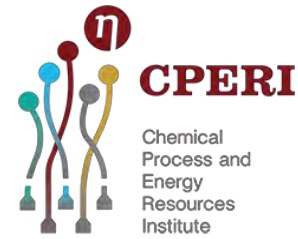




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Valorization potential of spoil heaps: from testing and geotechnical characterization to numerical modelling

Alexandros Theocharis, Ioannis Zevgolis, Nikolaos
Koukouzas, Christos Roumpos, Tryfon Mparbas

6-10-2022, Wroclow, Poland

Contents

- Geotechnical characterization of spoil material
- Constitutive modelling
- Numerical modelling

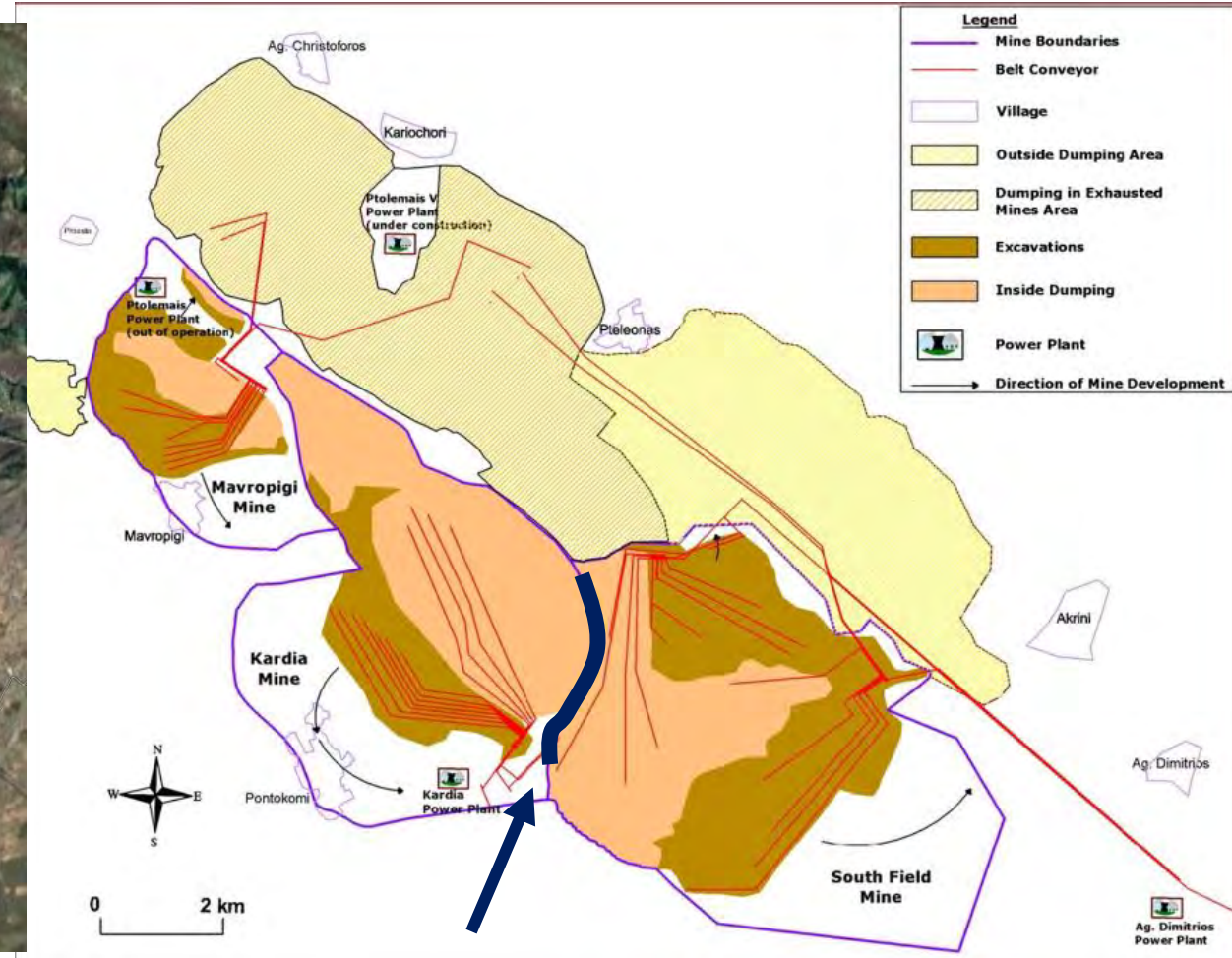
The spoil heap - location



General overview of the Ptolemais mines and the Soulou spoil heap (mid 2018)



Soulou spoil heap

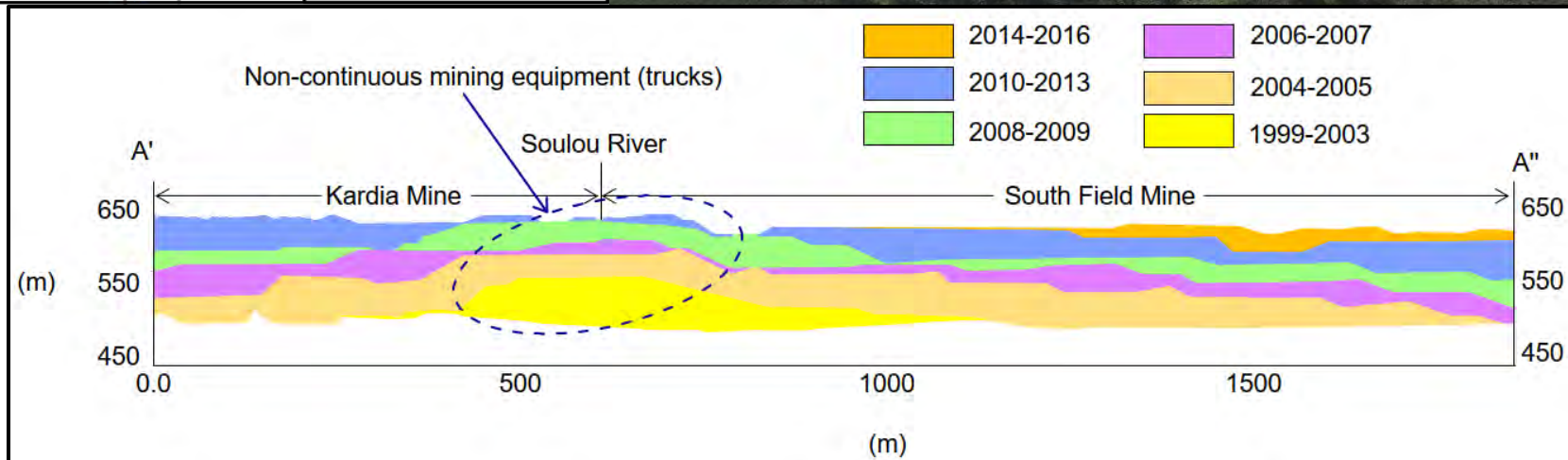
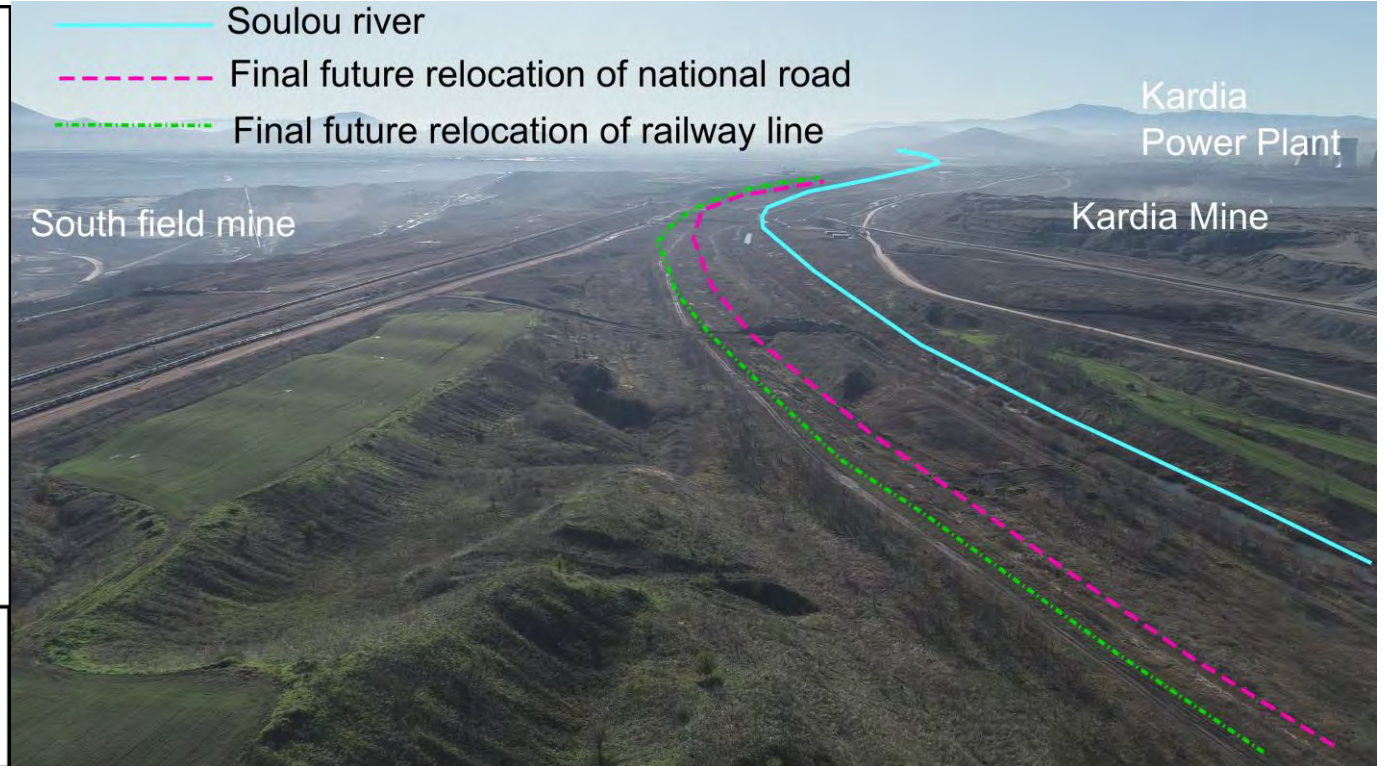
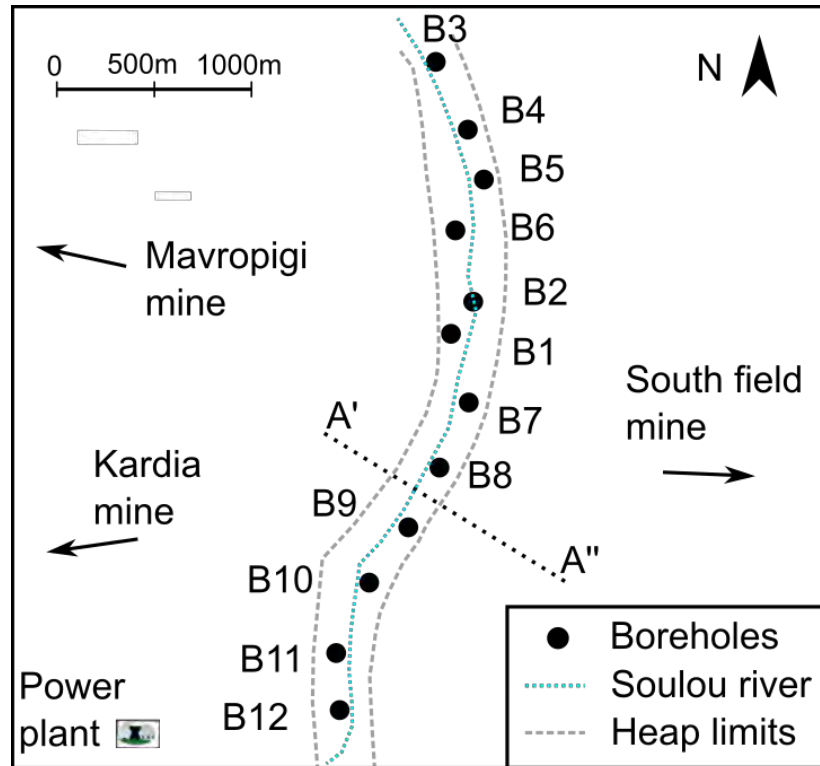


