Hydrocarbon Pipelines in Geo-hazard Areas: the Particular Case of Seismic Action

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Oil & Gas Pipelines

- Pipelines is the most efficient method for transporting energy resources.
- They require a significant design and construction investment, but ...
- ... when constructed, they enable the unhindered “flow” of energy resources.
- The decision for their construction is usually political and depends on the availability of oil & gas in the source area and the assurance of consumption in the target area.

Oil & Gas Pipelines

- The total length of high pressure transmission pipelines around the world has been estimated at 3,500,000 klm. The ‘split’ is:
- ~64% carry natural gas
- ~19% carry petroleum products
- ~17% carry crude oil

Oil & Gas Pipelines

- Pipeline systems are critical transportation infrastructures, essential to our standard of living, and to our economy.
- The future of hydro-carbon pipelines is both bright and challenging. They will continue to carry the bulk of our primary energy sources.
- However, the biggest challenge for the pipeline engineer is safety.
- Engineers need to ensure they perform both safely and securely, as pipelines “age”, have defects and undergo externally-induced actions.

Oil Pipeline Safety

- Pipelines are 40 times safer than rail tanks, and 100 times safer than road tanks for transporting hydrocarbons.
- Oil pipeline spills amount to about 1 gallon per million barrel-miles [USA Association of Oil Pipelines].
- In household terms, this is less than one teaspoon of oil spilled per thousand barrel-miles.

Note: One barrel, transported one mile (1609m), equals one barrel-mile, and there are 42 gallons (159 liters) in a barrel.

Oil & Gas Pipelines

- Pipelines are recognized as the safest method for transporting hydrocarbons.
- However, pipelines may fail due to many reasons:
  - External mechanical interference (third-party).
  - Corrosion (internal and external).
  - Pipe wall and weld defects.
  - **Ground-induced actions (geo-hazards).**
  - Above-standard operation (over-pressure)

Oil & Gas Pipelines

During design & construction, things seems to be under control.

What you want to avoid !

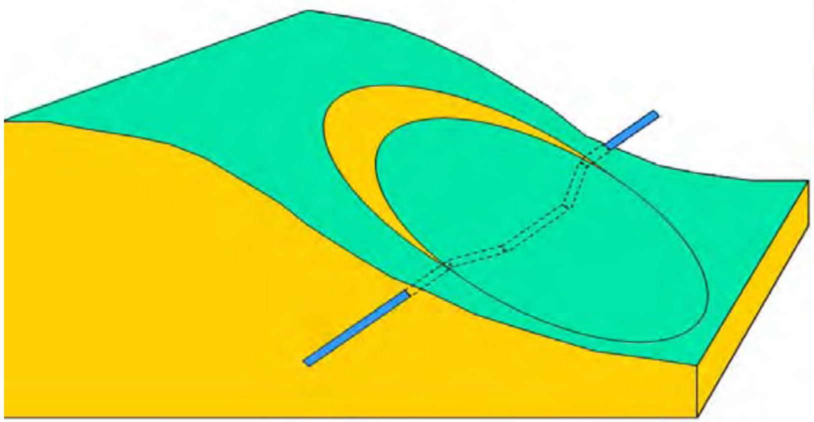
During operation, there are several threats that may lead to failure.

Ground-induced actions

- Landslides (slope stability)
- Differential settlements (soft soil conditions and mining subsistence).
- Seismic effects:
  - **Tectonic fault crossing**
  - Liquefaction and lateral spreading
  - Landslides and differential settlements
  - Wave effects (ground shaking), not very important

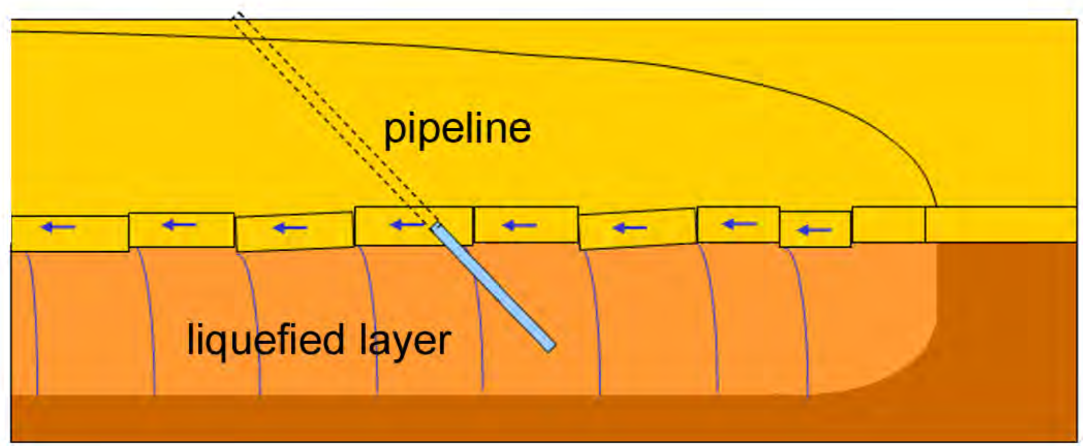
Pipeline geo-hazards

differential settlement

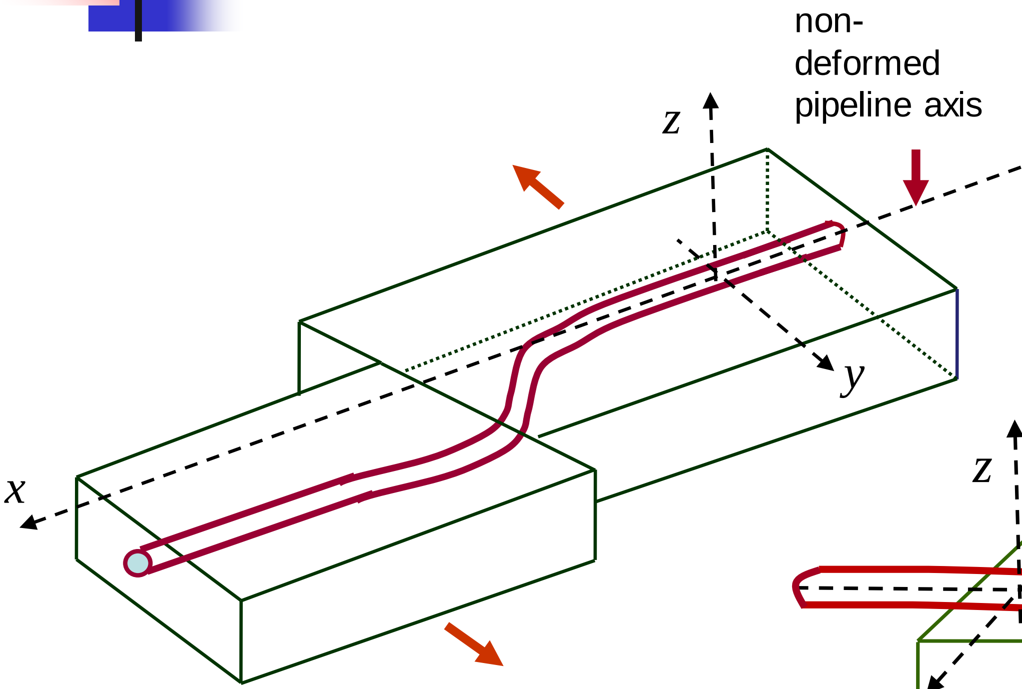


landslide

lateral spreading

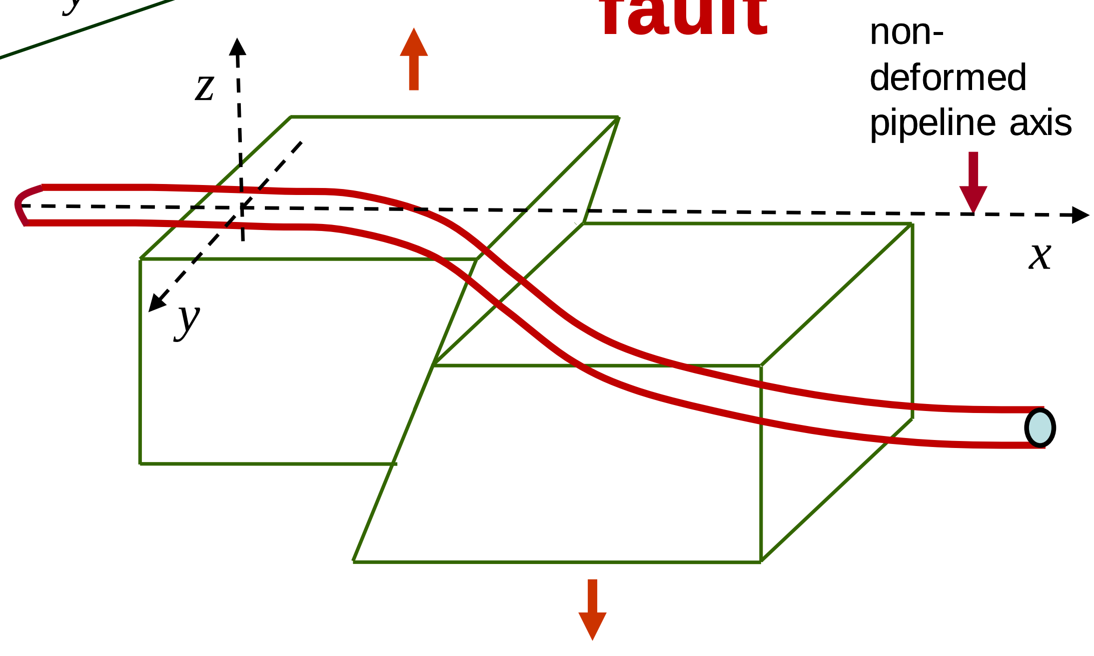


Pipeline geo-hazards



strike-slip horizontal fault

normal fault



Pipelines crossing active seismic faults

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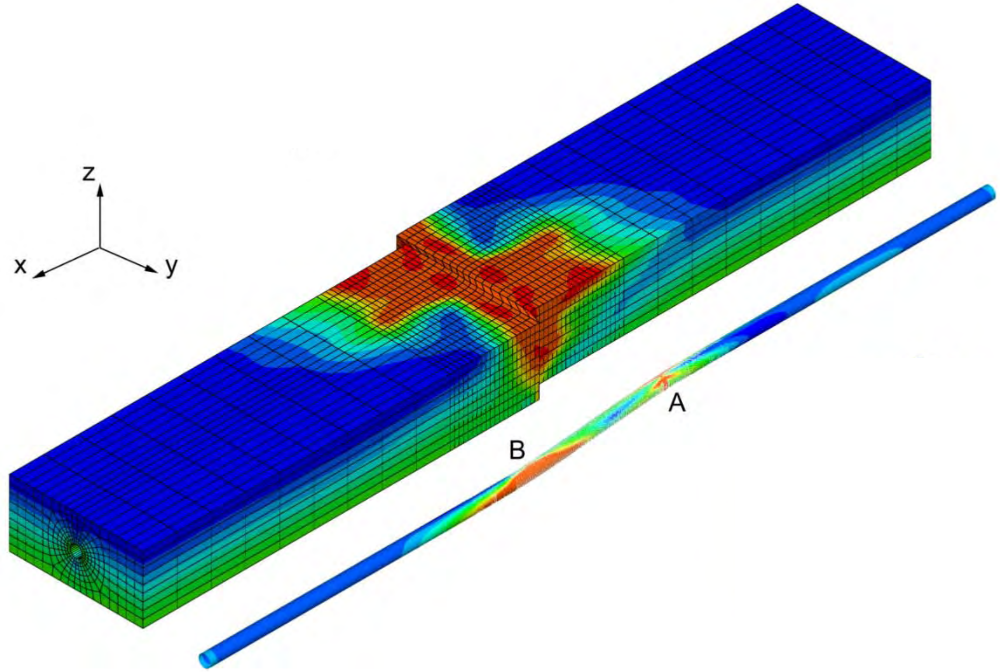
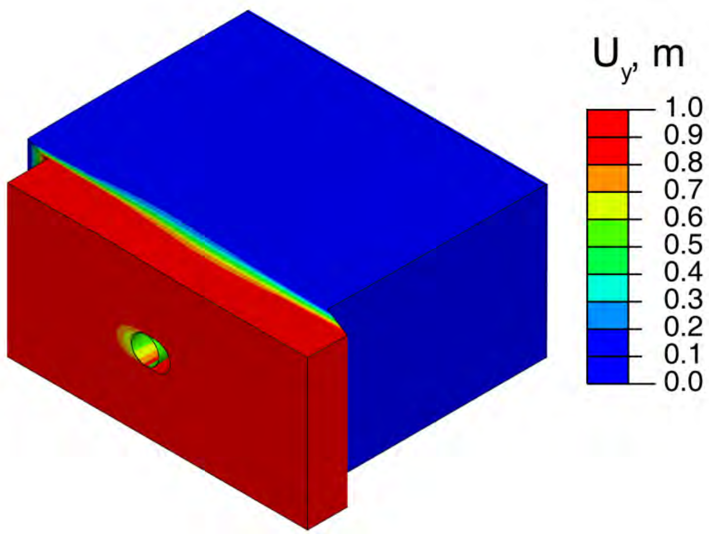
Pipelines in active faults

