The Plastic Domain Decomposition for Soil Foundation Structure Interaction Computations

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Outline

ESS Hypothesis

- NEHRP-94 seismic code states that: *"These [seismic] forces therefore can be evaluated conservatively without the adjustments recommended in Sec. 2.5 [i.e. for SS interaction effects]"*.
- Flexibility (elastic) of foundations and soils modifies dynamic properties of the SS system (Gazetas and Mylonakis)
- Reduction in stiffness (elasto–plasticity) of the SS system modifies those dynamic properties even more so
- Earthquake intensity increase, SS system period is elongated
- Earthquake period and SS period might (will) coincide

ESS System Energy Balance

- Energy balance: input (seismic) and dissipated (inelasticity, radiation, coupling) will control the fate of ESS system
- If energy dissipation $>$ input $\Rightarrow$ probably small damage
- If energy dissipation $<$ input $\Rightarrow$ probably large damage

Modeling ESS System

- Structural response is a function of a tightly coupled triad of dynamic characteristic of
  - Earthquake
  - Soil
  - Structure
- Use detailed numerical models to analyze prototype models
- Detailed numerical models require advancement in
  - Modeling techniques
  - Computational (software) methodology
  - Computer hardware (accessible parallel computers)

Parallel Elastic–Plastic Finite Element Computations

- Current Parallel FEM are
  - Well developed for elastic FEM
  - Undeveloped for elastic–plastic FEM
  - Well developed for homogeneous distributed memory parallel (DMP) computers,
  - Undeveloped for multiple performance (multi–generation) DMPs
- Need: dynamic computational load balancing for
  - multiple element types,
  - multiple material models
  - multiple compute node performances
  - multiple network performances

Plastic Domain Decomposition (PDD) Method

- Multi-objective optimization problem (minimize both the inter-processor communications, the data redistribution costs and create balanced partitions)
- computational load balancing adds overhead $T_{overhead} := T_{comm} + T_{regen}$
  - T_{comm} data communication load depending on network conditions.
  - T_{regen} model regeneration for new partitioning, application (model) dependent

PDD Optimization Model

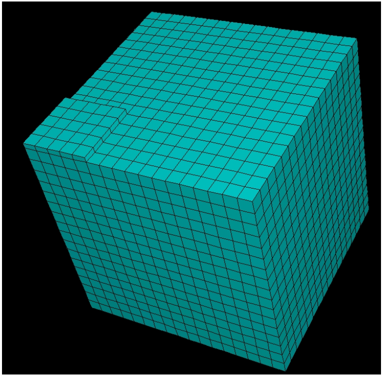
- Computional load among CPUs
  $T_j := \sum_{i=1}^{nel} ElemCompLoad[i], \quad j = 1, ..., nCPU$
- Goal: minimize maximum compute time (slowest CPU)
  $T_{max} := max(T_j) \;\; j = 1, ..., nCPU$
- Total compute time (not wall clock time) $T_{sum} := sum(T_j)$
- Best execution time (perfect load balancing) $T_{best} := T_{sum}/nCPU, \; \Rightarrow \; T_j \equiv T_{best}$ for each $j = 1, ..., nCPU$
- Best performance gain $T_{gain} := T_{max} - T_{best}$
- Computational load balancing is beneficial iff
  $T_{gain} \geq T_{overhead} = T_{comm} + T_{regen}$

PDD Implementation

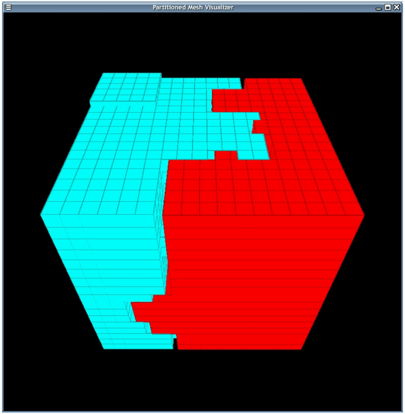
- ParMETIS dynamic graph partitioning libraries (Karypis et al.)
- PETSc solvers (Balay et al.)
- UCD upgraded OpenSees analysis model (Jie and Jeremić, McKenna)
- UCD CompGeoMech libraries (elements, material models, algorithms,...)
- Scalable to a large number of CPUs (2–1024 or more)
- Performance tuning and production runs on my cluster GeoWulf (UCD), LongHorn (TACC) and DataStar (SDSC)

