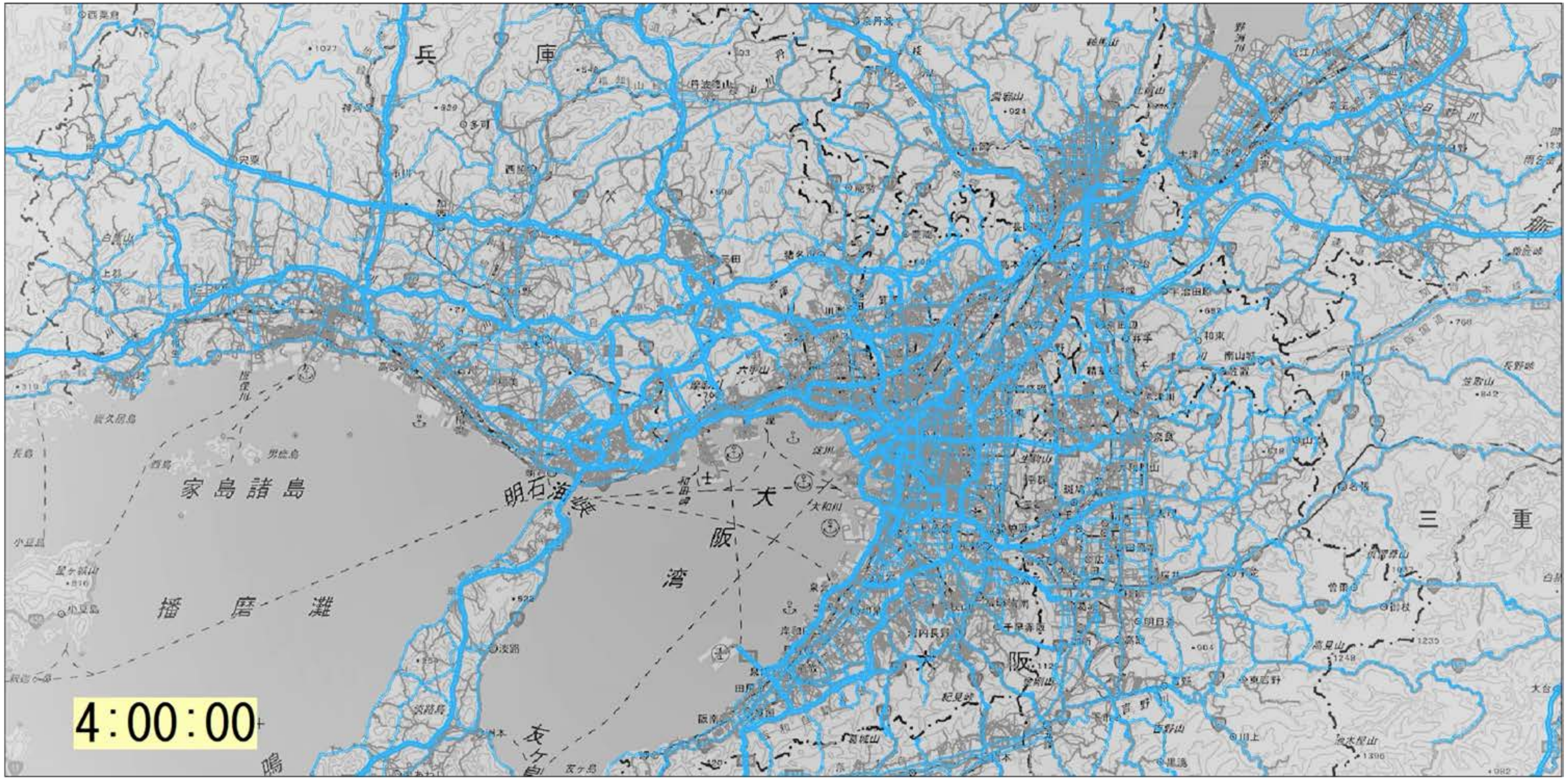
road: OpenStreetMap
AVS30: J-SHIS

	thickness [m]	Vs [m/s]	γt
surface layer	30	AVS30	10.
bedrock	50	700	10.



