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Benchmark Problem for the Stability of a Retaining Wall

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Geotechnical Problems

Numerical analysis of geotechnical problems:

Serviceability limit state (SLS): Deformation based approach

Ultimate limit state analysis (ULS): Strength based approach EQU, HYD, UPL, GEO-2, STR, GEO-3

Numerical analysis of geotechnical problems:

Geostatic (initial) stress state analysis

Sequence of (many) construction phases

Material fill, removal and replacement

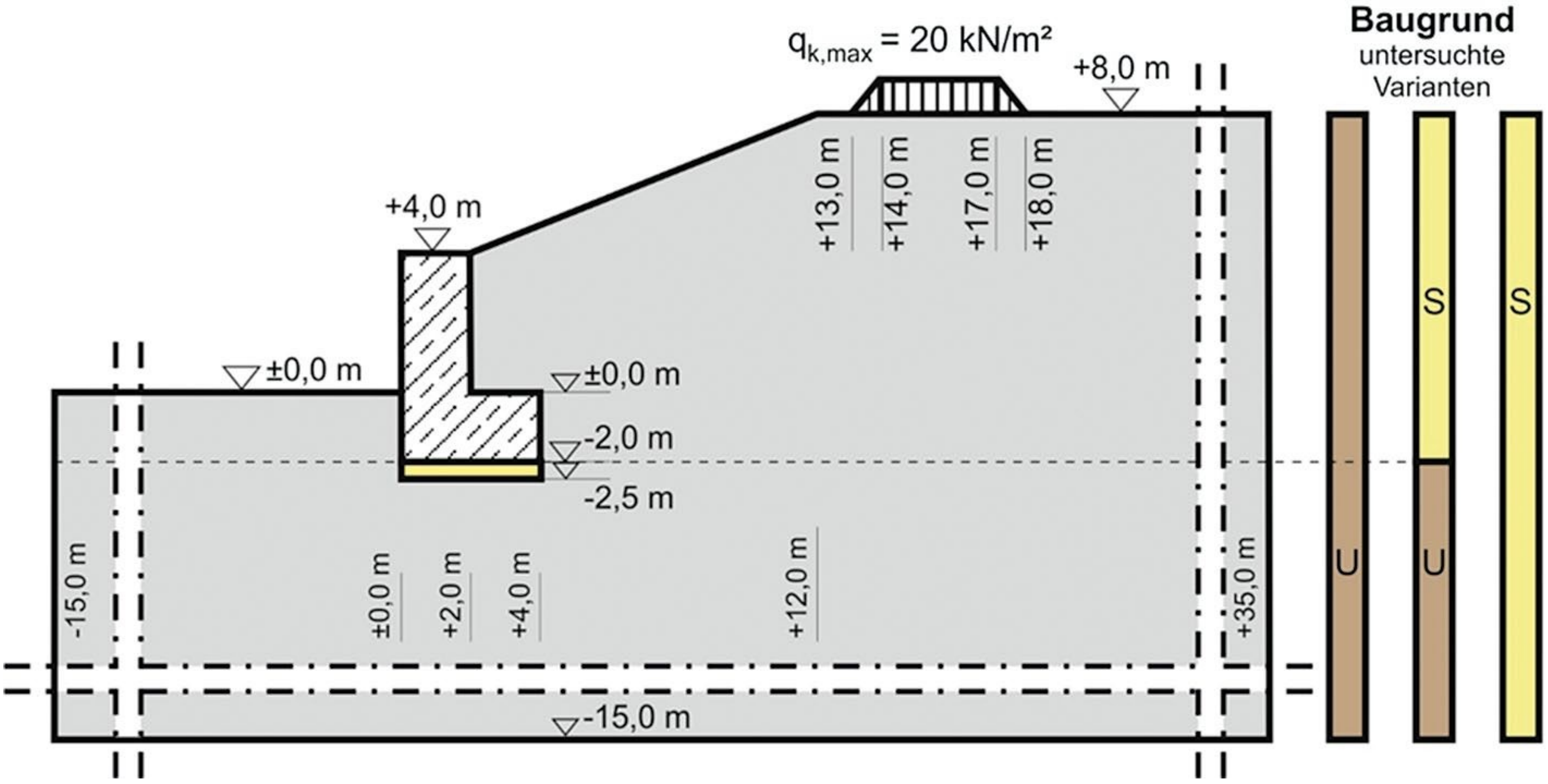
Potential change of material behaviour during and between construction phases

Numerical analysis of geotechnical problems:

Special attention is required to displacement, stress, internal variable and material property fields and their eventual superposition or manipulation between load phases

Benchmark Problem of a Retaining Wall

Benchmark Problem for the Stability of a Retaining Wall



Benchmark Problem for the Stability of a Retaining Wall – Geometry and soil layering

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Benchmark problem – material properties:

Silt (U /Si/):

$$E = 40\ [\mathrm{MN/m^2}]$$
$$\nu = 0.30\ [1]$$
$$\gamma = 20[\mathrm{kN/m^2}]$$
$$\varphi_k = 20\ [°]$$
$$c_k = 10.0\ [\mathrm{kN/m^2}]$$
$$\psi = 0.0\ [°]$$
$$\boldsymbol{\sigma_t = 0.0\ [\mathrm{kN/m^2}]}$$

Sand (S /Sa/)

$$E = 40\ [\mathrm{MN/m^2}]$$
$$\nu = 0.30\ [1]$$
$$\gamma = 20[\mathrm{kN/m^2}]$$
$$\varphi_k = 35\ [°]$$
$$c_k = 0.1\ [\mathrm{kN/m^2}]$$
$$\psi = 5.0\ [°]$$
$$\boldsymbol{\sigma_t = 0.0\ [\mathrm{kN/m^2}]}$$

Concrete:

$$E = 40\ [\mathrm{GN/m^2}]$$
$$\nu = 0.20\ [1]$$
$$\gamma = 25[\mathrm{kN/m^2}]$$

Benchmark problem – configurations:

Sand basemat under retaining wall

Case SiSi: Silt below and Silt beyond foundation level

Case SiSa: Silt below and Sand beyond foundation level

Case SaSa: Sand below and Sand beyond foundation level

Benchmark problem – analysis phases:

1. Geostatic stress state in the basement (stress adjustment or gravity loading)

2. Wall construction

3. Layered backfill (simplified)

4. Surface load (regarded as variable)

5. General stability of the construction

Benchmark problem – solution strategy:

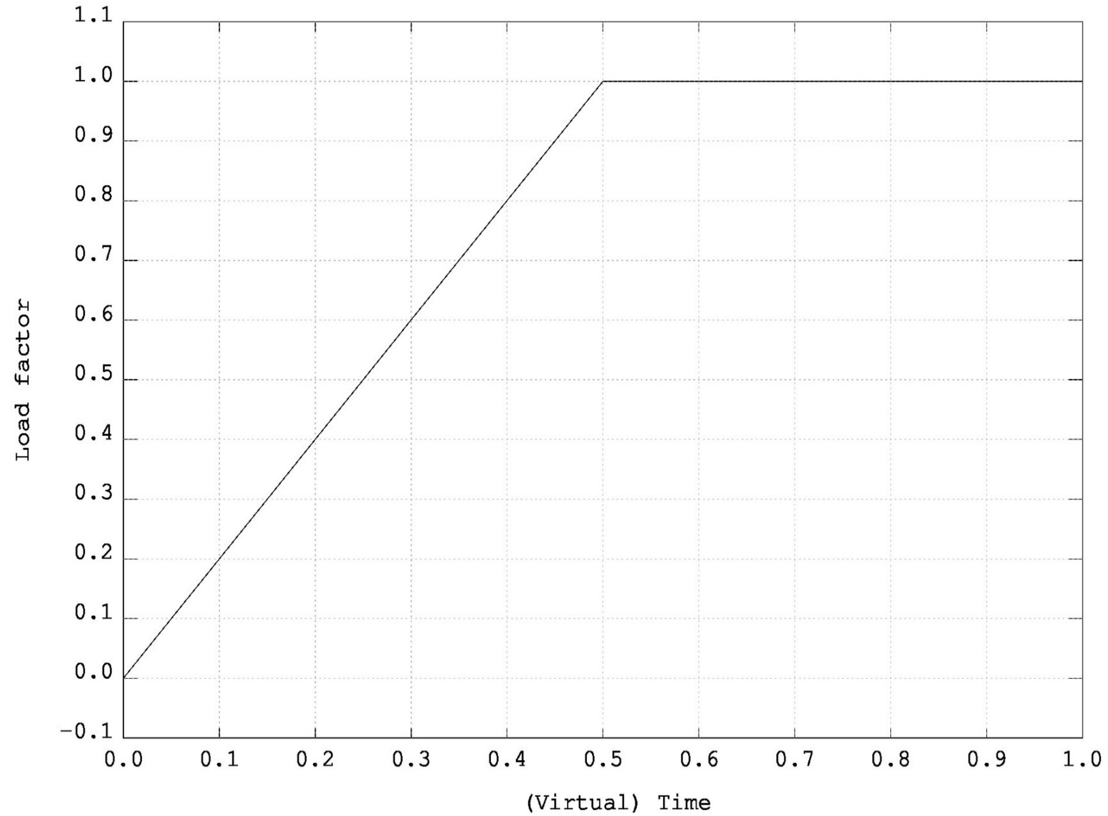
1. Treatment of the problem in plane strain

