Industrial Applications of Computational Mechanics Shear Walls and Fluids

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FEM - Reminder

- A mathematical method
- The real (continuous) world is mapped on to a discrete (finite) one.
- We restrict the space of solutions.
- We calculate the optimal solution within that space on a global minimum principle
- Don’t expect local precision

Plates (Slabs and shear walls)

- Classical plate bending solution (Kirchhoff)

$$K \, \Delta\Delta \, w = p$$

- Classical solution for shear walls (Airy stress function F)

$$\Delta\Delta \, F = 0$$

- FE / Variational approach for bending plates

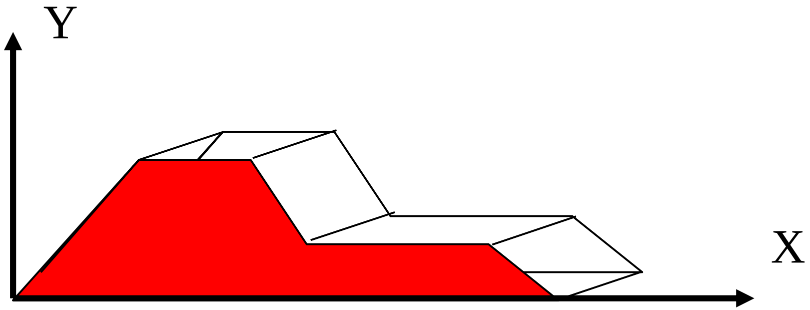
$$\Pi = \tfrac{1}{2} \int \kappa \, D \, \kappa \, dV = \text{Minimum}$$

- FE / Variational approach for shear walls

$$\Pi = \tfrac{1}{2} \int \varepsilon \, D \, \varepsilon \, dV = \text{Minimum}$$

Shear Walls

- Unknowns:
  Displacements $u=u_x$ and $v=u_y$
  Rotation φ_z is not defined (see Cosserat)
- Strains
  $\varepsilon_x = \partial u / \partial x \;;\; \varepsilon_y = \partial v / \partial y$
  $2\,\varepsilon_{xy} = \gamma_{xy} = \partial v / \partial x + \partial u / \partial y$
- stresses
  $\sigma_x , \sigma_y , \tau_{xy} [, \sigma_z]$
- Plane Strain Condition $\varepsilon_z = 0$
- Plane Stress Condition $\sigma_z = 0$



Plane Stress Condition

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \frac{E}{1-\mu^2} \begin{bmatrix} 1 & \mu & 0 \\ \mu & 1 & 0 \\ 0 & 0 & (1-\mu)/2 \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}$$

$$\begin{bmatrix} n_x \\ n_y \\ n_{xy} \end{bmatrix} = \frac{E \cdot t}{1-\mu^2} \begin{bmatrix} 1 & \mu & 0 \\ \mu & 1 & 0 \\ 0 & 0 & (1-\mu)/2 \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}$$

Extended Formulation

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \\ \sigma_z \end{bmatrix} = \frac{E}{(1+\mu)(1-2\mu)} \begin{bmatrix} 1-\mu & \mu & 0 & \mu \\ \mu & 1-\mu & 0 & \mu \\ 0 & 0 & (1-2\mu)/2 & 0 \\ \mu & \mu & 0 & 1-\mu \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \varepsilon_z \end{bmatrix}$$

- Shear modulus G = E/(2*(1+m)) at Position 3,3
- Plane Strain $\varepsilon_z = 0$
- Axisymmetric condition $\varepsilon_z = u/r$

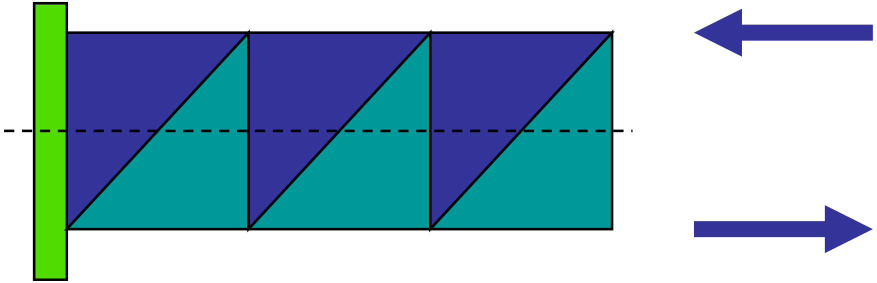
Remarks

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\\ \sigma_z\end{bmatrix} = \frac{E}{(1+\mu)(1-2\mu)}\begin{bmatrix}1-\mu & \mu & 0 & \mu\\ \mu & 1-\mu & 0 & \mu\\ 0 & 0 & (1-2\mu)/2 & 0\\ \mu & \mu & 0 & 1-\mu\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\\ \varepsilon_z\end{bmatrix}$$

- Incompressible limit
  - For $\mu = 0.5$ the matrix becomes singular
- Extensions for anisotropic behaviour via inverse matrix
  - E-Modulus in fibre direction $\varepsilon_x = \sigma_x/E_x + \mu_{xy} \bullet \sigma_y/E_y$
  - E-Modulus transverse to fibre direction (E_{90}) analogue
  - Poisson ratio for off diagonal term is not uniquely defined
  - Rotation of axis of Isotropy creates a fully populated matrix
  - Special effects for foams possible

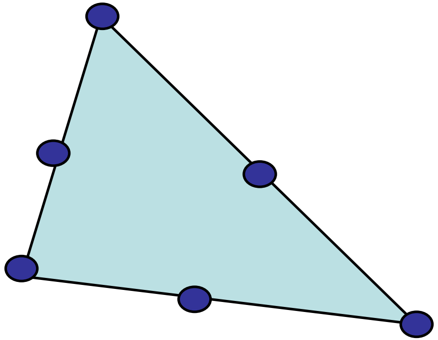
Membrane element

- constant strain triangular elements CST
    - Linear displacements
    - Constant stress



Enhanced triangular elements

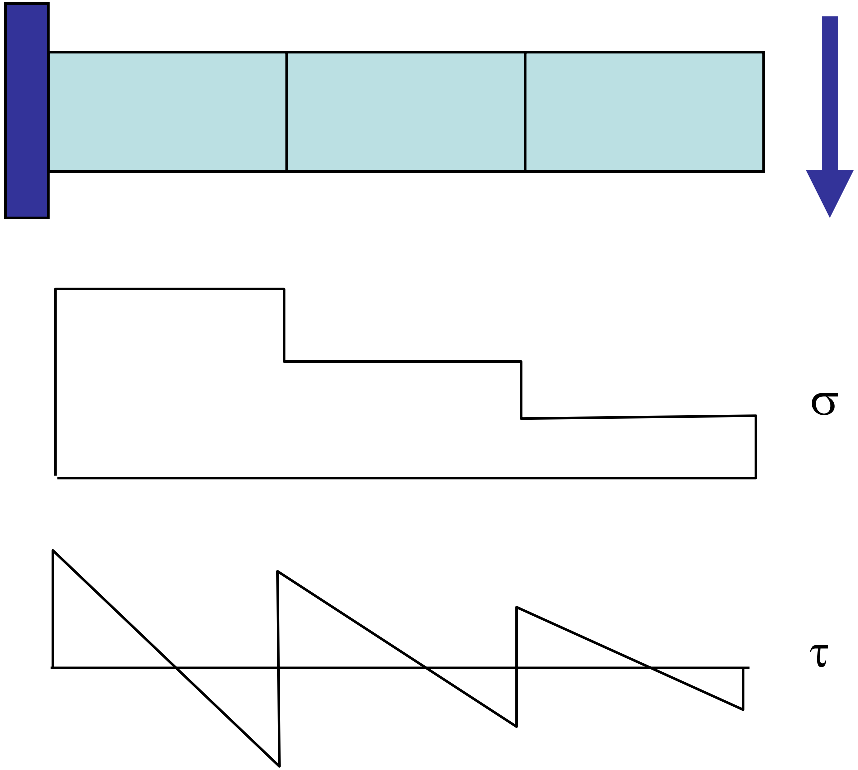
- LST – Element with 6 nodes
  - Complete quadratic function space



  - Drilling-Degrees of Freedom
    - The displacements of the mid nodes are calculated from the end nodes including the rotation

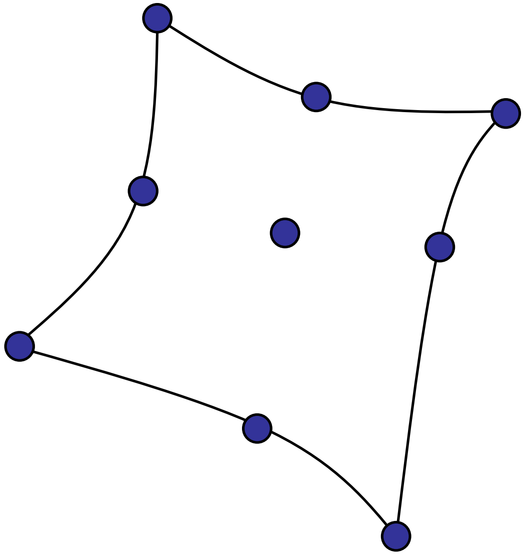
Membrane Elements

- Quadrilateral bilinear elements
  - Linear Displacements
  - Constant stress
  - Shear stress may become spurious



Enhancements

- Quadratic Shape functions
  - Lagrange Elements
    (nine noded)
  - Serendipity
    (without central node)
  - „Isoparametric“
  - “Isogeometric”



Disadvantages

- Uniform loadings creates nodal loads as:
  1/6 , 2/3 , 1/6
- Thus coupling with beam elements is difficult,
  i.e. we need also isoparametric beam elements
- Special coupling conditions (friction, no tension etc.) also difficult, i.e. we need isoparametric interface elements

Drilling Degrees I

- Same principle as with the triangular element
- Further mathematical tricks required to reduce the space of the shape functions compared to the Serendipity-Element
- Moments as nodal loads not easy to understand / handle
- Advantages for folded structures or shells expected
- My own benchmarks showed poor quality of results.

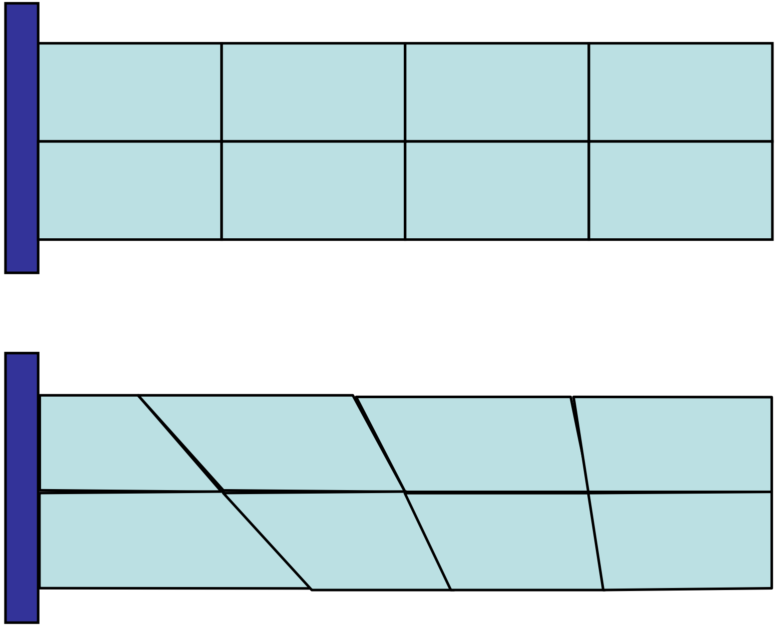
Enhancements

- Bilinear non conforming (Wilson)

  $u = ... + (1-s^2)\ q1 + (1-t^2)\ q2$

  $v = ... + (1-s^2)\ q1 + (1-t^2)\ q2$
- May model constant curvatures exactly
- Static Condensation
- Patch-Test fulfilled with a trick
  (Jacobi-Determinant is treated as constant)
- Newer approach: Assumed strains

Patchtest



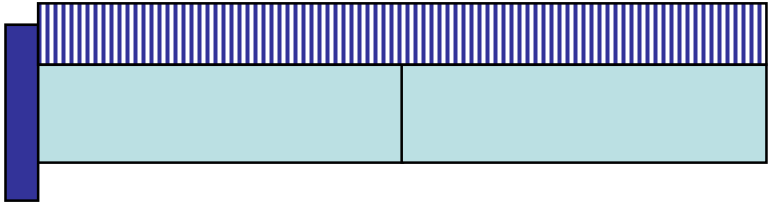
Patchtest (σ)

Moment	constant		linear		quadratic	
Mesh	x=0	x=l/2	x=0	x=l/2	x=0	x=l/2
Reference	1500	1500	1200	600	1200	300
R Q4+2	1500	1500	1051	600	940	337
V Q4+2	1322	1422	1422	701	773	452
R Q4	1072	1072	1072	428	659	240
V Q4	687	578	578	187	393	172

Patchtest (τ)

Moment	constant		linear		quadratic	
Mesh	x=0	x=l/2	x=0	x=l/2	x=0	x=l/2
Reference	0	0	50	50	100	50
R Q4+2	0	0	50	50	87.5	50
V Q4+2	58	28	65	80	130	73
R Q4	438	0	364	8	376	8
V Q4	502	220	380	294	366	11

Convergence of displacements



Mesh	u (Q4)	u (Q4+2)
1 x 8	0.715	1.035
2 x 16	0.939	1.036
4 x 32	1.010	1.038
8 x 80	1.021	1.039

Drilling Degrees II

- Better approach with a strain field (Hughes/Brezzi)

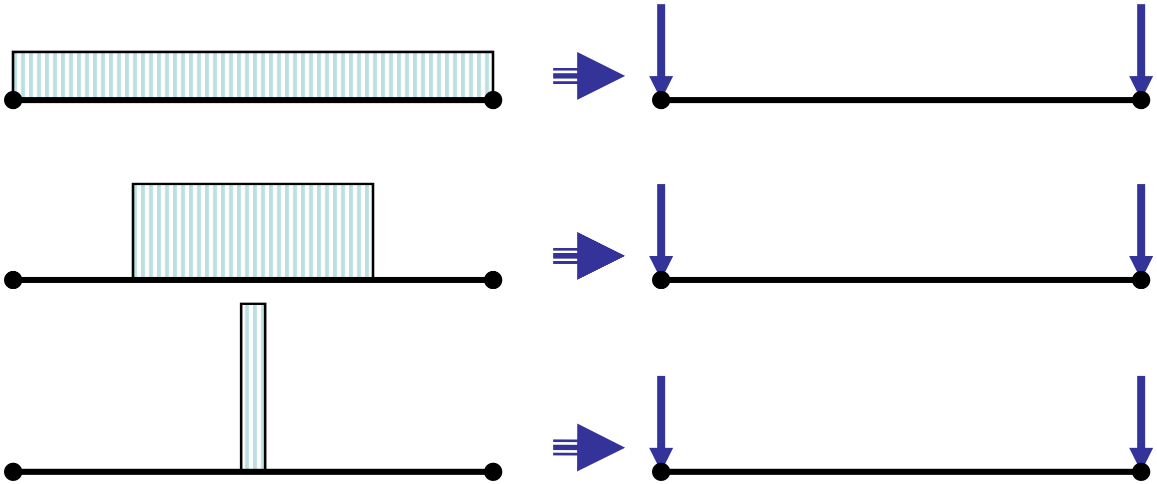
$$\Pi = \int (symm\,grad\,v) \cdot c \cdot (symm\,grad\,v)\, d\Omega +$$

$$\gamma \bullet \int \left| skew\,grad\,v - \omega \right|^2 d\Omega$$

- Constraint about the rigid body rotations
- Adding deformation energy makes the element stiffer
- Combination with nonconforming modes is recommended