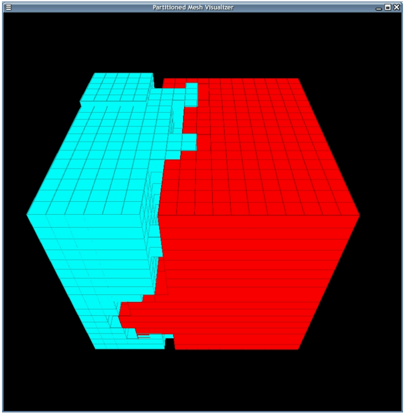
Simple PDD Example

- FEM model for soil foundation Interaction (4,938 Elements, 17,604 DOFs)
- Elastic–plastic soil
- Mild evolution of elastic–plastic zone
- Minimizing data redistribution
- Allowing higher tolerance for edge-cut
- Imbalance tolerance 5 %

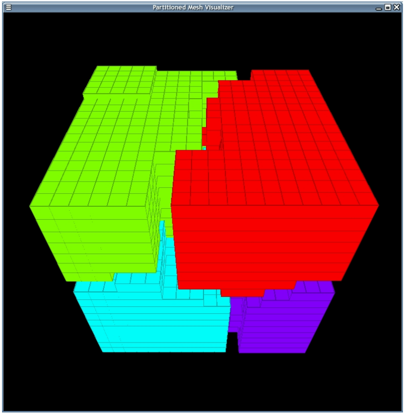


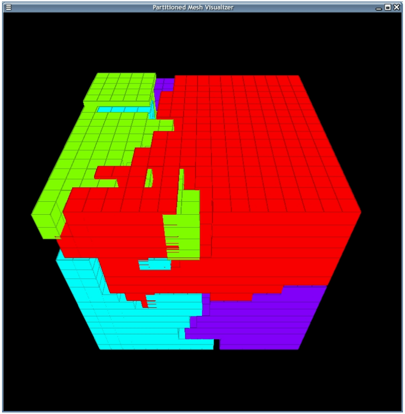
2 CPU PDD Partitioning–Repartitioning Example



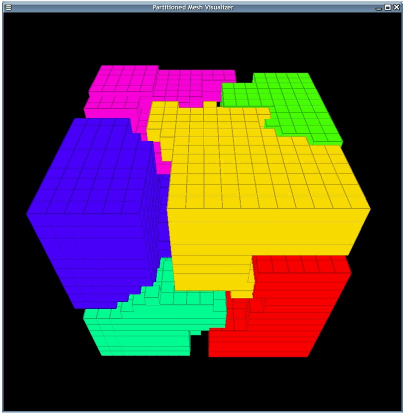


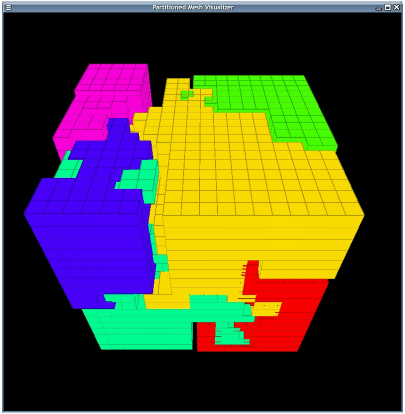
4 CPU PDD Partitioning–Repartitioning Example



