Poro-mechanical modelling of an in-situ loading experiment in a natural marsh in the Venice Lagoon

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Introduction

The survival of salt marshes is strictly connected to their elevation above mean sea level (MSL). The ability to keep up with sea-level rise is primarily controlled by the speed of sea-level rise, the amount of accumulated organic/inorganic sediments, and how fast the land is subsiding. Recent studies have shown that, in the absence of anthropogenic stressors, the elevation variation of a marshland surface is regulated by sediment deposition over the marsh surface, hydrological regime, erosion, and loss of vertical elevation due to natural compaction (Allen et al, 1999). The latter process, known as autocompaction, is caused by compaction of sediments under their own weight and can be significant in relatively young Holocene deposits (Zoccarato et al., 2018; Xotta et al., 2022). The hydro-geomechanical characterization of these young shallow deposits is not always straightforward. Gathering undisturbed samples for laboratory testing has many limitations because of the high porosity and compressibility of these loose sediments (Brain et al., 2015), and their high heterogeneity (Cola & Simonini, 2002), which makes small lab samples not representative for in-situ conditions and geomechanical behavior.

A campaign of novel in-situ loading tests was carried out in the Venice Lagoon (Italy) salt marshes from 2019 to 2022 (Zoccarato et al., 2022). In this work we describe the results of the first (out of four) loading test executed at the Lazzaretto Nuovo salt marsh and its model interpretation (Fig. 1). The experiment was set up to measure the salt marsh hydrological and geomechanical subsurface dynamics in undisturbed field conditions. The test replicates the standard oedometric test at the field scale, with loading conditions of a few kPa (i.e., the typical values driving autocompaction of shallow soils) and accounting for the vertical, in-situ heterogeneity of the marsh landform. The experiment consisted of several loading and unloading cycles with different duration and load, which was obtained by filling up to eight 500-l plastic tanks with seawater, for a maximum load of ~40 kN applied to a surface area of ~4 m2. A monitoring system tracks the marsh response to the applied loads using pressure and displacement transducers established at different depths and locations below the tanks. The collected measurements are interpreted using the 3-D coupled flow-deformation model by Ferronato et al. (2010), properly updated to account for the non-elastic constitutive relationship. The model was calibrated to provide reliable compressibility and hydraulic conductivity estimates for each monitored depth interval.

Methods

A coupled 3D poro-mechanical model solving the Biot (1941) equations was applied to reproduce the experimental loading test performed at the Lazzaretto Nuovo salt marsh. Specifically, we employed a three-field mixed (MFE) simulator, where the unknowns are the nodal displacements, Darcy's velocity through the element faces, and the elemental fluid pore pressure (Ferronato et al., 2010).

A hypo-plastic (or hypo-elastic) model is adopted to characterize the nonlinear constitutive relationship between the sediment compressibility and the vertical effective intergranular stress. The soil becomes stiffer as the vertical effective stress increases. The outcomes of the field experiment were used to calibrate the constitutive relationship describing the marsh mechanical behaviour. The initial parameters were estimated from the results of lab oedometric tests carried out on a few samples cored at the location of the experimental site.

The finite-element computational grid is more refined within the loading area and in the shallowest two m depth to obtain a more accurate solution in the part of the domain subjected to the largest stress changes. The subsurface build-up of the model was schematized to represent the lithological sequence resulting from sedimentary core analysis carried out at the site. A first 20-cm thick peat layer with the presence of halophyte roots overlies a silty soil. The presence of wooden pallets that support the tanks generating the load were also simulated. This rigid surface element ensures a uniform load distribution on the marsh surface. The wooden pallets and the deepest layers (below 6 m depth from the marsh platform) have been simulated using a linear elastic constitutive law with a prescribed constant stiffness E. The two superficial layers were simulated using a nonlinear soil compressibility vs effective stress constitutive law, whose coefficients together with the hydraulic conductivity, were calibrated. In addition, the role played by the mechanical hysteresis was accounted for during the unloading phase. The simulated domain is a portion of the lagoon subsurface with horizontal dimension 20 × 15 m and thickness 10 m, cantered at the applied load. The domain was discretized with 8-node hexahedral elements, totalling 217'392 nodes, 212'440 elements, and 642'216 faces where land displacements, groundwater pressure and velocity, respectively, were computed.

Results and discussions

Table 1 provides the hydro-geomechanical parameters obtained from the model calibration.