2. Definition of soil and retaining wall clusters, surfaces and contours

3. Definition of ALL external loads (self weight and charges)

4. Implementation of the construction phases by stepwise imposition of loads

Increasing load multiplicator function with equilibrium iteration

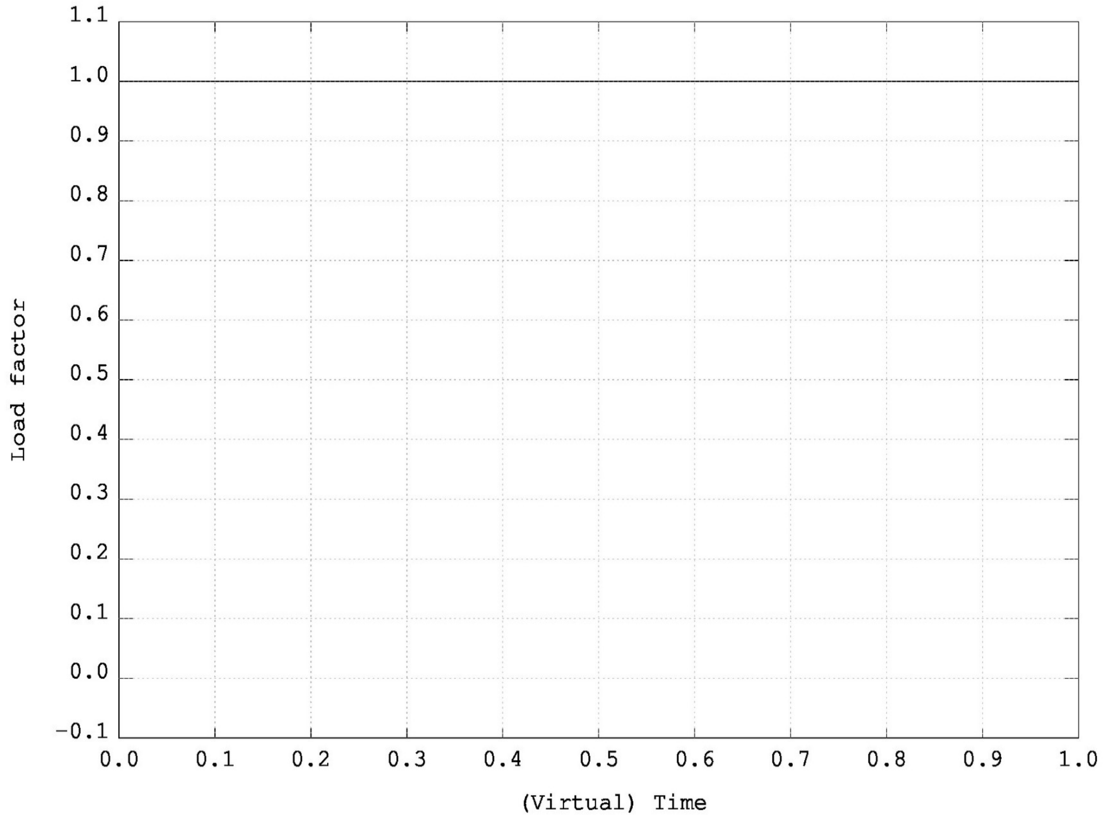


Load increase multiplicator

Benchmark Problem for the Stability of a Retaining Wall – Increasing load

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Constant load multiplicator function

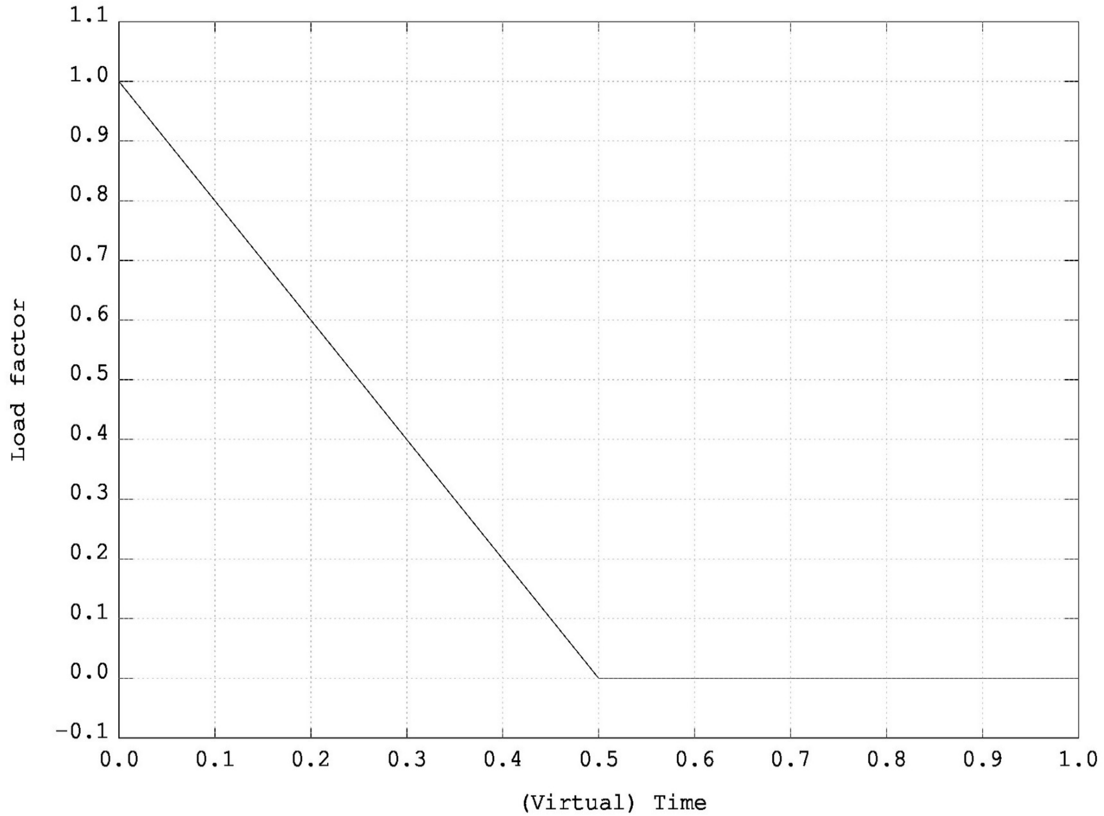


Load constant multiplicator

Benchmark Problem for the Stability of a Retaining Wall – Constant load

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Decreasing load multiplicator function with equilibrium iteration

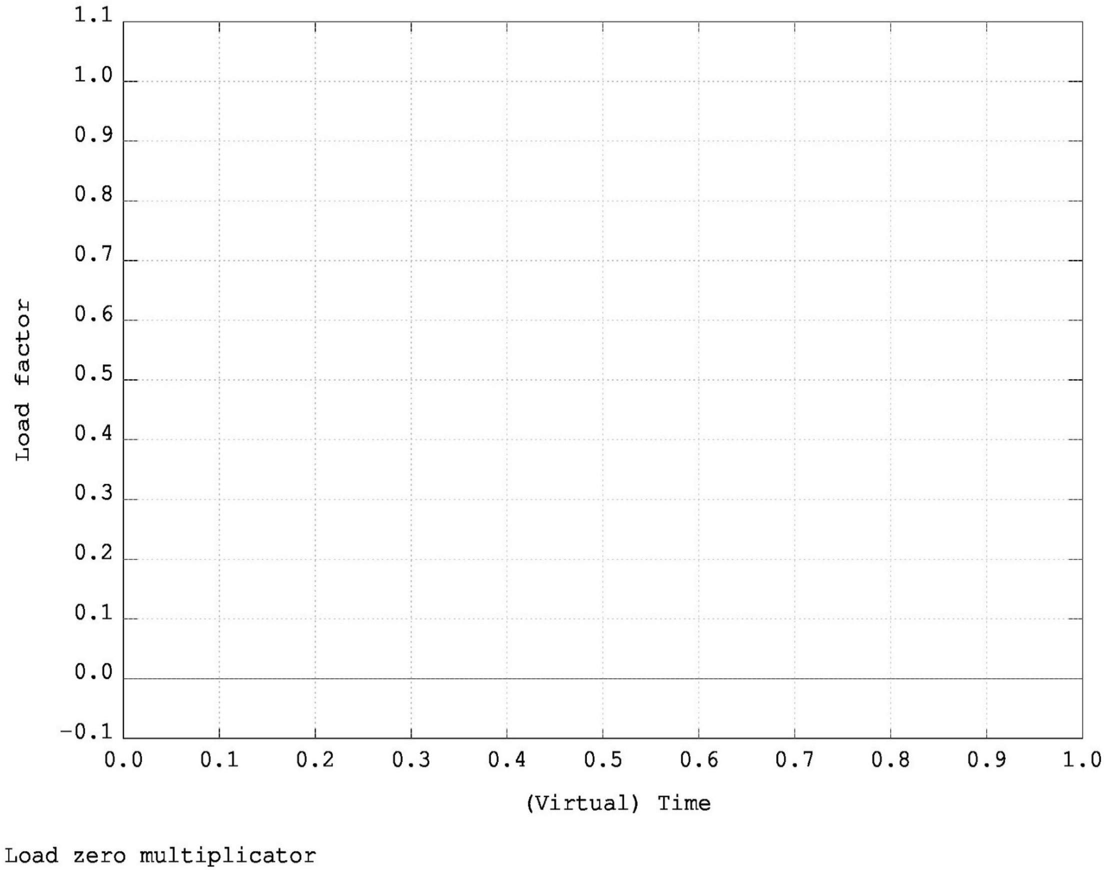


Load decrease multiplicator

Benchmark Problem for the Stability of a Retaining Wall – Decreasing load

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Zero load multiplicator function



Benchmark Problem for the Stability of a Retaining Wall – Zero load

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Solution of the Benchmark Problem:

Material model and parameters

Material model:

Drucker-Prager ideal elasto-plasticity without hardening or softening

Constant stiffness parameters

Adjustment of strength parameters to the average of Mohr-Coulomb compression and tension

Drucker-Prager strength parameters (?):

$$\mathrm{ALFA} = \mathrm{ETA} = \frac{2\sqrt{3}\,\sin(\varphi)}{9-\sin^2(\varphi)}\ ,\quad \mathrm{BETA} = \mathrm{MU} = \sqrt{\frac{2}{3}}\,(?)\ ,$$

$$\mathrm{K} = \mathrm{KL} = \frac{6\sqrt{3}\,c\,\cos(\varphi)}{9-\sin^2(\varphi)}\ ,$$

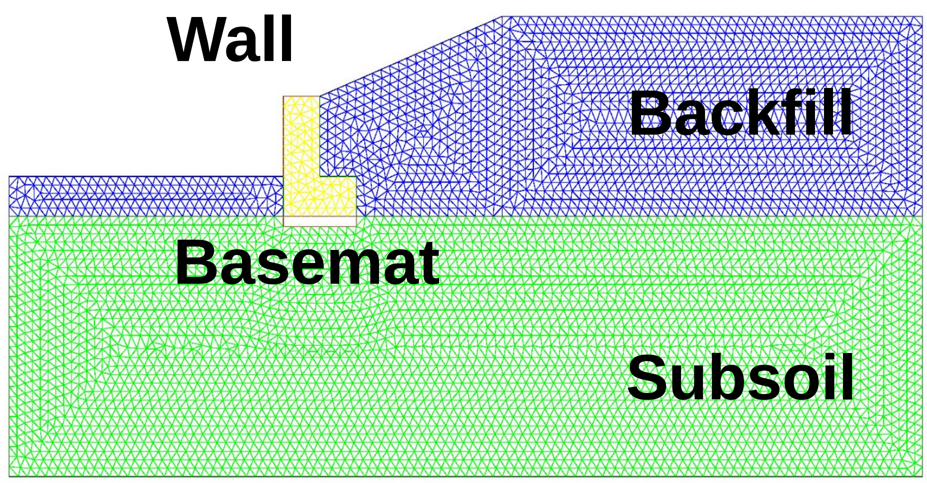
$$\mathrm{GAMM} = \frac{2\sqrt{3}\,\sin(\psi)}{9-\sin^2(\psi)}\ ,\quad \mathrm{DELT} = \sqrt{\frac{2}{3}}\,(?)$$

Solution of the Benchmark Problem:

Geometry and mesh

Soil clusters and mesh

Cast3M



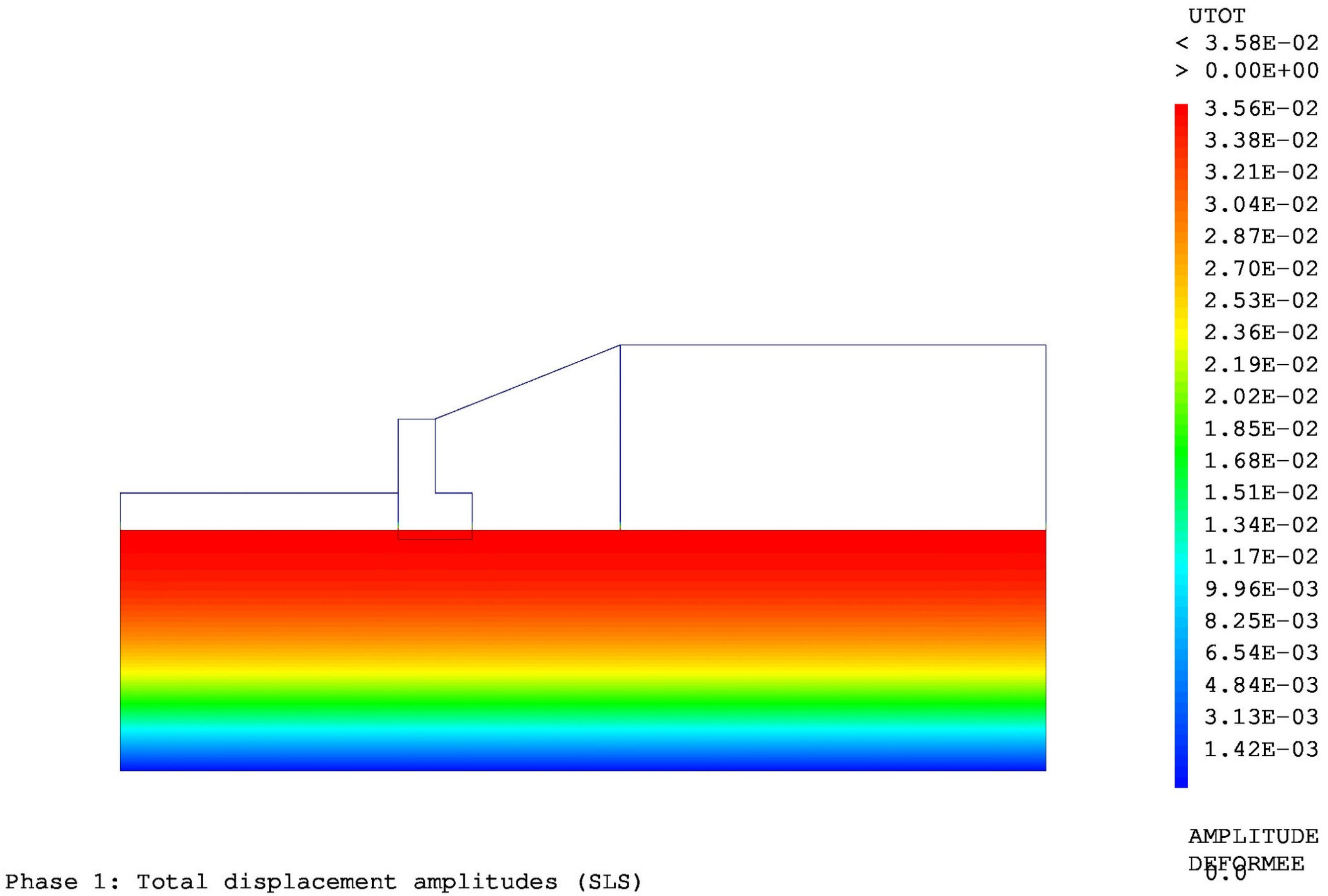
Retaining Wall – Geometry, soil clusters and wall – Subsoil, basemat, wall and backfill

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Solution of the Benchmark Problem:

Initial stress state (SLS)

SLS: Subsoil



Cast3M
SiSi

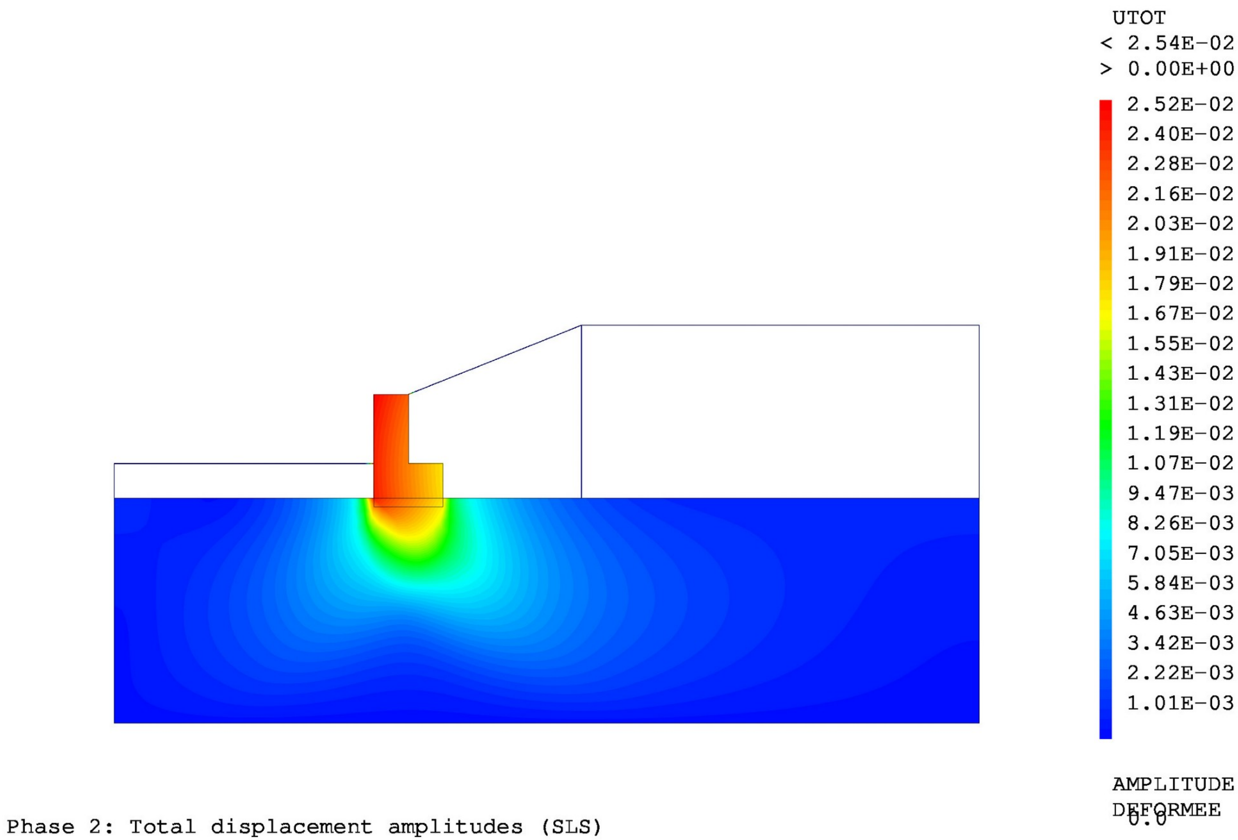
Retaining wall – Total displacement amplitudes in the subsoil under self weight

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Solution of the Benchmark Problem:

Construction of the retaining wall (SLS)

SLS: Retaining wall



Cast3M SiSi

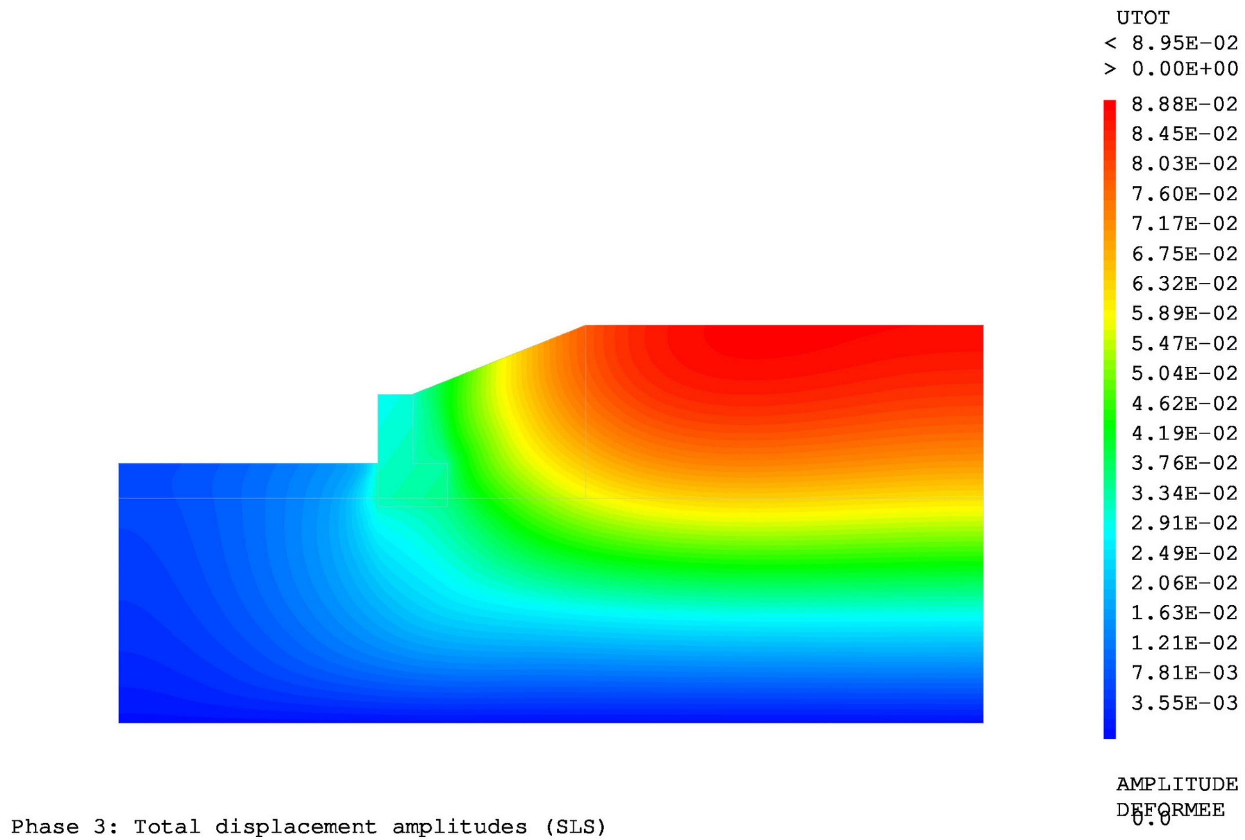
Retaining wall – Total displacement amplitudes after construction of the retaining wall

