Università degli Studi di Padova

ICEA

University of Delaware

La compattazione negli ambienti di transizione: casi studio nella laguna di Venezia

CLAUDIA ZOCCARATO - MSCA fellow

University of Padova, Department of Civil, Environmental and Architectural Engineering

University of Delaware, Department of Earth Science

www.preservewetlands.eu

LA SUBSIDENZA IN ITALIA

dal confronto tecnico-scientifico alla creazione di un gruppo di lavoro (iSUB-I)

I-SUB

Gruppo Nazionale Italiano sulla Subsidenza

Italian National Group on Land Subsidence

LAND SUBSIDENCE

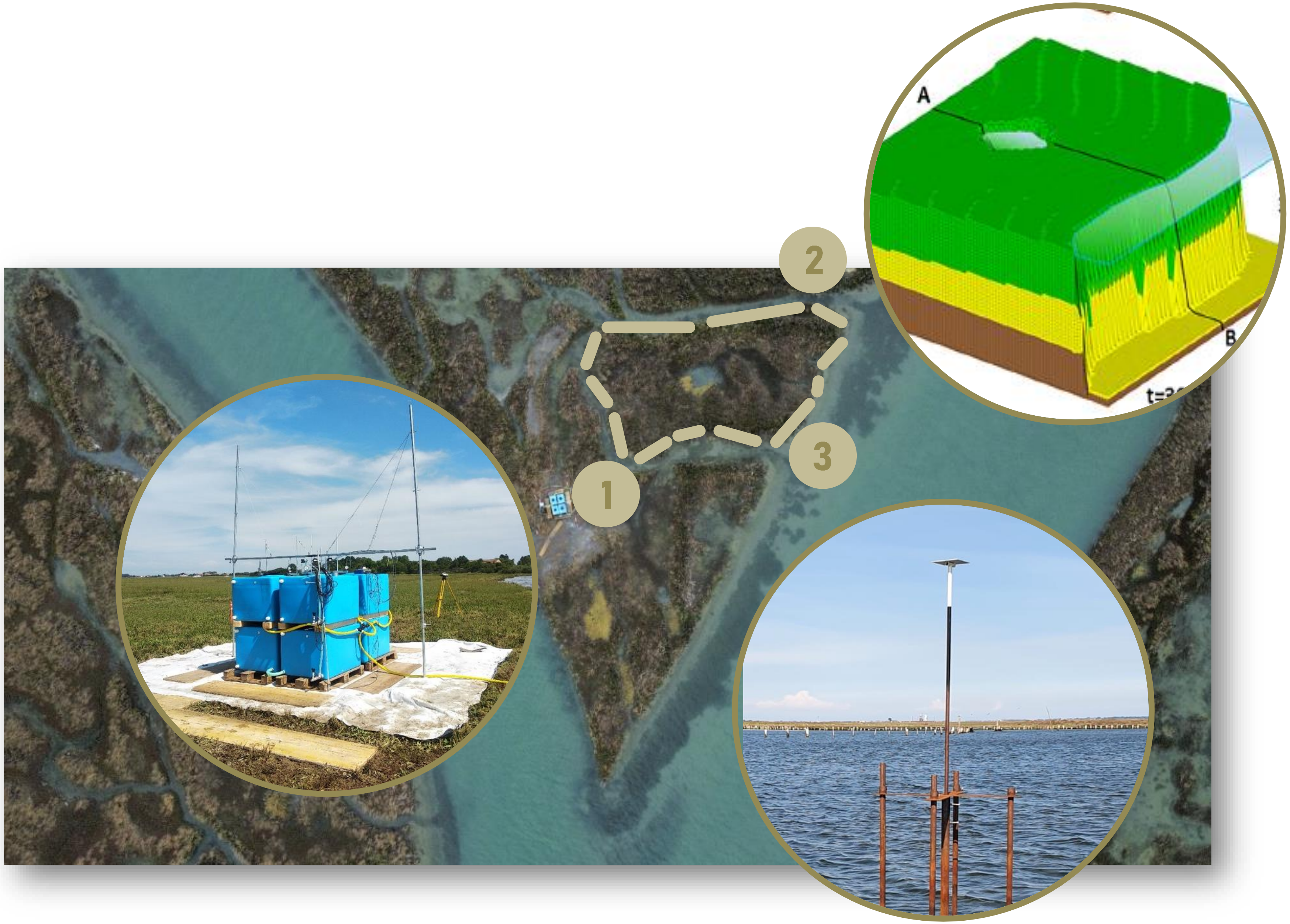
LaSII

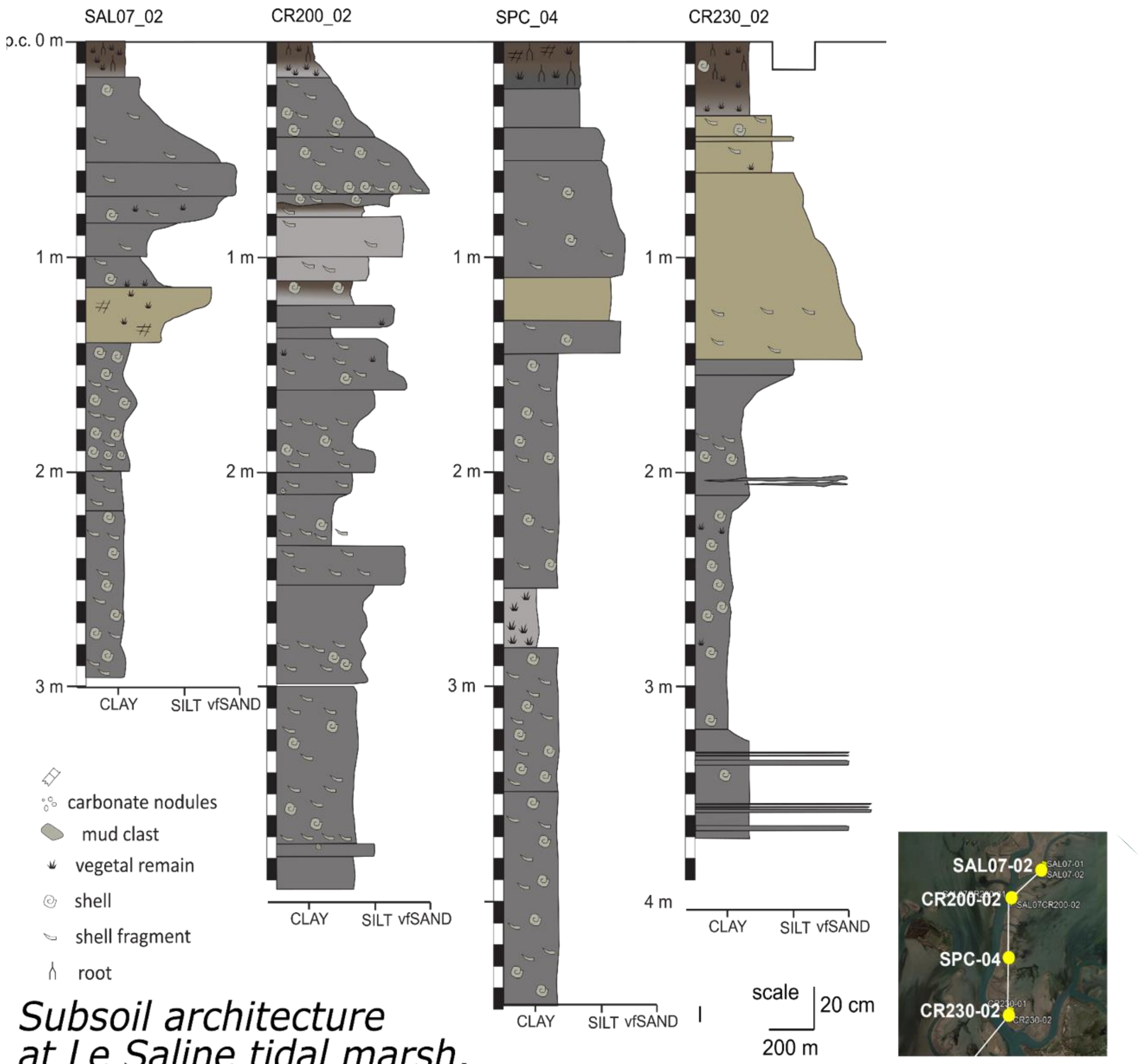
UNESCO

17 febbraio 2026

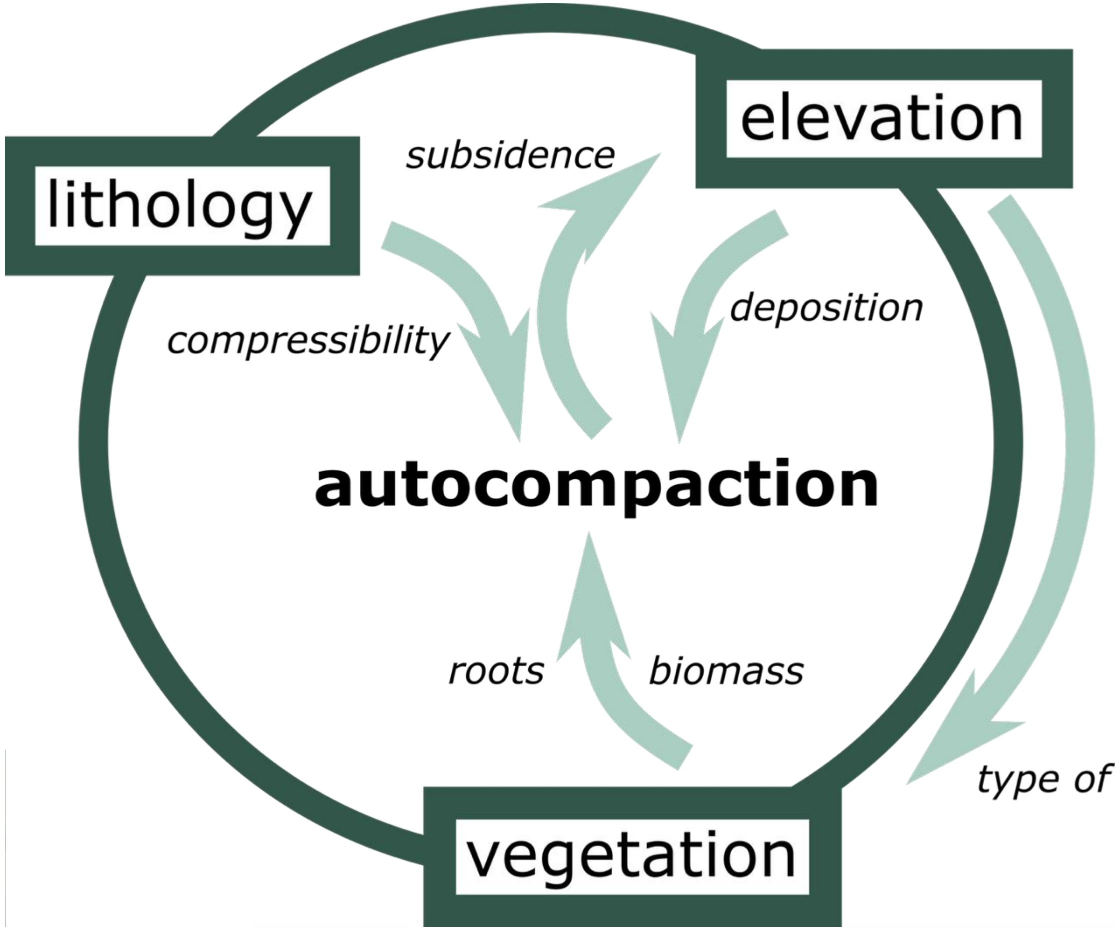
17-18 Febbraio 2026

Universita' di Padova
Dipartimento di Ingegneria Civile, Edile e Ambientale
Aula Magna, Via Marzolo, 9


2
3
1
A
B



Subsoil architecture at Le Saline tidal marsh, Venice Lagoon, Italy

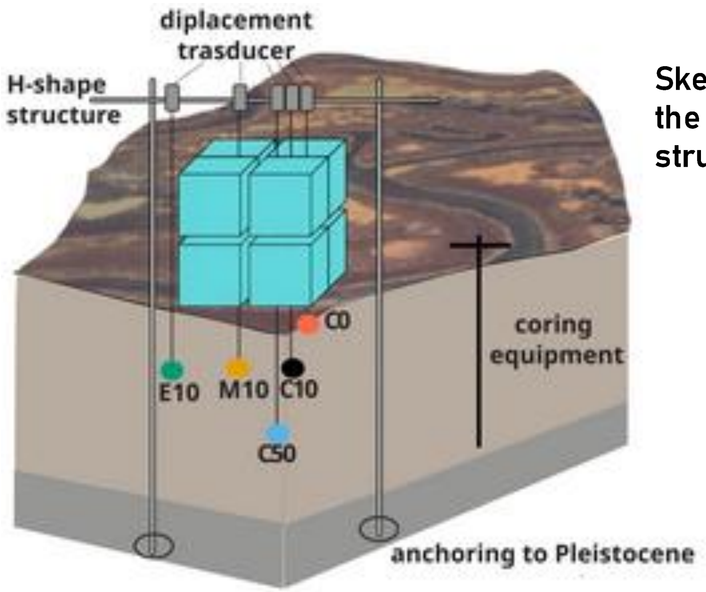


- Compressibility of shallow marsh sediments & role of heterogeneity
- Long-term numerical simulations to predict dynamics of sedimentation and compaction
- The role of autocompaction in artificial marshes

Spatial variability of vegetation at Le Saline salt marsh, Venice Lagoon, Italy

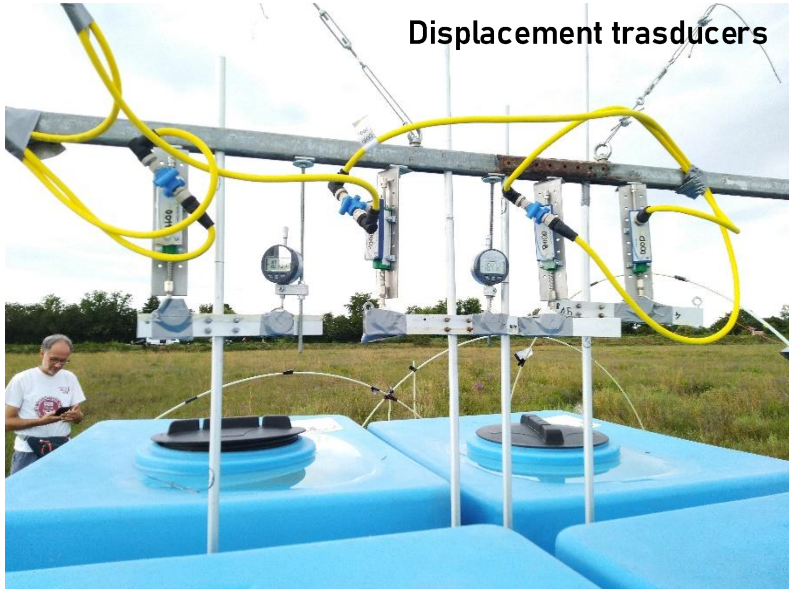
LOADING TESTS

MECHANICAL RESPONSE

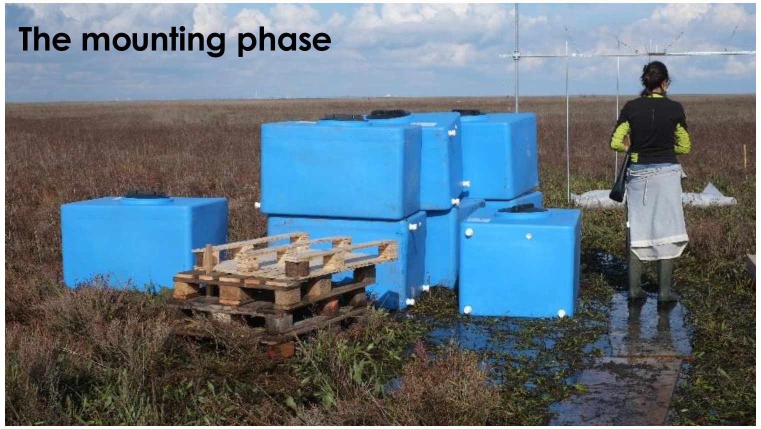


Sketch of the experiment showing the position of the monitoring instruments and the H-shaped structure anchored on the Pleistocene


