Nonlinear, Inelastic ESSI Analysis

SMiRT26 Tutorial II

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Outline

Outline

Introduction
    Motivation

Inelastic ESSI Analysis
    Analysis Phases
    Modeling and Simulation Components

Modeling and Simulation
    ESSI Modeling, Calibrations
    ESSI Simulation, Parameters

Summary

Motivation

Improve modeling and simulation for infrastructure objects

Reduction of modeling uncertainty

Choice of analysis level of sophistication

Goal: Predict and Inform

Engineer needs to know!

Dedication

Robert P. Kennedy, 1939-2018

"Response of a soil structure system is nonlinear, and I would really like to know what that response is!"

Nebojša Orbović, 1962-2021

"As an engineer, I have to know what are response sensitivities to modeling choices and model parameters."

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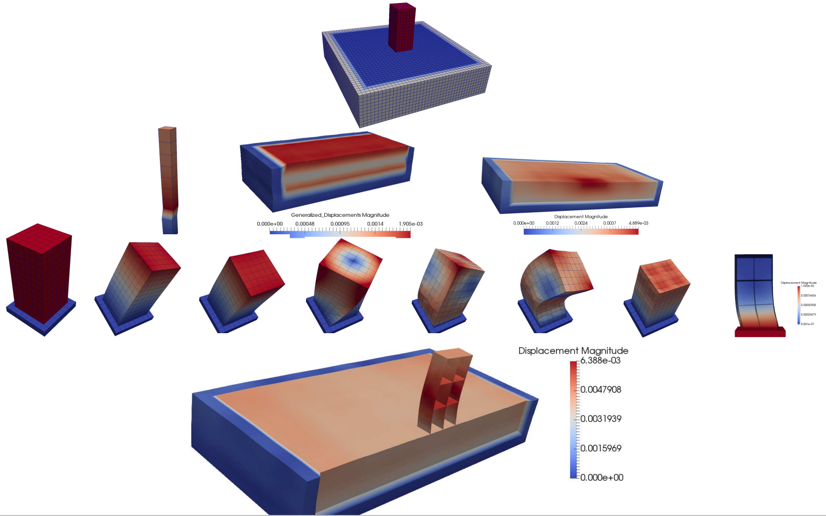
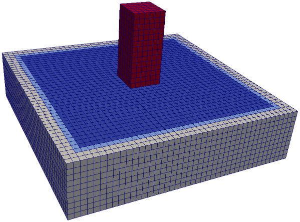
Analysis Modeling Phases



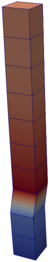
ESSI Modeling Phases

- Account for all model physical components
- Solids, structures and fluids
- Elastic, inelastic materials
- Static loads
- Dynamic loads
- Response quantities
- Engineer/Analyst builds confidence in analysis
- No surprises and no "reliance" on good luck!



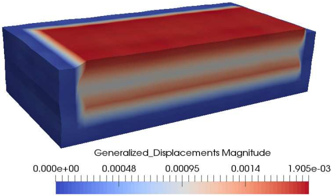
ESSI Modeling Phases

- 1D, 1C free field response
- Linear elastic material
- Inelastic material



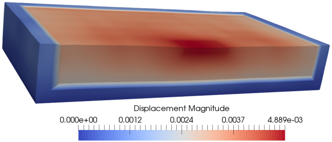
ESSI Modeling Phases

- 3D, 1C free field response
- Linear elastic material
- Inelastic material



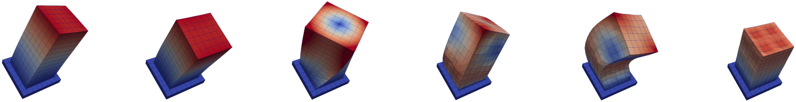
ESSI Modeling Phases

- 3D, 1C, part of SSI response
- 3D, 1C, add
  SSI components
- Linear elastic material
- Inelastic material



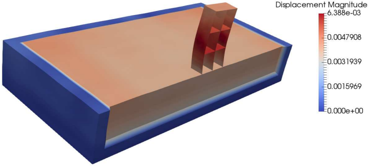
ESSI Modeling Phases

- Eigenvalue analysis



ESSI Modeling Phases

- Synthesis: full ESSI model



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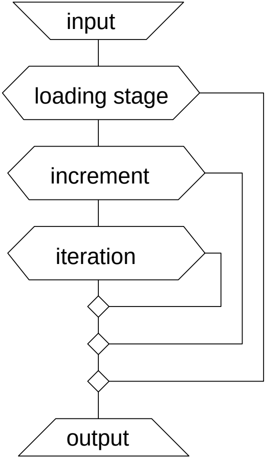
  ESSI Simulation, Parameters