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Solution of the Benchmark Problem:

Backfill behind the retaining wall (SLS)

SLS: Retaining wall



Cast3M SiSi

Retaining wall – Total displacement amplitudes after backfill behind the retaining wall

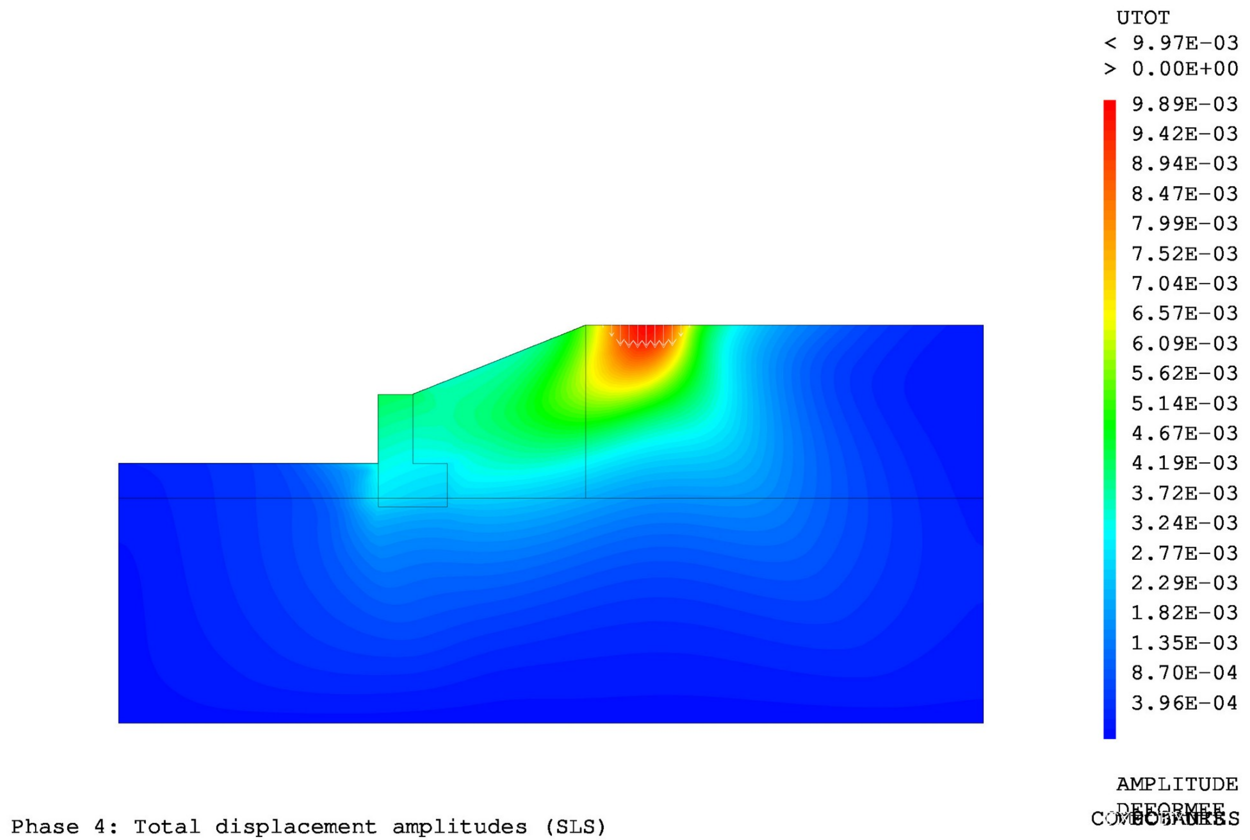
DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Solution of the Benchmark Problem:

Imposition of external load (SLS)

SLS: External load

Cast3M SiSi



Retaining wall – Total displacement amplitudes under imposed external load

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Solution of the Benchmark Problem:

The strength reduction method (ULS, GEO-3)

Strength reduction method:

Global safety factor concept: η

$$r_n = \left\| \mathbf{f} - \mathbf{K}\left(\varphi_{k,mob}, c_{k,mob}, \psi_{k,mob}, \sigma_{t,mob}\right) \cdot \mathbf{u}_n \right\| < \epsilon$$

$$\tan\varphi_{k,mob} = \frac{\tan\varphi_k}{\eta} \;,\; c_{k,mob} = \frac{c_k}{\eta} \;,\; \tan\psi_{k,mob} = \frac{\tan\psi_k}{\eta} \;,\; \sigma_{t,mob} = \frac{\sigma_{t,k}}{\eta}$$

Partial safety factor concept: $\mu, (\gamma)$

$$r_n = \left\| \mathbf{f} - \mathbf{K}\left(\varphi_{d,mob}, c_{d,mob}, \psi_{d,mob}, \sigma_{t,d,mob}\right) \cdot \mathbf{u}_n \right\| < \epsilon$$

$$\tan\varphi_{d,mob} = \mu \tan\frac{\varphi_k}{\gamma_\varphi} \;,\; c_{d,mob} = \mu \frac{c_k}{\gamma_c} \;,\; \tan\psi_{d,mob} = \mu \frac{\tan\psi_k}{\gamma_\psi} \;,\; \sigma_{t,d,mob} = \mu \frac{\sigma_{t,k}}{\gamma_{\sigma,t}}$$

Special case of the partial safety factors and dimensioning values of the strength parameters for analyses on the strength reduction method behaviour:

$$\gamma_{\varphi} = \gamma_{c} = \gamma_{\psi} = \gamma_{\sigma,t} = 1.0$$

$$\tan\varphi_{d} = \tan\varphi_{k} \quad , \quad c_{d} = c_{k} \quad , \quad \psi_{d} = \psi_{k} \quad , \quad \sigma_{t,d} = \sigma_{t,k}$$

Identity for the global safety factor and the utilisation factor under these conditions:

$$\mu = \frac{1}{\eta} \quad , \quad \eta = \frac{1}{\mu}$$

Strength reduction method:

Analysis is based on the limit equilibrium of external and internal forces in the model

Trivial solution: gradual reduction of the mobilized strength (manually or in a loop)

Advanced solution: recursive reduction of the mobilized strength using a search strategy based on a convergence criterion

Strength reduction method:

Restrictions on suitable material behaviour

Drucker-Prager, Mohr-Coulomb and Hoek-Brown ideal elasto-plasticity are considered to be adequate

Material models describing more sophisticated physics must be replaced and transformed before analysis phase

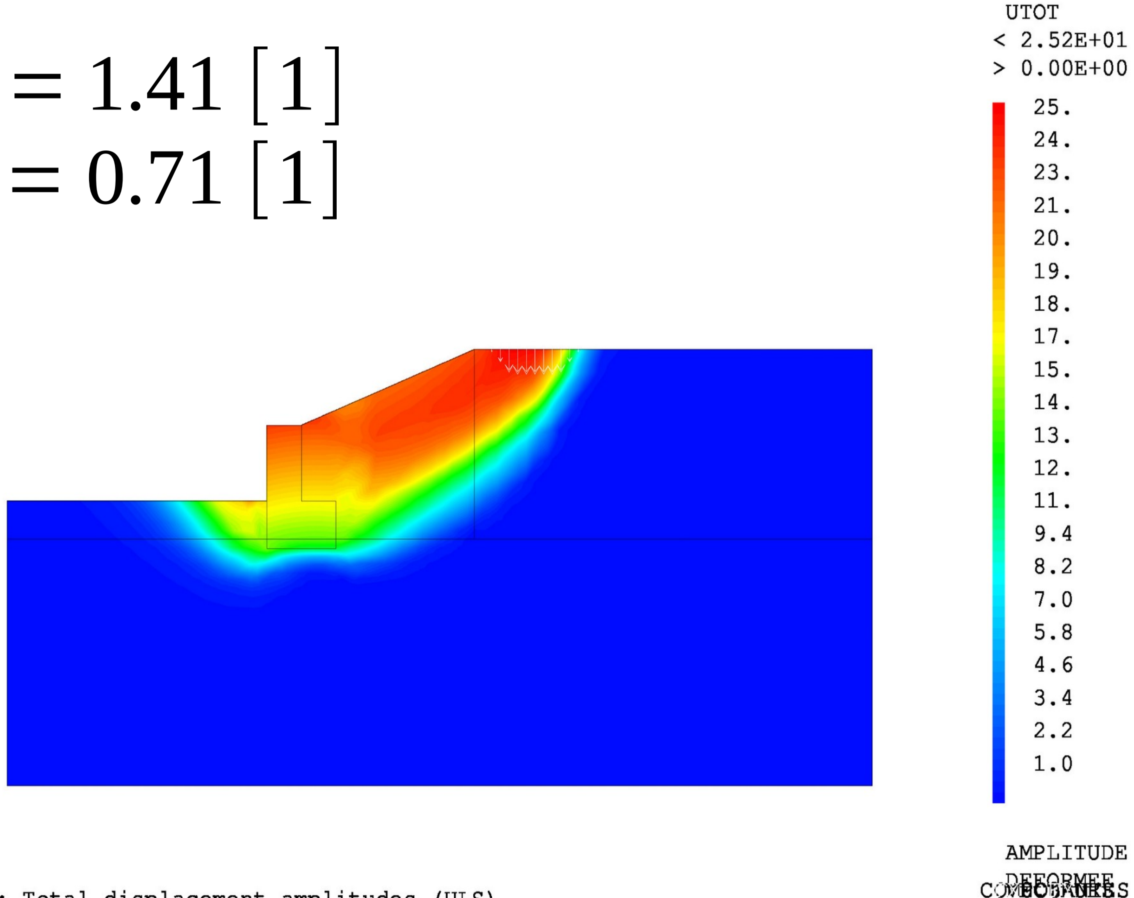
Solution of the Benchmark Problem:

General stability analysis with the strength reduction method (ULS, GEO-3)

ULS, Geo-3: Retaining wall displacements

$$\eta = 1.41\ [1]$$
$$\mu = 0.71\ [1]$$

Cast3M SiSi



Phase 5: Total displacement amplitudes (ULS)

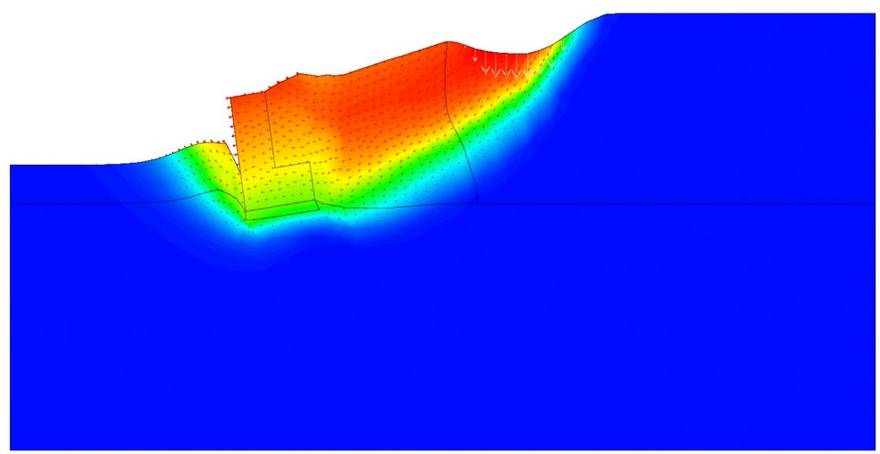
Retaining wall – Total displacements in ultimate limit state of the case SiSi