Loading test at Lazzaretto N. site


Displacement trasducers

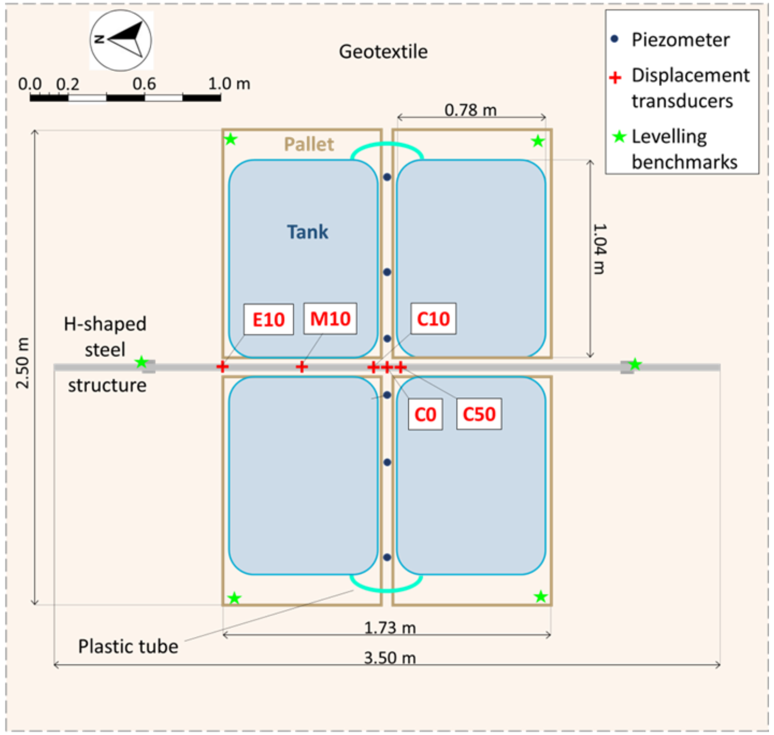

Unloading phase


The mounting phase

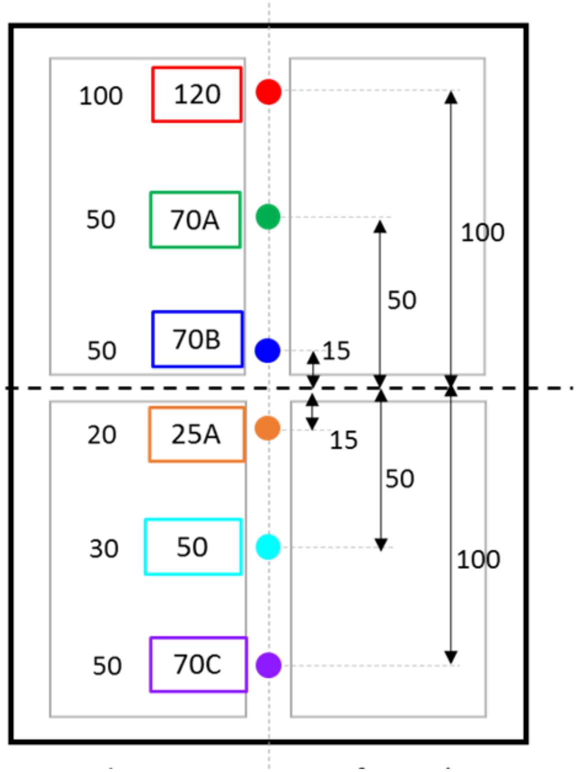
C. Zoccarato et al. In-situ loading experiments reveal how the subsurface affects coastal marsh survival. Commun Earth Environ 3, 264, 2022.

LOADING TESTS

MECHANICAL RESPONSE



Sketch of the loading with dimensions and location of the displacement transducers (micrometers)

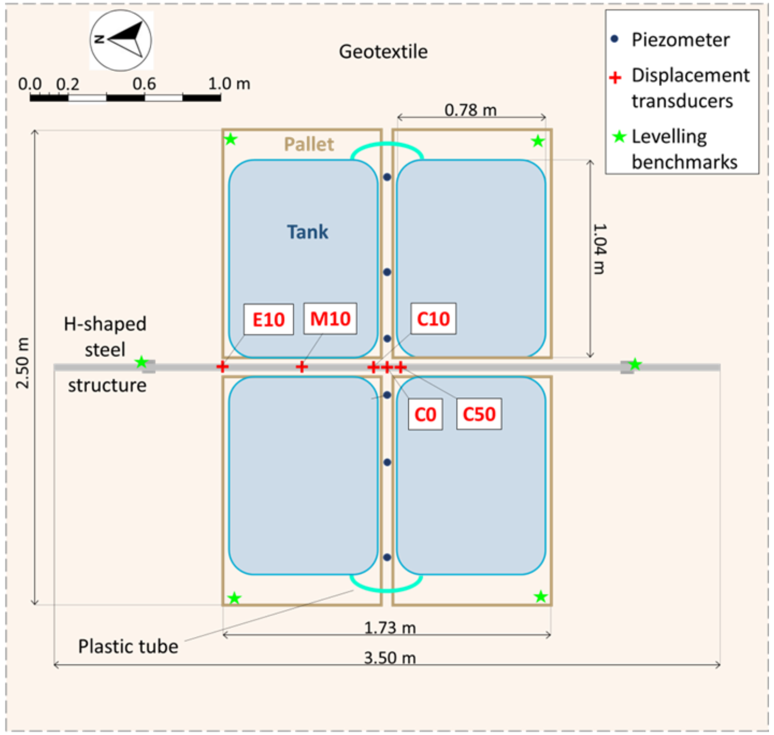


Sketch of the loading with dimensions and location of the pressure transducers

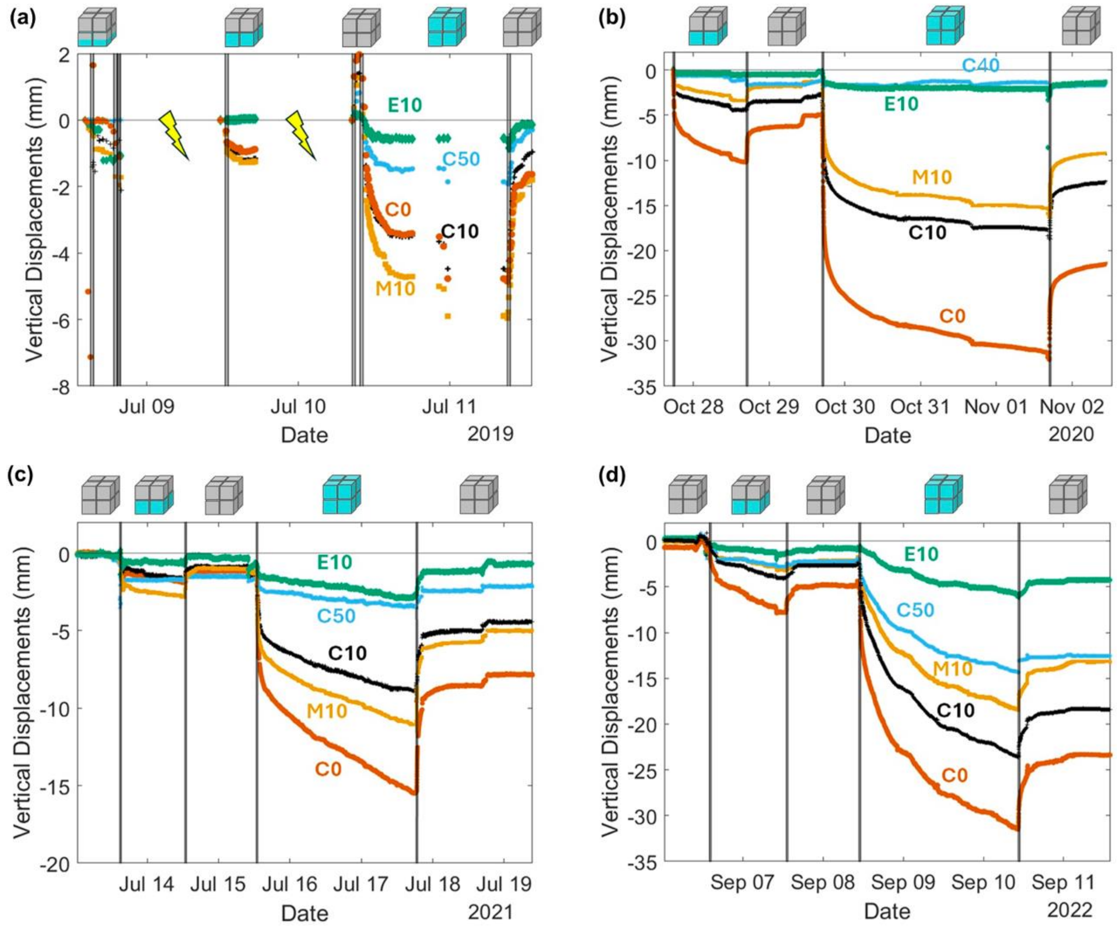
C. Zoccarato et al. In-situ loading experiments reveal how the subsurface affects coastal marsh survival. Commun Earth Environ 3, 264, 2022.

LOADING TESTS

MECHANICAL RESPONSE



Sketch of the loading with dimensions and location of the displacement transducers (micrometers)

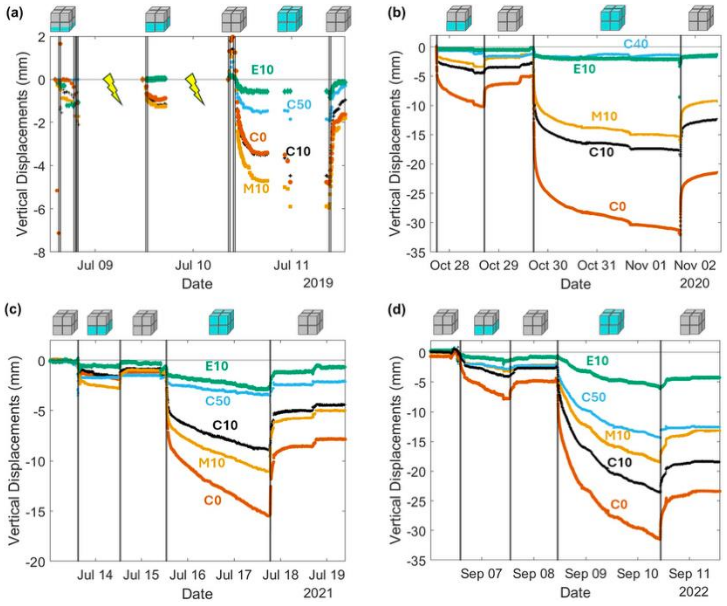


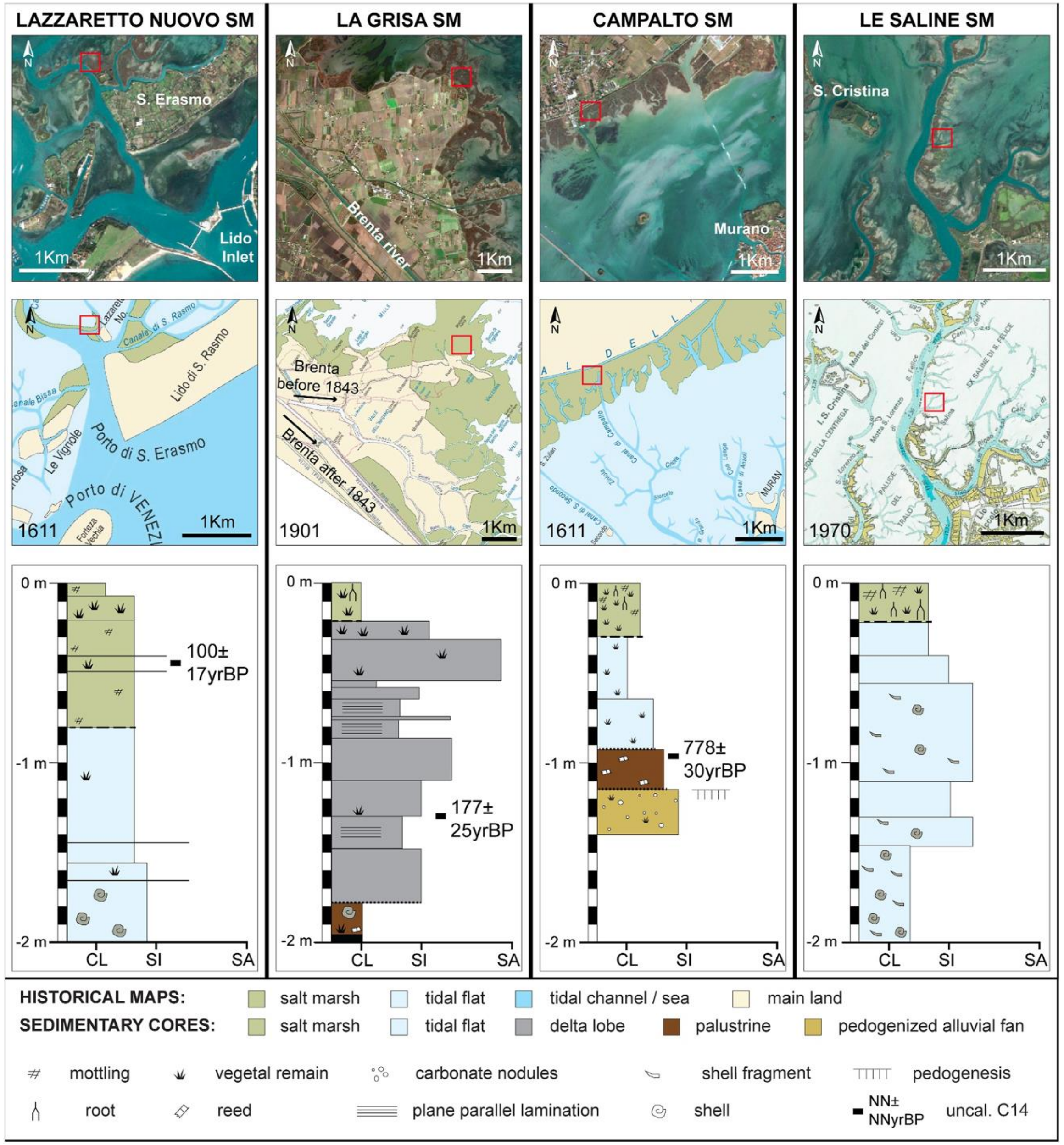
Vertical displacement registered by each sensor versus time measured during loading and unloading phases

C. Zoccarato et al. How Compressible Are Salt Marshes? Unique Field Experiments Combined With Advanced Modeling Provide Novel Insights From the Venice Lagoon. JGR Earth Surface, 130, e2025JF008539, 2025.