Soulou spoil heap

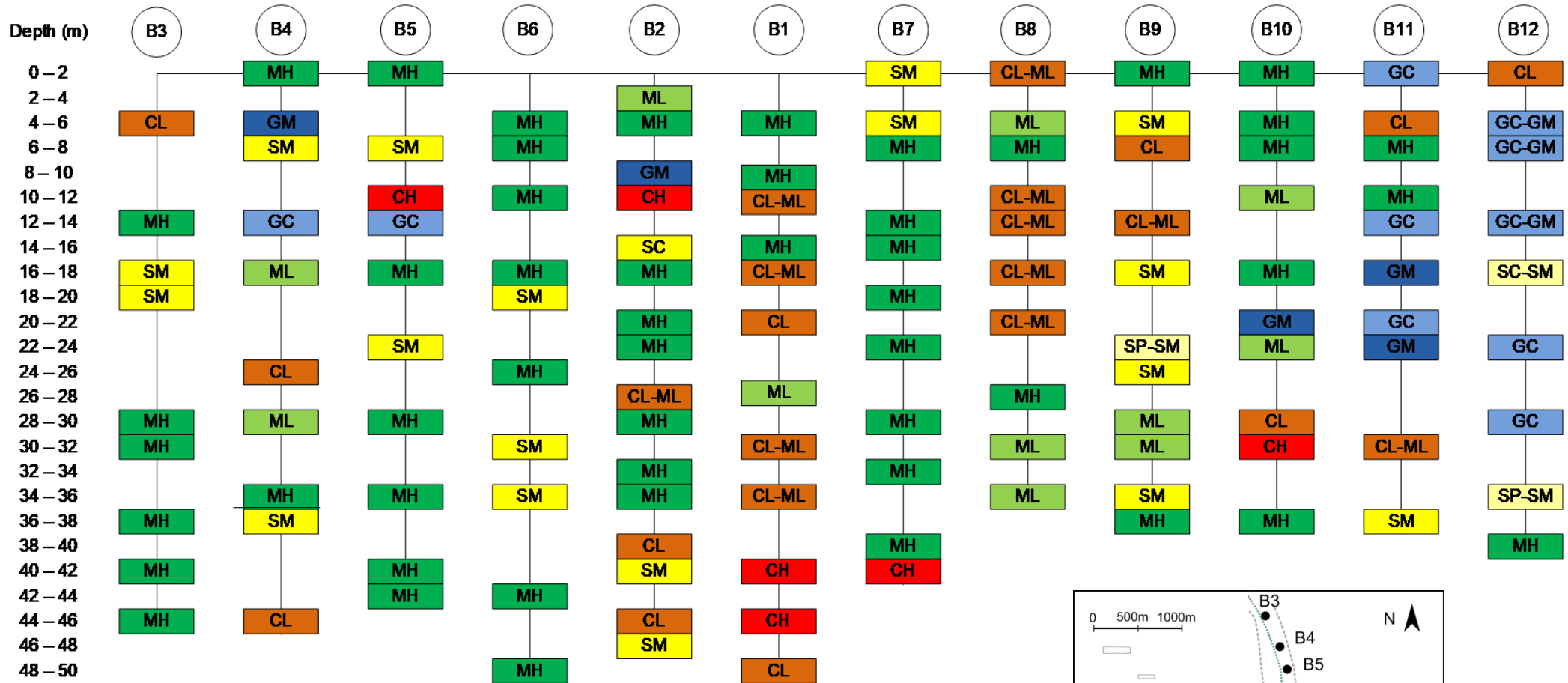
Spoil heap general overview



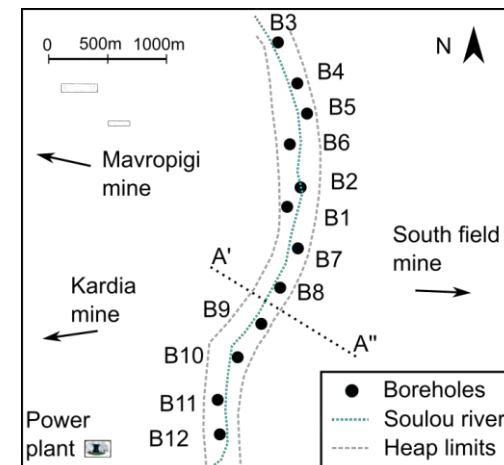
Geotechnical investigation



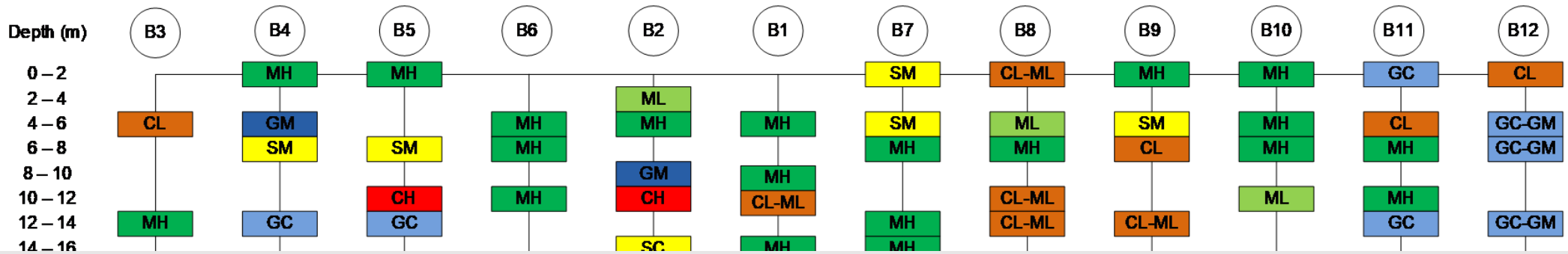
Geotechnical classification



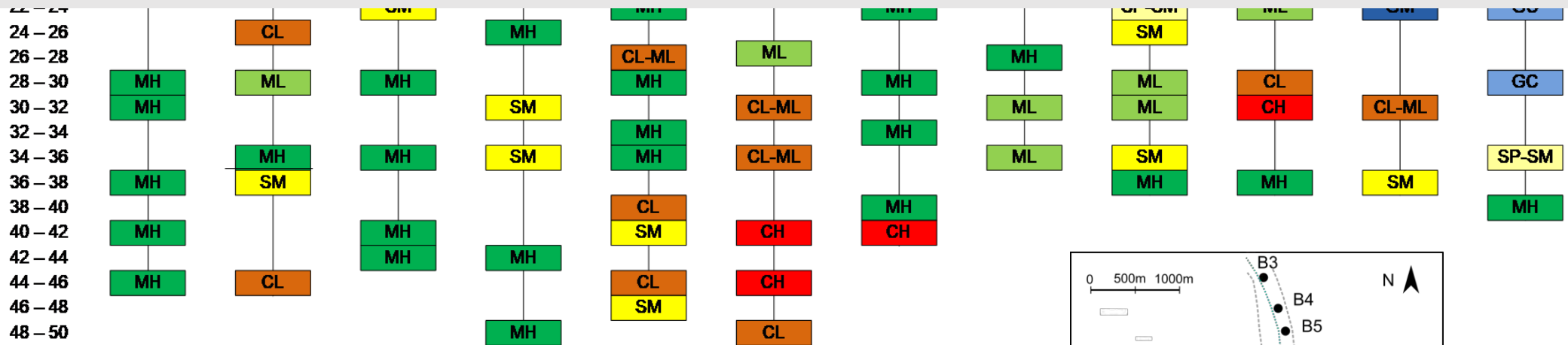
	Silts
	Silty sands
	Clays
	Sand/Gravel



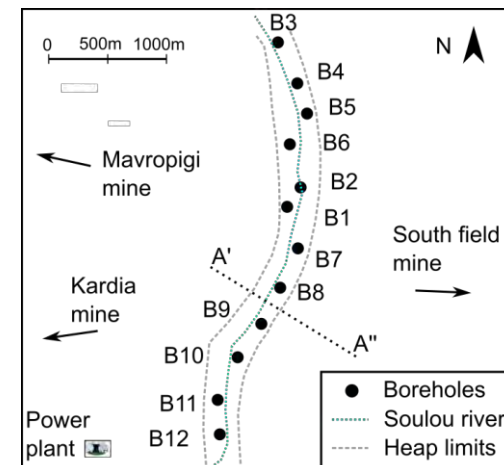
Geotechnical classification



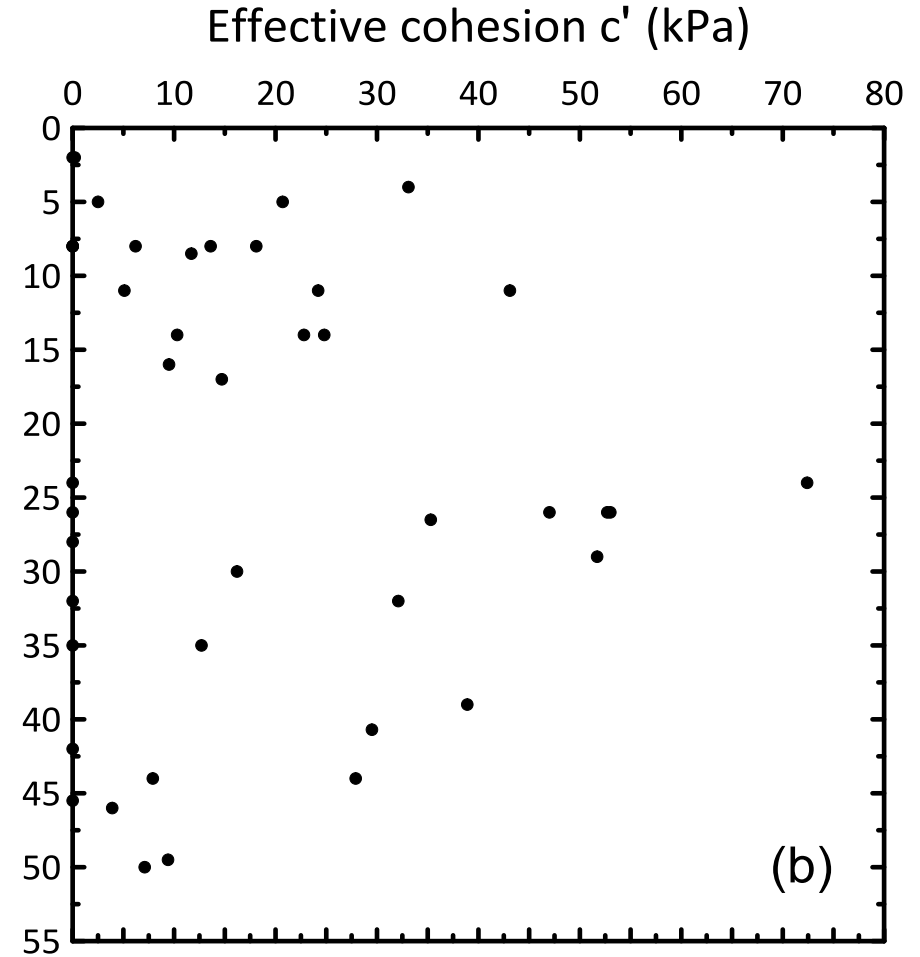
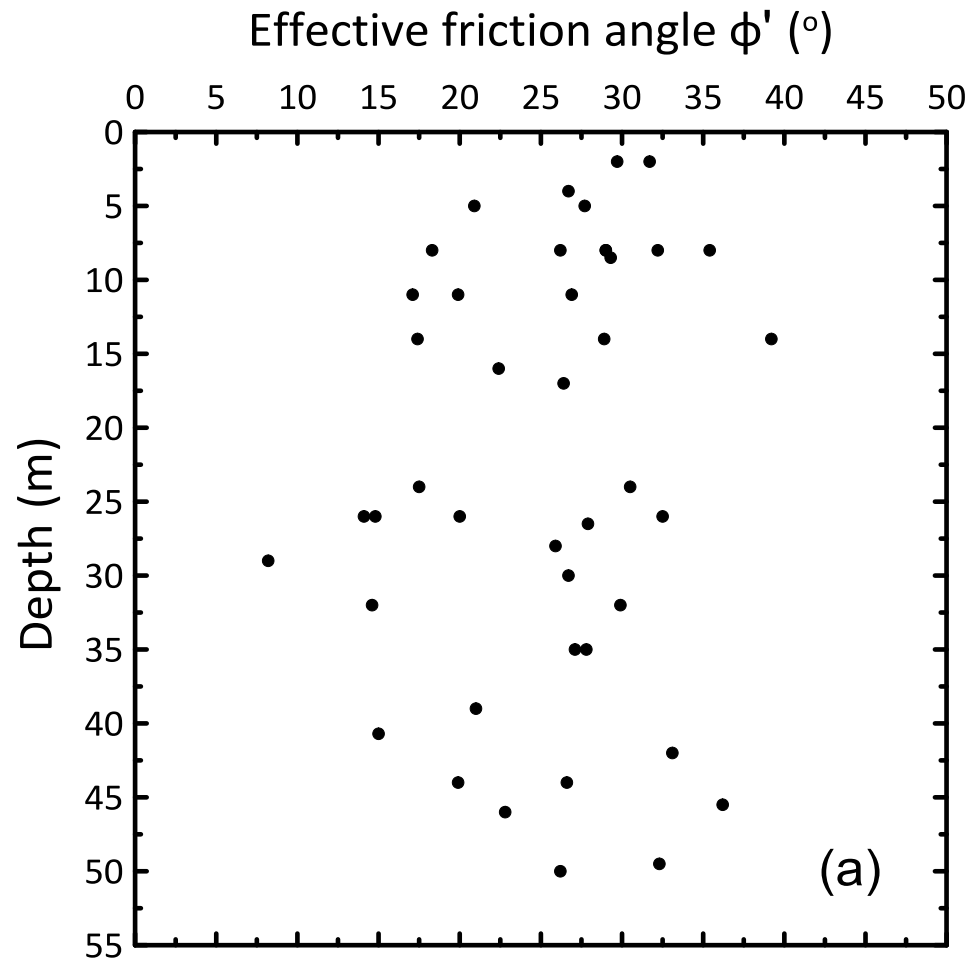
Spoil: one or many materials ?



