

断層問題に対するHPCの応用

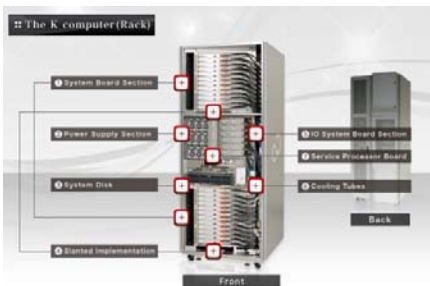
HPC: High Performance Computing

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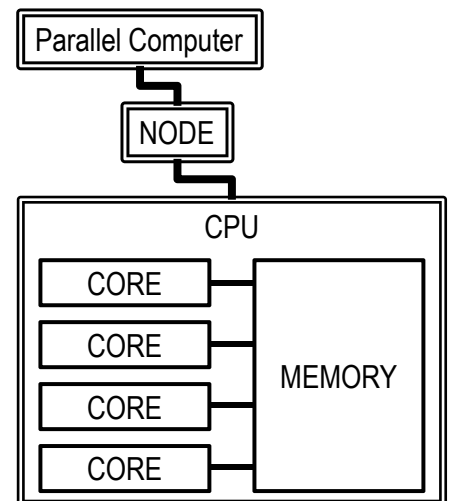
理化学研究所計算科学研究機構

HIGH PERFORMANCE COMPUTING



Parallel Computing

- Fast computation using many computation units
- Reduction of communication among computing units



Node	88,128	864 rack × 102
CPU	88,128	88,128 node × 1
core	705,024	88,128 CPU × 8

HPCの工学利用

◆ 大型並列計算機の計算性能

- 大自由度モデル 100億自由度
- 高速 10分/ステップ

◆ 課題

- ハードウェアの進歩に追従する持続可能なソフトウェアの維持・開発

◆ FEMを使う構造解析

- 金属材料を使う1D/2D構造部材から構成される構造物の解析には, HPCを利用するFEMは不要
- 鉄筋コンクリート・地盤材料から構成される, 比較的「バルク」な構造物の解析には, HPCを利用するFEMが必須

CFDと構造解析

◆ CFD (Computational Fluid Dynamics)

- 実験の代替となるようHPCを利用
- 乱流解析・衝撃解析
- 解析結果の品質保証



「ものづくり」のメインテーマ

◆ 構造解析

- 金属材料・棒板材・準静的のため, HPCは不要.
- 建設材料, 3次元, 動的のHPCは必須



汎用FEMパッケージの利用
品質保証ができるレベル?

HPCの断層問題への適用

◆直近の最大地震動の評価

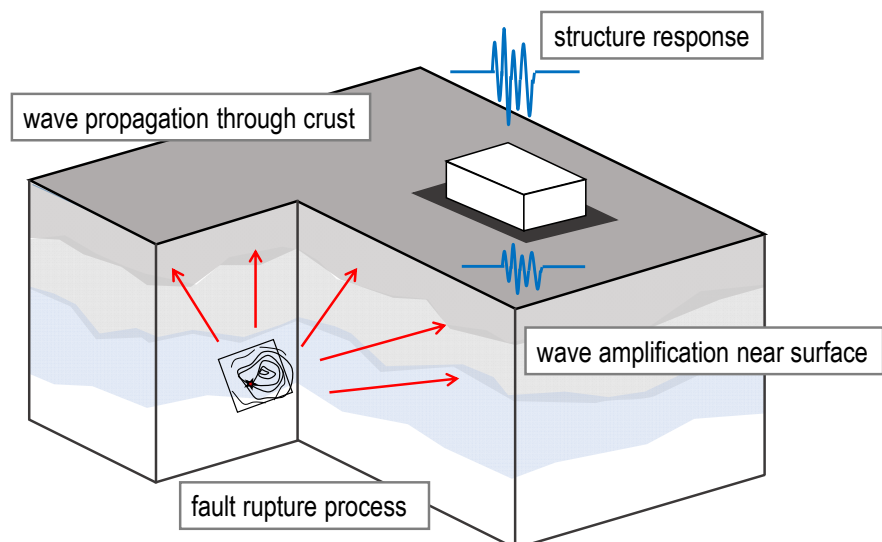
- 動的 未観測の「キラーパルス」の評価
- 非線形 岩盤・地盤材料
- 破壊 既往断層の滑り, 新たな断層の発生・進展