LOADING TESTS

MECHANICAL RESPONSE

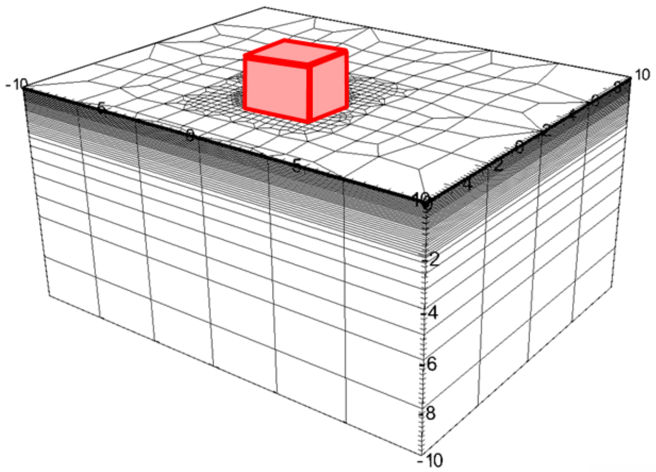




LOADING TESTS

MECHANICAL RESPONSE

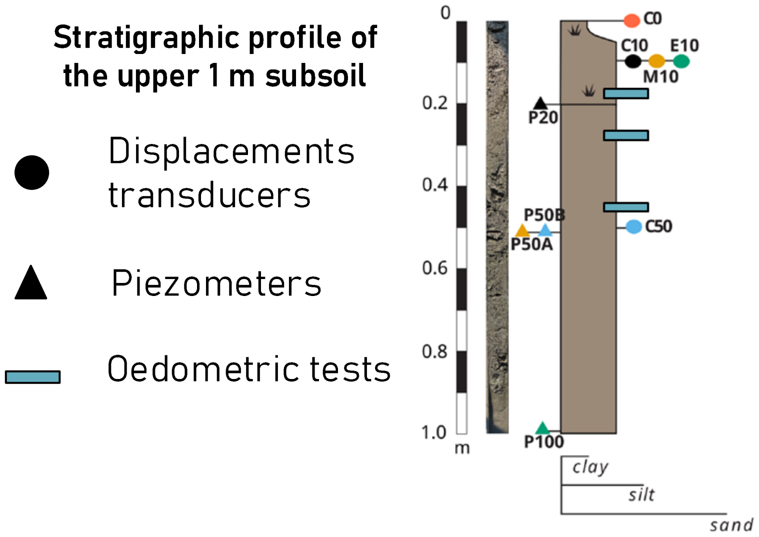
Horizontal view of the MFE mesh superposed to the Lazzaretto marsh



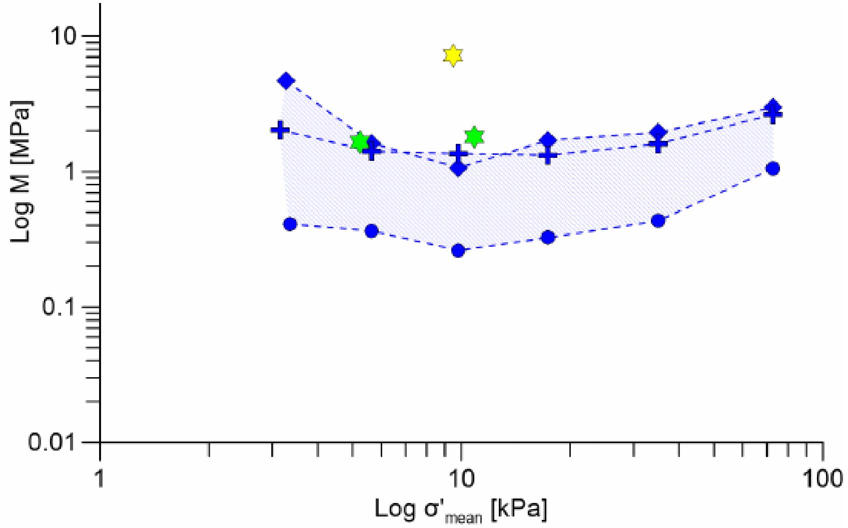
3D axonometric view of the MFE mesh with the load

Mechanical properties are derived by calibrating a coupled pressure-deformation model on the loading test response

Stratigraphic profile of the upper 1 m subsoil

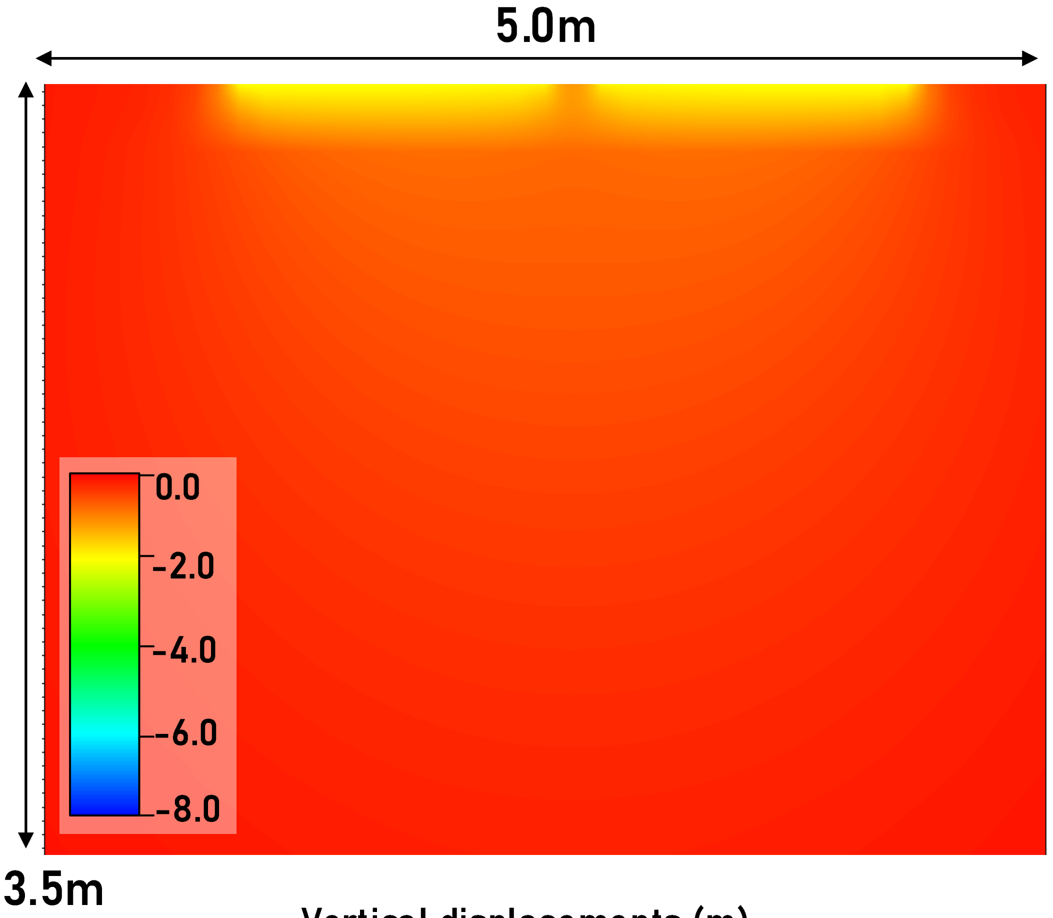


Lab oedometric modulus M

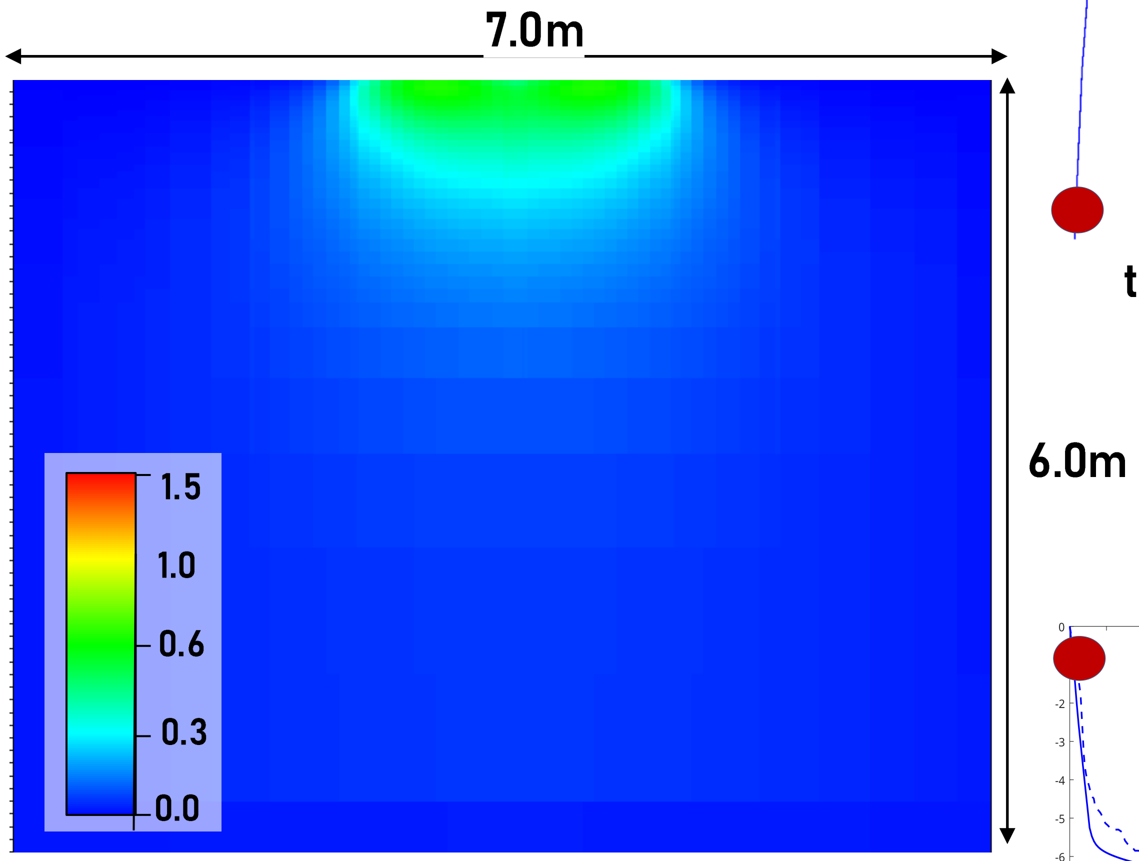


LOADING TESTS

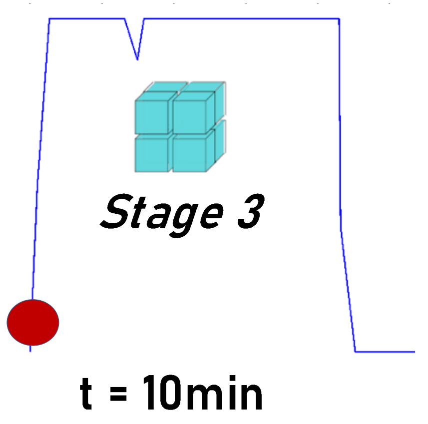
MECHANICAL RESPONSE

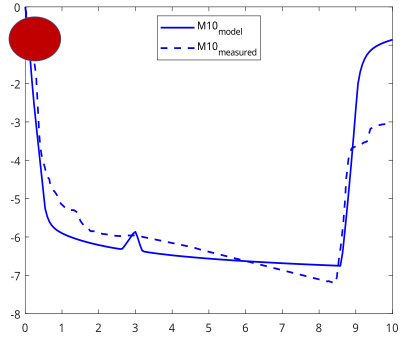


Vertical displacements (m)



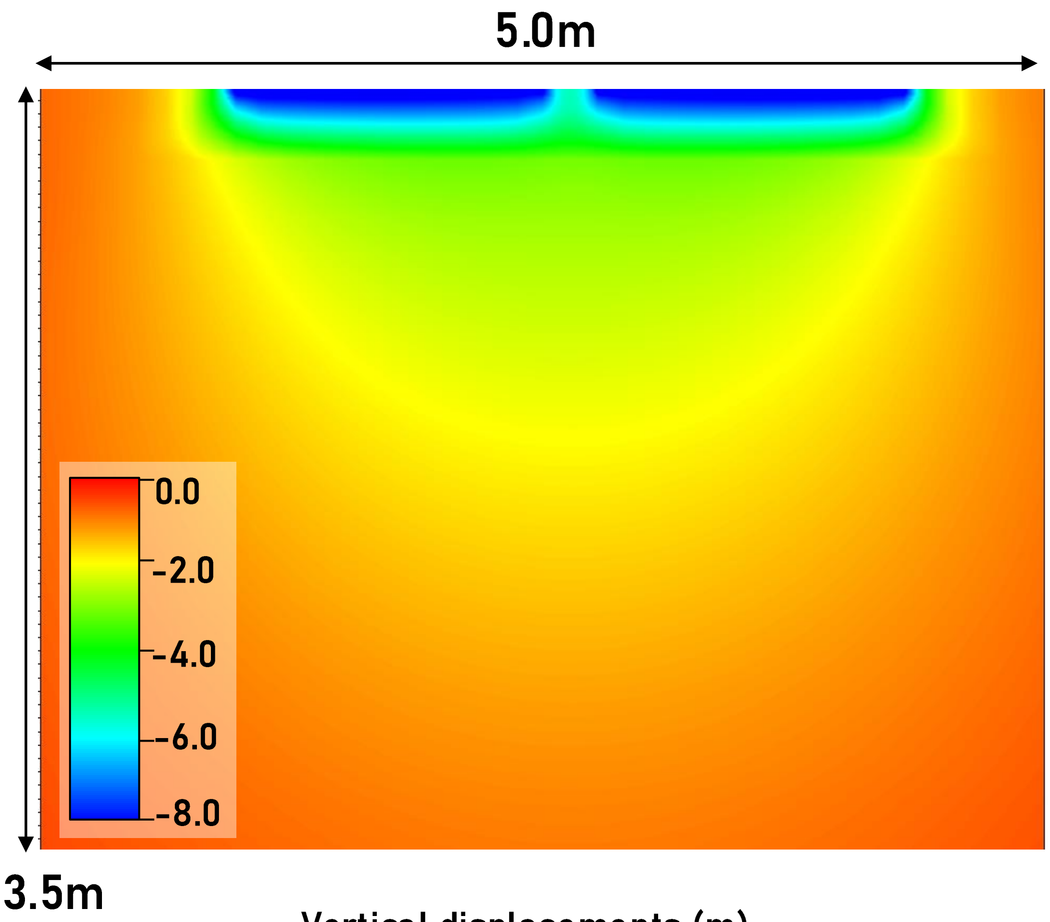
Pore overpressure (kPa)



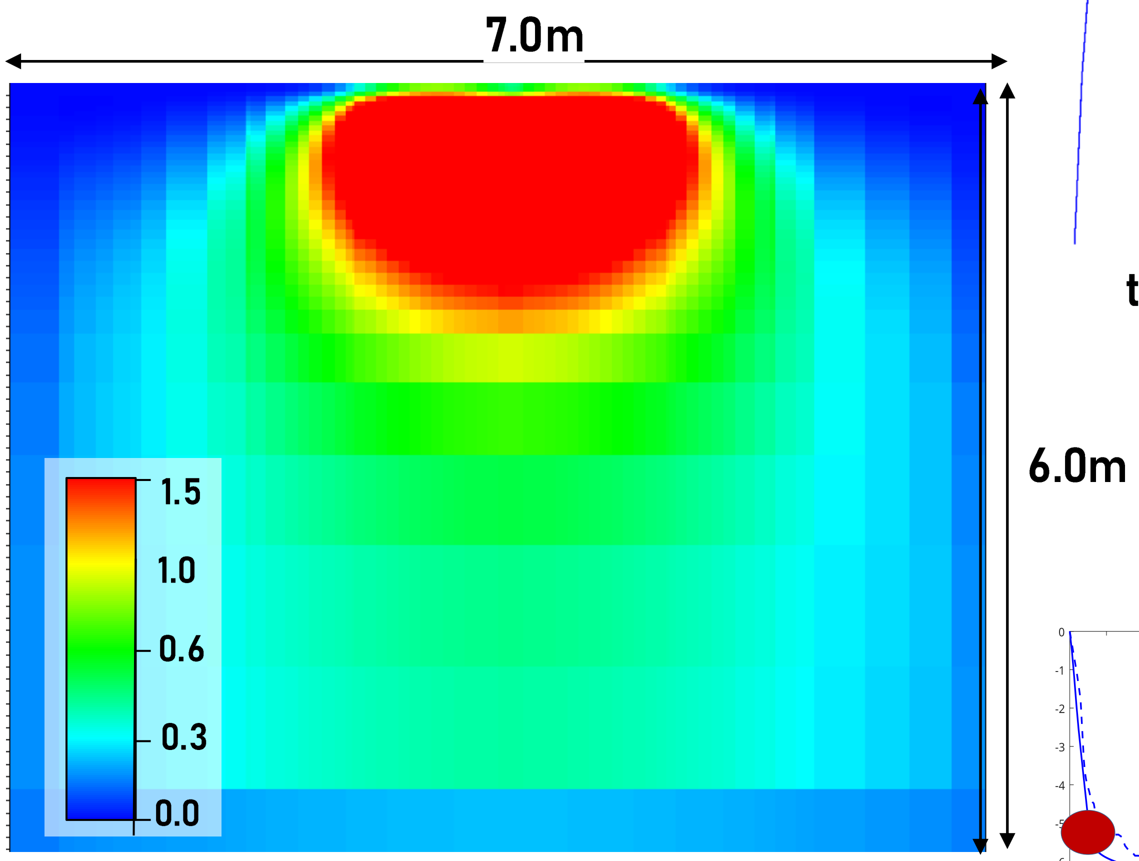


LOADING TESTS

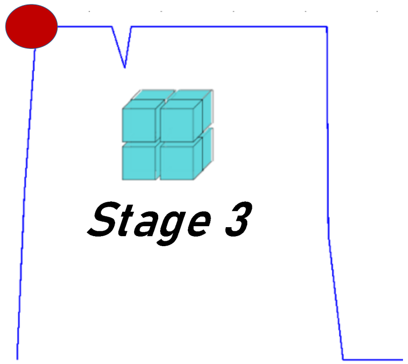
MECHANICAL RESPONSE



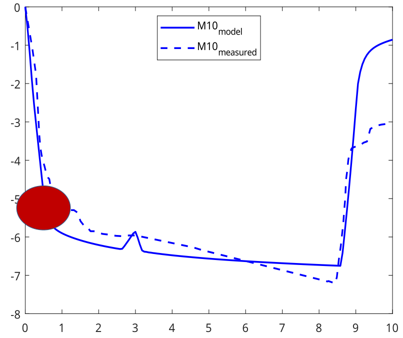
Vertical displacements (m)



Pore overpressure (kPa)

