Measured hydraulic properties for soft, sulfidic unconsolidated soils are used to explore their groundwater properties. Unlike rigid soils, falls in watertable depth cause these soils to shrink. The distribution of water in unconsolidated soil profiles increases with height above the watertable and decrease with depth below the watertable. Hydraulic conductivity decreases with depth below the watertable due to the weight of the overlying wet soil. The dependence of the specific yield of groundwater in unconsolidated soils on depth to the watertable is fundamentally different to that of non-swelling soils. These unique properties are due to the “card-house” structure of the clay colloids that are altered by changes in the pore-water chemistry, or applied loads or watertable elevation.

INTRODUCTION

Population growth and coastal urbanisation over the next fifty years will intensify pressures on coastal lowlands, particularly in the Asia-Pacific region. These regions supply food and habitat for many key fisheries and migratory birds. Their development must be based on understanding their unique groundwater hydrology [1]. In coastal regions, large areas \( [ca \, 10^8 \, ha] \) of waterlogged, unconsolidated, soft sulfidic coastal Holocene sediments, acid sulfate soils, were deposited following the last sea-level rise. Deposits of gel-like clay sediments, sometimes 40 m thick, occur with volumetric water
contents as high as 80% [1]. They cause engineering problems as they shrink on drying, deform and flow under surface loads and produce acid discharge on draining [2]. In this work we use measured hydraulic properties of gel soils to show the unique groundwater behaviour in these sulfidic, coastal clay soils.

SHALLOW GROUNDWATER IN SOFT SULFIDIC SEDIMENTS

Matric Potential Profiles

Water potentials and loads are in work per unit weight of water and units are metres (m) of water. The hydraulic head, \( \Phi \), is the sum of the gravitational potential, \( z \), (defined positive upwards with datum the base of the sediment) and the ‘manometric pressure’ of water in the soil, \( p_w \), [3],[4]. In compressible sediments, the overburden of wet soil together with any surface load, \( P_T \), is carried by both solid and liquid phases. The component of water potential due to these loads is the overburden potential, \( \Omega \), which must be included in the total potential [5]. For saturated, swelling soils near or beneath the watertable, an appropriate model for equilibrium is [5]:

\[
\Phi = z + p_w = z + \Psi(\vartheta) + \Omega = z + \Psi(\vartheta) + \left[ P_T + \int_0^Z \gamma(\vartheta, P(z')) dz' \right] = Z_W
\]  

Here, \( \Psi \) is the unloaded matric potential, \( Z_W \) is the watertable height above the base of the sediment, \( \vartheta \) is the moisture ratio (ratio of volume of soil water to volume of solid), \( Z_T \) is the position of the soil surface relative to the base of the deposit, and \( \gamma \) is the wet specific gravity of the sediment. The manometric pressure of water relative to atmospheric pressure is \( p_w = \Psi + \Omega \) and the position of the watertable is the surface where \( p_w = 0 \) or \( \Psi = -\Omega \). In rigid soils the watertable is the surface at which \( \Psi = 0 \).

To treat consolidation, a coordinate system is required that conserves the amount of solid in the soil profile. A material coordinate system \( m(z, \vartheta) \) can be defined as [5]:

\[
m(z, \vartheta) = \int_0^Z \frac{z}{[1/(1 + \vartheta)]} dz' = \int_0^Z \vartheta \, dz'
\]  

The material coordinate at position \( z \) is the total volume of solid per unit surface area in the profile up to height \( z \). Physical space coordinates follow from \( \vartheta(m) \) profiles:

\[
z = \int_0^m (1 + \vartheta) \, dm' = \int_0^m (1/\vartheta_s) \, dm'
\]  

In this material coordinate system, the equilibrium condition (1) is transformed to:
\[
\psi \left( \frac{1}{\gamma_s - 1} \right) m_T = - \left[ P_T + W + \left( 1 - \frac{m}{m_T} \right) \right] = - \left[ P_T^* + W^* + 1 - \frac{m}{m_T} \right]
\]

(4)

\[ W = Z_T - Z_W \] is depth of the watertable beneath the soil surface and \( m_T \) is the total volume of solid per unit area in the soil profile.

**Water Content Profiles**

Modelling equilibrium moisture content profiles in soft sediments requires the soil’s moisture characteristic, \( \mathcal{O}(\psi) \). For soft sulfidic coastal clays, \( \mathcal{O}(\psi) \) is modelled as [4]:

\[
\mathcal{O}(C, \psi) = A(C) - B(C) \ln \psi
\]

(5)

The parameters \( A \) and \( B \) are constants for a given clay matrix, and temperature but depend on pore water electrolyte concentration, \( C \). The water profile in material space is:

\[
\mathcal{O} = A - B \ln [P_T + W + (\gamma_s - 1)(m_T - m)]
\]

(6)

The model (6) predicts moisture contents that decrease with depth below the watertable and increase with height above the watertable, different from those in rigid systems. It also predicts applied surface loads and watertable act in the same way to reduce water contents in the profile. Table 1 lists parameter values in (5) for two sulfidic coastal soils, one from the Netherlands, the other from eastern Australia [4].