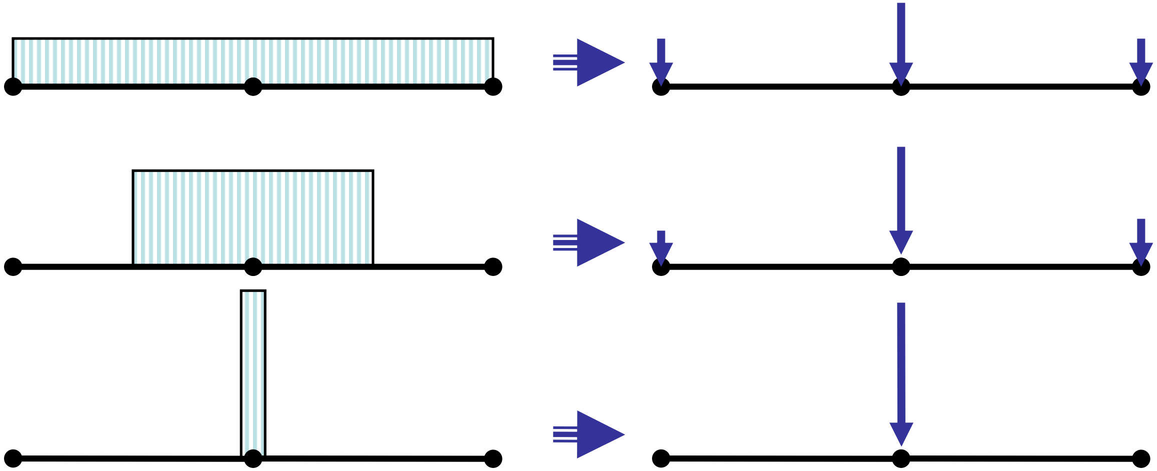
Loads

- Nodal loads are no point loads



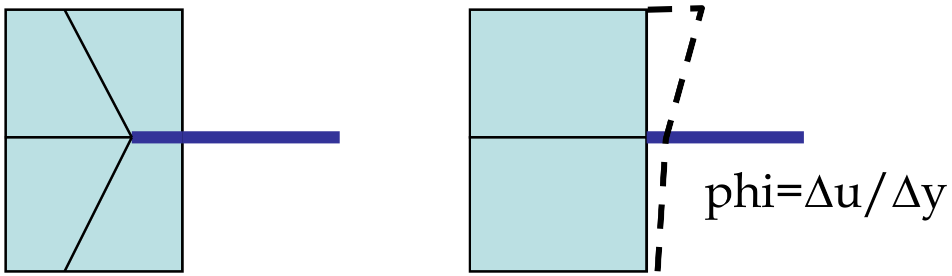
Loads

- Resolution of a mesh for loads



Moments

- There is no degree for that !
- Possibilities
  - Use more than one node
  - Kinematic Constraints, EST-Conditions
  - Drilling degrees of freedom

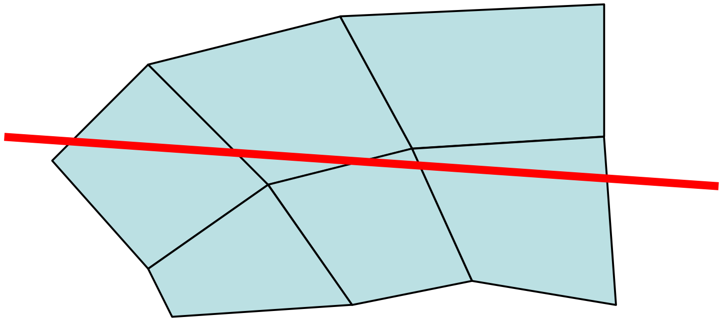


Result-Evaluation

- Direct solution: Displacements u
- Support Forces (Residuals) $f = K\,u - p$
  (exact for all degrees of freedom!)
- Stresses in elements
  - Centre (Mean value = Super convergent Point)
  - Gauss-Points
  - Nodes of elements (Extrapolation!)
- Mean values in nodes
- Error estimates

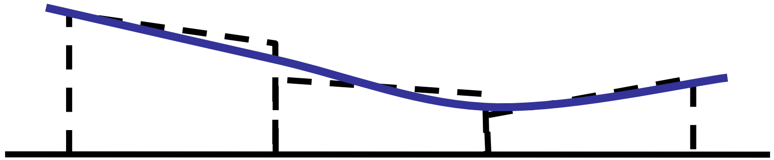
Equilibrium

- As it is the base for our solution it should be fulfilled for the residual forces even if system and loadings are completely garbage.
- It is not fulfilled within the elements
- It is not fulfilled at the edges of the elements
- It is not fulfilled within general cuts across the elements



Nodal stresses

- Stresses are discontinuous between elements

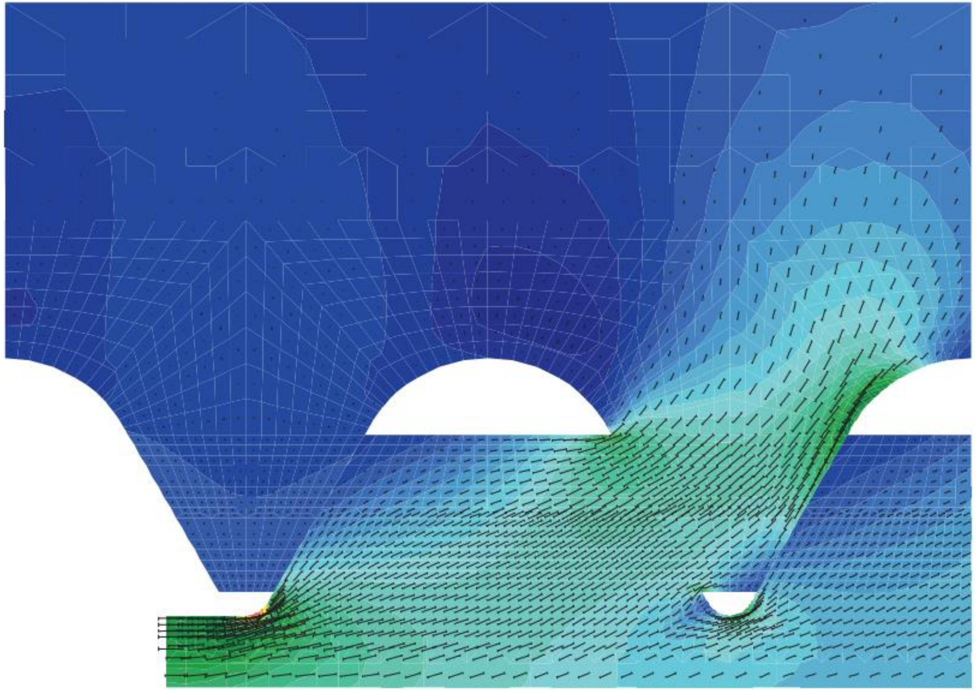


- The jump value of the stresses is a measure for the quality (e.g. error) of the solution for that mesh

Nodal stresses

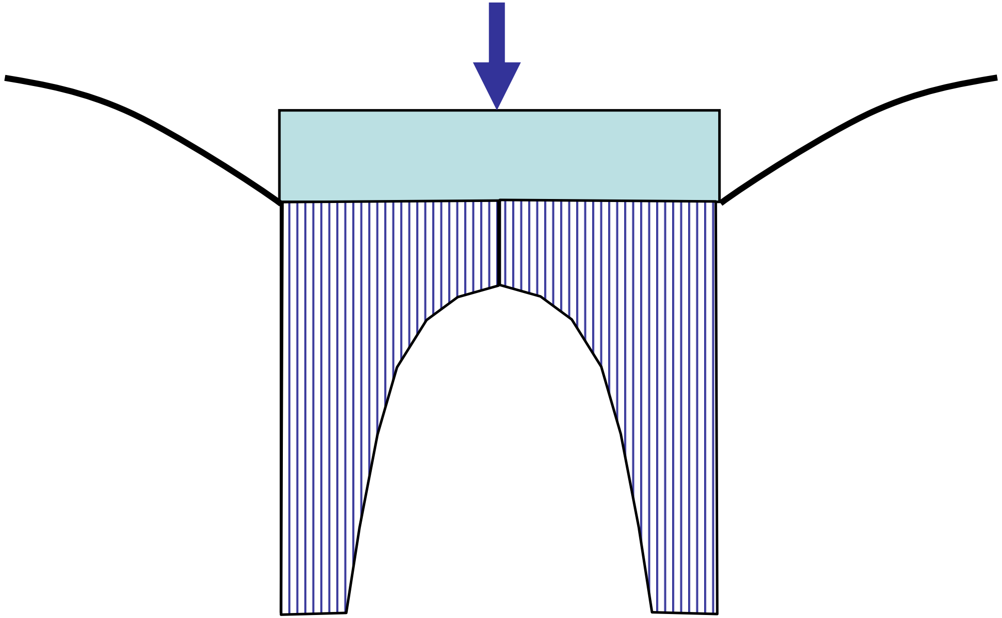
- Mean value of stresses in nodes to obtain „nicer“ pictures
  - Discontinuity of Thickness
  - Discontinuity of E-Modulus
  - Discontinuity of Geometry

Colours do not show all



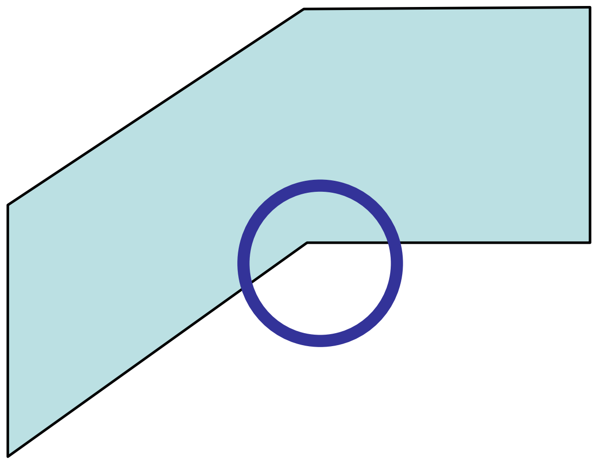
Singularities

- Rigid Footing on a half space



Singularities

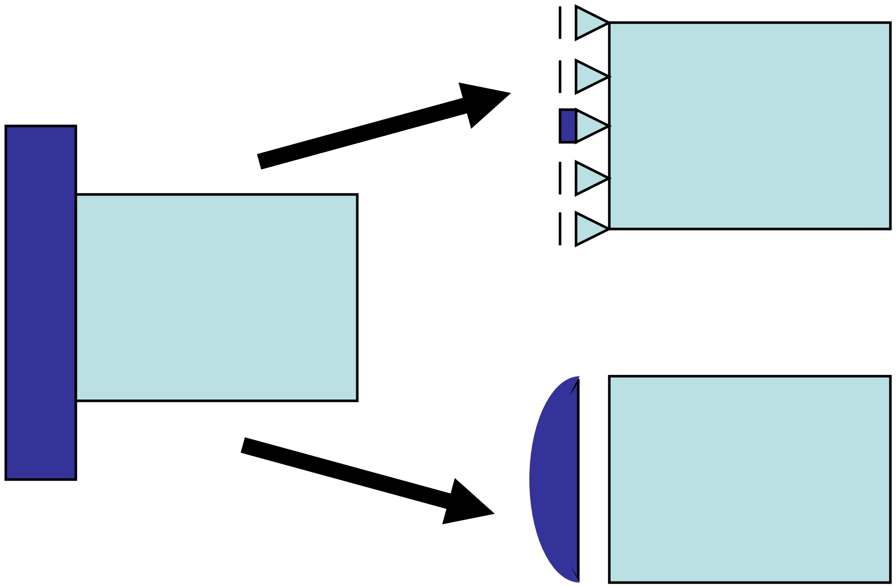
- Re-Entrant Corners



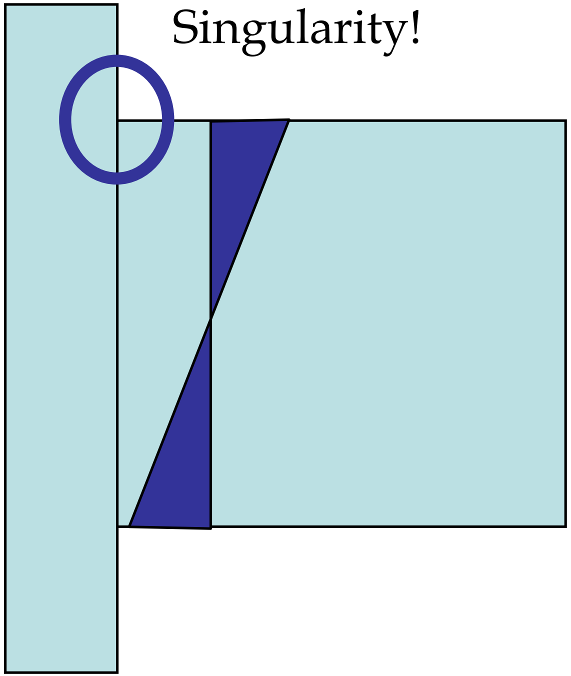
Adaptive Mesh Refinement

- At those locations where we have a large error estimate we refine the mesh either geometrically (h-Version) or we increase the Polynomial degree (p_Version) or both (hp-Version).
- Strong advantages compared to a uniform refinement
- Loads are not allowed to be defined for nodes or elements, but are required in a more general geometric way.
- For any design purpose we need results for all load cases at the same location.
  => a mesh for every load case makes life not easier.

Detail of supports



Detail of supports



- Element stress is discontinuous
- Nodal stresses as mean values are not correct at this point
- Separate the nodal stresses in groups

Remarks

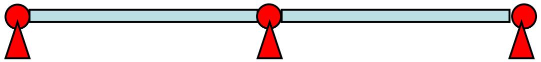
- Axissymmetric case
  - The strains are neither constant nor linear nor quadratic
  - None of the classical elements may describe this exactly
  - Integral of loads has to include the radius
  - But not the nodal loads !
- 3D case
  - Most of the plain strain issues are also valid
  - Two more shear stresses
  - Elements as Hexahedra or Tetrahedra or something in between
  - Mesh generation is a complex topic !