Parameters	Pallet	Superficial layer	Intermediate layer	Deep layer
Young modulus E (MPa)	10^4	-	-	10.0
Poisson coefficient ν (-)	0.2	0.2	0.2	0.2
Vertical permeability k_z (m/s)	5.0×10^{-7}	5.0×10^{-7}	5.0×10^{-6}	5.0×10^{-7}
Porosity	0.4	0.4	0.4	0.4
a (MPa^{-1})	-	230.0	572.0	-
b (-)	-	-7.5	-29.0	-
c (MPa)	-	0.2	4.0	-
Recompression ration r (-)	-	3.0	2.0	-
Surface void ratio (-)		1.8	0.8	

Table 1 Hydro-geomechanical parameters calibrated using vertical displacement and overpressure records from the field test conducted on the Lazzaretto Nuovo marsh. The coefficients a, b and c refer to a constitutive law of type $M = a\sigma_z^2 + b\sigma_z + c$ *where M is the edometric module (MPa) and* σ_z *the effective intergranular stress (MPa).*

The model results in terms of vertical displacements and overpressure during the main loading and unloading cycle are compared with field measurements at the sensor positions, i.e., at the surface (C0), at 0.1 m depth (C10, M10, E10) and 0.5 m depth (C50) (Fig. 1).

The comparison between the simulated and measured displacements in the field show that:

- the displacement dynamics over time is generally well captured by the model;
- the numerical model adequately reproduces the displacements measured below the artificial load. The maximum displacement during the loading phase amounts to 7 mm;

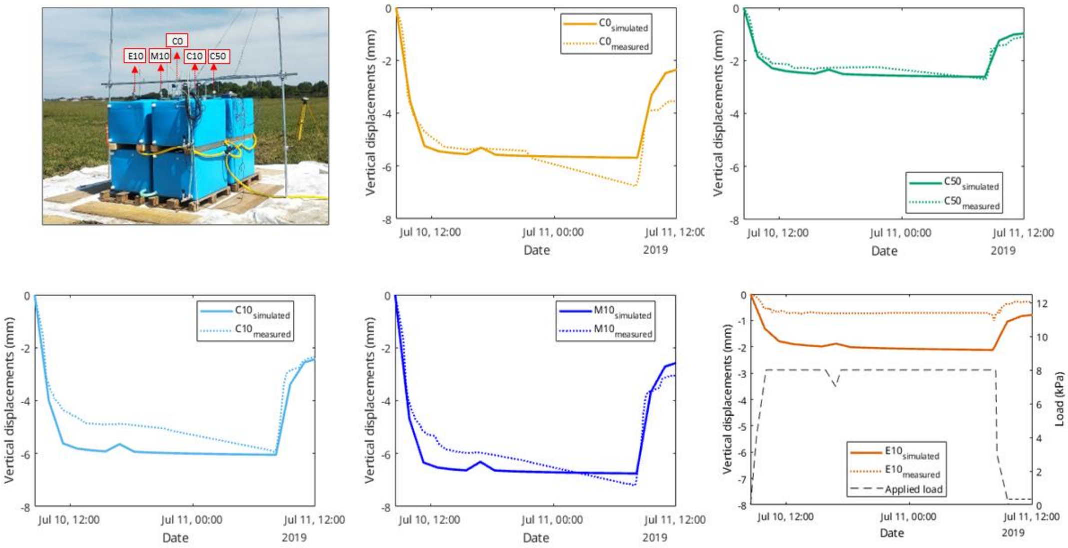

Figure 1 Vertical displacements vs time as measured by the sensors installed below the loading area and simulated with the mixed finite element numerical model. The comparison refers to a loading and subsequent unloading phase of about 8 kPa carried out during about one day. The top-left panel shows a photo of the loading experiment indicating the different sensors at the Lazzaretto Nuovo salt marsh.

- the displacements recorded by the external sensor E10 (1 mm) are overestimated by the model (2 mm);
- the unloading phase is properly simulated with a hysteresis factor of 3 for the superficial sediments and 2 for the underlying layer;
- the measured displacements show a linear deformation over time when the load is kept constant and the overpressure generated by the load itself dissipated (Fig.2). Clearly, creep (i.e., secondary, viscous deformation) characterizes this phase. However, the adopted constitutive law does not account for secondary deformation.