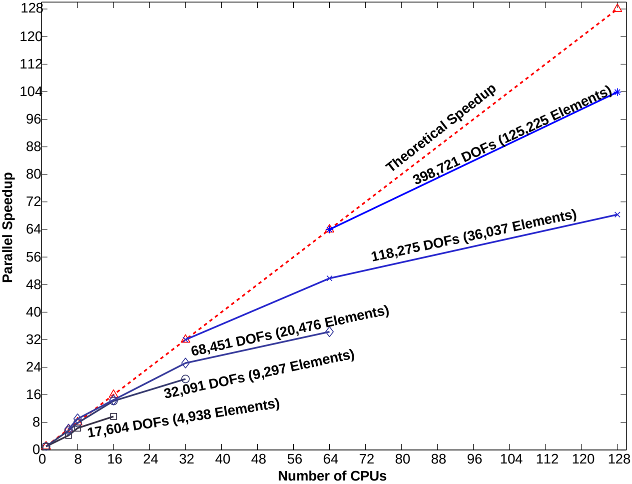


8 CPU PDD Partitioning–Repartitioning Example

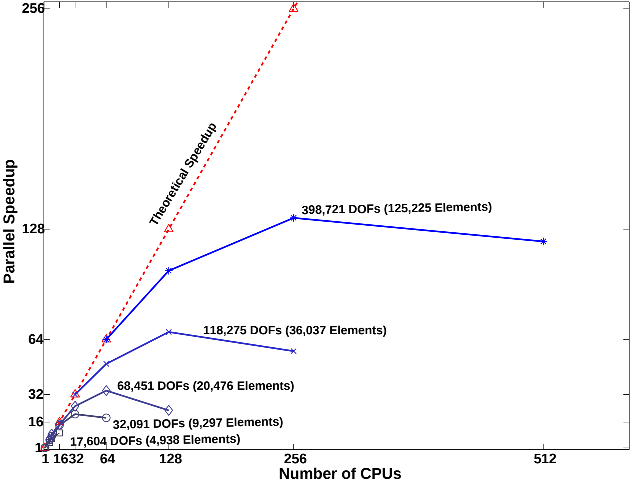




Speedup Overview



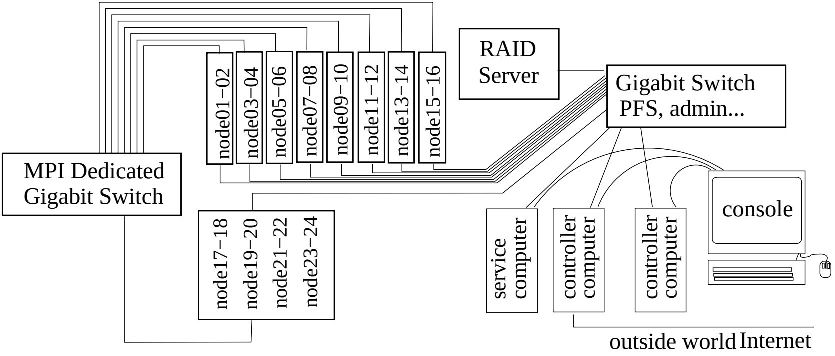
Speedup Overview



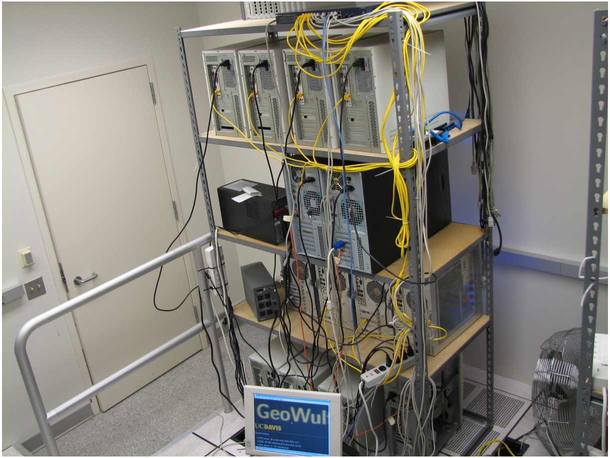
Parallel Supercomputer GeoWulf

- Distributed memory parallel computer
- Multiple generation compute nodes and networks
- Very cost effective!
- Same architecture as large parallel supercomputers (SDSC, TACC, EarthSimulator...)
- Local design, construction, available at all times!

