Modelling Shallow Groundwater in Soft, Sulfidic, Coastal Sediments

I. White[a], B.C.T. Macdonald[b] and M. D. Melville[b]

[a]*Centre for Resource and Environmental Studies, The Australian National University, Canberra ACT 0200, Australia (ian.white@cres.anu.edu.au)*

[b]*School of Geography, The University of New South Wales, Sydney, NSW 2052, Australia*

Abstract: Large areas (~10^8 ha) of the world's coastal lowlands contain marine-origin, sulfidic, sediments. Many have shallow watertables, are gel-like and contain up to 80% water in deposits sometimes 40m thick. They pose significant engineering and environmental problems due to shrinkage on dewatering, deformation and flow under surface loads and the production of highly acidic drainage due to oxidation of sulfides following falls in the shallow watertable. Their groundwater hydrology differs markedly from that of rigid systems. Here, their unique shallow-groundwater properties are modelled. The model shows that watertable position, overburden, and pore water electrolytes affect the equilibrium pressures and water contents above and below the watertable. The influence of watertable depth, surface loads and groundwater electrolyte concentrations on shrinkage of sediments are modelled. The hydraulic conductivity below the watertable is shown to depend on overburden and watertable depth. The specific yield of the groundwater decreases rapidly with depth of the watertable. A simple model is used to predict dewatering times for consolidating sediments using vertical wick drains. Model estimates are between 10 and 100 years depending on drain spacing. Increasing the groundwater electrolyte concentration may decrease this by over 40%.

Keywords: Groundwater; Acid sulfate soils; Swelling sediments; Consolidation; Dewatering

1. INTRODUCTION

Population growth, demand for food, and coastal urbanisation over the next fifty years will intensify pressures on coastal lowlands. These highly productive regions supply food and habitat for many key fisheries and migratory birds. Development must be based on an understanding their unique groundwater hydrology.

Large areas of waterlogged, soft sulfidic coastal Holocene sediments, known as acid sulfate soils, were deposited following the last sea-level rise. Deposits, sometimes 40 m thick, of gel-like sediments occur that have volumetric water contents as high as 80% [White et al., 1997].

Developments on these sediments require drainage or dewatering. Lowering shallow watertables can have severe consequences for downstream ecosystems. Sulfides in these soils oxidise producing sulfuric acid that leaches out aluminium and iron from the soil. Discharge of acid groundwater into streams causes the death of gilled organisms and plants and the corrosion of infrastructure [Sammut et al., 1996]. In this work we model shallow groundwater in these soft, sulfidic, coastal clay soils.

2. SHALLOW GROUNDWATER IN SOFT SULFIDIC SEDIMENTS

2.1 Matric Potential Profiles

Here, water potentials and loads are expressed in work per unit weight of water and units are metres (m) of water. The hydraulic head, Φ, is the sum of the gravitational potential, z, (here defined positive upwards with datum the base of the sediment) and the 'manometric pressure' of water in the soil, p_w (the tensiometer-pressure). In compressible sediments, the overburden of wet soil together with any surface load, P_T, is carried by both the solid and liquid phases. The component of potential in the water phase due to these loads is the overburden potential, Ω, which must be included in the total potential [Smiles, 2000]. For saturated, swelling soils near or beneath the watertable, an appropriate model for equilibrium is [Smiles, 2000]:

$$\begin{aligned}\Phi &= z + p_w = z + \psi(\vartheta) + \Omega \\ &= z + \psi(\vartheta) + \left[P_T + \int_z^{Z_T} \gamma(\vartheta, P(z'))dz' \right] = Z_W\end{aligned} \tag{1}$$

Here, ψ is the unloaded matric potential, Z_W is the watertable height above the base of the swelling soil deposit, ϑ 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 γ is the wet specific gravity of the sediment. The manometric pressure of water relative to atmospheric pressure in swelling systems is $p_w = \psi + \Omega$ and the position of the watertable is the surface where $p_w = 0$ or $\psi = -\Omega$. This is quite different from rigid soils where the watertable is the surface at which $\psi = 0$.

To treat volume change, a coordinate system is required that conserves the amount of solid in the soil profile. An appropriate material coordinate system $m(z,\vartheta)$ is defined as [Smiles, 2000]:

$$m(z,\vartheta) = \int_0^z [1/(1+\vartheta)]dz' = \int_0^z \theta_s dz' \tag{2}$$

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

$$z = \int_0^m (1+\vartheta)dm' = \int_0^m (1/\theta_s)dm' \tag{3}$$

In this material coordinate system, the equilibrium condition (1) is transformed to:

$$\frac{\psi}{(\gamma_s - 1)m_T} = -\left[\frac{P_T + W}{(\gamma_s - 1)m_T} + \left(1 - \frac{m}{m_T}\right) \right] \tag{4}$$

$W = Z_T - Z_W$ 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. The scaling parameter $(\gamma_s - 1)m_T$ in (4) is the total 'buoyant' specific volume of solid per unit area.