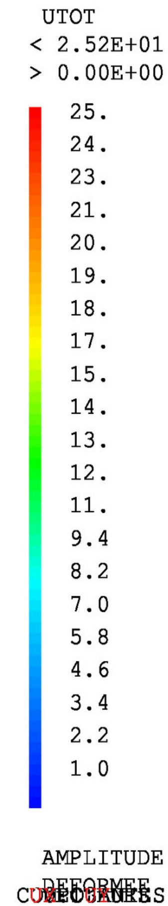
DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

ULS, Geo-3: Retaining wall failure kinematics

$$\eta = 1.41\ [1]$$
$$\mu = 0.71\ [1]$$

Cast3M SiSi





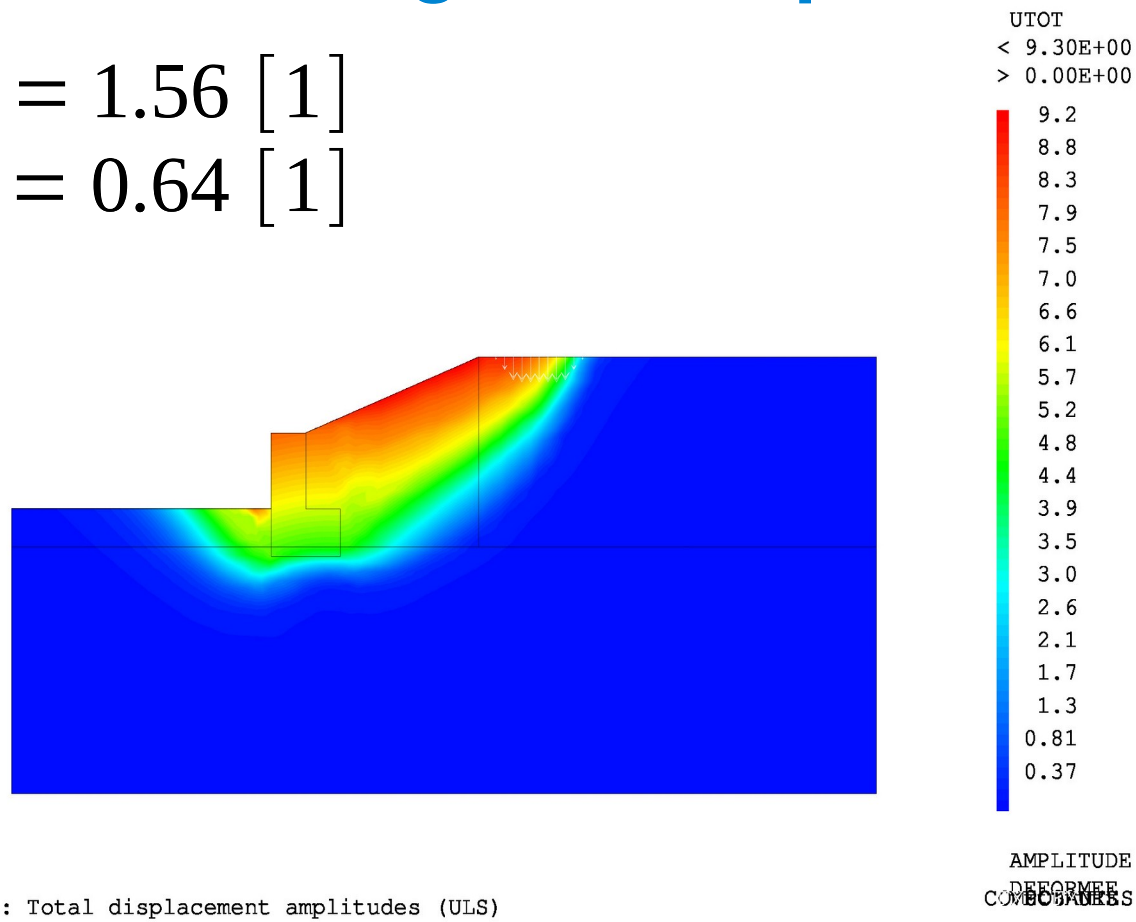
Retaining wall – Kinematics and total displacements in ultimate limit state of the case SiSi

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

ULS, Geo-3: Retaining wall displacements

$$\eta = 1.56\ [1]$$
$$\mu = 0.64\ [1]$$

Cast3M SiSa



Phase 5: Total displacement amplitudes (ULS)

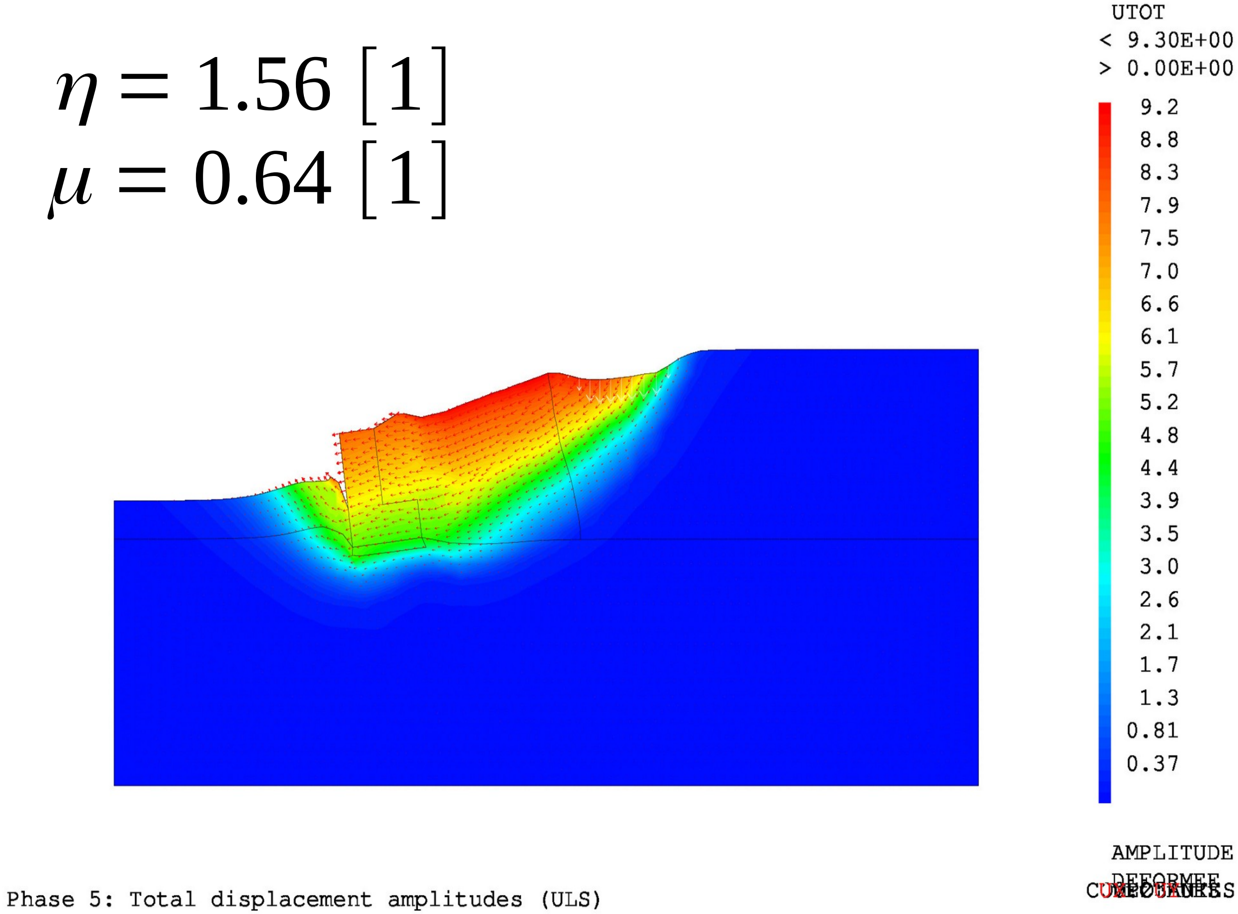
Retaining wall – Total displacements in ultimate limit state of the case SiSa