Construction Stages

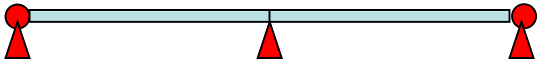
- Classical Approach: We build and then we switch gravity on ?
- There are many cases, especially with non linearity where the simulation of the construction process becomes essential
  - Dam construction
  - Tunnelling
  - Bridges
- Effects to consider:
  - Stress path
  - Change of forces due to creep
  - Adding or removing parts of the structure

A simple beam example

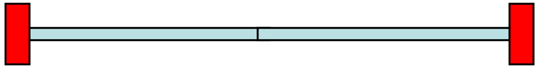
- Two single span beams



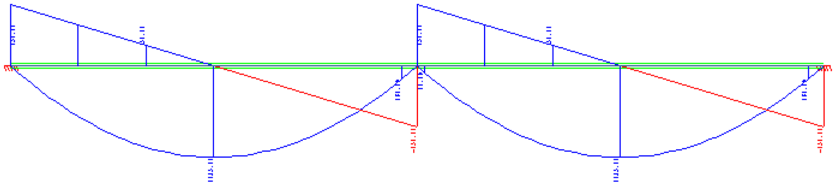
- Connected to a continuous beam
  => Creep will change the forces towards the continuous case

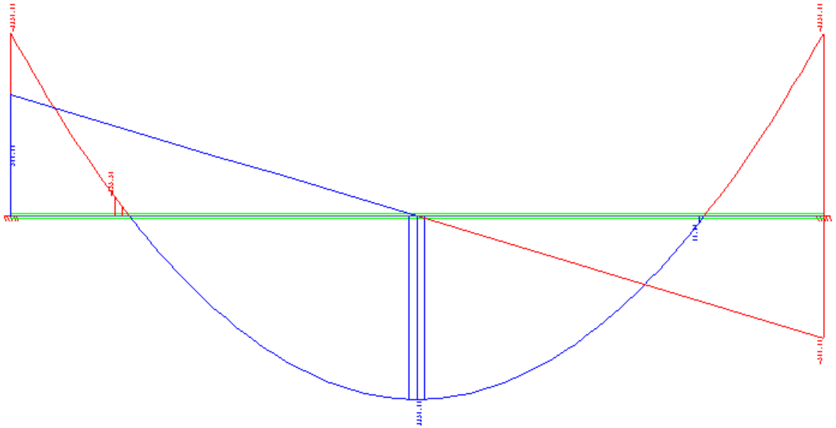


- Changed to a single span beam
  => Moment distribution will be different



Removal of central support





How is this done best ?

- First Principle: Strain increments!
- Consider each load case not in total but as difference to the primary state before
- New stresses are old stresses + tangential stiffness times strain increments

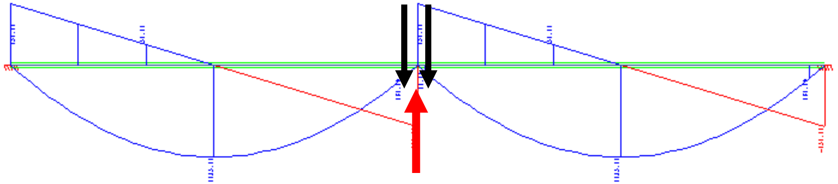
$$\sigma_{new} = \sigma_{old} + E_t \cdot \Delta\varepsilon$$

Incremental loads

- The stresses of the primary load case are in equilibrium with the loadings and support forces of the primary estate
- The load vector of the new case is the difference between the total load vector and the residual load vector of the primary stresses.

$$\Delta P = P_{total} - \int B^T \sigma_{primary} dV$$

How it works



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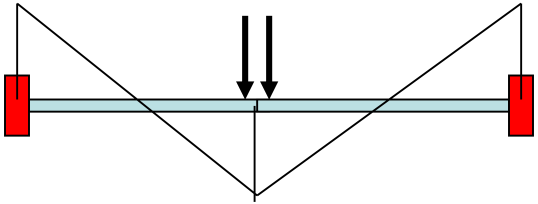

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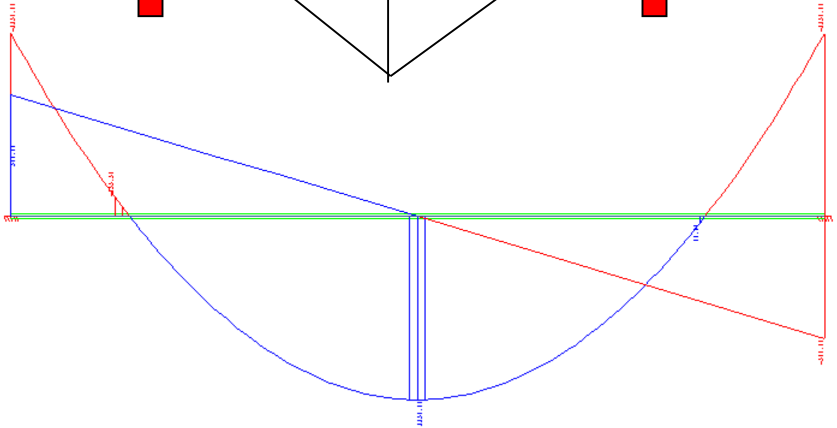
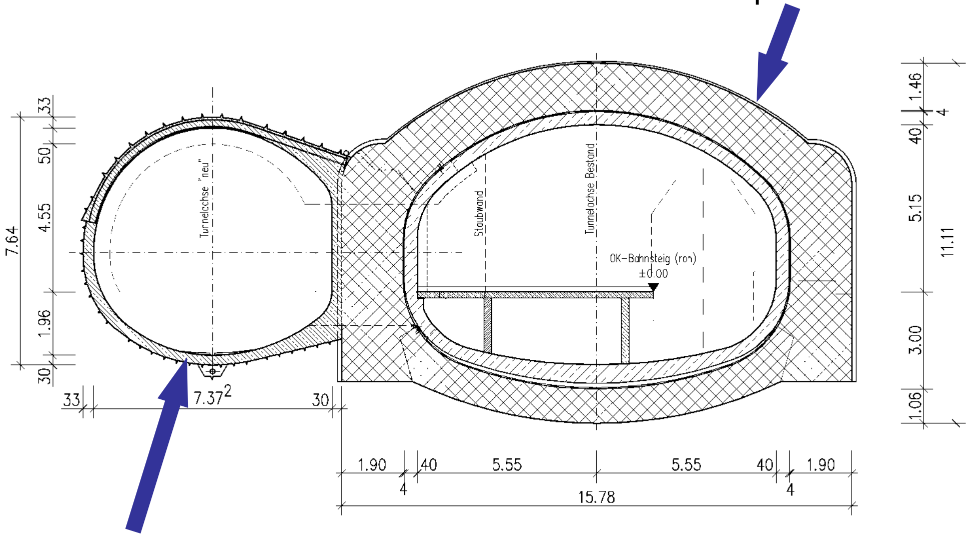


Last not least

- Partially removed or activated systems
  - Shotcreet hardening
  - Tunnelling
  - Loss of strength due to many effects
  - Icing and deicing a soil
- The full set of tools
  - Factor for Stiffness
  - Factor for primary stress
  - Factor for primary loading

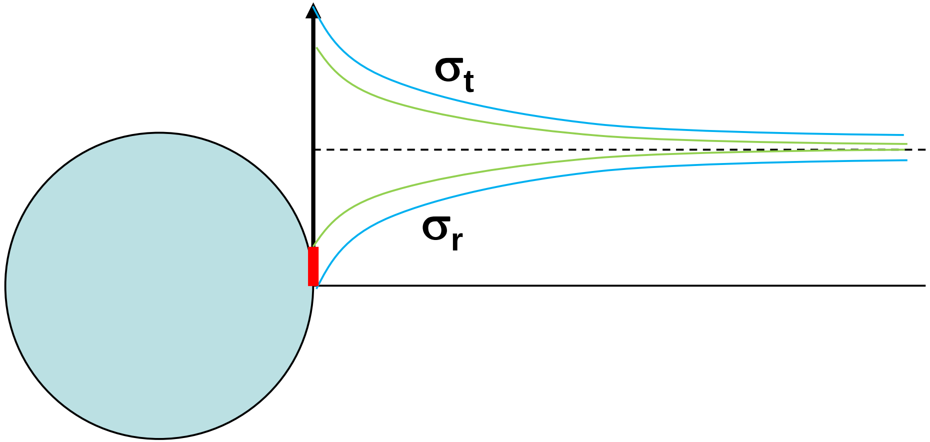
Enlargement of Metro Station Marienplatz Munich

Old Tunnel
Designed to withstand the full overburden pressure



New Tunnel
Designed to support/ mobilize the soil's load carrying capacity

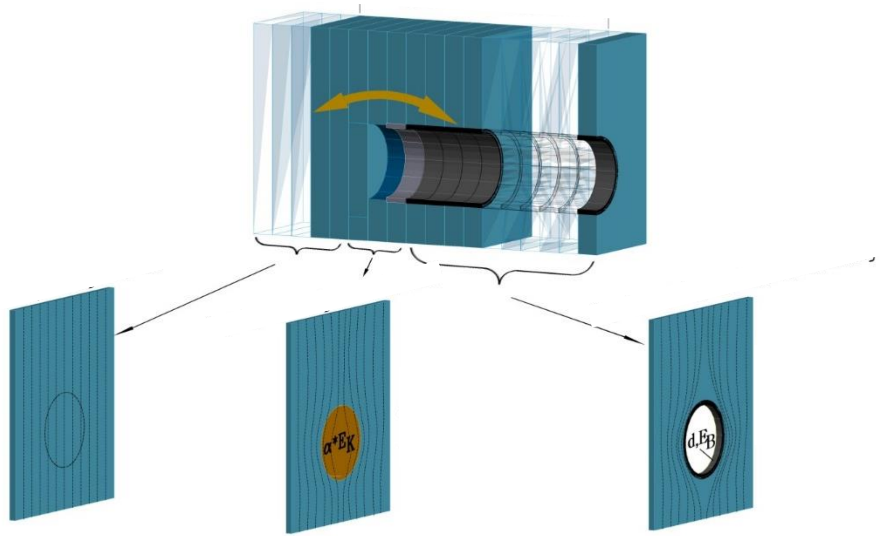
„New“ Austrian Tunneling Method



- Stress differences exceeding the strength yield plastic deformations
- A small outward pressure of the lining will inhibit this
- This pressure is obtained if the lining is in place before deformation starts

Analytical Model

- Analysis at a set of representative cross-section slices under plane strain conditions
- Incorporating 3D stress redistribution effects by $\Rightarrow$ stiffness reduction method (α-Method)

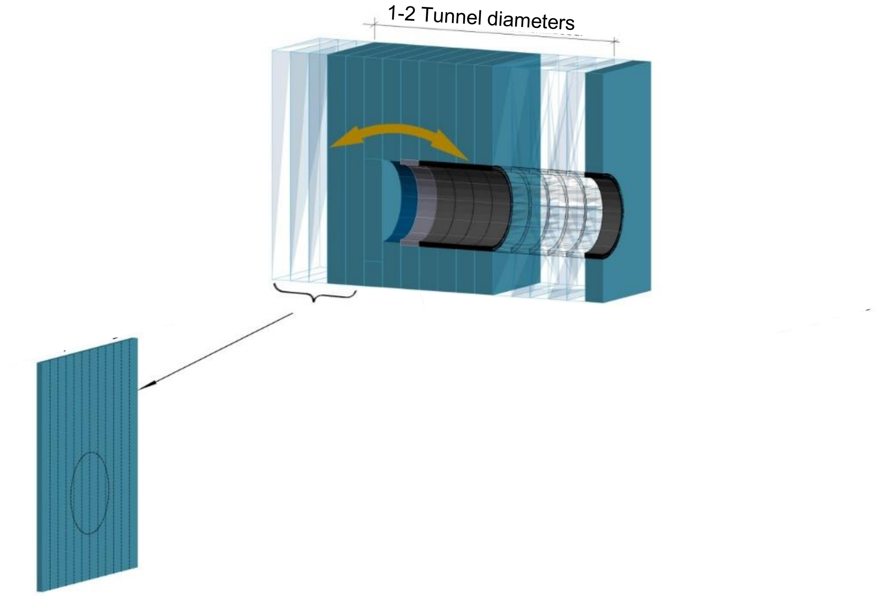


Primary Estate

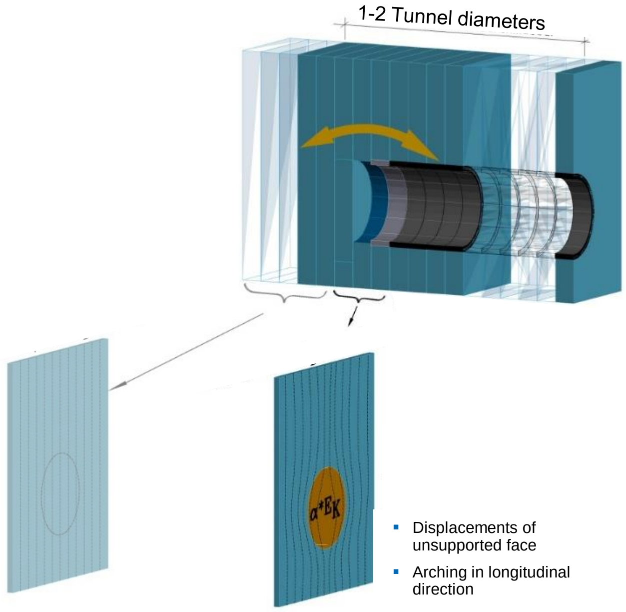
Reduced axial strain of Tunnel („Softening“)

Plane system with hole and linings

Stiffness reduction method (α-Method)



Stiffness reduction method (α-Method)

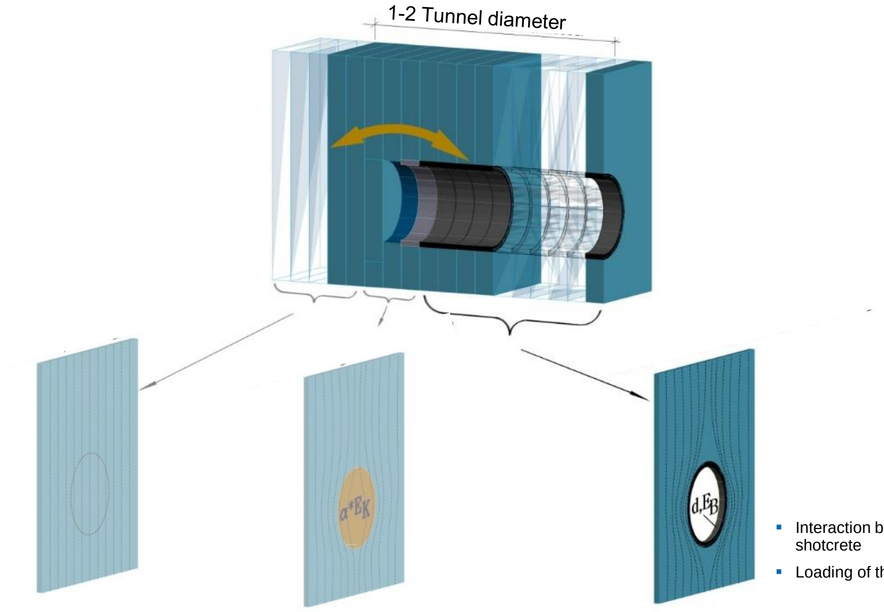


- Displacements of unsupported face
- Arching in longitudinal direction

Primärspannungs-Zustand

Reduced axial strain of Tunnel („Softening“)