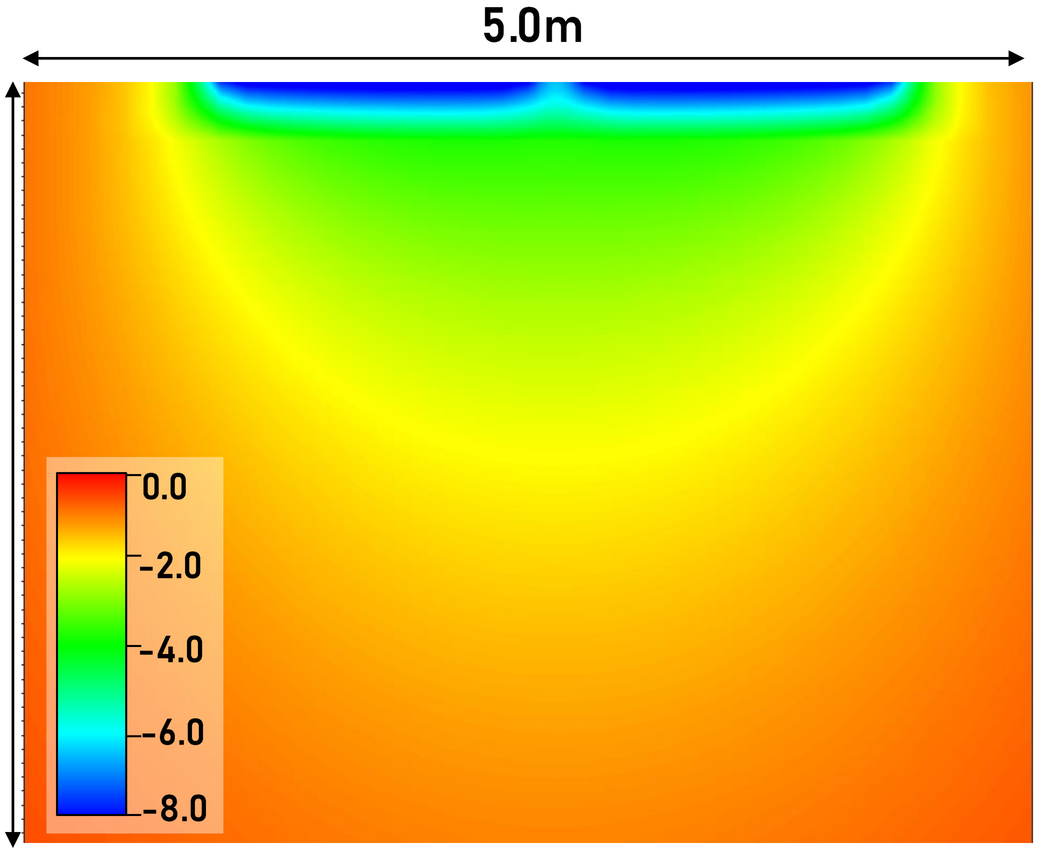


t = 1h 30min



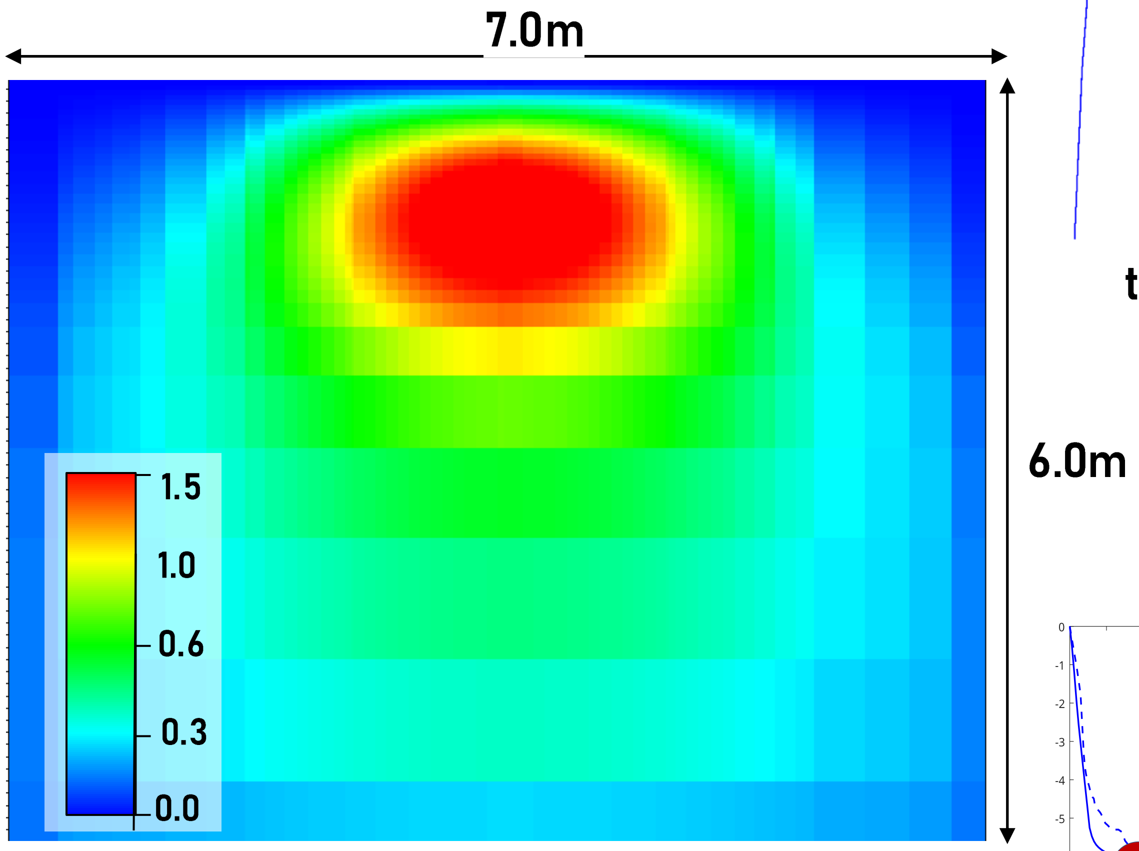
LOADING TESTS

MECHANICAL RESPONSE

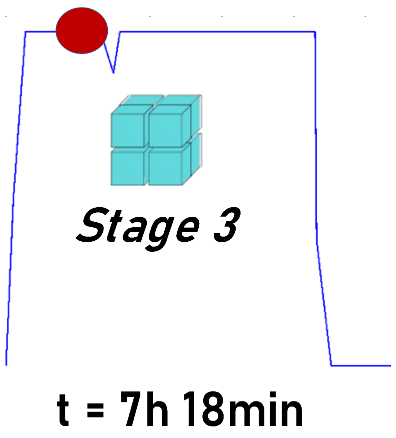


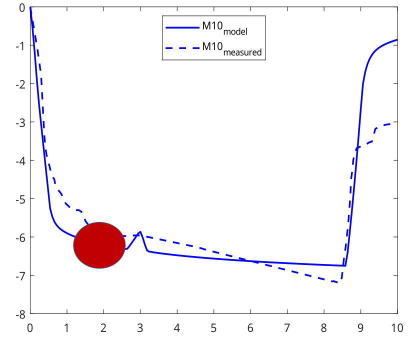
3.5m

Vertical displacements (m)



Pore overpressure (kPa)

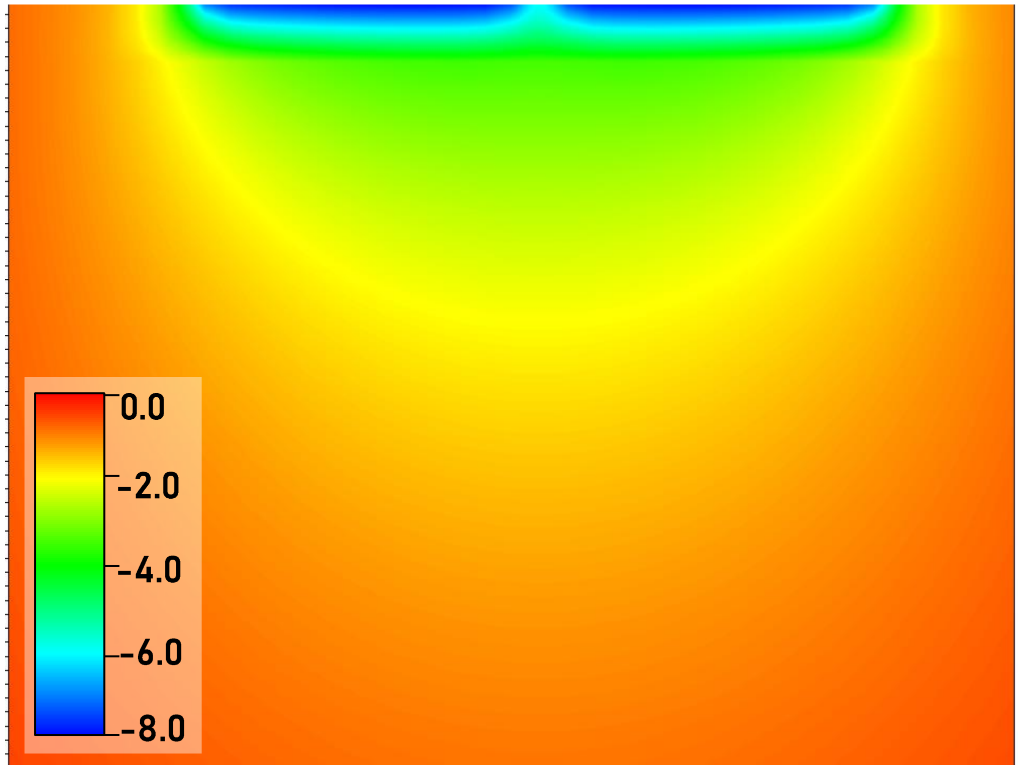




LOADING TESTS

MECHANICAL RESPONSE

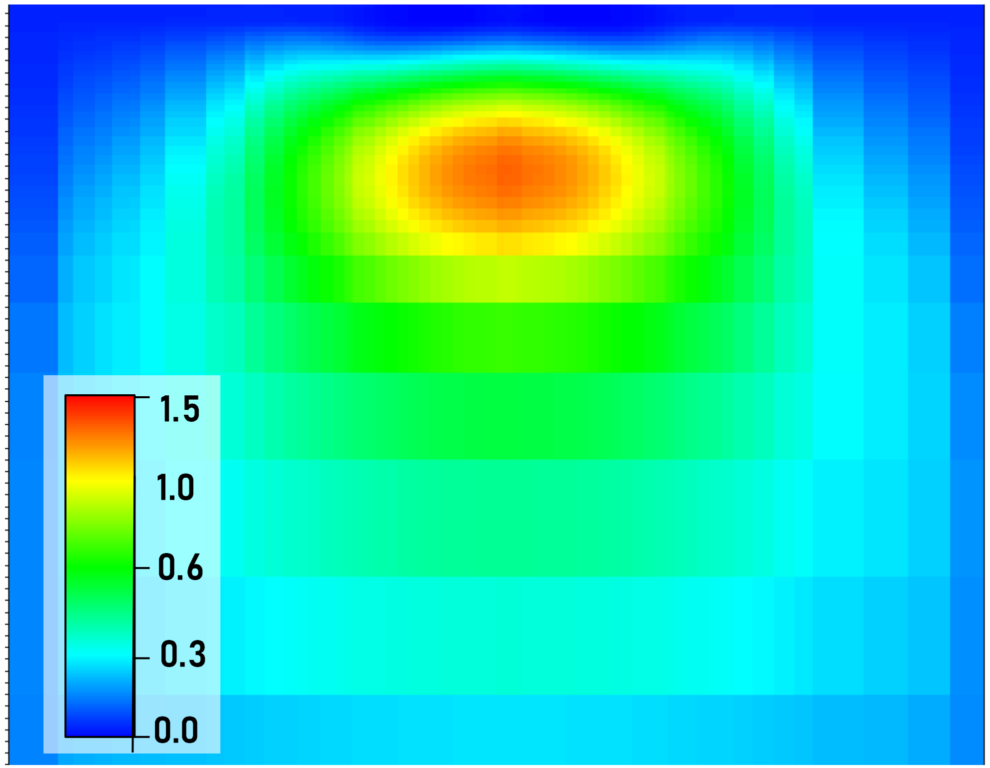
5.0m



3.5m

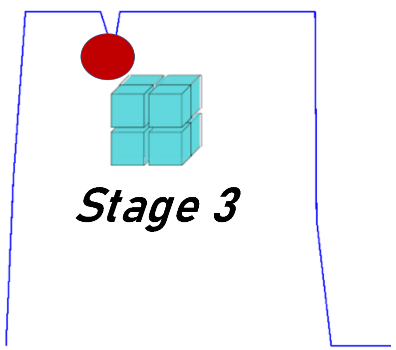
Vertical displacements (m)

7.0m

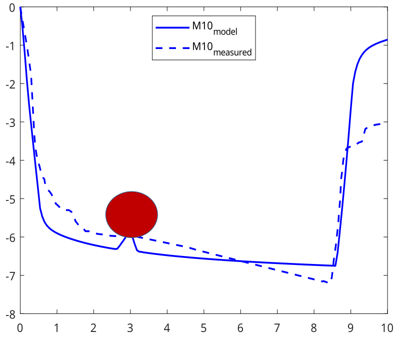


6.0m

Pore overpressure (kPa)

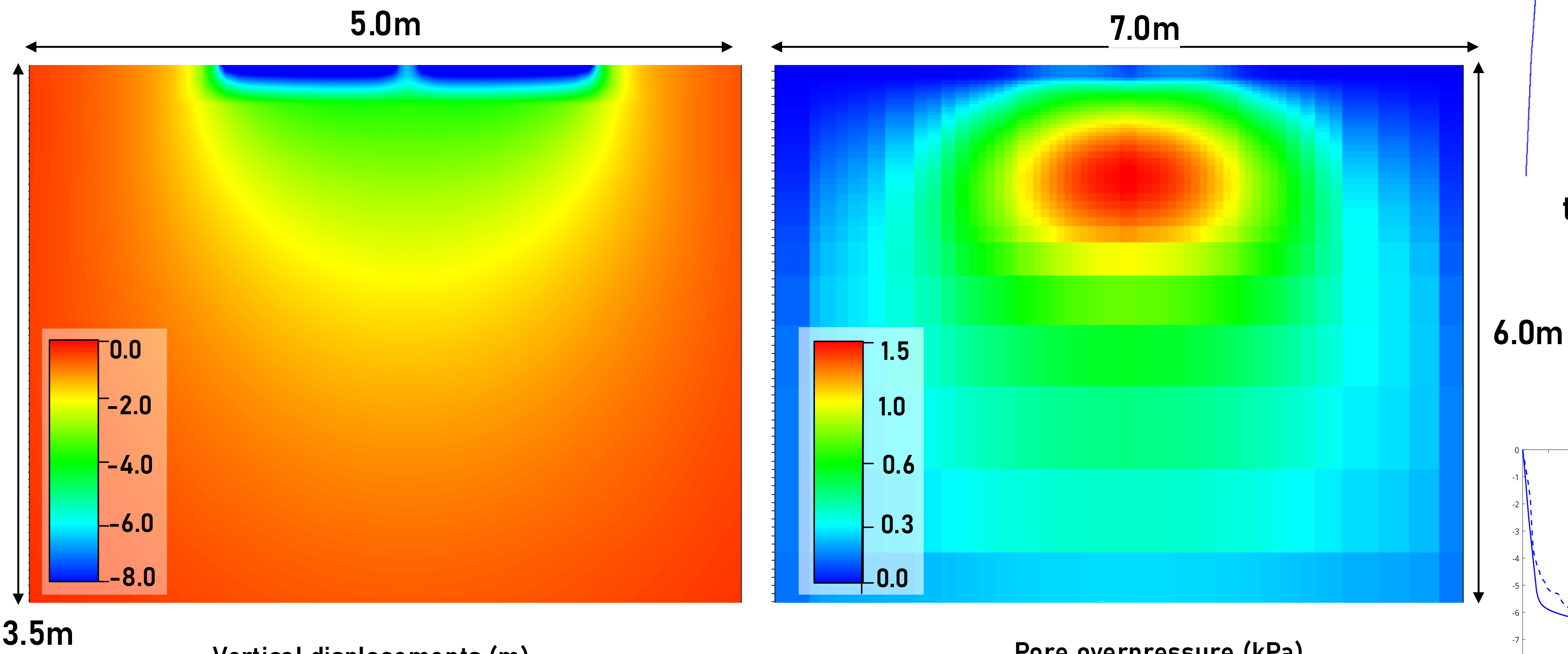


t = 8h 18min



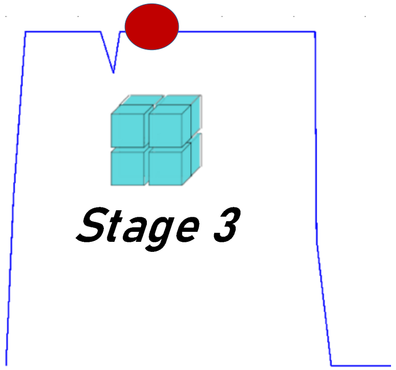
LOADING TESTS

MECHANICAL RESPONSE

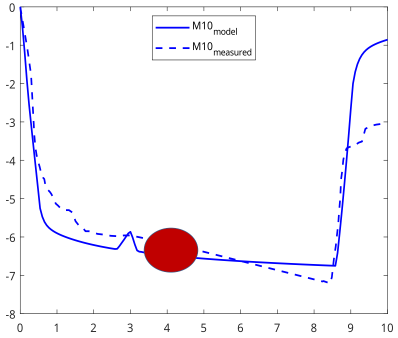


Vertical displacements (m)