◆断層変位の確率的評価

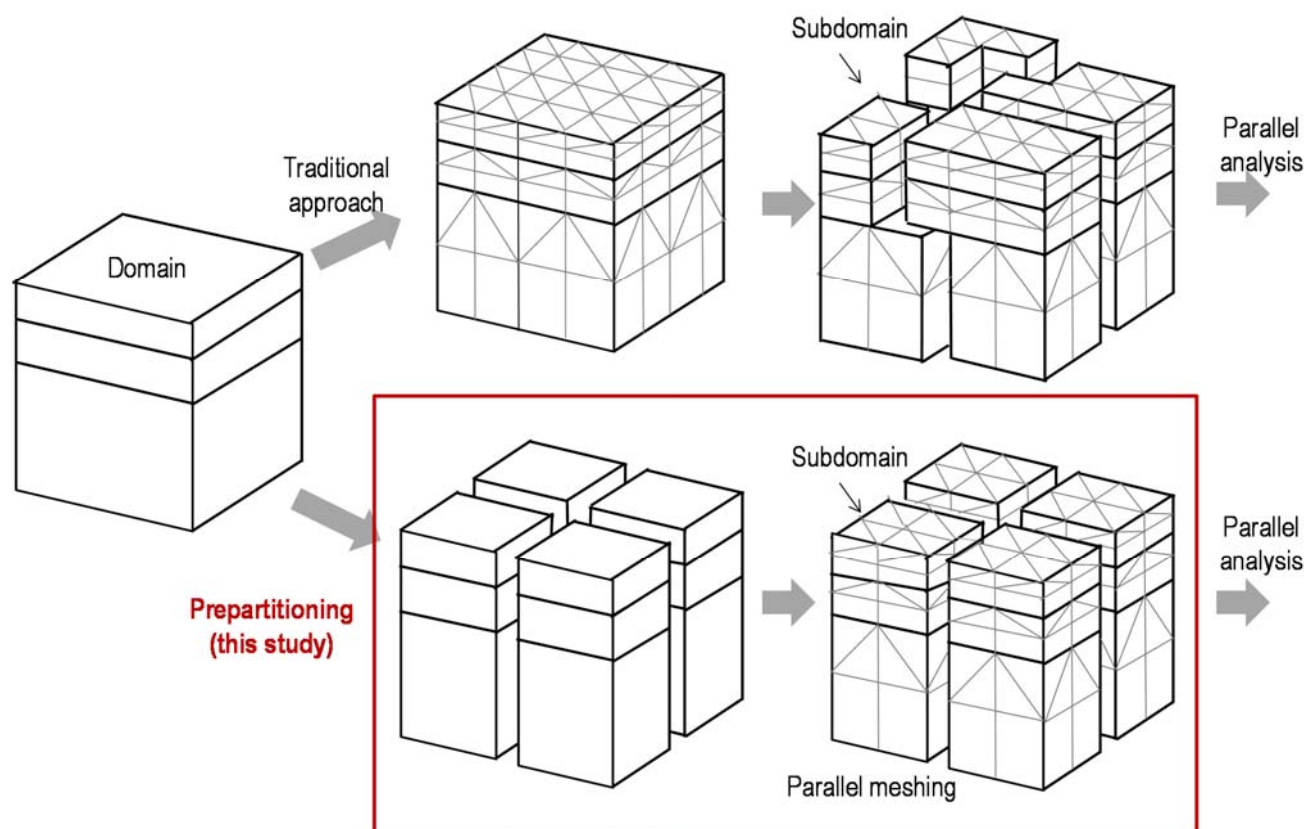
- 発生確率
- 断層の出現位置・出現長さ
- 断層変位量

地殻・地盤・建屋のMMA解析

- 地殻構造
- 地盤構造
- 構造物



並列計算のための領域分割



並列計算のための数値計算

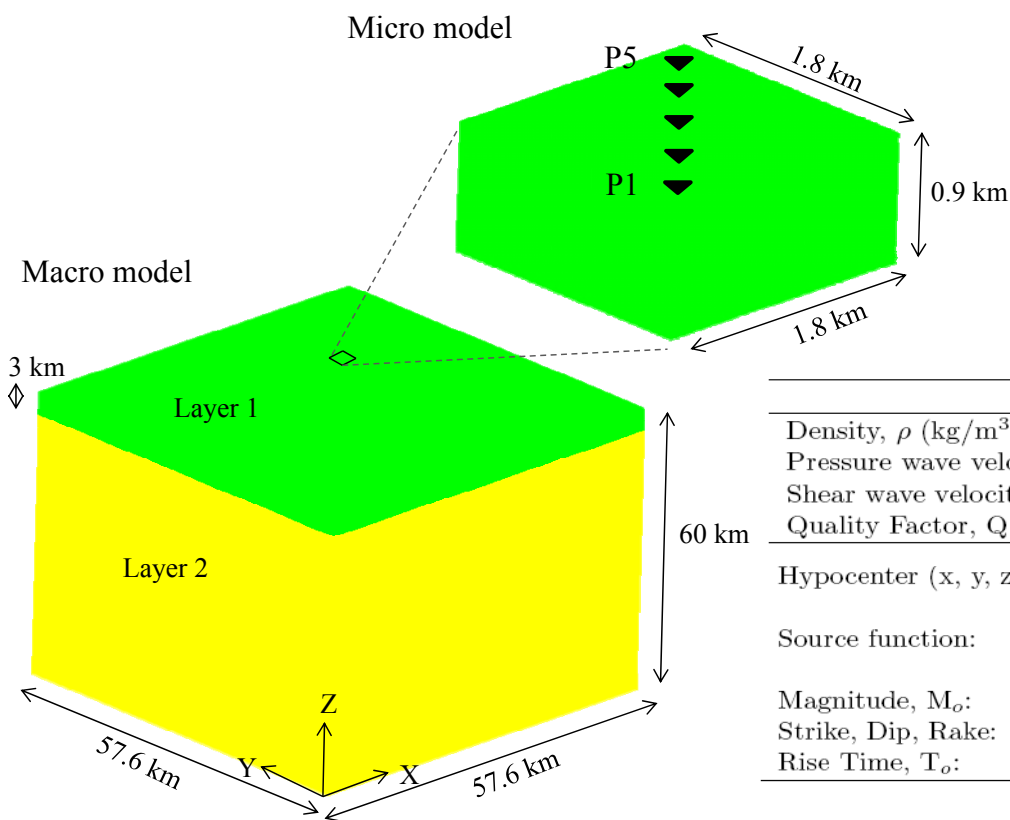
◆ 高速ソルバ: 前処理付CG法

- 幾何マルチグリッド (Geometric multi-grid)
- 精度混合演算 (Mixed precision arithmetic)

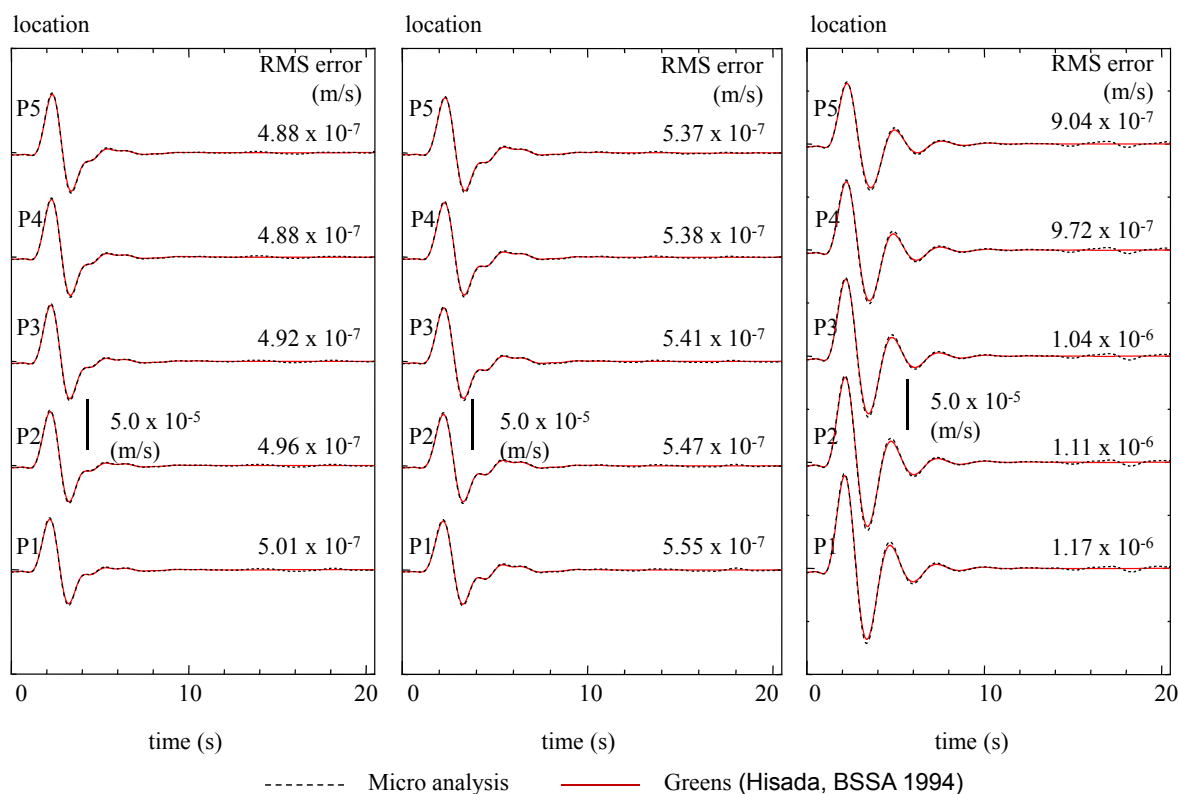
◆ 要素技術

- メモリアクセスの高速化のためのEBE (Element-by-Element) 剛性マトリクス
- 直交離散化基底を使った集中質量マトリクス
- 高効率I/Oのための圧縮列収納
- 時間積分の高速化のための高次予測子

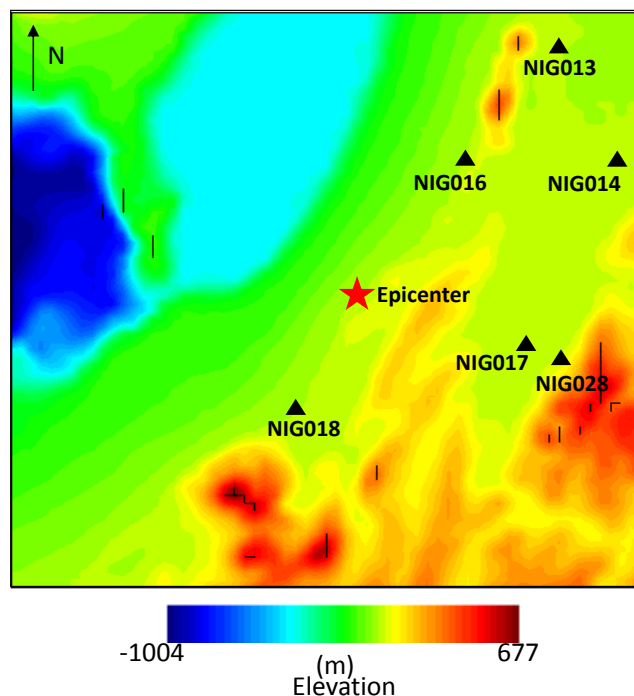
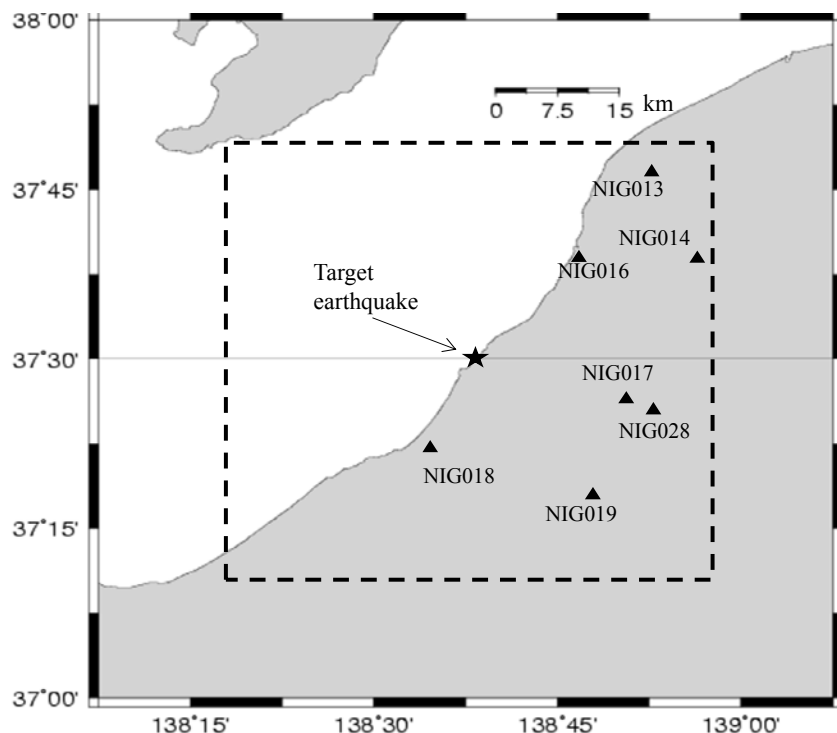
数値検証用モデル



