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Effect of capping on the consolidation of hydraulic fills

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Abstract. In land reclamation projects, dredged clay, typically deposited in a highly saturated and very soft state, remains inaccessible for construction or instrumentation for a long period of time. Capping has become a practical approach to enable early site access and accelerate ground improvement. Placing an unsaturated clay layer above the reclaimed fill, usually obtained from onshore excavation works and commonly referred to as a cap, allows the restoration of accessibility at an earlier stage when dealing with hydraulically dredged clay. This study investigates the effect of the unsaturated cap on the consolidation behaviour of the underlying saturated dredged clay when subjected to sand surcharge preloading. The presence of an unsaturated cap influences the rate of consolidation, depending on its permeability, thickness, retention characteristics, and atmospheric conditions, affecting pore-pressure dissipation, surface drainage, and suction equalisation between the cap and the dredged clay. Using coupled hydro-mechanical numerical modelling, an insight into the influence of the unsaturated state on the long-term response of the reclamation is given. The results indicate that the degree of saturation of the cap can significantly influence the consolidation behaviour and long-term response of the reclamation. Partially saturated caps can delay pore-pressure dissipation by modifying drainage conditions and increasing storage within the system.

1 Introduction

Land reclamation projects have traditionally relied on sand fill due to its favourable drainage characteristics and high shear strength. However, the increasing scarcity of suitable sand resources, combined with environmental constraints, has encouraged the use of alternative locally available materials [1, 2]. One such material is dredged clay, which is often generated as a by-product of nearby dredging operations. In recent years, dredged clay has been increasingly used as a fill material in land reclamation projects to mitigate sand shortages and promote more sustainable reclamation practices [3-5].

Hydraulically placed clay fill typically forms a very soft, highly saturated layer with extremely low shear strength and permeability. As a result, the reclaimed surface often remains inaccessible for construction activities and ground improvement works for a considerable period following placement. To restore site accessibility, one of the techniques currently adopted is carefully placing a clay layer, from onshore excavation works, over the soft dredged clay surface. Atmospheric exposure can induce partial saturation within the cap, enhancing its stiffness and modifying its hydraulic response. The cap is then overlain by a 1 to 2m layer of sand, to eventually achieve a platform that provides sufficient bearing capacity to allow early site access for instrumentation installation and ground improvement works such as prefabricated vertical drains (PVDs) installation and surcharge loading.

Capping has been successfully implemented in large-scale land reclamation projects and has proven effective in restoring early accessibility to hydraulically reclaimed sites. However, the presence of a partially saturated cap overlying a saturated clay deposit alters the hydro-mechanical boundary conditions and may influence the consolidation behaviour of the underlying dredged clay.

In particular, the cap may affect consolidation through several mechanisms, including modification of surface drainage conditions, suction redistribution within the cap, and changes in hydraulic conductivity and retention behaviour of the near-surface layer. The formation of desiccated crusts in soft clay slurries has been widely studied in the context of evaporation-induced stiffening and shrinkage; however, these studies primarily consider naturally formed crusts [6, 7]. In contrast, field applications involve the deliberate placement of an engineered cap layer, which alters the hydraulic boundary conditions of the system. The influence of such caps on pore-pressure dissipation and consolidation of the underlying hydraulic fill remains insufficiently understood, particularly when partial saturation governs both storage and flow behaviour.

This study starts investigating these effects using coupled hydro-mechanical numerical modelling. The objective is to evaluate how the time-dependent hydraulic state of the cap influences pore-pressure dissipation, drainage conditions, and consolidation rates in the underlying saturated dredged clay.