Pore overpressure (kPa)

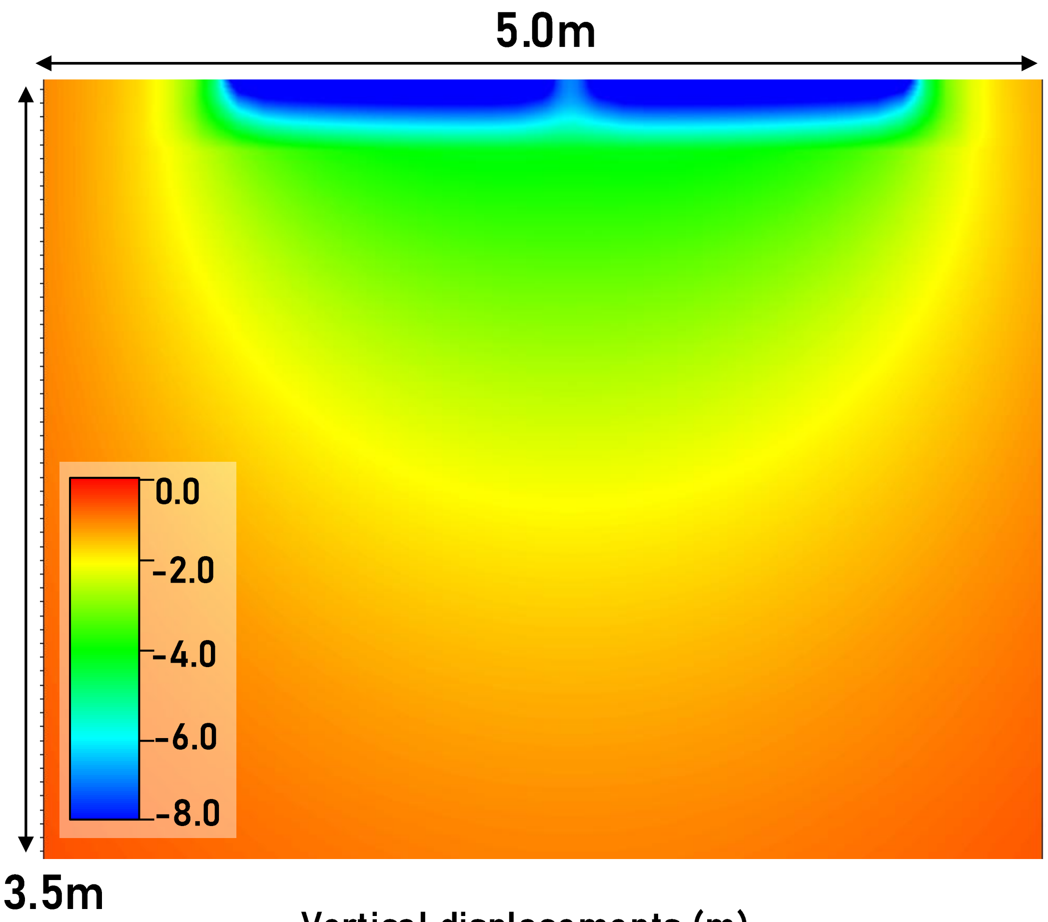


t = 8h 48min

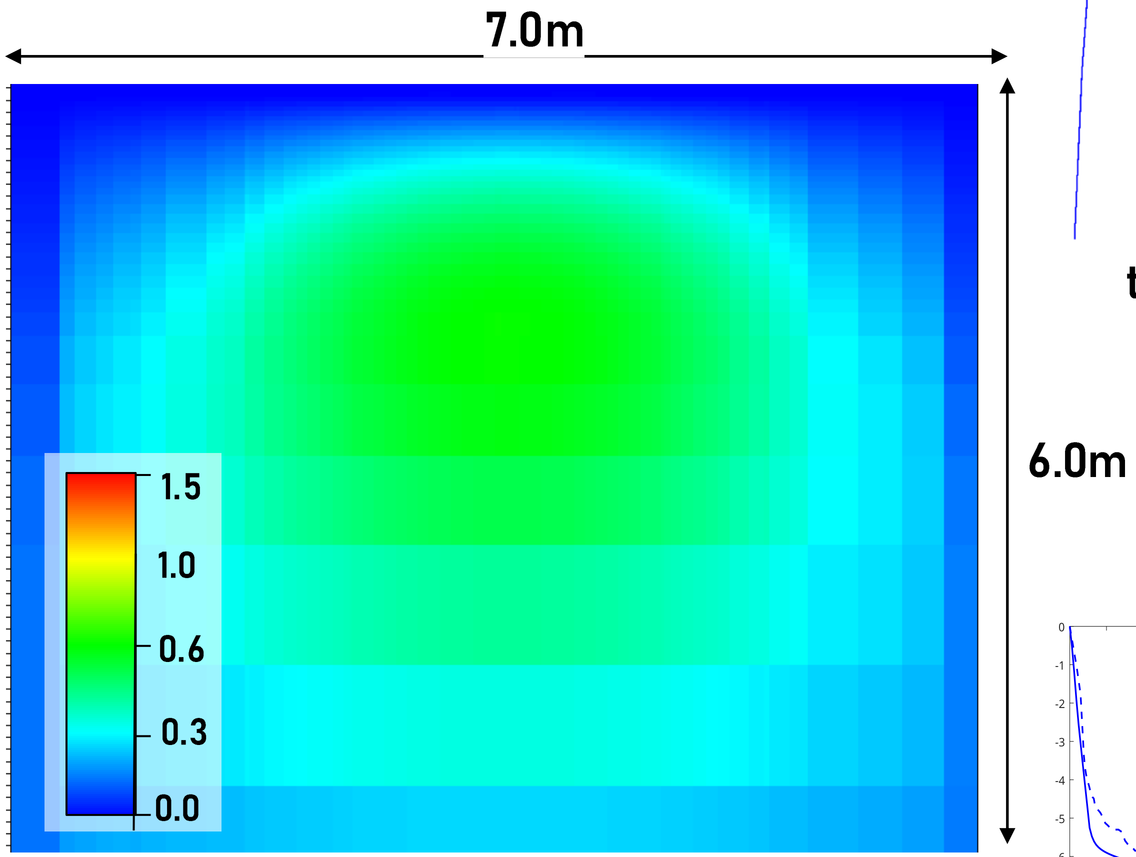


LOADING TESTS

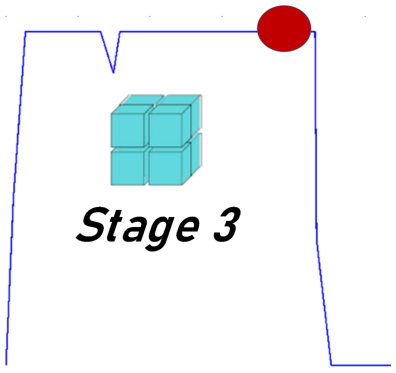
MECHANICAL RESPONSE



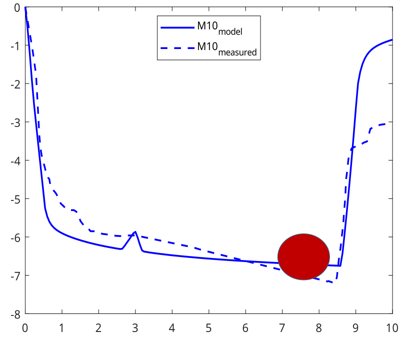
Vertical displacements (m)



Pore overpressure (kPa)

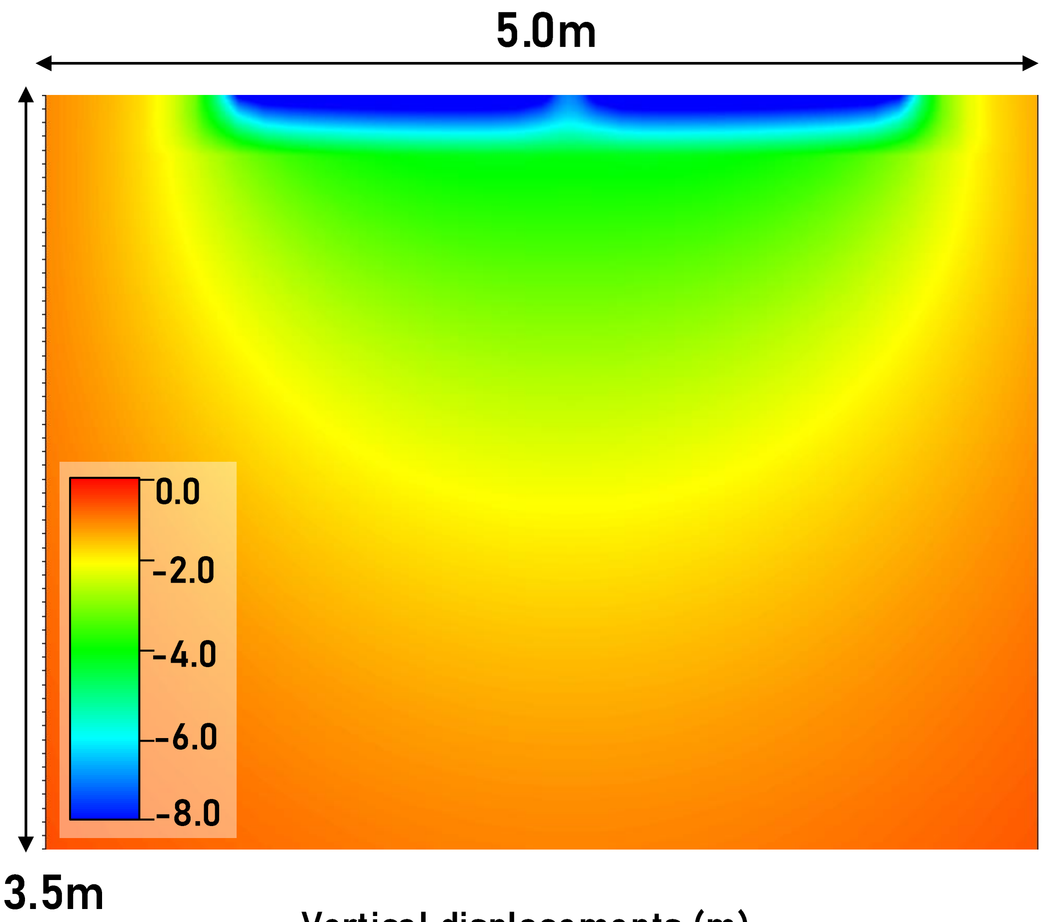


t = 23h 42min

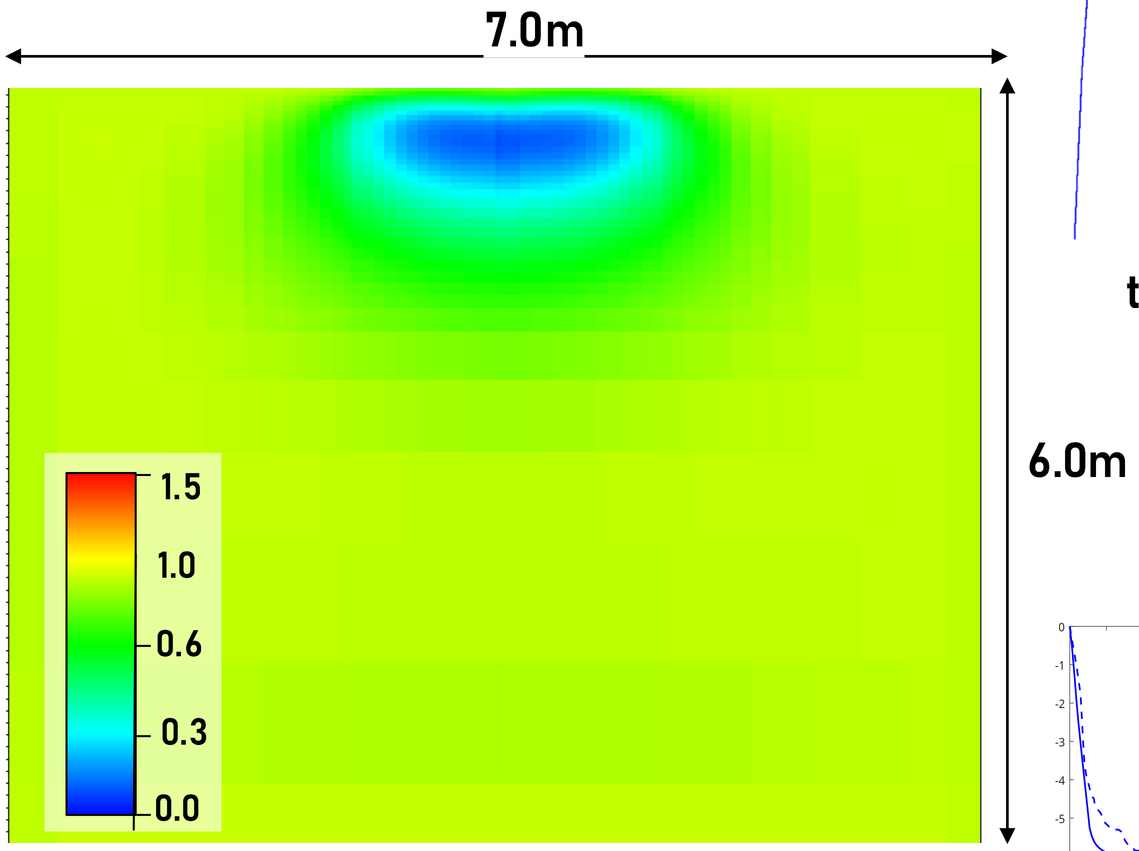


LOADING TESTS

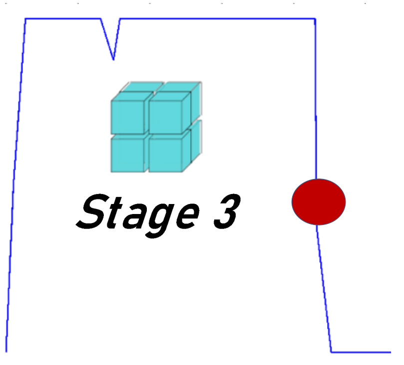
MECHANICAL RESPONSE



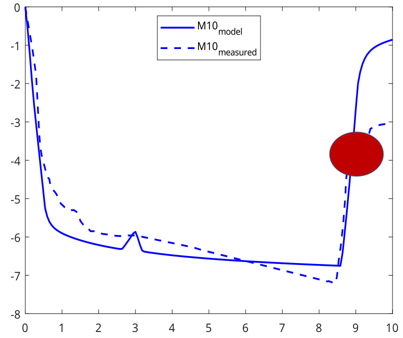
Vertical displacements (m)



Pore overpressure (kPa)



t = 24h



LOADING TESTS

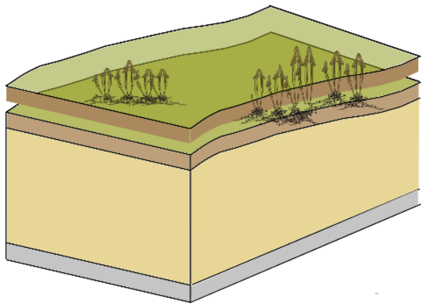
MECHANICAL RESPONSE

Table 3
Summary of the Hydro-Geomechanical Parameters, Hydraulic Conductivity (k), Soil Stiffness (Young Modulus E), Unloading (or Reloading) to Virgin Loading Stiffness (s) and Initial Preconsolidation Stress ($\sigma_{p,0}$) at the Four Experimental Sites as Obtained From the Modelling Interpretation of the In Situ Loading Tests

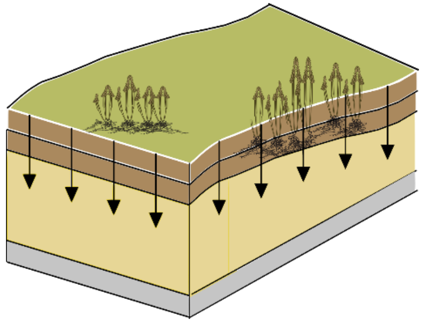
Site	Marshland Feature	Depth range (m)	k (m/s)	E (MPa)	s (–)	$\sigma_{p,0}$ (kPa)
Lazzaretto Nuovo	Bounding Major Tidal Channels	0.0–0.3	$5 \cdot 10^{-6}$	0.1–0.3	3.0	4.0
		0.3–2.0	$5 \cdot 10^{-6}$	2.0–4.0	3.0	4.0
		2.0–10.0	10^{-7}	10.0–20.0	–	4.0
La Grisa	Over Deltaic Deposits	0.0–0.3	$2.5 \cdot 10^{-4}$	0.04–0.3	3.0	4.0
		0.3–2.0	$10^{-4} - 10^{-6}$	3.0–8.0	2.0	4.0
		2.0–10.0	10^{-7}	10.0–20.0	–	4.0
Campalto	Over Shallow Pleistocene Plain	0.0–0.3	10^{-6}	0.1–0.6	2.6	8.0
		0.3–2.0	$7 \cdot 10^{-5}$	4.0	1.7	8.0
		2.00–10.0	10^{-7}	10.0–20.0	–	8.0
Le Saline	Recently Developed	0.0–0.3	$9 \cdot 10^{-5}$	0.06–0.8	3.6	2.0
		0.3–2.0	10^{-6}	2.0	2.6	2.0
		2.0–10.0	10^{-7}	10.0–20.0	–	2.0

C. Zoccarato et al. How Compressible Are Salt Marshes? Unique Field Experiments Combined With Advanced Modeling Provide Novel Insights From the Venice Lagoon. JGR Earth Surface, 130, e2025JF008539, 2025.