Summary

ESSI Modeling

- ESSI inelastic modeling, mechanics
    - Soil
    - Interfaces/Joints/Contacts
    - Foundation
    - Superstructure
- ESSI inelastic simulation, numerics
    - Constitutive integrations, explicit/implicit
    - FEM static solution advancement
    - FEM dynamic solution advancement, time stepping

ESSI Simulation



Material Models

- Linear elastic, all materials
- Nonlinear elastic, solids
- Soil, solids/3D, dry, saturated and partially saturated)
- Rock, solids/3D, dry, saturated and partially saturated)
- Contact, soft and hard, gap, 2-node/3D, dry and saturated
- Base isolator and dissipator 2-node/3D
- Concrete, solids/3D, wall/2D, beam/1D
- Steel, beam/1D and solid/3D

Material Models for Soil and Rock, Total σ

Fully saturated clay and rock with very low permeability, dry solid bricks

- `vonMises`
- `vonMisesArmstrongFrederick`
- `vonMisesMultipleYieldSurface`
- `vonMisesMultipleYieldSurfaceGoverGmax`

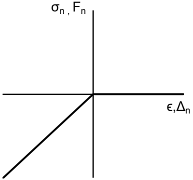
Material Models for Soil and Rock, Effective σ

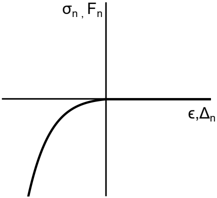
Dry and/or partially saturated/unsaturated and/or fully saturated clay and rock with any permeability, dry bricks and u-p-U bricks

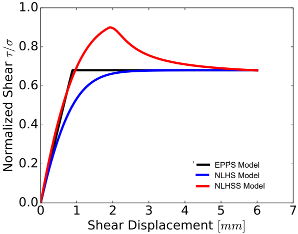
- `DruckerPrager`
- `DruckerPragerArmstrongFrederickLE`
- `DruckerPragerArmstrongFrederickNE`
- `DruckerPragerNonAssociateLinearHardening`
- `DruckerPragerNonAssociateArmstrongFrederick`
- `roundedMohrCoulomb`
- `CamClay`
- `DruckerPragerMultipleYieldSurface`
- `DruckerPragerMultipleYieldSurfaceGoverGmax`
- `RoundedMohrCoulombMultipleYieldSurface`
- `TsinghuaLiquefactionModel`
- `sanisand2004`
- `sanisand2008`

Material Models for Interface, Effective Stress

- Axial hard contact (hard surfaces)
- Axial soft contact (soil-concrete)
- Shear Elastic perfectly plastic shear contact
- Shear Elastic hadrdening plastic shear contact
- Shear Elastic hardening and softening shear contact







Material Models for Interface, Normal and Shear

- `BondedContact`
- `ForceBasedHardContact`
- `ForceBasedSoftContact`
- `ForceBasedCoupledHardContact`
- `ForceBasedCoupledSoftContact`
- `StressBasedHardContact_ElPPlShear`
- `StressBasedHardContact_NonLinHardShear`
- `StressBasedHardContact_NonLinHardSoftShear`
- `StressBasedSoftContact_ElPPlShear`
- `StressBasedSoftContact_NonLinHardShear`
- `StressBasedSoftContact_NonLinHardSoftShear`
- `StressBasedCoupledHardContact_ElPPlShear`
- `StressBasedCoupledHardContact_NonLinHardShear`
- `StressBasedCoupledHardContact_NonLinHardSoft`
- `StressBasedCoupledSoftContact_ElPPlShear`
- `StressBasedCoupledSoftContact_NonLinHardShear`
- `StressBasedCoupledSoftContact_NonLinHardSoftShear`

Material Models for Concrete

- `DruckerPrager`
- `DruckerPragerArmstrongFrederickLE`
- `DruckerPragerArmstrongFrederickNE`
- `roundedMohrCoulomb`
- `FariaOliverCerveraConcrete`
- `uniaxial_fiber_concrete02`

Material Models for Steel

- `vonMises`
- `vonMisesArmstrongFrederick`
- `uniaxial_fiber_steel01`
- `uniaxial_fiber_steel02`