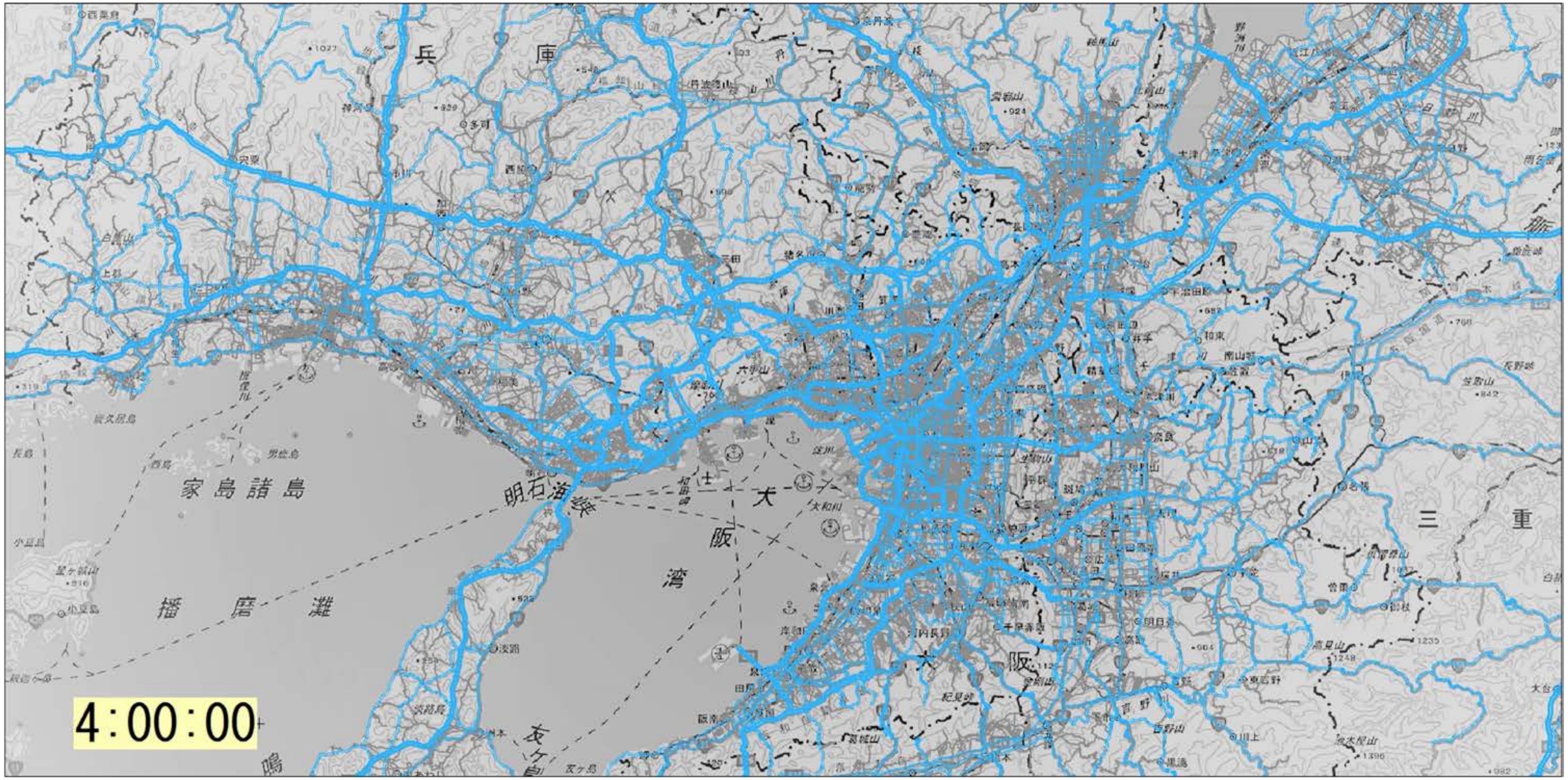
TRAFFIC FLOW SIMULATION

ordinary

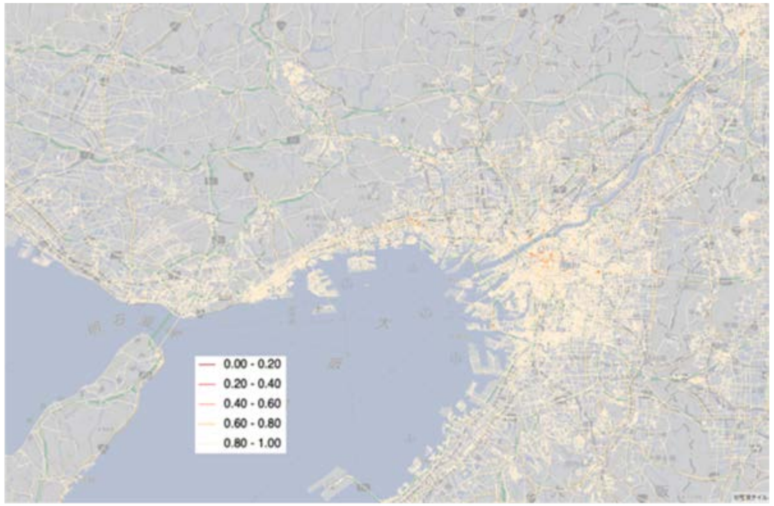