2 Numerical model

To investigate the influence of the cap on consolidation behaviour, a series of numerical simulations were

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conducted using CODE_BRIGHT, a finite element code for coupled thermo-hydro-mechanical analysis of porous media [8]. The preliminary analysis presented in the following was performed by solving the mechanical equilibrium and water mass balance coupled problem.

$$\frac{\partial}{\partial t}(\phi S_r) + \nabla . \mathbf{q} = 0 \tag{1a}$$

$$\mathbf{q} = -k \, \nabla h \tag{1b}$$

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = 0 \tag{1c}$$

where ϕ is the porosity, S_r is the degree of saturation, $\mathbf{q}$ is the Darcy (volumetric) flux, k(Sr) is the hydraulic conductivity as a function of saturation, h is the hydraulic head, $\boldsymbol{\sigma}$ is the total stress tensor, and $\mathbf{b}$ represents body forces per unit volume.

In the present formulation, water flow is assumed to occur exclusively in the liquid phase, and vapour transport is neglected. The gas phase is not explicitly modelled; however, its influence is implicitly accounted for through the soil-water retention relationship, which governs the degree of saturation.

Two different scenarios were considered for the cap:

- Near fully saturated condition (Near-Sat): the cap is made of homogeneous saturated clay, where little atmospheric drying has occurred;
- Partially saturated condition (Partial-Sat): the cap is made of lumps of onshore clay, which is more prone to desaturation under interaction with the atmosphere.

The scenarios above represent the two limiting hydraulic states of the cap in the field, corresponding to varying degrees of atmospheric drying and saturation.

A reference ideal case was also considered, in which the entire soil profile is assumed fully saturated and suction effects are neglected. Although not representative of field conditions, this case reflects the simplified assumptions commonly adopted in preliminary design. It serves to verify the numerical model against Terzaghi's one-dimensional consolidation solution and provides a baseline for comparison with the capped scenarios.

2.1 Geometry

The numerical model represents a simplified one-dimensional vertical section of a land reclamation project. The stratigraphy includes 27 m of hydraulically dredged clay, overlain by a layer of clay from onshore excavation works forming the cap.

A one-dimensional formulation was adopted to focus on the vertical consolidation behaviour of the soil system, assuming that deformation and fluid flow occur predominantly in the vertical direction before the vertical drains are installed.

A total of 124 quadrilateral elements and 189 nodes were used, with linear interpolation shape functions. The model geometry and the adopted mesh are shown in Fig. 1.

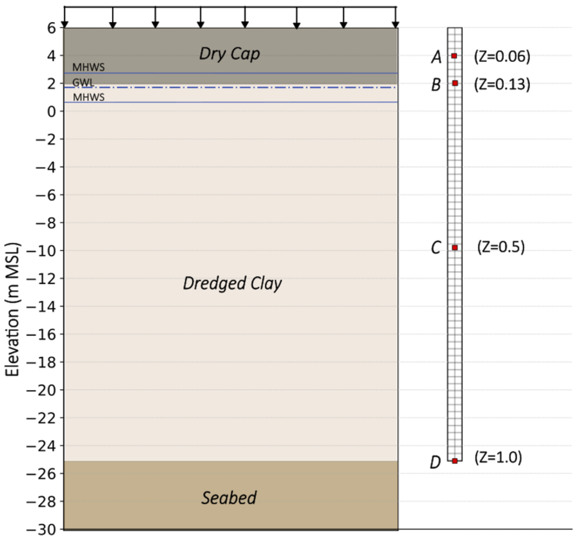

Fig. 1. Model geometry and mesh.

2.2 Material properties

The primary objective of this study is to investigate the hydraulic processes governing consolidation and pore-pressure dissipation. For this reason, a linear elastic constitutive model was adopted for the soil skeleton. In the unsaturated state, the same law was used to describe the stress–strain relationship in terms of net stress. The consolidation response was characterised using a saturated coefficient of consolidation $C_{v,sat} = 3.3 \times 10^{-4}$ m^2/s, which is representative of hydraulically dredged clays.

The unsaturated hydraulic behaviour was described using the Van Genuchten soil-water retention model [9], which relates matric suction to the effective degree of saturation:

$$S_e = [1 + (\alpha\psi)^n]^{-m} \tag{2}$$

where S_e is the effective degree of saturation, ψ is the matric suction, α is related to the air-entry suction, and n and m define the slope of the curve.