解析解との比較

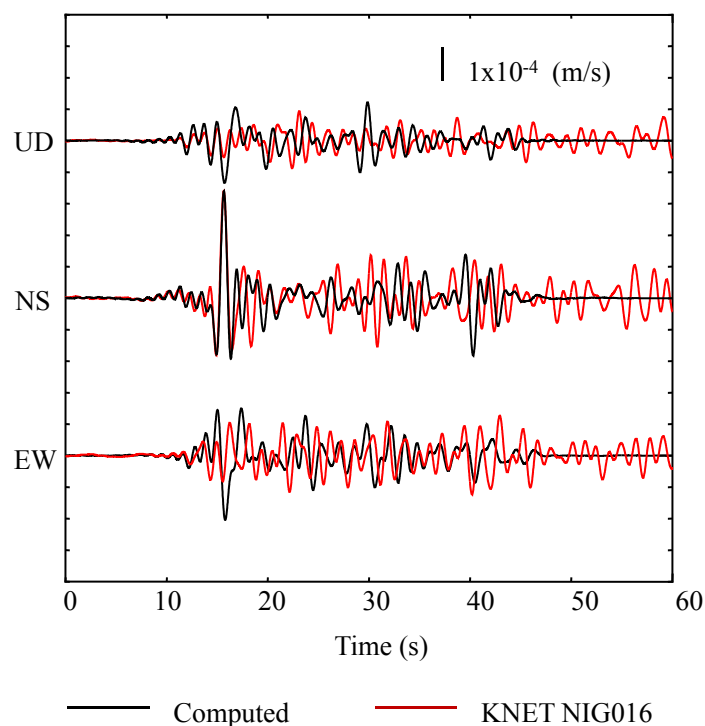
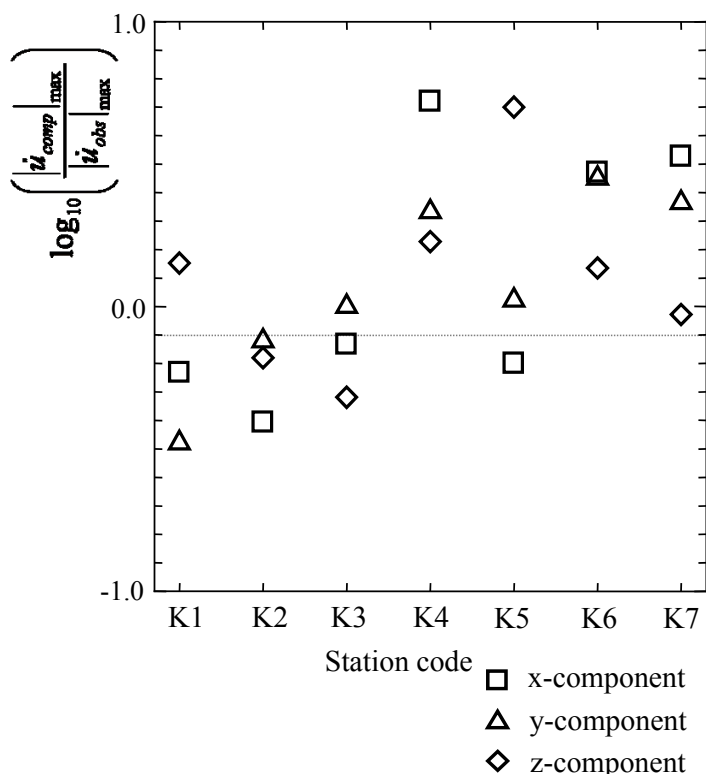


観測された小地震の再現



2007/07/16 M_w 4.4

観測された小地震の再現



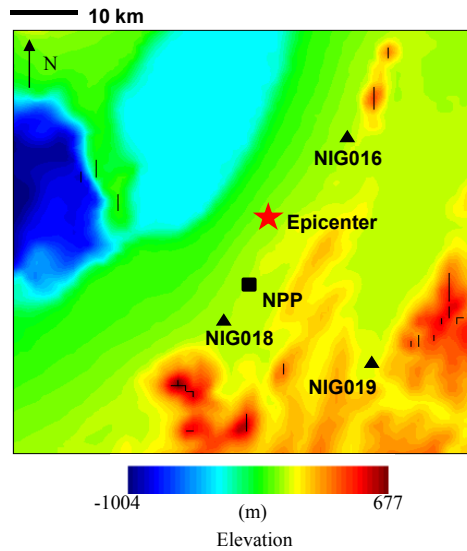
中越沖地震

断層すべり: *を使用

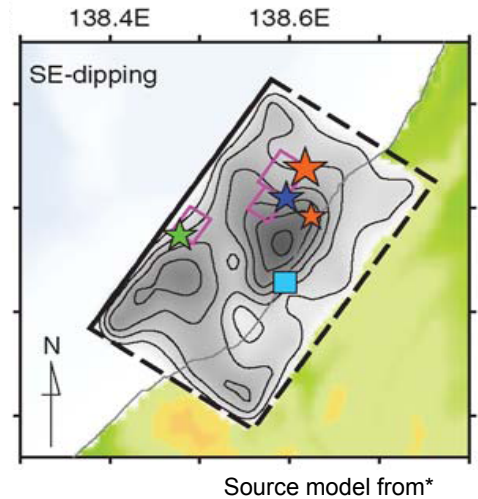
Target domain



Locations

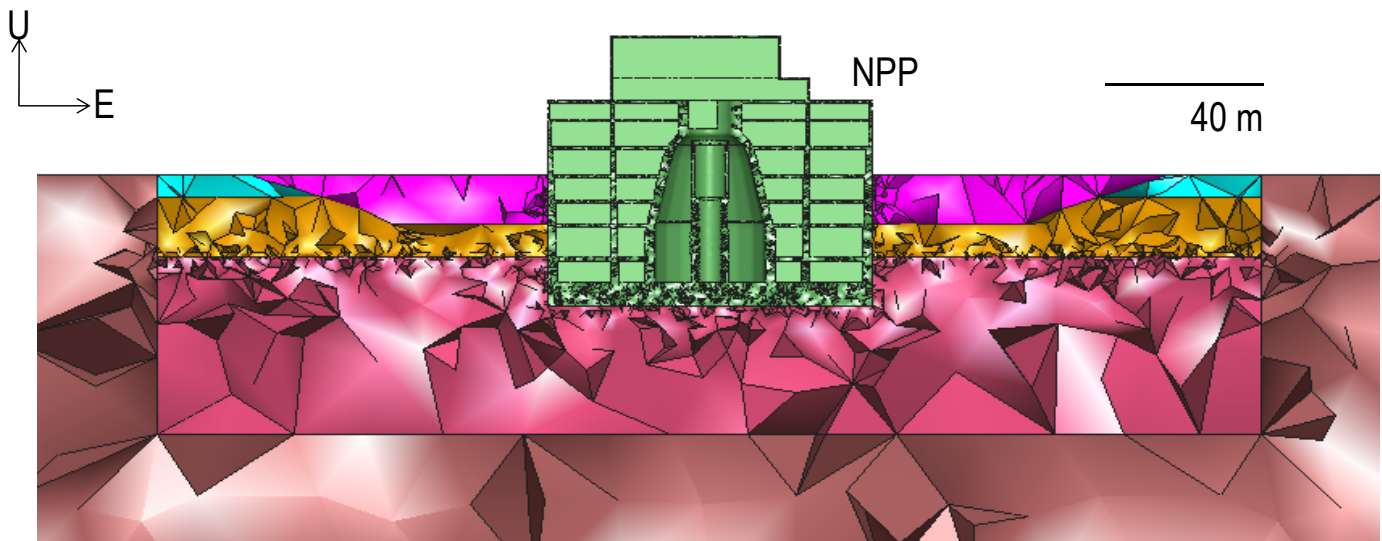


Fault-slip data



* H. Miyake, K. Koketsu, K. Hikima, M. Shinohara, T. Kanazawa, "Source fault of the 2007 Chuetsu-oki, Japan, Earthquake," Bull. Seismol. Soc. Am., 100, [1], 384-391 (2010).