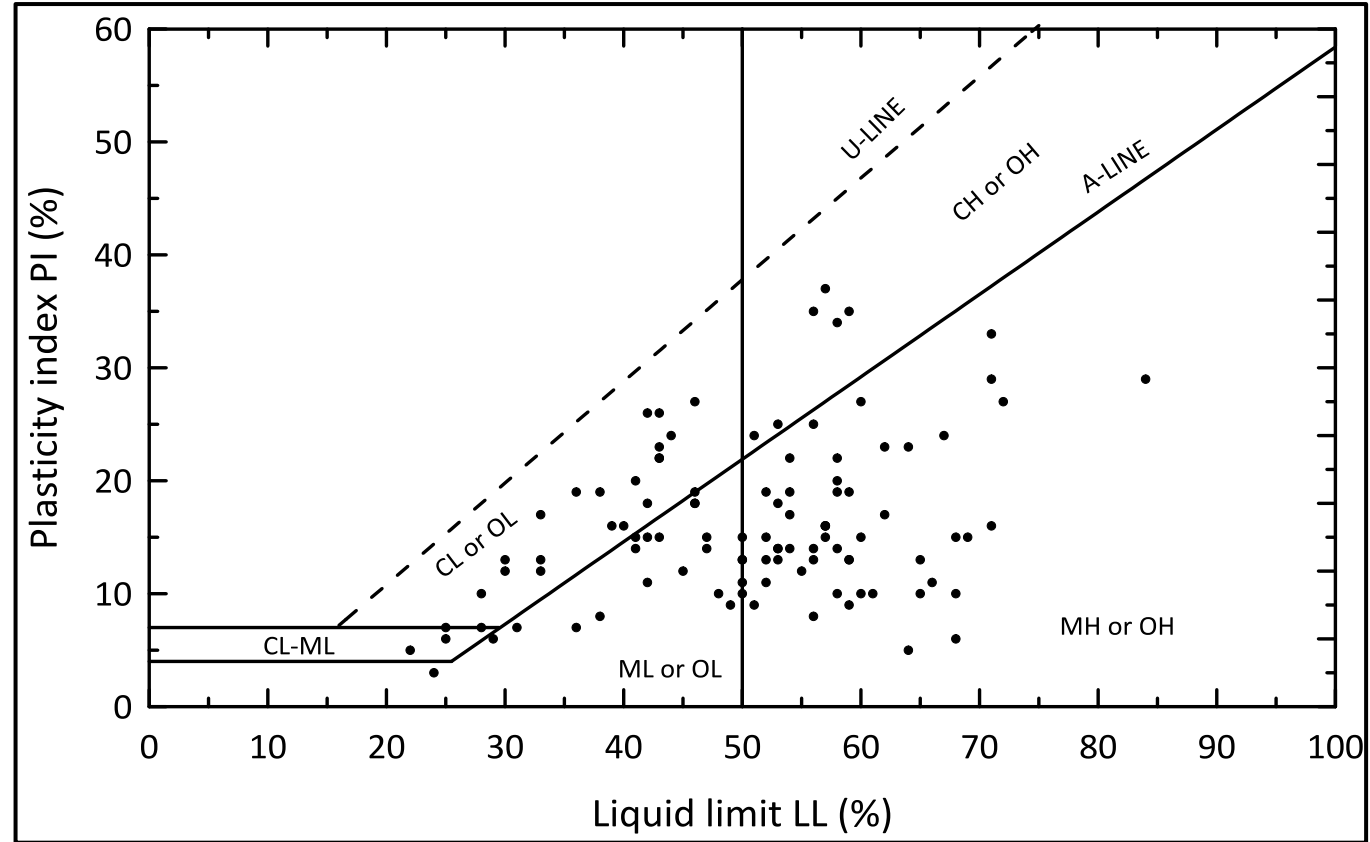
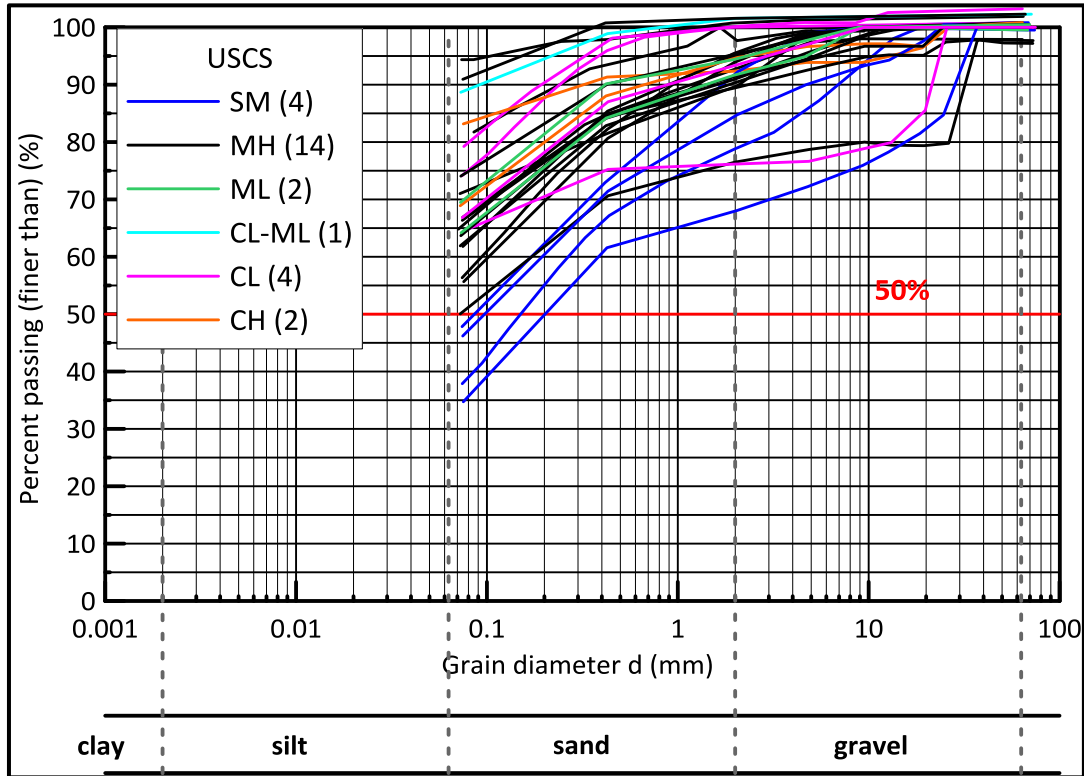
	Silts
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	Sand/Gravel



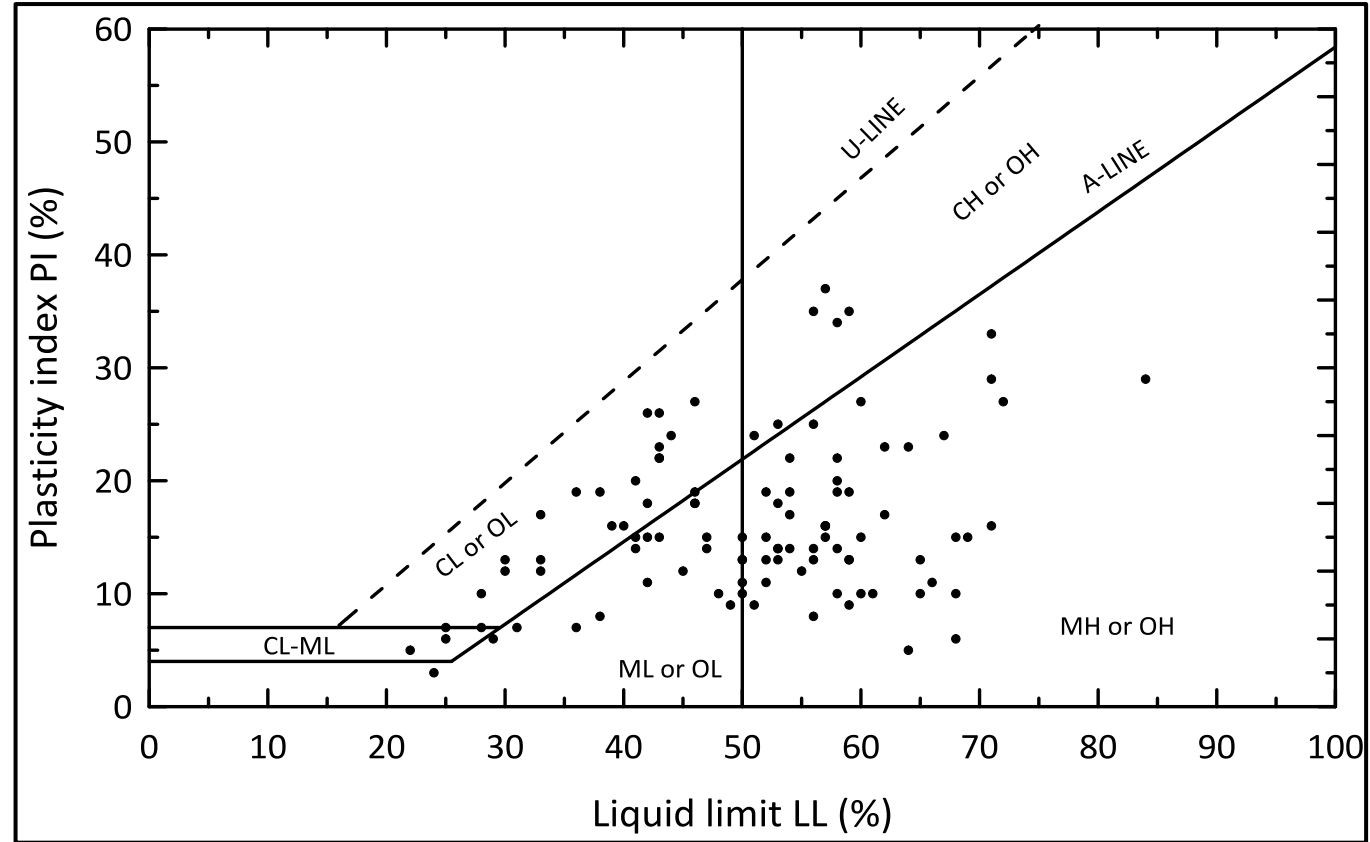
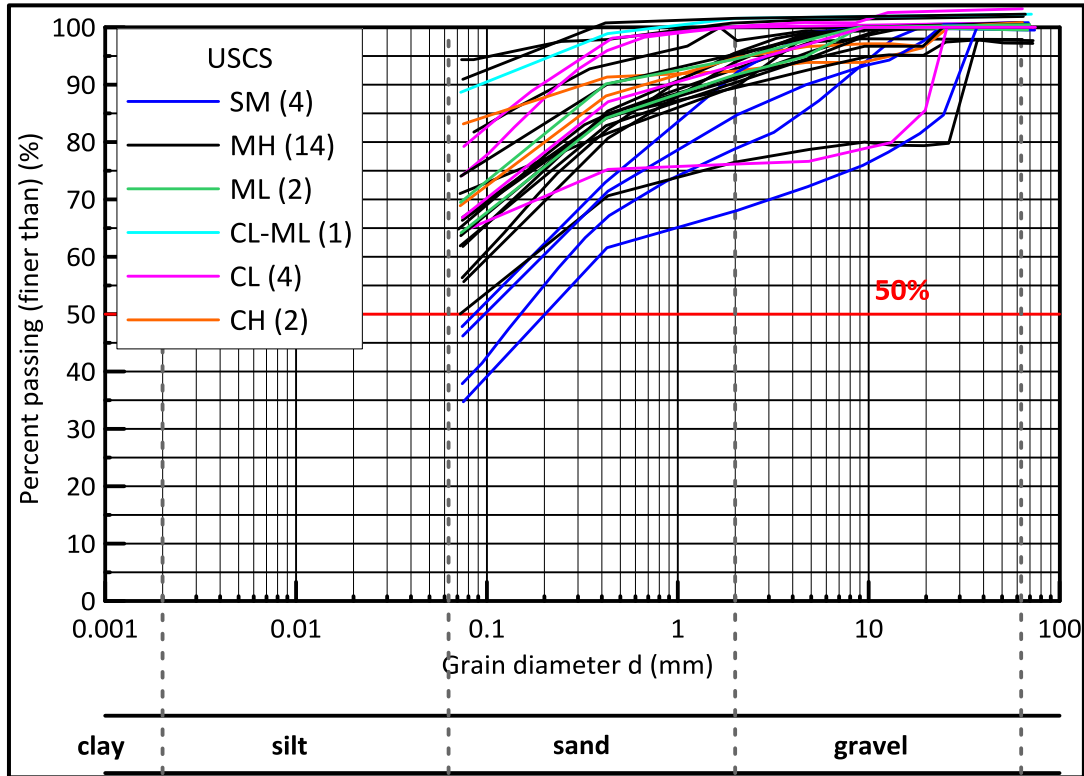
Spoil: one or many materials ? Stratigraphy? Structures?