The variation of hydraulic conductivity with saturation was represented using a power-law relationship:

$$k(S) = k_{sat} S_e^{\beta} \tag{3}$$

where k_{sat} is the saturated hydraulic conductivity and β is a parameter that governs the dependence of hydraulic conductivity on the effective degree of saturation. A value of β=5 was adopted, based on literature experimental data [10].

Two different retention curves were adopted to reproduce the different scenarios described earlier. In particular, the partially saturated case was characterised by a significantly lower minimum degree of saturation and lower air entry suction value compared to the near-saturated condition. The corresponding soil-water retention curves are presented in Fig. 2.

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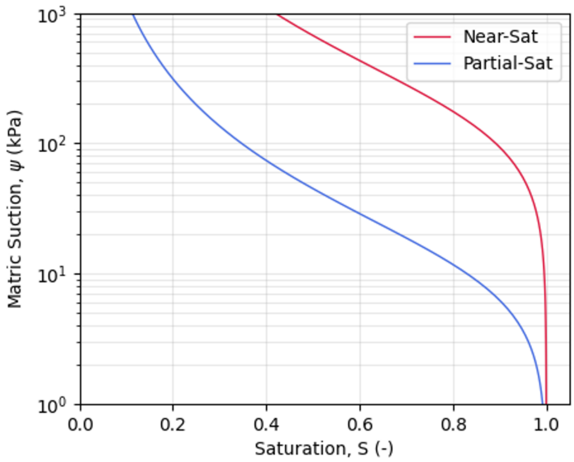


Fig. 2. Soil-Water retention curve.

2.3 Initial and boundary conditions, and time stepping scheme

The ground water table in the model was set to +2 m MSL, which was adopted for the two scenarios. Above the groundwater table, an initial hydrostatic suction profile was imposed to represent unsaturated conditions within the cap. For the near-saturated and the partially saturated scenarios, a constant suction boundary condition was applied at the ground surface, consistent with the initial hydrostatic profile. This represents a condition where the cap remains in equilibrium with the piezometric surface, maintaining a prescribed suction at the surface.

In contrast, the fully saturated reference case was defined assuming a fully saturated soil profile. To achieve this, the groundwater table was raised to +6 m, and atmospheric pressure was imposed at the ground surface, representing a fully drained boundary condition.

No-flux boundary conditions were imposed along the lateral and bottom boundaries, ensuring that flow occurs only in the vertical direction. Following model initialisation, an instantaneous uniform surcharge load of 20 kPa was applied on day 1 at the ground surface to simulate the placement of the sand cap. The resulting evolution of pore pressure, saturation, and water flux was analysed over time.

Time integration was performed using an implicit scheme with a weighting parameter θ=0.5. An adaptive time-stepping strategy was adopted, with a maximum time step of 3.5×10^{-3} days (5 minutes).

3 Results

To assess the effects of capping on the consolidation of the reclamation, the results are presented in terms of pore pressure evolution at different points along the depth, and pore pressure isochrones. In addition, a closer look at the saturation and flow patterns within the cap is included.

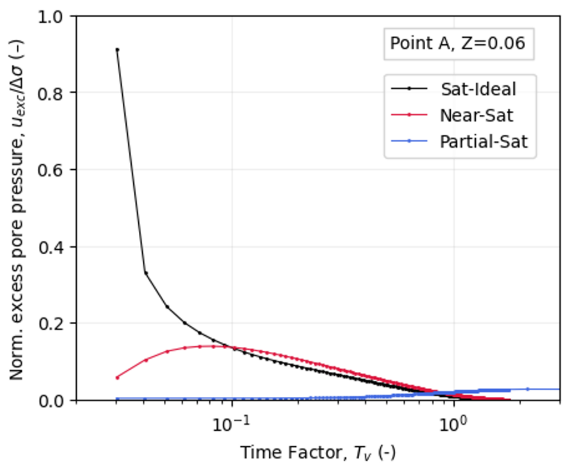
For consistency with classical consolidation theory, the results are expressed in dimensionless form, with reference to the corresponding saturated conditions.

