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Numerical modelling of revitalization options for reclamation of high-plasticity spoil dumps

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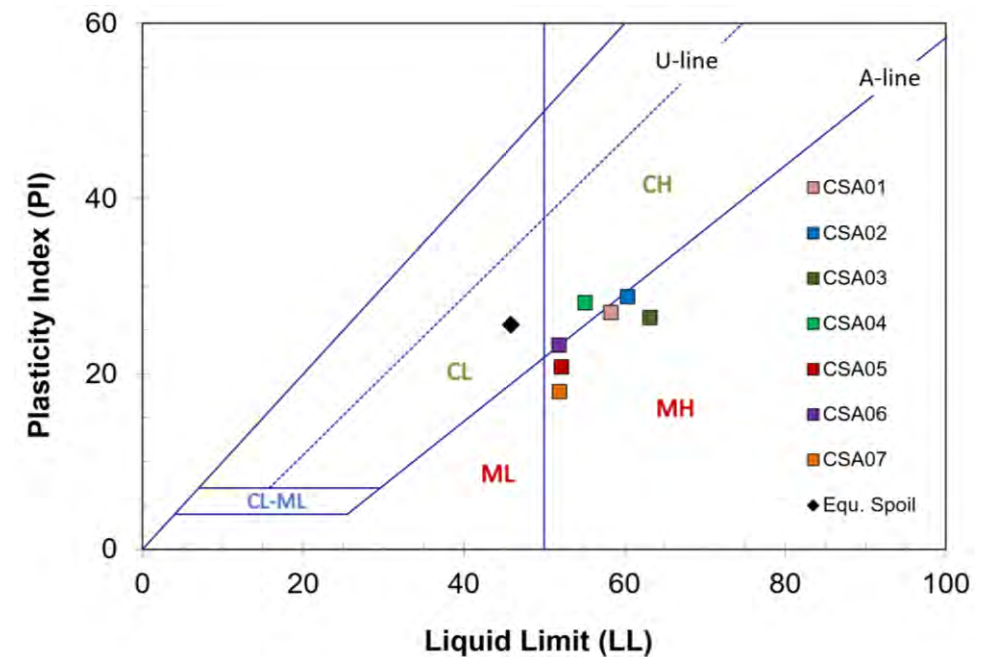




- Premise: open-pit mine overburden soil (or spoil) materials are heterogeneous and can contain large proportions of high-plasticity clay.
- Challenge: use of spoil for revitalisation of open-pit mine areas



Image source: photocase.com



Data from testing of samples from CSA Open Pit mine



- Premise: open-pit mine overburden soil (or spoil) materials are heterogeneous and can contain large proportions of high-plasticity clay.
- Challenge: use of spoil for revitalisation of open-pit mine areas
- Objective: Accurate numerical modelling of complex spoil response to loading for 2 revitalisation options:

Creation of pit lakes using mine spoils



Image source: [imagelinkglobal.com](https://www.imagelinkglobal.com)

Wind turbines on mine spoils

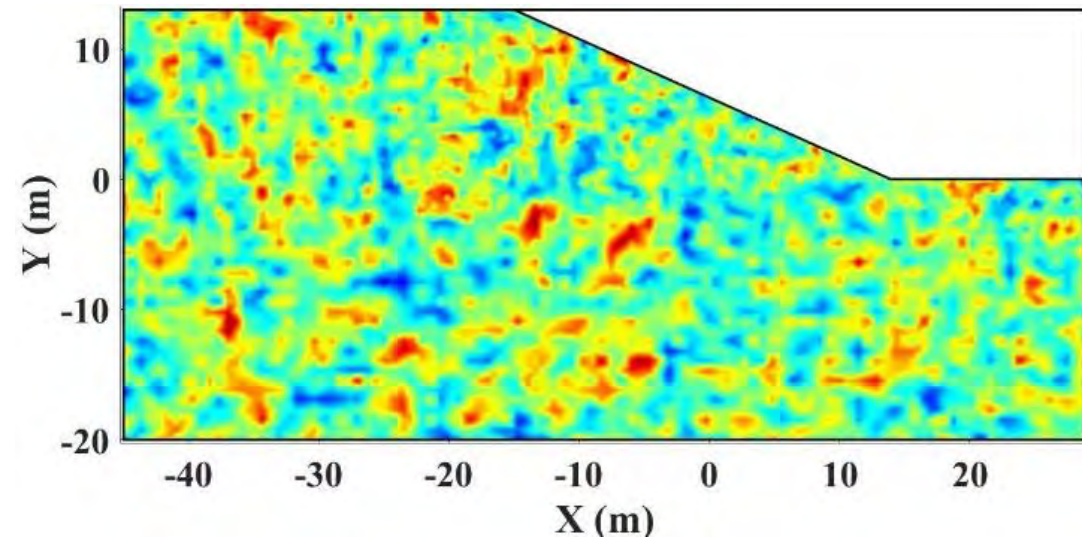
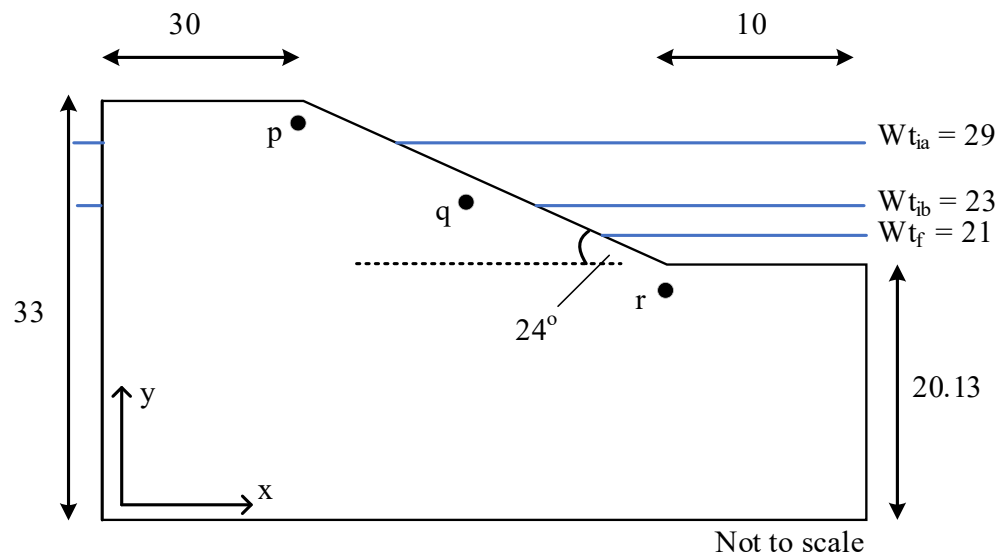


Image source: [windeurope.org](https://www.windeurope.org)



Option 1: Use of mine spoils for creation of pit lakes (RAFF project)

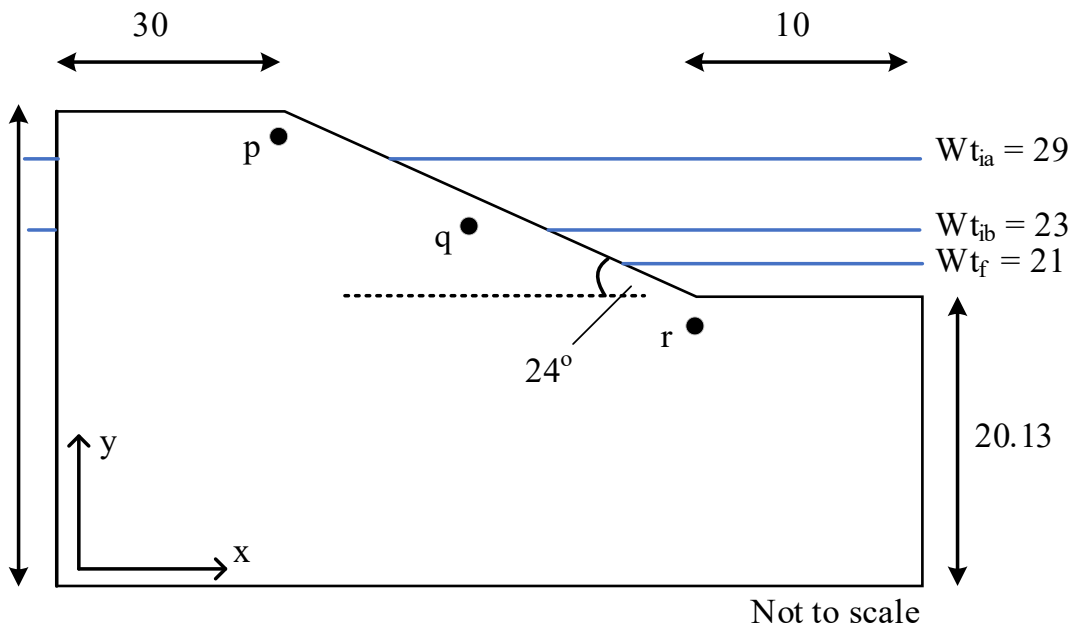
- Specific challenge: effect of spoil variability on lake slope displacements during seasonal variation of water levels
 - 2D finite element analyses using ABAQUS
 - 24 degree slope based on critical section from Lake Most, Czech Republic
 - Analyses considered **unsaturated soil** effects on effective stresses and the **spatial variation** of material properties within slope





Option 1 – Use of mine spoils for pit lakes - RAFF

- Two initial positions of the ground water table at the left (crest) side boundary were considered (measured from the model base): $WT_{ia} = 29$ m and $WT_{ib} = 23$ m.
- The initial water table within the slope was assumed to be horizontal, hence the initial reservoir level was also 29 m and 23 m from the bottom of the problem domain.