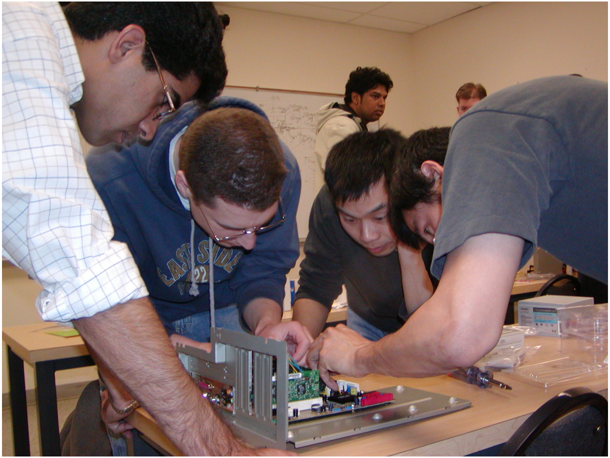
GeoWulf: Parallel Supercomputer Architecture



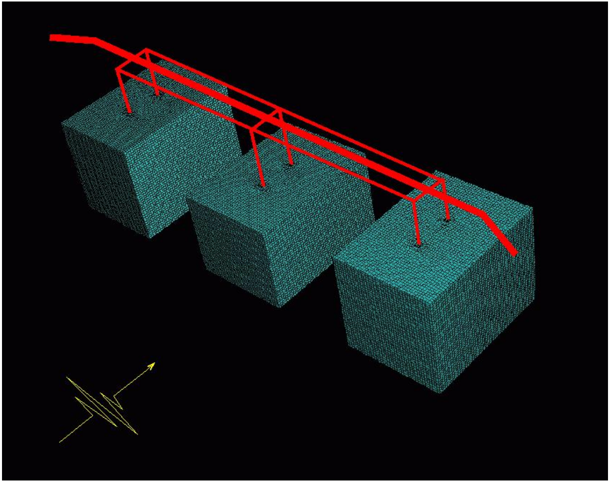
GeoWulf: Demistifying Parallel Supercomputing



GeoWulf: Local Development



Detailed 3D FEM Model (one of)



Model Components

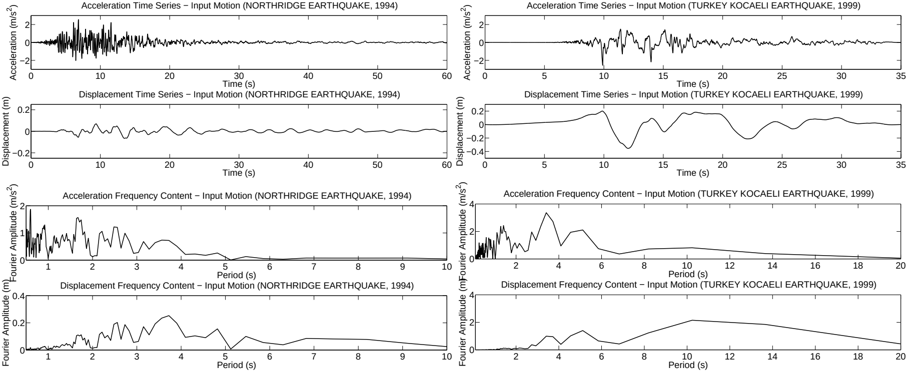
- Soils: elastic–plastic solids (yield land potential surface Drucker-Prager, kinematic hardening Armstrong-Frederick) (UCD: Jie and Jeremić)
- Structure non–linear beam–column elements (fiber element) (UCB: Fenves, UW: Eberhardt)
- Piles: non–linear beam–column elements (fiber element) (UCD: Jie and Jeremić)
- Two types of soil: stiff soil (UT, UCD), soft soil (Bay Mud)
- Use of the Domain Reduction Method (DRM) (Bielak et al.) for seismic input into FEM model