Explicit and Implicit Constitutive Integration

- Explicit, forward Euler
  - Faster elastic-plastic calculations
  - Simplest elastic-plastic integration
  - Error accumulation
  - Tangent stiffness, used for explicit, noniterative global level
- Implicit, backward Euler
  - Slower elastic-plastic calculations
  - Most sophisticated elastic-plastic integration
  - Error controlled through user defined tolerance
  - Consistent stiffness, used for implicit, Newton iterations on global level

FEM Equilibrium Iterations

- Global, finite element level equilibrium iterations
- Convergence criteria
    - Force, unbalanced, relative, abs. minimum check
    - Force, unbalanced, average
    - Force, unbalanced, absolute
    - Displacement, incremental, relative, abs. minimum check
    - Displacement, incremental, average
    - Displacement, incremental, absolute
    - Energy, incremental, relative, abs. minimum check
    - Energy, incremental, average
    - Energy, incremental, absolute

Outline

Sand Models

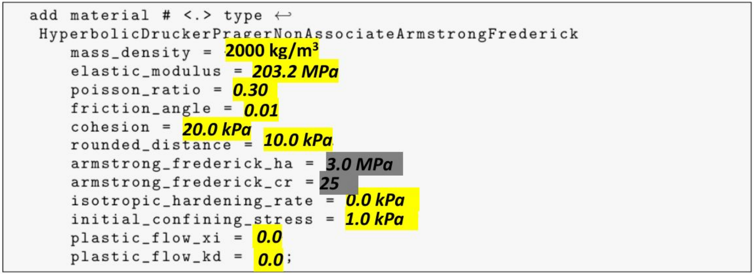
- Hyperbolic Drucker-Prager model with non-associated plastic flow and Armstrong-Frederick rotational kinematic hardening
- For example:
  - Density: $\rho = 2000 kg/m^3$
  - Wave velocity: $Vs = 200 m/s \quad Vp = 375 m/s$
  - Strength parameter: $c = 20 kPa$, $\phi = 36^o$
- From elasticity:
  - $E = 203.2 MPa \quad v = 0.3$
- Target shear strength at 10m: $\sigma = 10m * 2000kg/m^3 * 9.81m/s^2 = 196.2kPa$
  - $\tau = c + \sigma \tan(\phi) = 20\ kPa + 196.2kPa * \tan(36^o) = 165kPa$

$$v = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

$$G = \rho V_s^2$$

$$\mathrm{E} = 2G(1 + v)$$

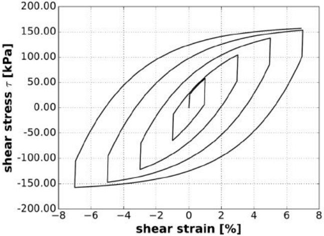
Sand Models



```
add material # <.> type ↩
 HyperbolicDruckerPragerNonAssociateArmstrongFrederick
   mass_density = 2000 kg/m^3
   elastic_modulus = 203.2 MPa
   poisson_ratio = 0.30
   friction_angle = 0.01
   cohesion = 20.0 kPa
   rounded_distance = 10.0 kPa
   armstrong_frederick_ha = 3.0 MPa
   armstrong_frederick_cr = 25
   isotropic_hardening_rate = 0.0 kPa
   initial_confining_stress = 1.0 kPa
   plastic_flow_xi = 0.0
   plastic_flow_kd = 0.0;
```

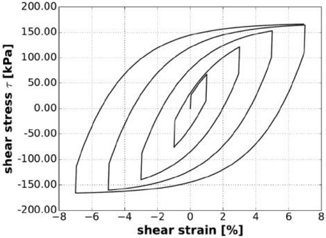
Sand Models

Initial trial:



H_a= 3 MPa
C_r= 25

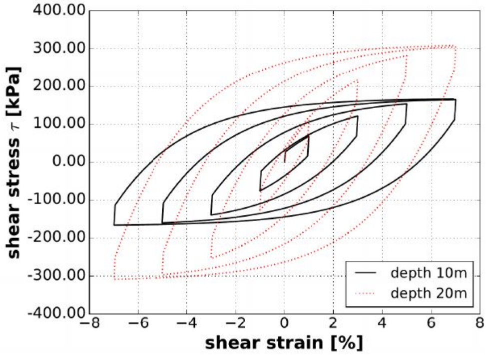
Fine tuned:



H_a= 4 MPa
C_r= 32

Sand Models

Check for depth/pressure dependency



Clay Models

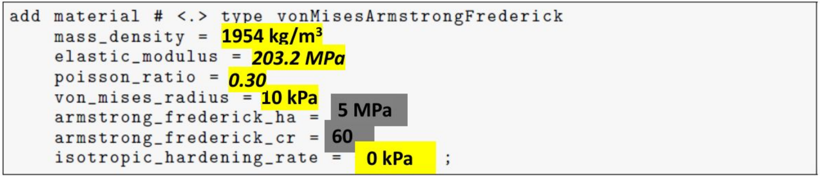
- Density: *ρ = 1954kg/m³*
- Wave velocity: *Vs = 200m/s Vp = 375m/s*
- Undrained shear strength*: Su = 40kPa*

$$v = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

$$G = \rho V_s^2$$

$$E = 2G(1 + v)$$

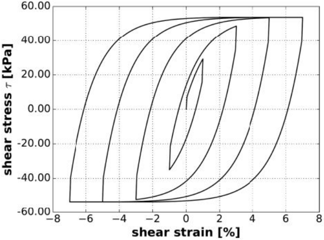
Initial trial:



```
add material # <.> type vonMisesArmstrongFrederick
    mass_density = 1954 kg/m³
    elastic_modulus = 203.2 MPa
    poisson_ratio = 0.30
    von_mises_radius = 10 kPa
    armstrong_frederick_ha = 5 MPa
    armstrong_frederick_cr = 60
    isotropic_hardening_rate = 0 kPa ;
```

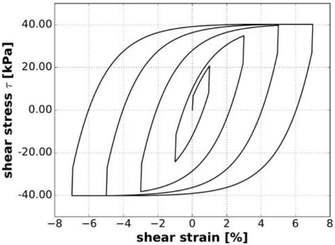
Clay Models

Initial trial:



H_a= 5 MPa
C_r= 60

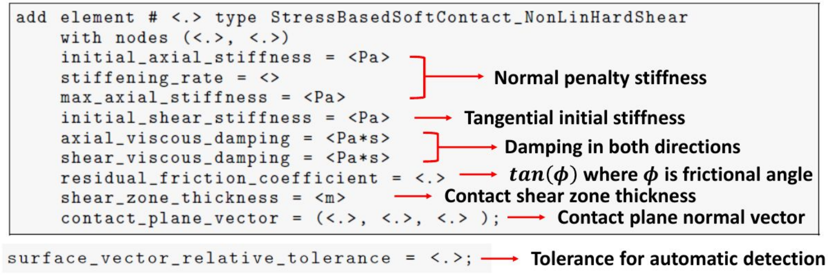
Fine tuned:



H_a= 3 MPa
C_r= 50

Interface/Contact/Joint Models

- Stress based soft contact with nonlinear hardening shear behavior
  - 9 parameters



```
add element # <.> type StressBasedSoftContact_NonLinHardShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

```
surface_vector_relative_tolerance = <.>;
```

Normal penalty stiffness

Tangential initial stiffness

Damping in both directions

$tan(\phi)$ **where** ϕ **is frictional angle**

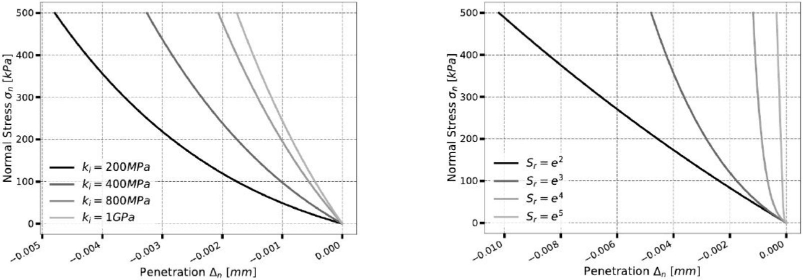
Contact shear zone thickness

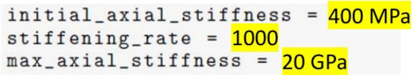
Contact plane normal vector

Tolerance for automatic detection

Interface/Contact/Joint Models

- Calibration of **axial-normal** direction



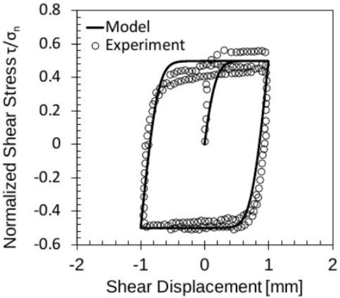


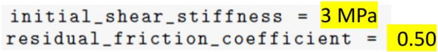
```
initial_axial_stiffness = 400 MPa
stiffening_rate = 1000
max_axial_stiffness = 20 GPa
```

Interface/Contact/Joint Models

- Calibration of **shear** direction

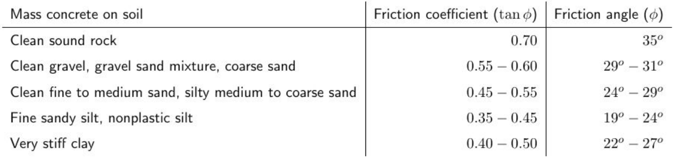
Smooth sand – Steel interface *Shahrour and Rezaie(1997)*



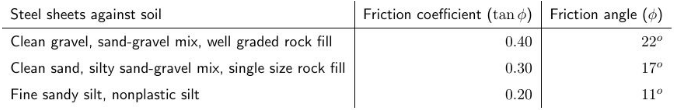