2.2 Water Content Profiles

Modelling equilibrium moisture content profiles in soft sediments requires knowledge of the soil's moisture characteristic, $\vartheta(\psi)$. For soft sulfidic coastal clays, $\vartheta(\psi)$ can be modelled as [White et al., 2001]:

$$\vartheta(C,\psi) = A(C) - B(C)\ln|\psi| \tag{5}$$

The parameters A and B are constants for a given clay matrix, and temperature but depend on pore water electrolyte concentration, C. From (4) and (5) the moisture profile in material space is:

$$\vartheta = A - B\ln[P_T + W + (\gamma_s - 1)(m_T - m)] \tag{6}$$

The model (6) predicts moisture contents, which decrease with depth below the watertable and increase with height above the watertable, quite 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 a marine-origin clay soil from the Netherlands, the other an estuarine soil from McLeods Creek on the Tweed River, eastern Australia [White et al., 2001].

Table 1. Moisture characteristic (5) parameters, solid specific gravity and approximate pore solution composition for two saturated swelling soils [White et al., 2001].

Sediment	A	B	γ_s	Pore Solution
Netherlands marine-origin	3.24	0.25	2.57	Seawater
Eastern Australian estuarine-origin	2.32	0.30	2.55	4% Seawater

The moisture ratio term on the left-hand side of (6) can be normalised with the water content difference between the surface and the base of the soil, $\vartheta_0 - \vartheta_T = B\ln[(P_T^* + W^* + 1)/(P_T^* + W^*)]$ where $P_T^* + W^* = (P_T + W)/[(\gamma_s - 1)m_T]$ and the water content at the soil surface is $\vartheta_T = A - B\ln(P_T + W)$. The normalised moisture ratio model is soil-parameter-independent:

$$\frac{\vartheta - \vartheta_T}{\vartheta_0 - \vartheta_T} = \frac{\ln[(P_T^* + W^* + 1 - m/m_T)/(P_T^* + W^*)]}{\ln[(P_T^* + W^* + 1)/(P_T^* + W^*)]} \tag{7}$$

This model predicts that the water content profile will be relatively constant below the watertable only for deep watertables or large P_T.

2.3 Water Table Depth and Consolidation

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

$$z = m\{1 + A - B[\ln\{(\gamma_s - 1)m_T\} - 1]\} + m_T B \left[\left(P_T^* + W^* + 1 - \frac{m}{m_T} \right) \ln \left(P_T^* + W^* + 1 - \frac{m}{m_T} \right) - \left(P_T^* + W^* + 1 \right) \ln \left(P_T^* + W^* + 1 \right) \right] \quad (8)$$

The total depth of the deposit under any surface load or watertable depth, $Z_T(P_T^*, W^*, m_T)$, follows from (8):

$$Z_T(P_T^*, W^*, m_T) = Z_T(0) - m_T B \left[\left(P_T^* + W^* + 1 \right) \ln \left(P_T^* + W^* + 1 \right) - \left(P_T^* + W^* \right) \ln \left(P_T^* + W^* \right) \right] \quad (9a)$$

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

$$Z_T(0) = m_T [1 + A - B\{\ln[(\gamma_s - 1)m_T] - 1\}] \quad (9b)$$

The effect of applied surface loads and watertable depths on consolidation is found from (9). Figure 1 shows the effect of watertable depth on the consolidation of an unloaded $(P_T = 0)$ deposit modelled by (9) 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. This is consistent with measurements [White et al., 2001].

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 [Philip, 1969]. Figure 2 shows the modelled 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.

It is assumed that once the watertable reaches the soil surface water drains away freely. Figure 2 shows that the impact of the load initially is to raise 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 with the passage of fronts. The model predicts these will result in watertable fluctuations of up to 0.2 m.