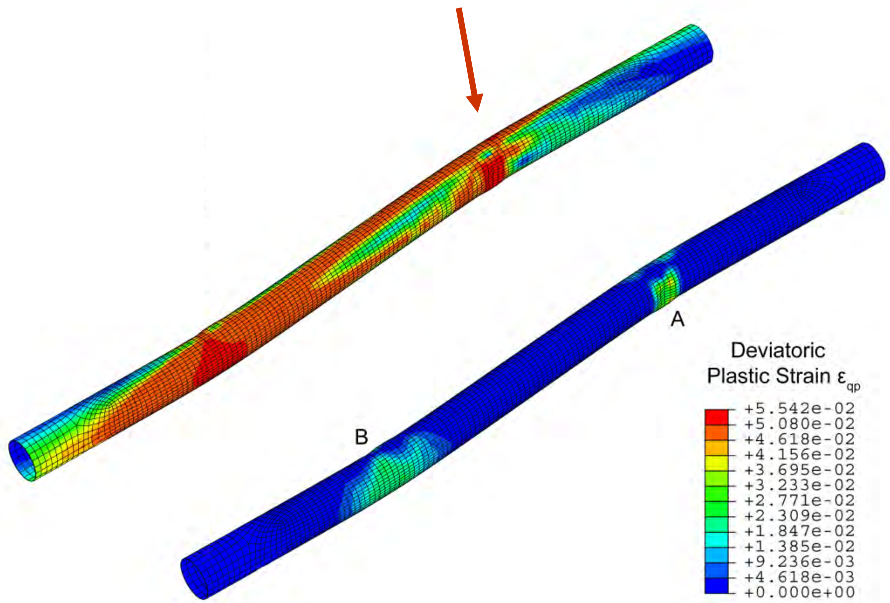
- Our work is a large investigation of pipeline behavior in geo-hazard areas.
- Numerical simulation with nonlinear finite element behavior; support by experimental testing (under development).
- The work is aimed at:
  - describing pipeline mechanical behavior
  - determining failure modes for various soil and pipe parameters
  - developing guidance for safe pipeline design in geo-hazard areas

Pipeline at active fault



Fault movement results in pipeline bending, development of significant stresses and strains, that may cause pipeline failure



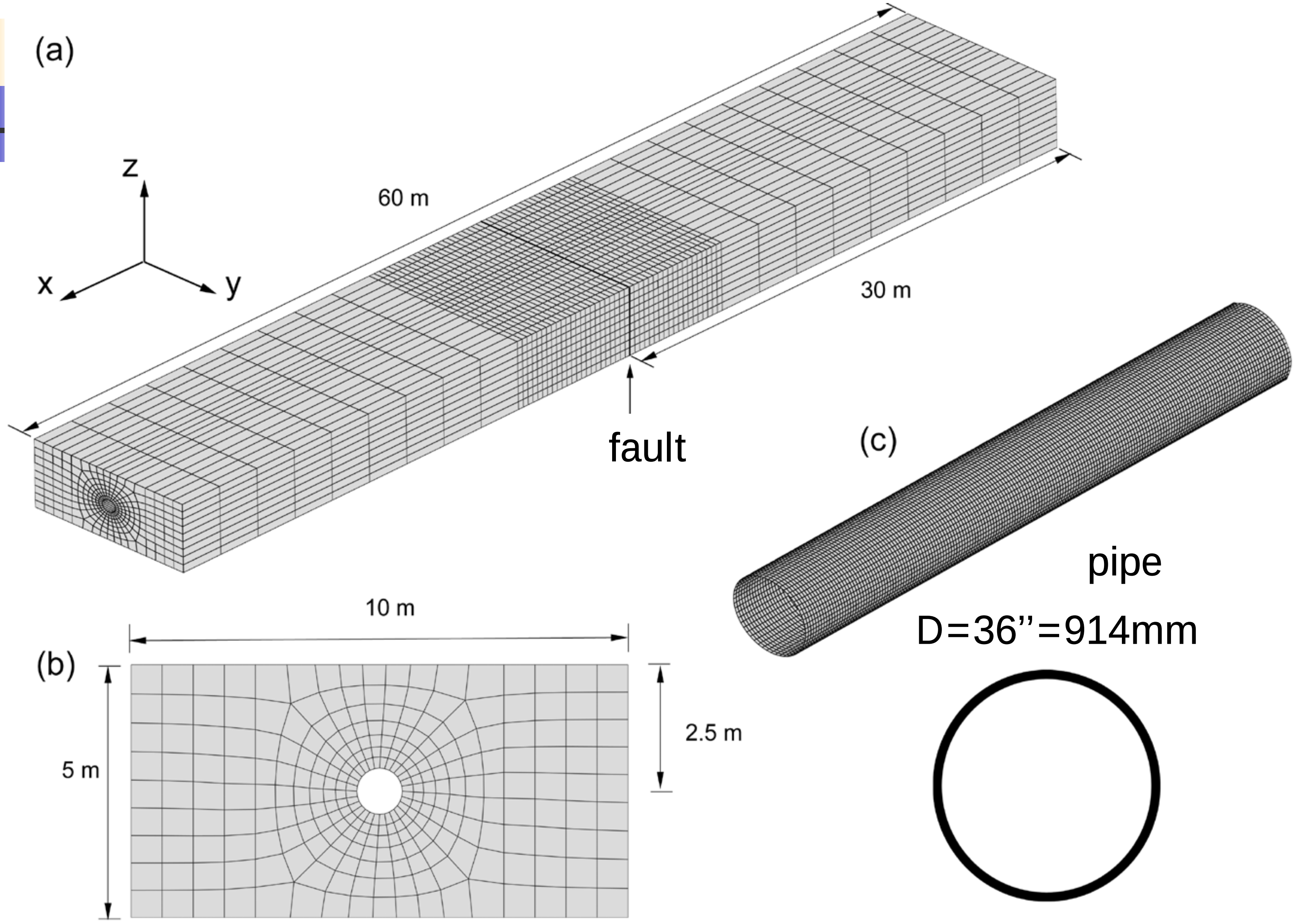


Finite element analysis

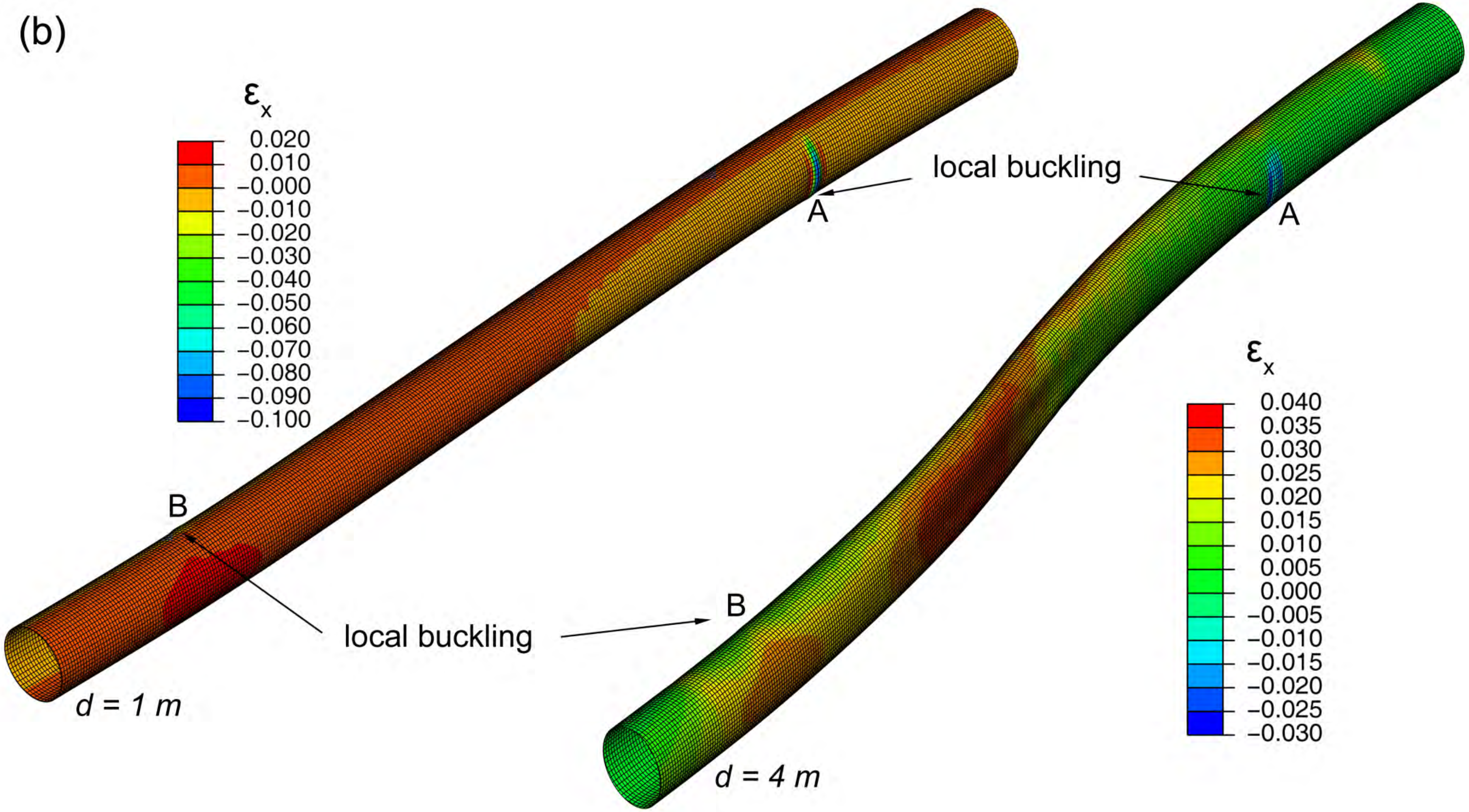
Finite element simulation

- finite element program ABAQUS 6.7
  nonlinear geometry – inelastic effects
- three-dimensional rigorous finite element model
  both **pipe and soil** simulated with finite elements
- inelastic material model for the soil
  Mohr-Coulomb; development of more elaborate models
- inelastic material behavior for the steel pipeline
  J_2 flow theory, isotropic hardening
- contact algorithm
  smooth contact or friction
- imposed fault movement
  displacement-controlled algorithm