**Water Table Depth and Consolidation**

The relation between the space and material coordinates follows from (5) and (3):

\[
z = m \left[ 1 + A - B \left[ \ln \left( \frac{1}{\gamma_s - 1} m_T \right) - 1 \right] \right] + m_T B \left[ \left( P_T^* + W^* + 1 - \frac{m}{m_T} \right) \ln \left( P_T^* + W^* + 1 - \frac{m}{m_T} \right) - (P_T^* + W^* + 1) \ln (P_T^* + W^* + 1) \right]
\]

(7)

Table 1. Moisture characteristic (5) parameters, solid specific gravity and approximate pore solution composition for two saturated swelling soils [4].

<table>
<thead>
<tr>
<th>Sediment</th>
<th>A</th>
<th>B</th>
<th>( \gamma_s )</th>
<th>Pore Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netherlands marine-origin</td>
<td>3.24</td>
<td>0.25</td>
<td>2.57</td>
<td>Seawater</td>
</tr>
<tr>
<td>Eastern Australian estuarine-origin</td>
<td>2.32</td>
<td>0.30</td>
<td>2.55</td>
<td>4% Seawater</td>
</tr>
</tbody>
</table>
Water Table Depth and Consolidation

The relation between the space and material coordinates follows from (5) and (3):

\[
z = m\left[1 + A - B\left(\ln\left(\gamma_s - 1\right) - 1\right)\right] + m_T B \left[P_T^* + W^* + 1 - m \frac{m_T}{P_T^* + W^* + 1}\ln\left(P_T^* + W^* + 1\right) - \left(P_T^* + W^* + 1\right)\ln\left(P_T^* + W^* + 1\right)\right]
\]

(7)

The total depth of the sediment, \(Z_T(P_T^*, W^*, m_T)\), follows from (7):

\[
Z_T(P_T^*, W^*, m_T) = Z_T(0) - m_T B \left[P_T^* + W^* + 1\ln\left(P_T^* + W^* + 1\right) - \left(P_T^* + W^* + 1\right)\ln\left(P_T^* + W^* + 1\right)\right]
\]

(8a)

where \(Z_T(0)\), depth of unloaded soil with the watertable at the soil surface (\(W = 0\)) is:

\[
Z_T(0) = m_T \left[1 + A - B\left(\ln\left(\gamma_s - 1\right) - 1\right)\right]
\]

(8b)

The effect of applied surface loads and watertable depths on consolidation is found from (8). Figure 1 shows the effect of watertable depth on the consolidation of an unloaded (\(P_T = 0\)) soil modeled by (8) for both soils in Table 1. Here the initial deposit thickness is 10 m. A tension saturated zone of 2 m is assumed above the watertable [4].

Imposed surface loads such as air pressure changes also alter the elevation of the watertable. In a closed system, the model predicts the increase in watertable height is equal to the imposed load, \(P_T\) [3]. Figure 2 shows the modeled impact of imposed surface load on the elevation of both the soil surface and watertable in the eastern Australian soil, when the water table was initially 1.5 m below the soil surface. Once the watertable reaches the soil surface water drains away freely. Figure 2 shows that the load initially raises the watertable to the soil surface. Once the watertable has reached the soil surface, consolidation commences. Changes in atmospheric pressure equivalent to 0.1 to 0.2 m can occur. The model predicts these result in watertable fluctuations of up to 0.2 m.

To predict moisture profiles in physical space, the total volume of solid per unit surface area, \(m_T\), for a given depth of an unloaded swelling sediment, with watertable at the surface, may be calculated iteratively from equation (8b). The moisture profile in material space can then be calculated from (5) and the corresponding position in physical space is found from (7) for any applied surface load and watertable depth.

Figure 3 shows the predicted moisture profiles in physical space for an initially 10 m thick, unloaded profile of the eastern Australian soil with a watertable at 0.1 m and for dimensionless imposed loads, \(P_T^*\), of 1 and 10. Significant consolidation of the soil surface and the dewatering of the profile brought about by applied surface loads are apparent in Figure 3. A dimensionless load of 1 corresponds to a load of 4.9 tonnes/m².
Figure 1. Dependence of the position of the soil surface on the depth to the shallow watertable for the two soils in Table 1. The unloaded soils with watertables at the soil surface were both 10 m thick initially.