ミクロ解析モデル

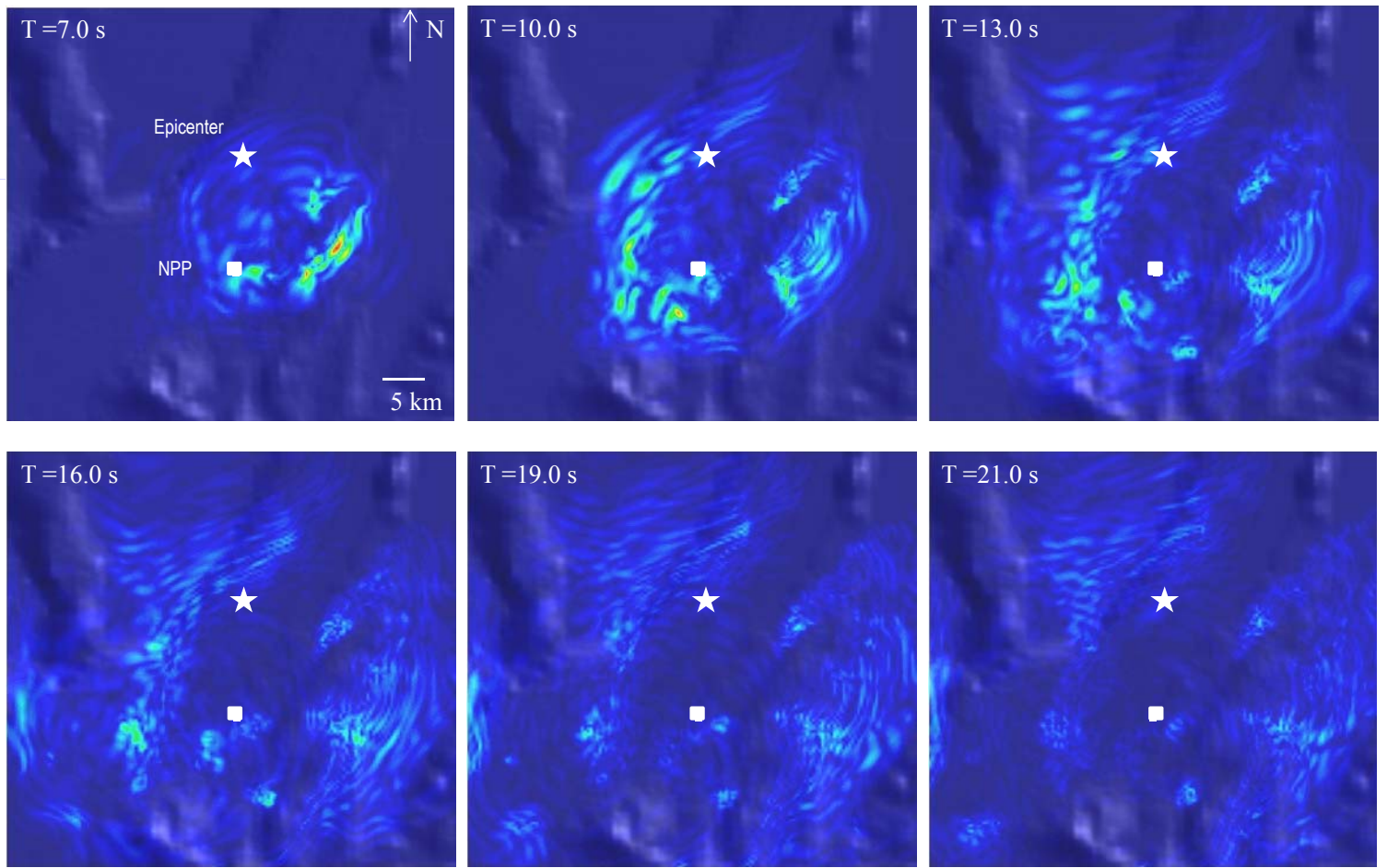


NPP:

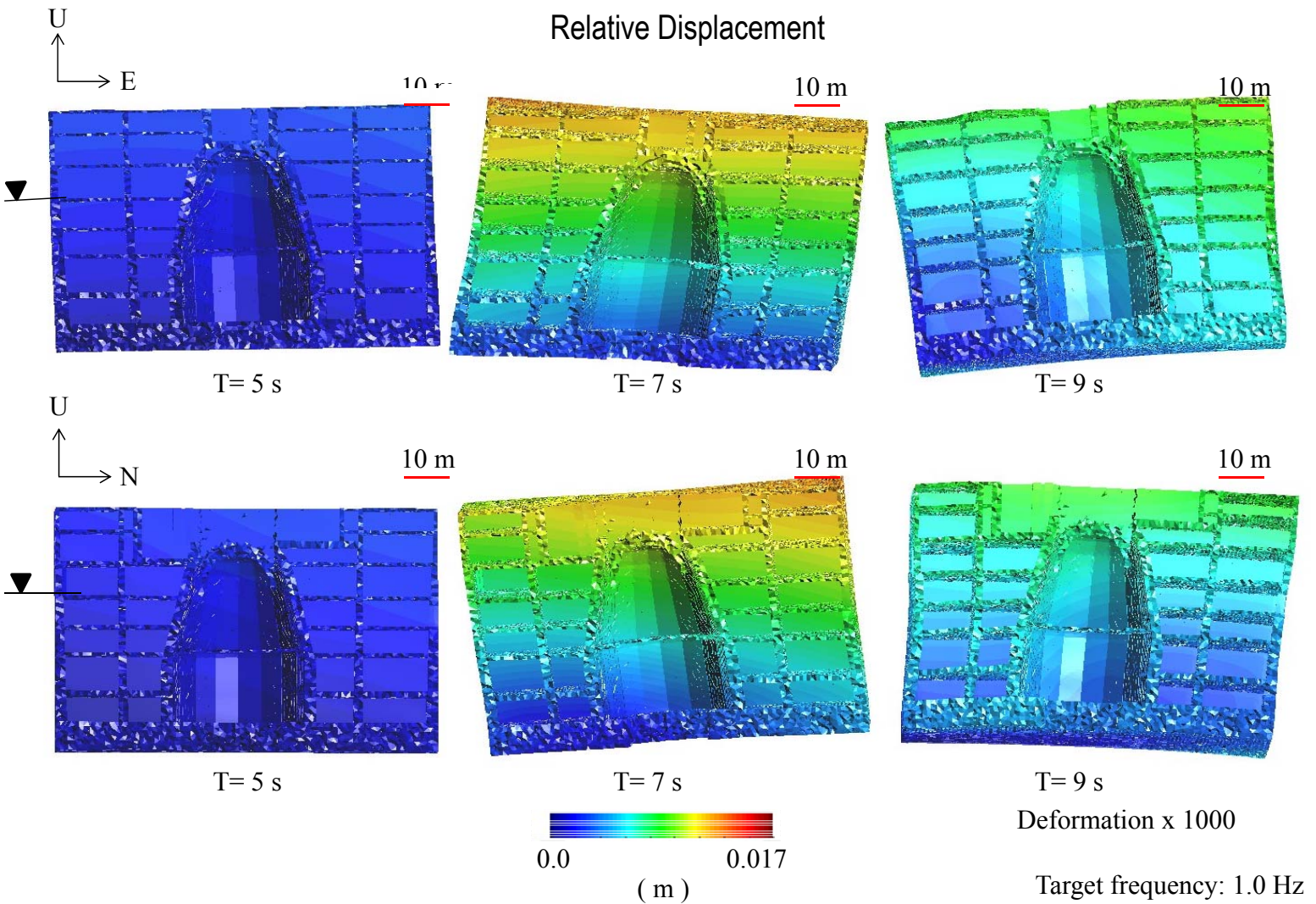
Wall thickness: 0.5~2.5 m

Floor thickness: 0.5~1.0 m

Base mat thickness: 6.5 m

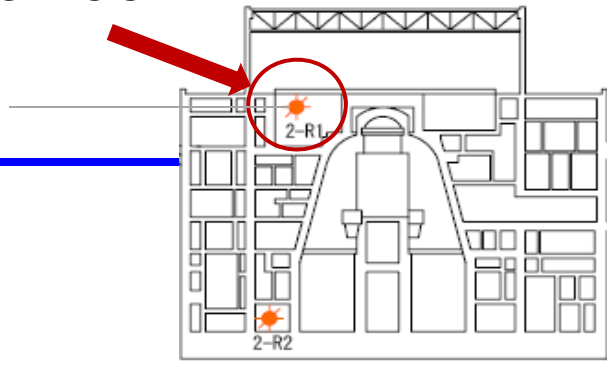


Large velocity amplitudes near the NPP
T = 7 to 21 seconds

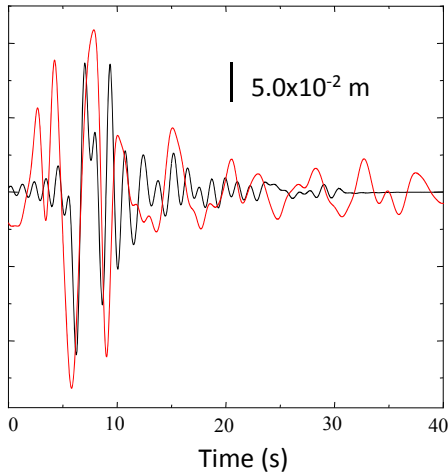


Elev. 15.5m

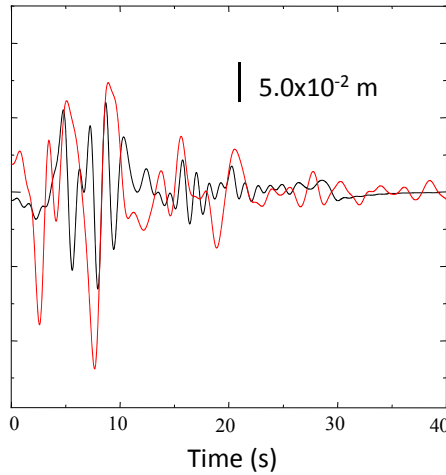
NPPの変位 (Bldg. 2)