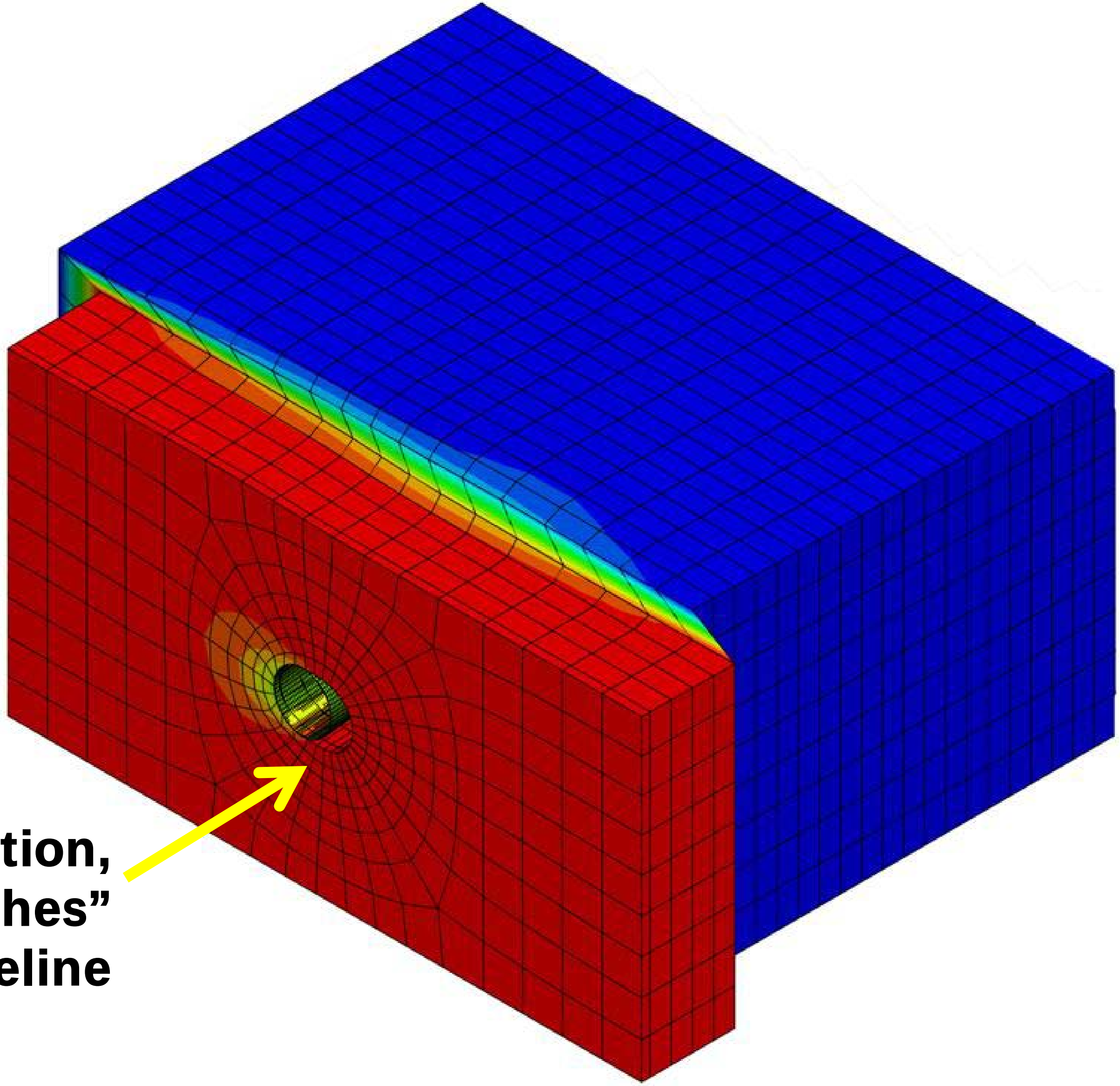
Finite element model



Pipeline at active fault

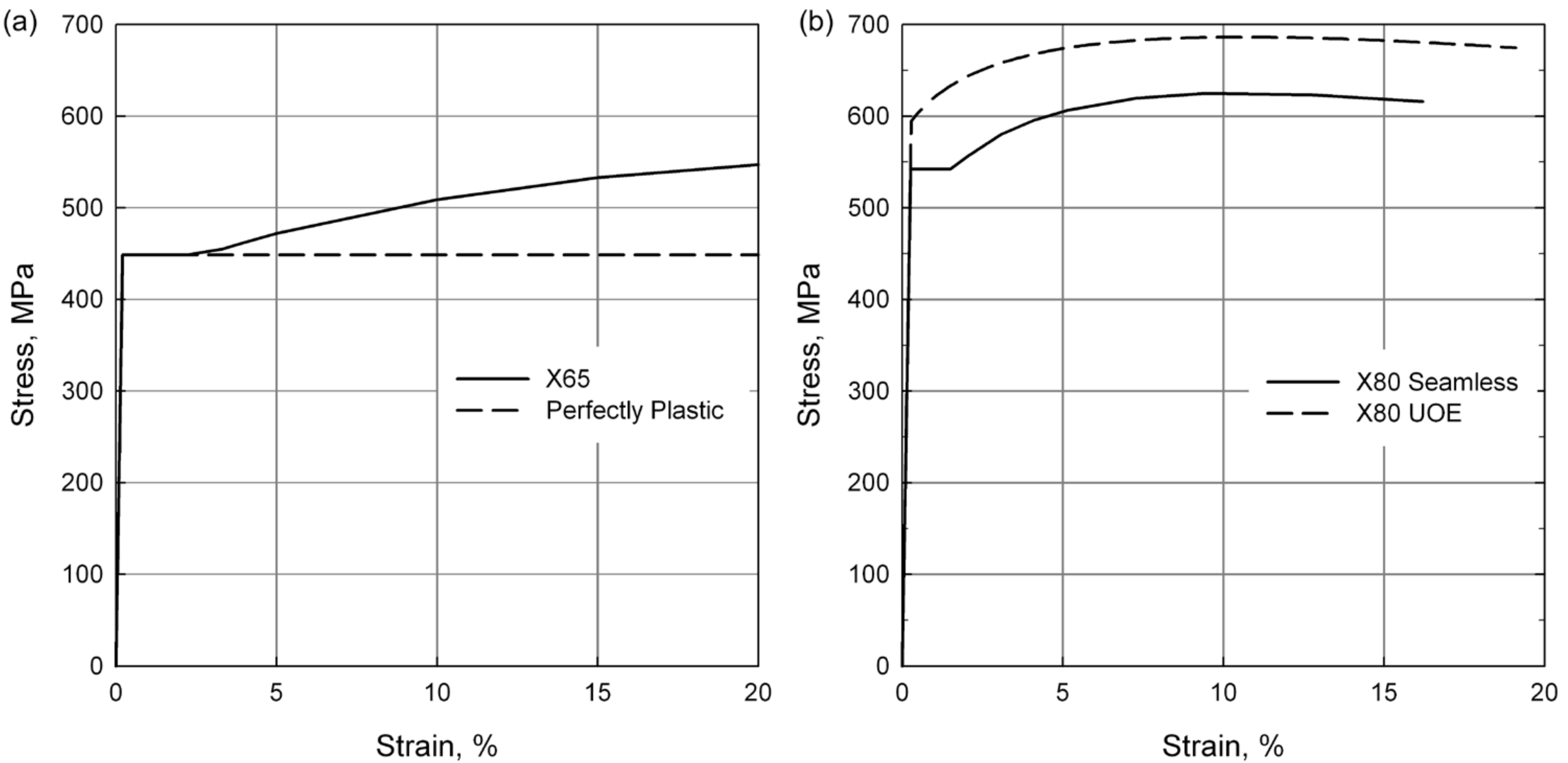


Soil – pipe interaction



with deformation, soil "detaches" from pipeline

Steel material

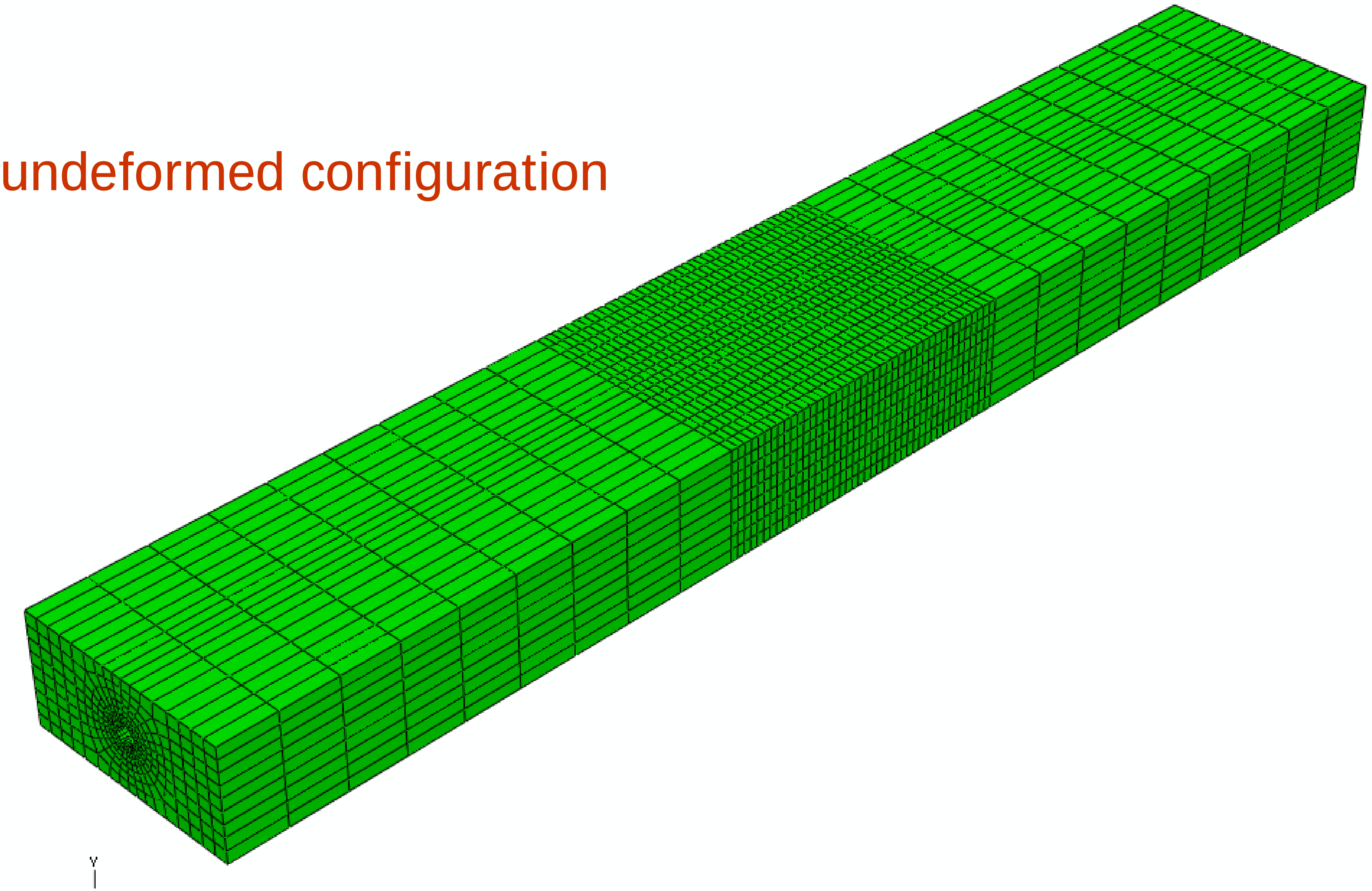


Parameters of analysis

- Soil cohesion and modulus; typical clay and sand soils are investigated.
- Type and direction of fault.
- Width of the fault zone.
- Pipeline diameter-to-thickness ratio (D/t)
- Pipe material yield stress and hardening.
- Level of internal pressure