TRAFFIC FLOW SIMULATION

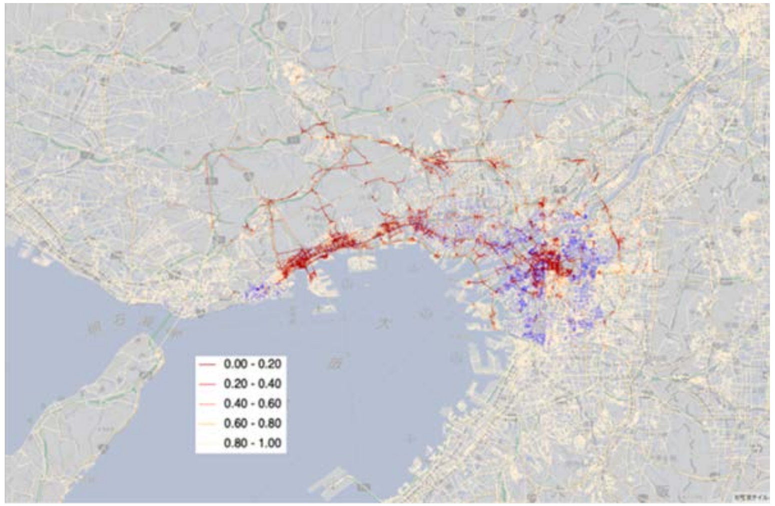
post-earthquake (basic scenario)