- Two cases of reservoir water drawdown
 - (i) from 29 m to 21 m
 - (ii) 23 m to 21 m (closely represents Lake Most)
- Four drawdown velocities considered
 - $D_v = 0.05$ (slow), 0.1, 1, and 2 (fast) m/day
- Pore pressures monitored at crest ('p'), middle ('q'), and toe ('r')



- Spoil stiffness (E) and saturated permeability coefficient (k_{sat}) were varied.
 - $E = 10 \text{ MPa}, 100 \text{ MPa}, 500 \text{ Mpa}$
 - $k_{sat} = 1.11 \text{ m/day}, 0.11 \text{ m/day}, \text{ and } 0.011 \text{ m/day}$
- Deterministic values of spoil shear strength parameters (c', ϕ') according to lab test data for samples from the CSA open pit mine
- Unsaturated spoil parameters were obtained from Masoudian et al. (2019b).

Mean cohesion (kPa)	10
Mean friction angle ($^\circ$)	22
Dilation angle ($^\circ$)	5
Mean elastic stiffness (MPa)	100
Dry unit weight (kN/m^3)	14.56
Mean initial void ratio	0.94
Permeability coefficient (m/day)	0.11
Residual degree of suction	0.27
Suction constant (/ kPa)	0.167
Tortuosity coefficient	-4
SWCC exponent	1.7

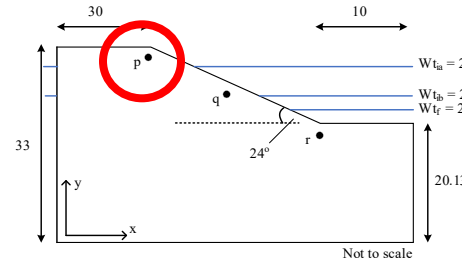


Deterministic analyses: effect of rate of drawdown

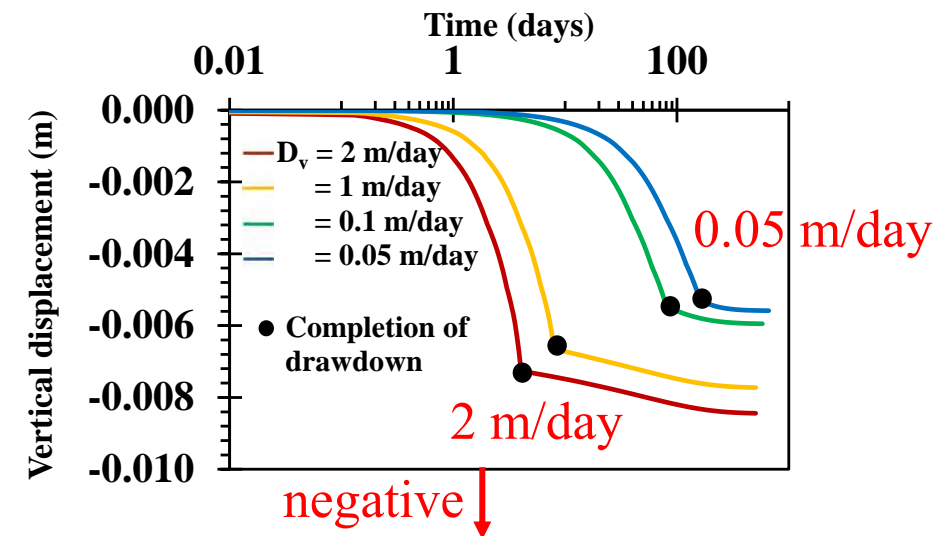
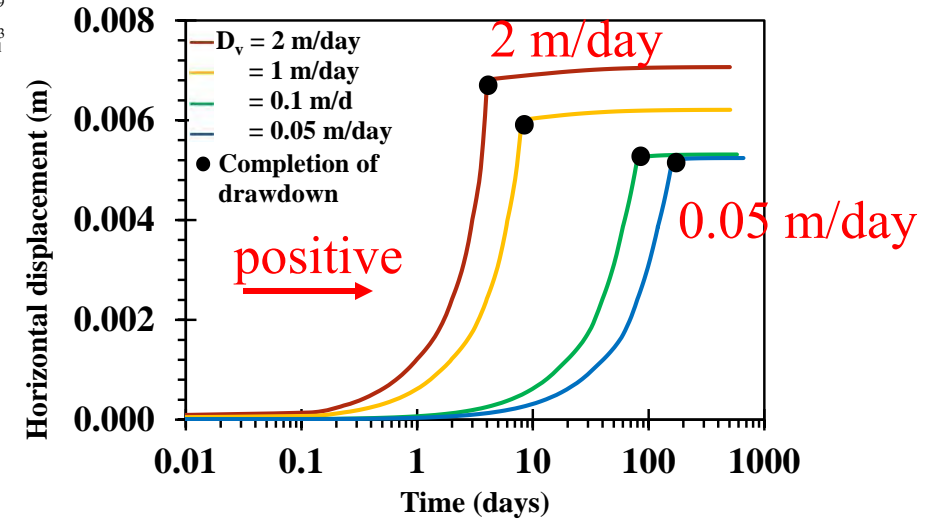
- Drawdown velocity $D_v = 0.05, 0.1, 1, \text{ and } 2$ m/day
- Other parameters constant (according to previous Table).
- Reservoir level lowered from $WT_{ia} = 29$ m to $WT_f = 21$ m.

Observations:

- Slope crest displaces more for faster drawdown rate
- After completion of drawdown (marked by black dots), the settlement rate of the slope becomes almost constant with time.



Crest displacements





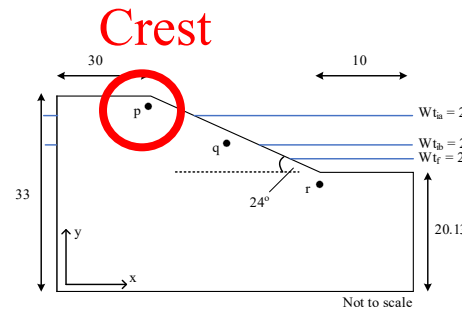
Option 1 – Use of mine spoils for pit lakes - RAFF

Deterministic analyses: effect of permeability

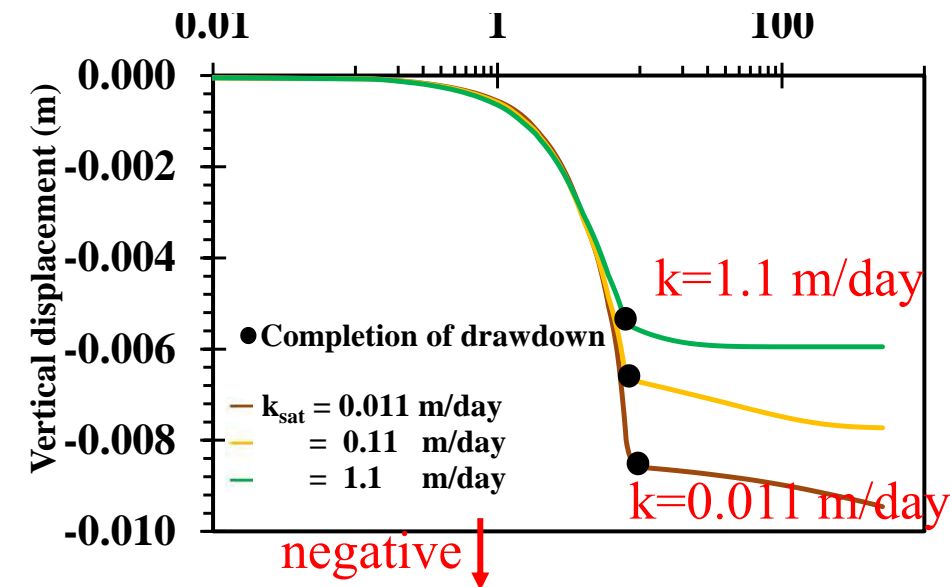
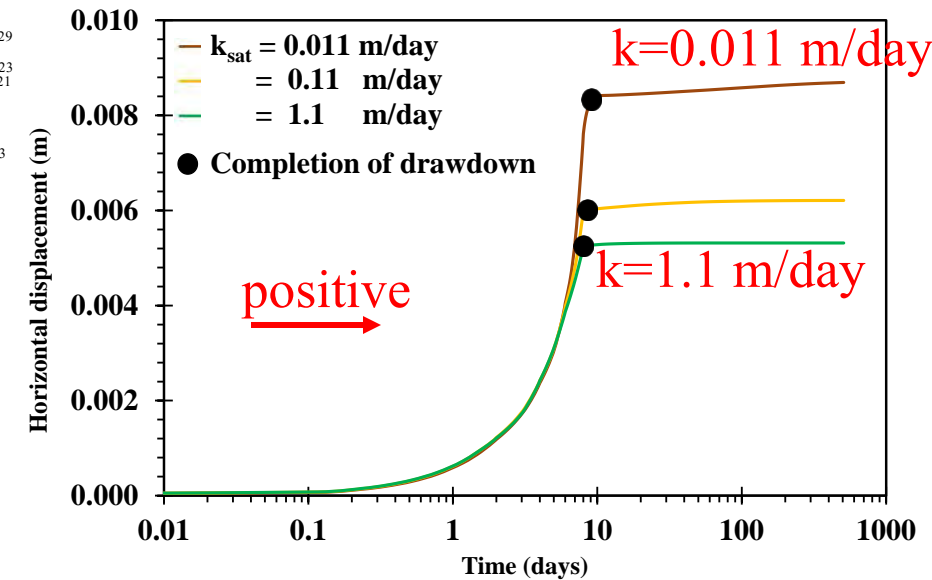
- Three values of spoil permeability
 - $k_{sat} = 1.11 \text{ m/day}$, 0.11 m/day , and 0.011 m/day
- Drawdown rate 0.11 m/day ; drawdown depth 29-21 m.
- Other parameters constant (according to previous Table).