```
initial_shear_stiffness = 3 MPa
residual_friction_coefficient =  0.50
```

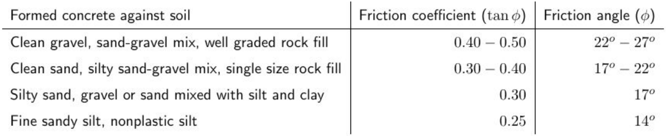
Interface/Contact/Joint Models



Mass concrete on soil	Friction coefficient ($\tan\phi$)	Friction angle (ϕ)
Clean sound rock	0.70	35^o
Clean gravel, gravel sand mixture, coarse sand	$0.55 - 0.60$	$29^o - 31^o$
Clean fine to medium sand, silty medium to coarse sand	$0.45 - 0.55$	$24^o - 29^o$
Fine sandy silt, nonplastic silt	$0.35 - 0.45$	$19^o - 24^o$
Very stiff clay	$0.40 - 0.50$	$22^o - 27^o$

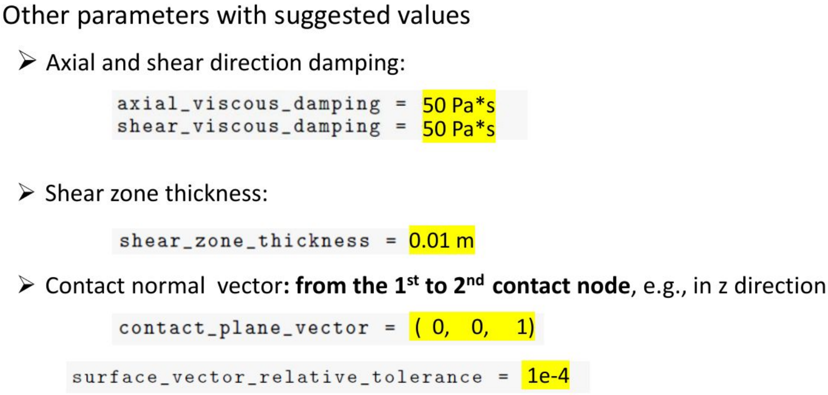


Steel sheets against soil	Friction coefficient ($\tan\phi$)	Friction angle (ϕ)
Clean gravel, sand-gravel mix, well graded rock fill	0.40	22^o
Clean sand, silty sand-gravel mix, single size rock fill	0.30	17^o
Fine sandy silt, nonplastic silt	0.20	11^o



Formed concrete against soil	Friction coefficient ($\tan\phi$)	Friction angle (ϕ)
Clean gravel, sand-gravel mix, well graded rock fill	$0.40 - 0.50$	$22^o - 27^o$
Clean sand, silty sand-gravel mix, single size rock fill	$0.30 - 0.40$	$17^o - 22^o$
Silty sand, gravel or sand mixed with silt and clay	0.30	17^o
Fine sandy silt, nonplastic silt	0.25	14^o

Interface/Contact/Joint Models



Other parameters with suggested values

- Axial and shear direction damping:

```
axial_viscous_damping = 50 Pa*s
shear_viscous_damping = 50 Pa*s
```

- Shear zone thickness:

```
shear_zone_thickness = 0.01 m
```

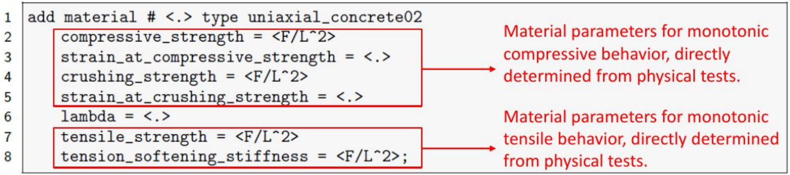
- Contact normal vector: **from the 1st to 2nd contact node**, e.g., in z direction