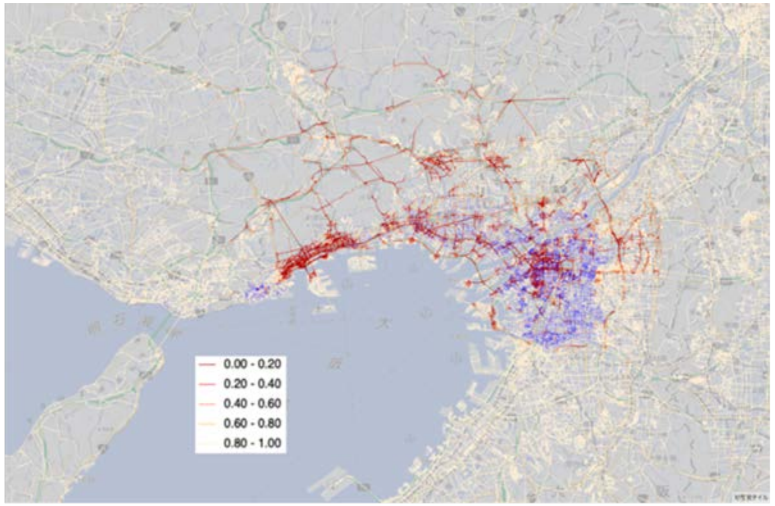
TRAFFIC FLOW SIMULATION: SUMMARY



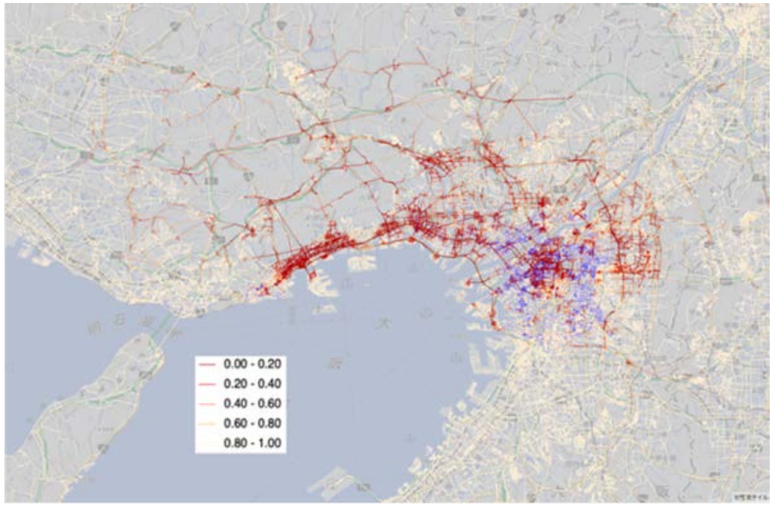
ordinary



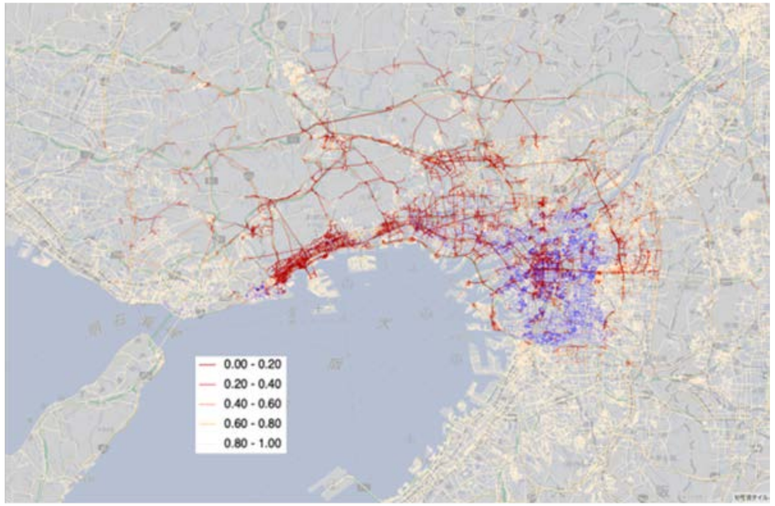
east



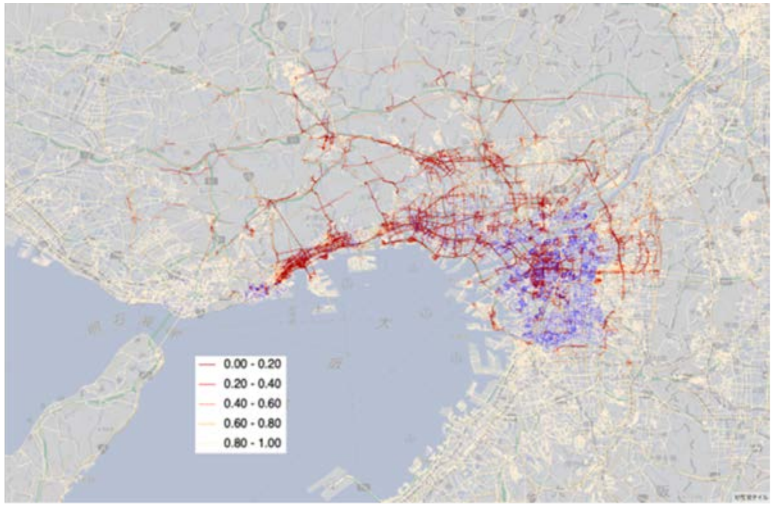