The Soulou spoil heap - Geotechnical classification

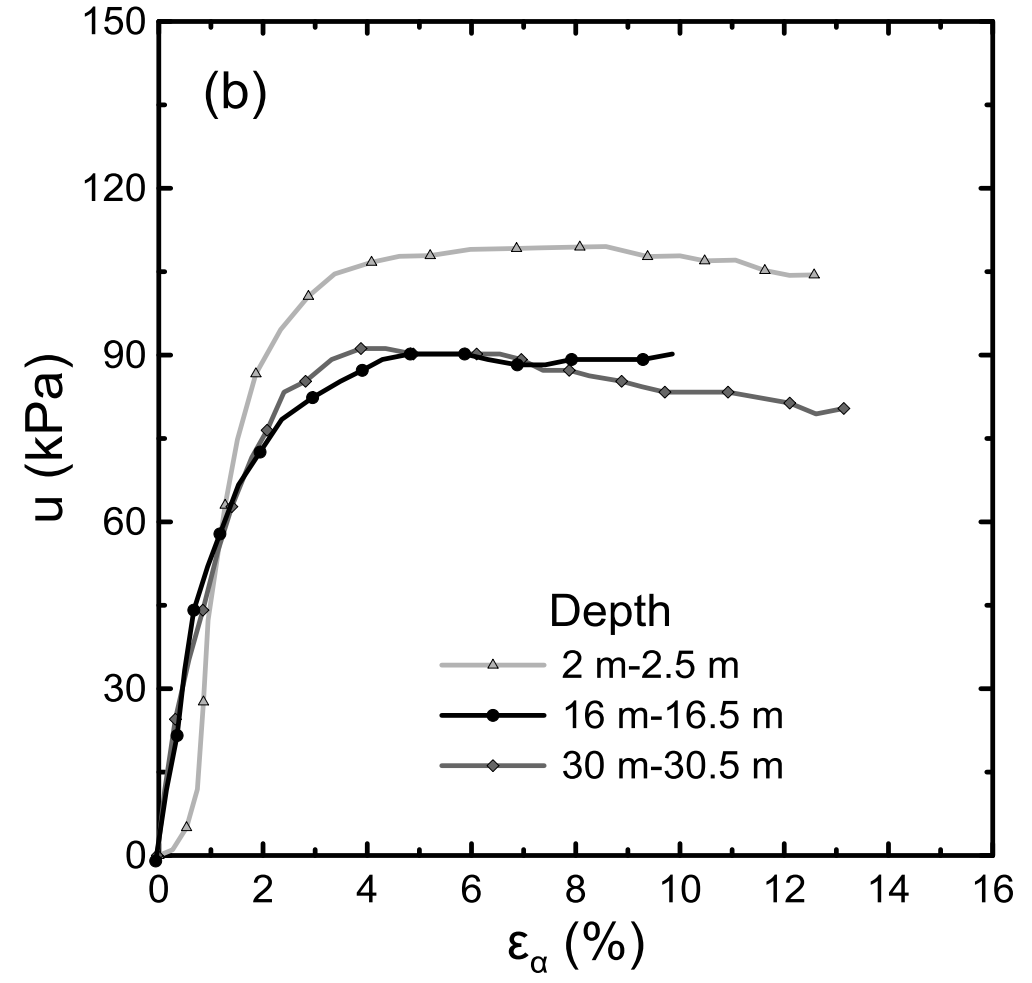
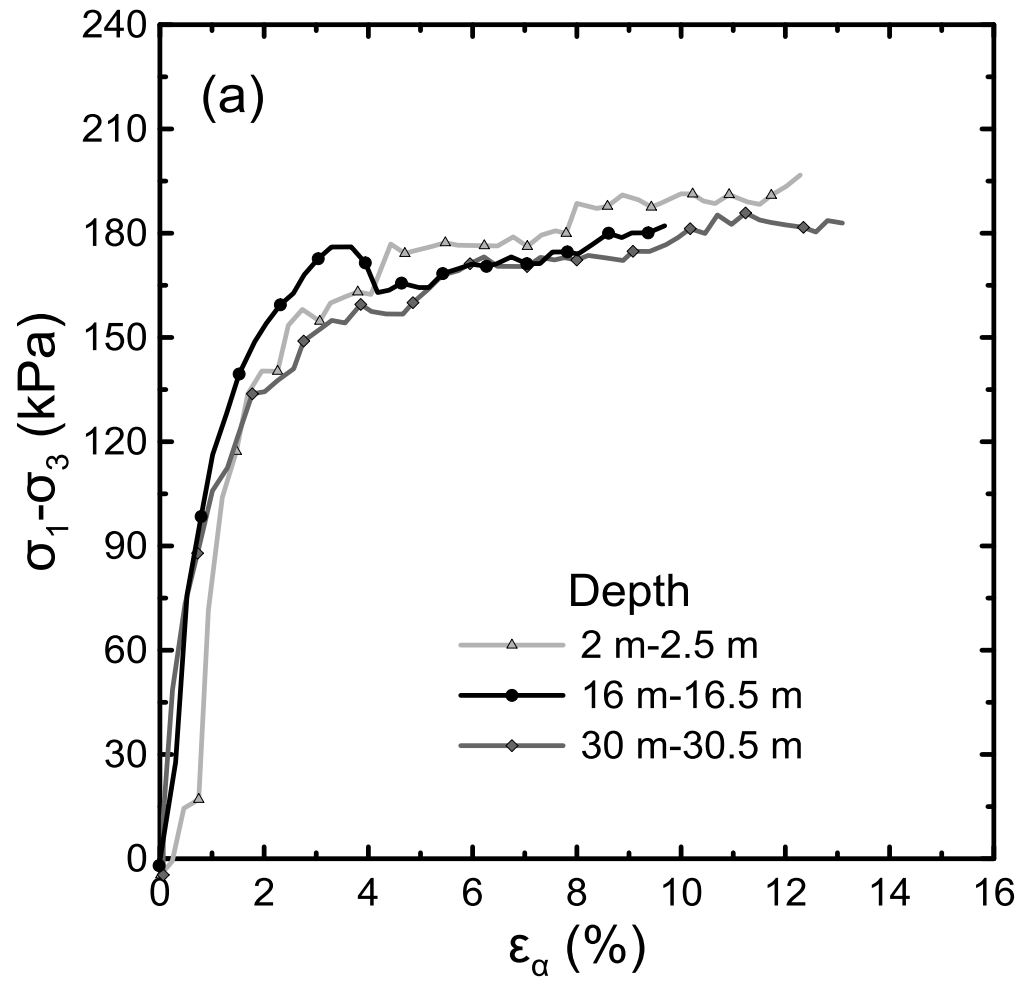


The Soulou spoil heap - Geotechnical classification



One material with very high variability (MH)

The Soulou spoil heap - Triaxial tests (CUPP)



Spoil material and Constitutive models

Geotechnical data:

- Classification and index properties
- Triaxial tests (consolidated, undrained)
- Oedometric tests

Monotonic, stress-strain curves:

- Models to represent the monotonic response
- Monotonic response similar to a normally consolidated clay

Possible models:

- Simple models
(e.g. Mohr-Coulomb linear-elastic perfectly-plastic) 5 parameters
- Non-linear isotropic elasto-plastic models
(e.g. Hardening soil, Softening/hardening) 7+ parameters
- Non-linear isotropic advanced (and sophisticated) models
(e.g. Modified cam-clay, Soft-soil, Clay Hypoplasticity) 5+ parameters + assumptions
- Non-linear anisotropic models (e.g. Saniclay, Anisotropic Hypoplasticity) 7++ parameters
- ...

Spoil material and Constitutive models

- ❖ Heterogeneity of spoil material
- ❖ Disturbance and differences from in-situ soils (arising from physical processes)
- ❖ Difficulty in identifying representative material
- ❖ Unknown behavior under complex loading paths

Possible models:

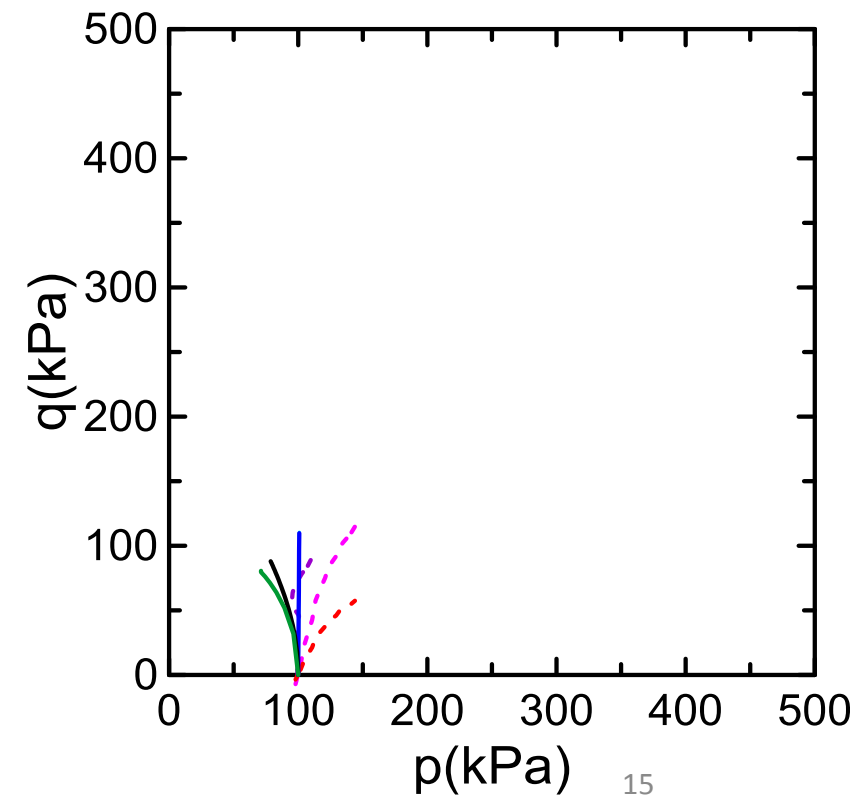
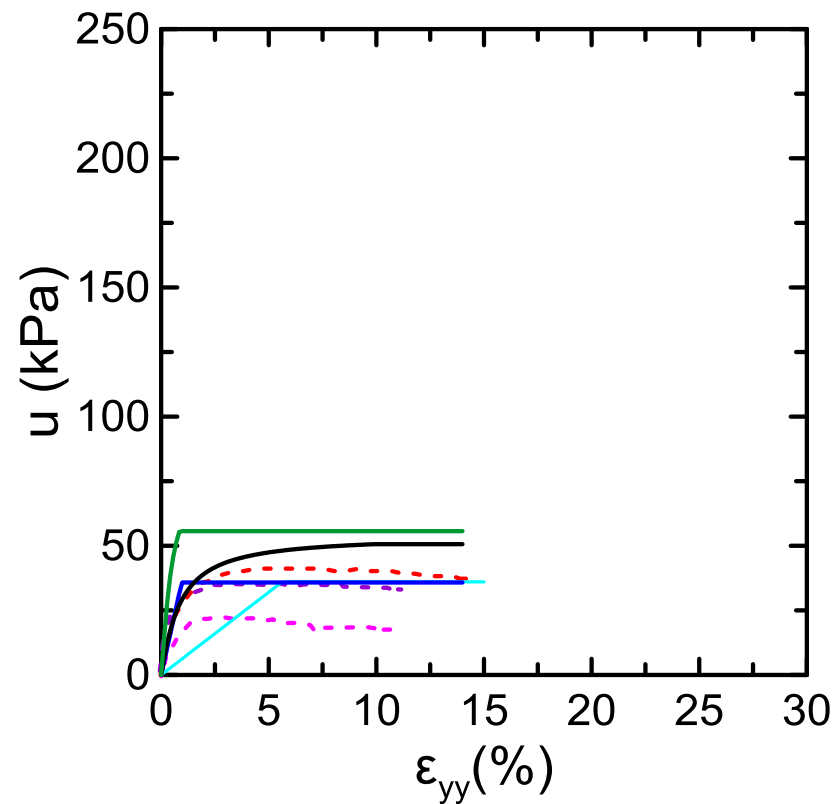
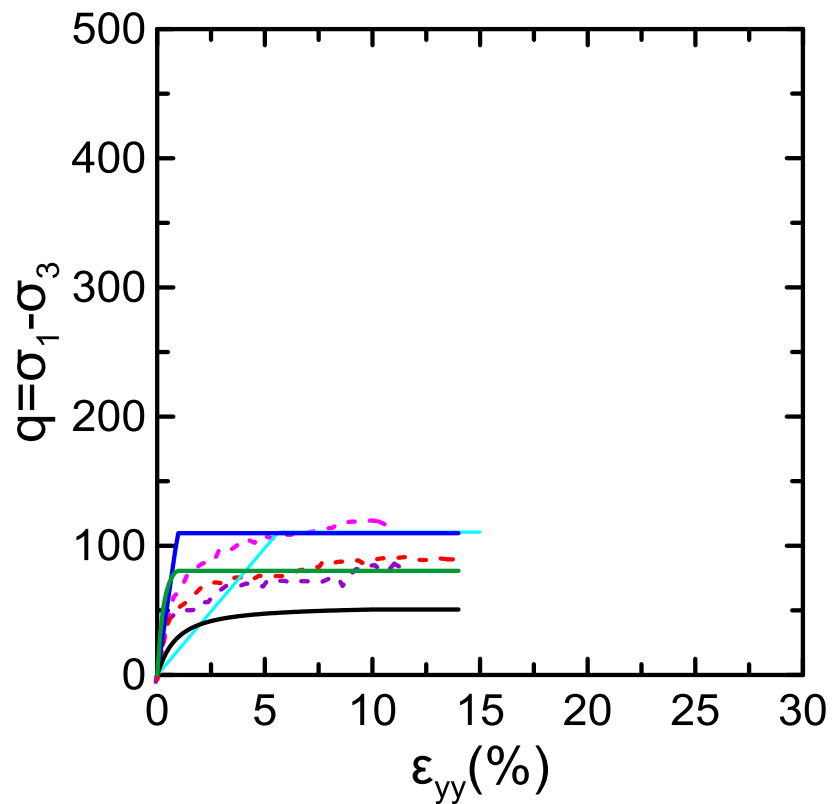
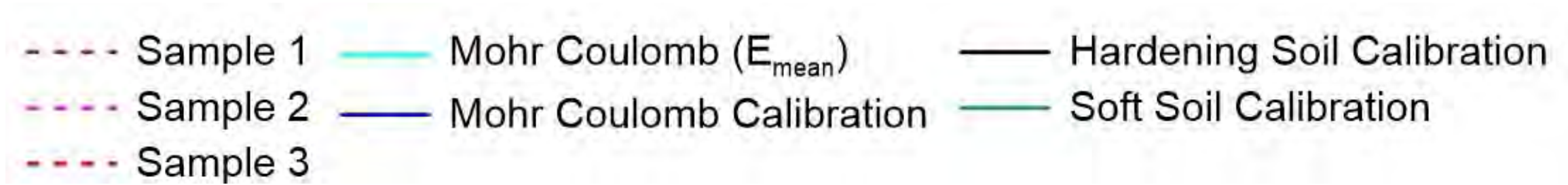
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- Non-linear anisotropic models (e.g. Saniclay, Anisotropic Hypoplasticity) 7++ parameters
- ...