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

ULS, Geo-3: Retaining wall failure kinematics

$$\eta = 1.56\ [1]$$
$$\mu = 0.64\ [1]$$

Cast3M
SiSa

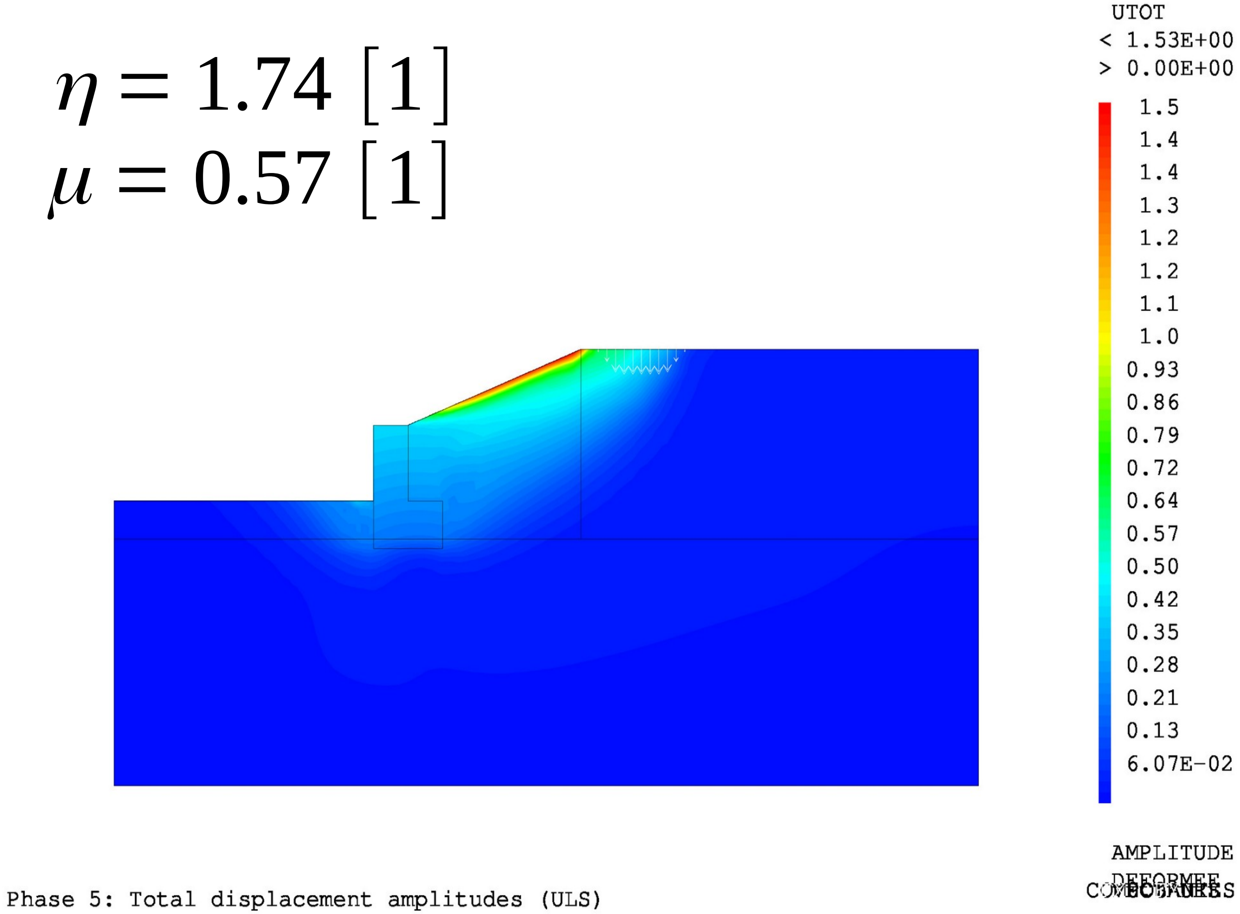


Retaining wall – Kinematics and total displacements in ultimate limit state of the case SiSa
DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

ULS, Geo-3: Retaining wall displacements

$$\eta = 1.74\ [1]$$
$$\mu = 0.57\ [1]$$

Cast3M
SaSa



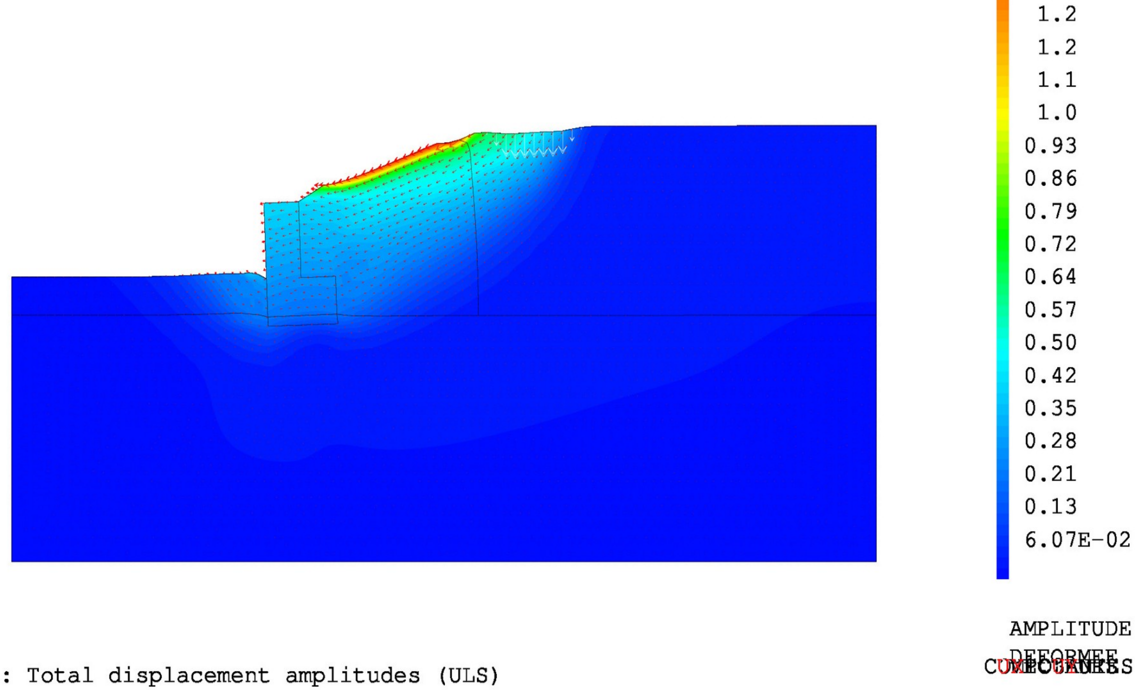
Retaining wall – Total displacements in ultimate limit state of the case SaSa

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

ULS, Geo-3: Retaining wall failure kinematics

$$\eta = 1.74\ [1]$$
$$\mu = 0.57\ [1]$$

Cast3M
SaSa



Retaining wall – Kinematics and total displacements in ultimate limit state of the case SaSa

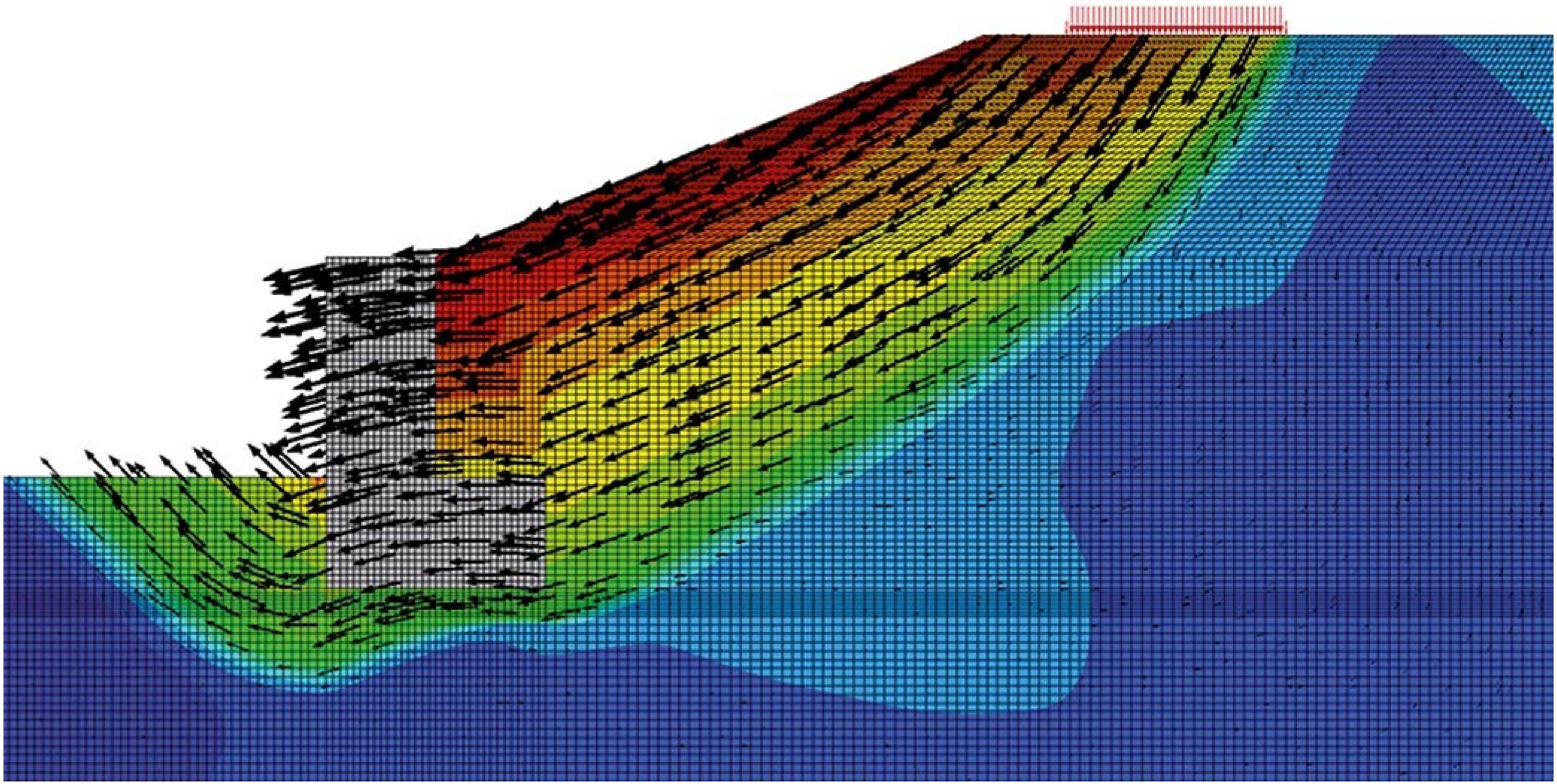
DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Solution of the Benchmark Problem:

General stability analysis with the strength reduction method (ULS, GEO-3)