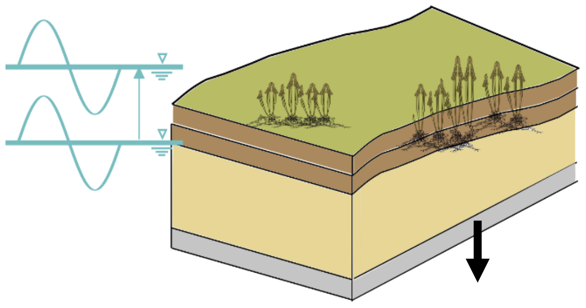
LONG-TERM EVOLUTION OF COASTAL ECOSYSTEMS



Sedimentation (inorganic/organic) or sediment infilling

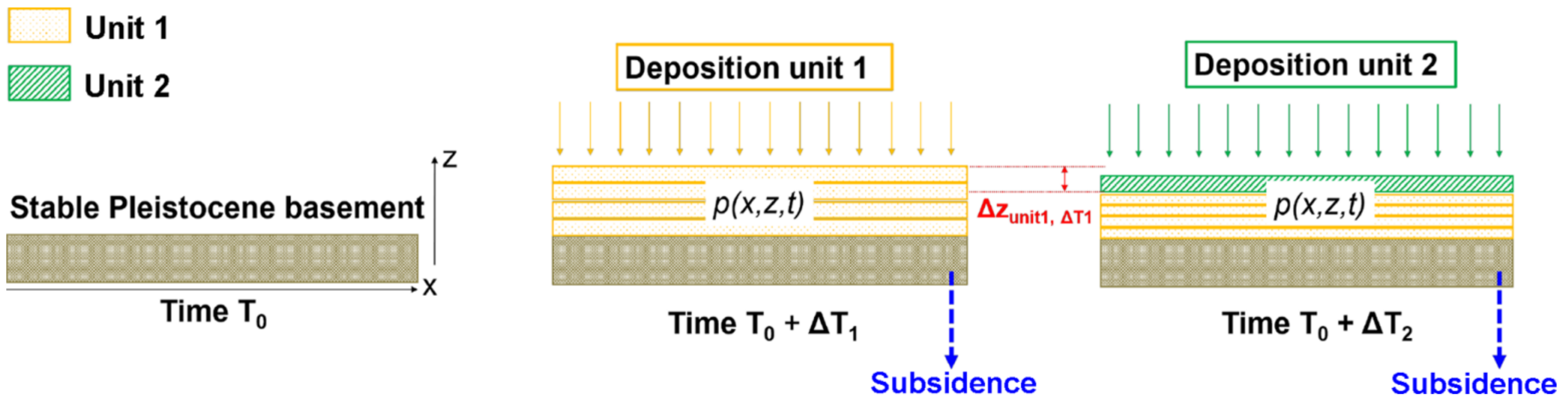


Auto-compaction: reduction of thickness due to consolidation

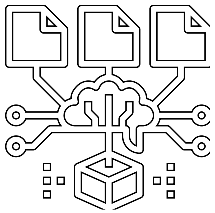


Relative sea-level rise (sea-level rise, auto-compaction, deep subsidence)

Depositional and consolidation mechanisms



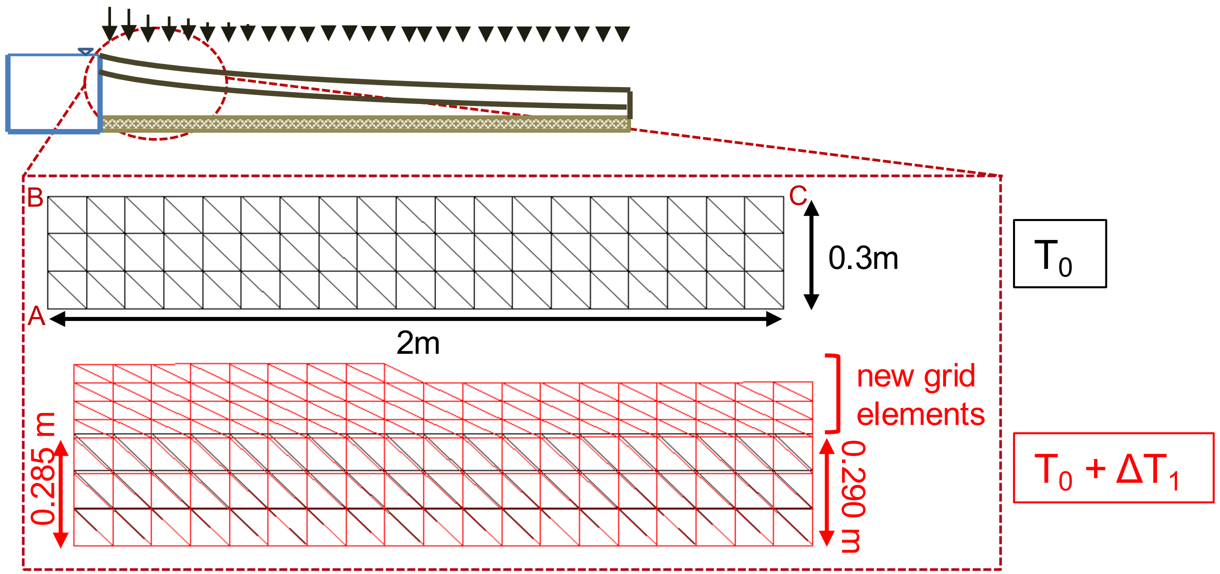
LONG-TERM EVOLUTION OF COASTAL ECOSYSTEMS



NATSUB2D development

$$\nabla \cdot \left(\frac{K}{\gamma}\nabla p\right) = \left(c_b(\sigma_z) + \phi\beta\right) Dp - c_b(\sigma_z)(1-\phi_0)(\gamma_s - \gamma)\,\omega\, dt$$

$$u(z,t) = -\int_0^z \frac{\alpha(\sigma_z)\sigma_z}{1-\alpha(\sigma_z)\sigma_z}\,dz$$



2D groundwater flow simulator coupled to a 1D vertical geomechanical module based on Terzaghi's principle (we solve for pressure and displacements)

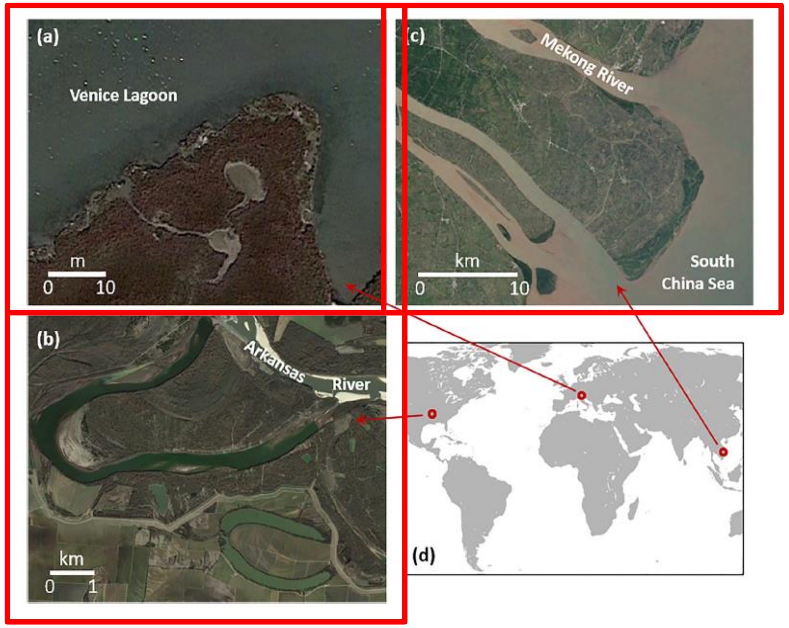
Evolving domain with new elements for sedimentation and deforming elements for compaction

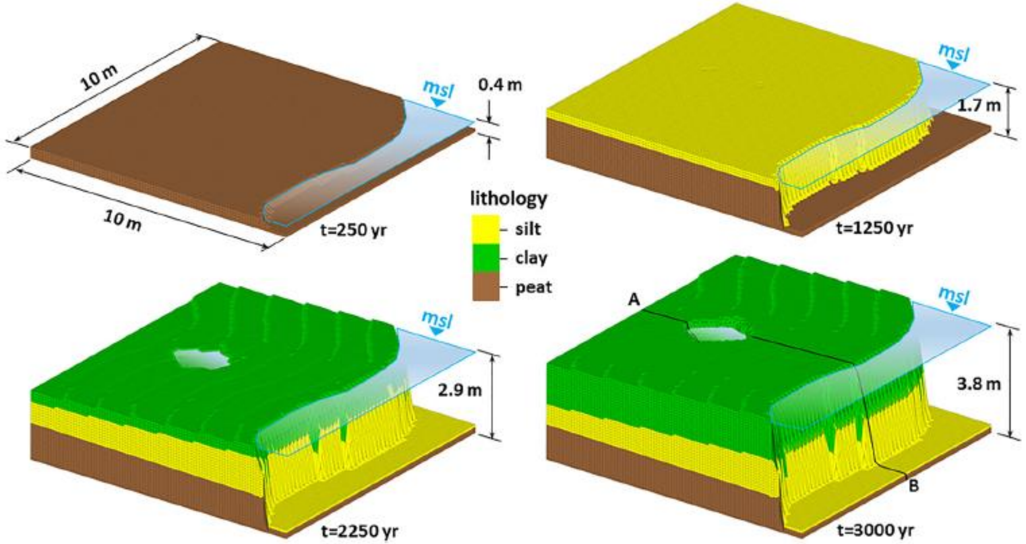
Finite Element discretization with a deforming/accreting mesh (Lagrangian approach for large deformations)

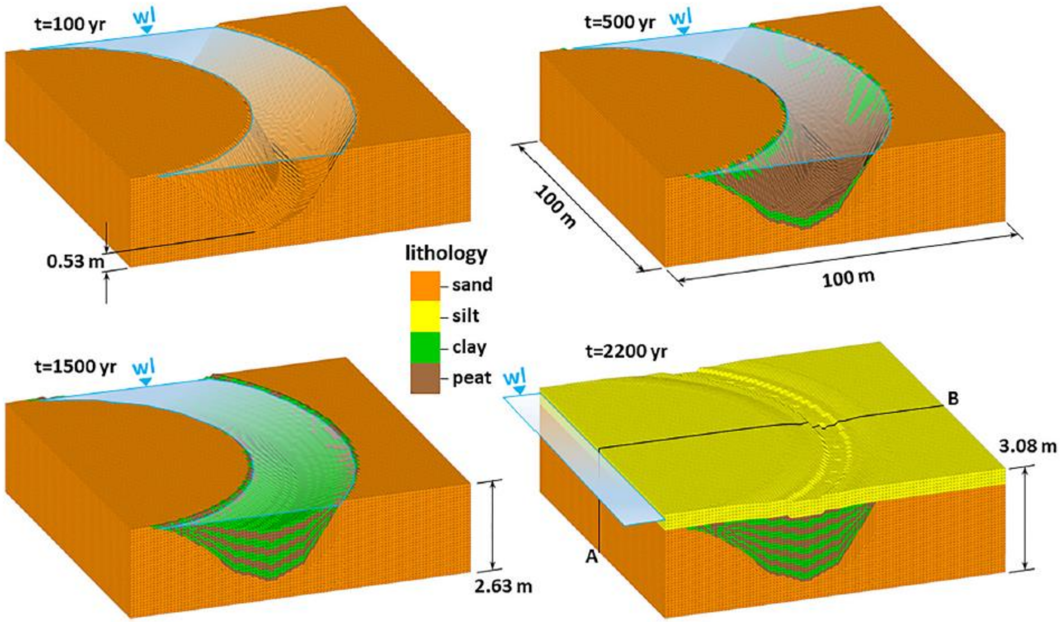
Soil properties (hydraulic conductivity, porosity, compressibility, bulk density) depend on the effective stress

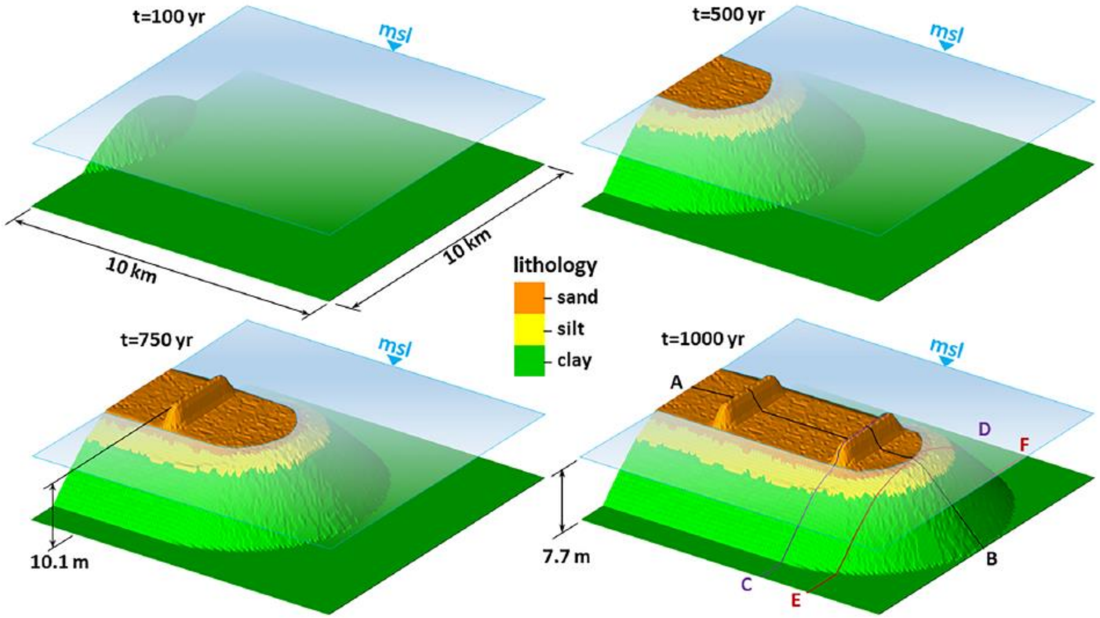
C. Zoccarato, P. Teatini. Numerical simulations of Holocene salt-marsh dynamics under the hypothesis of large soil deformations, Advances in Water Resources, 110 (2017), 107-119.