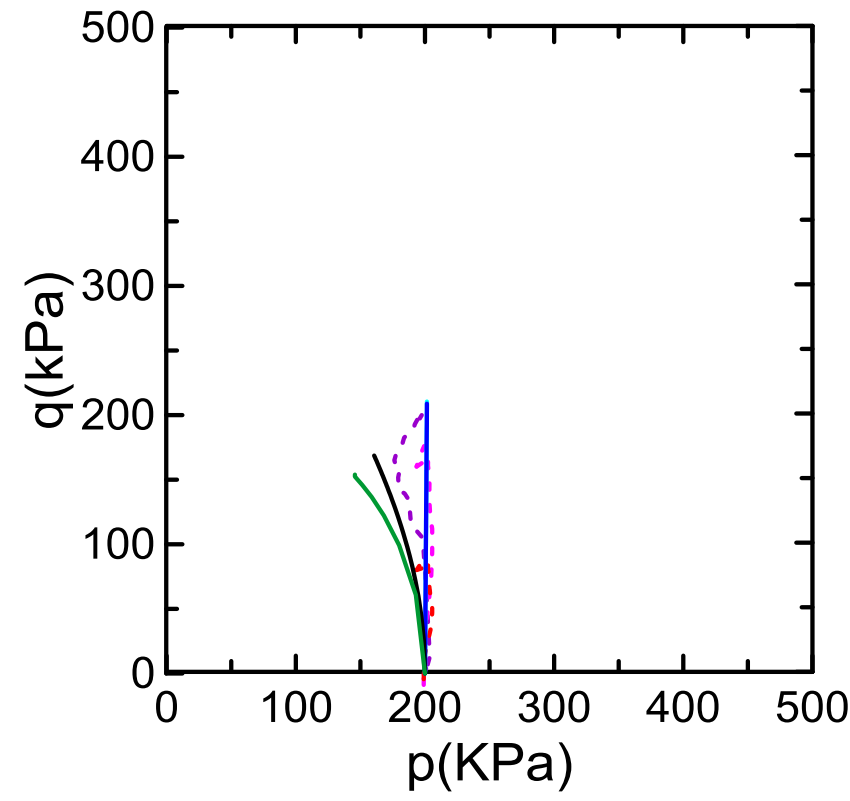
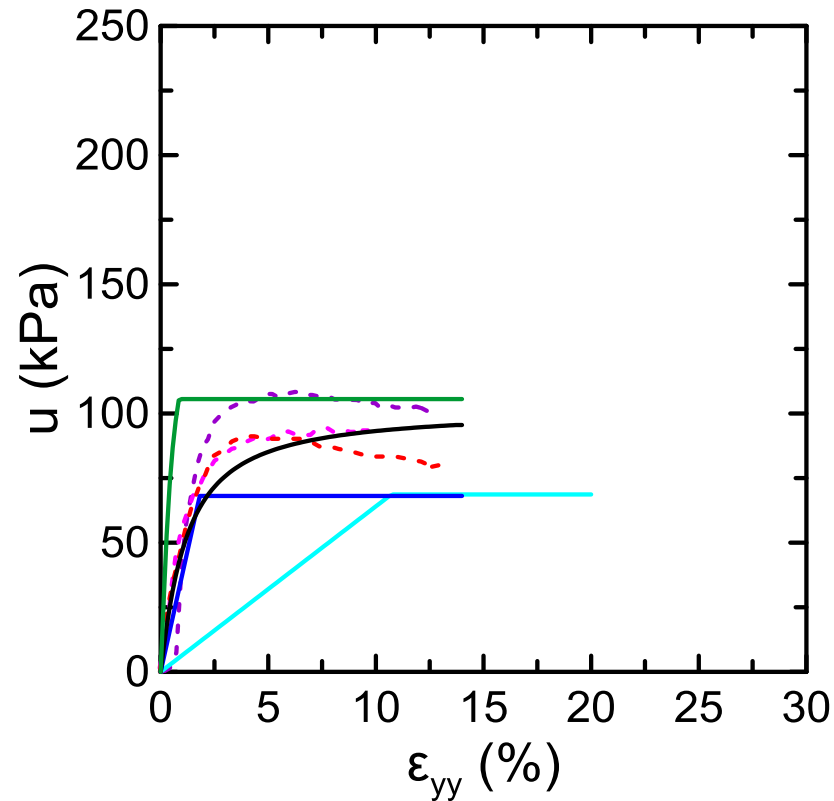
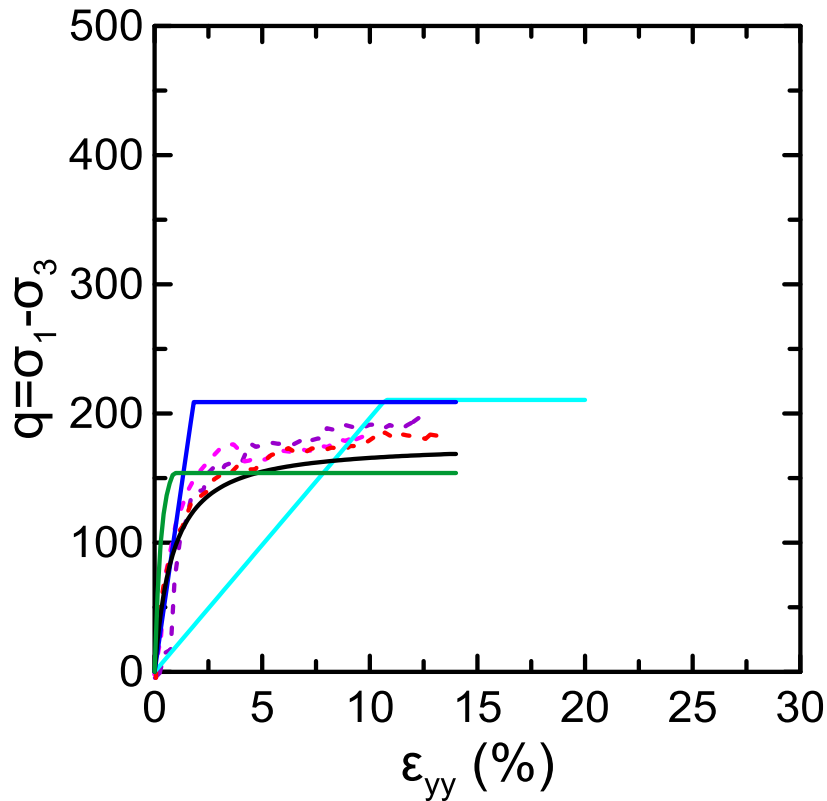
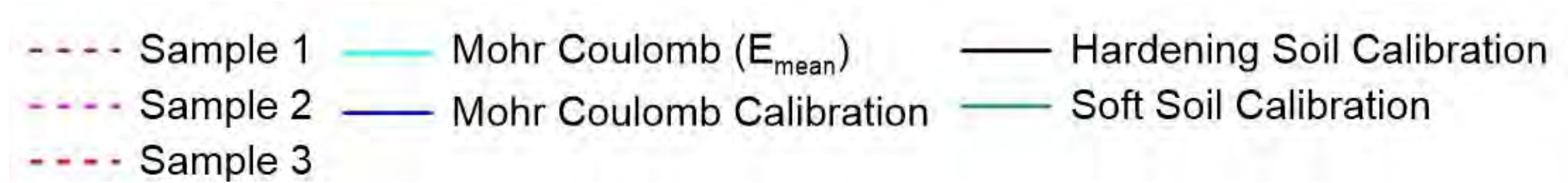
Undrained triaxial tests