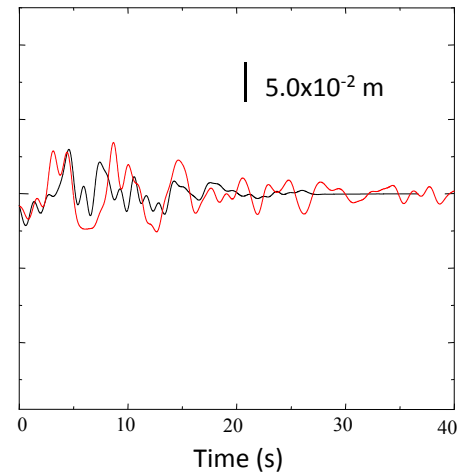
EW component



NS component



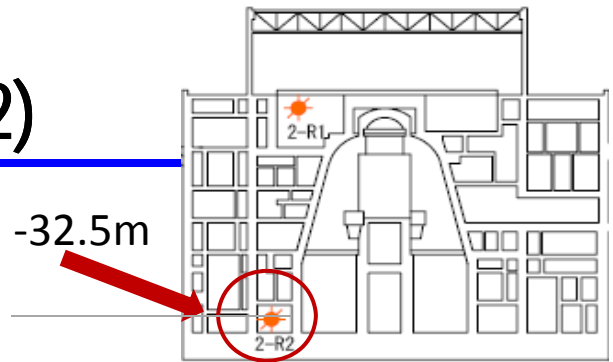
UD component



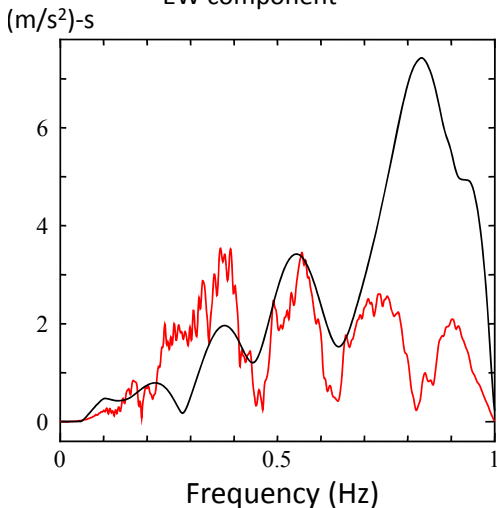
— Observed — Computed

NPPの応答加速度 (Bldg. 2)

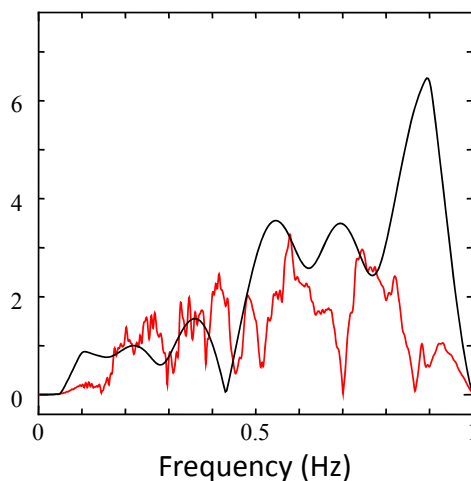
Elev. -32.5m



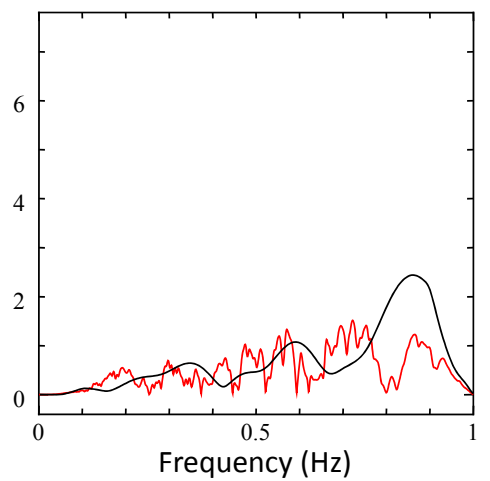
EW component



NS component



UD component



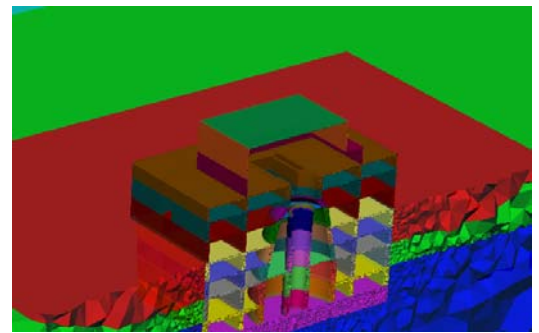
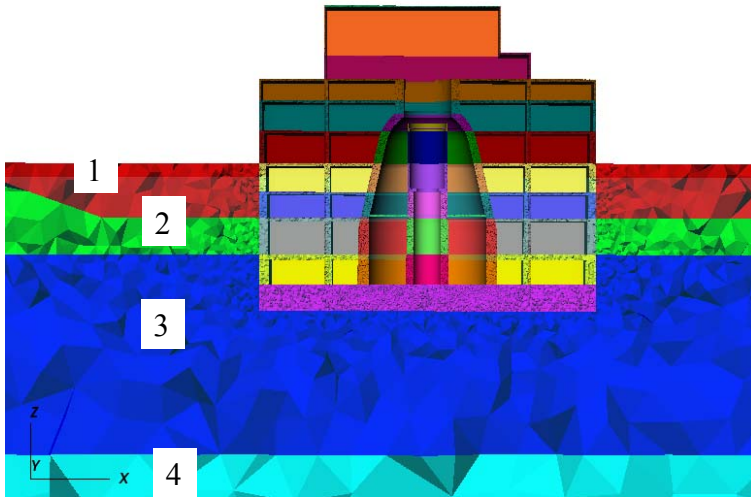
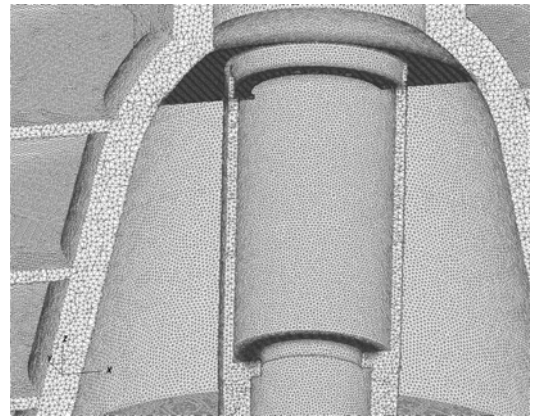
— Observed — Computed

domain dimension 540 x 540 x 250 m
 number of nodes 33,613,809
 number of elements 22,443,096

NPP MODEL



MatID	Vp (m/s)	Vs (m/s)	ρ (kg/m ³)	h (%)
1	1529.7	300	1825	5
2	1529.7	300	2000	5
3	1580.7	310	1780	5
4	1625.1	490	1700	3
5	1710.8	560	1750	3