LONG-TERM EVOLUTION OF COASTAL ECOSYSTEMS

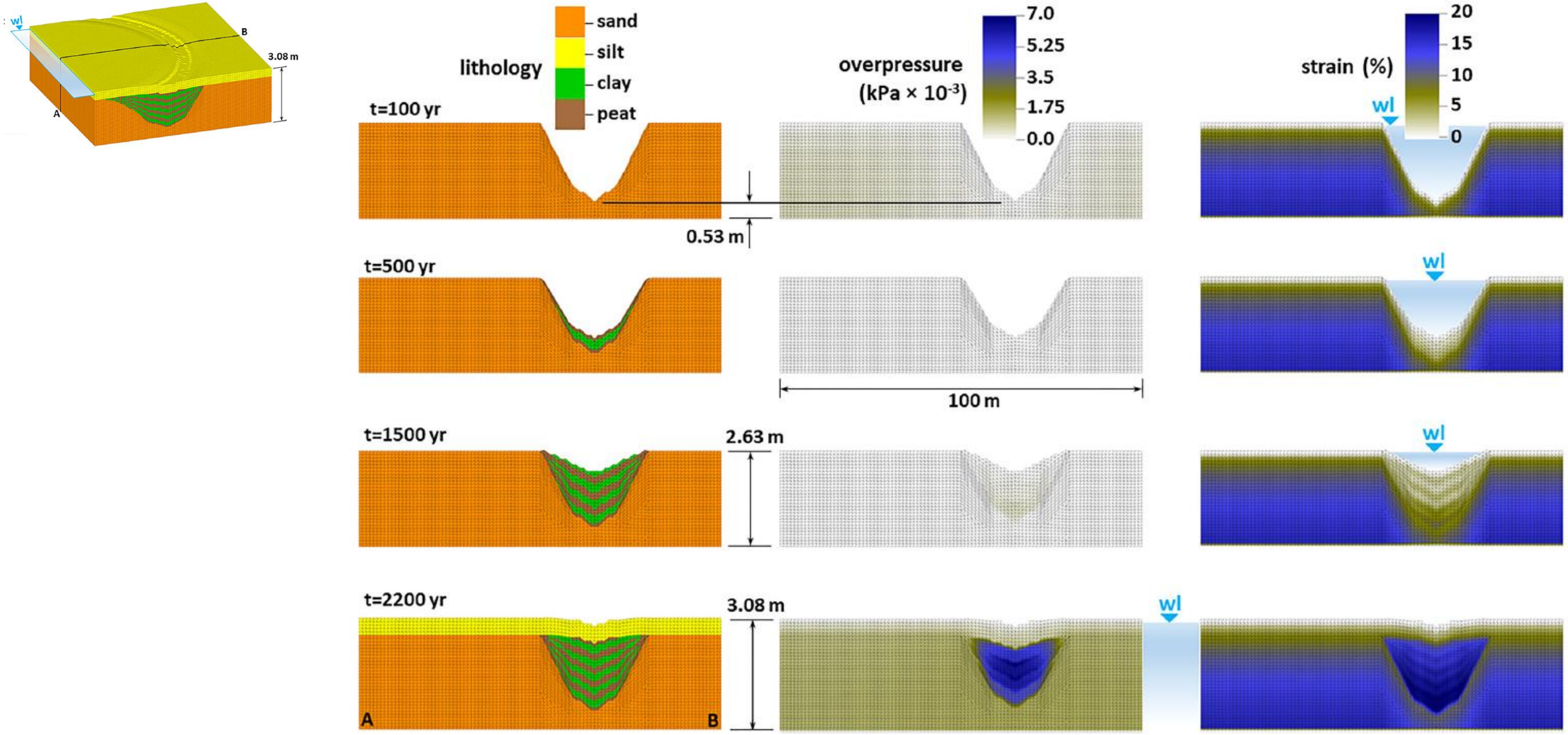






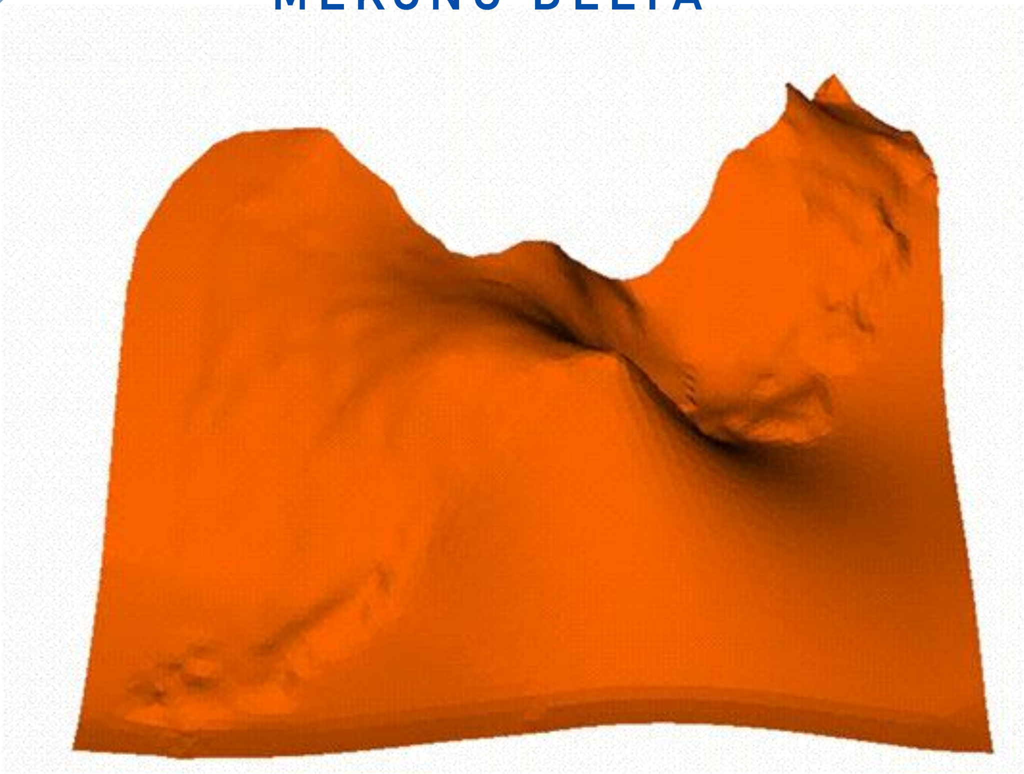


LONG-TERM EVOLUTION OF COASTAL ECOSYSTEMS



LONG-TERM EVOLUTION OF COASTAL ECOSYSTEMS

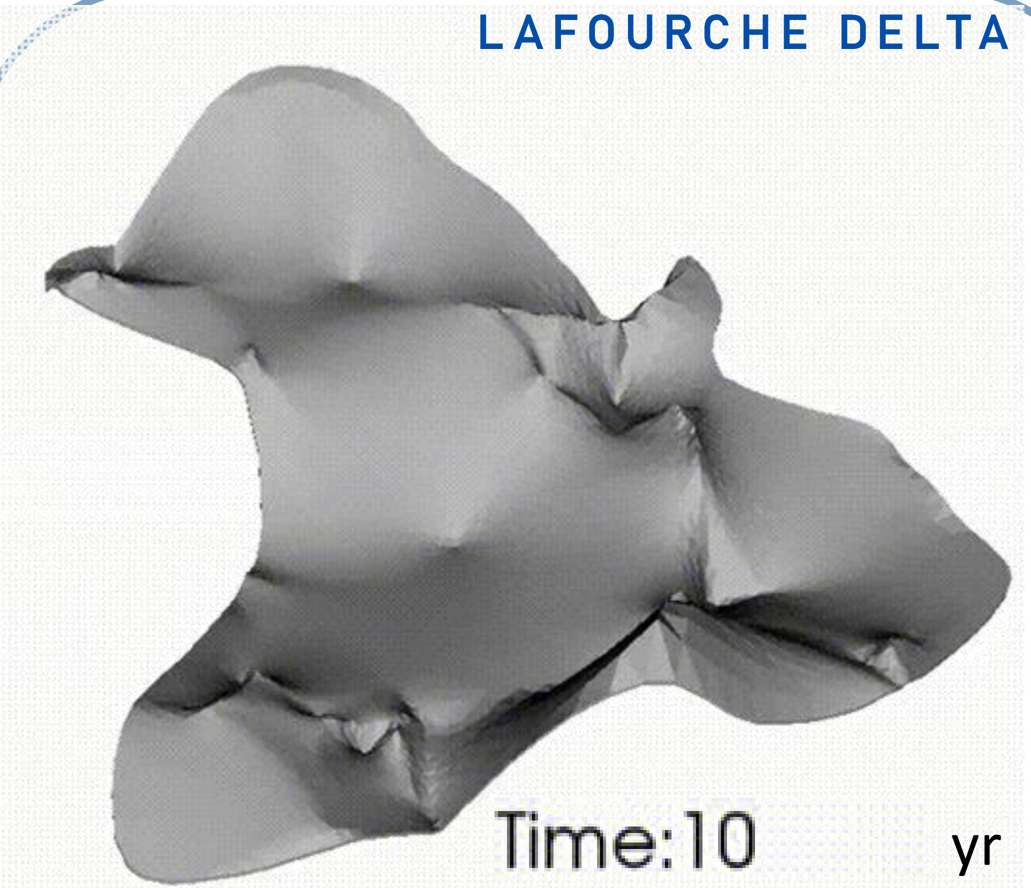
MEKONG DELTA



On average:
Z_{DEM} = 0.80 m a.s.l
Z_{MODEL} = 0.30 m

Mean error over 20m thickness:
ε = 2.5 %

LAFOURCHE DELTA



On average:
Z_{DEM} = 0.07 m a.s.l.
Z_{MODEL} = 0.30 m

Mean error over 50m thickness:
ε = 1 %

ARTIFICIAL SALT MARSHES

(a)

Le Sorelle A salt marsh

(b)

Lago della Pietra salt marsh

Long-term elevation ?

Past marsh reconstruction projects have not always been successful:

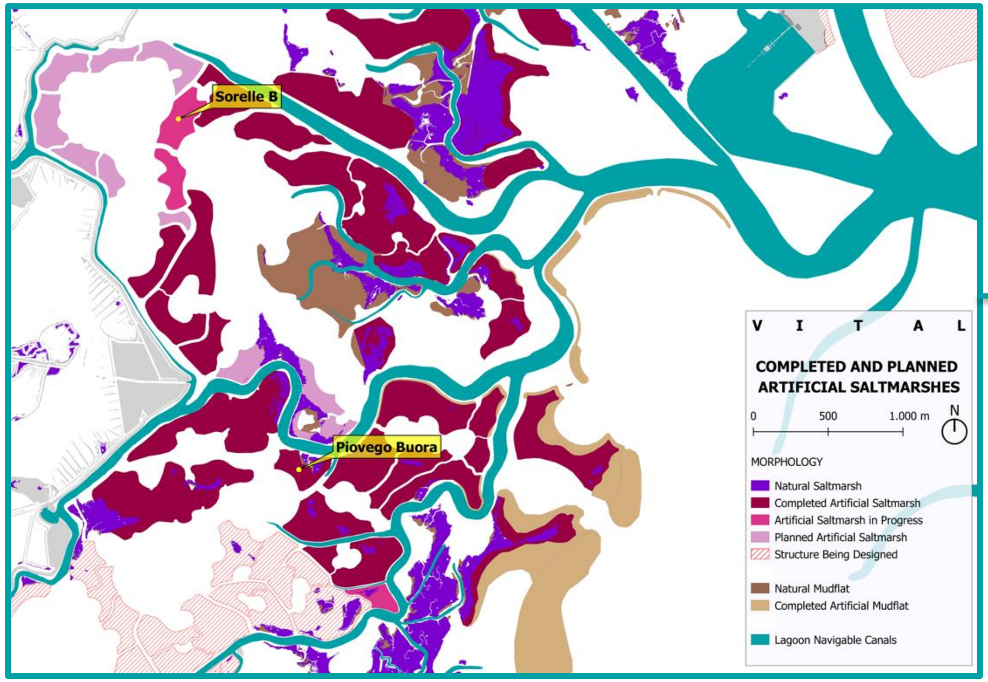
(a) significant areas become permanently submerged only a few years after their construction

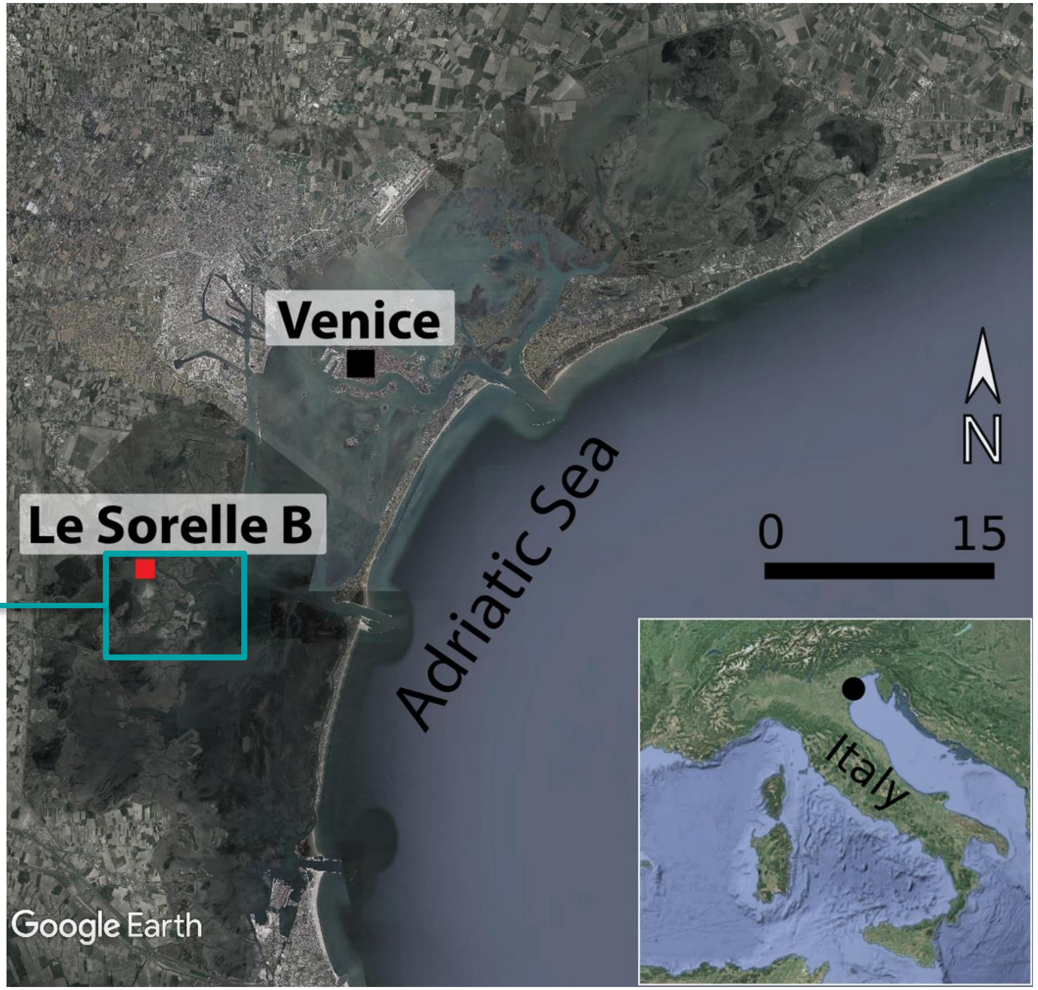
(b) vegetation cover remains more patchy and less biodiverse than on natural marshes

ARTIFICIAL SALT MARSHES

GOAL Investigate the role of subsidence and auto-compaction in salt marsh restoration projects

Many restoration projects have been implemented in the Lagoon of Venice (Italy) to reestablish former tidal marshlands