basic



land



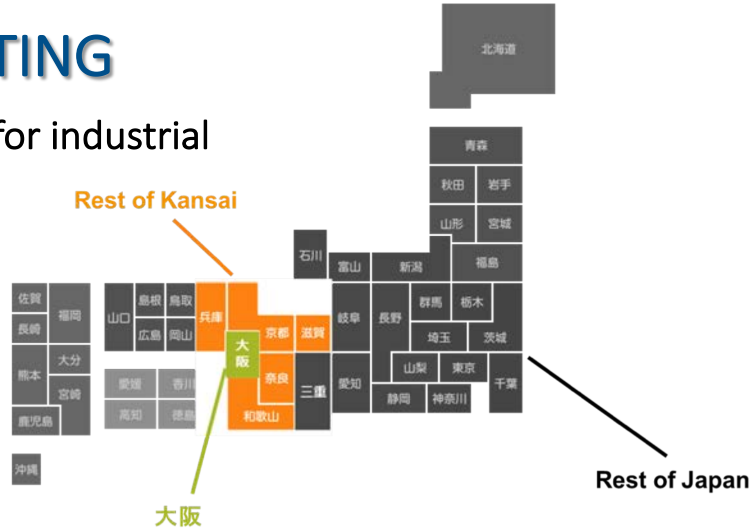
land x1.5



land x1.3 (G)

ECONOMIC SIMULATION: PROBLEM SETTING

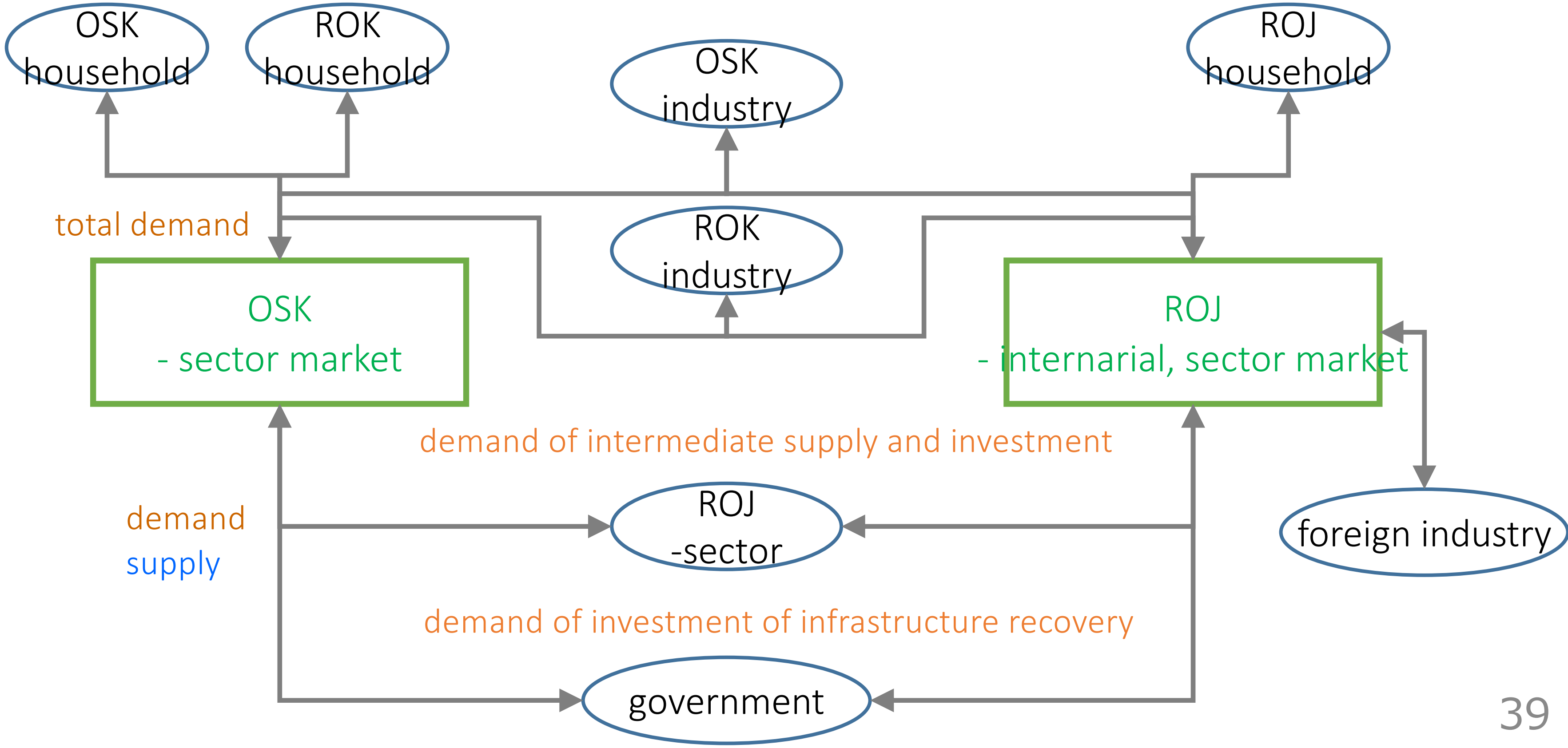
dynamic problem for industrial activities