Figure 2. Impact of imposed surface load on the elevation of the watertable and the soil surface for the eastern Australian soil. The watertable was initially at \( W = 1.5 \) m.

**EFFECT OF GROUNDWATER ELECTROLYTES**

The properties of “quick” clay soils are altered by adding electrolytes to the soil water [6]. Here we model, the dependence of water content profiles on groundwater electrolyte concentration. Smiles et al. [7] measured the concentration dependence of \( A \) and \( B \) in (5) for dilute bentonite slurries when the electrolyte was NaCl. Their data is modeled [8] as:

\[
\frac{A(C)}{A_0} = \frac{B(C)}{B_0} = 1 - 0.12 \ln \left( \frac{C}{C_0} \right)
\]

(9)

\( A_0 \) and \( B_0 \) are values of \( A \) and \( B \) at an arbitrary reference electrolyte concentration \( C_0 \).

Normalising with a reference concentration removes any specific soil dependence [8]. We assume here the model (9) is valid for the estuarine-origin soil in Table 1. The change in soil water profiles with both imposed surface loads and a three-fold increase in groundwater electrolyte concentration are also shown in Figure 3. Even a modest increase in groundwater concentration has an impact on sediment consolidation. The impact of increasing the groundwater electrolyte concentration on the consolidation of the soil surface is shown in Figure 4. A 30-fold increase in solution concentration (equivalent to
seawater) produces the same consolidation as an applied surface load of 40 tonnes/m².

Figure 3. Moisture profiles during consolidation and dewatering of an initially 10 m deep soil profile with watertable depth of 0.1m. The impact of non-dimensional surface loads and a three-fold increase in groundwater electrolyte concentration.

Figure 4. Consolidation of the eastern Australian sediment initially 10 m thick with watertable at the soil surface as a function of applied surface pressure. Also shown is the predicted impact of increasing the NaCl concentration in groundwater.

DEWATERING SULFIDIC SEDIMENTS

Dewatering is dependent on the specific yield, $Y$, of the sediments. For these shallow watertable systems, the specific yield is defined as the change in total water stored in the profile per unit change in watertable height $\partial \sigma / \partial Z_W$ [3] which follows from (6) and (8).

$$Y = \frac{\partial \sigma}{\partial Z_W} = \frac{B}{\gamma_s - 1} \ln \left[ \frac{P_T^* + W^* + (\gamma_s - 1) m_T}{P_T^* + W^*} \right]$$  \hspace{1cm} (10)

Figure 5 shows the specific yield of the Australian soil for a range of watertable depths. Under small surface loads, when the watertable is close to the surface the specific yield is very large. This is due to the ability of the unloaded soil to swell. In the unloaded soil, at watertable depths of around 1 m, typical for this soil, the specific yield is about 0.35, similar to that observed in the field. As the load on the surface or the depth to the watertable increases, the specific yields decreases. Figure 5 shows with a load of 10 m, specific yield is almost constant, around 0.07, nearly independent of watertable depth.
The flow equation for one-dimensional vertical flow in saturated, swelling materials, flow is based on Darcy’s equation, but with flow relative to the solid particles [5]. Swelling counteracts gravity, which can be ignored [4]. The flow equation is:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial m}\left( k_m \frac{\partial \psi}{\partial m} \right)
\]  

(11)

In (12), \( t \) is time, \( k_m \) is the ‘material’ hydraulic conductivity which is related to hydraulic conductivity \( K(\theta_p) \) by \( K(\theta_p) = (1 + \varphi)k_m(\varphi) \). The material conductivity, \( k_m \), determines the rate of dewatering of the soil for any given surface load. The hydraulic conductivities of both soils in Table 1 are modelled by \( K(\psi) = 1.4 \times 10^{-9} \psi^{-1} \), which is small. In soft sediments \( K(\psi) \) beneath the watertable depends on depth in the sediment, unlike in rigid aquifers. Figure 6 shows the predicted impact of watertable depth on the profiles of \( K(\psi) \) in a 10 m thick sediment.

**CONCLUDING REMARKS**

The models developed here for shallow groundwater in soft sulfidic sediments are analytic and can be run in simple spreadsheets. The groundwater hydrology of these gel-like sediments differs fundamentally from that in non-deformable materials. The models
predict the impacts of surface loads, water table depth and groundwater electrolyte concentration on groundwater properties and sediment consolidation. All predictions should be tested. The model shows that the groundwater electrolyte concentrations critically determine dewatering of sediments. This provides a method of developing these areas without harmful environmental impacts. The model predicts that the time to dewater these sediments through surface loading and wick-drainage is very long but substantial decreases can be achieved by increasing the groundwater salt concentration.

**Acknowledgements**

This work was supported by the Australian research Council under grant DP0345145.

**REFERENCES**