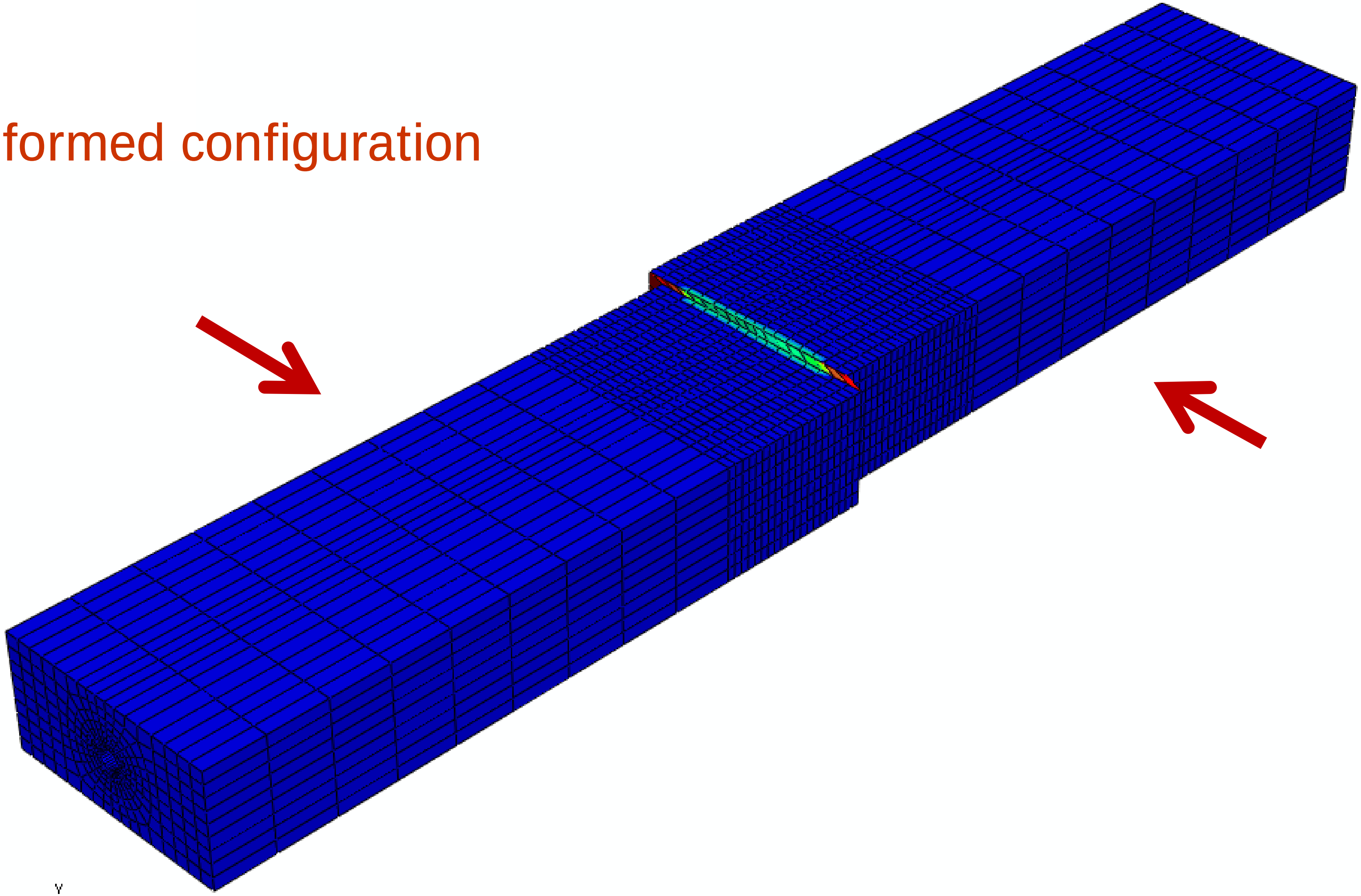
Numerical results

undeformed configuration

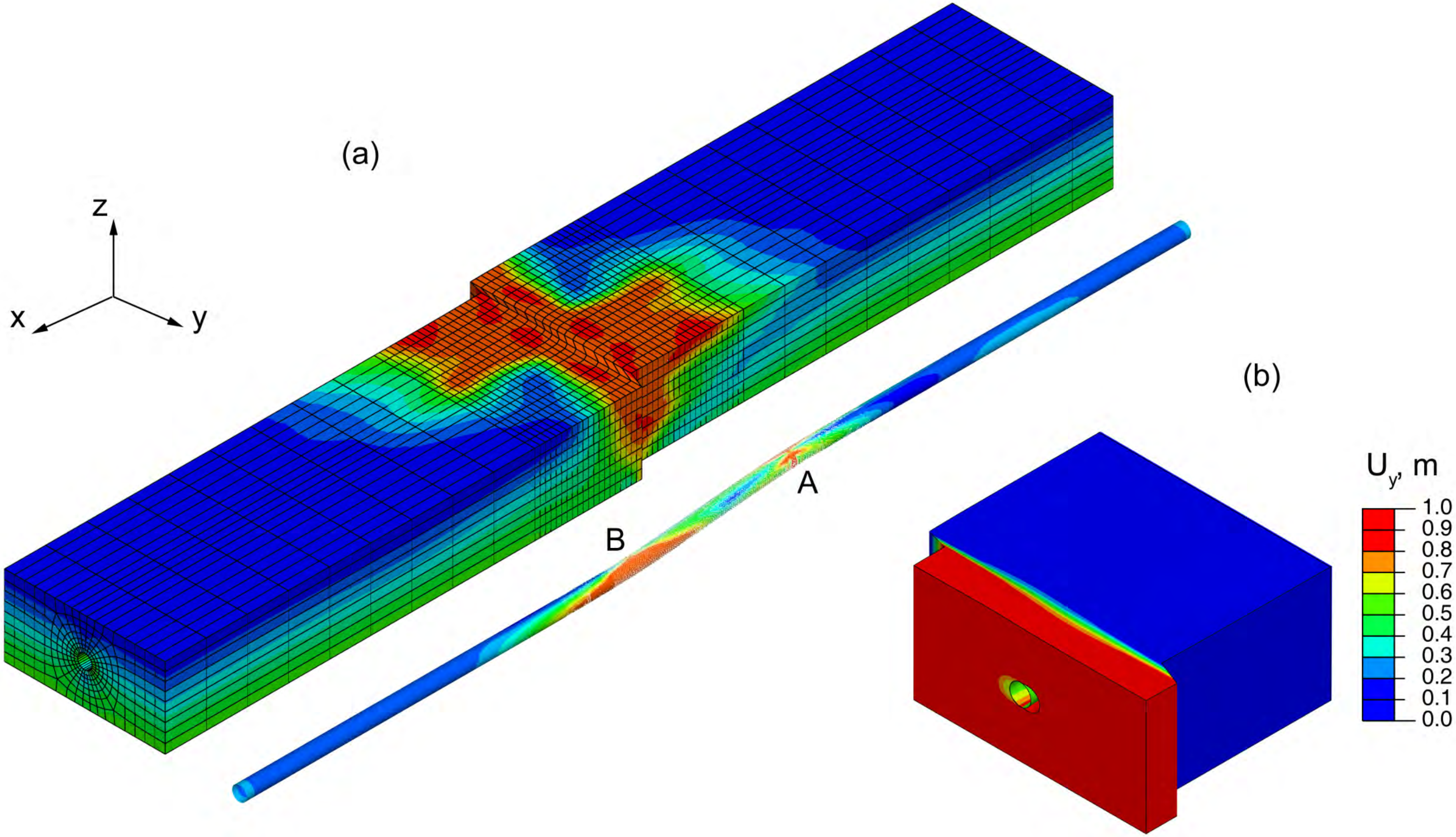


Numerical results

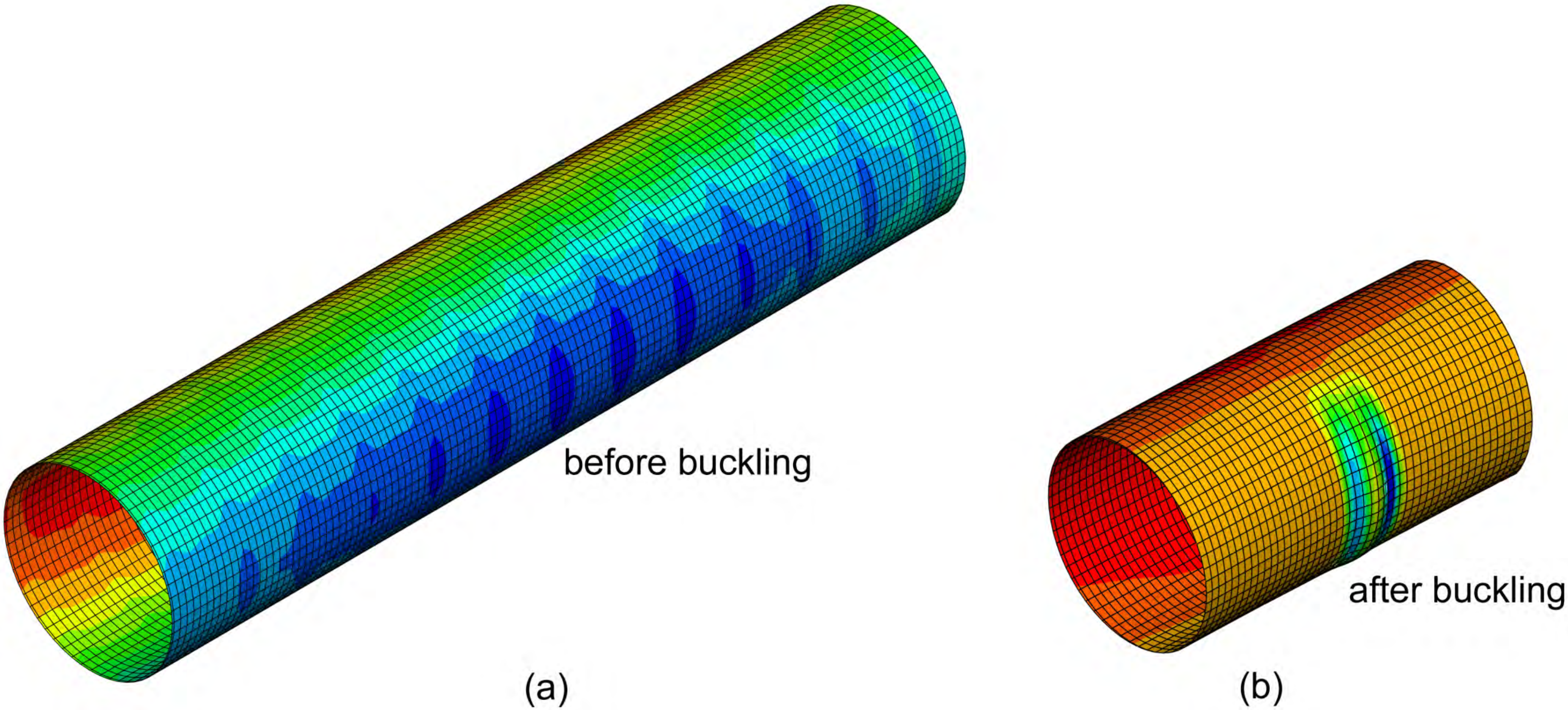
deformed configuration



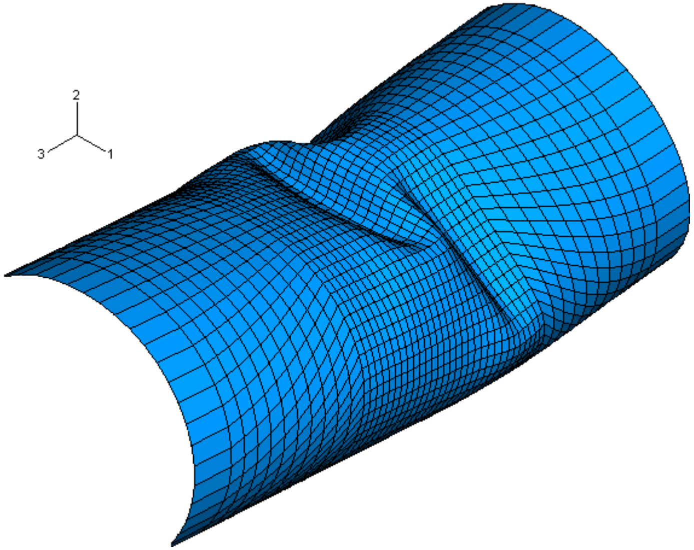
Numerical results

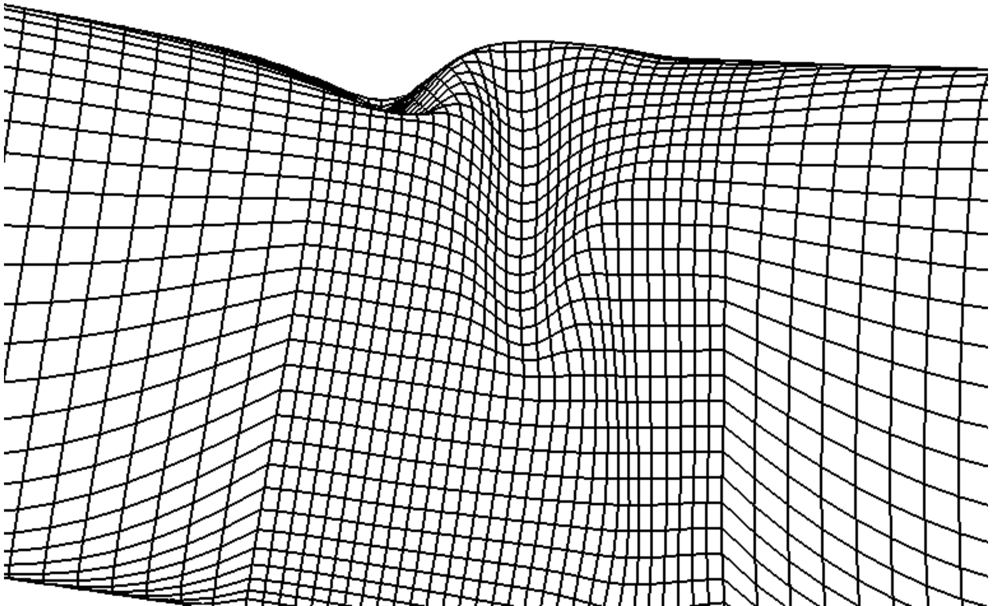


Numerical results



Buckle simulation