Stiffness reduction method (α-Method)



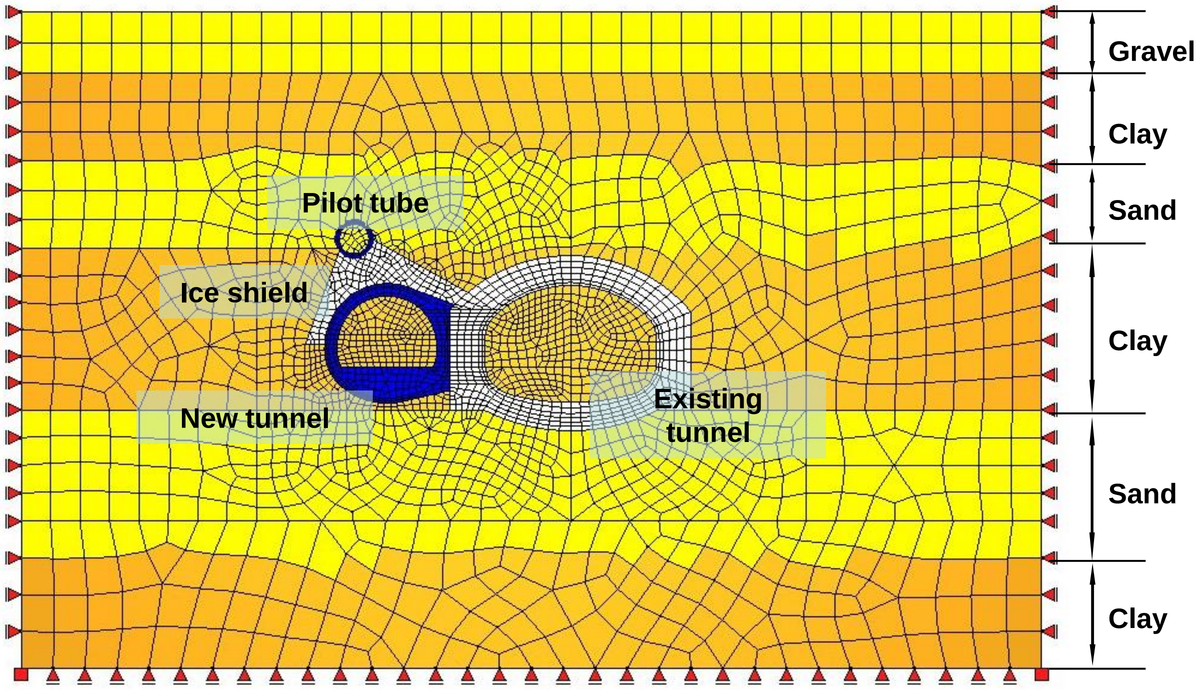
- Interaction between soil and shotcrete
- Loading of the linings

Primärspannungs-Zustand

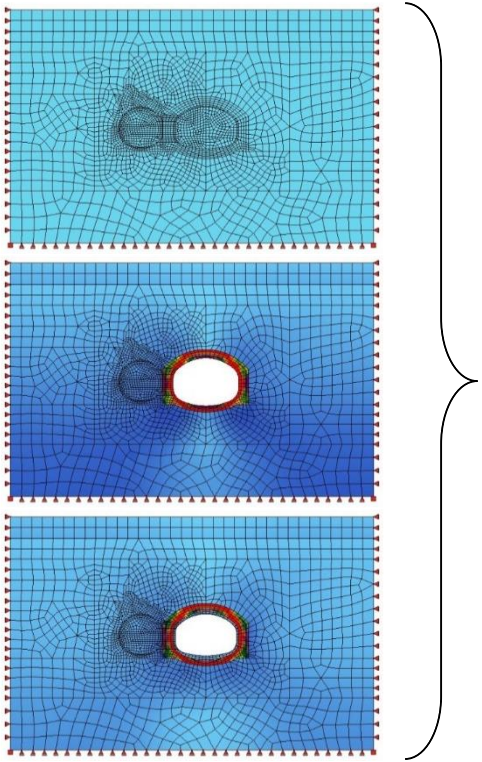
Entspannter Tunnelkern („Aufweichen“)

Final 2D system with hole and linings

Finite element model



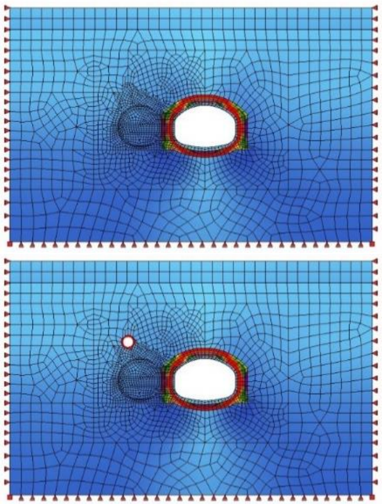
Simulation 1st stage: primary stress state



Simulating the historic construction process

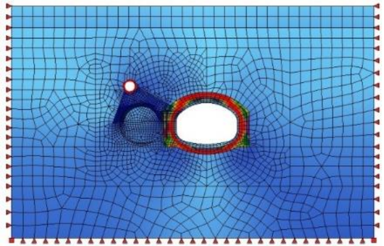
⇒ generating a model loading state that reflects the situation prior to construction activity

Simulation 2nd stage: preparatory steps

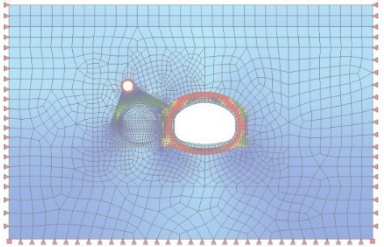


- Drainage of lower aquifer
- Installation of pilot tunnel

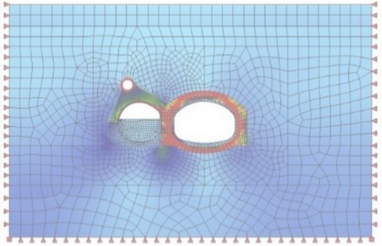
Simulation 3rd stage: tunnelling process



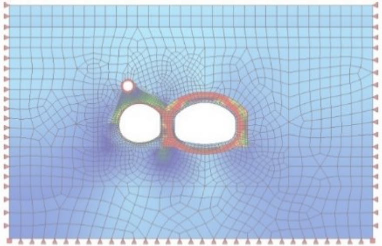
- Soil freezing



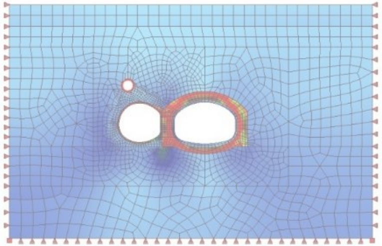
- Relaxation of calotte region



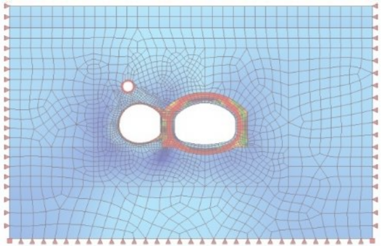
- Excavation calotte
- Installation shotcrete lining



- Excavation base
- Installation shotcrete lining

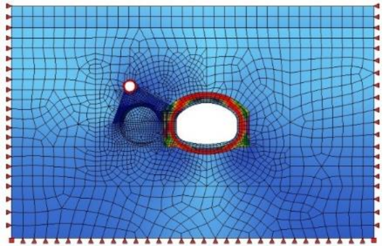


- Defrosting

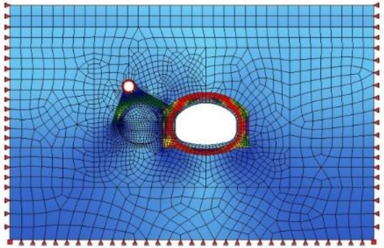


- Drainage turning-off

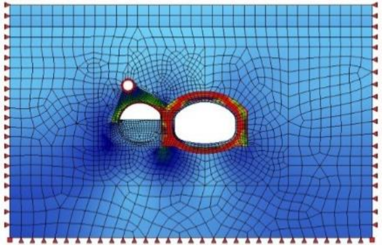
Simulation 3rd stage: tunnelling process



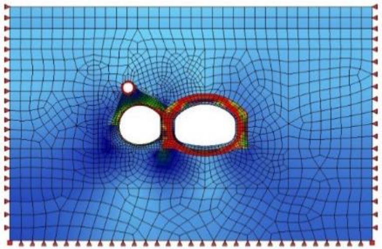
- Soil freezing



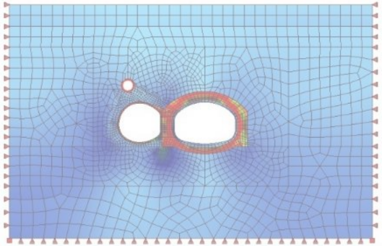
- Relaxation of calotte region



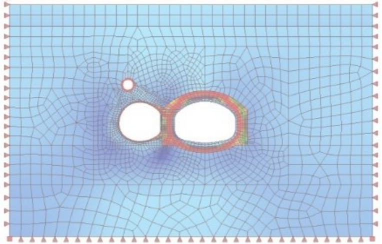
- Excavation calotte
- Installation shotcrete lining



- Excavation base
- Installation shotcrete lining

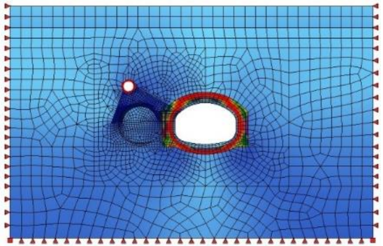


- Defrosting

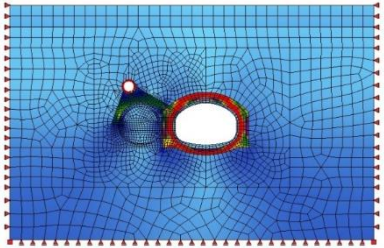


- Drainage turning-off

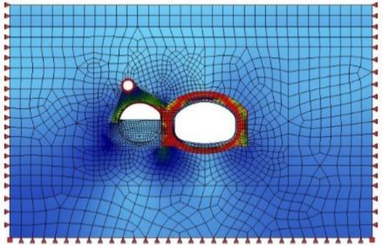
Simulation 3rd stage: tunnelling process



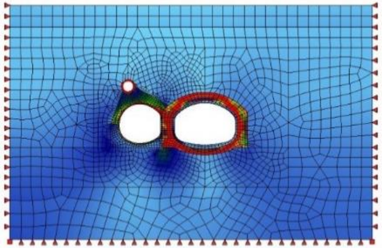
- Soil freezing



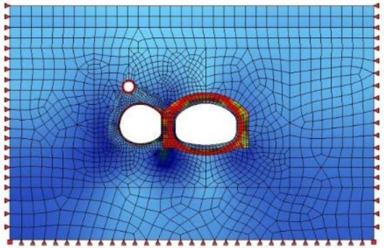
- Relaxation of calotte region



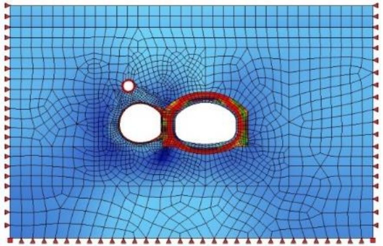
- Excavation calotte
- Installation shotcrete lining



- Excavation base
- Installation shotcrete lining

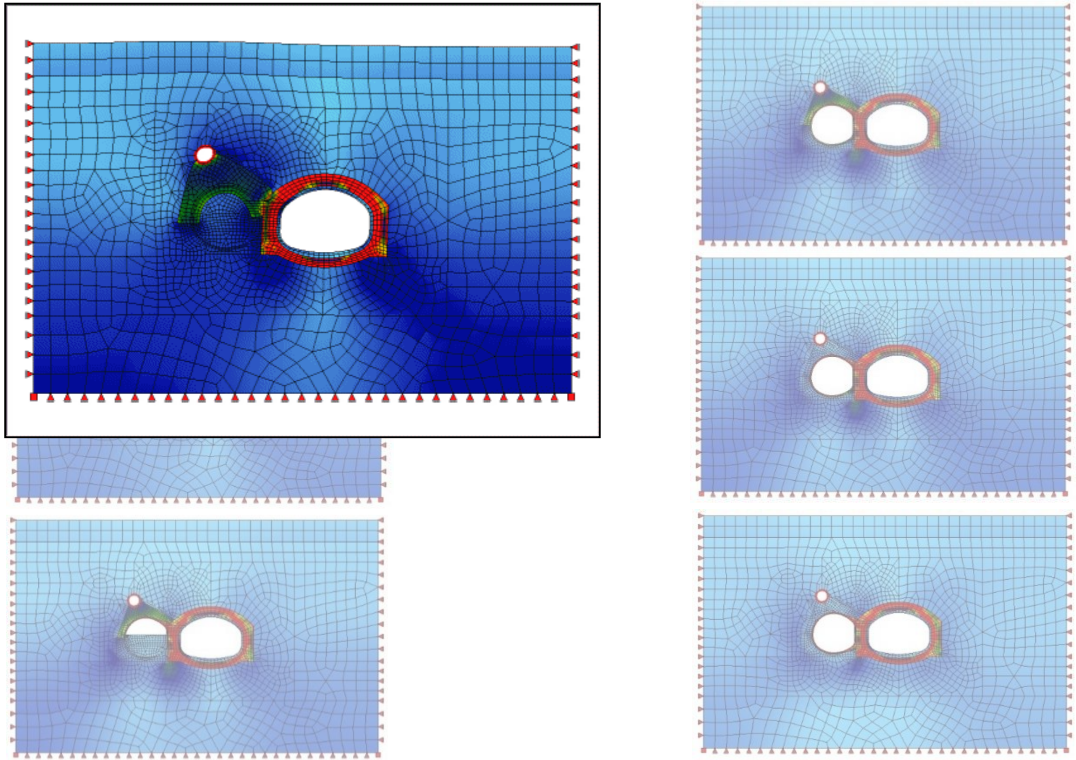


- Defrosting



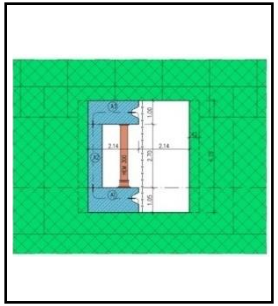
- Drainage turning-off

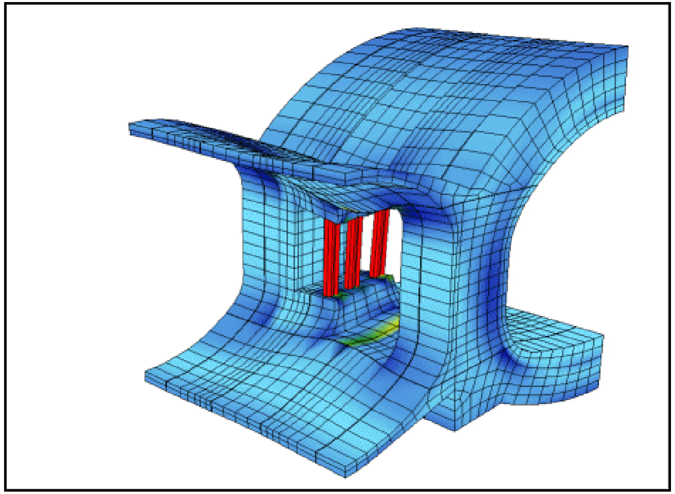
Soil freezing



Simulating the 3D cross cutting process

- There are some more phases in 3D ....