Observations:

- Slope displacements largest for lowest permeability spoils



Crest displacements





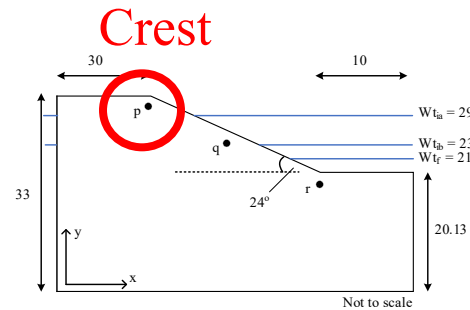
Option 1 – Use of mine spoils for pit lakes - RAFF

Deterministic analyses: effect of spoil stiffness

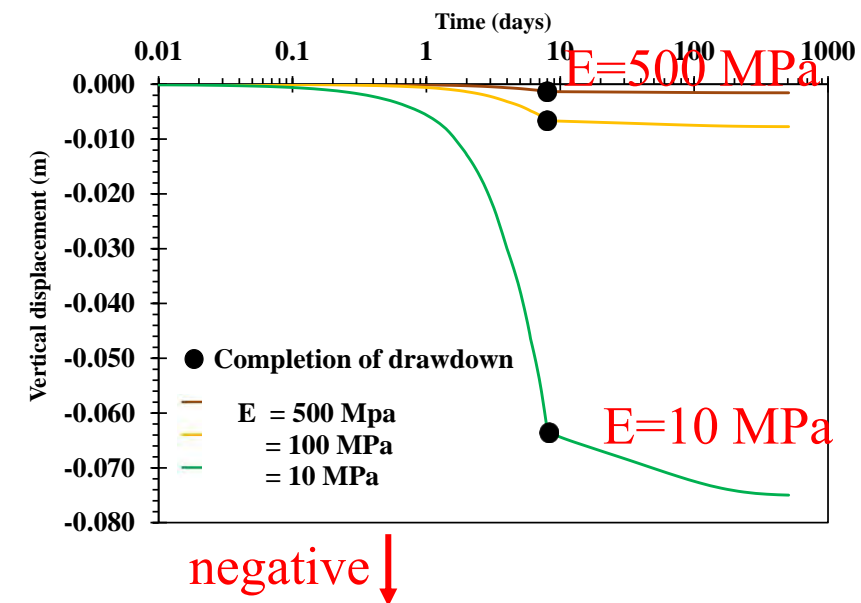
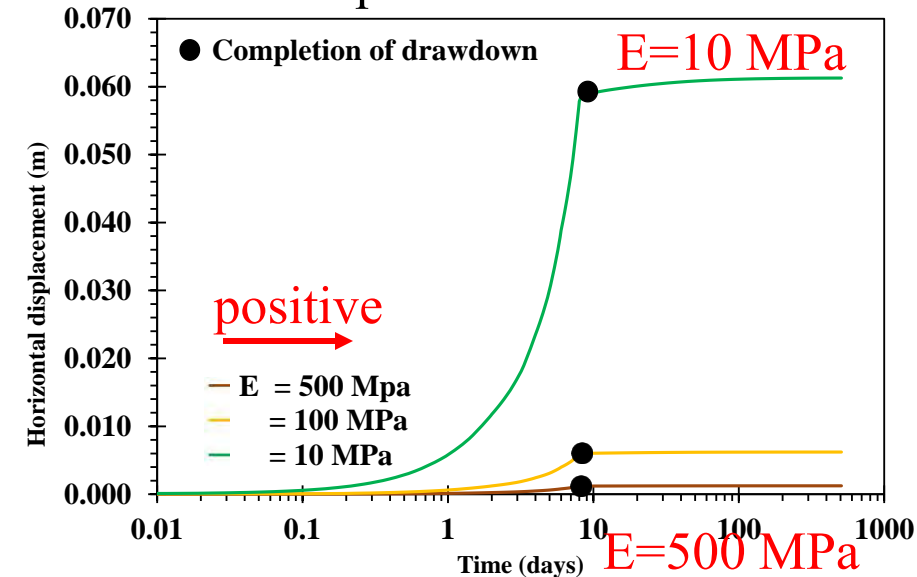
- Three values of spoil stiffness
 - $E = 10, 100, \text{ and } 500 \text{ MPa}$.
- Drawdown rate 0.11 m/day ; drawdown depth $29\text{-}21 \text{ m}$.
- Other parameters constant (according to previous Table).

Observations:

- Lower stiffness gives highest displacements



Crest displacements

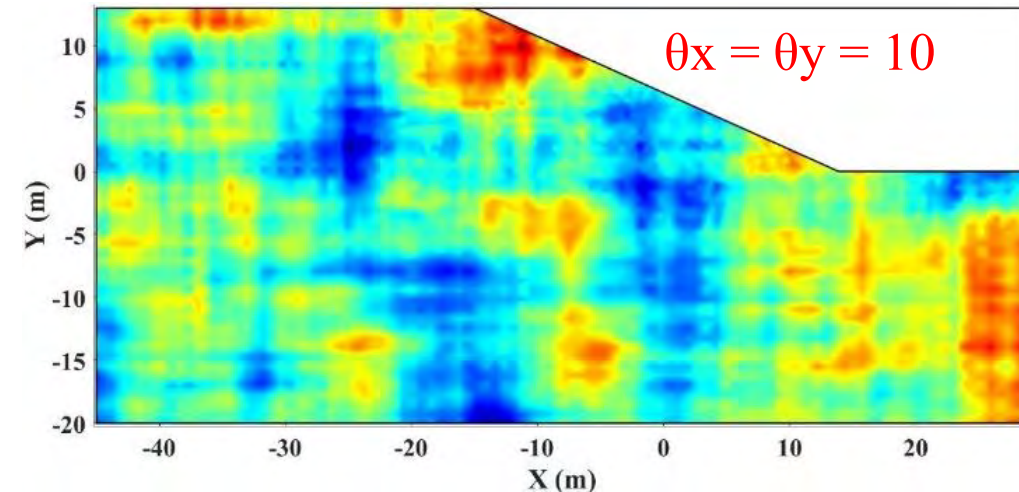
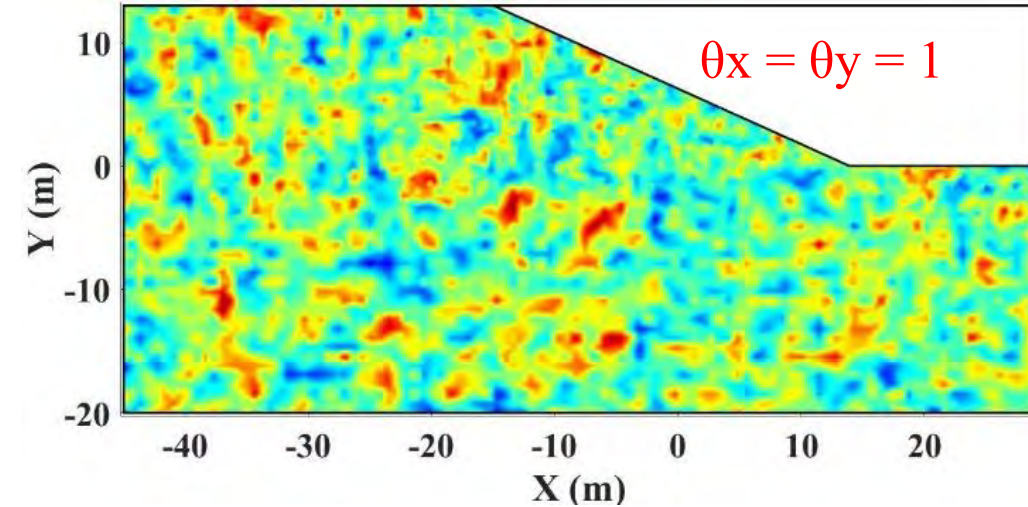




Random field probabilistic analyses

- Lognormally distributed random fields for:
 - cohesion c'
 - friction angle ϕ'
 - elastic stiffness E
 - void ratio e
- Spoil permeability coefficient (k) varies spatially as it is directly related to the void ratio
- Coefficient of variation (CoV) denotes the randomness of spoil properties: higher CoV = highly random
- Auto-correlation lengths in horizontal (θ_x) and vertical (θ_y) direction express spatial correlation
 - lower values of θ_x and θ_y indicate that the spoil is highly heterogeneous.

Random fields of friction angle of spoil



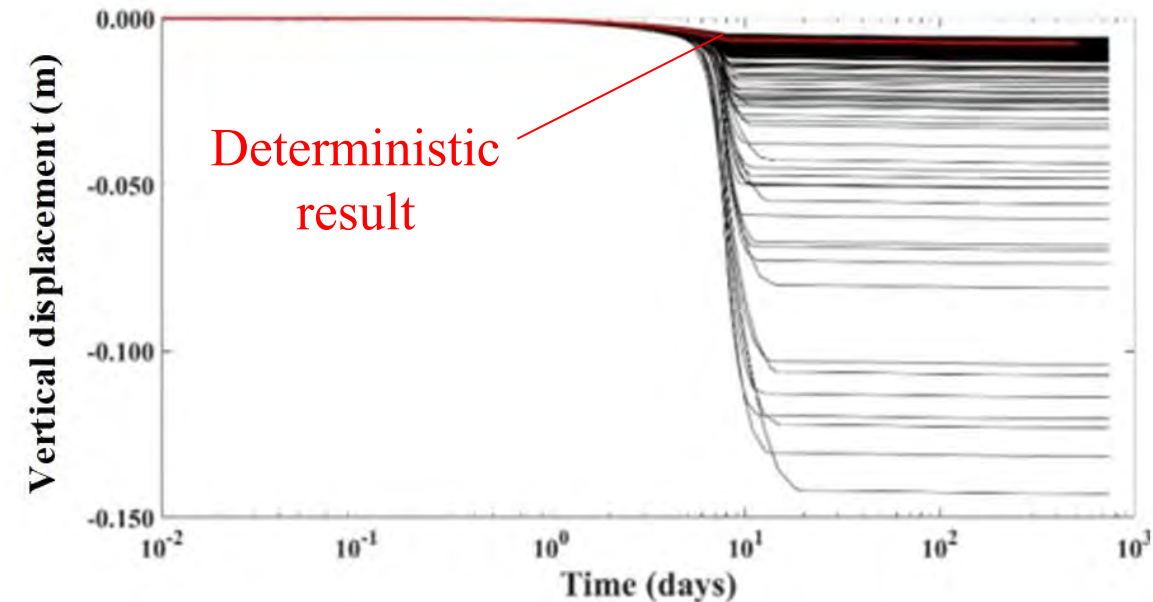


Random field probabilistic analyses

- Typical result of vertical displacement at the slope crest from 400 Monte-Carlo simulations:
 - $\theta_x = \theta_y = 1$
 - $CoV_c = 20\%$, $CoV_\phi = 5\%$, $CoV_E = 10\%$, $CoV_e = 15\%$.
- Mean values of other parameters from previous table.
- Drawdown rate of 1 m/day.

