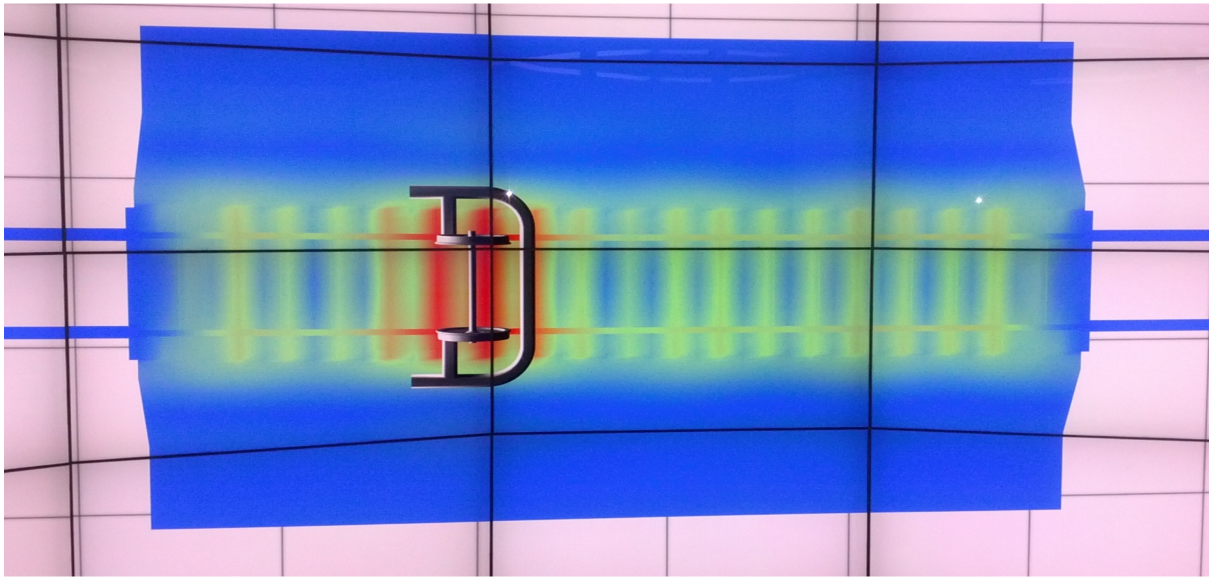
Coupled Multibody and Finite Element Modeling for Simulating Vehicle-Track-Substructure Interaction



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Acknowledgements

Collaborators:

Andrew Johnson, Jason Leigh, UIC Electronic Visualization Laboratory

Ahmed Shabana, Antonio Recuero, Liang Wang, UIC Computational Dynamics Laboratory

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Rail substructure is essential for performance

Ballast, subballast, and subgrade:

- Support track structure
- Provide drainage
- Damp track vibrations

Some potential issues

- Differential settlement, especially at transitions
- Increased maintenance
- Passenger comfort
- Vibrations in nearby structures

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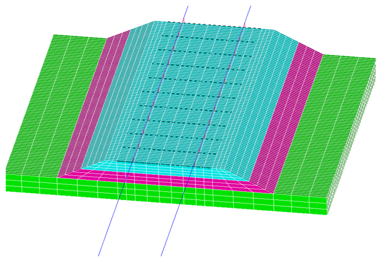
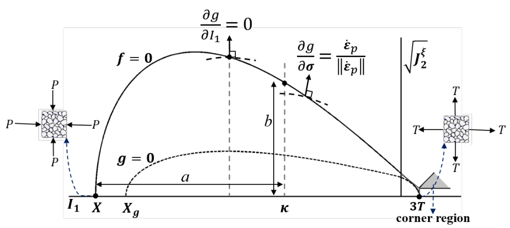
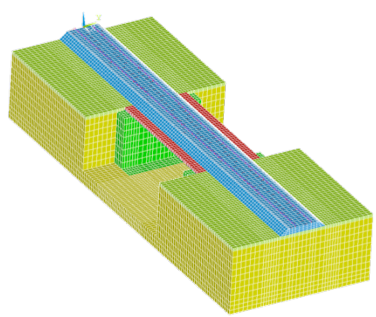
Outline



Elastic soil coupling with Rail Multibody Simulation

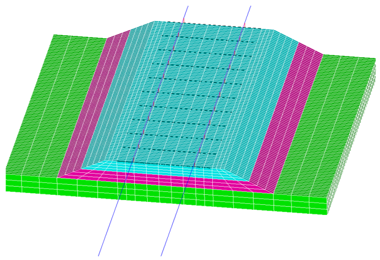


Elasto-viscoplastic soil model



Ongoing work

Outline



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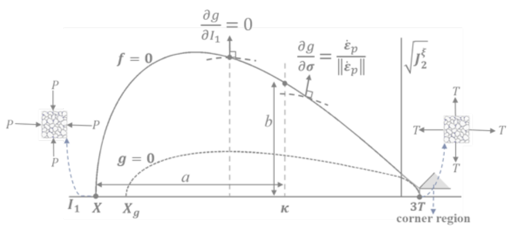