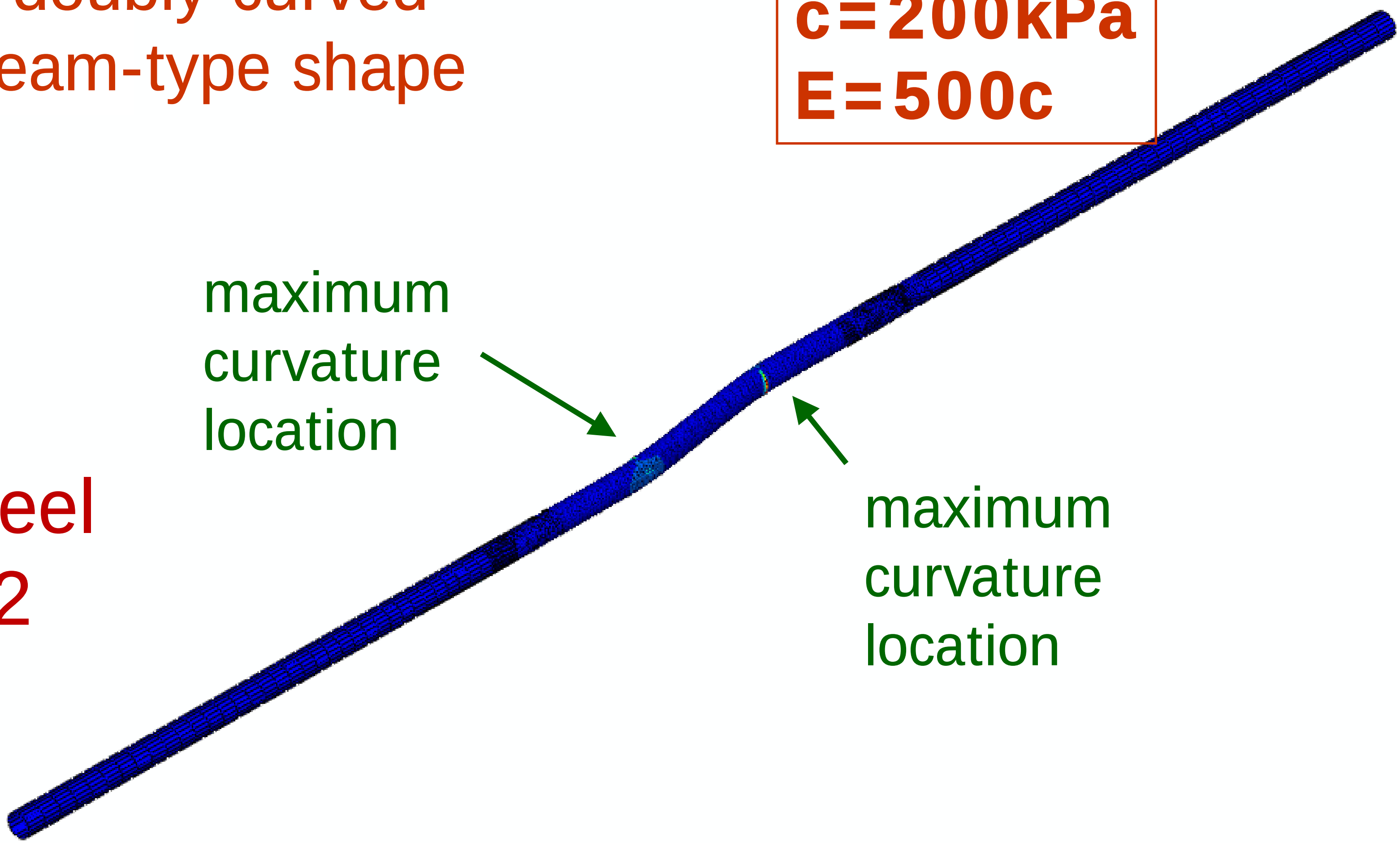


Pipe deformation

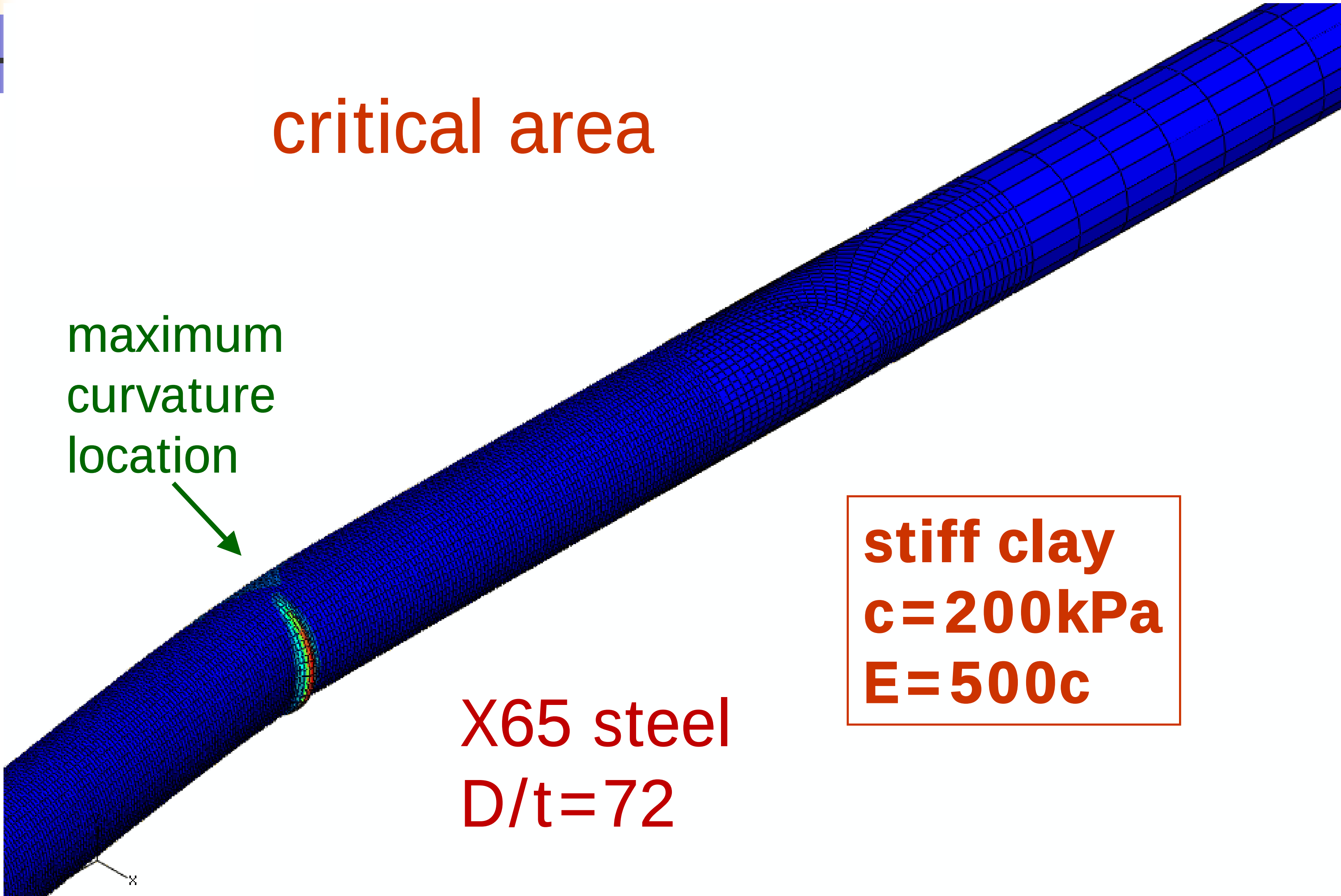
a doubly-curved beam-type shape

stiff clay
c=200kPa
E=500c

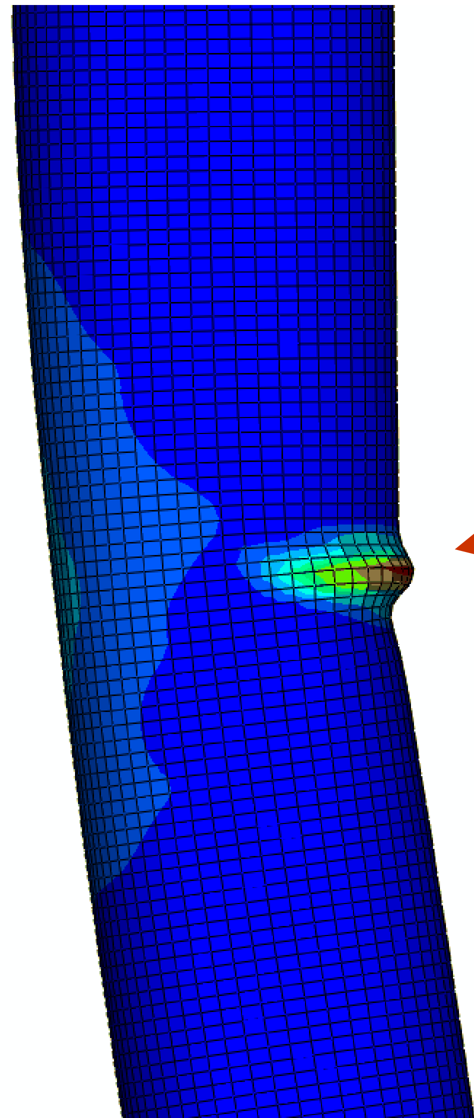
X65 steel
D/t=72



Pipe deformation



Pipe deformation



stiff clay
c=200kPa
E=500c

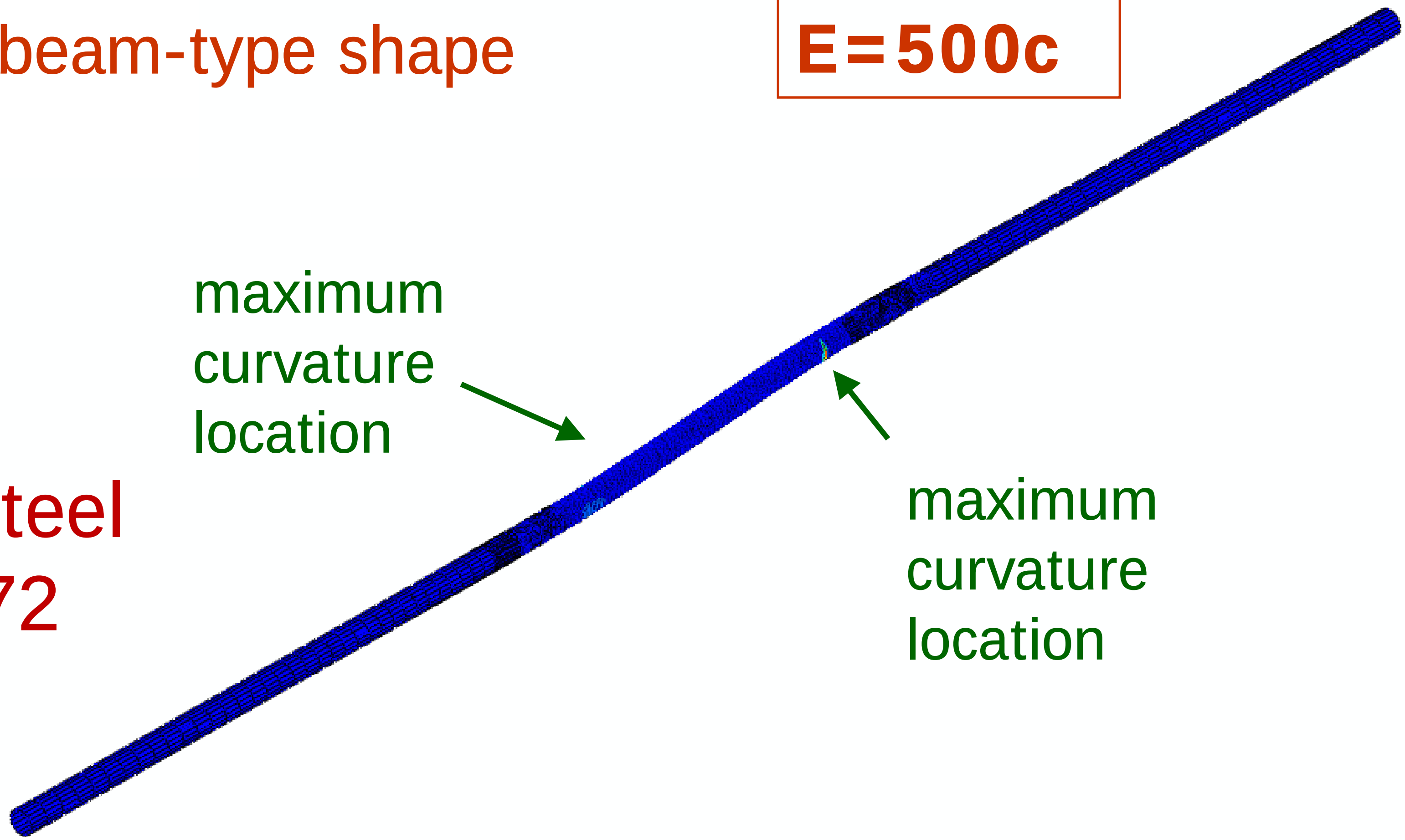
buckled shape

X65 steel
D/t=72

