PARALLEL SIMULATION IN TUNNEL ENGINEERING

APPLICATION

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Outline

• Motivation
• Problem Description
  – Tunnel Simulation Model
  – Governing Equations
  – Discretization
• Software Overview & Parallelization Implementation
• Numerical Examples
• Conclusions
Motivation

• What is a tunnel for urban infrastructure?
  – Nothing but a tube under ground
  – Used for train traffic (frequently)
  – Or urban street (likely for the above-ground tunnel)

• Why do we do tunnel simulation?
  – Understand the impact of tunnel construction on existing urban infrastructure (i.e buildings)
  – Compute the risk factor
  – Optimize the construction process parameters
  – Build a prediction model
Modern Tunneling Concept: Mechanized Tunneling
PROBLEM DESCRIPTION
Geometry Description of the Tunnel

Representative Model

FEM Model

Lining

TBM

Ground

Mortar grouting
Governing Equations

- PDEs

\[
\text{div} \left[ \sigma^s - p^w \mathbf{1} \right] + \left[ (1 - n) \rho^s + n \rho^w \right] \mathbf{g} = 0
\]

\[
\text{div} \, \dot{\mathbf{u}}^s + \text{div} \left[ \frac{K}{\mu^w} (\text{grad} \, p^w + \rho^w \mathbf{g}) \right] = 0
\]

- Stress-Strain relationship

\[
\sigma^s = C^e : (\varepsilon - \varepsilon^p)
\]

\[
\sqrt{J_2 \left( \frac{1}{2} \sigma^s : \sigma^s \right)} + \eta I_3 (\sigma^s) - \xi c (\dot{\varepsilon}^p) \leq 0
\]

\[
\sigma^s = C^e (p^\prime) : (\varepsilon - \varepsilon^p)
\]

\[
\left( \frac{q}{Mp^\prime} \right)^n + \frac{\ln \left( \frac{p^\prime}{p_{o,j}^\prime} \right)}{\ln r} \leq 0
\]
Discretization

- Initial boundary value problem
  \[ \text{find } u^h, p^h \in U^h, P^h, \mathcal{L} (u^h, p^h, v^h, q^h) = f(v^h, q^h) \forall v^h \in V^h, q^h \in Q^h \]

- Q2-P1 discretization
  \[ u^h = \sum N_i \hat{u}_i \quad p^h = \sum N_i \hat{p}_i \]

- Galerkin method:
  \[ K_{ij} = \mathcal{L} (N_i, N_j) = \begin{bmatrix} K_{uu} & K_{wu} \\ K_{uw} & K_{ww} \end{bmatrix}_{ij} \]

In which:
\[ K_{uu}^e = \int_{\Omega} B^T D_e B |J| dX \quad K_{uw}^e = - \int_{\Omega} B^T I_v N_p |J| dX \]
\[ K_{wu}^e = 0 \quad K_{ww}^e = - \int_{\Omega} B^T \frac{K}{\mu_w} B |J| dX \]
Material Inhomogeneity

Ground

Ground

Ground

Ground

E ~ 1e6 MPa

E ~ 1e3~1e9 MPa

E ~ 3e10 MPa

Mortar Grouting

Lining Support

Excavated soil

E ~ 2.1e11 MPa
PARALELLIZATION
Software Infrastructure

[2] Balay et al, PETSc user manual
Software Infrastructure

Heavy used of:
+ boost shared_ptr
+ Template
+ boost ublas
Python interface

Core modules

KRATOS kernel:
- variables and data base
- sparse matrix, dense matrix, vector
- basic solution strategies
- abstract base classes of elements, conditions, constitutive laws, ...
- I/O functionality
- Python interface
- linear solvers
- geometries
- numerical integration
Software Design

- MortarApplication
  + Mortar Tying/Contact

- MetisApplication
  + Domain Decomposition

- DistributedBuildersApplication
  + Parallel Assembly (MPI)

- PetscSolversApplication
  + Parallel Linear Algebra (solver/preconditioner)

+ domain decomposition

+ wrappers for Mat, Vec
  + preallocation
  + ghost layer communication

+ construct preconditioner
  + call KSPSolve
NUMERICAL EXAMPLES
Numerical Example 1

- Fracture Simulation using Phase Field method
  - # nodes: 1.759.004
  - # elements: 10.188.671
  - # dofs: 5.277.012
  - MPI processes = 64
  - GMRES + BoomerAMG
  - Staggered solver
    - Displacement field: ~120s
    - Phase field fracture: ~18s
Numerical Example 2

- Reference Tunnel Project 1
  - One phase (pure displacement) discretization
  - No contact between the Tunnel Boring Machine and the soil
  - 433.298 nodes
  - 303.398 tets
  - 1,205,521 dofs
  - 8 Mpi processes
  - GMRES + BoomerAMG + diagonal scaling
Numerical Example 2
Numerical Example 2

- Reference Project 1

**Average linear solving time per step**

**Speed up**

**Saving: 2d -> 3hrs**
Numerical Example 3

- Reference Project 2
  - Two phase discretization
  - Critical State Soil Model
  - Penalty Contact between the Tunnel Boring Machine and the soil
  - 8 Mpi processes
  - Direct solver: MUMPS
Numerical Example 3
Numerical Example 3

- Timing with different mesh

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<th>#nodes</th>
<th>88724</th>
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Tunnel Simulation With Isogeometric Method

Standard Isoparametric Finite Element VS Isogeometric Finite Element
Tunnel Simulation With Isogeometric Method

Parallel Simulation in Tunnel Engineering Application
Conclusions

• The parallelization works and produces expected results

• One phase solve => AMG works as expected

• MUMPS does not scale

• Future works:
  – Development of block preconditioner for two-phase and contact problem
  – Tuning multigrid solver
  – Integrate SNES
THANK YOU!

QUESTIONS?

This work is part of sub-project C1, within Collaborative Research Centre SFB837 - [http://sfb837.sd.rub.de](http://sfb837.sd.rub.de) - Interaction Modeling in Mechanized Tunneling - Ruhr University Bochum, Germany