```
contact_plane_vector = ( 0,   0,   1)
```

```
surface_vector_relative_tolerance = 1e-4
```

Concrete Models

- Real-ESSI Domain Specific Language (DSL):



```
add material # <.> type uniaxial_concrete02
    compressive_strength = <F/L^2>
    strain_at_compressive_strength = <.>
    crushing_strength = <F/L^2>
    strain_at_crushing_strength = <.>
    lambda = <.>
    tensile_strength = <F/L^2>
    tension_softening_stiffness = <F/L^2>;
```

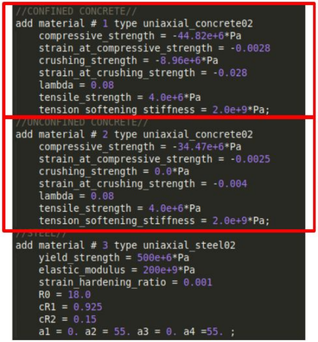
Material parameters for monotonic compressive behavior, directly determined from physical tests.

Material parameters for monotonic tensile behavior, directly determined from physical tests.

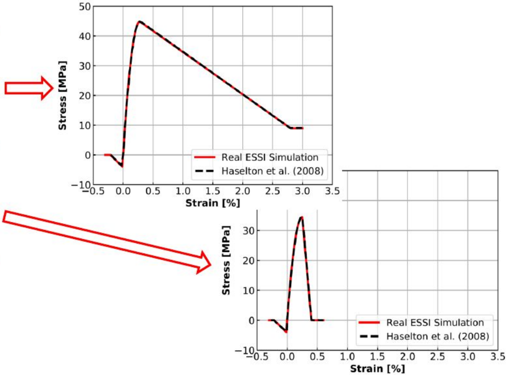
- Parameter **lambda** controls the unloading/reloading behavior of the concrete material model. If cyclic response of the model is important, physical tests involving cyclic loading is recommended to calibrate the value of lambda.

Concrete Models

- Example

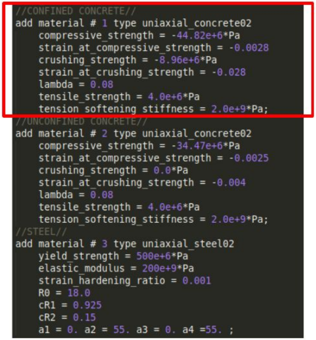


```
//CONFINED CONCRETE//
add material # 1 type uniaxial_concrete02
    compressive_strength = -44.82e+6*Pa
    strain_at_compressive_strength = -0.0028
    crushing_strength = -8.96e+6*Pa
    strain_at_crushing_strength = -0.028
    lambda = 0.08
    tensile_strength = 4.0e+6*Pa
    tension_softening_stiffness = 2.0e+9*Pa;
//UNCONFINED CONCRETE//
add material # 2 type uniaxial_concrete02
    compressive_strength = -34.47e+6*Pa
    strain_at_compressive_strength = -0.0025
    crushing_strength = 0.0*Pa
    strain_at_crushing_strength = -0.004
    lambda = 0.08
    tensile_strength = 4.0e+6*Pa
    tension_softening_stiffness = 2.0e+9*Pa;
//STEEL//
add material # 3 type uniaxial_steel02
    yield_strength = 500e+6*Pa
    elastic_modulus = 200e+9*Pa
    strain_hardening_ratio = 0.001
    R0 = 18.0
    cR1 = 0.925
    cR2 = 0.15
    a1 = 0. a2 = 55. a3 = 0. a4 =55. ;
```



Concrete Models

- Example



```
//CONFINED CONCRETE//
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    crushing_strength = 0.0*Pa
    strain_at_crushing_strength = -0.004
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    a1 = 0. a2 = 55. a3 = 0. a4 =55. ;
```
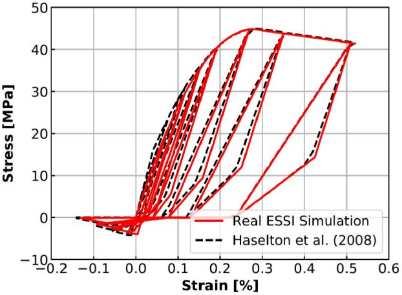
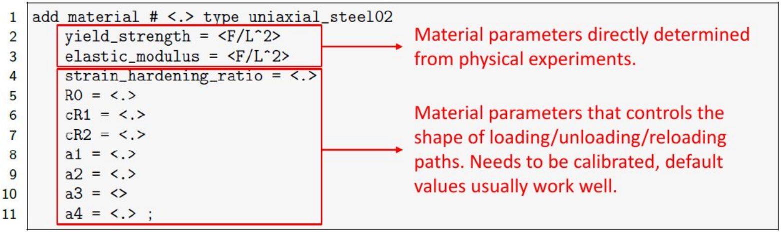



Steel Models

- Real-ESSI Domain Specific Language (DSL):