Pipe deformation

a “smoother”
beam-type shape

soft clay
c=50kPa
E=500c

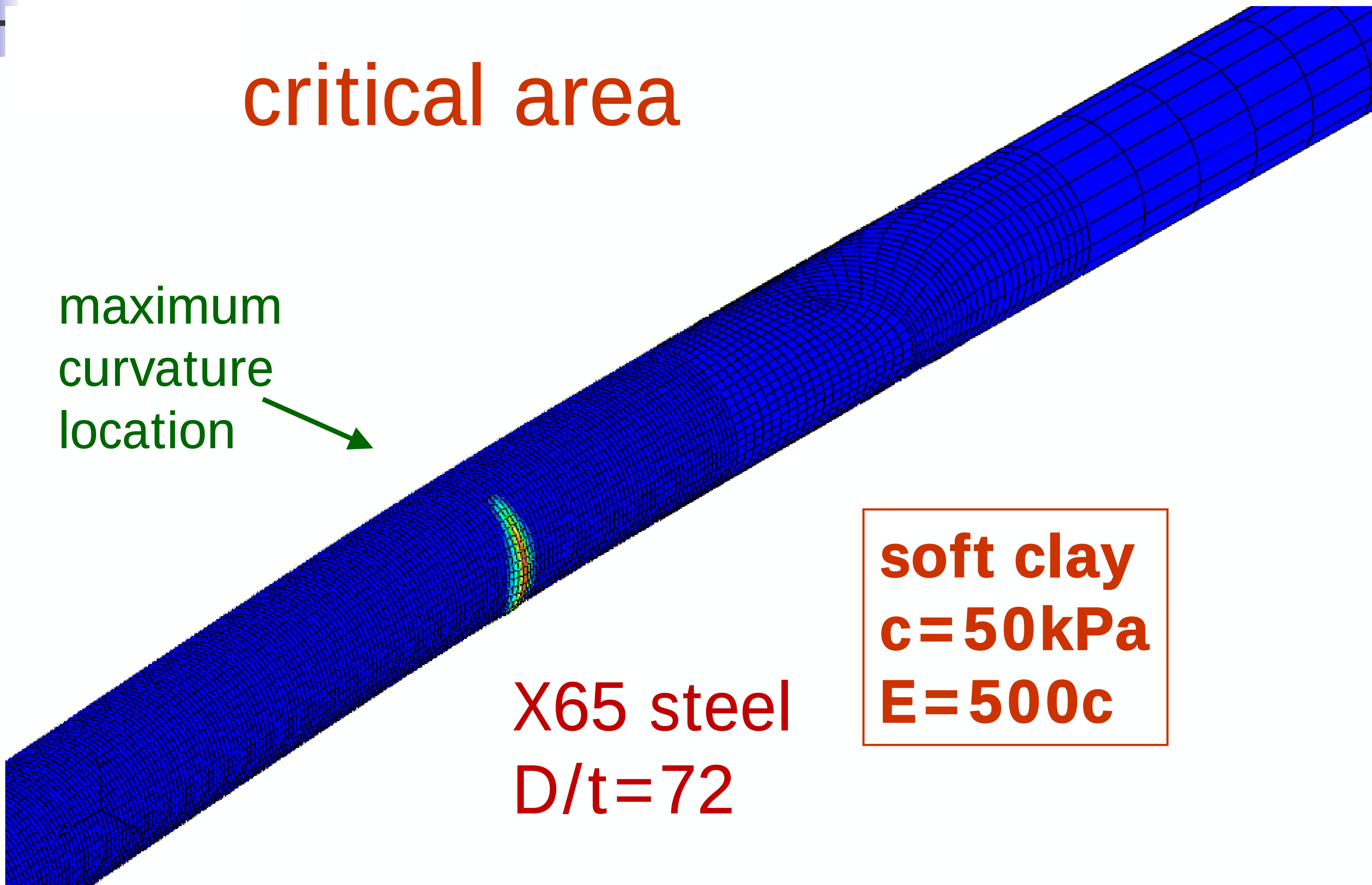


X65 steel
D/t=72

Pipe deformation

critical area

maximum
curvature
location

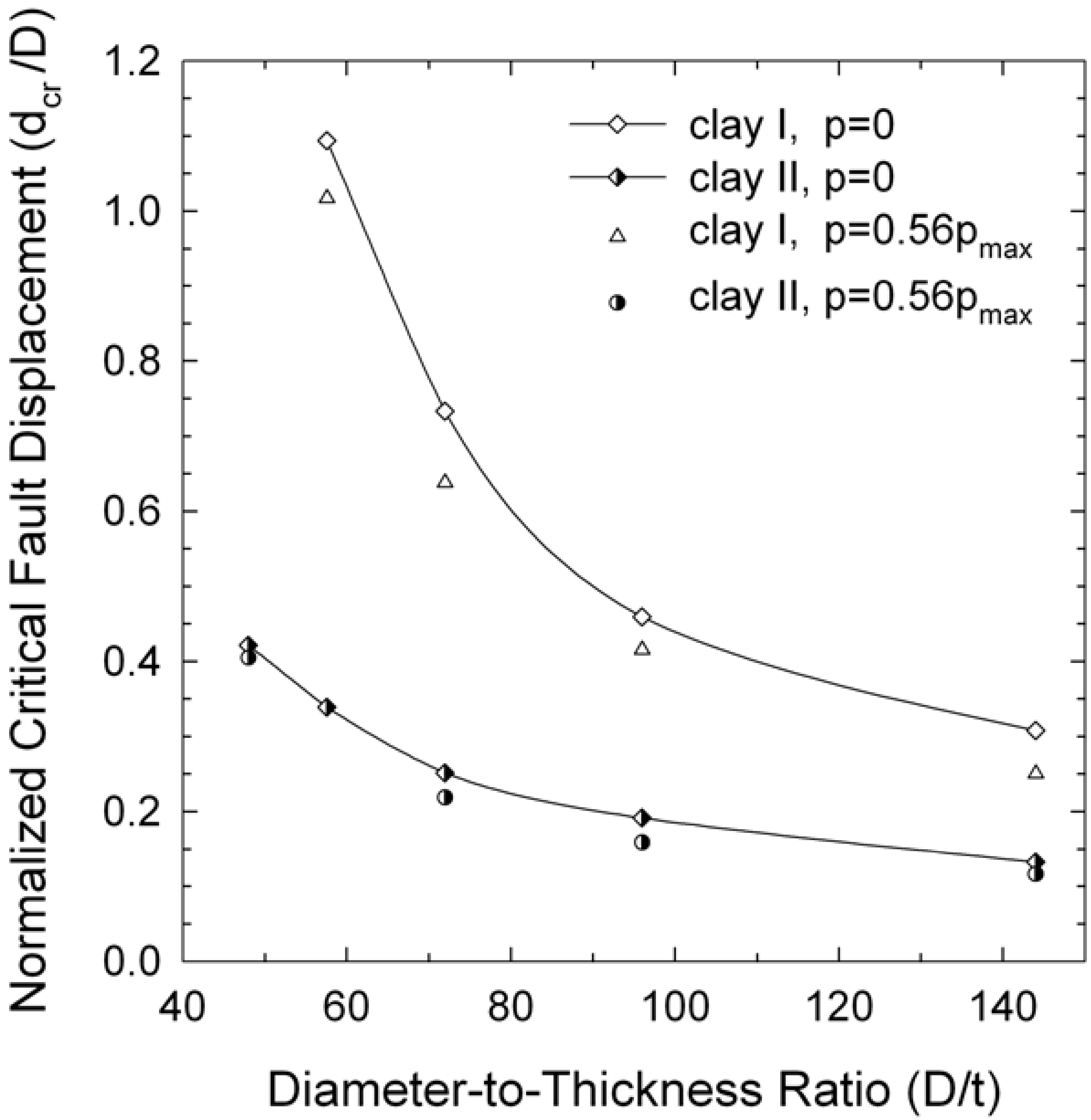


X65 steel
D/t=72

soft clay
c=50kPa
E=500c

Cohesive soils

- X65 pipe
- normal fault
- Clay I (soft)
- Clay II (stiff)