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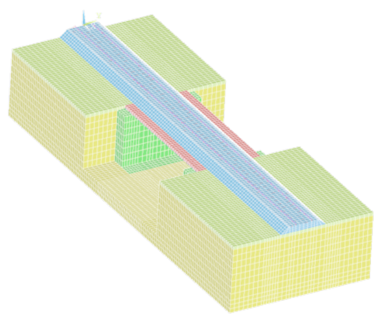
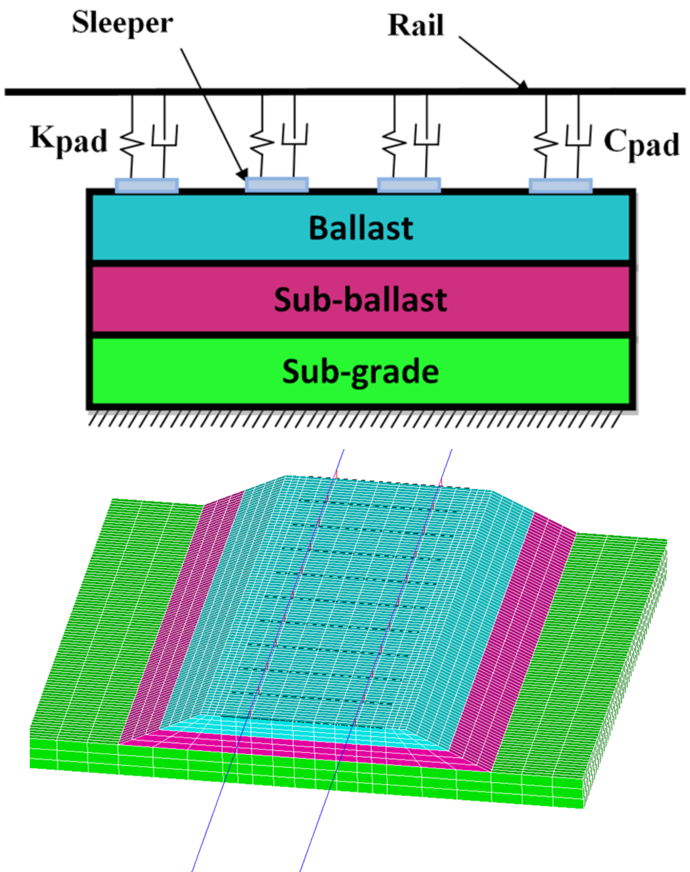


Ongoing work

Elastic modeling of soil can simulate dynamic response of track substructure

Coupling procedure

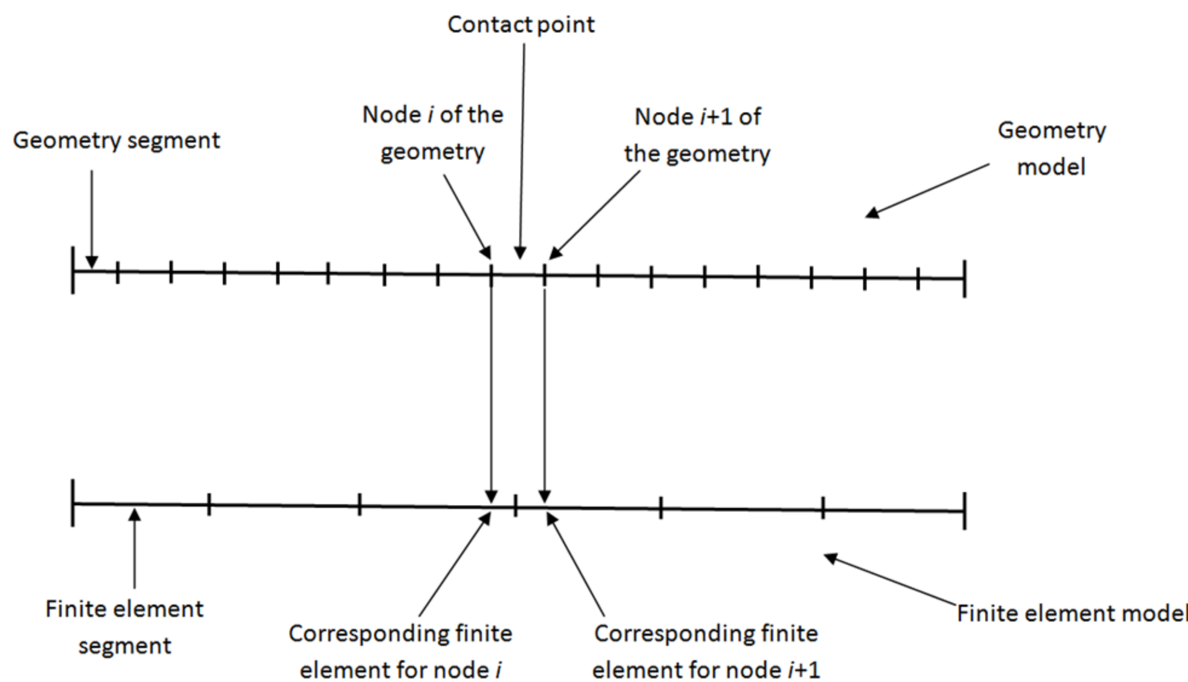
- Construct geometric model of track and substructure
- Create finite element discretization to find mass and stiffness matrices
- Extract relevant mode shapes, modal mass and stiffness
- Use mass and stiffness values to run multibody simulation of train
- Reconstruct total deformation and other quantities of interest



Run time depends on number of modes and rail nodes, not substructure geometry

Wheel-rail contacted calculated in SAMS/rail

- Multibody dynamics code calculates dynamic interaction or rigid and flexible bodies coupled by algebraic constraints
- SAMS/rail includes sophisticated calculation of wheel-rail contact points and forces