Excess pore pressure is normalised with respect to the applied load as $u_{exc}/\Delta\sigma$, where $\Delta\sigma = 20kPa$, depth is expressed as a normalised coordinate $Z = z/H_{dr}$, where H_{dr} is the drainage path, and time is represented using the time factor:

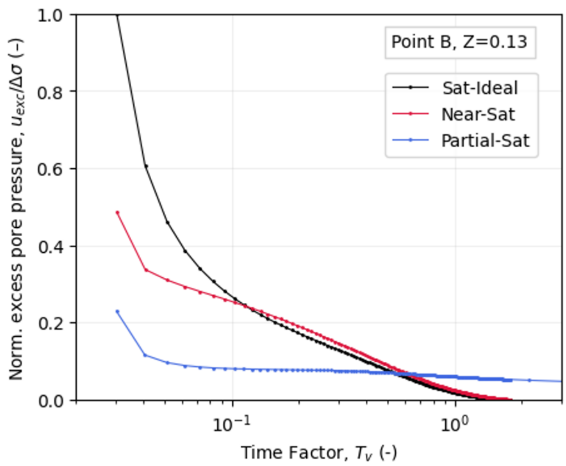
$$T_v = \frac{C_{v,sat}\ t}{H_{dr}^2} \tag{4}$$

Fig. 3 and Fig. 4 show the evolution of the normalised excess pore pressure at four nodes located within the soil profile: points A and B within the cap, where Z=0.06 at +4 m MSL and Z=0.13 at +2 m MSL, and points C and D within the dredged clay reclamation, where Z=0.5 at −9.5 m MSL and Z=1 at −25 m MSL, as indicated in the first figure. Fig. 5 and Fig. 6 present the corresponding normalised excess pore pressure isochrones at selected times for the analysed cases.

For the saturated reference case, the dissipation pattern follows the classical monotonic behaviour expected. The numerical solution was verified against the analytical solution provided by Terzaghi's one-dimensional consolidation theory, showing a very good agreement.



(a)



(b)

Fig. 3. Pore pressure evolution in the cap at (a) point A and (b) point B.

In the near-saturated cap scenario, the excess pore pressure within the cap remains initially low. Although the degree of saturation remains high (minimum $S_r \approx 97\%$), the presence of a small air fraction introduces additional compressibility within the cap. Despite this effect, the dissipation behaviour at the monitoring points within the underlying dredged clay closely follows that of the fully saturated reference case, indicating that the near-saturated cap has a limited influence on deeper consolidation behaviour.

In the partially saturated cap scenario, the cap is significantly more compressible due to its lower degree of saturation (minimum $S_r \approx 50\%$). As a result, only very small excess pore pressures develop within the cap immediately after loading, as part of the applied load is accommodated by compression of the pore air rather than by an increase in pore water pressure.