Outcome:

- The deterministic analysis result shown as red line:
 - significantly less displacement than many of the probabilistic results:
 - 235 out of the 400 (59%) of probabilistic results were greater than the deterministic analysis.
- Probabilistic analyses are important for slope stability analyses of spoil materials.



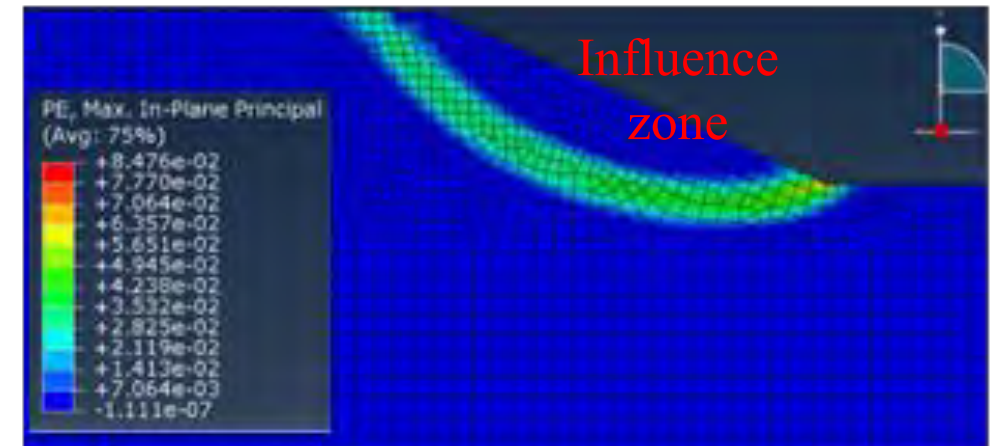
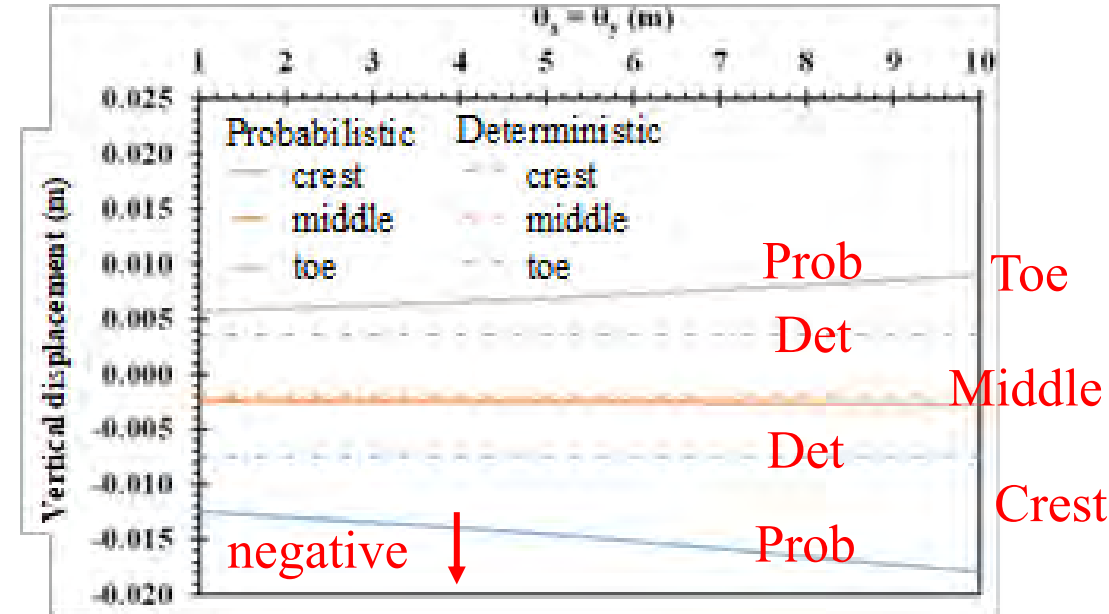
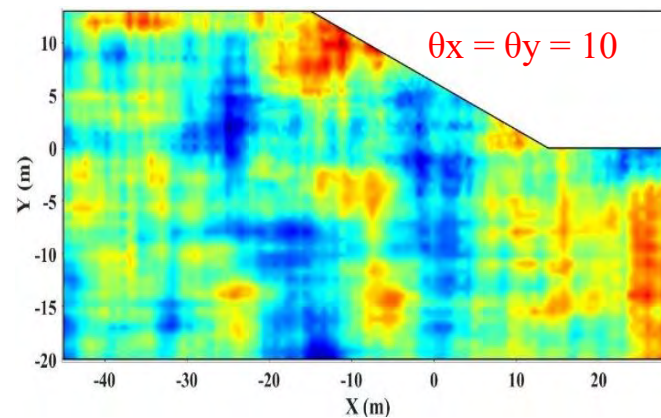
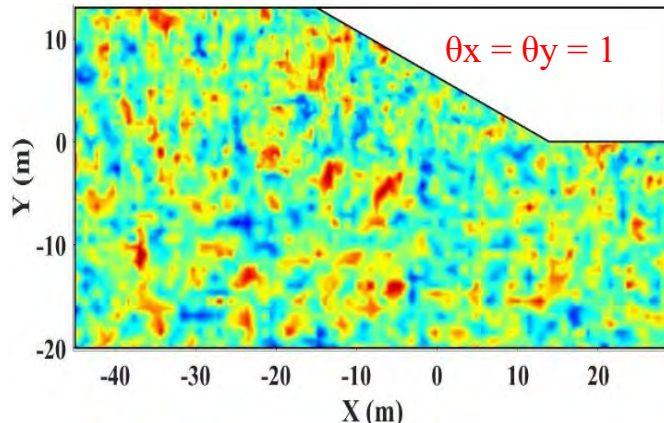
Random field probabilistic analyses: Effect of correlation

length θ for isotropic random fields

- $\theta_x = \theta_y = 1, 5, 10$

Observations:

- Increasing correlation lengths increases the deviation between deterministic and mean probabilistic value
- This occurs because of larger “patches” of weak material within “influence zone” as correlation length θ increases.
- Important to measure/control spatial variability in slopes



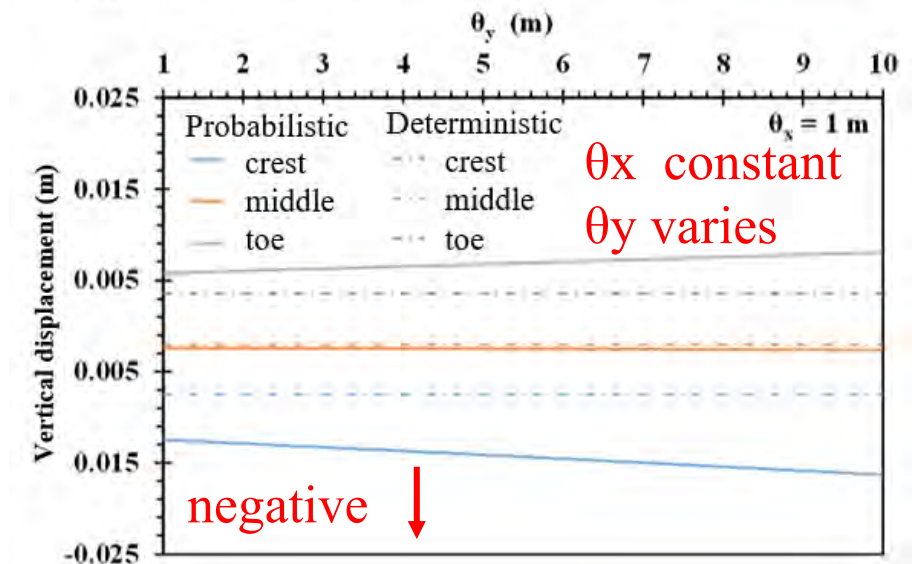
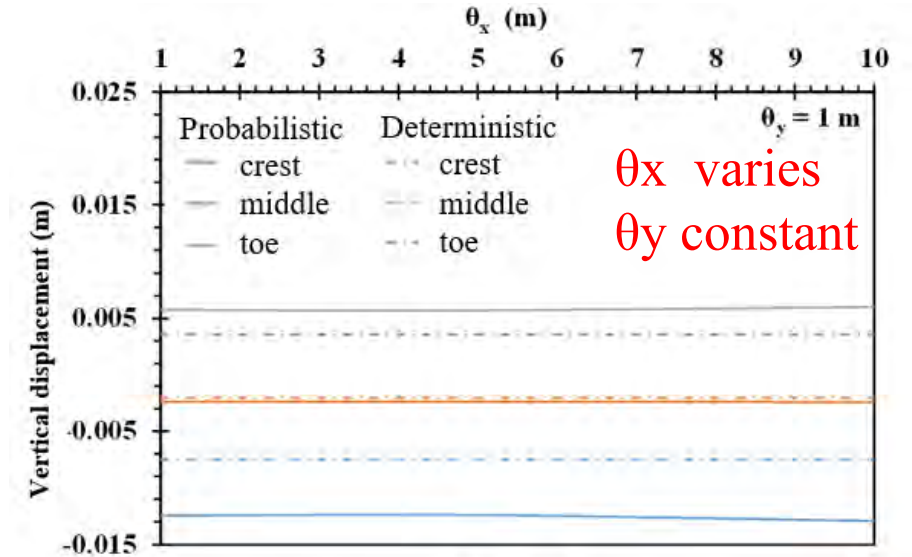


Random field probabilistic analyses: Effect of anisotropic correlation lengths

- $\theta_y = 1$; $\theta_x = 1, 5, 10$
- $\theta_x = 1$; $\theta_y = 1, 5, 10$

Observations:

- Increasing variability in the vertical direction mainly affects the vertical displacements; horizontal displacements were not sensitive to this change.
- Results of horizontal displacements (not shown here) indicated that increasing variability in the horizontal direction mainly affects the horizontal displacements; vertical displacements are less sensitive to this change.