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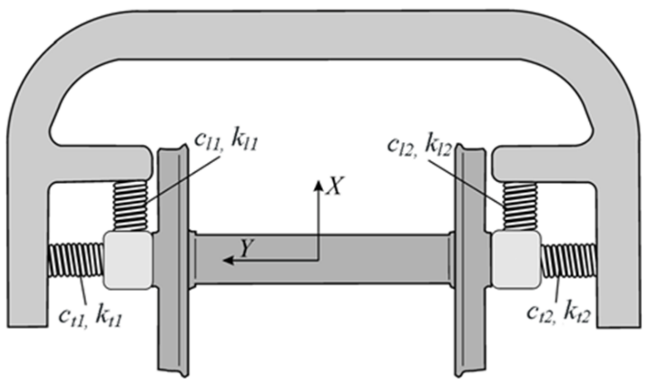
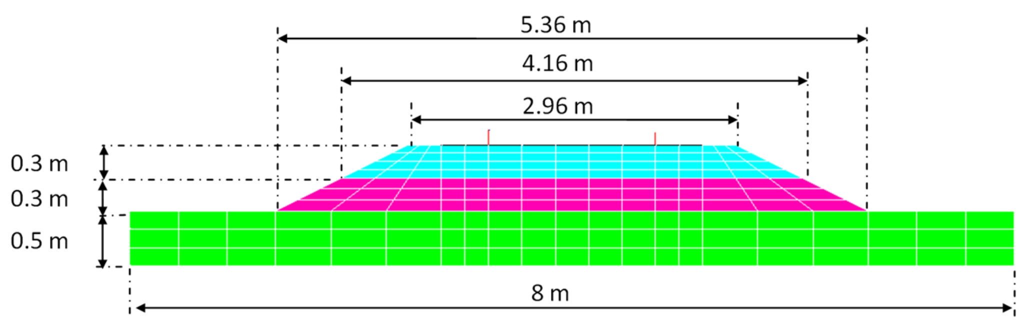
Example - suspended wheelset on elastic soil

Wheelset:

Mass	1568 kg
I_{xx}	656 kgm^2
I_{yy}	168 kgm^2
I_{zz}	656 kgm^2
$k_{l1} = k_{l2}$	13,500 N/m
$k_{t1} = k_{t2}$	25,000 N/m
$c_{l1} = c_{l2}$	1000 Ns/m
$c_{t1} = c_{t2}$	0 Ns/m



Substructure Geometry:



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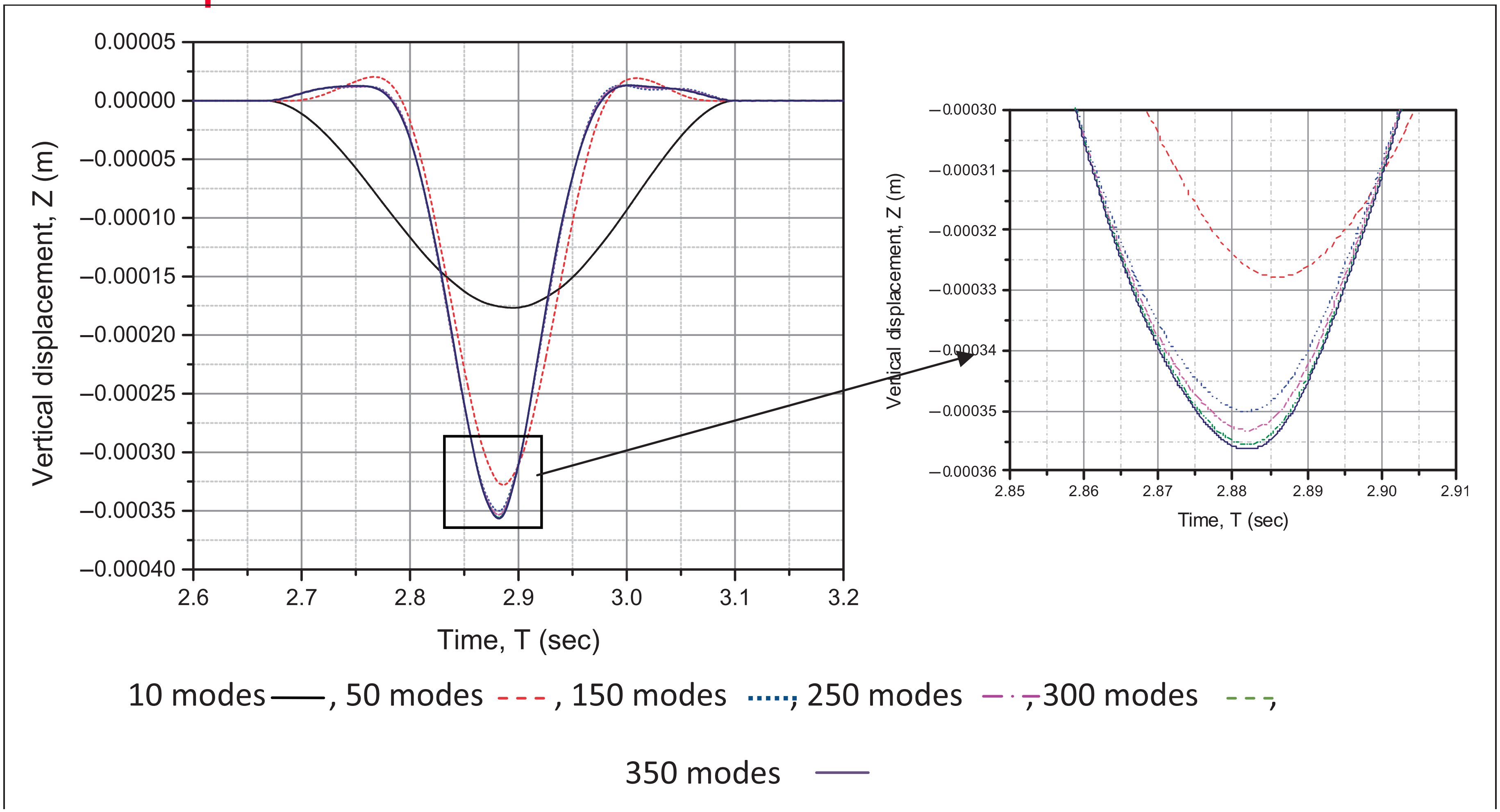
Example - suspended wheelset on elastic soil