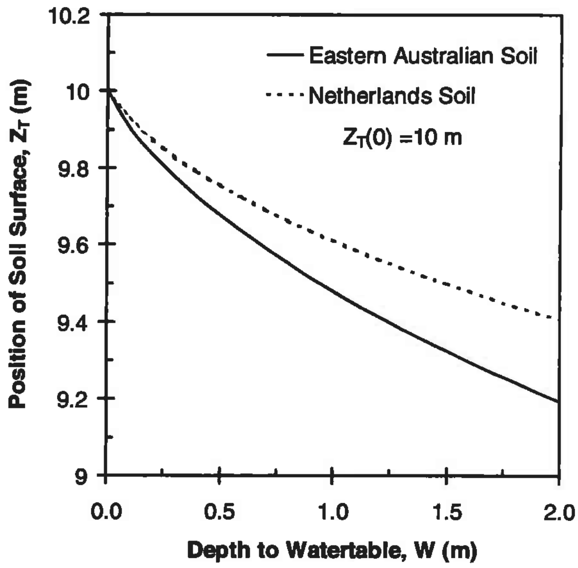

Figure 1. Dependence of the position of the soil surface on the depth to the shallow watertable for the two coastal sulfidic soils in Table 1. The unloaded soils with watertables at the soil surface were both 10 m thick initially.

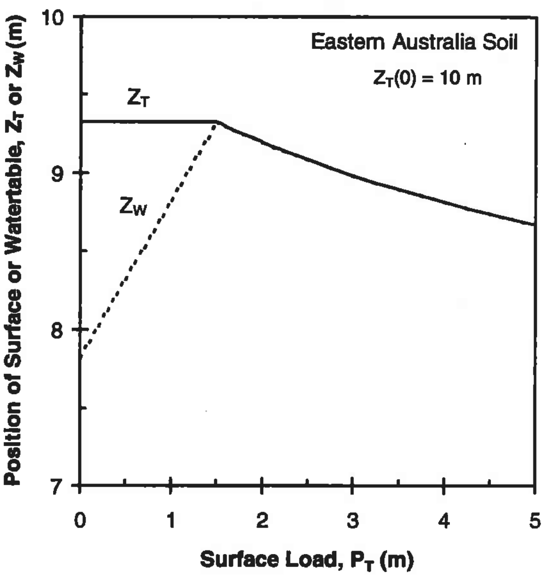

Figure 2. Impact of imposed surface load on the elevation of the watertable and the soil surface for the eastern Australian soil. The watertable was initially at $W = 1.5$ m.

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 (9b). The moisture profile in material space can then be calculated from (5) and the corresponding position in physical space is found from (8) for any applied surface load and watertable depth.

Figure 3 shows the predicted moisture profiles in physical space for an initially 10m 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.

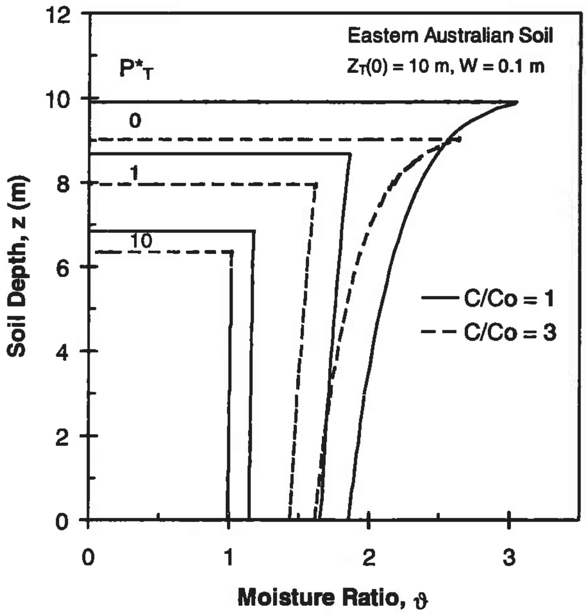

Figure 3. Moisture profiles during consolidation and dewatering of an initially 10 m deep soil profile with watertable depth of 0.1m. The impact of non-dimensional surface loads and a three-fold increase in groundwater electrolyte concentration.

Significant consolidation of the soil surface and the dewatering of the profile brought about by applied surface loads are apparent in Figure 3, where a dimensionless surface load of 1 corresponds to a surface load of 4.9 tonnes/m^2.

3. GROUNDWATER ELECTROLYTES

The rheological properties of "quick" clay soils are dramatically altered by adding electrolytes to the soil water [Rosenqvist, 1966]. Here we model, in an approximate sense, the dependence of water content profiles on groundwater electrolyte concentration. Smiles et al. [1985] measured the concentration dependence of A and B in (5) for dilute bentonite slurries when the electrolyte was NaCl. Their data can be modelled [White, 2001]:

$$\frac{A(C)}{A_0} = \frac{B(C)}{B_0} = 1 - 0.12 \ln\left(\frac{C}{C_0}\right) \tag{10}$$

where 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 [White, 2001]. We will assume here, for illustrative calculations that the model (10) is valid for the estuarine-origin soil in Table 1.