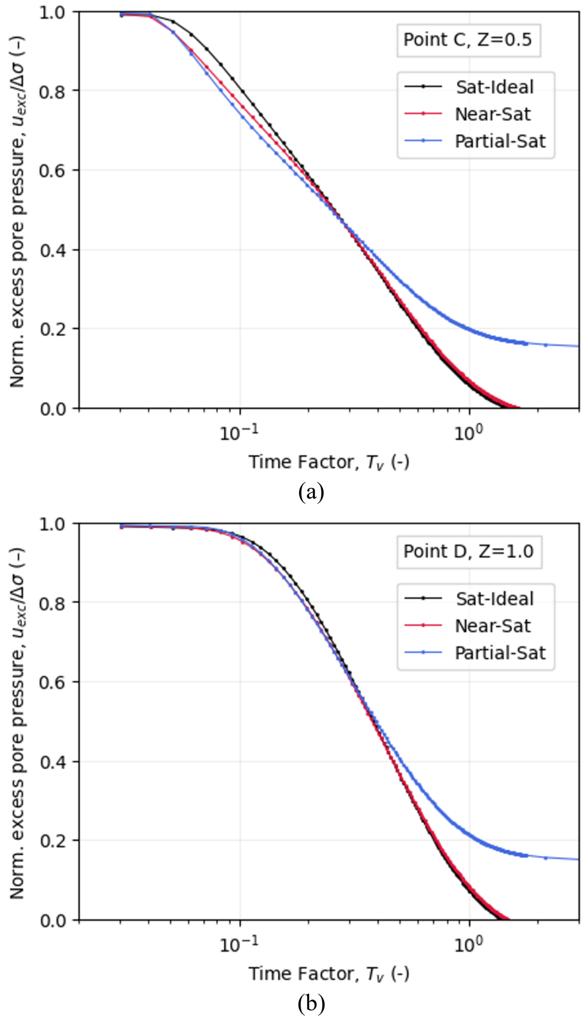


Fig. 4. Pore pressure evolution in the dredged clay reclamation at (a) point C and (b) point D.

While the small excess pore pressures generated in the cap eventually dissipate completely, the behaviour of the underlying dredged clay differs from the previous cases. As shown in Fig. 4, a residual excess pore pressure of approximately 2 kPa remains even after 2000 days, indicating that full dissipation is not achieved within the simulated period.

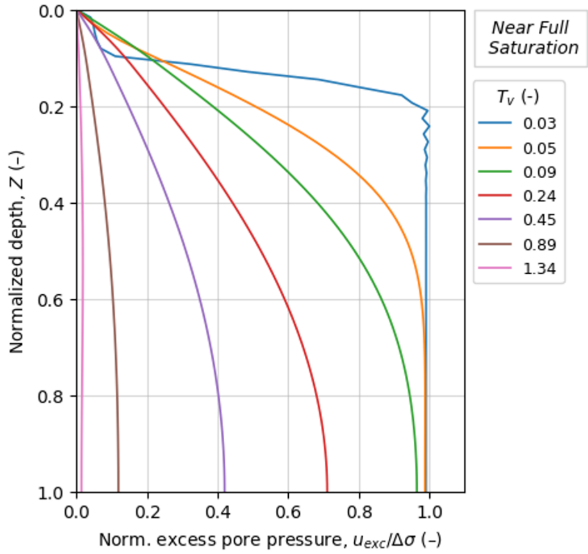


Fig. 5. Near full saturation scenario: Excess pressure isochrones.

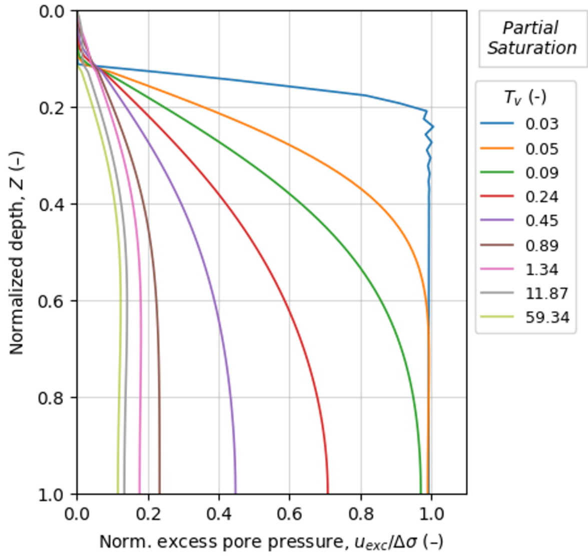


Fig. 6. Case 2: Excess pore pressure isochrones.

4 Discussion

The excess pore pressure dissipation trend in the cap is attributed to the reduced hydraulic conductivity and the storage capacity of the partially saturated cap, which modifies the upward drainage conditions of the underlying saturated clay. To further investigate that, the discharge, saturation, and excess pore pressure at Z=0.06 (z=+4m) are plotted in Fig. 7.