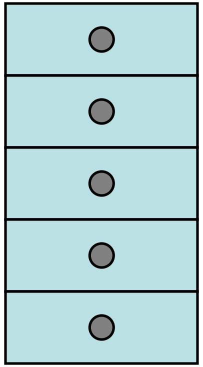




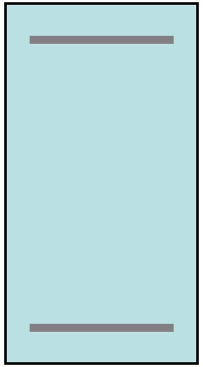
Design

- Finite Element Analysis is linear in general
- Design is based on ultimate loads and plasticity
- The real ultimate loading depends on all elements within the structure.
- Thus, you may be either
  - Not economical
  - Not save

Example of a Beam



5 “membrane” elements
Each obtaining its individual reinforcement



Classical
beam element

M = 250 kN

	Stress		Reinforcement	
Element	Theoret.	FE	Classical	FE
1	-11.11	-11.03		485
2	-5.56	-5.51		106
3	0.00	0.00		0
4	5.55	5.51		694
5	11.11	11.03	1973	1391
Sum			1973	2676
Beam design with distribution from FE-Results				2658

M=250 kNm, N= -500 kN

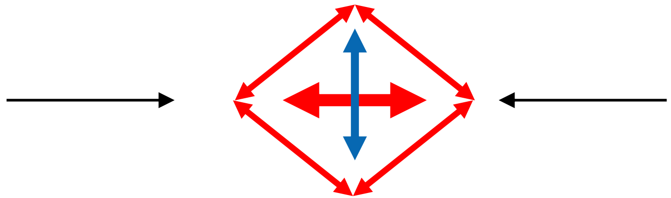
	Stress		Reinforcement	
Element	Theoret.	FE	Classical	FE
1	-13.89	-13.81	540	985
2	-8.33	-8.29		160
3	-2.79	-2.78		54
4	2.79	2.73		344
5	8.33	8.29	1262	1040
Sum			1802	2583
Beam design with distribution from FE-Results				2244

M=250 kN, N= -1000 kN

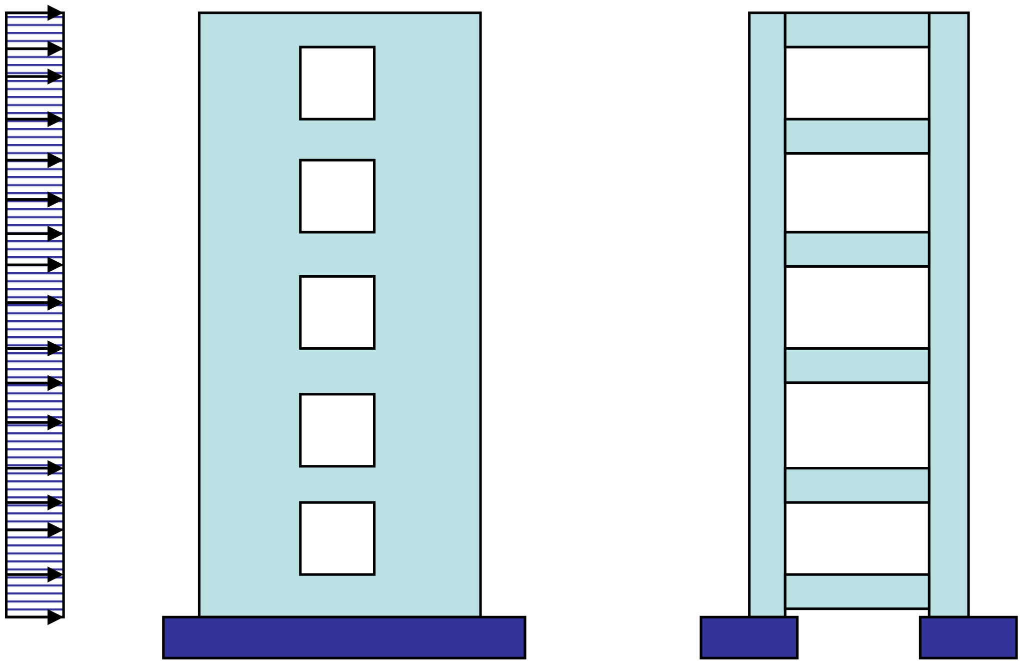
	Stress		Reinforcement	
Element	Theoret.	FE	Classical	FE
1	-16.67	-16.58	1359	1486
2	-11.11	-11.06		492
3	-5.56	-5.56		107
4	0.00	0.05		0
5	5.56	5.48	1359	691
Sum			2718	2776
Beam design with distribution from FE-Results				2260

Design of Shear Walls

- Direction of principal stresses
- Direction of reinforcements
- Direction of cracks
- Models available from Baumann / Leonhardt or Stiglat/Wippel
- Analysis based on minimum of deformation work
- A bunch of detailed problems - be careful e.g. inclined compressive reinforcement



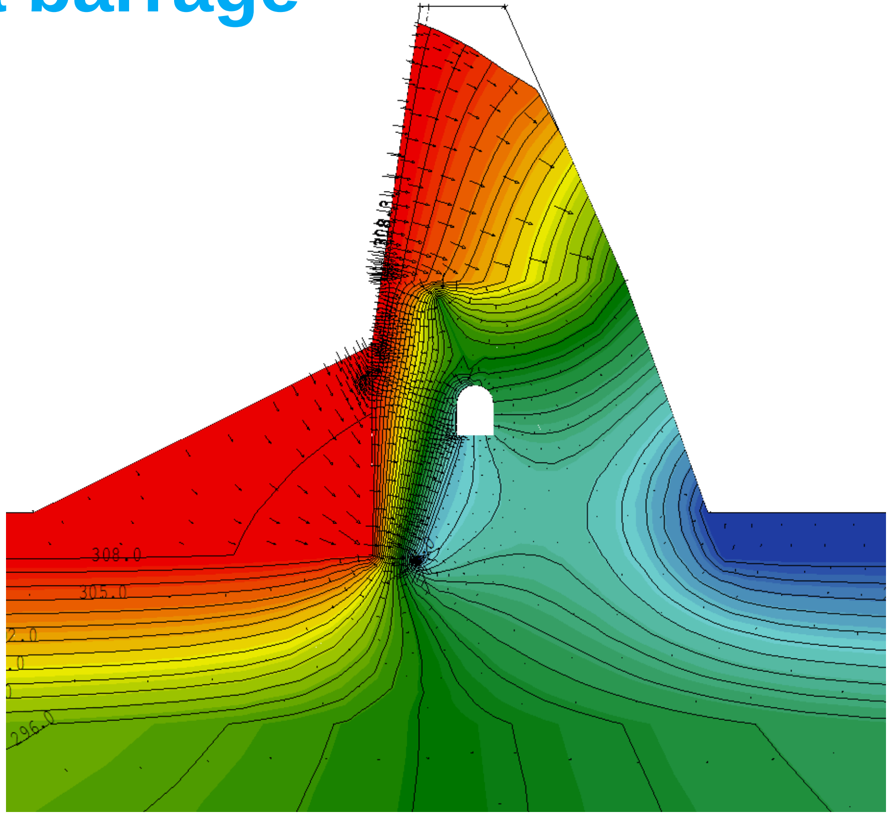
Structured shear walls



Structured Shear Walls

	Beams	Mod. Stiff. in nodes	Rigid Nodes	FE Solution
N (left)	25.6	133.2	133.2	117.8
V (left)	200.1	187.7	195.2	191.8
M (left)	-2818	-2216	-2251	-2316
N (right)	-25.6	-133.2	-133.2	-117.8
V (right)	137.4	149.8	142.3	145.5
M (right)	-2612	-2146	-2112	-2199

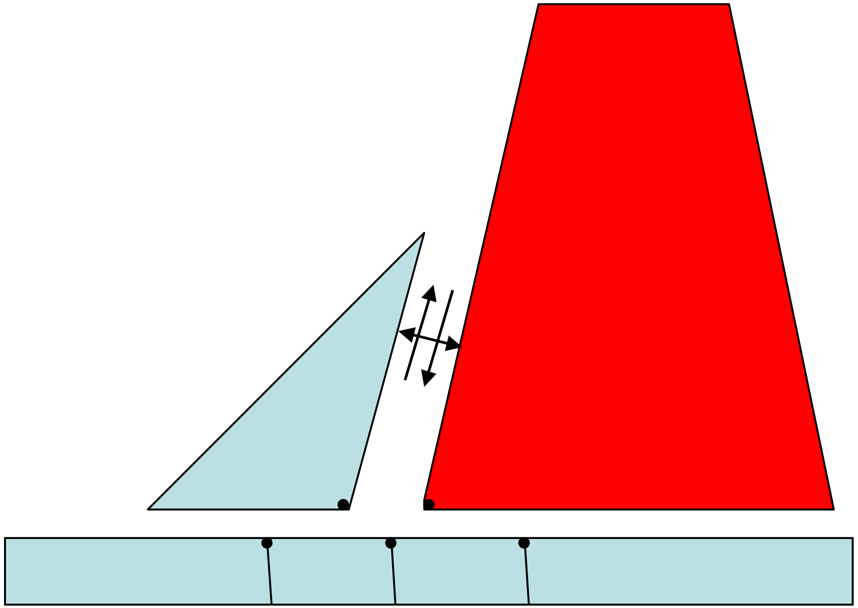
Example of a barrage

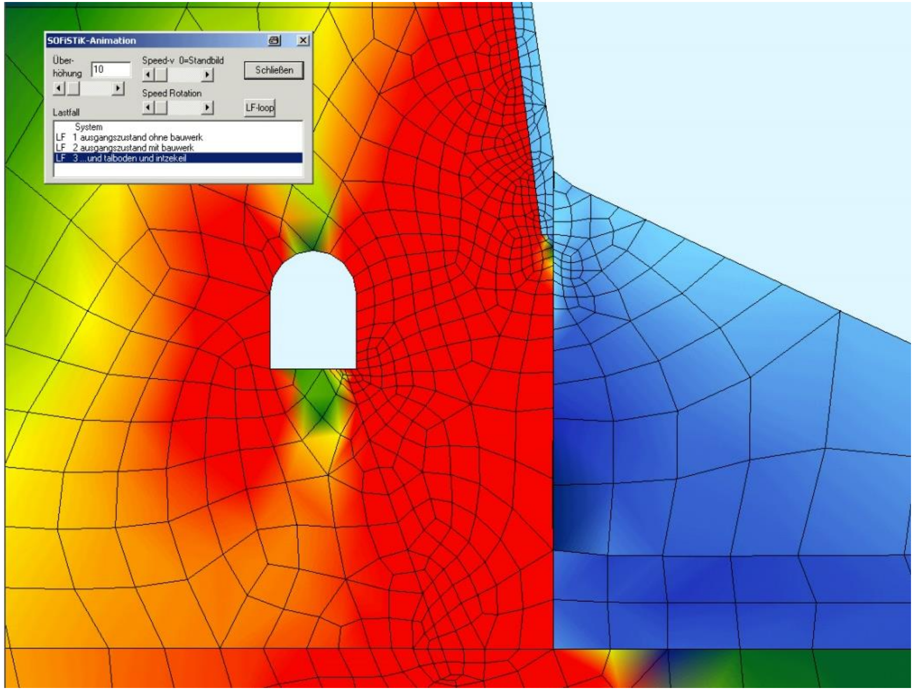


Problem

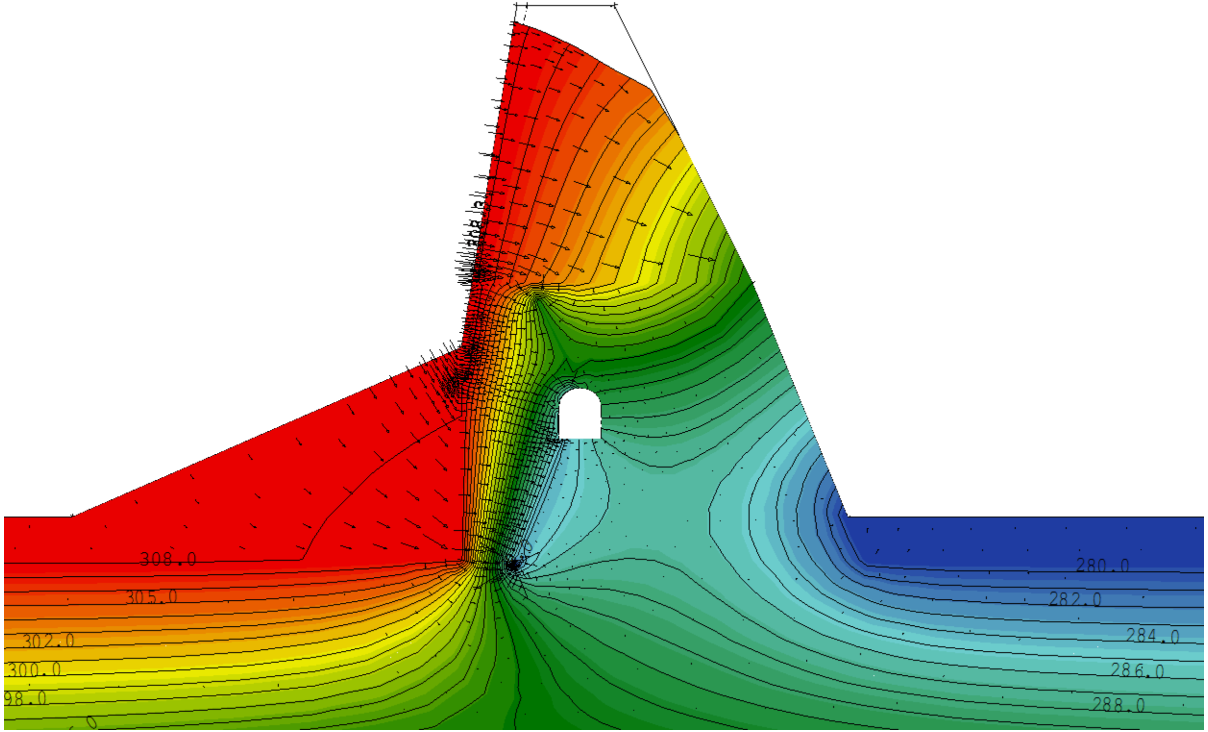
- Stability of a barrage (height 32,50 m / width 21 m)
- Load cases to be considered:
  - Seepage
  - Temperature
  - Ice pressure
  - Earthquake
- On the water side there is an additional brickwork and a so called „Intze-Keil“ to ensure water tightness
- Non linear material for rock and dam