Fig. 2a shows a comparison of the pressure recorded by the piezometer in the most superficial layer (0.2 m depth) and the respective value provided by the model, which has been appropriately shifted to consider the depth of the measuring point. The tide significantly impacts the recorded trends and make the comparison with the model not straightforward. The main peak of the interstitial water pressure recorded by the sensor (about 0.30 m H2O) is caused by the tidal peak. The effect of the 8 kPa load and subsequent unloading may be quantified in 0.04-0.05 m. The two subpanels in Figure 2a show that the model outcome satisfactorily matches the over-pressure and under-pressure evolution over time and the maximum and minimum values. Fig. 2b shows the modelled overpressure for a vertical section across the loading area subsurface at three distinct moments, i.e., at beginning and the end of the loading phase and after the unloading.

Conclusions

In-situ loading tests and their numerical interpretation represent a powerful tool to understand the importance of natural soil compaction in controlling the capability of soil marshes to keep peace with sea-level rise. The reproduction of the experiment results through a fully-coupled geomechanical simulator has allowed the estimation of the hydrological and geomechanical properties of the superficial layers of salt marshes in the Venice Lagoon, at a scale much more representative than that of traditional laboratory tests. The calibrated constitutive law allows to satisfactorily capture the recorded movements throughout both loading and unloading stages, although it cannot reproduce the creep behavior. This effect will be the object of future work together with the analyses of datasets collected from other loading tests recently conducted in the Venice Lagoon. They will provide a first clear picture of the hydro-geomechanical variability of shallow soils in this unique depositional environment. The outcome highlights the importance to properly account for the role of the "subsurface system" when studying processes occurring on the marsh surface like sediment accretion. The geomechanical features that will derive from field experiment modelling will improve long-term biomorpho-geomechanical models of tidal marsh evolution.

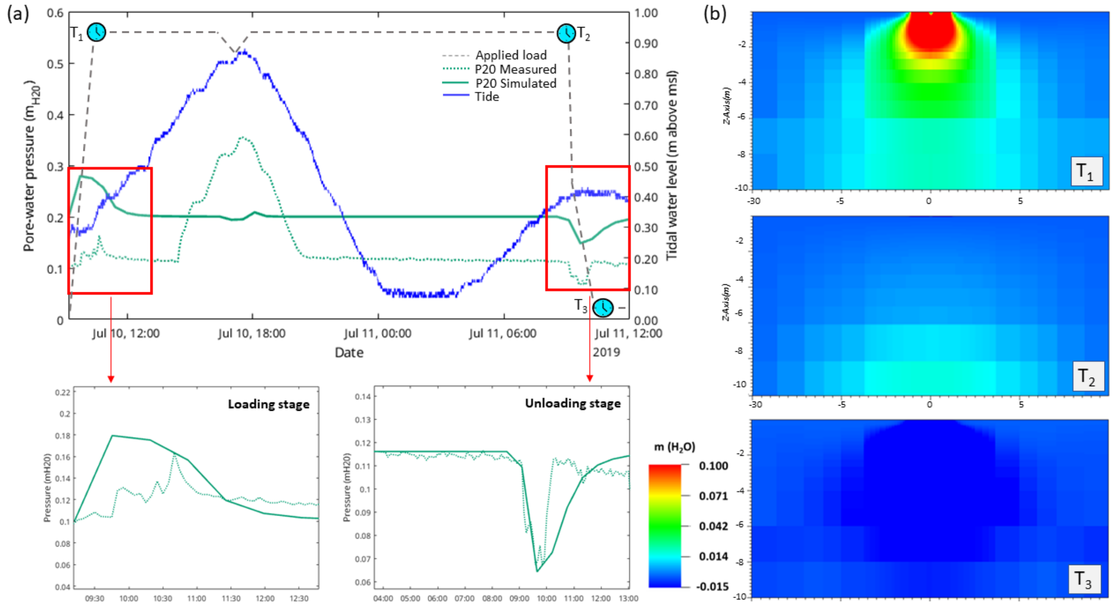

Figure 2 a) Comparison between measured and modelled overpressure (green). The two zoom windows (below) facilitate the comparison of measured and modelled overpressure during the loading and unloading stages. The tidal fluctuation and the behavior of the load applied on the marsh surface are provided. b) Overpressure on a vertical section through the load center as obtained with the calibrated model. The comparison refers to different temporal instants: (T1) 1.5 hours from the start of the load application, (T2) 24 hours after the load application, and (T3) at the end of the load removal.

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