Modeling Issues

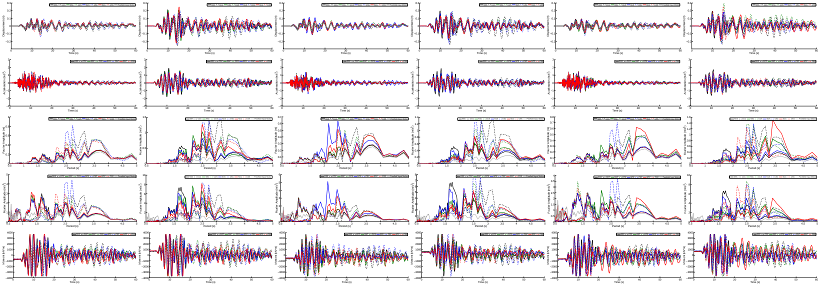
- Construction process
- Deconvolution of given surface ground motions
- No artificial damping (only mat. dissipation, radiation)
- Element size issues (filtering of frequencies)

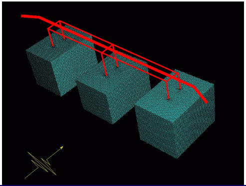
elem. #	elem. size	f_{cutoff}	min. $G^{ep}/Gmax$	γ
12K	1.00 m	10 Hz	1.0	<0.5 %
15K	0.90 m	>3 Hz	0.08	<1.0 %
150K	0.30 m	10 Hz	0.08	<1.0 %
500K	0.15 m	10 Hz	0.02	<5.0 %