Rail and substructure parameters

Rigid rail length	40 (on both sides)	m	Poisson's ratio of a sleeper (ε_s)	0.25	
Gage length	1.5113	m	Cross-sectional area of a sleeper (A_s)	513.8×10^{-4}	m^2
Flexible rail length	6.5	m	Second moment of inertia of a sleeper, I_{yy}	$25{,}735 \times 10^{-8}$	m^4
Stiffness of the rail (E_r)	210×10^9	N/m^2	Second moment of inertia of a sleeper, I_{yy}	$18{,}907 \times 10^{-8}$	m^4
Density of the (ρ_r)	7700	kg/m^3	Timoshenko shear coefficient of a sleeper	0.83	
Poisson's ratio of the rail (ε_r)	0.3		Stiffness of the ballast (E_b)	260×10^6	N/m^2
Cross-sectional area of the rail (A_r)	64.5×10^{-4}	m^2	Density of the ballast (ρ_b)	1300	kg/m^3
Second moment of inertia of the rail, I_{yy}	2010×10^{-8}	m^4	Poisson's ratio of the ballast (ε_b)	0.3	
Second moment of inertia of the rail, I_{zz}	326×10^{-8}	m^4	Stiffness of the sub-ballast (E_{sb})	200×10^6	N/m^2
Timoshenko shear coefficient for the rail	0.34		Density of the sub-ballast (ρ_{sb})	1850	kg/m^3
Length of a sleeper	2.36	m	Poisson's ratio of the sub-ballast (ε_{sb})	0.35	
Gap between sleepers	0.65	m	Stiffness of the sub-grade (E_{sg})	200×10^6	N/m^2
Stiffness of a sleeper (E_s)	64×10^9	N/m^2	Density of the sub-grade (ρ_{sg})	1850	kg/m^3
Density of a sleeeper (ρ_s)	2750	kg/m^3	Poisson's ratio of the sub-grade (ε_{sg})	0.3	
Stiffness coefficient of a pad (K_{pad})	26.5×10^7	N/m	Damping coefficient of the pad (C_{pad})	4.6×10^4	Ns/m

Results can be visualized with help from Electronic Visualization Laboratory

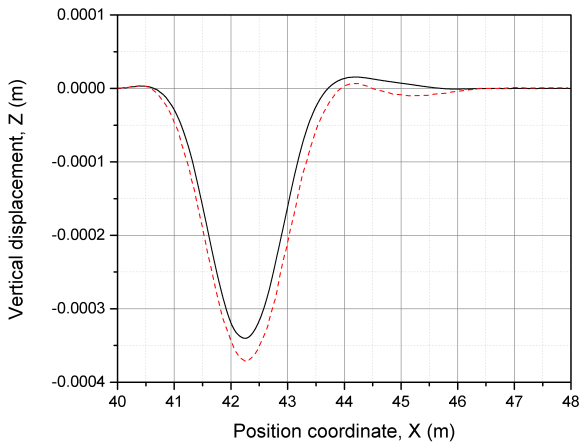
Displacement of rail can be calculated

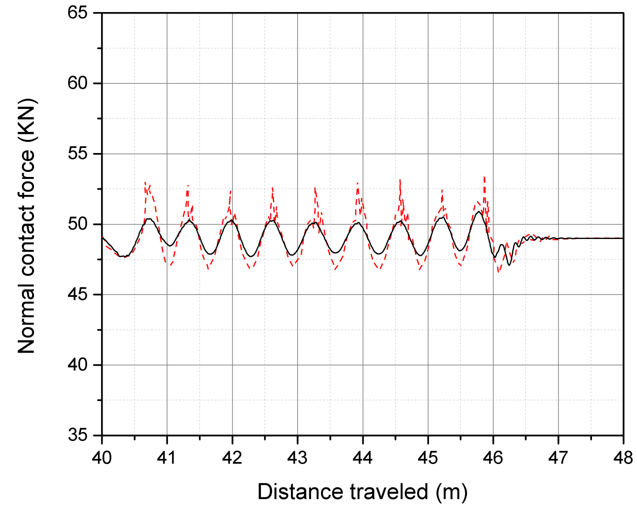


Many modes are necessary for accurate solution of a concentrated, moving load.

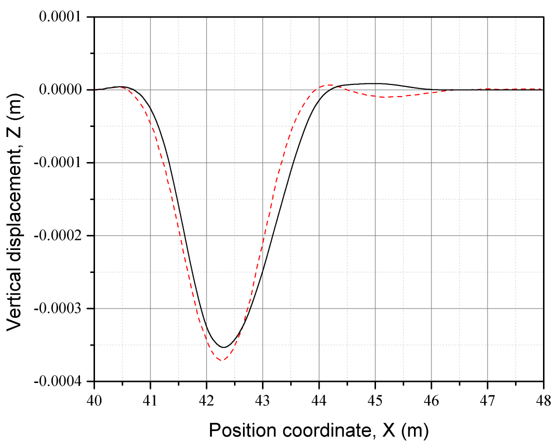
Results can be compared for “normal” track and unsupported tie