Cohesive soils

- X65 pipe
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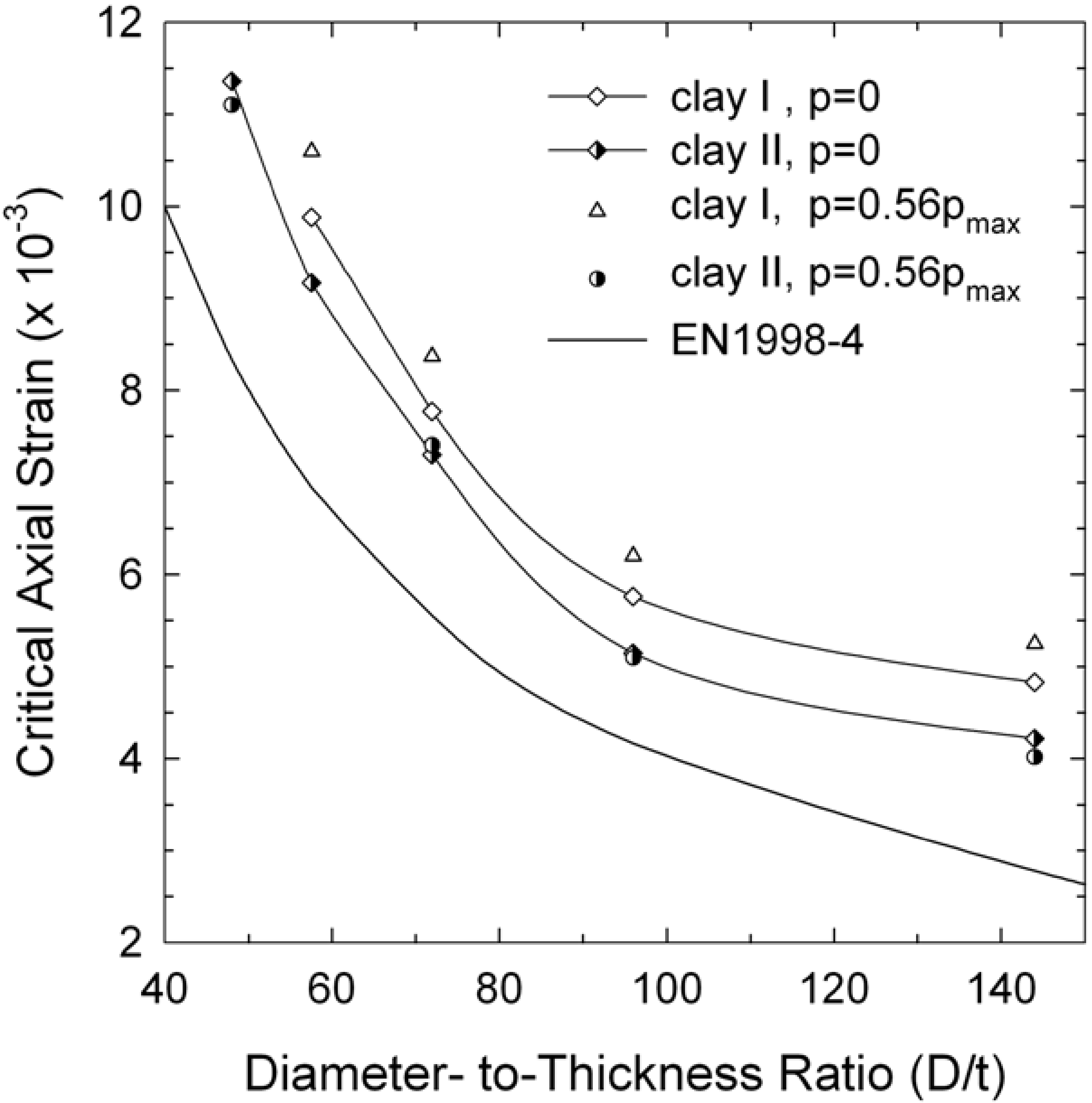
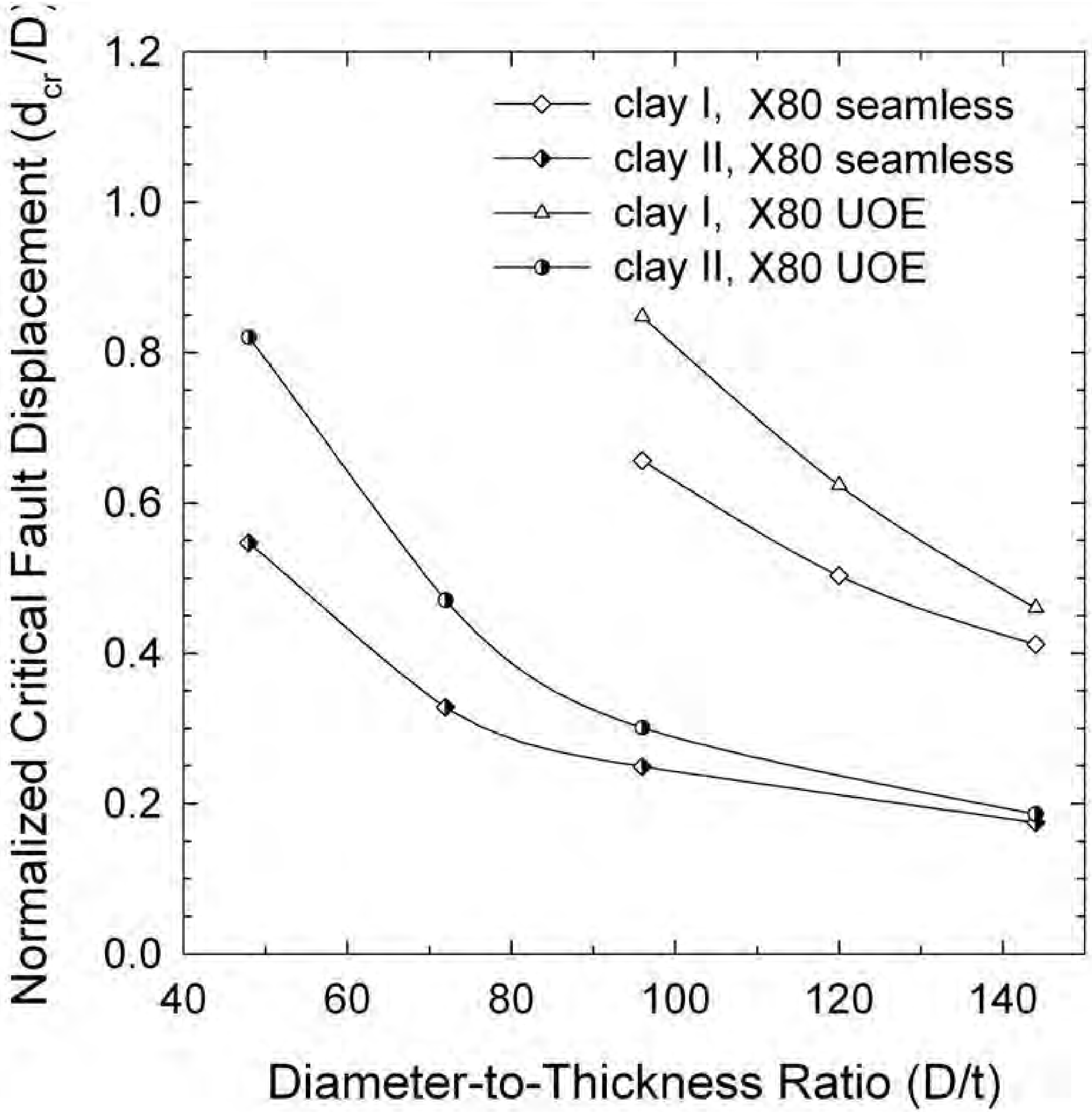


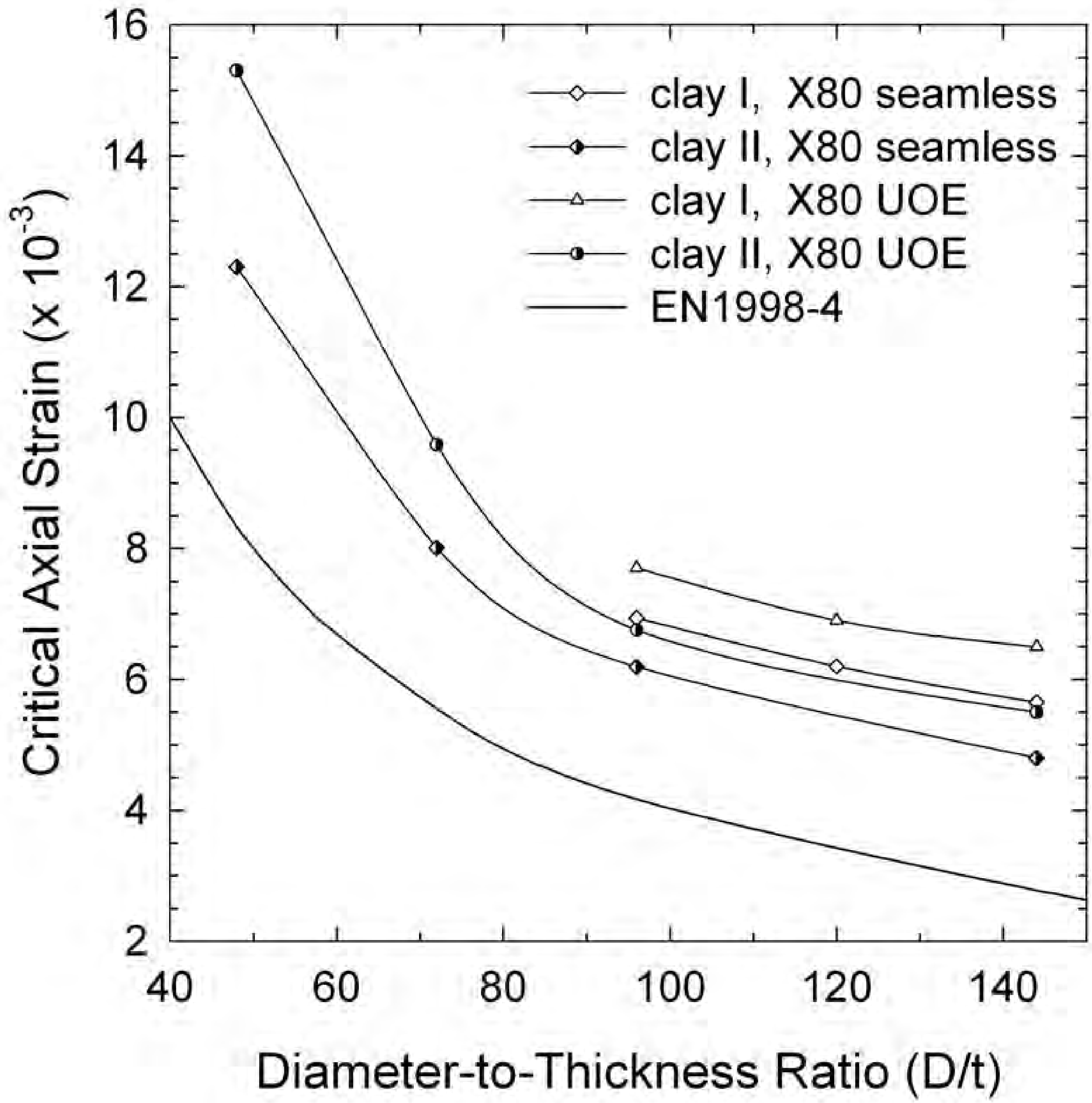
Cohesive soils

- X80 pipe
- normal fault
- Clay I (soft)
- Clay II (stiff)

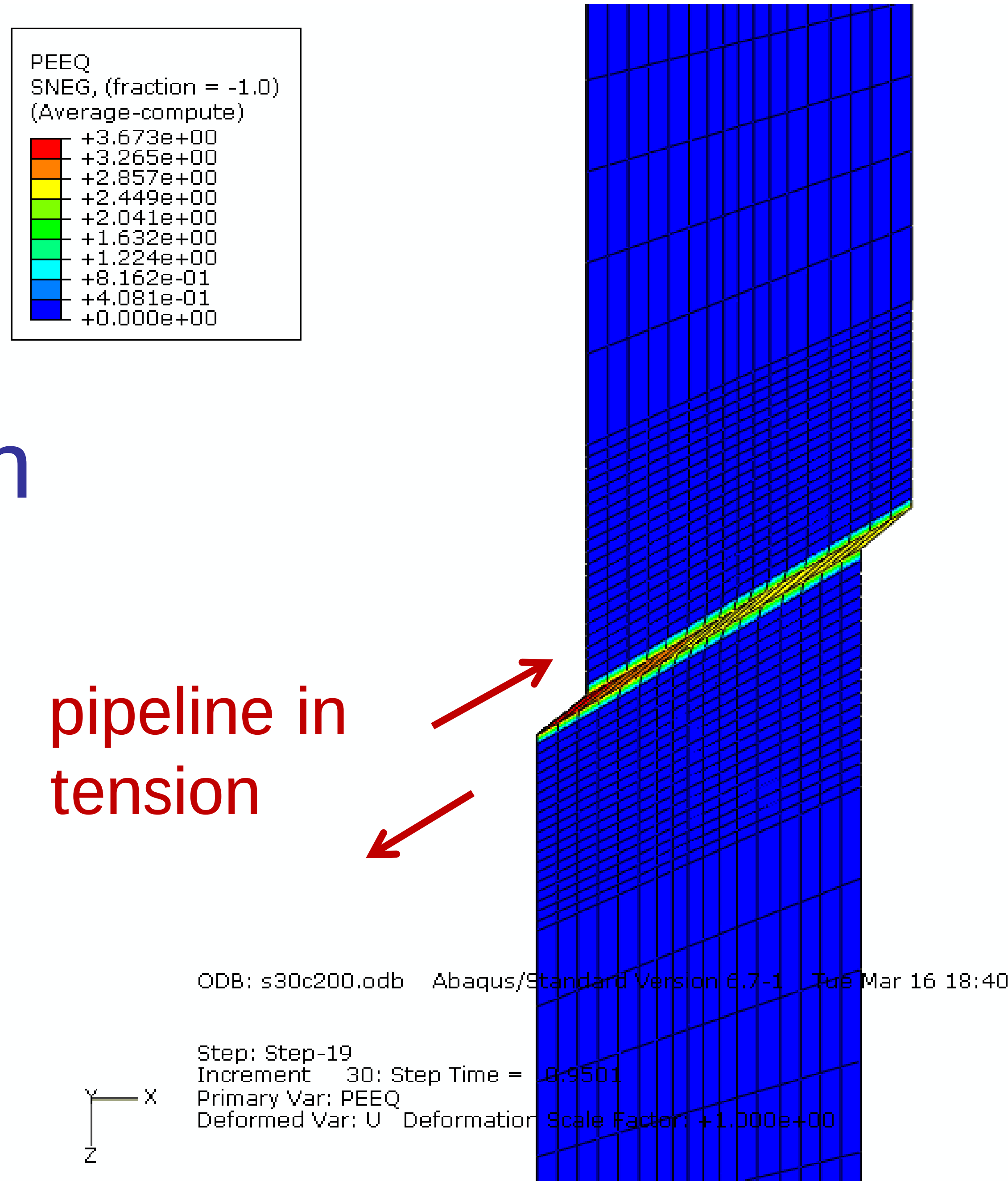


Cohesive soils

- X80 pipe
- normal fault
- Clay I (soft)
- Clay II (stiff)