Northridge and Kocaeli Input Motions

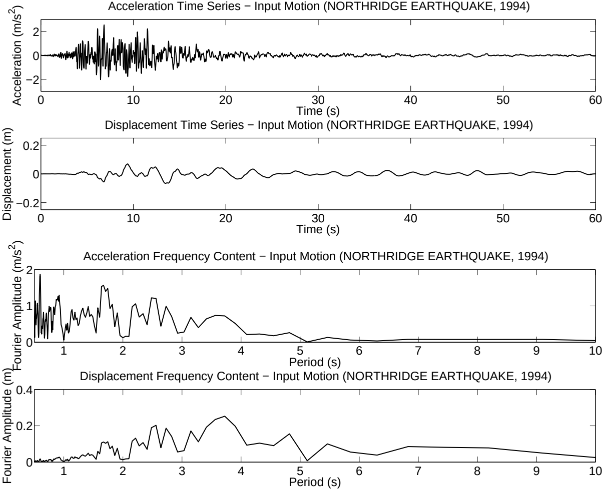


Simulation Results

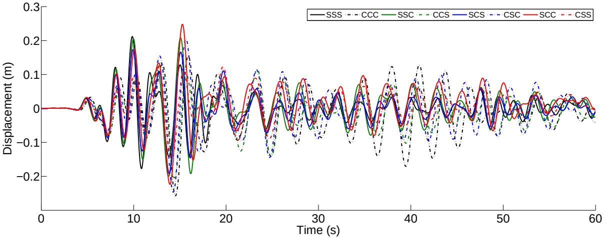


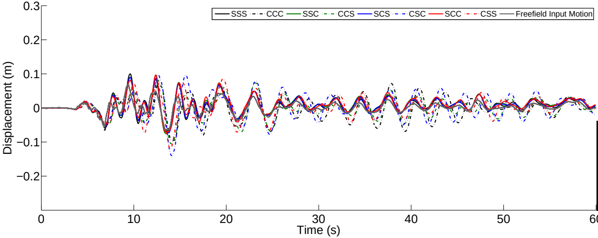


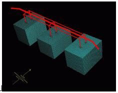
Northridge Input Motions



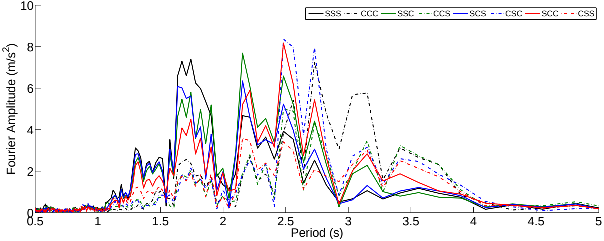
Short Period E.: Left Bent, Structure and Soil, Disp.

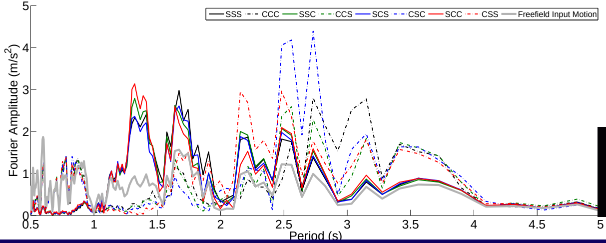


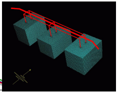




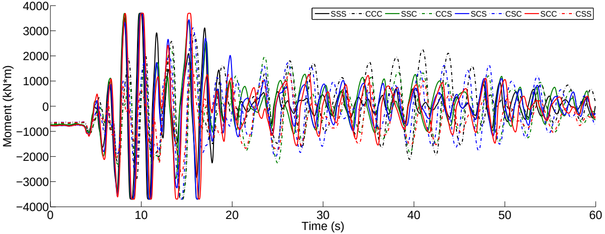
Short Period E.: Left Bent, Structure and Soil, Acc.Sp.

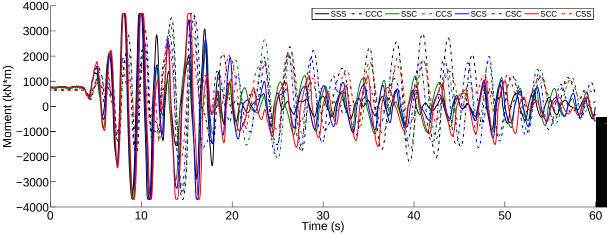


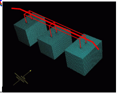




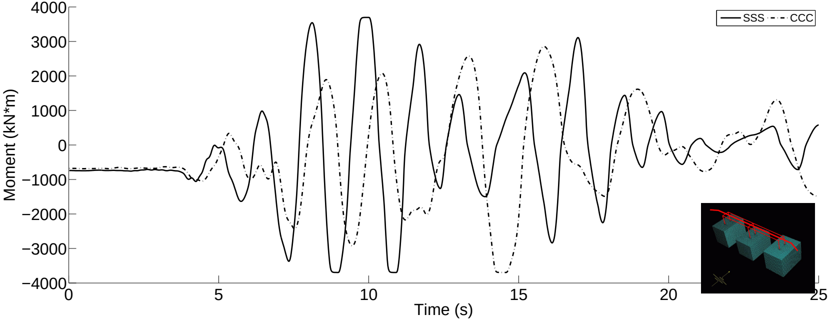
Short Period E.: Left Bent, Structure and Soil, M.