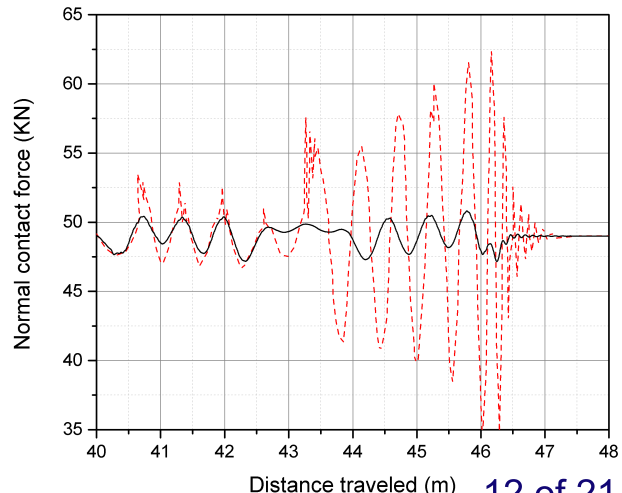
Normal rail displacement and contact force between ties



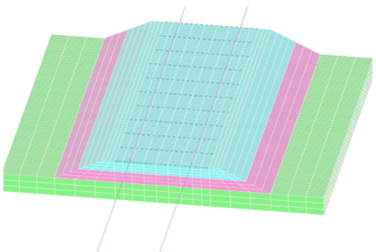


Rail displacement for unsupported tie





Outline



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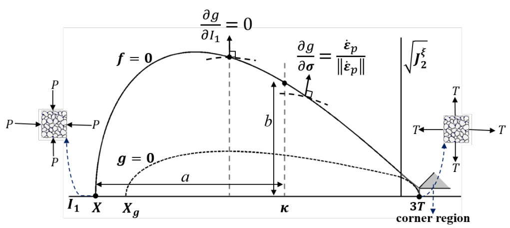
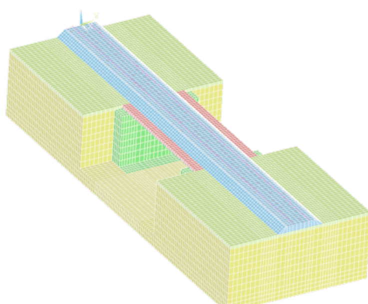


Elasto-viscoplastic soil model



Ongoing work

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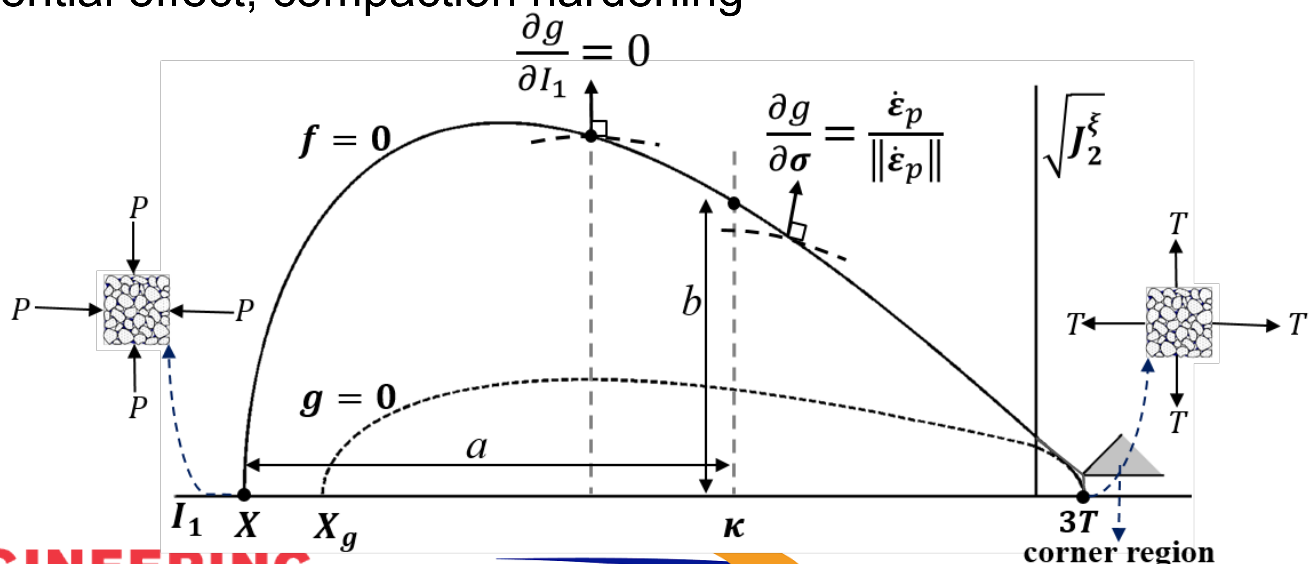
Permanent deformation requires inelastic modeling

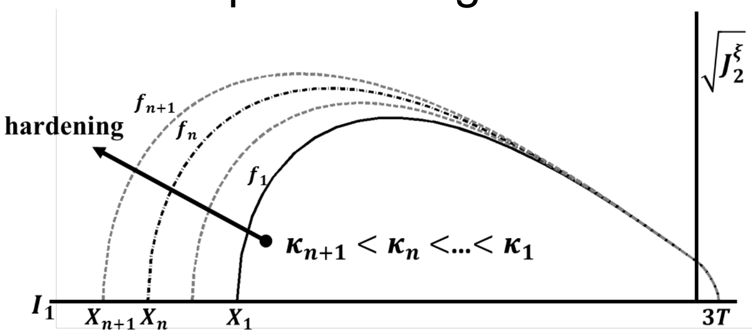
Important features for ballast, subballast and subgrade settlement:

- Dilation at low pressure, compaction higher
- Rate dependence
- Kinematic hardening to capture Bauschinger effect in cyclic loading
- Other features for improved accuracy: nonassociativity, strength differential effect, compaction hardening

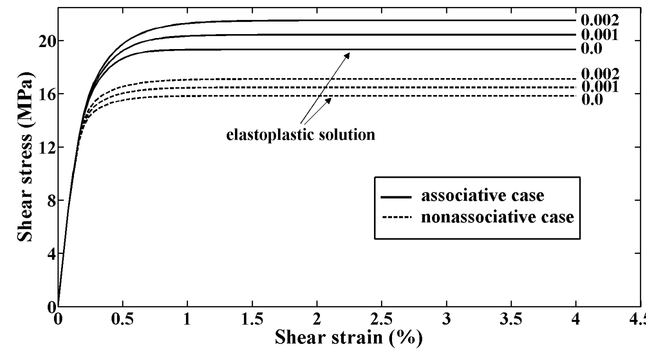


We have adapted the Sandia GeoModel, a cap palsticity model, to captures these features.

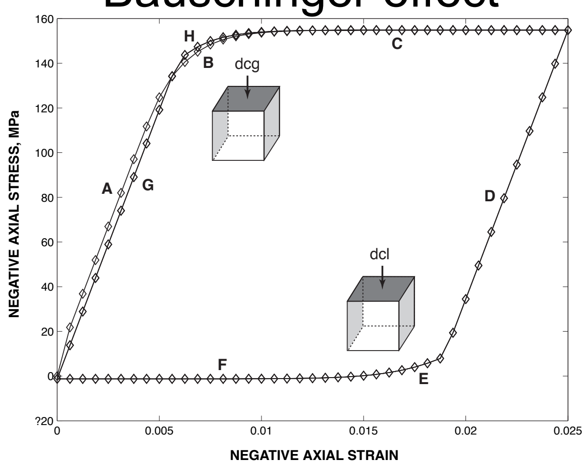
Cap hardening



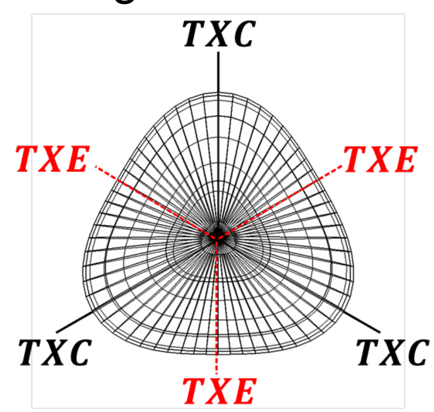
Rate dependence



Bauschinger effect



Strength differential



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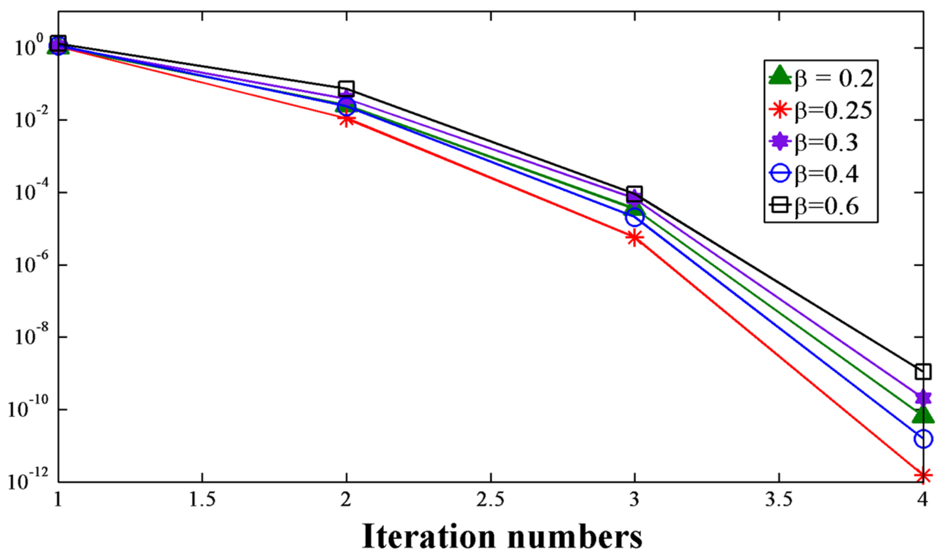
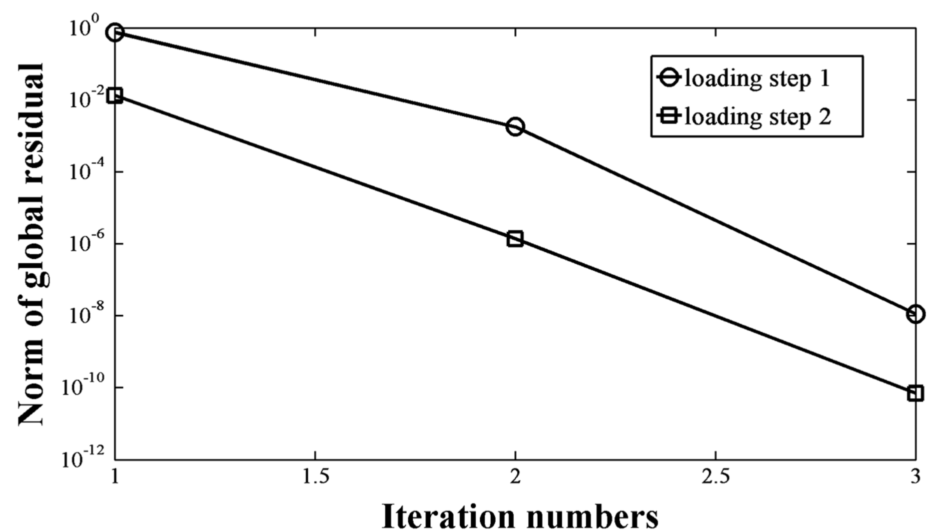
Recent modifications have improved robustness and efficiency