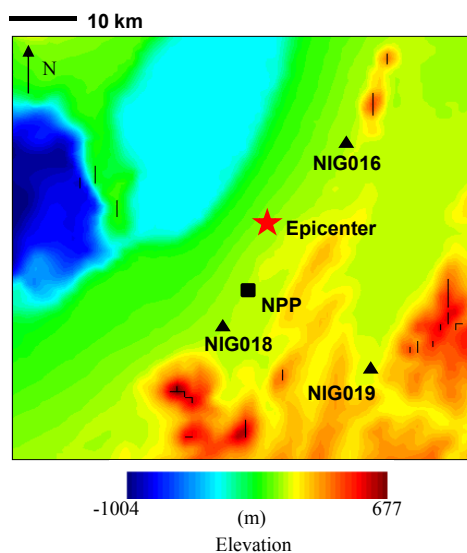


2007 CHUUETSU OKI EARTHQUAKE

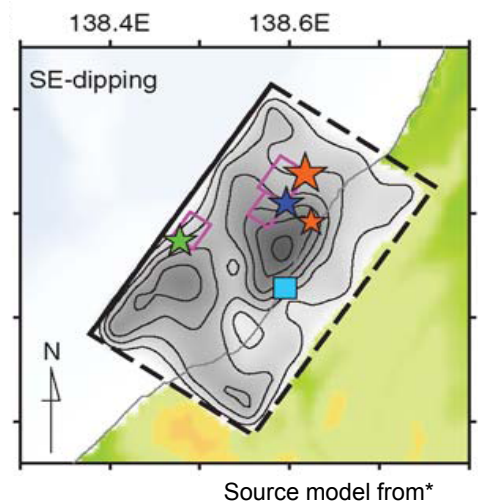
Target domain



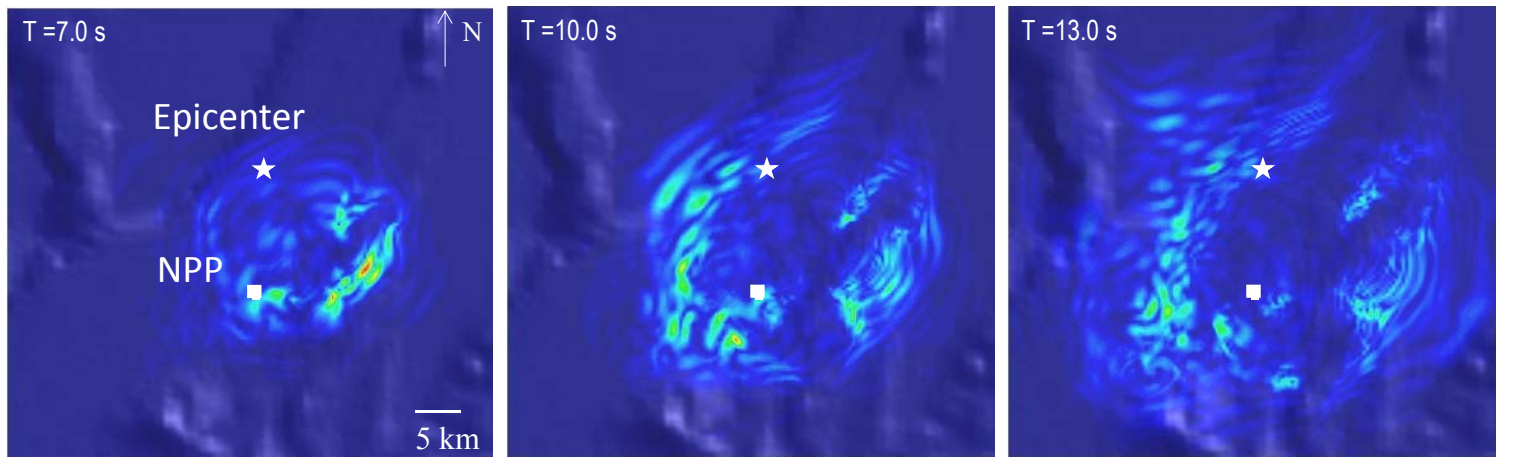
Locations



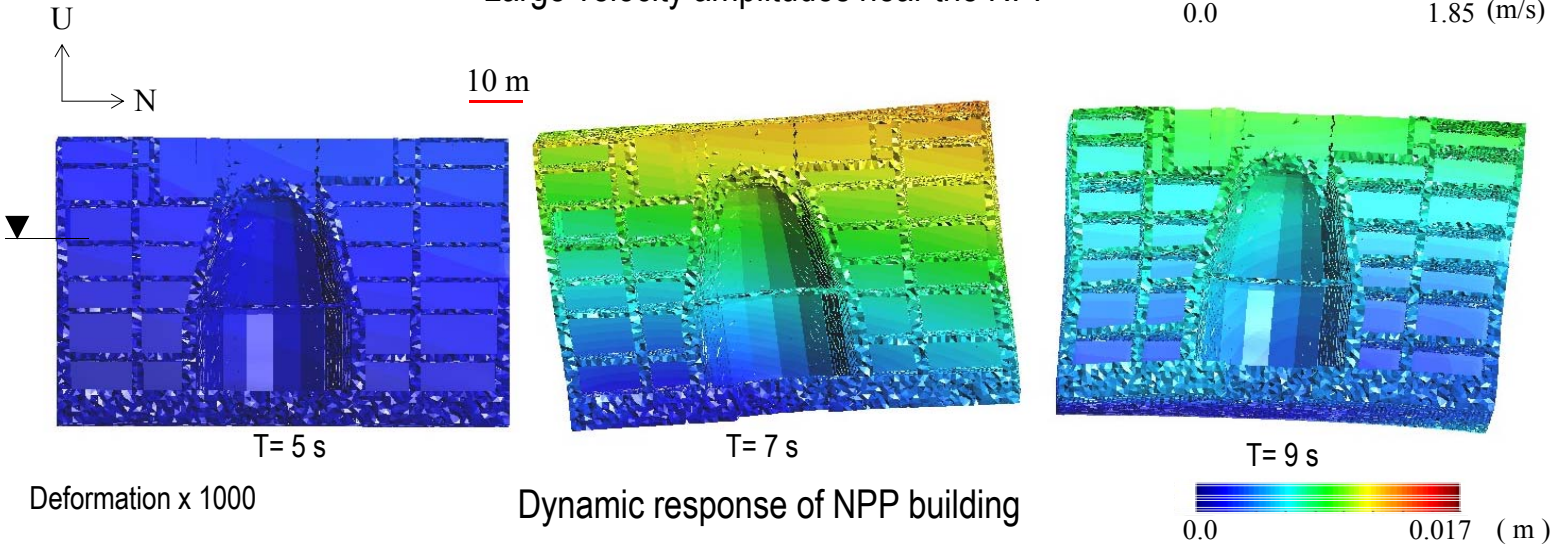
Fault-slip data



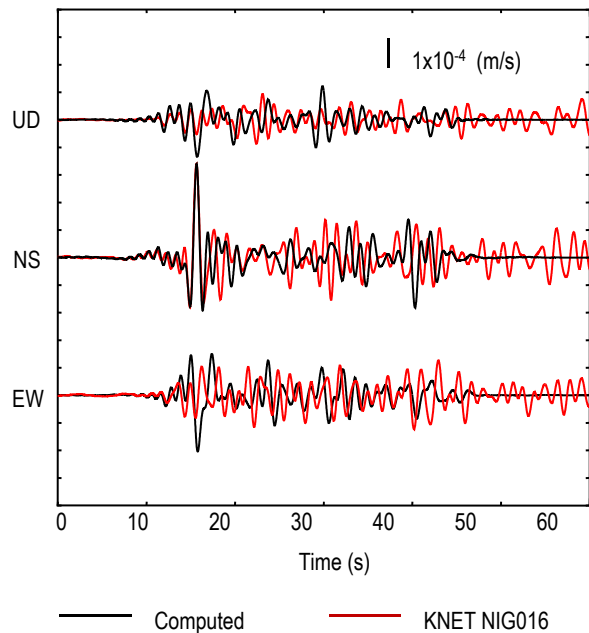
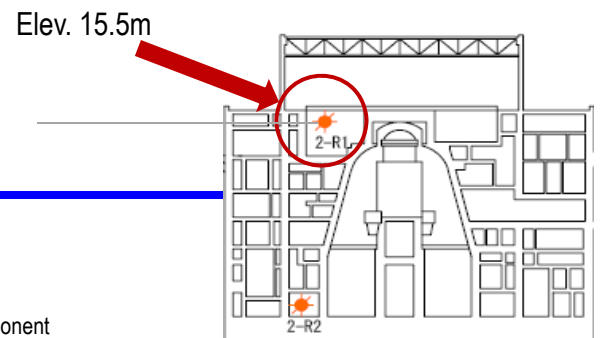
* H. Miyake, K. Koketsu, K. Hikima, M. Shinohara, T. Kanazawa, "Source fault of the 2007 Chuetsu-oki, Japan, Earthquake," Bull. Seismol. Soc. Am., 100, [1], 384-391 (2010).



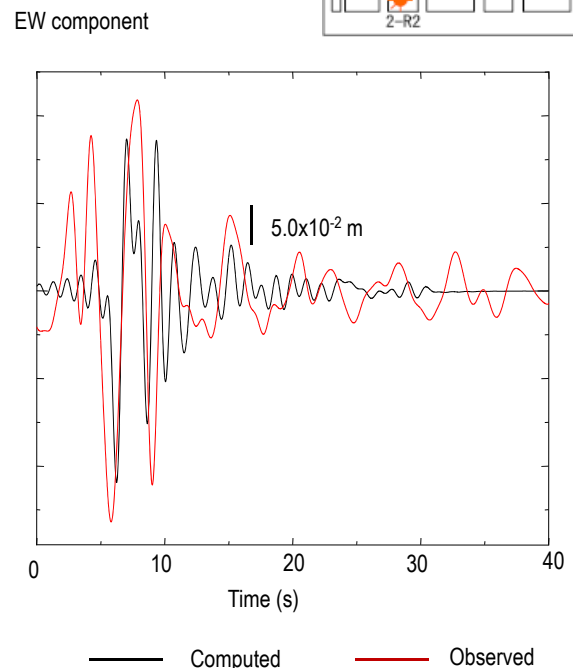
Large velocity amplitudes near the NPP



RESULTS



Ground motion at observation site



Seismic response of NPP building

NEW STAGE OF HPC APPLICATION

◆ Capability Computing for Accuracy

- A mass-spring system solution is an approximation of an HPC FEM solution.
- The HPC FEM solution provides more accurate estimation, even though it needs large scale numerical computation.

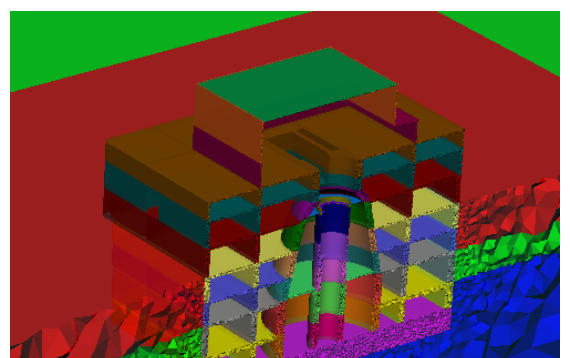
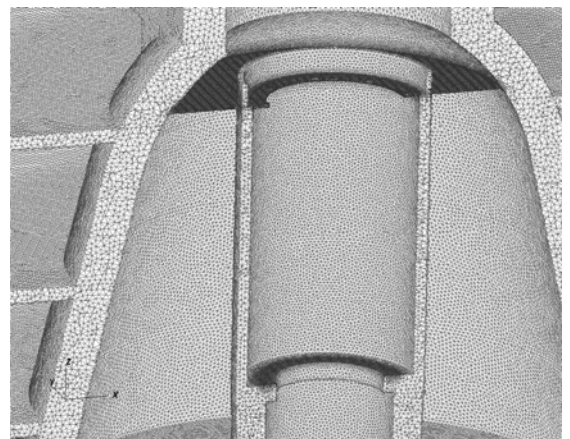
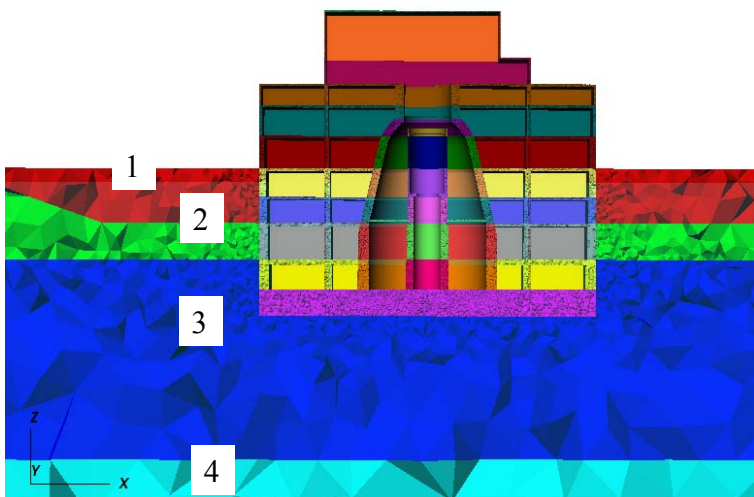
◆ Capacity Computing for Uncertainty

- Numerous models generated for one target are analyzed to account for effects of uncertainty on response.
- Uncertainty probability is converted to response probability via HPC computation.