$$\sigma_3 = 100 \text{ kPa}$$



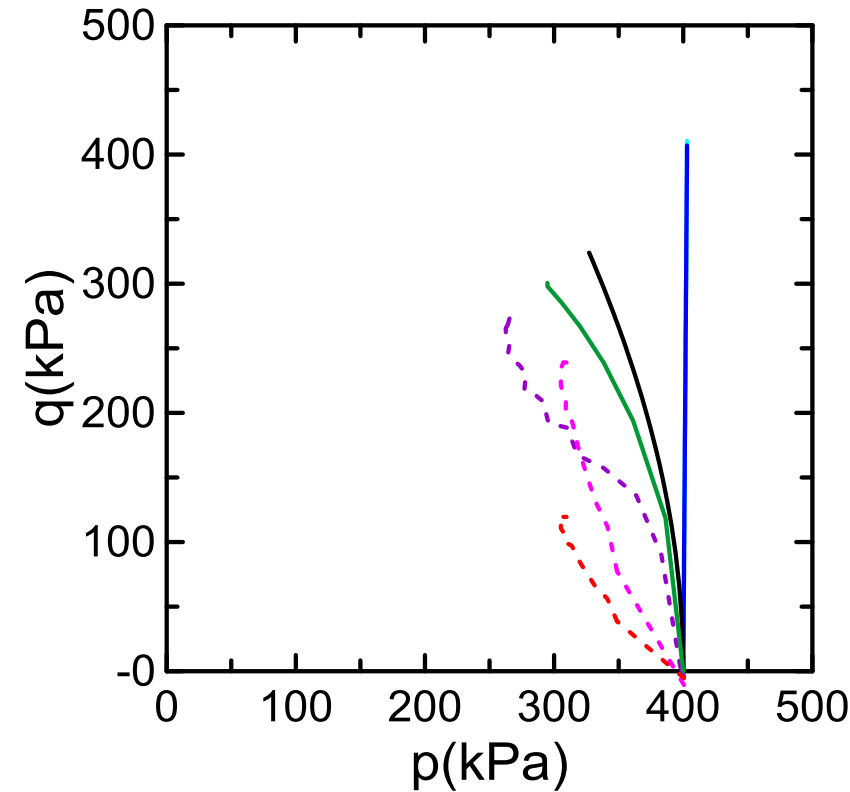
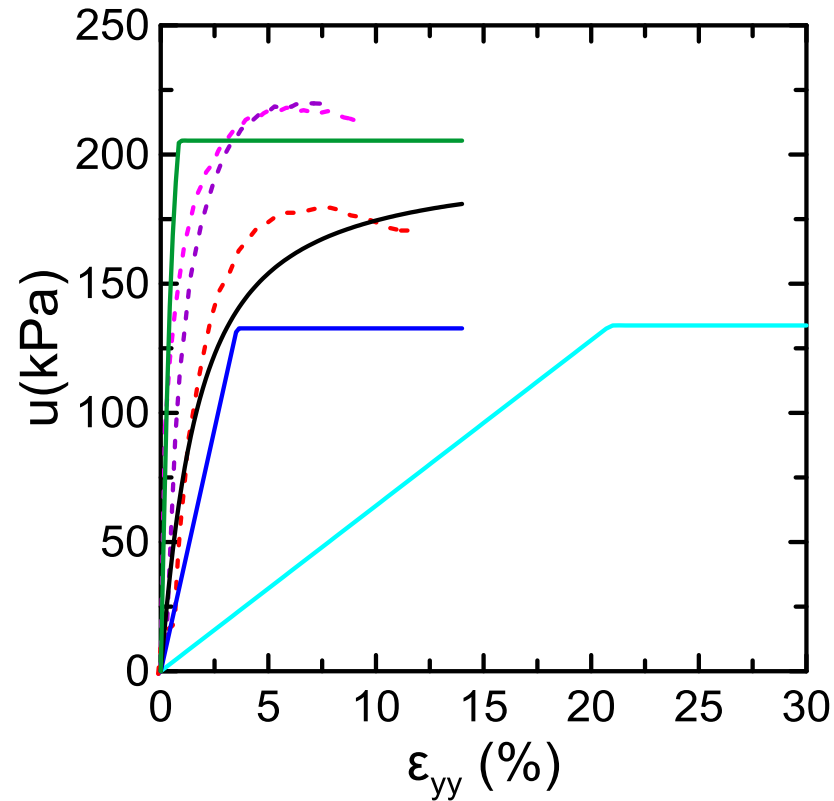
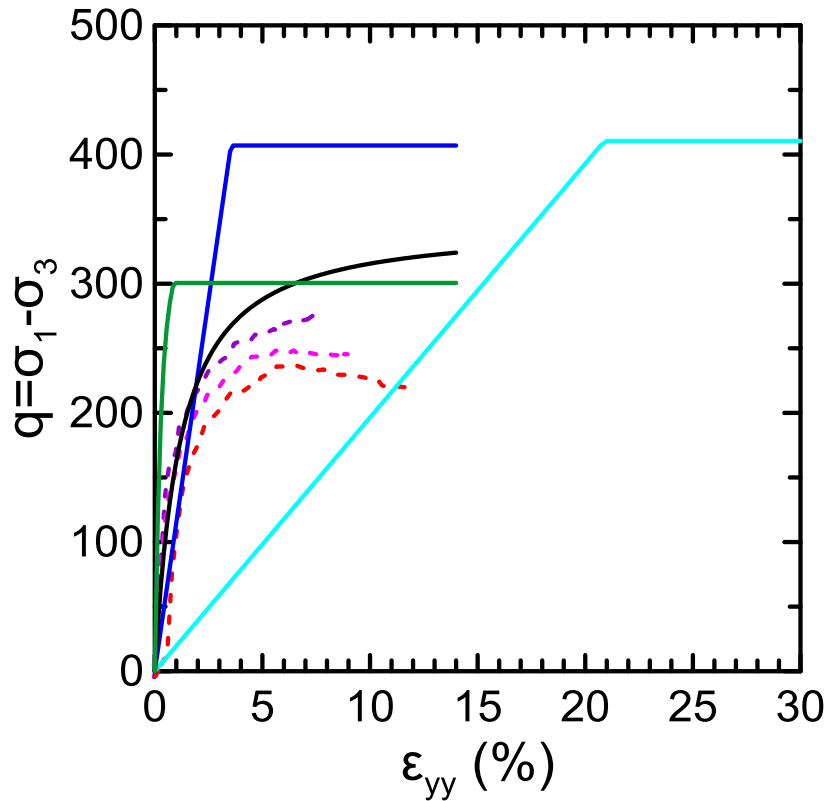
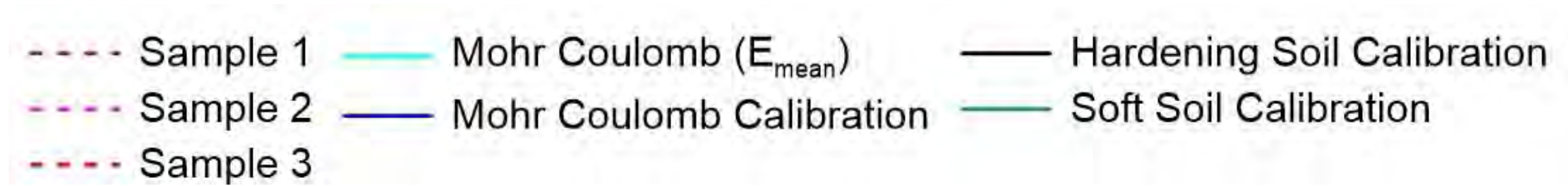
Undrained triaxial tests

$$\sigma_3 = 200 \text{ KPa}$$



Undrained triaxial tests

$$\sigma_3 = 400 \text{ kPa}$$



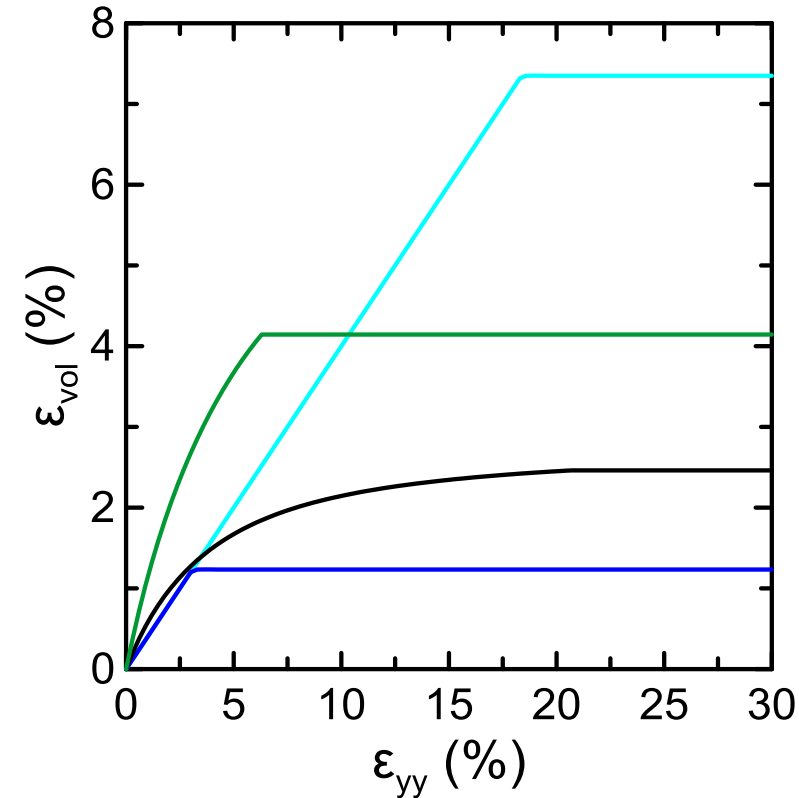
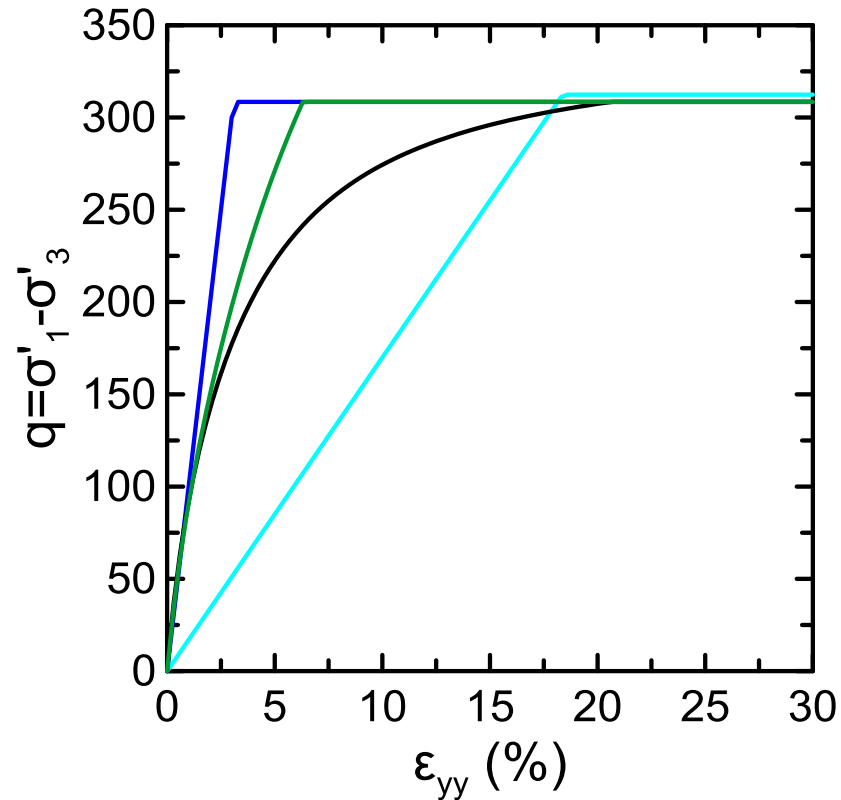
Constitutive model calibrations

Parameters	Mohr-Coulomb	Hardening Soil	Soft Soil
E or E ₅₀ (kPa)	10,000	5,000	-
ϕ (°)	25	25	25
c (kPa)	5	5	5
ψ (°)	0	0	0
v	0.3	-	-
m	-	0.5	-
E _{oed} (kPa)	-	5,000	-
C _c	-	-	0.2
C _r	-	-	0.037

Drained Triaxial Test – Simulation

$$\sigma_c = 200 \text{ KPa}$$

- Mohr Coulomb Calibration
- Mohr Coulomb E_{mean}
- Hardening Soil Calibration
- Soft Soil Calibration



- The behavior of the spoil material under drained conditions is important being the long term response.
- The Mohr Coulomb calibration fails quicker on the smallest volumetric strains.
- On the contrary, Mohr Coulomb with the E_{mean} value fails last and has the higher volumetric strains.
- Both hardening soil and soft soil, lie in between the two Mohr Coulomb results.

Constitutive Models - Comments

- Mohr-Coulomb calibration fits adequately well the apparent monotonic behavior, but cannot accurately follow the changes in behavior due to hydrostatic pressure build-up.
- Hardening soil model follows better the pore pressure increase during undrained triaxial shear and accurately represents the non-linear nature of response. However, spoil material builds up pore pressures more rapidly with the increase of hydrostatic pressure with respect to the model.
- Soft soil represents more accurately pore pressure build up but, due to that, proposes a more rapid deviatoric stress increase than experiments.
- Overall, it is observed that hardening soil and soft soil are more accurate than Mohr-Coulomb model.

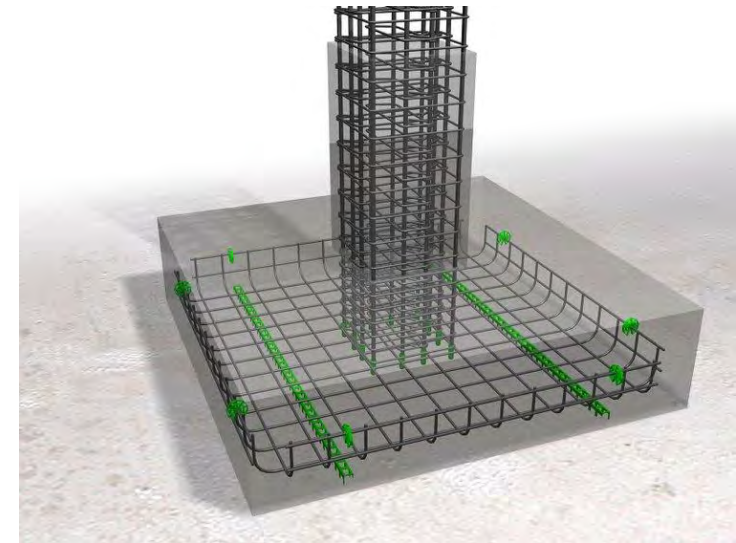
Construction Scenarios for spoil heap reclamation:

Question: What could we build on spoil material?