3 REGIONS

1.	OSK (Osaka)	Osaka
2.	ROK (Rest of Kansai)	Kyoto, Hyogo, Shiga, Nara, Wakayama
3.	ROJ (Rest of Japan)	

36 INDUSTRIAL SECTORS (4320 ENTERPRISES)



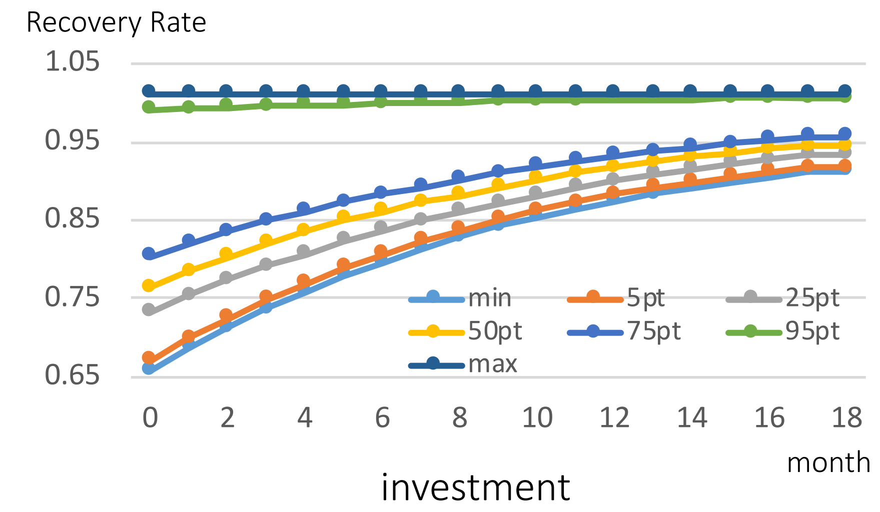
Data source

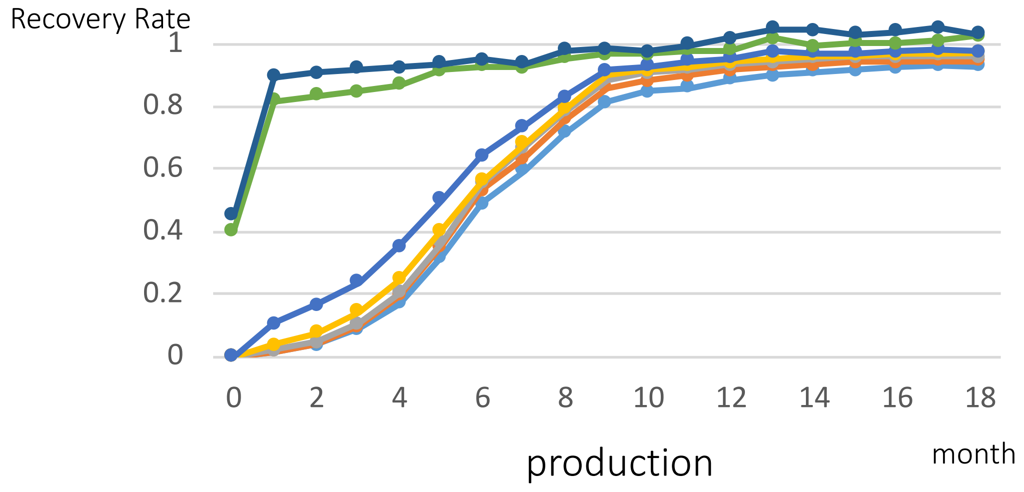
- synthesized data of residential building damage
- Cabinet Office, Report of Stock Damage at Great East Japan Earthquake
- fragility and recovery curve
- Enterprise data