Random field probabilistic analyses: Effect of coefficient of variation

Observations:

- Increasing CoV has a significant impact on ground displacements
 - Increasing CoV by 1.5 to 2 times results in displacement increase of up to 8 times.

Details	Crest	Middle	Toe
Low CoV: $CoV_c = 20\%$, $CoV_\phi = 5\%$, $CoV_E = 10\%$, $CoV_e = 15\%$	-0.013	-0.003	0.006
Medium CoV: $CoV_c = 30\%$, $CoV_\phi = 10\%$, $CoV_E = 15\%$, $CoV_e = 20\%$	-0.033	-0.004	0.019
High CoV: $CoV_c = 40\%$, $CoV_\phi = 15\%$, $CoV_E = 20\%$, $CoV_e = 25\%$	-0.071	-0.006	0.049



Conclusions: Option 1 – Use of mine spoils for pit lakes - RAFF

- Vertical displacements higher for relatively high rates of drawdown and larger drawdown depths
- Relatively low permeability and low stiffness spoils result in larger slope displacements
- The effect of spatial variability of spoils on slope displacements was found to be significant.
 - Slope displacements in large number of probabilistic analyses were greater than the deterministic analyses
- For isotropic random fields (i.e. correlation lengths $\theta_x = \theta_y$), with increasing correlation length, the deviation between deterministic and mean probabilistic values increases
 - Due to large “patches” of weak soil in the slope “influence zone”
 - Important to understand/control spatial characteristics of spoil materials in area of slopes
- Spatial variability was more significant for greater drawdown depths as the range of variation in the “influence zone” of the slope was greater than that for the lower drawdown case.
- The anisotropy (i.e. correlation lengths $\theta_x \neq \theta_y$) was shown to mainly affect displacements in the direction where the anisotropy existed (e.g. vertical anisotropy mainly affected vertical displacements)
- Increasing coefficient of variation of spoil parameters increased mean probabilistic vertical displacements at all locations within the slope.



Option 2: Installation of wind turbines on mine spoils heaps (SUMAD project)

- Specific challenge: Development of an advanced constitutive model for spoil-structure interaction problems
 - 2D finite element analyses using ABAQUS
 - heterogeneous (linearly increasing) undrained shear strength (random spatial variability is not considered)
 - prediction of foundation response under both monotonic and cyclic loading.
 - A bounding surface plasticity model (BSP) is proposed;
 - BSP model becomes needed for cyclic loading due to hysteretic response and a progressive convergence of the stress-strain curve to a particular state after a certain number of cycles.



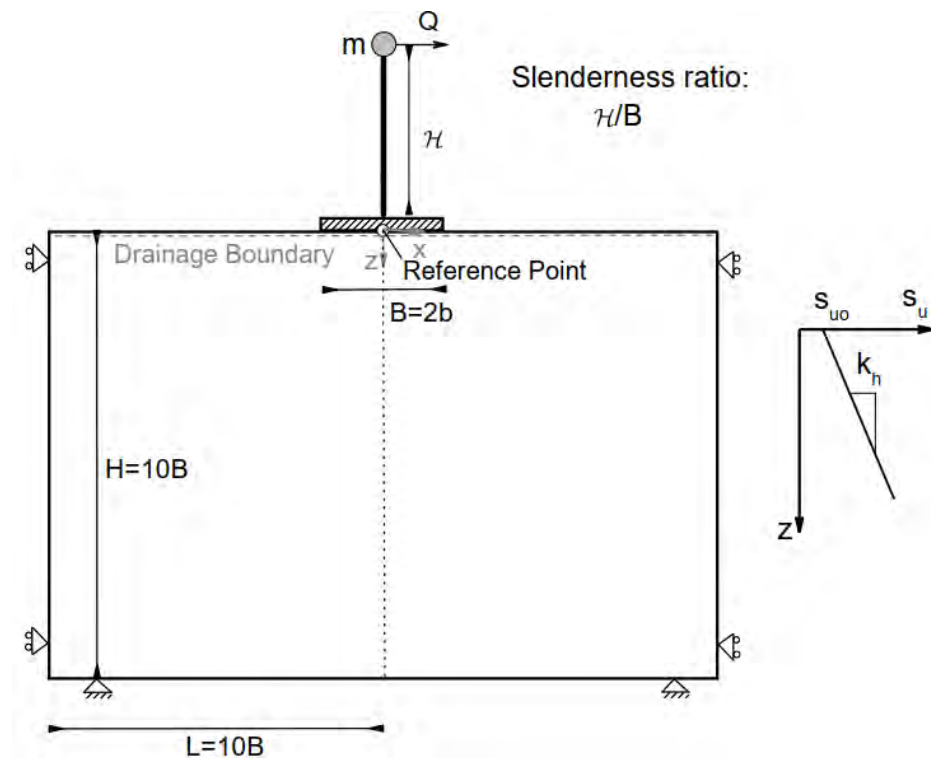
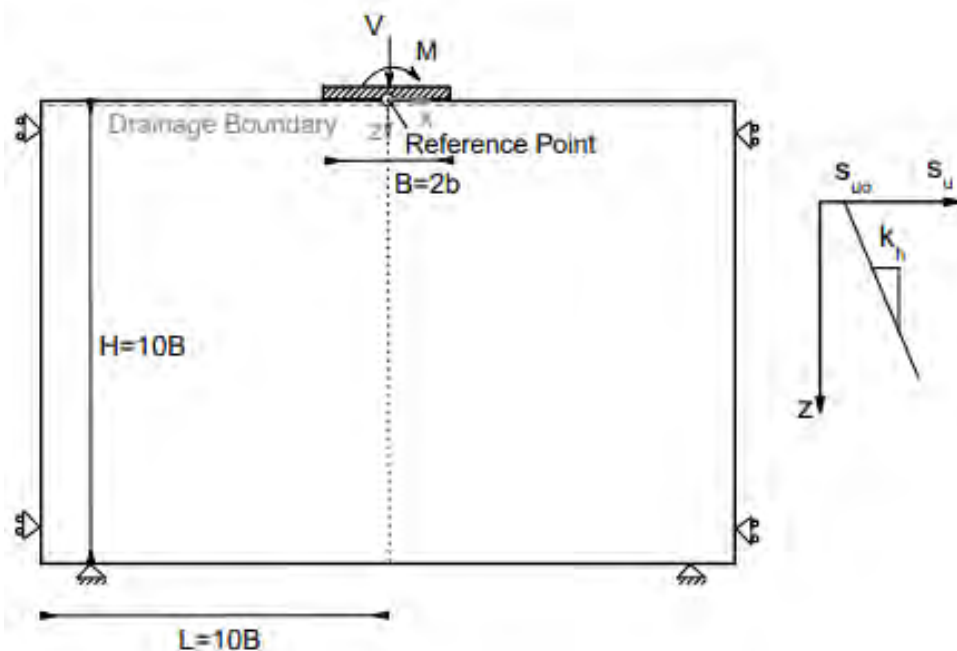
Two shallow foundation loading scenarios are considered:

Problem 1:

surface strip footing under pure moment-vertical loading (M-V)

Problem 2:

surface strip footing under moment-horizontal-vertical loading (M-H-V)





Constitutive model:

- An isotropic version of the BSP model is utilized, which retains a simple formulation and additionally involves a damage factor for capturing soil strength degradation effects under a cyclic load action.
- Model parameters calibrated using element-scale laboratory tests:
 - Isotropic and 1D consolidation tests
 - Monotonic consolidated-undrained (CU) triaxial tests for normally consolidated (NC) clay
 - Undrained triaxial tests for varying over-consolidation ratio (OCR) states