Friction between Soil and Dam

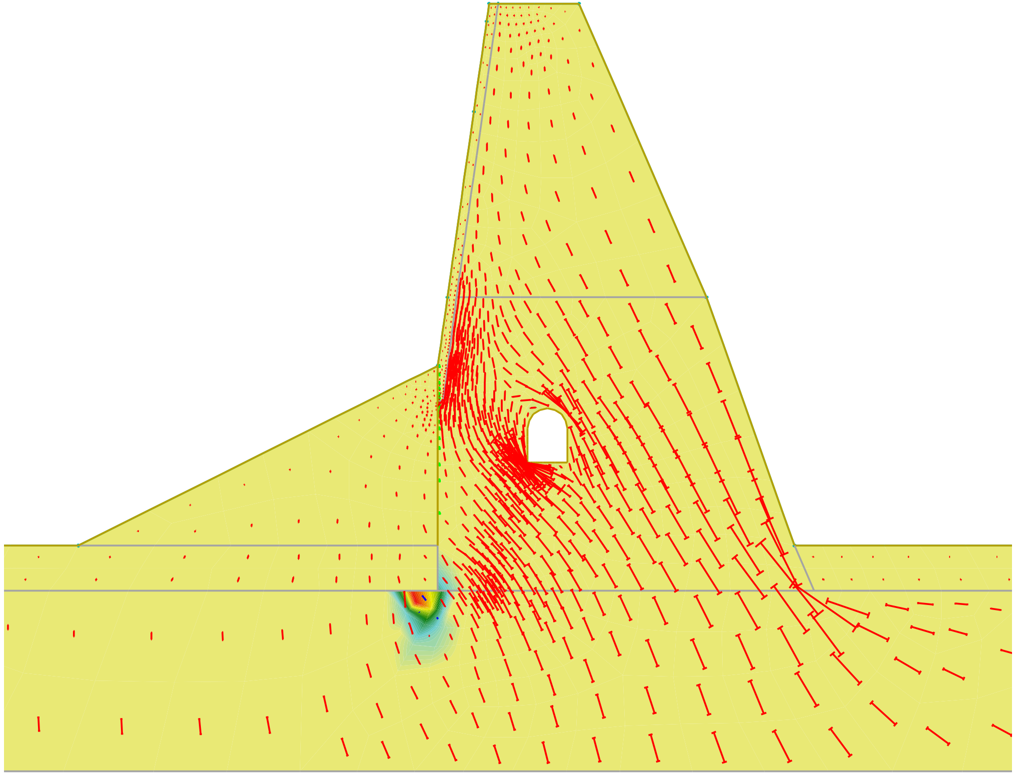




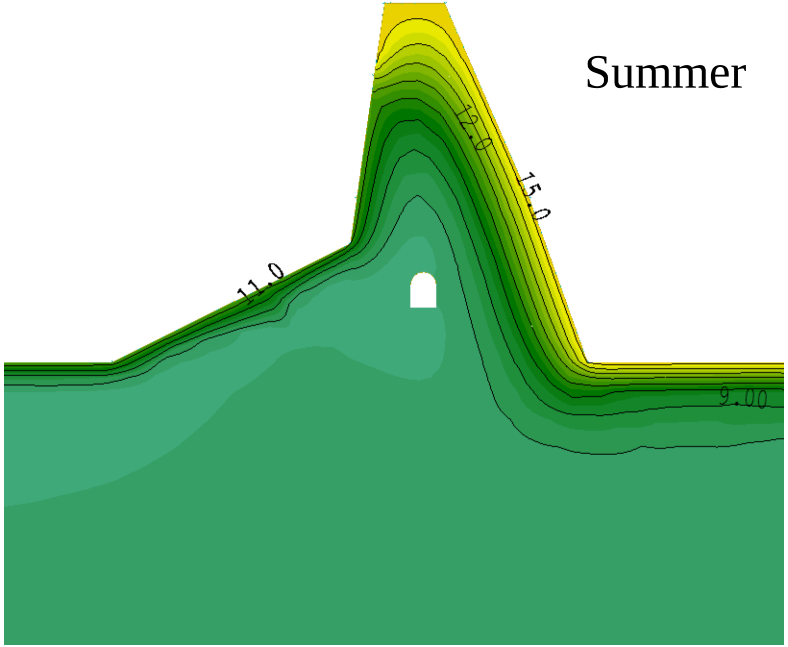
Seepage through dam

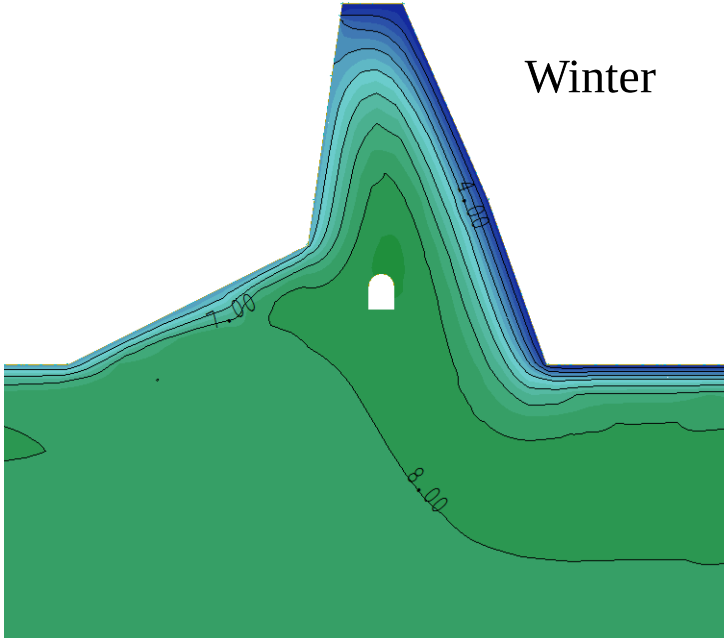


Stresses including seepage



Transient Temperatures

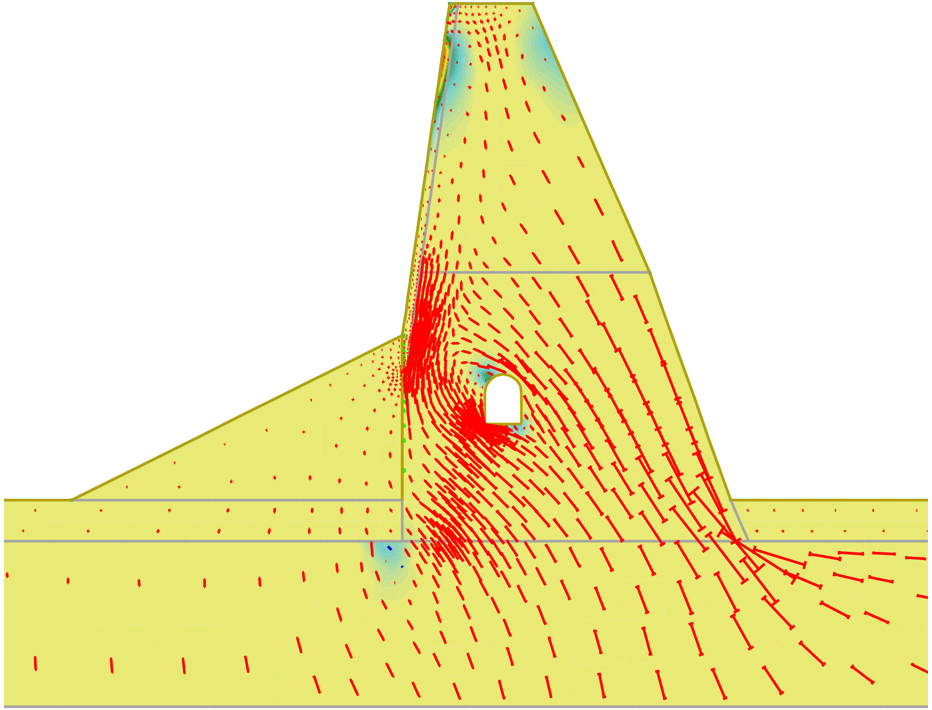




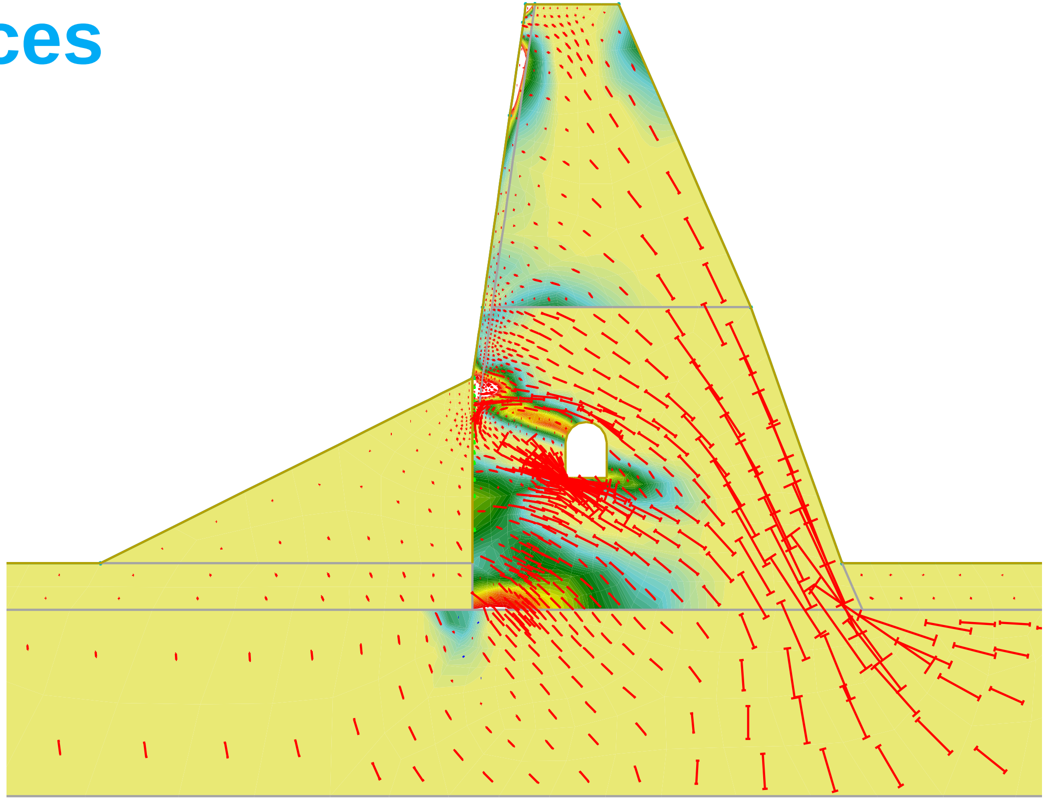
Earthquake

- There is a fluid structure interaction problem
- A simple approach just adds some mass to the barrage according to the distribution of Westergard
- You have to add a mass value depending on the distance of the nodes and their depth.
- How ?
  - Excel sheet (if you know the coordinates)
  - With a cubic load distribution (if you have good software)

Stresses including Earthquake



Near Collapse with 7 x Earthquake forces



Fluid-Elements - Eulerian Approach

- Differential equation connecting velocity of non viscous fluid to pressure:

$$\nabla p = -\rho_f \dot{u}$$

- The density of the fluid is constant
- Velocities are so small that higher order effects may be neglected, (Convection, Cavitation etc.).
- Shear stresses (viscous effects) are neglected

Fluid Structure Interaction

- Flow is described by velocities (Eulerian-Approach)
- Structure is described by displacements (Lagrangian Approach)
- Coupling quite complex

Lagrange Approach for Fluids

- Stresses with Compression and Shear modulus:

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\\ \sigma_z\end{bmatrix} = \frac{E}{(1+\mu)(1-2\mu)}\begin{bmatrix}1-\mu & \mu & 0 & \mu\\ \mu & 1-\mu & 0 & \mu\\ 0 & 0 & (1-2\mu)/2 & 0\\ \mu & \mu & 0 & 1-\mu\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\\ \varepsilon_z\end{bmatrix}$$

$$K = \frac{E}{3(1-2\mu)}$$

$$G = \frac{E}{2(1+\mu)}$$

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\\ \sigma_z\end{bmatrix} = \begin{bmatrix}K+\frac{4}{3}G & K-\frac{2}{3}G & 0 & K-\frac{2}{3}G\\ K-\frac{2}{3}G & K+\frac{4}{3}G & 0 & K-\frac{2}{3}G\\ 0 & 0 & G & 0\\ K-\frac{2}{3}G & K-\frac{2}{3}G & 0 & K+\frac{4}{3}G\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\\ \varepsilon_z\end{bmatrix}$$

- Quite Common in Soil Mechanics
- Limit State G => 0, μ => 0.5
- Some viscous effects possible