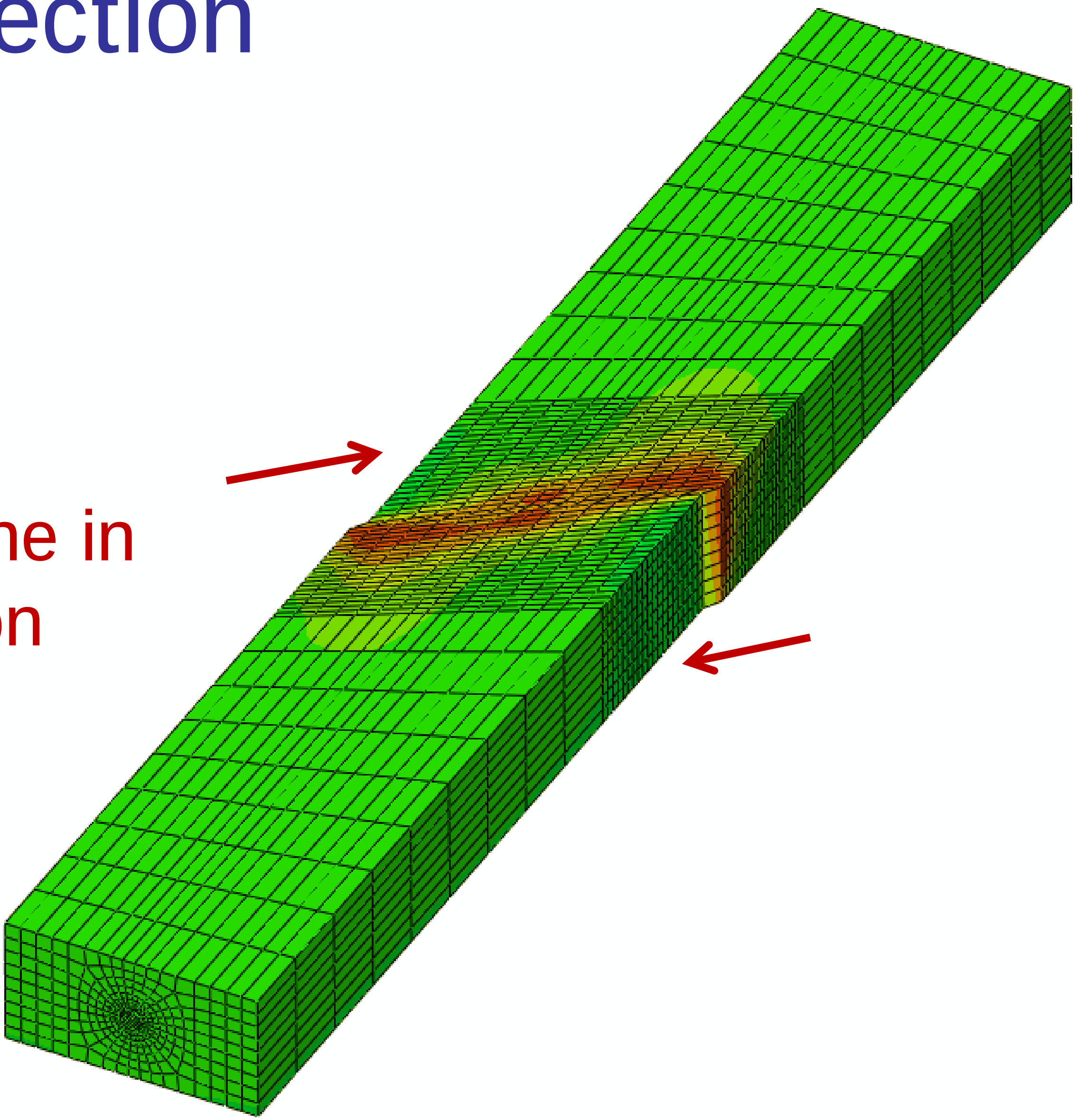


Fault at an oblique direction

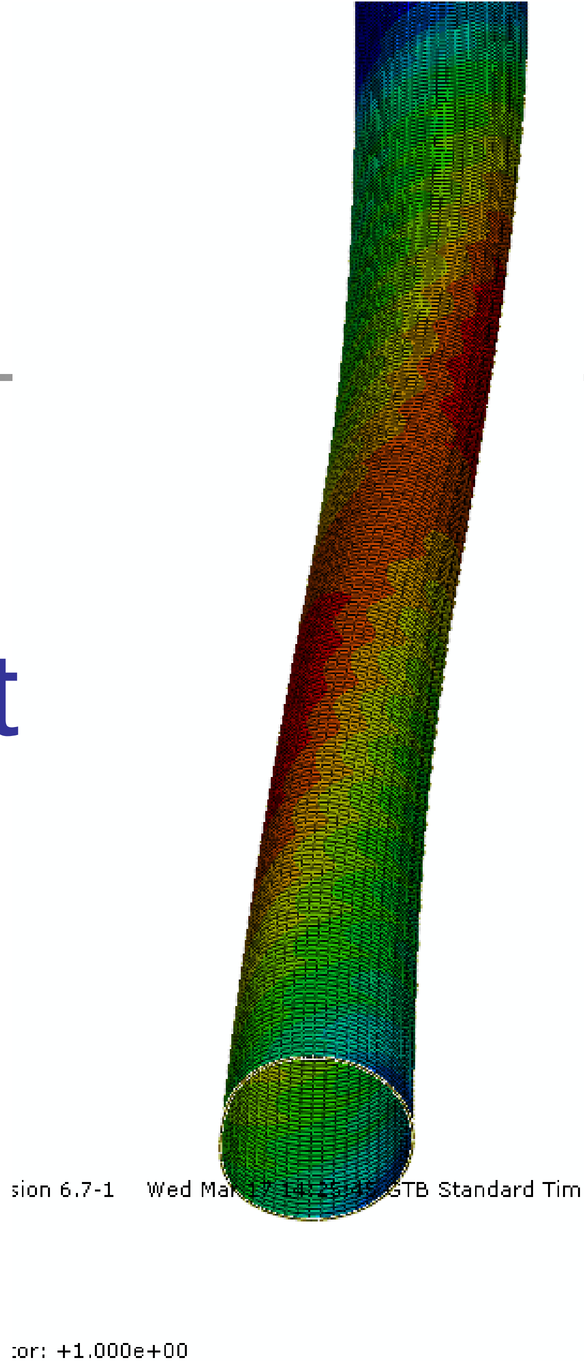


Fault at an oblique direction

pipeline in tension



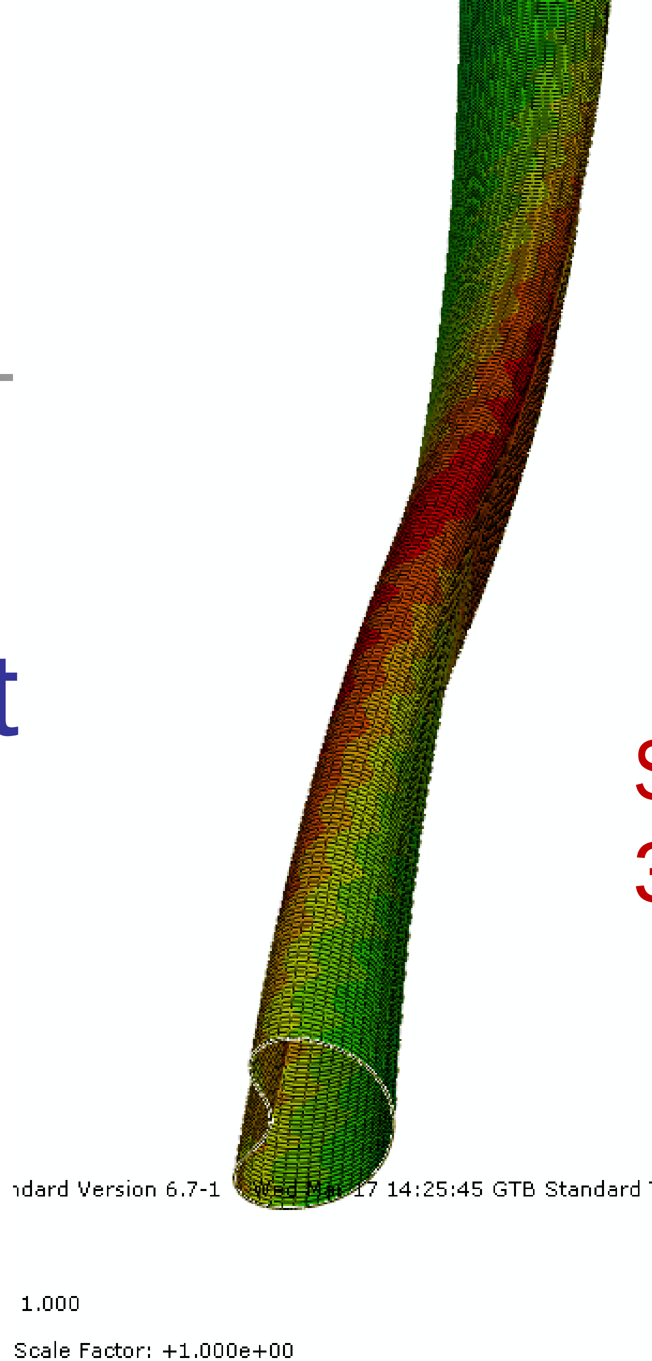
Fault displacement 80 cm



Soft clay

30^{o} angle

Fault displacement 150 cm



Soft clay

30^{o} angle

Conclusions

- Seismic (permanent) action imposes a threat for the structural integrity of the pipeline.
- Pipeline tectonic faults may cause wall buckling, cross-sectional distortion that may lead to pipe wall rupture.
- Development of numerical finite element models can be used as a numerical lab for simulating pipeline behavior.
- Results can be used for design purposes.
- Need for guidelines to design pipelines in high-seismicity areas.

Future work

- Examine behavior under normal and reverse fault movement.
- Extend to other types of geo-hazard: landslides, settlements, lateral spreading.
- Design a full-scale device for experimental investigation of the soil-pipeline interaction under strike-slip fault displacement for experimental verification.
- Propose “special measures” for mitigating geo-hazard risk of failure in the steel pipeline.

Publications

- Vazouras, P., Karamanos, S. A., and Dakoulas, P., "FINITE ELEMENT ANALYSIS OF BURIED STEEL PIPELINES UNDER STRIKE-SLIP FAULT DISPLACEMENTS", *Soil Dynamics & Earthquake Engineering,* 30 (11), 1361–1376, Nov. 2010*.*
- Vazouras, P., Karamanos, S. A., and Dakoulas, P., "NUMERICAL SIMULATION OF BURIED STEEL PIPELINE MECHANICAL BEHAVIOR IN ACTIVE FAULT AREAS", ASME Conference on *Offshore Mechanics & Earthquake Engineering*, Rotterdam, June 2011*.*
- Vazouras, P., Karamanos, S. A., and Dakoulas, P., "STRUCTURAL BEHAVIOR OF BURIED STEEL PIPELINES IN ACTIVE FAULT AREAS", *under preparation.*

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