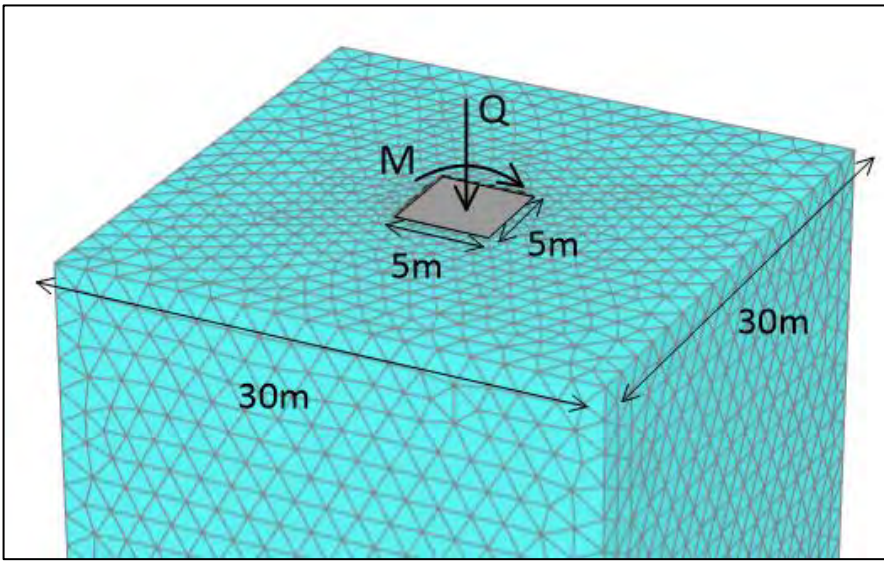
Reclaiming a spoil heap by a highway road, founding an onshore wind turbine or a building (e.g. office building, warehouse).

Monotonic loading are only used.

2D and 3D Finite Element Analysis were employed and the three calibrated constitutive models.



Small building



- Square shallow footing
- Loads: Q , M
- Small buildings \rightarrow Q : 2-3 MN , M : 1,5-2 MNm
- Goal : Develop a curve indicating what combinations of Q , M are acceptable \rightarrow Failure Envelope (Q, M)

FOUNDATION DIMENSIONS		
L (m)	B (m)	H (m)
5	5	0,8

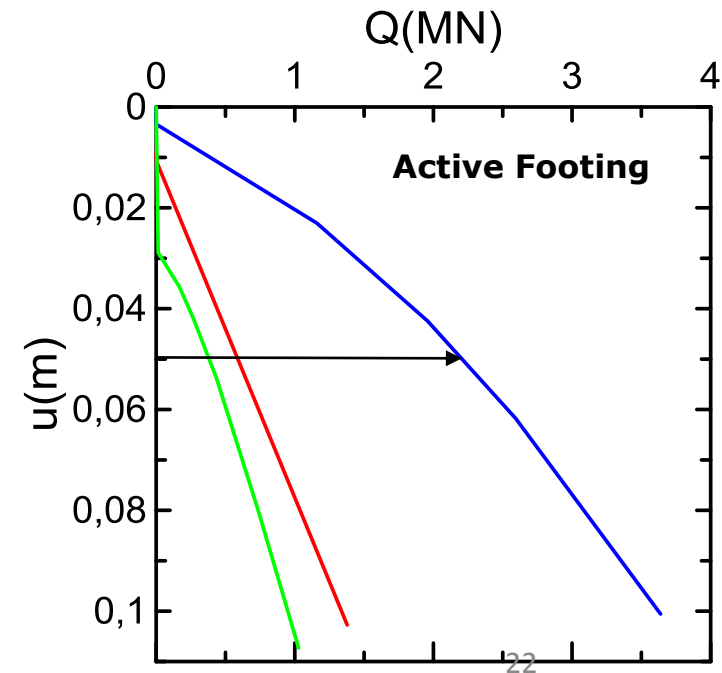
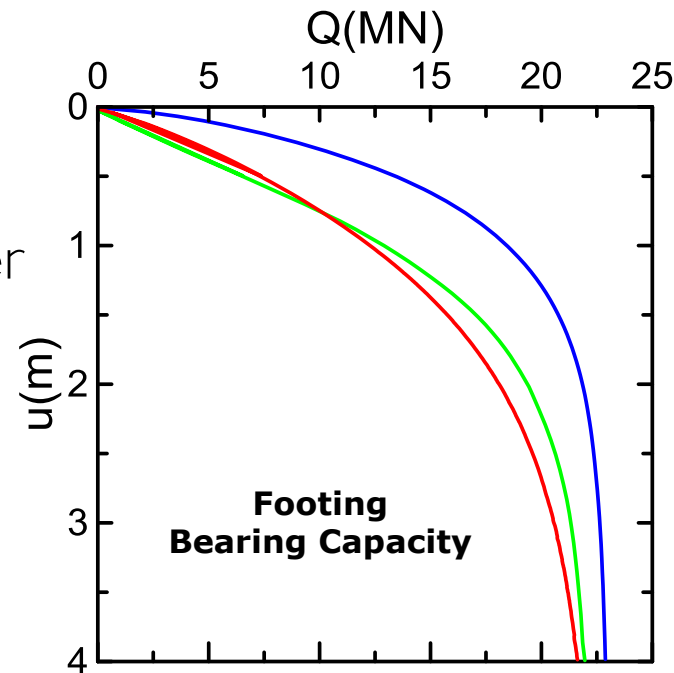
— Mohr Coulomb — Soft Soil — Hardening Soil

Assumptions

- Spoil material is simulated as one layer with uniform properties.
- Footing Material: Reinforced Concrete

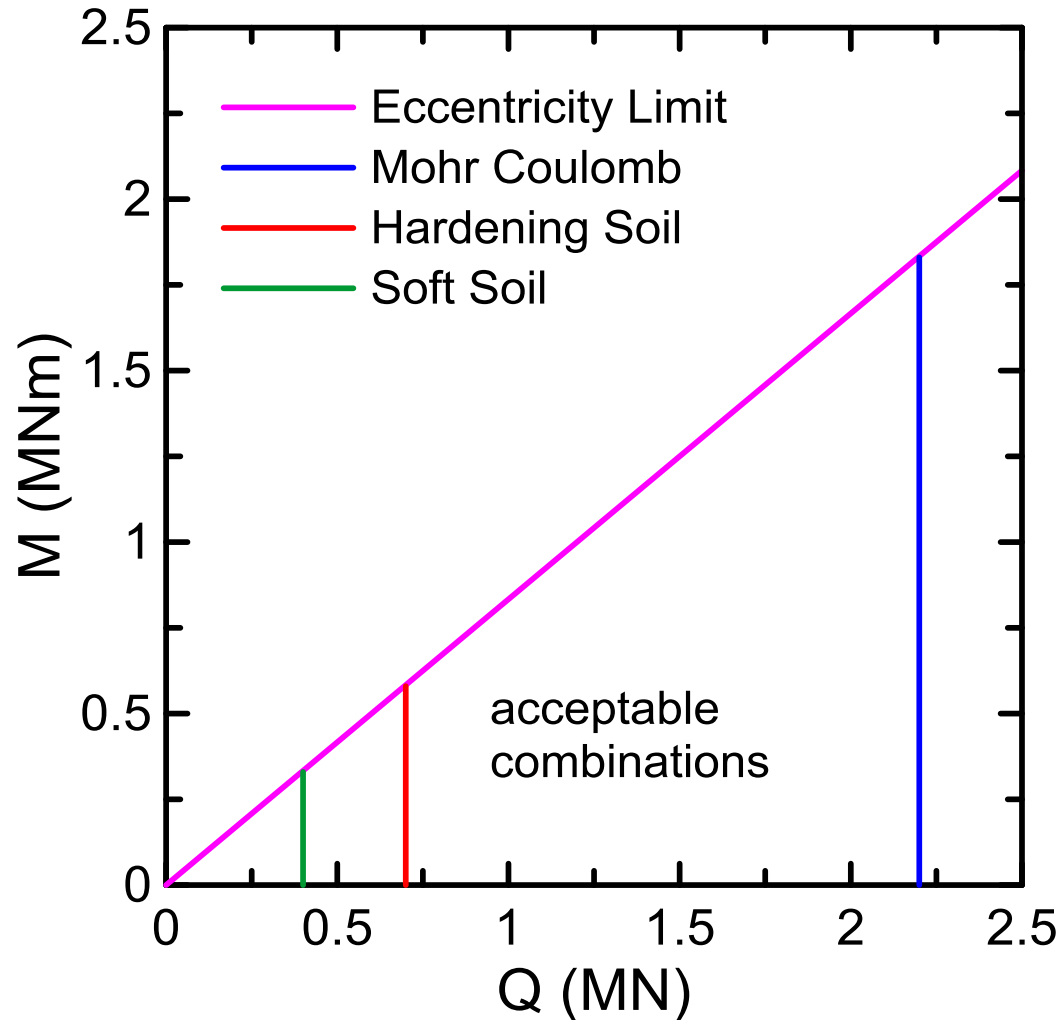
Failure Criteria by EC-7 :

- Eccentricity $e \leq B/6$
- $U_{max} = 5 \text{ cm}$



Small building

Failure Envelope : Eccentricity $e \leq B/6$ and $u_{\max} = 5\text{cm}$



Conclusions:

Results are strongly affected by the constitutive model:

- Mohr-Coulomb gives barely acceptable loads considering typical values for small buildings.
- Hardening Soil and Soft Soil indicate that the spoil material cannot bare loads of a small building as the typical loads exceed the bearing capacity.

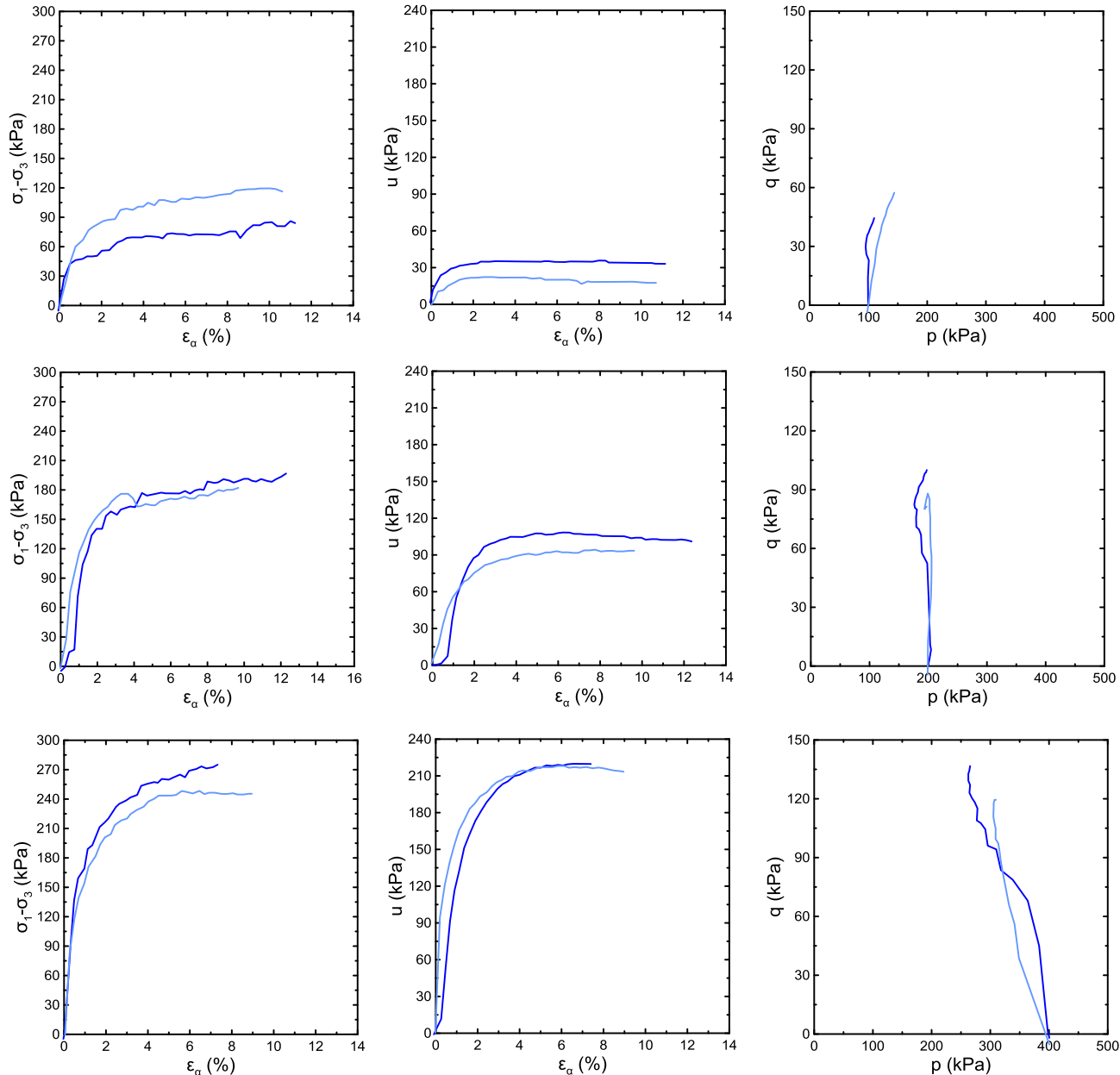
Spoil material definitely needs improvement.