Major Uncertainties

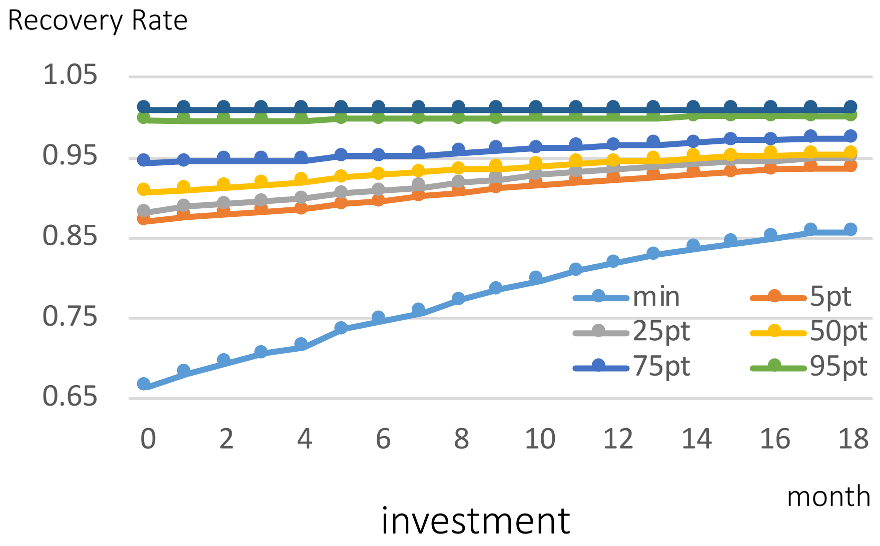
- Combination of lifeline and supply chain restart

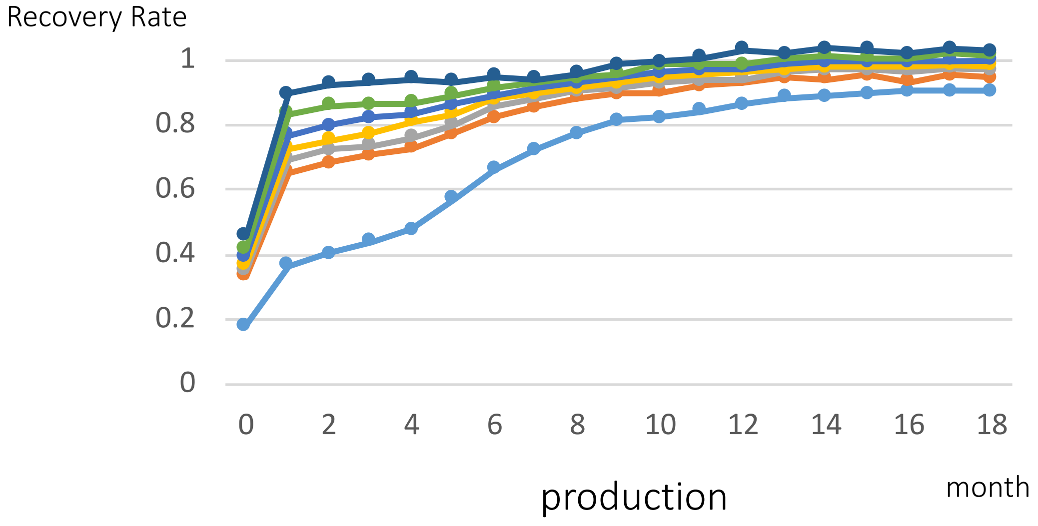
ECONOMIC SIMULATION: RECOVERY OF INDUSTRY