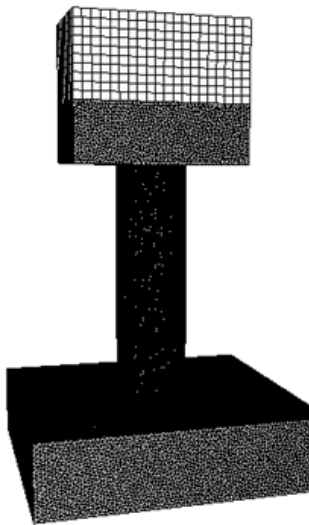
IMPROVED MODEL

domain dimension 540 x 540 x 250 m
number of nodes 33,613,809
number of elements 22,443,096

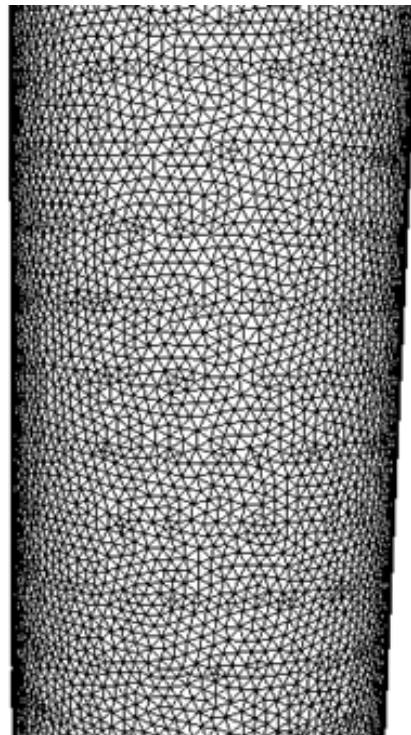
MatID	Vp (m/s)	Vs (m/s)	ρ (kg/m ³)	h (%)
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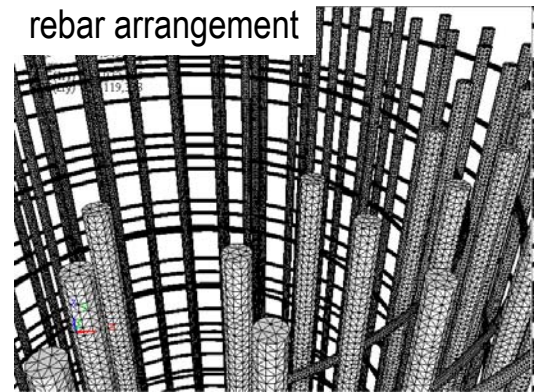
FUTURE MODEL: RC PIER



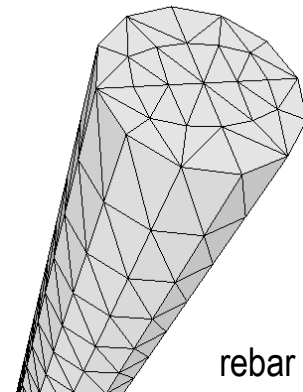
whole view



column: concrete



rebar arrangement



rebar

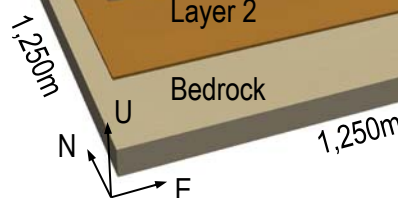
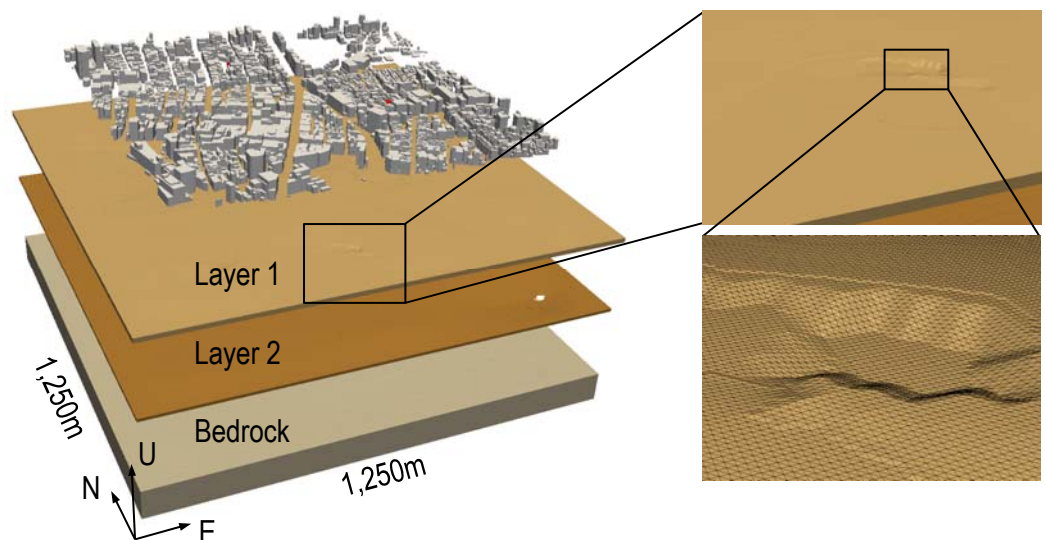
FUTURE MODEL: GROUND



- domain of 1,250 x 1,250 m (3 layers)
- 15 Hz: minimum element dimension 1.0 m
- numerical convergence in 5 ~ 15 Hz

	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	∞

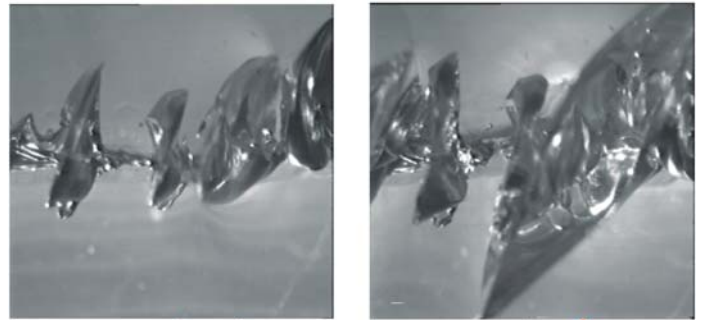
DOF	1,022,630,349
Node	340,876,783
Element	252,737,051



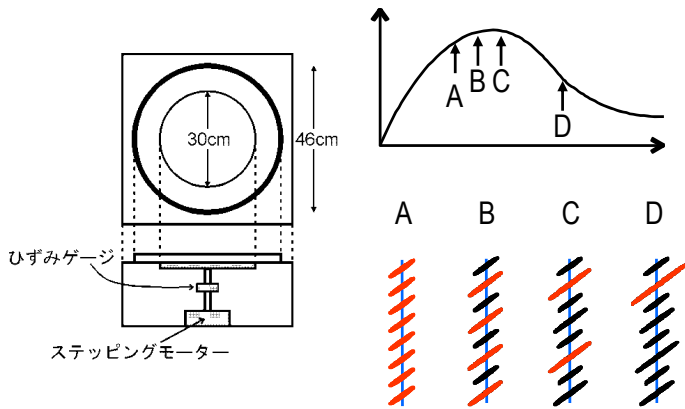
活断層の物理

自然現象としての断層形成の解明

- 破壊現象
量子力学では未だ扱えない？
- 分岐現象
予測可能か不可能か？



雁行断層の模擬実験：せん断破壊と分岐の繰り返し



Analysis of variability in response that is induced by uncertainty of material property/distribution

STOCHASTIC FEM

$$(c(x, \omega)u_{,i}(x, \omega))_{,i} = 0$$



stochastic variational problem

$$J^\omega(c, u) = \int_{\Omega} \int_B \frac{1}{2} c(x, \omega) u_{,i}(x, \omega) u_{,i}(x, \omega) ds P(d\omega)$$

$$c(x, \omega) = \sum_n c^n \varphi^n(x) \xi^n(\omega)$$

$$u(x, \omega) = \sum_m u^m(x) \Gamma^m(\omega)$$

$$J^\omega = \int_B \frac{1}{2} \sum_{m,m'} c^{mm'}(x) u_{,i}^m(x) u_{,i}^{m'}(x) ds$$