```
add material # <.> type uniaxial_steel02
    yield_strength = <F/L^2>
    elastic_modulus = <F/L^2>
    strain_hardening_ratio = <.>
    R0 = <.>
    cR1 = <.>
    cR2 = <.>
    a1 = <.>
    a2 = <.>
    a3 = <>
    a4 = <.> ;
```

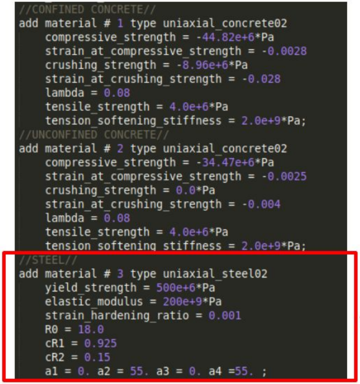
Material parameters directly determined from physical experiments.

Material parameters that controls the shape of loading/unloading/reloading paths. Needs to be calibrated, default values usually work well.

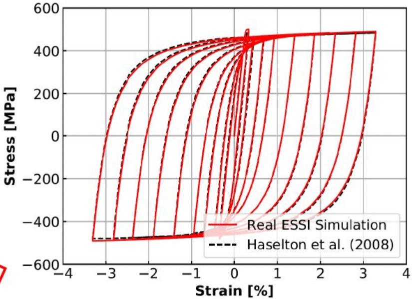
- Recommended values:
  - strain_hardening_ratio = 0.01, R0 = 18, cR1 = 0.925, cR2 = 0.15
  - a1 = 0, a2 = 55, a3 = 0, a4 = 55

Steel Models

- Example

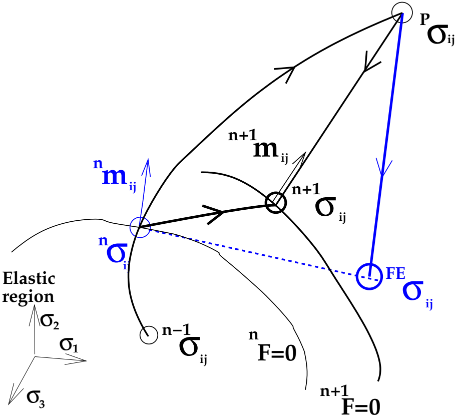


```
//CONFINED CONCRETE//
add material # 1 type uniaxial_concrete02
    compressive_strength = -44.82e+6*Pa
    strain_at_compressive_strength = -0.0028
    crushing_strength = -8.96e+6*Pa
    strain_at_crushing_strength = -0.028
    lambda = 0.08
    tensile_strength = 4.0e+6*Pa
    tension_softening_stiffness = 2.0e+9*Pa;
//UNCONFINED CONCRETE//
add material # 2 type uniaxial_concrete02
    compressive_strength = -34.47e+6*Pa
    strain_at_compressive_strength = -0.0025
    crushing_strength = 0.0*Pa
    strain_at_crushing_strength = -0.004
    lambda = 0.08
    tensile_strength = 4.0e+6*Pa
    tension_softening_stiffness = 2.0e+9*Pa;
//STEEL//
add material # 3 type uniaxial_steel02
    yield_strength = 500e+6*Pa
    elastic_modulus = 200e+9*Pa
    strain_hardening_ratio = 0.001
    R0 = 18.0
    cR1 = 0.925
    cR2 = 0.15
    a1 = 0. a2 = 55. a3 = 0. a4 =55. ;
```



Outline

Explicit and Implicit Constitutive Integration Algorithms



Constitutive Integration, Explicit