OSK, 36 sectors: top 5 % industrial sector makes fast recovery in 2 months, while others gradually recovers in 8 months





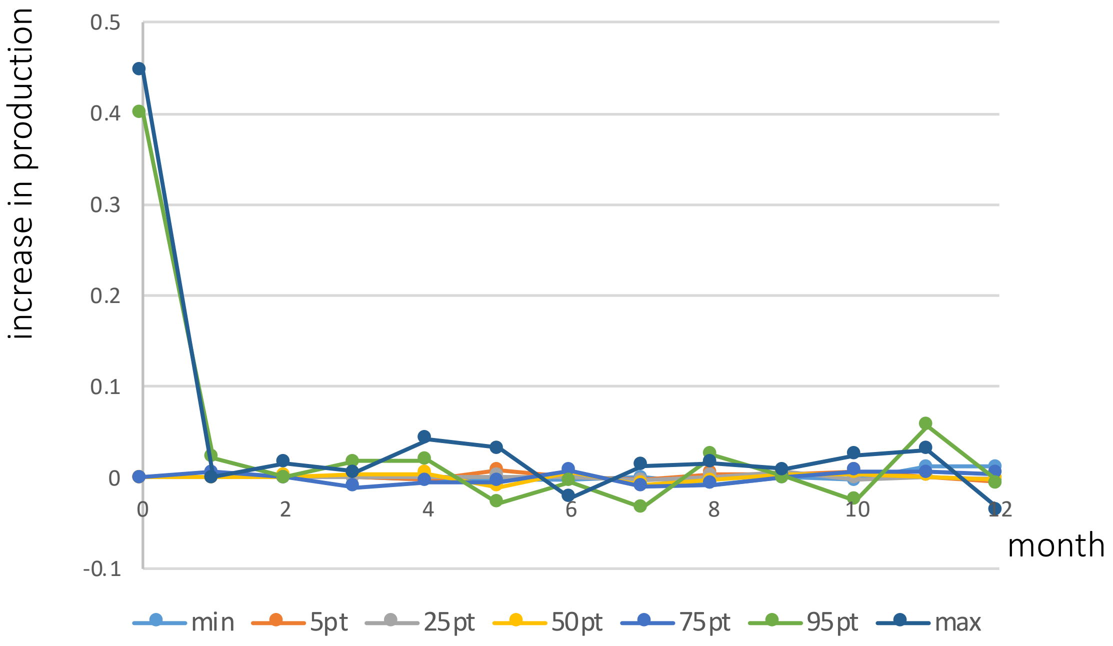
ROK, 36 sectors

ECONOMIC SIMULATION: EFFECTS OF RECOVERY PLAN ON INDUSTRY

Infrastructure Recovery Plan and Evaluation

	standard plan 12 months	Speed-up		
		3 months	6 months	9 months
plan evaluation function: W_kihon10	-1.523 10^8	-1.446 10^8	-1.432 10^8	-1.443 10^8

standard plan of 12 quoter recovery → need for speed-up of 6 quarters



(pt: percentile)

- Little difference induced by speed-up of recovery plan for this problem setting
- Significant effects observed in early stage of recovery only for industry sectors less damaged → additional recovery plan needed to minimize difference in damage and recovery

Industrial Sector Recovery: Increase in production if speed-up of 6 months is adopted

CONCLUDING REMARKS

- FUGAKU Project for Integrated Earthquake Simulation

- Goal of Earthquake Simulation: Required Resolution
  - Structural response: 1 ~ 10 Hz, time resolution 0.1 sec
  - S-wave velocity of surface ground: 100 m/s, spatial resolution 10 m
  - Damage of structural members and connecting parts: spatial resolution 10 m
  - Much coarser resolution of social science simulation

- Uncertainty in Earthquake Disaster Estimation: Required Number of Scenarios
  - Earthquake scenarios: scale, process, number, etc.
  - Urban area models: configurations, materials, etc.
  - Social activity models: traffic, economic, attribute data, initial conditions

- Earthquake Disaster Mitigation and Strengthening of Resilience
  - Need for sufficiently high resolution
  - Need for worst scenarios for pre-disaster preparedness and post-disaster action