Water

- Compression modulus

  K = 2000 N/mm2

- dynamic Viscosity

  h = 0.00000000165 Ns/mm^2

- Shear Modulus very small

$$\tau = G * \gamma = G * \frac{\dot{\gamma}}{\omega} = \eta * \dot{\gamma}$$

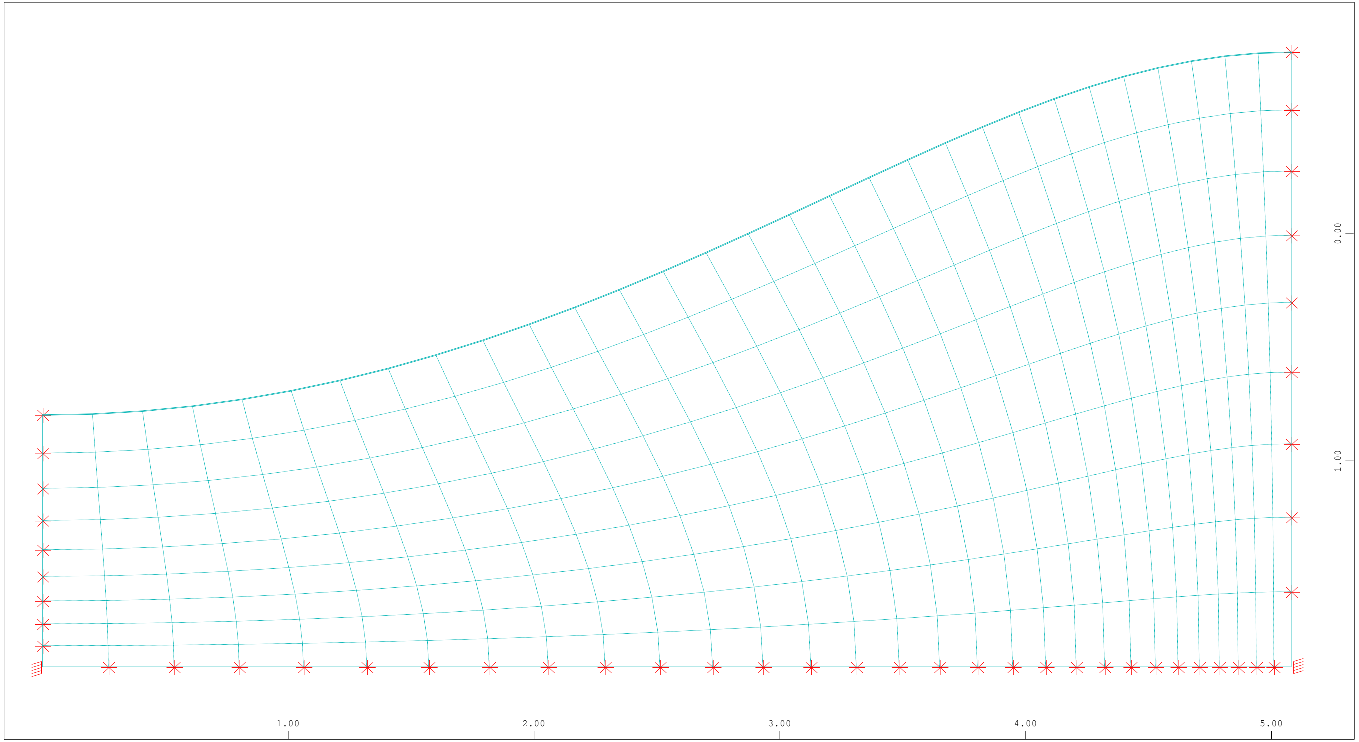
$$\Rightarrow \quad G = \eta * \omega$$

First Test

```
HEAD WATERTANK
NODE   1 0.00 0.0 ;   10 = 1.905
     301 5.08 0.0 ; 310 = 1.905

MAT 1 K 2E6 G 2E3 GAM 10.0
```

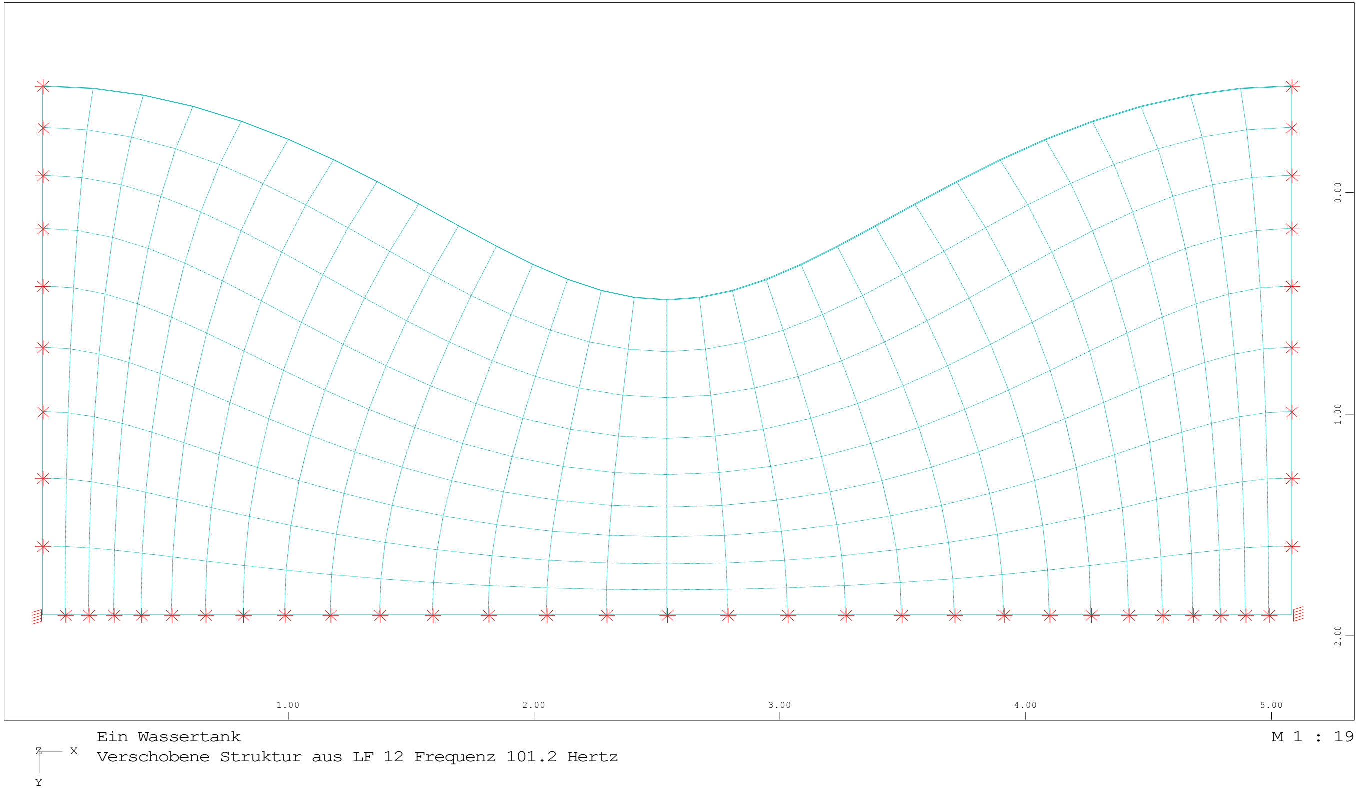
WINGRAF 3397 13.04.99 Katz+Bellmann - Beratende Ingenieure VBI



Ein Wassertank
Verschobene Struktur aus LF 11 Frequenz 70.5 Hertz in 2.00-facher
Überhöhung

M 1 : 19

WINGRAF 3397 13.04.99 Katz+Bellmann - Beratende Ingenieure VBI



Ein Wassertank
Verschobene Struktur aus LF 12 Frequenz 101.2 Hertz

M 1 : 19

1^{st} Eigen frequency

G-Modulus	Plane Strain	K+G plane strain	Plane Stress
200 000	70.61	70.45	69.18
2000	8.19	7.08	6.94
20	3.55	0.71	0.69
0.2	4.50	0.07	0.069
Reference	0.36	0.36	0.36

Flaws

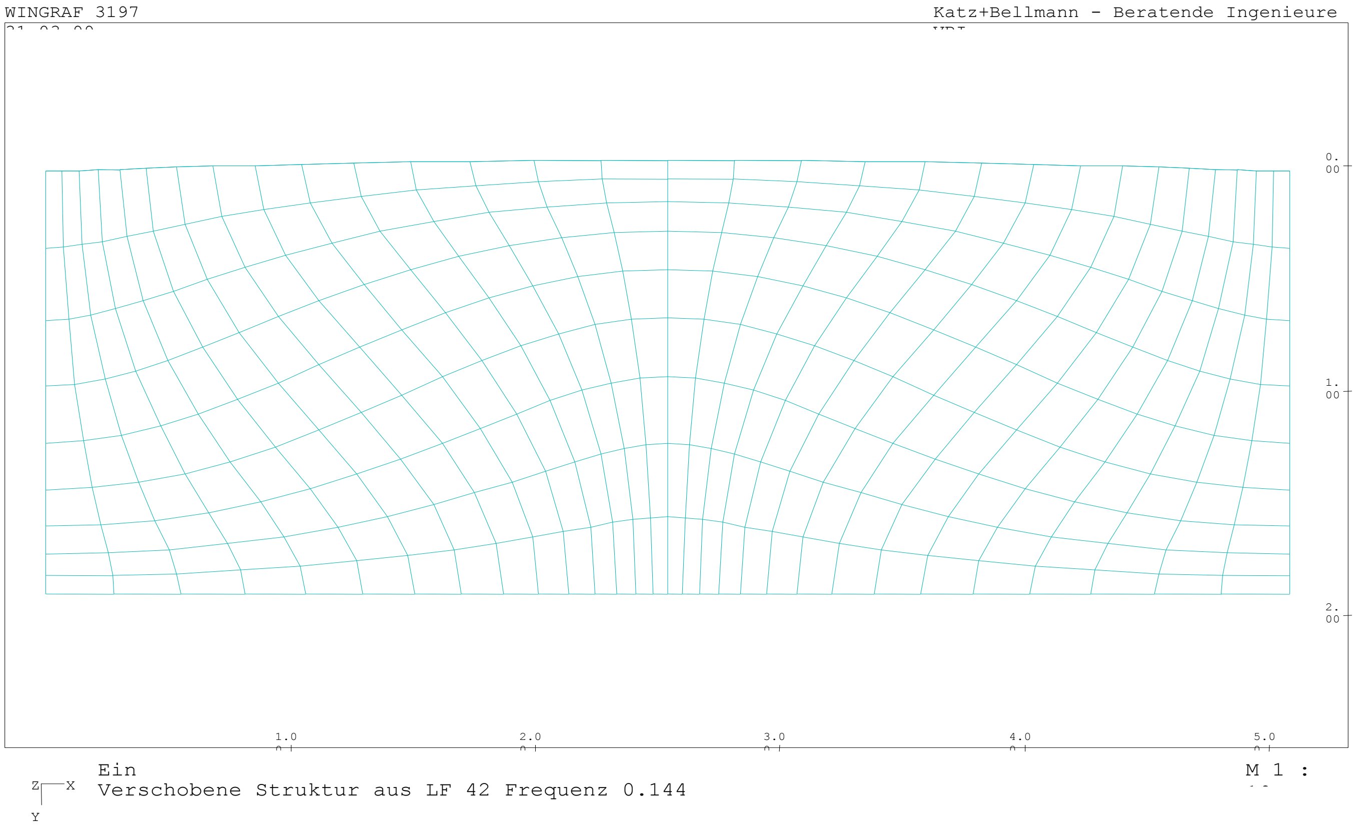
- Locking of incompressible media

  => Three field approximation

- Potential of free surface is missing

```
BOUN 1 TITLE 'Free Surface'
BOUN 1 301 10 CY 10.0
```

==> Frequencies become bounded

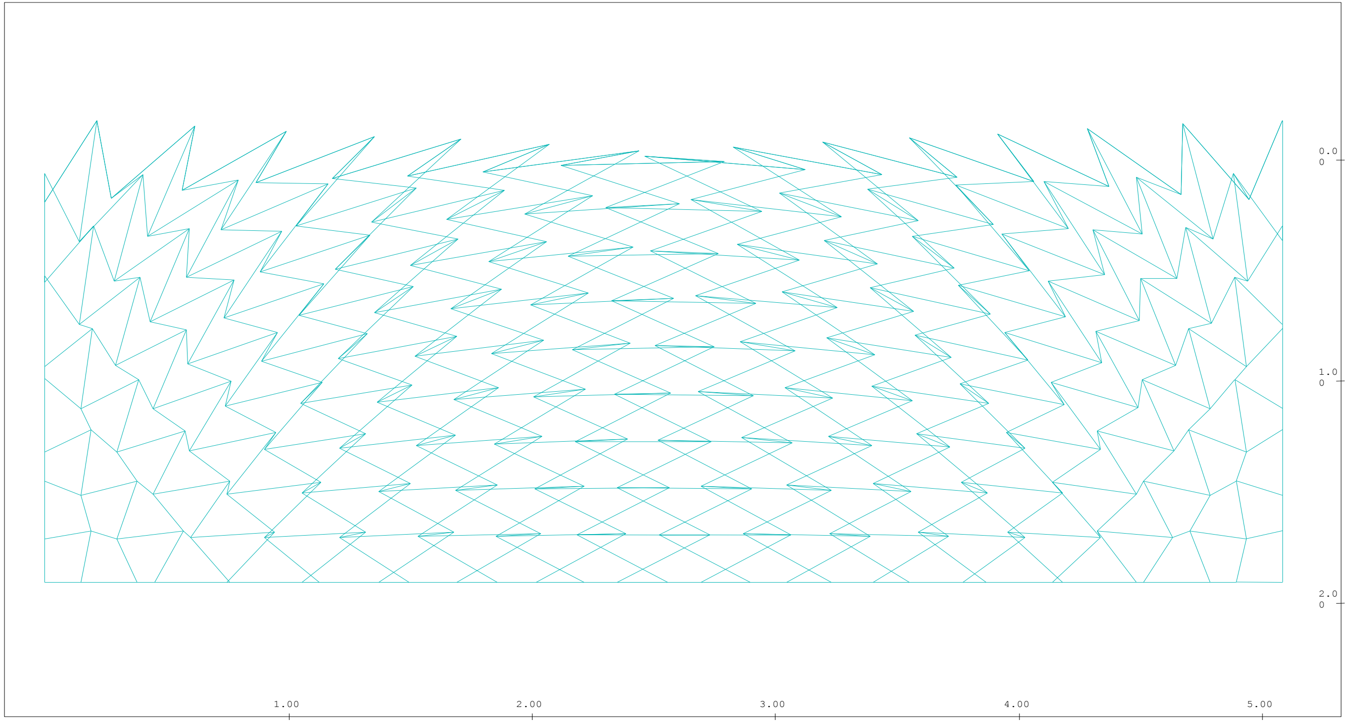

WINGRAF 3197
Katz+Bellmann - Beratende Ingenieure
0.
00
1.
00
2.
00
1.0
2.0
3.0
4.0
5.0
Ein
Verschobene Struktur aus LF 42 Frequenz 0.144
M 1 :
Z
X
Y

Flaws

- Stiffness of surface now larger then fluid stiffness
- Rotational deformations have no stiffness

  => Introduce Penalty function

WINGRAF 3197 31.03.99 Katz+Bellmann - Beratende Ingenieure VBI



Z X
Y

Ein Wassertank M 1 : 19
Verschobene Struktur aus LF 43 Frequenz 0.697 Hertz in 0.500-facher Überhöhung