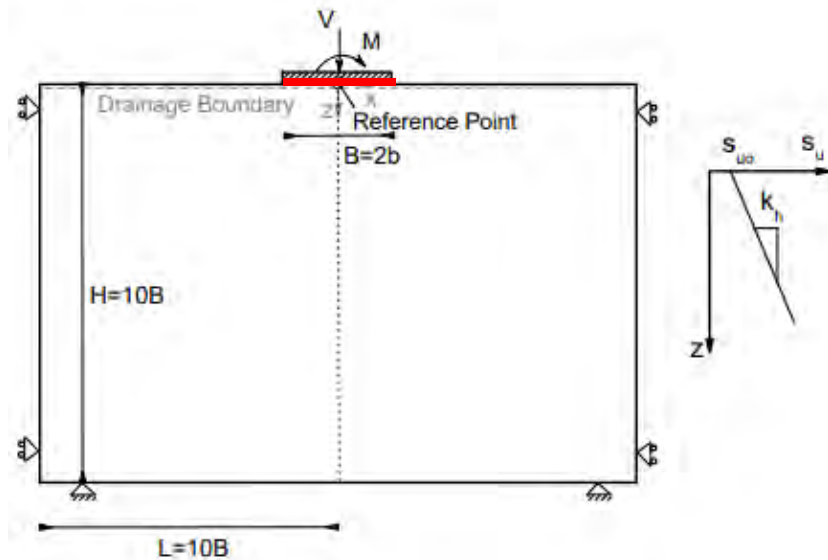
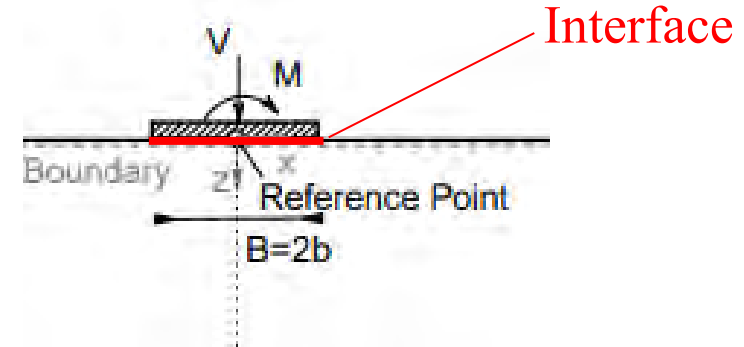
Parameters	Symbol	Value	
Slope of normal compression line in $e-\ln p^{\wedge'}$ space	λ	0.26	
Slope of recompression line in $e-\ln p^{\wedge'}$ space	κ	0.035	
Slope of critical state line for triaxial compression	M_c	1.15	$\gamma_M = 0.65$
Poisson ratio	ν	0.15	
Projection centre for triaxial compression	C	0	
Size of elastic nucleus for triaxial compression	s_c	1.55	$\gamma_s = 0.85$
Shape configuration parameter	R	2.4	
Hardening parameter for triaxial compression	h_c	370	$\gamma_h = 0.65$
Degradation parameter	α	0.1	
Unit weight (kN/m^3)	γ	17	
Void ratio at $p^{\wedge'} = 1\text{kPa}$ on NCL	e_N	2.4	
Permeability (m/s)	k	1×10^{-10}	

e = void ratio; $\gamma_M, \gamma_s, \gamma_h$: quantities related to triaxial extension when compared to associated values under triaxial compression.



Problem 1: surface strip footing under pure moment-vertical loading (M-V)

- Quasi-static analysis performed where a rotational displacement was applied at the footing centre under the action of a constant vertical load (M-V action).
- The resultant forces and displacements are accordingly measured at the reference point
- Also consider effect of assumed soil-foundation interface



Normalised parameters:

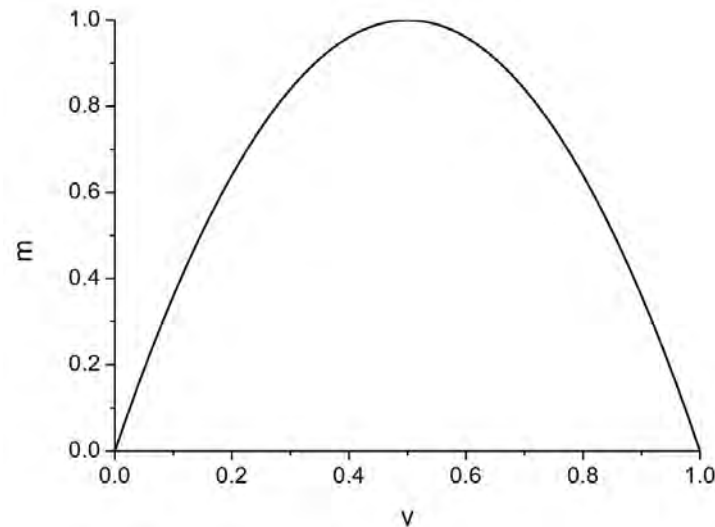
	Vertical	Horizontal	Moment
Load	V	Q	M
Ultimate Load	V_u	Q_u	M_u
Dimensionless Load	$\mathcal{V} = V/V_u$	\mathcal{Q}	$\mathcal{M} = M/M_u$
Normalized load wrt Ultimate Load	$v = V/V_u$	$q = Q/Q_u$	$m = M/M_u$
Displacement	w	δ	ϑ



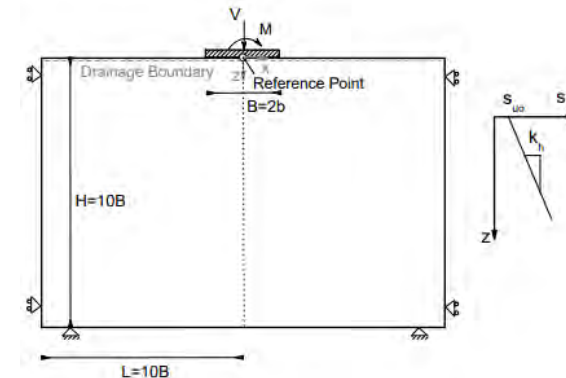
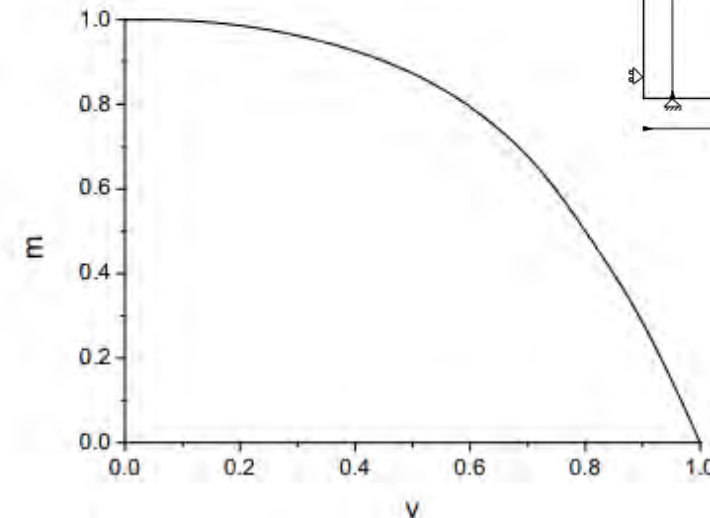
Problem 1: surface strip footing under pure moment-vertical loading (M-V)

- Static moment capacity (monotonic): tensionless versus fully-bonded interface:
 - Tensionless: max bearing capacity when $v=V/V_u=0.5$
 - Moment capacity = 0 when $v=0$ or $v=1$
 - Fully bonded: ultimate moment capacity is maximum at a very high vertical safety factor (vertical load $v=0$), and progressively decreases with increasing vertical load