```
 define NDMaterial constitutive integration algorithm ↩
      Forward_Euler;
```

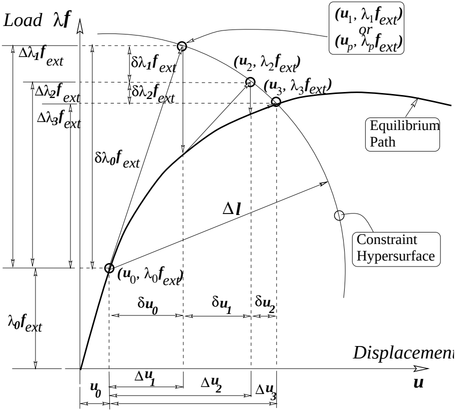
```
define NDMaterial constitutive integration algorithm ↩
    Forward_Euler_Subincrement
  number_of_subincrements = 10;
```

Constitutive Integration, Implicit

```
define NDMaterial constitutive integration algorithm ↩
    Backward_Euler
  yield_function_relative_tolerance = 1E−4
  stress_relative_tolerance = 1E−4
  maximum_iterations = 30;
```

```
define NDMaterial constitutive integration algorithm ↩
    Backward_Euler_Subincrement
  yield_function_relative_tolerance = 1E−4
  stress_relative_tolerance = 1E−4
  maximum_iterations = 30
  allowed_subincrement_strain = 1E−5;
```

Nonlinear FEM Solution



Static Solution Advancement

```
define algorithm With_no_convergence_check;
```

```
define solver UMFPack;
define convergence test Absolute_Norm_Displacement_Increment
   tolerance = 1E−6 maximum_iterations = 30 ;
define algorithm Newton;
define load factor increment 1/10;
simulate 10 steps using static algorithm;
```

```
define convergence test Relative_Norm_Unbalanced_Force
      tolerance = 1e−2 minimum_absolute_tolerance = 1e4
      maximum_iterations = 50;
define algorithm Newton;
define solver UMFPack;
define load factor increment 1/100;
simulate 100 steps using static algorithm;
```

Static Solution Advancement

```
// Gravity Stage –– Structure
new loading stage "Gravity_Structure";
include "Gravity_Load_Structure.fei";
include "Gravity_Load_Soil.fei";

  if(IS_PARALLEL==0)
    {define solver UMFPack;}
  else
    {define solver parallel petsc "–pc_type lu ↩
          –pc_factor_mat_solver_package mumps";}
define NDMaterial constitutive integration algorithm
   Forward_Euler_Subincrement number_of_subincrements = 10;
define convergence test Relative_Norm_Unbalanced_Force
        tolerance = 1e–2 minimum_absolute_tolerance = 1e4
        maximum_iterations = 50;
define algorithm NewtonLineSearch;
gam = 0.7; bet = 0.25*(0.5+gam)^2;
define dynamic integrator Newmark with gamma = gam beta = bet;
simulate 1000 steps using transient algorithm time_step = 10*s;
```

Dynamic Solution Advancement

```
dt=0.005*s;
gamma_val=0.6;
beta_val= 0.25*(0.5 + gamma_val)^2;
define dynamic integrator Newmark with
  gamma = gamma_val beta = beta_val ;
define algorithm With_no_convergence_check;
define solver ProfileSPD;
Nsteps = ceil(100*s/dt);
simulate (Nsteps) steps using transient algorithm time_step = dt;
```

```
dt=0.01*s;
alpha_val=-0.05;
define dynamic integrator Hilber_Hughes_Taylor with
  alpha = alpha_val;
define algorithm With_no_convergence_check;
define solver ProfileSPD;
Nsteps = ceil(100*s/dt);
simulate (Nsteps) steps using transient algorithm time_step = dt;
```

Dynamic Solution Advancement

```
//Dynamic: EQ
new loading stage "Dynamic";
motion_scale = 1.0;
include "Dynamic_Load.fei";
  if(IS_PARALLEL==0)
    {define solver UMFPack;}
  else
    {define solver parallel petsc "–pc_type lu ↩
          –pc_factor_mat_solver_package mumps";}
define NDMaterial constitutive integration algorithm
   Forward_Euler_Subincrement number_of_subincrements = 10;
define convergence test Relative_Norm_Unbalanced_Force
        tolerance = 1e–2 minimum_absolute_tolerance = 1e3
        maximum_iterations = 50;
define algorithm NewtonLineSearch;
gam = 0.7;
bet = 0.25*(0.5+gam)^2;
define dynamic integrator Newmark with gamma = gam beta = bet;
output every 10 steps;
simulate 25000 steps using transient algorithm time_step = 0.001*s;
```

Outline

Summary

- Expert engineer, analyst
- Full control of modeling, physical parameters
- Full control of simulation, numerical parameters
- Sensitivity of analysis results to modeling parameters
- Sensitivity of analysis results to simulation parameters
- Numerical modeling to predict and inform
- Education and Training is the key!