This behaviour can be interpreted using the governing equation for unsaturated flow, derived from mass conservation and Darcy's law (Equations (1a) and (1b)):

$$n\frac{dS_r}{dh}\frac{\partial h}{\partial t} = \nabla \cdot (k(S_e)\nabla h) \tag{5}$$

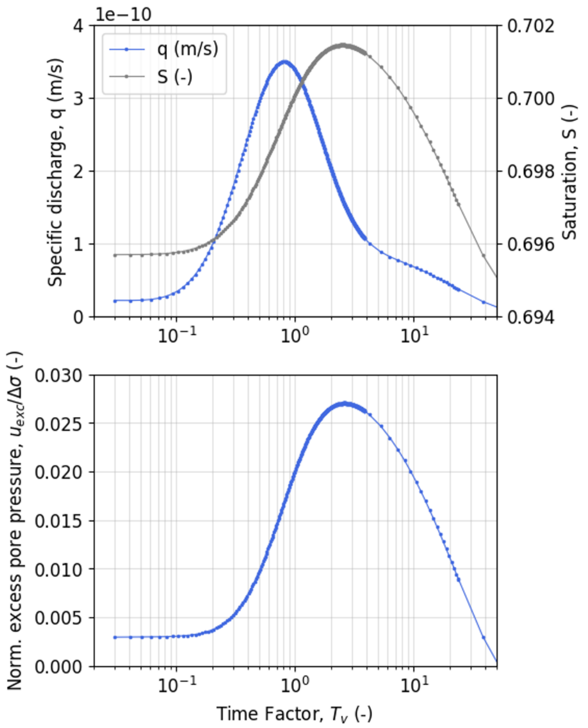


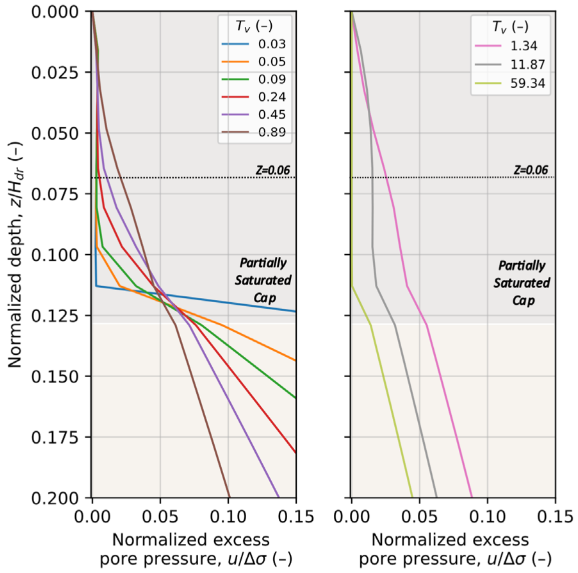
Fig. 7. Specific discharge, saturation, and normalised excess pore pressure time evolution at Z=0.06 in partially saturated cap.

The term $\frac{dS_r}{dh}$ in Equation (5) represents the storage capacity associated with changes in saturation related to suction and is governed by the soil-water retention response.

Due to the small excess pore pressures developing within the partially saturated cap, the pore pressure distribution is initially nearly uniform, as observed in Fig. 8, resulting in a low hydraulic gradient across the layer. Since flow in Darcy's law is proportional to the hydraulic gradient, the resulting upward discharge is initially limited.

At the same time, water from the underlying dredged clay flows into the cap, while the reduced hydraulic conductivity of the partially saturated layer restricts drainage toward the surface. Consequently, inflow from the clay temporarily exceeds outflow through the cap, leading to transient storage within the layer. This storage-dominated regime results in an increase in pore pressure within the cap, accompanied by a corresponding increase in saturation.

As saturation increases, the hydraulic conductivity $k(S_e)$ of the cap also increases. This progressively enhances the hydraulic gradients and associated discharge, allowing drainage to become more efficient. As a result, the system transitions from a storage-dominated to a flow-dominated regime, and the excess pore pressure dissipates.



(a) (b)

Fig. 8. Normalised excess pore pressure isochrones in the top 6 meters (a) inflow into the cap > outflow, (b) outflow > inflow.