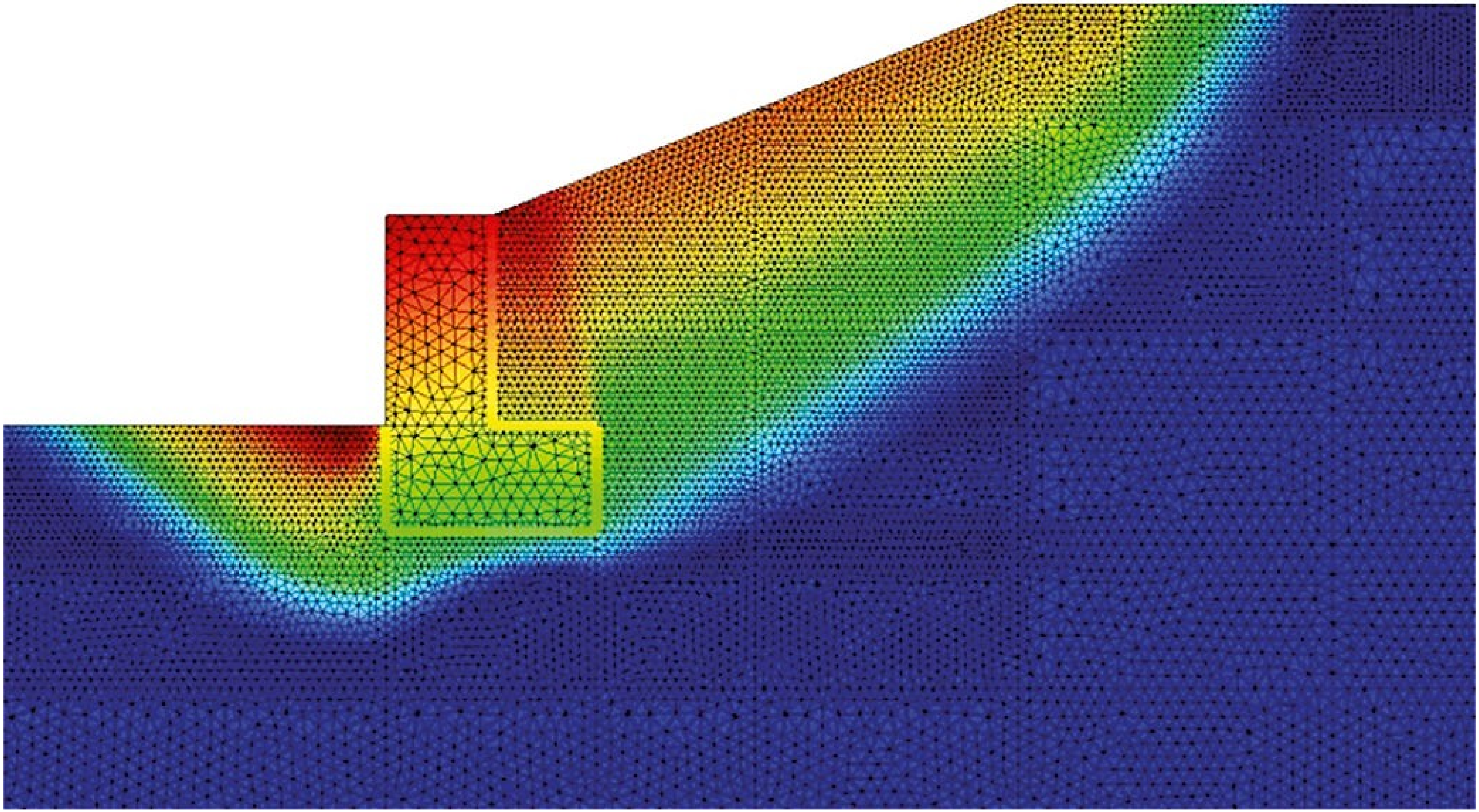
Alternative solution examples

ULS, Geo-3: Failure kinematics, Flac3D



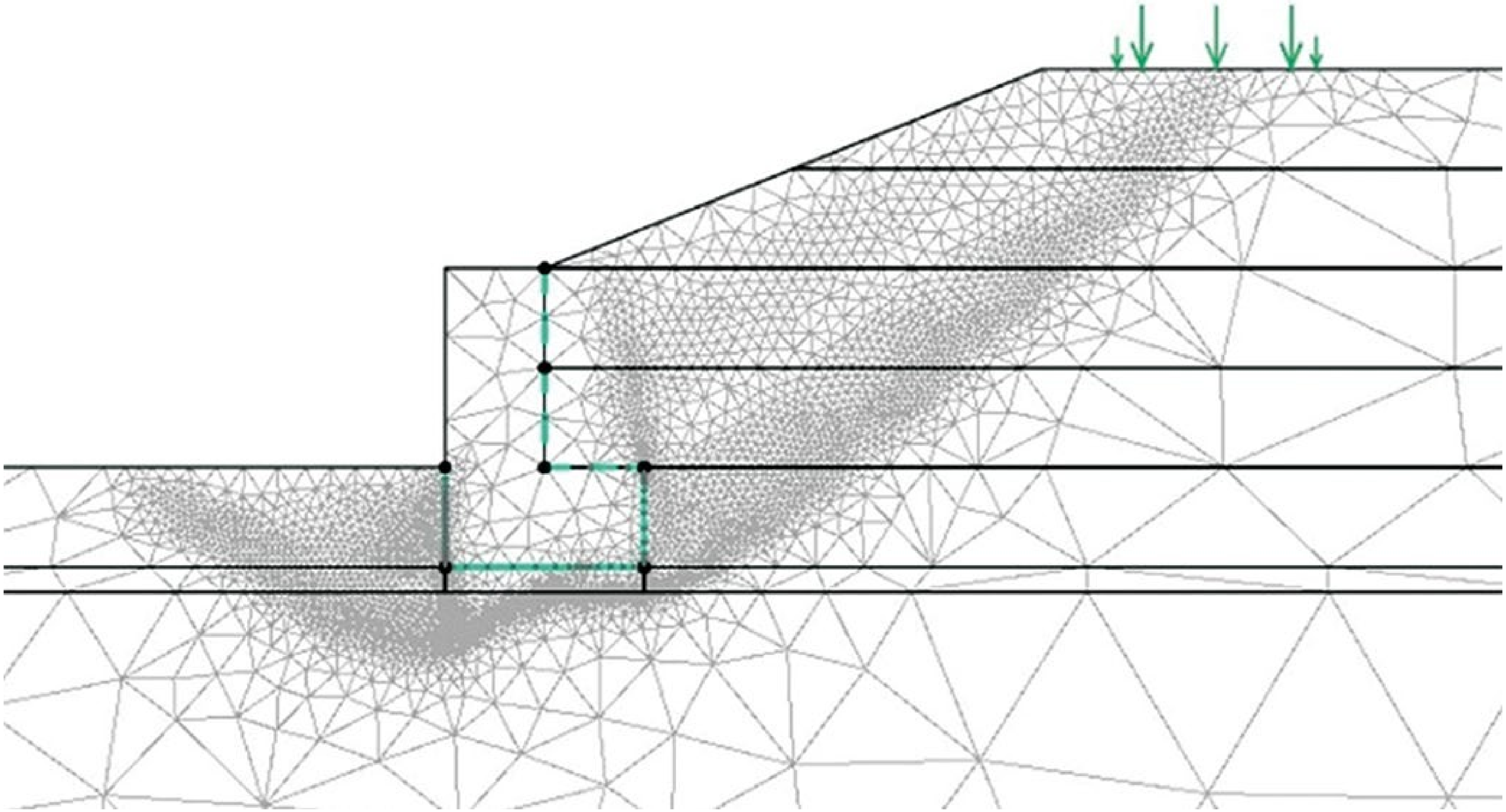
Retaining wall – Total displacements in ultimate limit state with the code Flac3D (FDM)
DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

ULS, Geo-3: Failure kinematics, Tochnog



Retaining wall – Total displacements in ultimate limit state with the code Tochnog (FEM)
DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

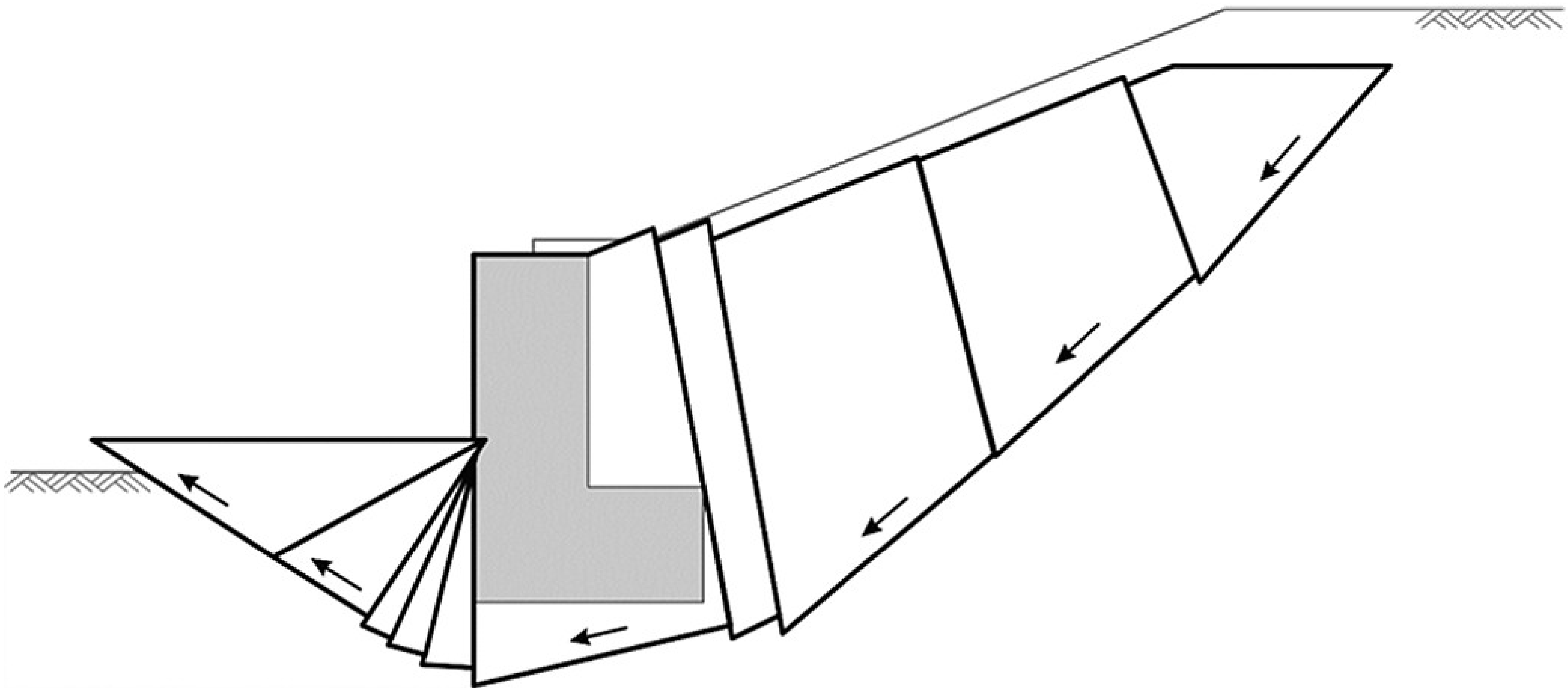
LEM: Limit Equilibrium Method



Retaining wall – Ultimate limit state analysis with the Limit Equilibrium Method (LEM)

DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

KEM: Kinematic Element Method



Retaining wall – Ultimate limit state analysis with the Kinematic Element Method (KEM)
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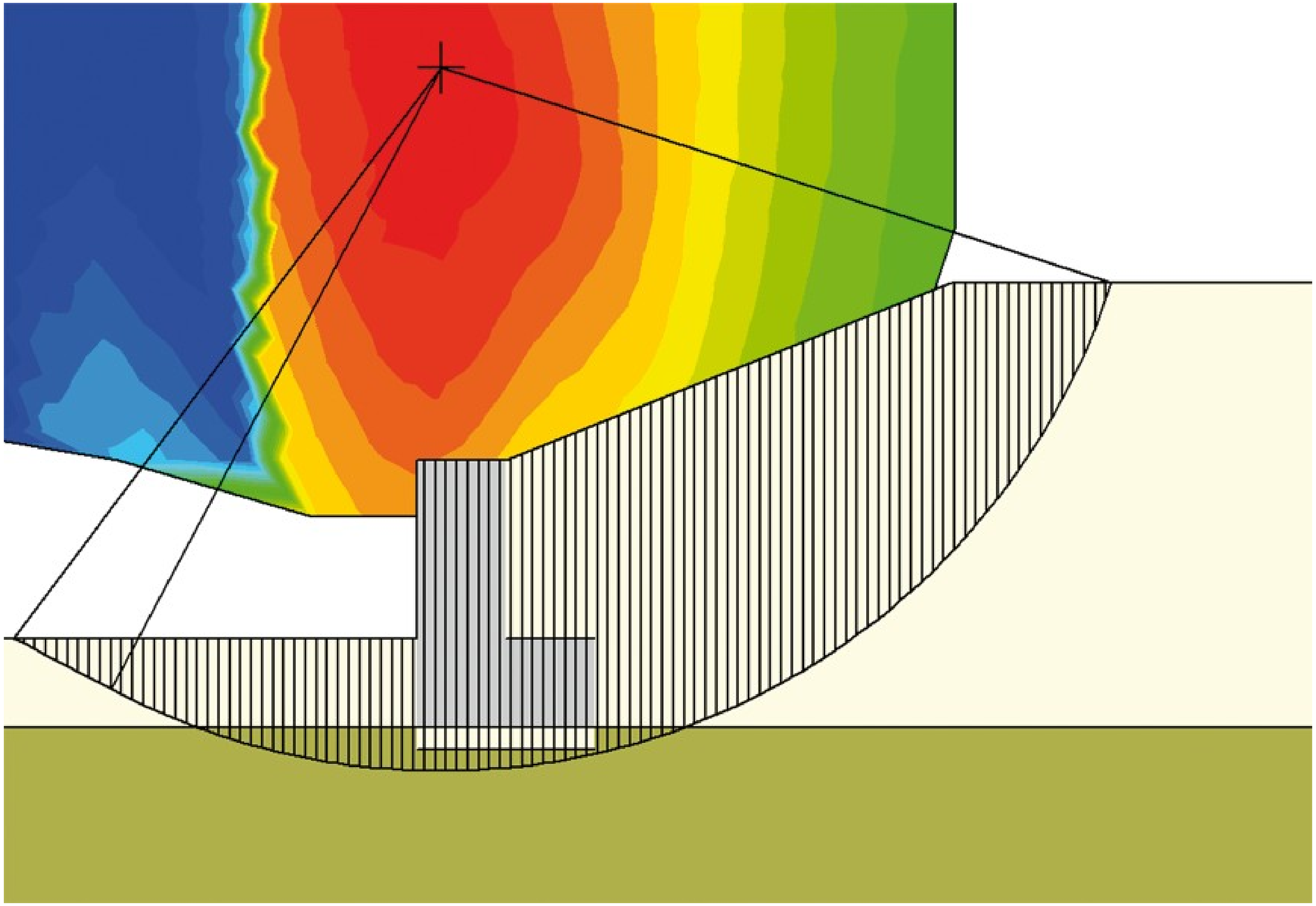
Method of slices with circular slip surface



Retaining wall – Ultimate limit state analysis with the method of slices (e.g. Bishop method)

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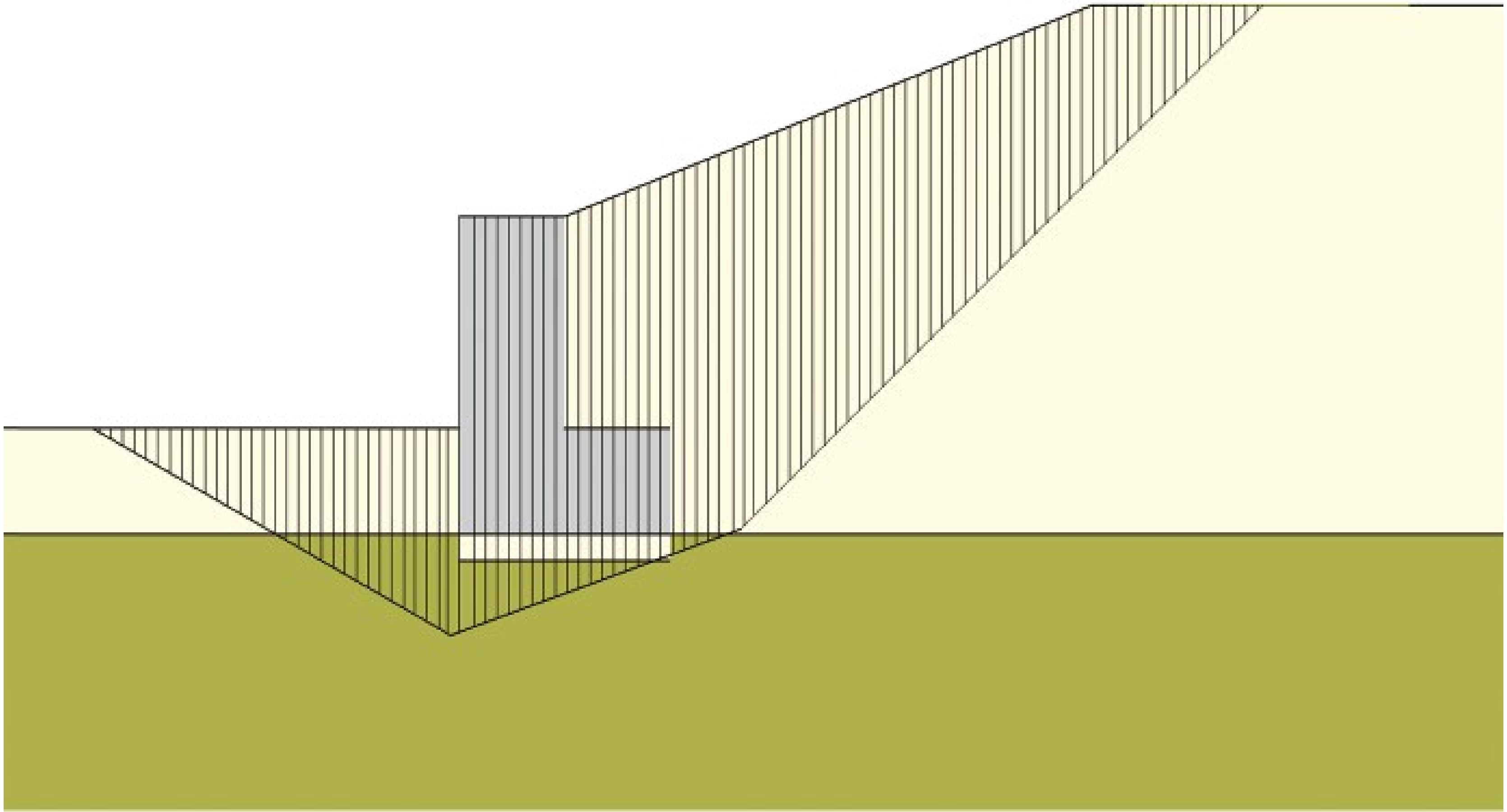
Method of slices with polygonal slip surface



Retaining wall – Ultimate limit state analysis with the method of slices (e.g, Janbu method)
DGGT e.V., AK1.6: Stability Calculation with FEM with Strength Parameter Reduction; Geotechnik 42(2019), no.2, p.88-97.

Solution of the Benchmark Problem:

General stability analysis with the strength reduction method (ULS, GEO-3)

Results

Global safety factors /utilisation factors/

Solver:1	Method:	SiSi:	SiSa:	SaSa:
Plaxis	FEM	1.36	1.56	1.78
Z-Soil	FEM	1.36	1.58	1.78
Tochnog	FEM	**1.41**	**1.56**	**1.74**
Sofistik	FEM	1.40	1.61	1.83
Flac3D	FDM	1.41	1.63	1.83
Optum G2	LEM	1.34-1.37	1.50-1.60	1.79-1.83
KEM	KEM	1.43	1.58	1.93
Bishop / Janbu	Slices	1.58 / 1.24	1.89 / 1.44	2.19 / 1.71
Cast3M	**FEM**	**(1.41) /μ=0.71/**	**(1.56) /μ=0.64/**	**(1.74) /μ=0.57/**

Summary and conclusions

Geotechnical problems:

Construction in (many) individual phases

Increasing load factors for material placement (fill) and decreasing load factors for material removal (excavation) taking stiffness modelling correctly into account

Constant load factors for existing and zero load factors for future charges

Geotechnical problems:

Serviceability limit state (SLS) computations for deformation analysis

Ultimate limit state (ULS) computations for stability analysis

Strength reduction method is a powerful numerical technique implementing different safety concepts

Cast3M in Geotechnical problems:

Serviceability limit state (SLS) analyses deliver adequate quantitative results

Ultimate limit state (ULS) analyses deliver adequate failure kinematics

Ultimate limit state (ULS) analyses should be considered as a promiseful experimental feature for the moment

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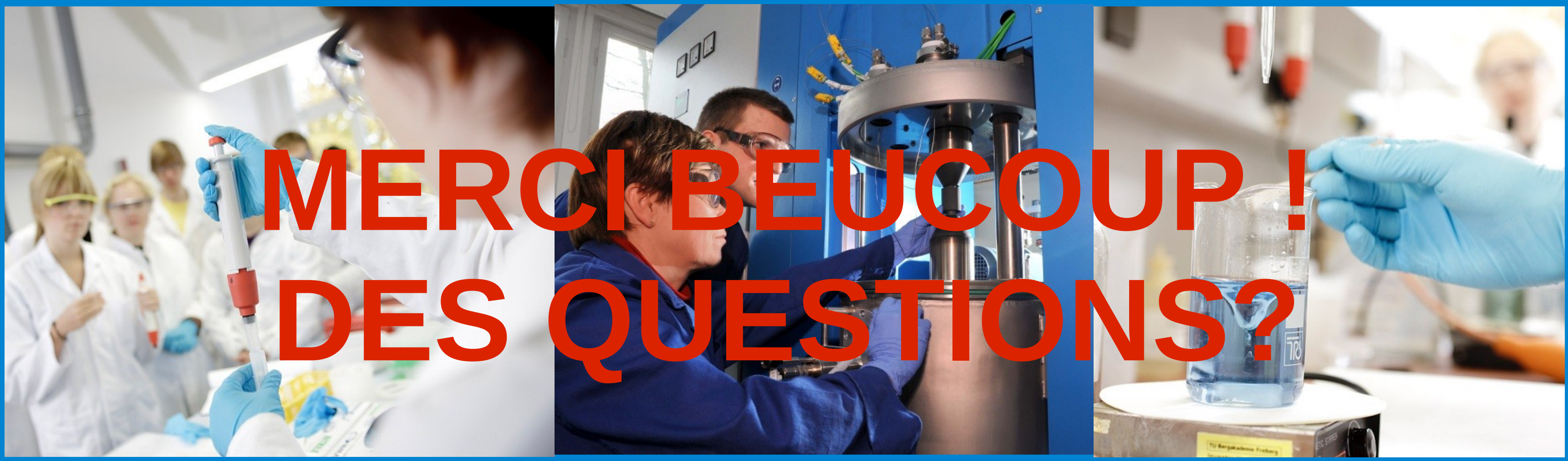

MERCI BEUCOUP !
DES QUESTIONS?

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