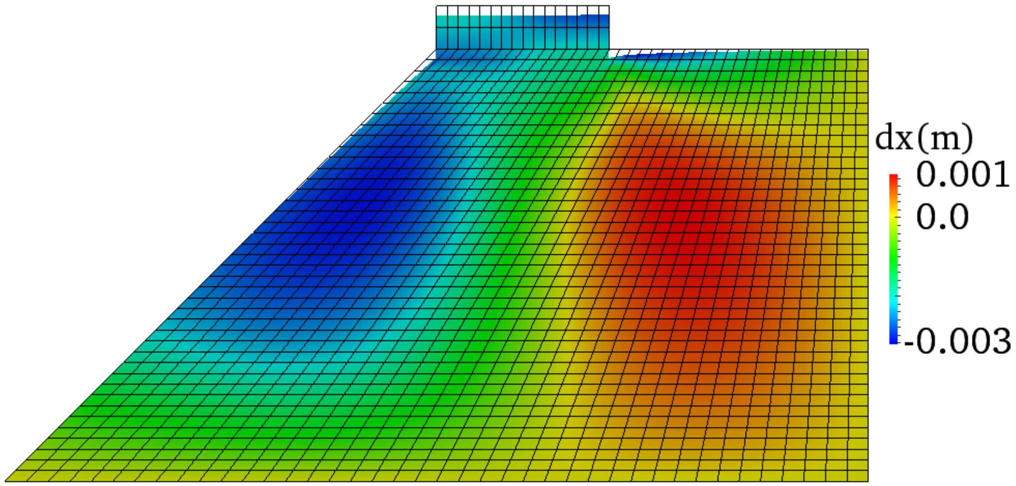
- Reparameterized yield function
- Normalized units of local residual

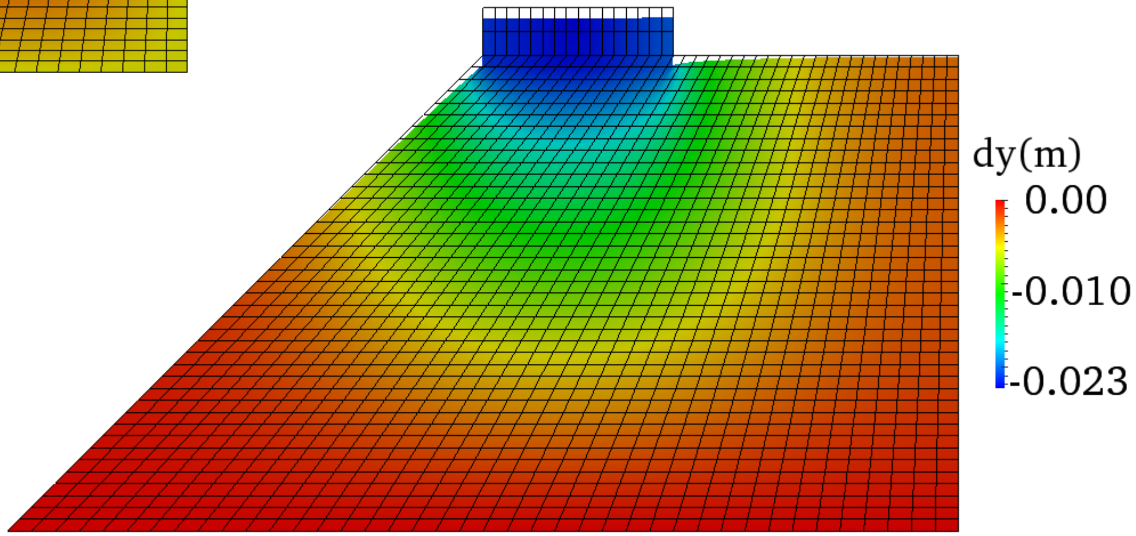
Both local and global residuals show quadratic convergence





The model can be used in large-scale finite element problems





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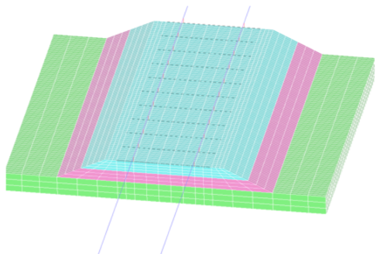

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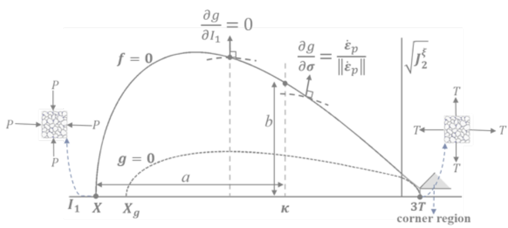