Conclusions

- Soulou spoil heap characterization:
 - Highly heterogeneous spoil heap, exceeding the usual variability
 - Overall this is a spoil heap characterized by fine-grained materials
 - The spoil mass was considered as one, unified spoil material with significant uncertainty; characteristic material is high plasticity silt
- Constitutive models for spoil material:
 - Simple and advanced models were employed for the monotonic response: Mohr-Coulomb, Hardening soil and Soft soil models
 - Overall, hardening soil and soft soil are more accurate than Mohr Coulomb model
- Numerical modelling:
 - Inadequate for shallow foundations.
 - Ground improvement techniques must be implemented - low stiffness and strength due to its creation and nature.

Thank you !

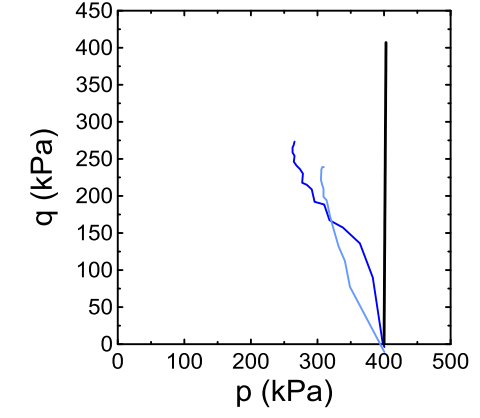
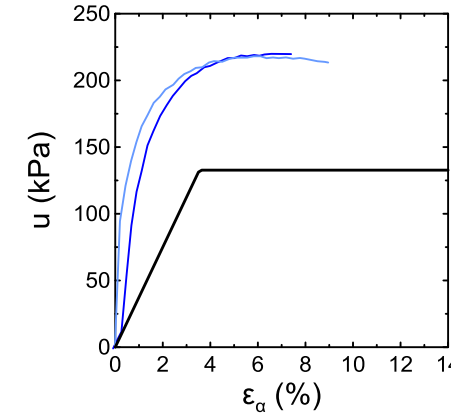
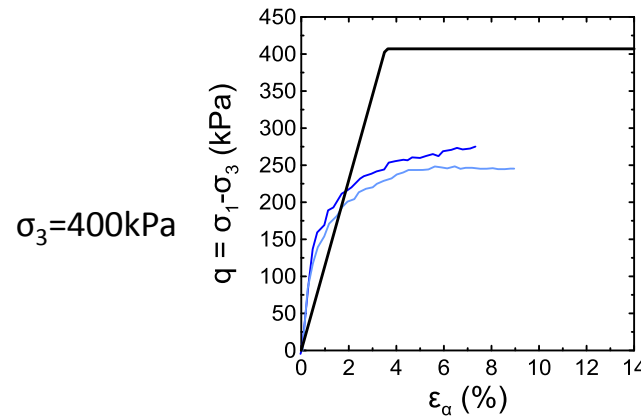
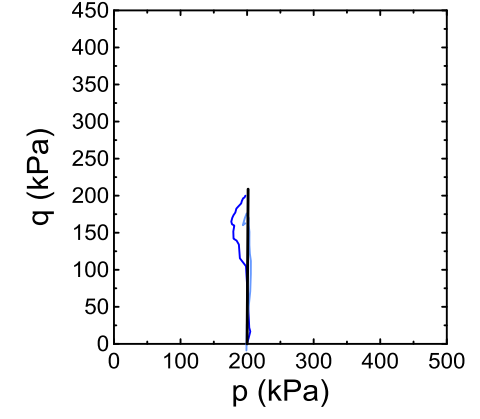
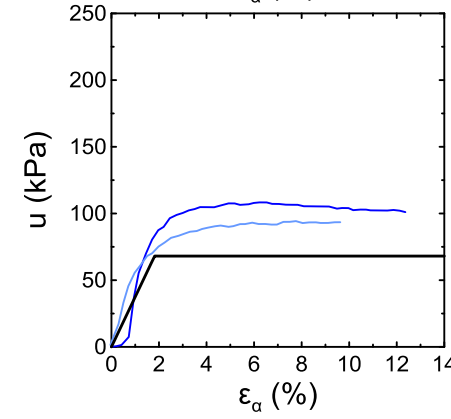
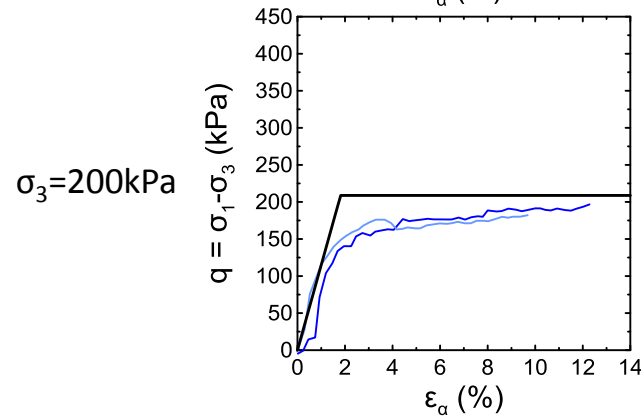
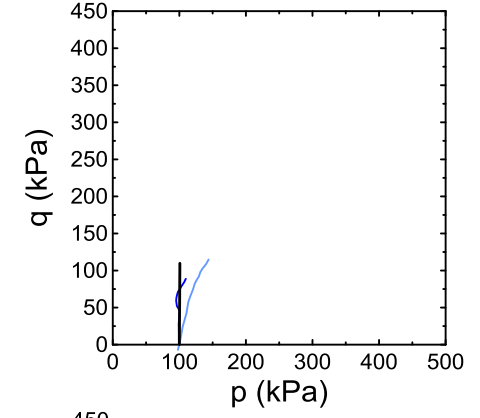
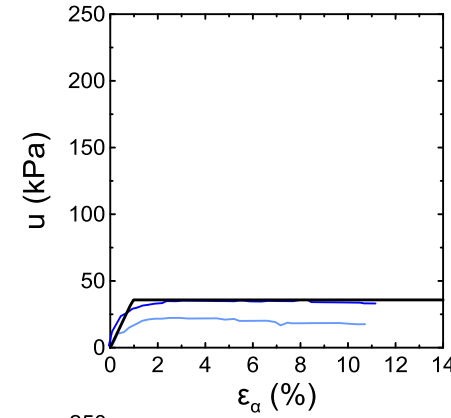
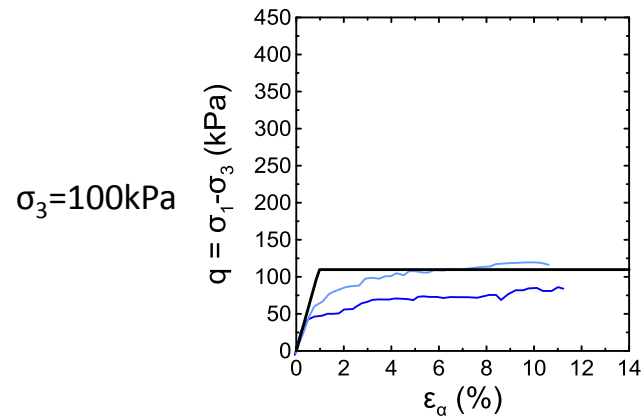
Validation and calibration framework



Parameters	Mohr Coulomb	Hardening Soil	Soft Soil
E (kPa) or E_{50} (kPa)	10,000	5,000	-
ϕ (°)	25	25	25
c (kPa)	5	5	5
ψ (°)	0	0	0
v	0,3	-	-
m	-	0,5	-
E_{oed} (kPa)	-	5,000	-
C_c	-	-	0,2
C_s	-	-	0,037

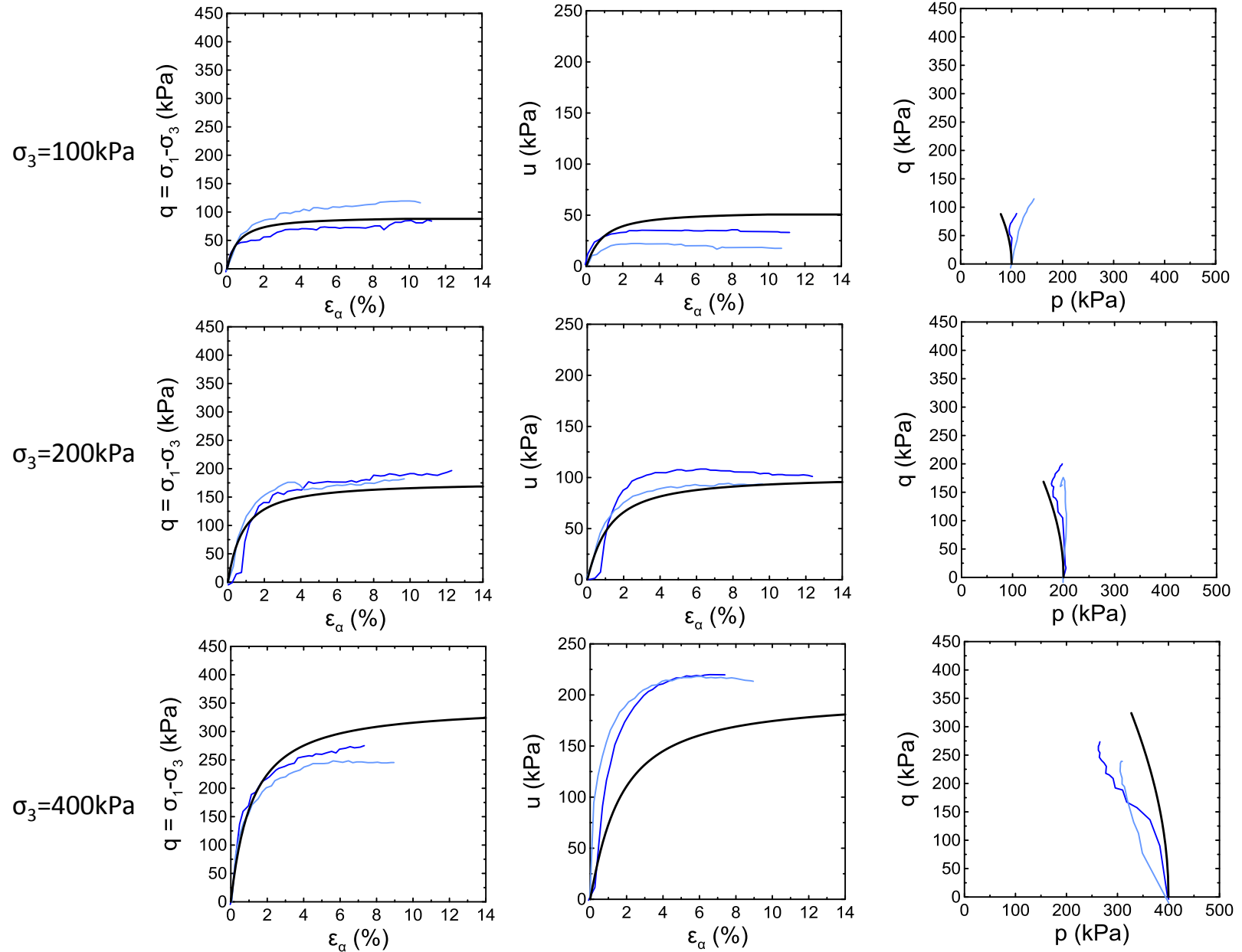
Mohr-Coulomb calibration

Parameters	Mohr Coulomb
E (kPa)	10,000
ϕ ($^{\circ}$)	25
c (kPa)	5
ψ ($^{\circ}$)	0
ν	0,3



Hardening Soil calibration

Parameters	Hardening Soil
E_{50} (kPa)	5,000
ϕ (°)	25
c (kPa)	5
ψ (°)	0
m	0,5
E_{oed} (kPa)	5,000



Mohr-Coulomb – Soft Soil

Parameters	Soft Soil
ϕ (°)	25
c (kPa)	5
ψ (°)	0
C_c	0,2
C_s	0,037