KL expansion:
covariance of c
is decomposed

PC expansion:
Hermit polynomial of

$$c^{mm'}(x) = \sum_n c^n \varphi^n(x) \langle \xi^n \Gamma^m \Gamma^{m'} \rangle$$

$$\langle E \rangle = J^\omega(c, u^e)$$

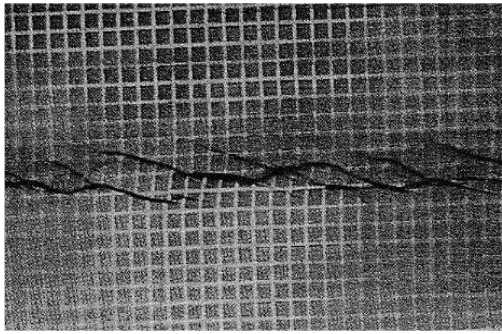
bounding medium
for deterministic u



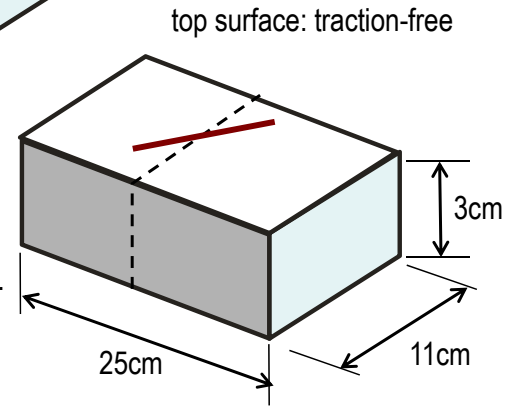
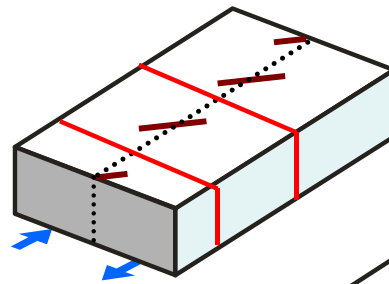
$$\sum_m (c^{mm} u_{,i}^m(x))_{,i} = 0$$

governing equation of PC expansion coefficients

PROBLEM SETTING



Riedel shear bands (by Tani & Ueda)

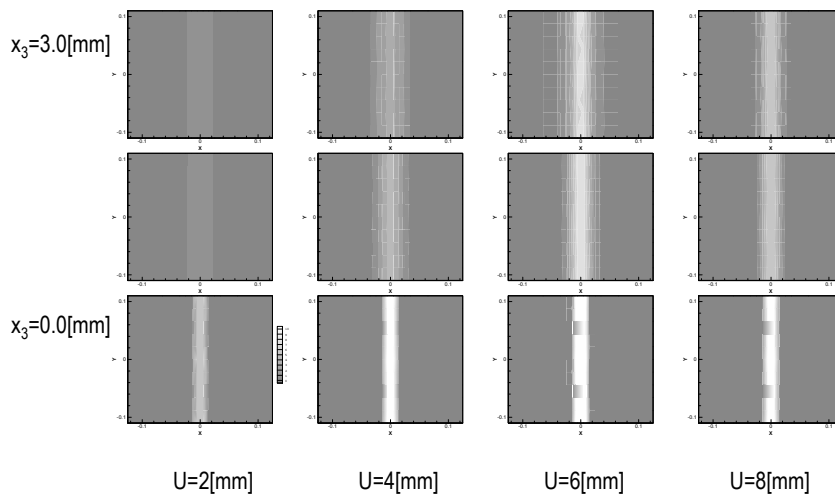


material parameters

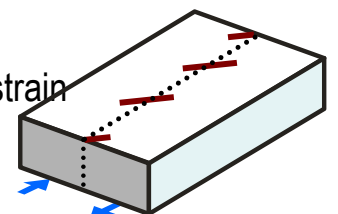
mean of E (kgf/cm^2)	12.5
ν	0.25
friction angle ($^\circ$)	51
SD of E (kgf/cm^2)	0.15
corelation length of E (cm)	50

periodic structure model for surface layer

EVOLUTION OF SHEAR BAND



evolution of plastic deformation: distribution of maximum shear strain



periodic structure model

NOJIMA EARTHQUAKE FAULT

Model

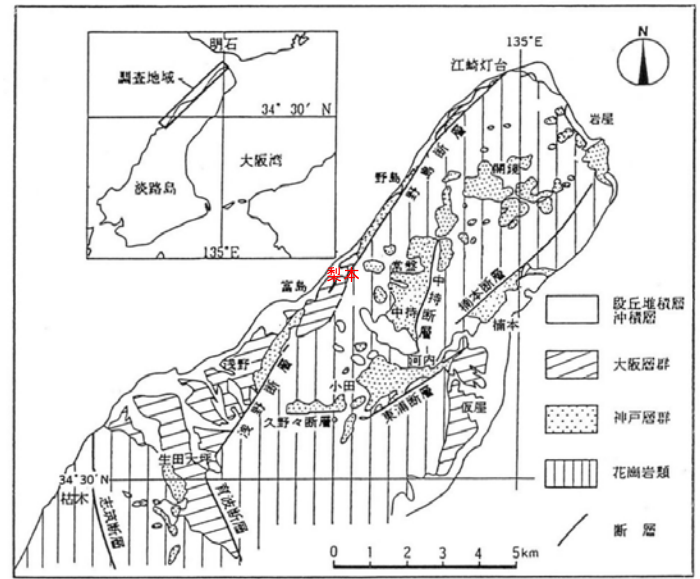
- configuration thickness 4.8[m]
- angle dip: 90[deg], direction: 45[deg]

Results of Simulation

- echelon faults (bifurcation)
- comparison of configuration
- failure probability

parameters of material property

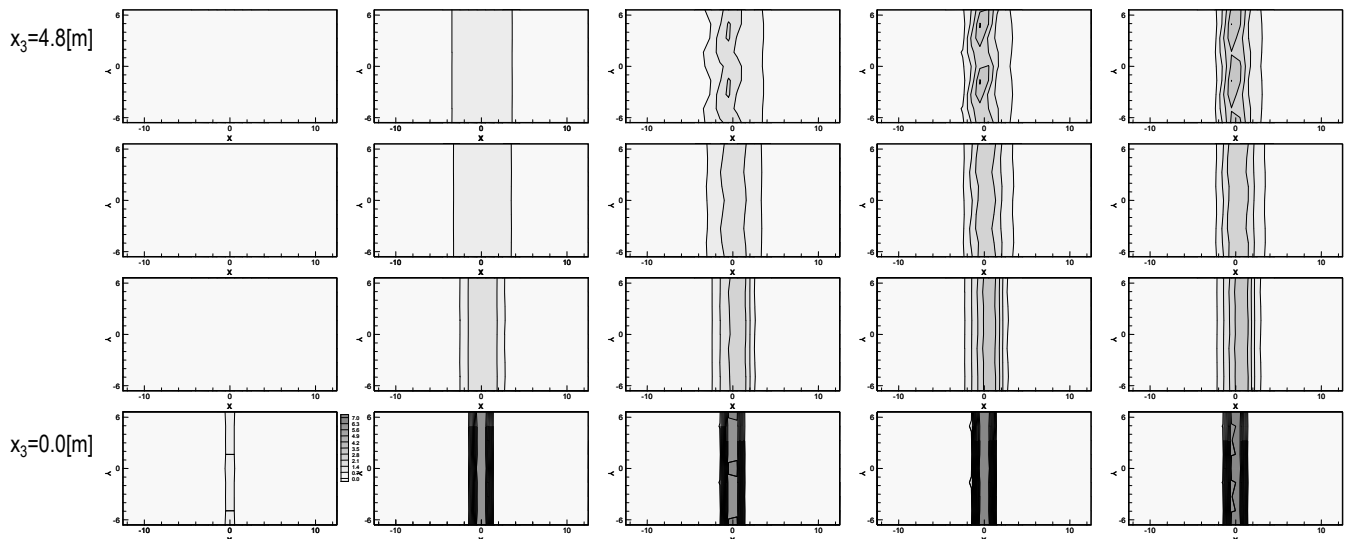
mean Young modulus [kN/m ²]	6125
Poisson ratio	0.25
density [g/cm ³]	2.1
friction angle [deg]	51
cohesion [kN/m ²]	38
standard deviation of Young modulus [%]	30
correlation length of Young modulus [m]	2



geological map of Nojima Island

ECHELON FAULTS (BIFURCATION)

coupling of lateral and normal faulting



evolution of plastic deformation: distribution of maximum shear strain

おわりに

◆HPCを利用できるFEMの開発・利用

- 品質保証: 数値計算の収束性, 実験結果の再現
- 高速ソルバとモデル自動構築
- capability computing と capacity computing

◆HPCの利用が望まれる断層問題

- 直近の最大地震動評価
- 断層変位の確率評価

計算科学・計算機科学との境界での持続的コード開発が重要であり,
ソフトウェア工学の利用が必須