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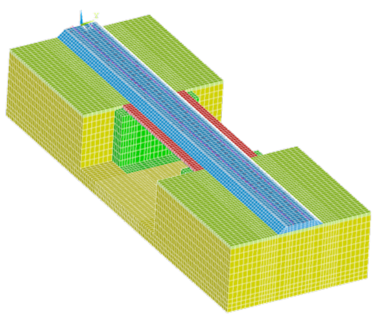
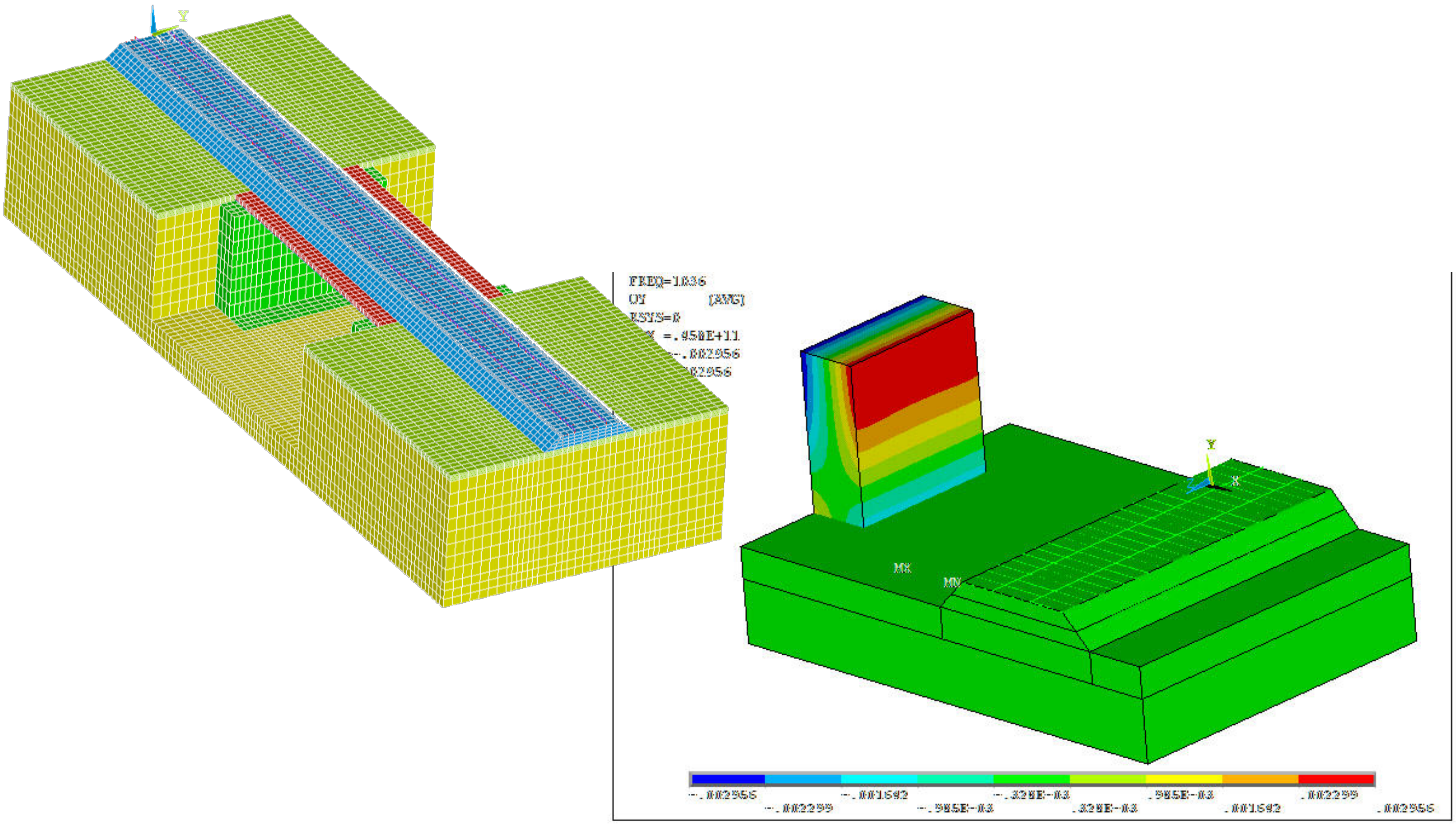


Ongoing work

This linear elastic model is now being applied to bridge approaches and building vibrations



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This viscoplastic model will be coupled to the multibody model by a linear approximation

- Use linear stiffness to calculate displacements
- Use the displacement to calculate full stress and plastic strain
- Since inelastic deformation is small over a given event, rerun loads
- Periodically update geometry to account for settlement

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Conclusions

- Continuum modeling of track substructure lead to more accurate modeling of train dynamics
- Can be applied to a variety of problems related to rail geotechnics, including building vibration and transitions
- More advanced soil modeling necessary to capture permanent settlement (ballast fouling and degradation needs further modification)

References

[1] Motamedi, M. H., Foster, C. D., (2015), "An improved implicit numerical integration of a non-associated, three-invariant cap plasticity model with mixed isotropic/kinematic hardening for geomaterials" *IJNAMG*, In Press.

[2] El-Ghandour, Ahmed I., Martin B. Hamper, and Craig D. Foster. "Coupled finite element and multibody system dynamics modeling of a three-dimensional railroad system." *JRRT* (2014): 0954409714539942.

[3] Recuero, A. M., J. L. Escalona, and A. A. Shabana. "Finite-element analysis of unsupported sleepers using three-dimensional wheel–rail contact formulation." *JMD* 225.2 (2011): 153-165.

[4] C.D. Foster, R.A. Regueiro, A.F. Fossum, and R.I. Borja. (2005), "Implicit numerical integration of a three-invariant, isotropic/kinematic hardening cap plasticity model for geomaterials" *CMAME*, Vol. 194, Nos. 50-52, 5109-5138.