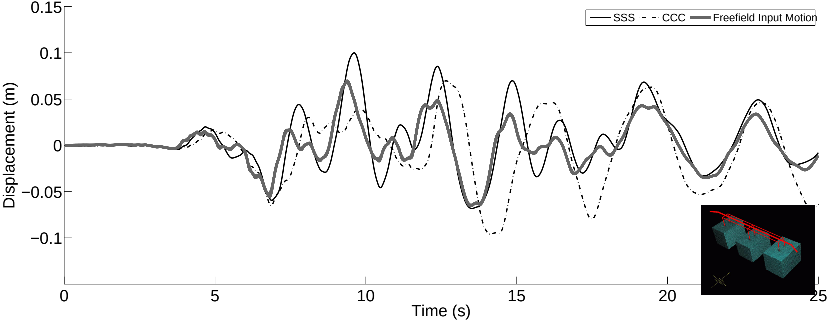




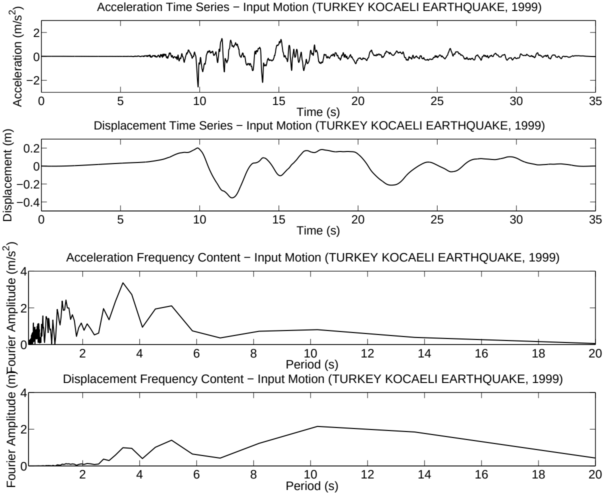
Short Period E.: Left Bent, Bending Moments



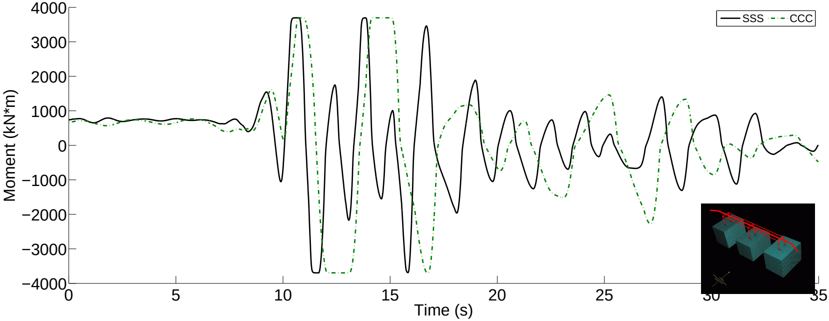
Short Period E.: Left Bent, Free Field vs Real Disp.



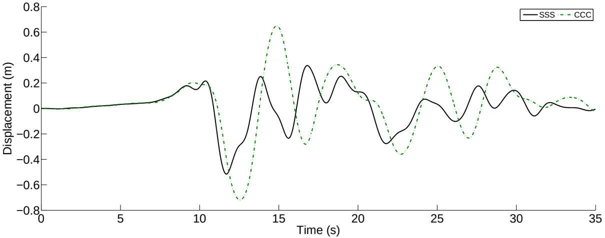
Kocaeli Input Motions

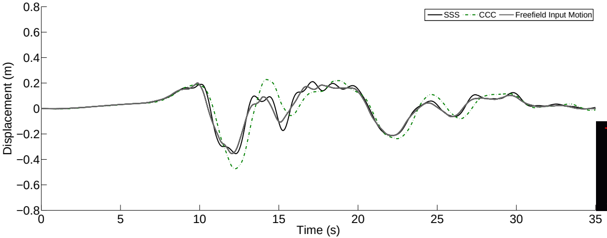


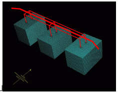
Long Period E.: Left Bent, Bending Moments.



Long Period E.: Left Bent, Structure and Soil, Disp.







Summary

- High fidelity numerical models of ESS systems
- High performance computational tools (software and hardware) developed and available
- **Matching Triad**: Earthquake, Soil and Structure (**ESS**) interaction determines possible benefits or detriments
- Program sources and tools available in public domain (GPL) at Author's web site