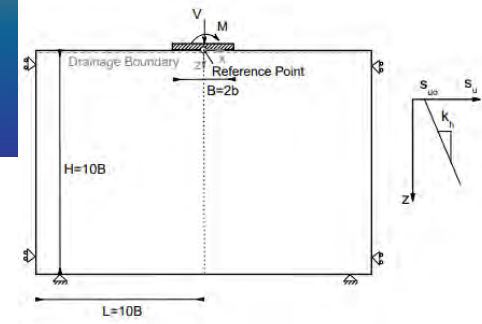
Tensionless interface



Fully bonded interface



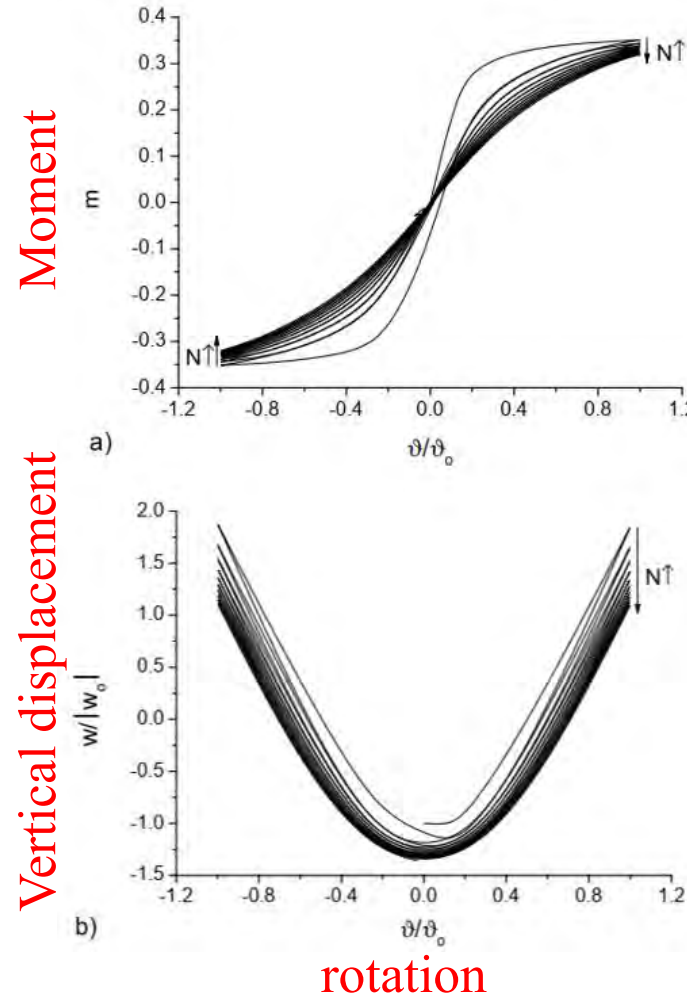
Normalized load wrt Ultimate Load	$v = V/V_u$	$q = Q/Q_u$	$m = M/M_u$
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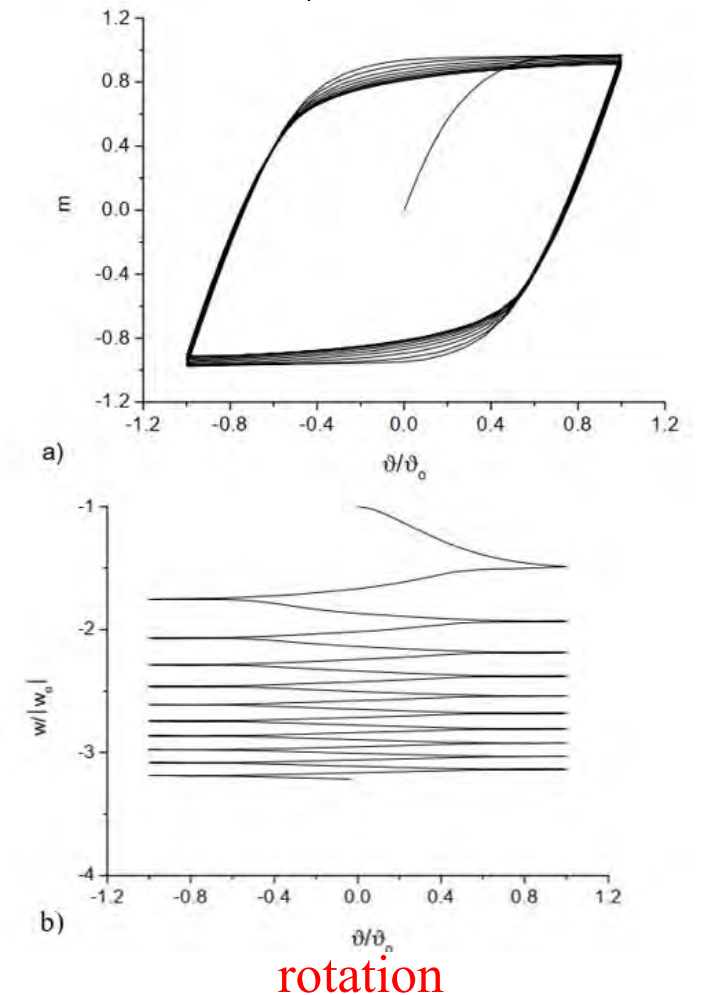
Problem 1: surface strip footing under pure moment-vertical loading (M-V): Cyclic moment capacity:

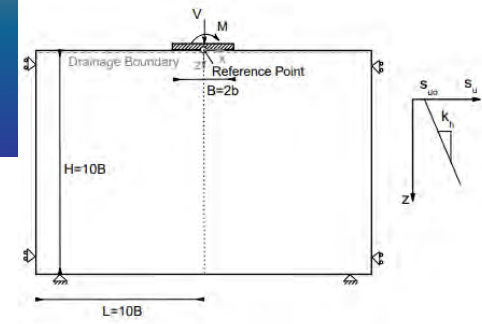
- Tensionless:
 - moment hardening or softening depending on the vertical load level
 - moment softening rate decreases with the number of cycles (material nonlinearity).
 - substantial footing uplift at the maximum rotation angle $\vartheta = |\vartheta_0|$ (geometric nonlinearity) that tends to decrease with the number of cycles
 - slight settlement accumulation at $\vartheta = 0$ (soil plasticity).

Tensionless interface



Fully bonded interface

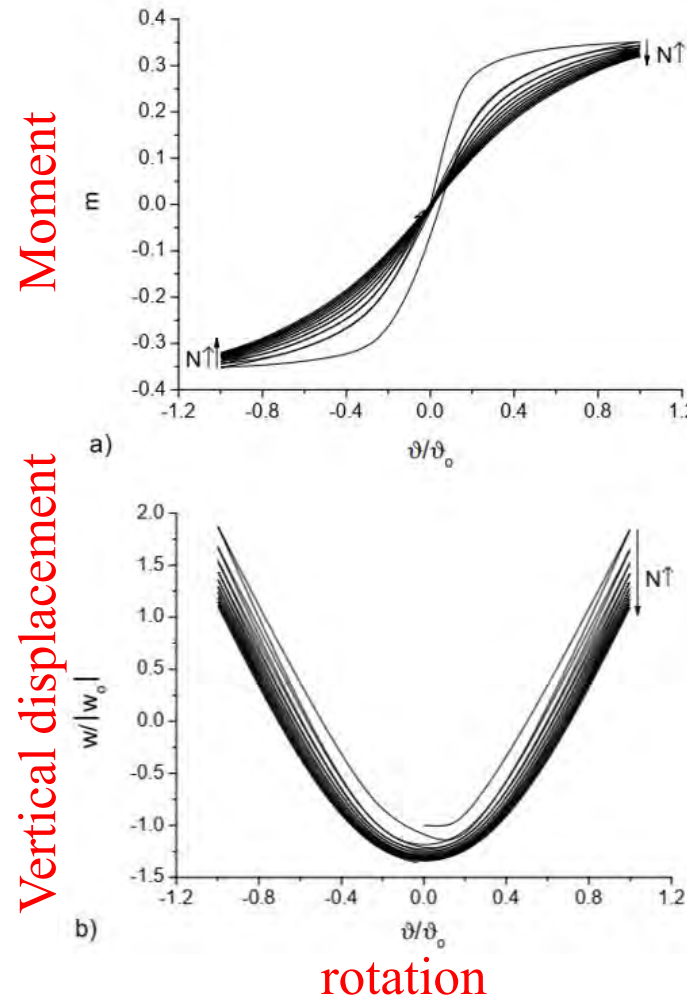




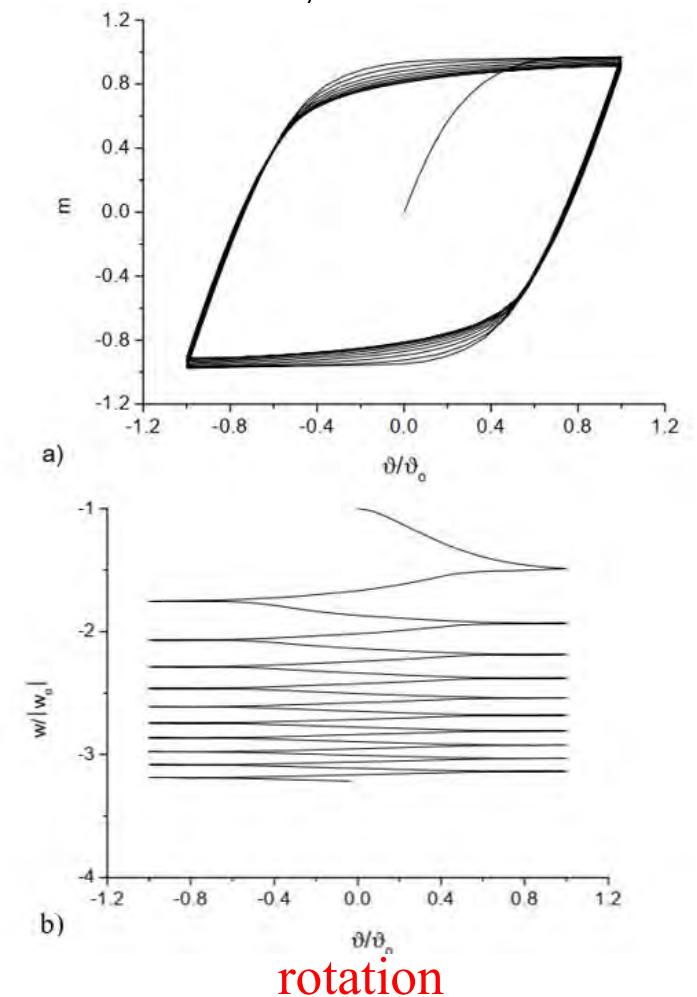
Problem 1: surface strip footing under pure moment-vertical loading (M-V): Cyclic moment capacity:

- Fully bonded:
 - a very stiff response of moment $m - \vartheta$
 - The enclosed area of the moment-rotation angle is large (high damping ratio), and its shape remains almost unchanged during the cyclic loading.
 - considerable settlement accumulation with cyclic loading.

Tensionless interface



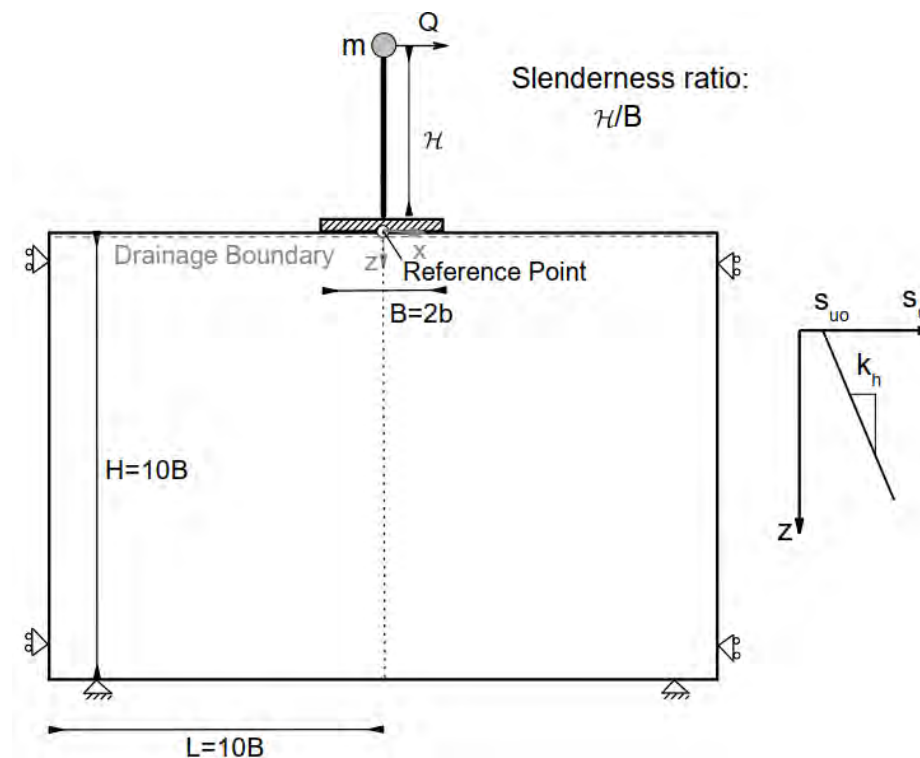
Fully bonded interface





Problem 2: surface strip footing under moment-horizontal-vertical loading (M-H-V)