ARTIFICIAL SALT MARSHES

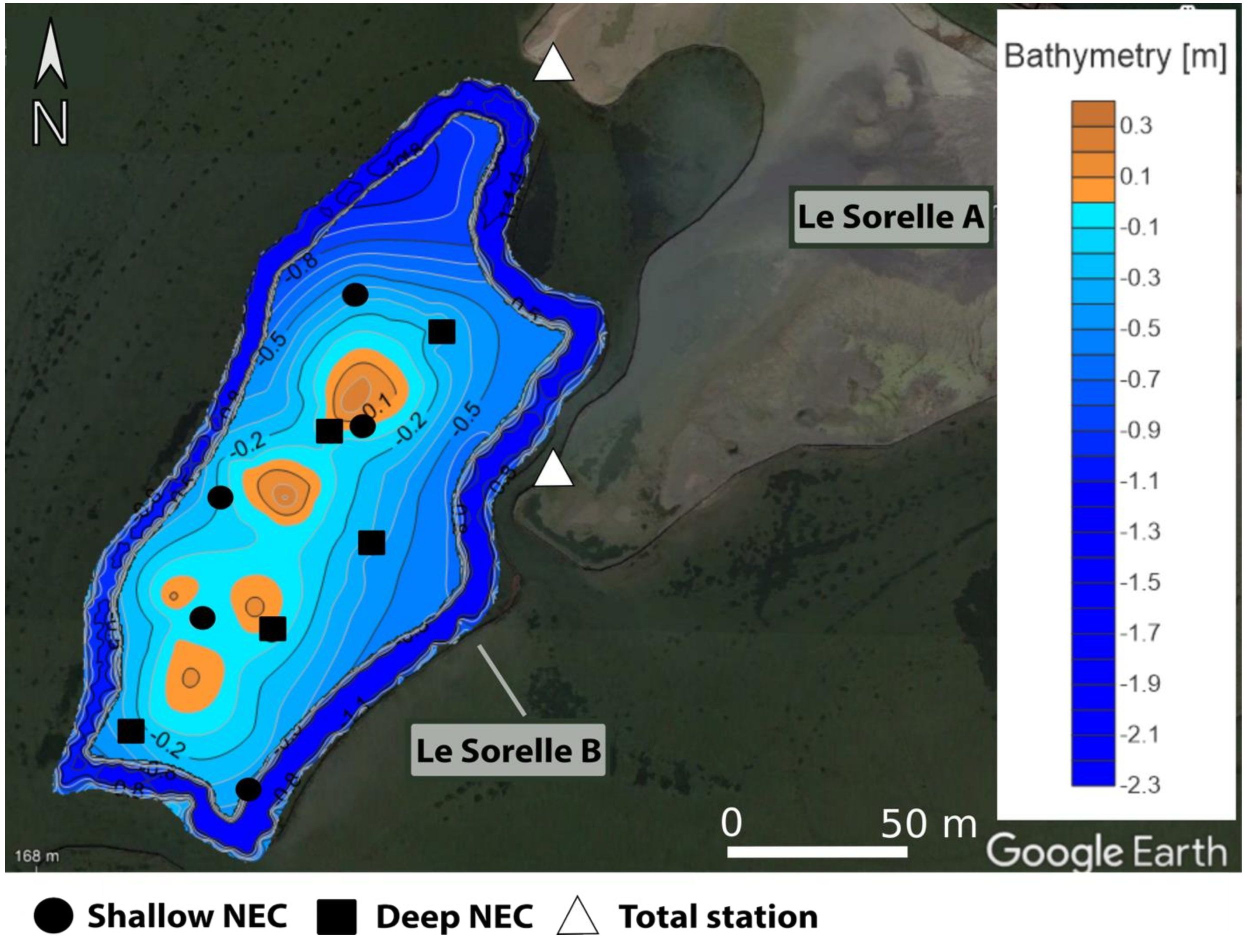
LE 'SORELLE B'

Sediment retention structure build during summer 2021

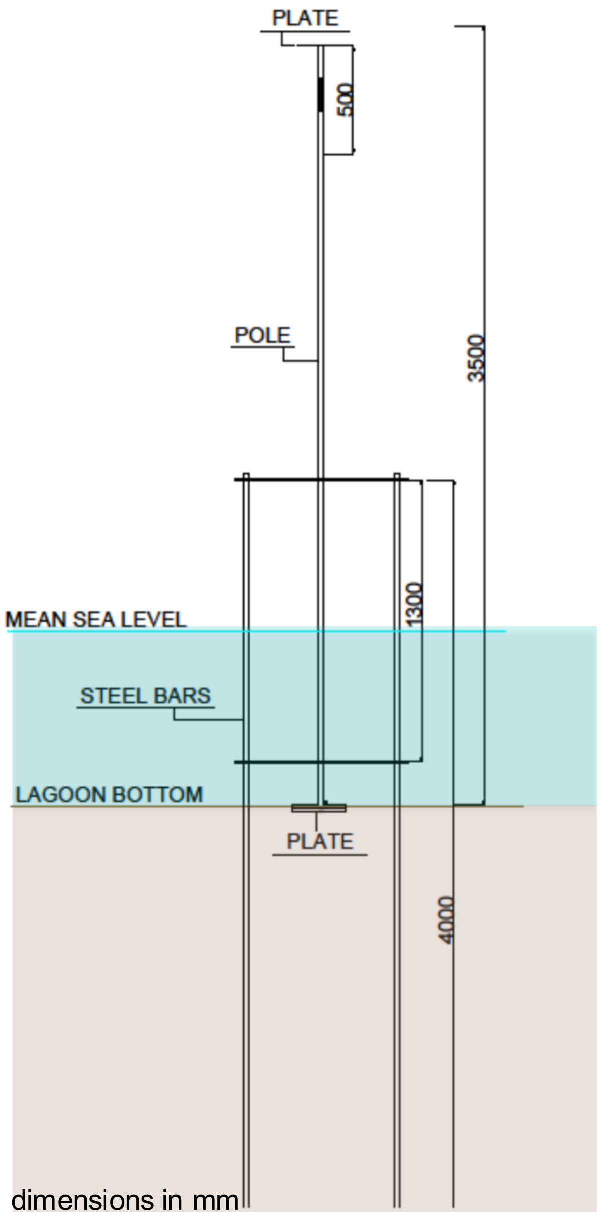
Fall 2021: 1st sediment infilling started
Fall 2022: 2nd sediment infilling started

ARTIFICIAL SALT MARSHES

NEC STATIONS – SEPTEMBER 2021



ARTIFICIAL SALT MARSHES

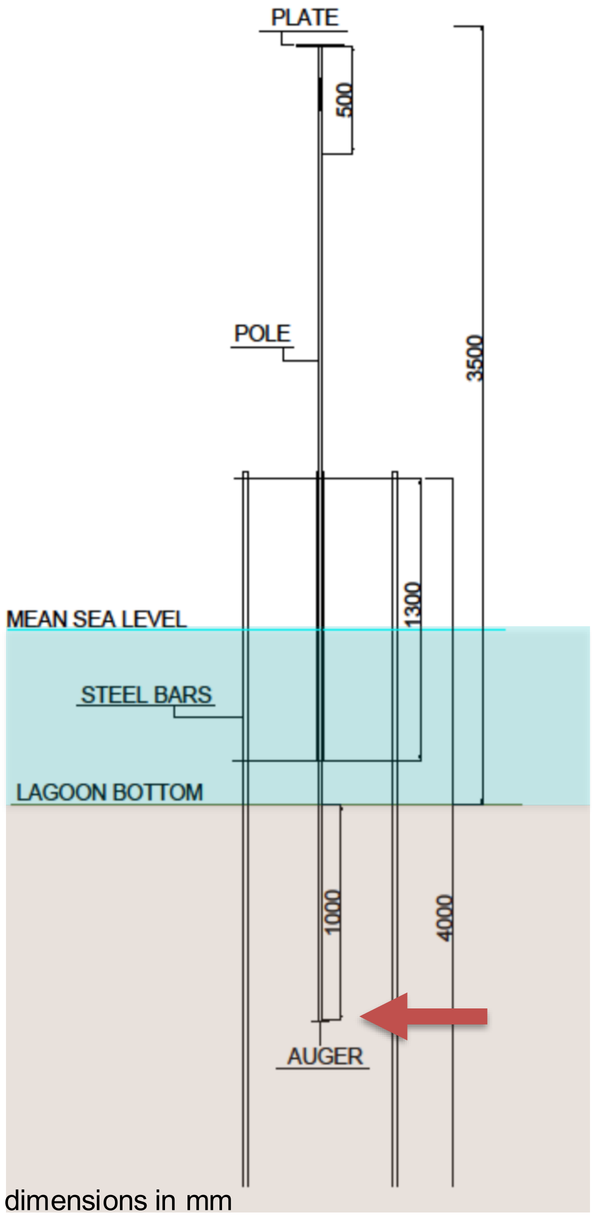


- Four steel bars set into the lagoon subsurface down to a 2-m depth to keep a central steel pole free to move vertically with respect to its specific foundation level.
- The foundation consists of a plate resting on the top of the pristine lagoon bottom

We measure the elevation change from Le Sorelle A by looking to the black-and-white strips on the top of the NEC with a mm-accuracy topographic intersection technique using a total station.

Reference points are monitored using the GNSS technique.

ARTIFICIAL SALT MARSHES

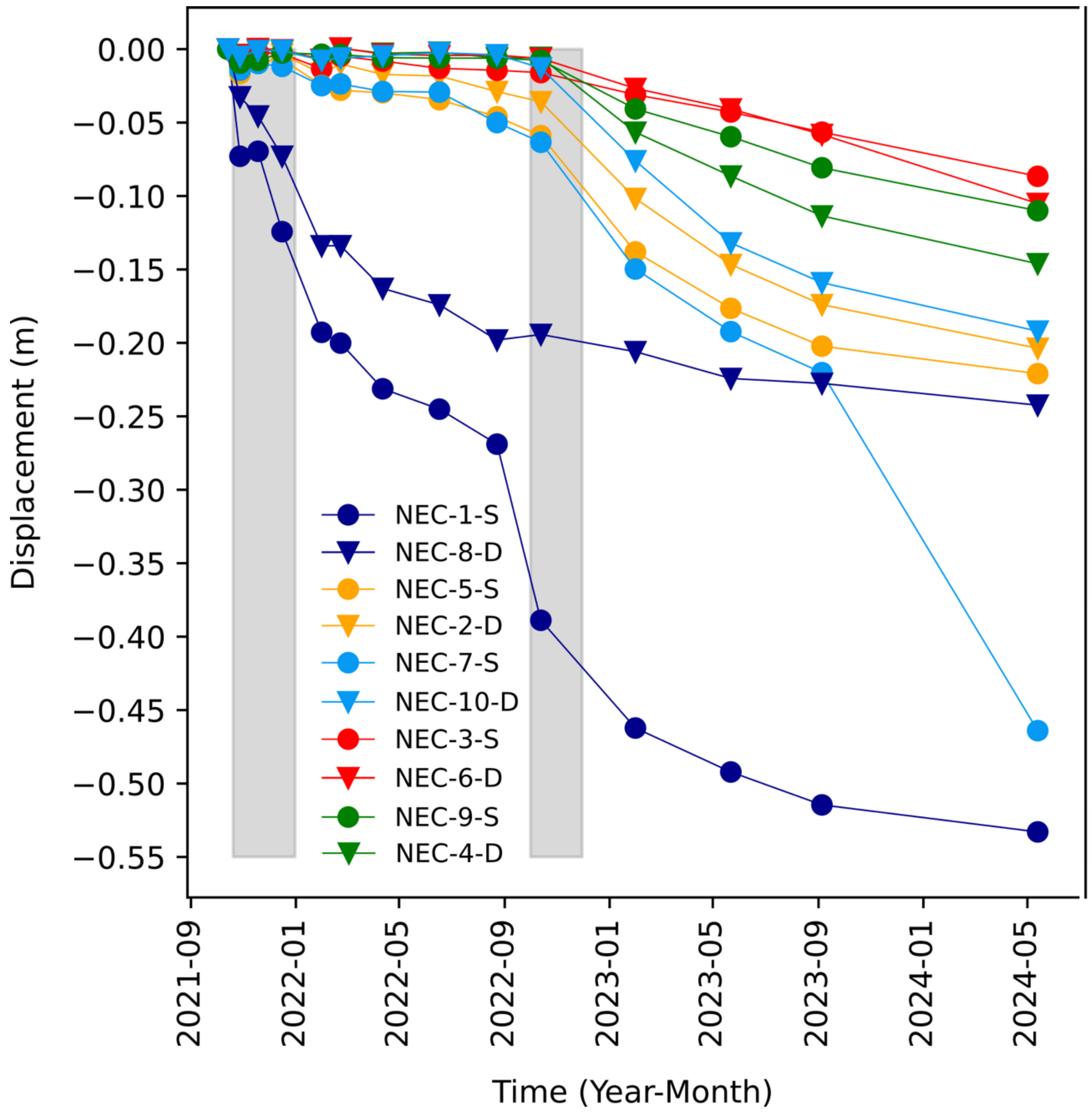


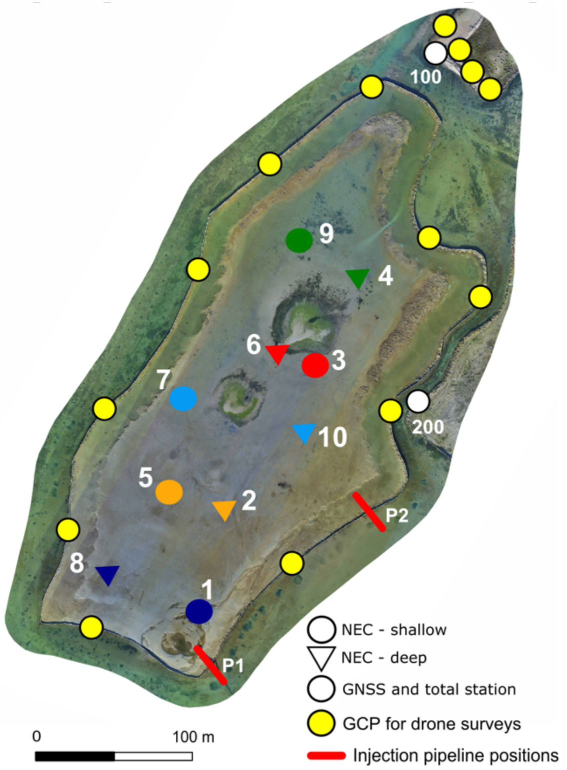
- Four steel bars set into the lagoon subsurface down to a 2-m depth to keep a central steel pole free to move vertically with respect to its specific foundation level.
- The foundation consists of an anchor inserted into the subsurface to a depth of interest (about 1-m depth)

We measure the elevation change from Le Sorelle A by looking to the black-and-white strips on the top of the NEC with a mm-accuracy topographic intersection technique using a total station.

Reference points are monitored using the GNSS technique.

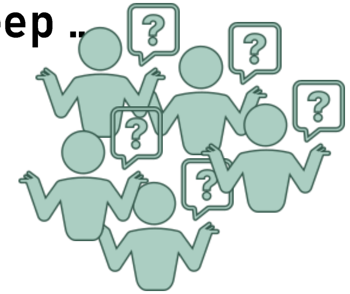
ARTIFICIAL SALT MARSHES

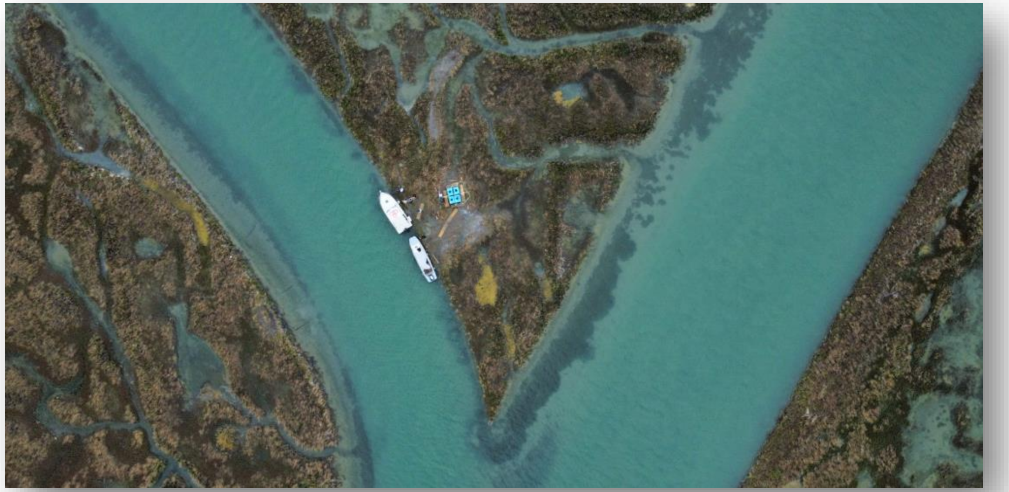




CONCLUSIONS

- Autocompaction is a non-negligibile component of land subsidence
- A modelling framework is proposed to assess and predict autocompaction under the hypothesis of large deformations
- Coupling of surficial and subsurface processes is crucial to determine the long-term survival of salt marshes
- Research gaps to be addressed are the role of roots as sediment stabilizers, overconsolidation of sediments, interaction with biochemical processes, creep ..





GRAZIE

Acknowledgments to

Pietro Teatini
Luigi Tosi
Riccardo Xotta
Marta Cosma
Sandra Donnici
Selena Baldan
Philip Minderhoud
Cristina Da Lio
Paolo Zorzan
Massimo Fabris
Andrea Menin
Michele Monego
Alessandro Bergamasco

Claudia Zoccarato | claudia.zoccarato@unipd.it |
ICEA - Department of Civil, Environmental and Architectural Engineering, University of Padova, Italy