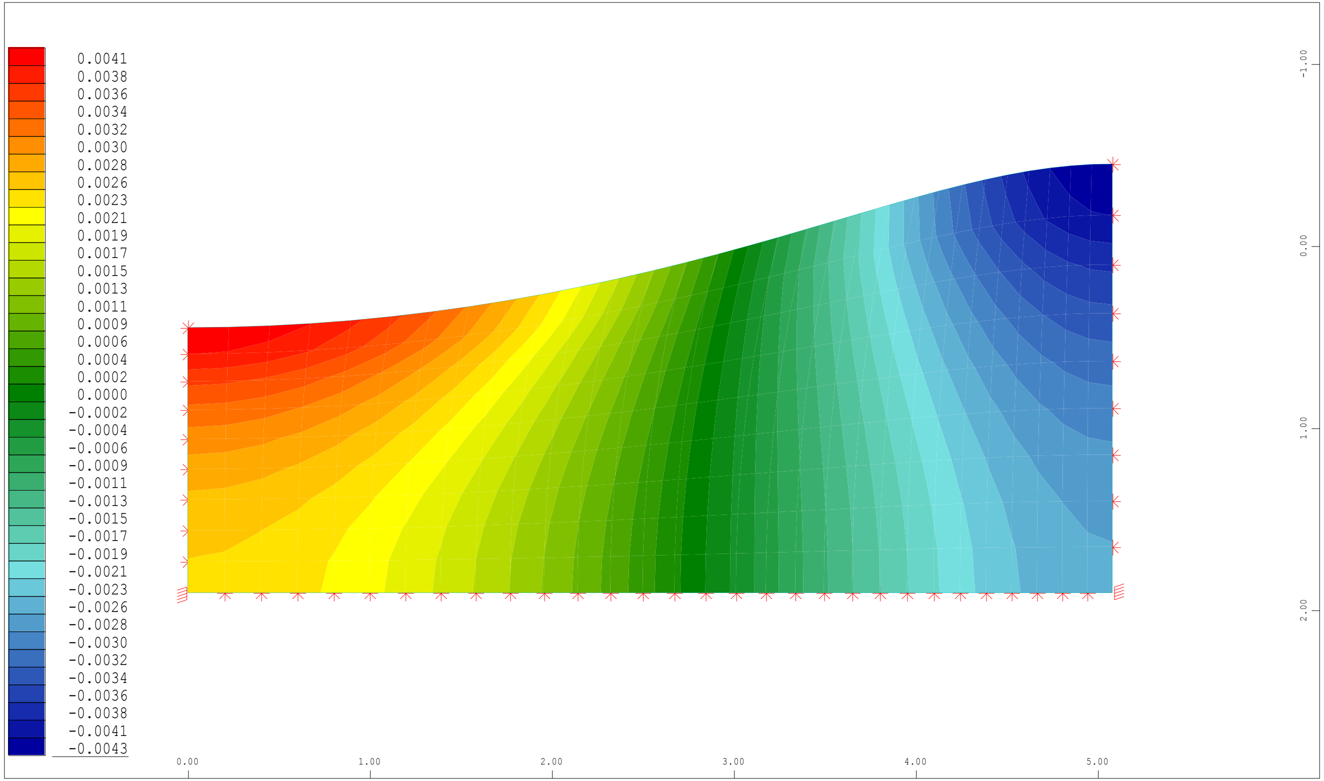
Flaws

- „spurious modes“
- Mass matrix has still modes which are suppressed in the stiffness matrix
  => Projection by Kim/Yong

Eigenfrequencies

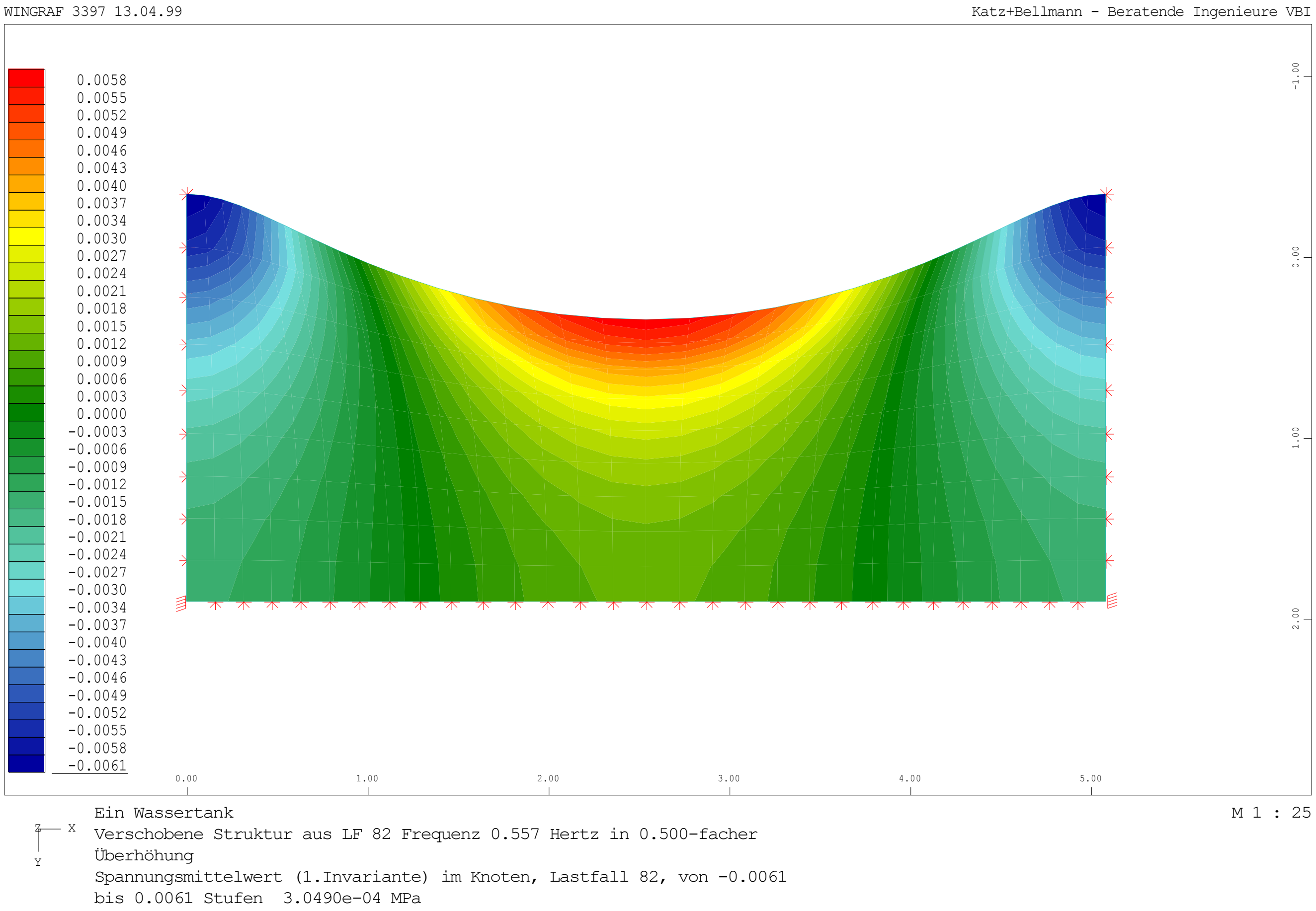
G-Modulus	f1	f2	f3
200 000	70.455	101.210	
2000	7.101	10.246	13.254
20	0.951	1.846	2.730
0.2	0.371	0.582	0.730
0.02	0.361	0.557	0.689
Reference	0.357	0.555	

WINGRAF 3397 13.04.99 Katz+Bellmann - Beratende Ingenieure VBI



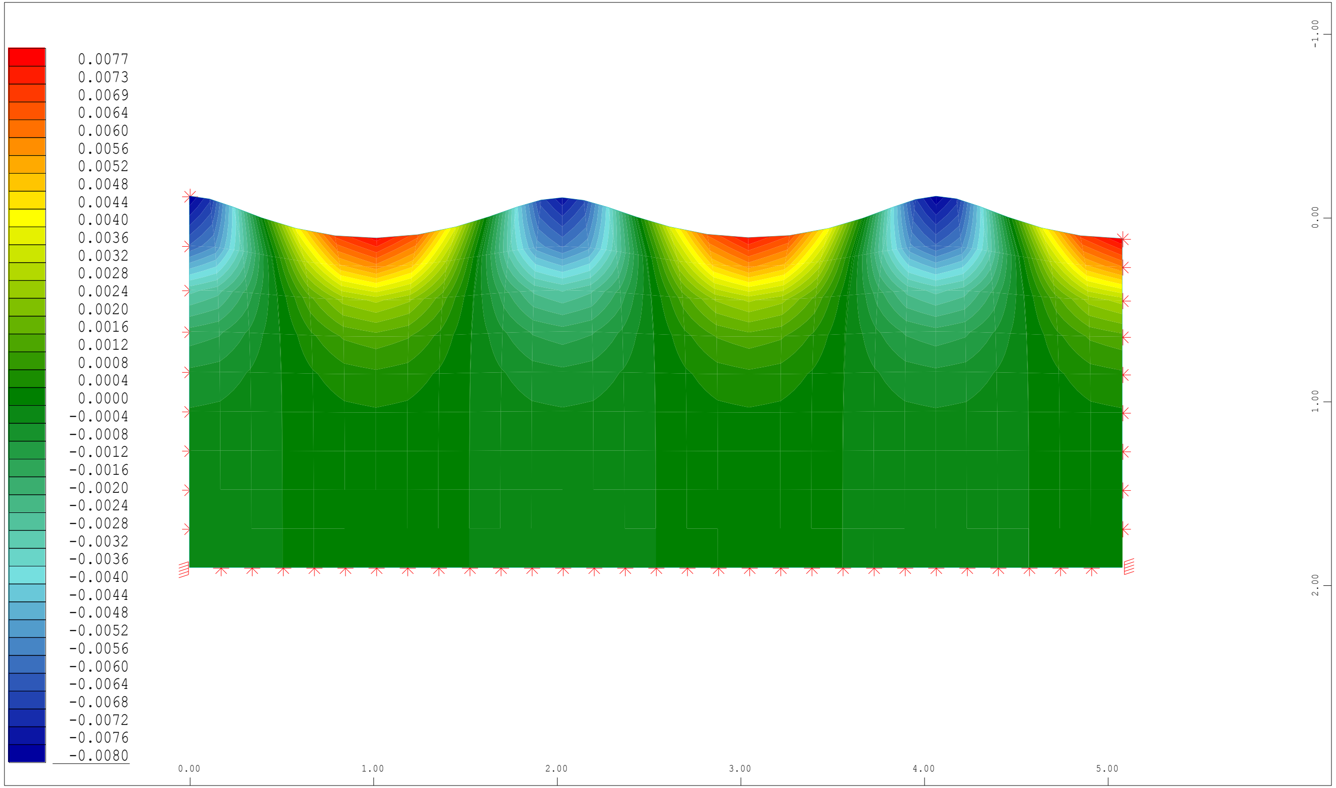
Ein Wassertank
Verschobene Struktur aus LF 81 Frequenz 0.361 Hertz
Spannungsmittelwert (1.Invariante) im Knoten, Lastfall 81, von -0.0043
bis 0.0043 Stufen 2.1329e-04 MPa

M 1 : 25



WINGRAF 3397 13.04.99
Katz+Bellmann - Beratende Ingenieure VBI
0.0058
0.0055
0.0052
0.0049
0.0046
0.0043
0.0040
0.0037
0.0034
0.0030
0.0027
0.0024
0.0021
0.0018
0.0015
0.0012
0.0009
0.0006
0.0003
0.0000
-0.0003
-0.0006
-0.0009
-0.0012
-0.0015
-0.0018
-0.0021
-0.0024
-0.0027
-0.0030
-0.0034
-0.0037
-0.0040
-0.0043
-0.0046
-0.0049
-0.0052
-0.0055
-0.0058
-0.0061
0.00
1.00
2.00
3.00
4.00
5.00
-1.00
0.00
1.00
2.00
Z X
Y
Ein Wassertank
Verschobene Struktur aus LF 82 Frequenz 0.557 Hertz in 0.500-facher
Überhöhung
Spannungsmittelwert (1.Invariante) im Knoten, Lastfall 82, von -0.0061
bis 0.0061 Stufen 3.0490e-04 MPa
M 1 : 25

WINGRAF 3397 13.04.99 Katz+Bellmann - Beratende Ingenieure VBI

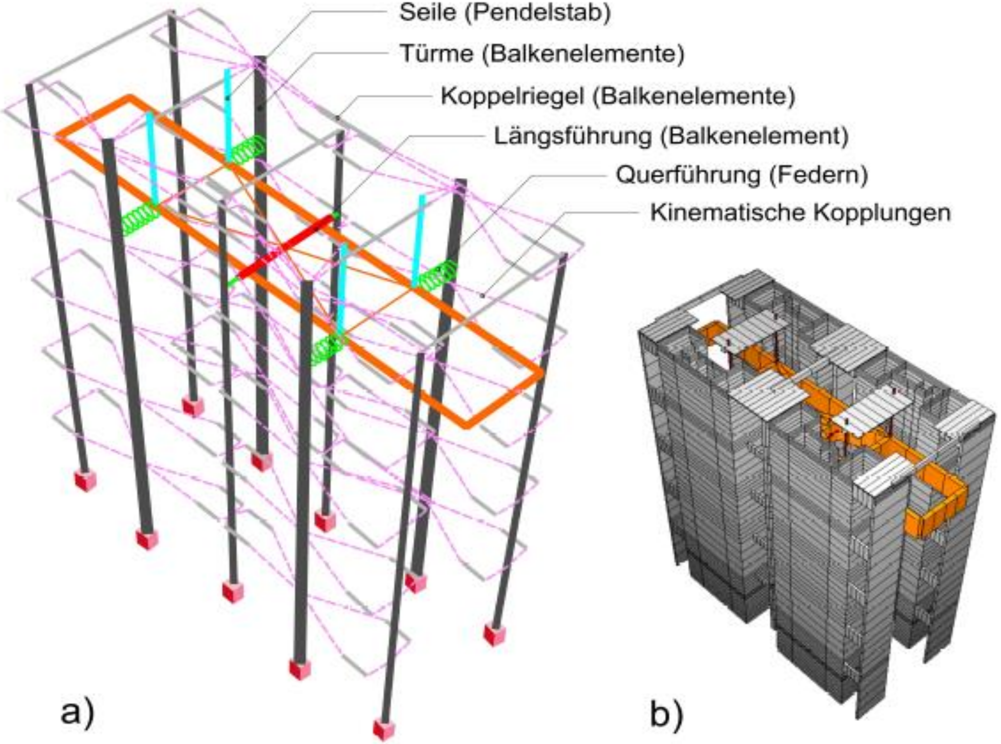


M 1 : 25

Z X
Y

Ein Wassertank
Verschobene Struktur aus LF 85 Frequenz 0.891 Hertz in 0.100-facher Überhöhung
Spannungsmittelwert (1.Invariante) im Knoten, Lastfall 85, von -0.0080 bis 0.0081 Stufen 4.0254e-04 MPa

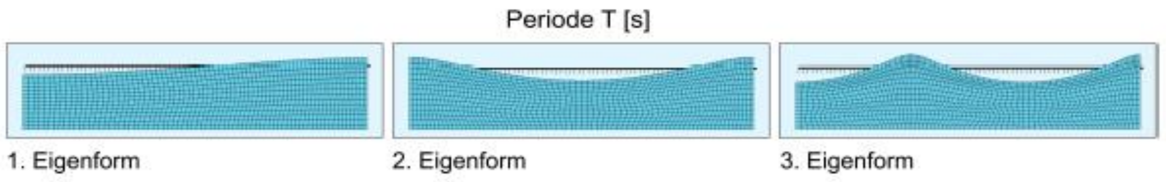
Three Gorges Dam China



SOFiSTiK

Problem of Water in trough

- Ship elevator investigated by
  Krebs & Kiefer Karlsruhe with SOFiSTiK
- Seismic response of sloshing water in trough
- CFD Model with ca 1 Million cells
- 3D model of water with ca 1000 lagrange elements



Comparison CFD / FEM