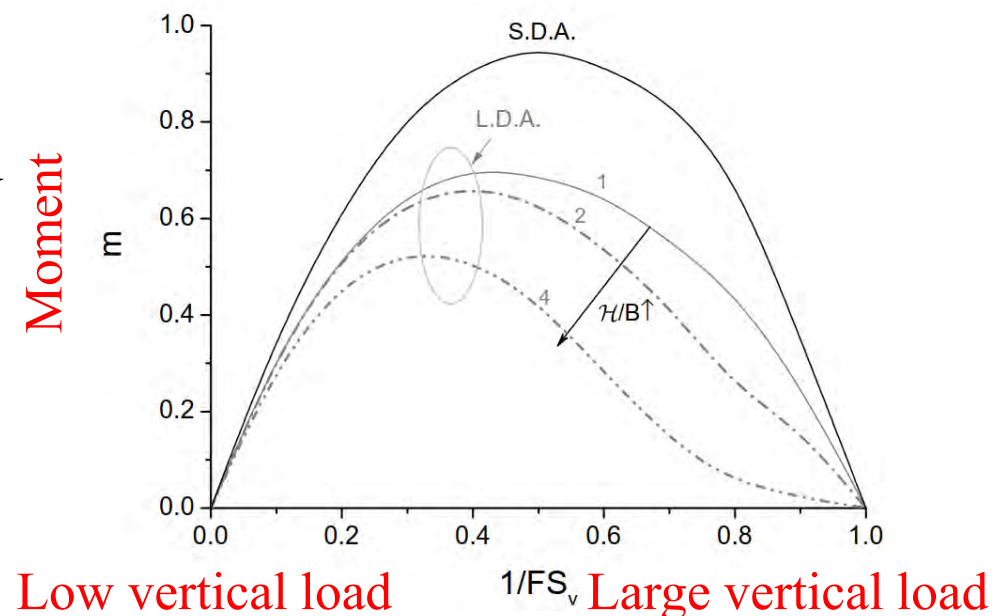
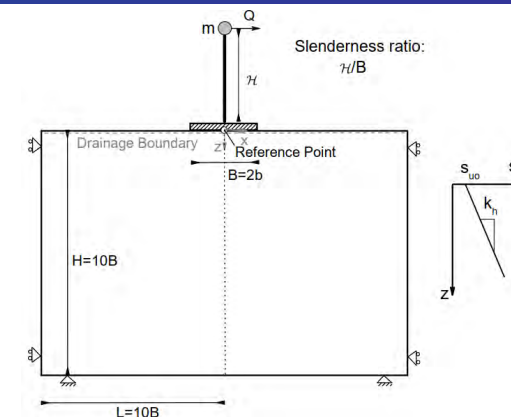
- Identical geometric and boundary conditions as Problem 1
- Elevated mass m acted upon by load Q .
- Represents a slender rigid structure with slenderness ratio H/B .
- Standard small-displacement analyses (SDA) compared against large-displacement analyses (LDA)
 - evaluate geometric non-linearities: P - δ effects
- Tensionless interface
- Monotonic and cyclic loading





Problem 2: surface strip footing under moment-horizontal-vertical loading (M-H-V)

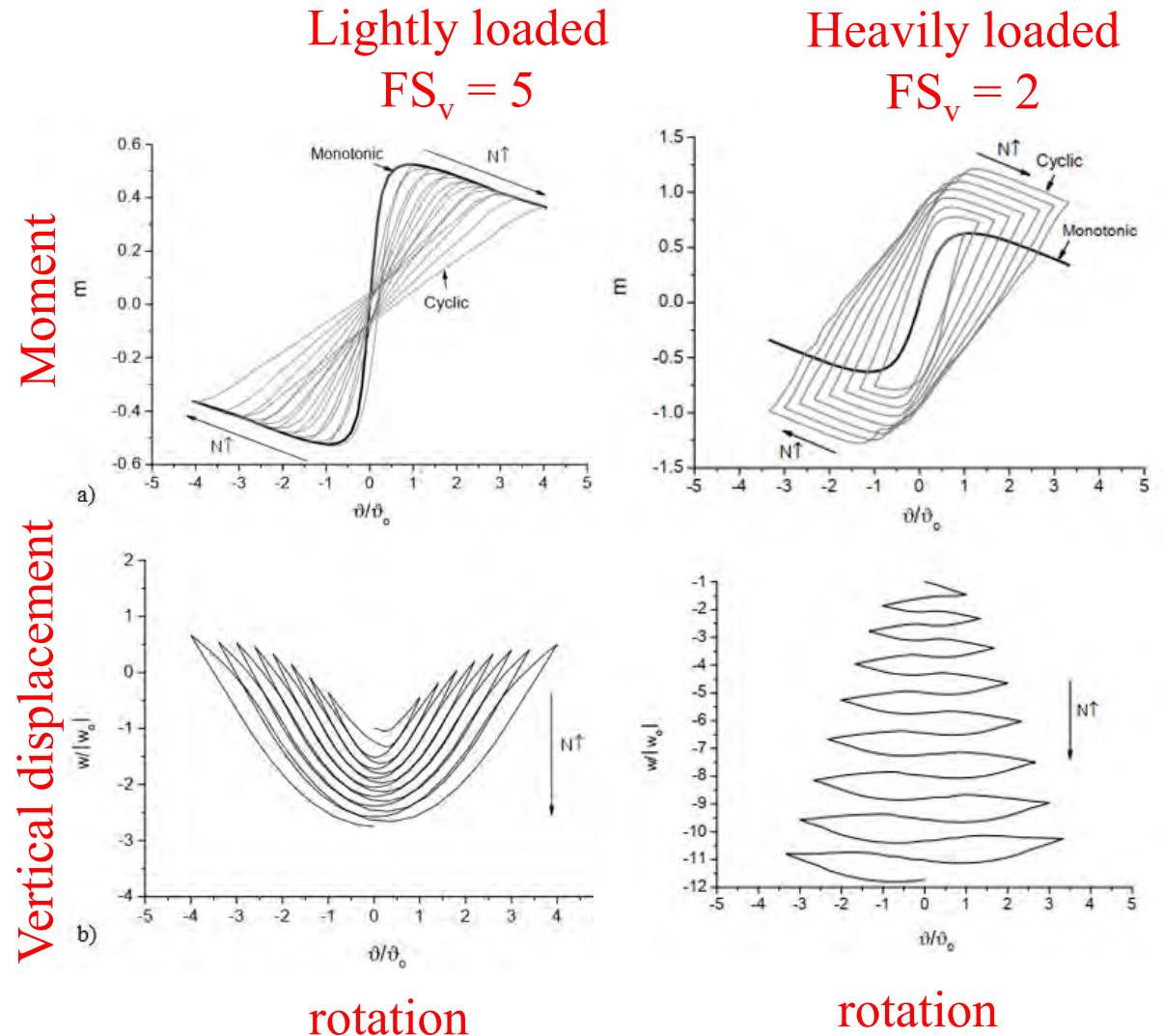
- Monotonic pushover:
 - Geometric nonlinearities (P - δ effects) from the Large Displacement Analysis LDA have significant softening effect on moment capacity compared to Small Displacement Analysis SDA.
 - The P - δ effects are more pronounced for heavily loaded structures (vertical safety factor $FS_v = 1$) and higher slenderness ratios





Problem 2: surface strip footing under moment-horizontal-vertical loading (M-H-V)

- Cyclic pushover analysis:
 - Lightly loaded $FS_v=5$:
 - Softening response with loading cycle, converging on monotonic response.
 - Moderate accumulation of vertical settlements
 - Heavily loaded $FS_v=2$:
 - Hardening response with loading cycle, contrasts to monotonic response
 - Significant accumulation of vertical settlements.





Conclusions: Option 2 – Wind turbines on mine spoils - SUMAD

- For combined loading of shallow foundations, moment capacity is significantly higher when a fully-bonded interface is considered when compared to a tensionless interface.
- For a pure moment-vertical load action, the shape of the failure envelope is highly affected by the interface
 - focus was placed on the tensionless interface (more relevant to onshore wind turbine foundations)
- For the thin structure-footing system under M-H-V loading, a dominant footing uplift mechanism is obtained for light structures and the opposite holds for heavily loaded structures, where a significant settlement accumulation occurs during cyclic loading.
- For a typical vertical safety factor ($FS_v < 5$), a mixed mechanism is observed - even if footing uplift may be initially present, its magnitude is progressively reduced as the number of cycles increases due to material nonlinearities.
- the moment capacity of the thin structure-footing system decreases as the slenderness ratio and/or the vertical safety factor increases.
- If a large deformation analysis (L.D.A.) is considered, the moment capacity non-symmetry decreases with the slenderness ratio, while the opposite holds for a small deformation analysis (S.D.A.), regardless of the heterogeneity degree.



Thank you

Funding:

EU's Research Fund for Coal and Steel under the projects:

- “RAFF – Risk Assessment of Final Pits during Flooding” Grant No. 847299
- “SUMAD - Sustainable Use of Mining Waste Dumps” Grant No. 847227.