The transition is further evidenced by the change in curvature of the pore pressure profiles in Fig. 8. The initial concave shape reflects a storage-dominated regime, with $\nabla^2 h > 0$, corresponding to a negative divergence of the flow field and indicating net inflow into the cap. As dissipation progresses, the profiles become convex, with $\nabla^2 h < 0$, corresponding to a positive divergence of the flow field, where outflow exceeds inflow and drainage becomes the governing mechanism.

To investigate the role of the non-linear coupled response of the unsaturated cap on the time scale, an additional simulation was carried out with a coefficient of consolidation reduced by one order of magnitude through compressibility. The results highlight deviation of the response from the classical linear solution of the one-dimensional consolidation problem.

The corresponding pore pressure profiles are presented in Fig. 9. In the deeper part of the profile, the responses at identical time factors T_v exhibit similar shapes, consistent with the linear scaling behaviour expected from classical consolidation theory. However, clear deviations from this scaling are observed within the cap layer. In particular, the profiles at identical T_V do not coincide, which indicates that the response is not governed solely by a linear diffusion process. This behaviour reflects the role of the non-linear evolution of both the storage term and the hydraulic conductivity in the partially saturated cap. As a result, the consolidation response depends not only on the dimensionless time factor, but also on the actual time-dependent evolution of the hydraulic state.

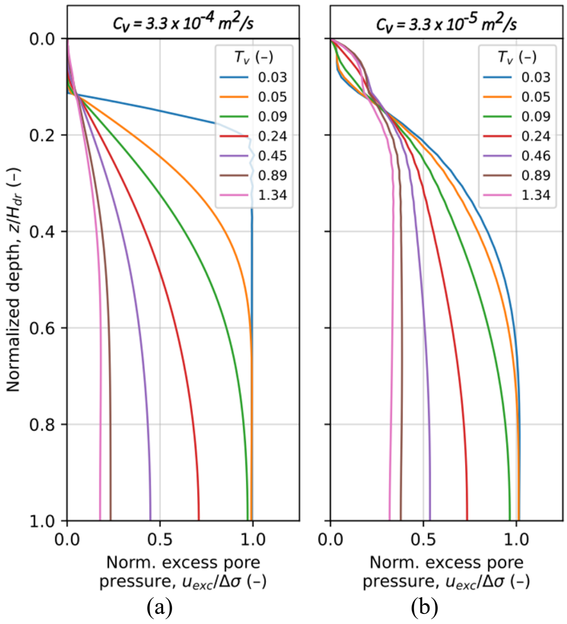


Fig. 9. Normalised excess pore pressure profiles at different time factors Tv, two coefficients of consolidation: (a) $C_v = 3.3 \times 10^{-4}$ m²/s, and (b) $C_v = 3.3 \times 10^{-5}$ m²/s.

5 Conclusions

The influence of the cap on the consolidation behaviour of hydraulically placed dredged clay has been investigated using coupled hydro-mechanical numerical modelling. The results demonstrate that the hydraulic state of the cap plays a key role in controlling pore-pressure dissipation and overall consolidation response.

For the near-saturated cap condition, the behaviour remains comparable to classical saturated consolidation, with only minor deviations observed due to the presence of compressible air. In contrast, a partially saturated cap significantly alters the consolidation process. The reduced hydraulic conductivity and increased storage capacity associated with partial saturation lead to a temporary storage-dominated regime, in which inflow from the underlying clay exceeds outflow through the cap. This results in delayed dissipation and the persistence of excess pore pressures within the system.

These findings demonstrate that partially saturated caps can substantially modify drainage conditions and consolidation behaviour, highlighting the importance of accounting for unsaturated hydraulic processes in the analysis of reclamation systems. In particular, the results indicate that vertical drainage systems, such as prefabricated vertical drains (PVDs), play a critical role not only in accelerating consolidation, but also in facilitating drainage when upward flow is hindered by the presence of a partially saturated cap.

Further work will investigate and assess the time-dependent response of the system under evaporation and rainfall cycles, using site-specific meteorological data.

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