The change in soil water content profiles with both imposed surface loads and a three-fold increase in groundwater electrolyte concentration are also shown in Figure 3. Even a relatively modest increase in groundwater concentration has a dramatic impact on sediment consolidation. The modelled impact of increasing the groundwater electrolyte concentration on the consolidation of the soil surface is shown in Figure 4. A 30-fold increase in soil solution concentration (equivalent to seawater) produces approximately the same consolidation as an applied surface load of 40 tonnes/m^2.

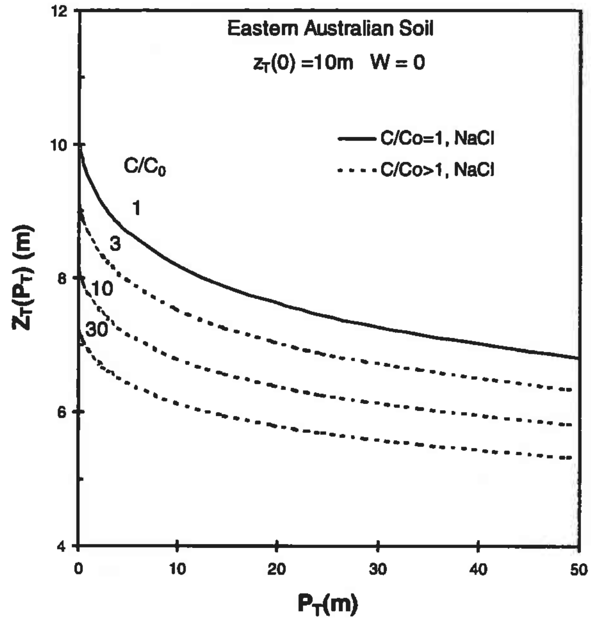

Figure 4. Consolidation of the eastern Australian sediment initially 10 m thick with watertable at the soil surface as a function of applied surface pressure. Also shown is the impact of increasing the NaCl concentration in groundwater.

4. DEWATERING SULFIDIC SEDIMENTS

Dewatering is fundamentally important in managing these soft soils. 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 $\partial\varpi/\partial Z_W$ [Philip, 1969]. This can be modelled from (6) and (8).

$$Y = \frac{\partial \varpi}{\partial Z_W} = \frac{B}{\gamma_S - 1} \ln\left[\frac{P_T^* + W^* + (\gamma_S - 1)m_T}{P_T^* + W^*}\right] \quad (11)$$

Figure 5 shows the specific yield of the eastern Australian soil for a range of watertable depths.

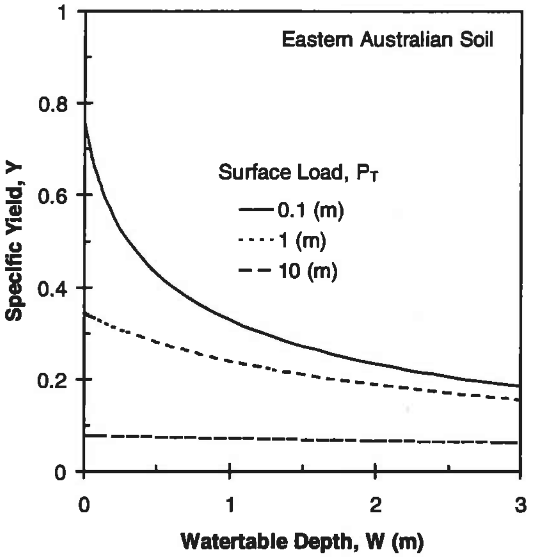

Figure 5. Specific yield of an acid sulfate soil deposit in eastern Australia as a function of watertable depth and surface loads.

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 that with a load of 10 m, probably an upper limit for these soils, the specific yield is almost constant, around 0.07, and is nearly independent of watertable depth. the.

The flow equation for one-dimensional vertical flow in saturated, swelling materials assumes that flow is given by Darcy's equation, but with flow relative to the solid particles [Smiles, 2000]. Swelling counteracts the force of gravity and in soft sulfidic systems gravity can be ignored [White et al, 2001]. The flow equation is:

$$\frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial m}\left(k_m \frac{\partial \psi}{\partial m}\right) \quad (12)$$

In (12), t is time, , k_m is the 'material' hydraulic conductivity which is related to hydraulic conductivity $K(\theta_W)$ by $K(\theta_W) = (1+\vartheta)k_m(\vartheta)$. The material conductivity, k_m determines the rate of water movement and hence the rate of dewatering of the soil for any given surface load. The hydraulic conductivities of both soils in Table 1 are modelled by $K(\psi) = 1.4\times10^{-9}|\psi|^{-1}$, 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.

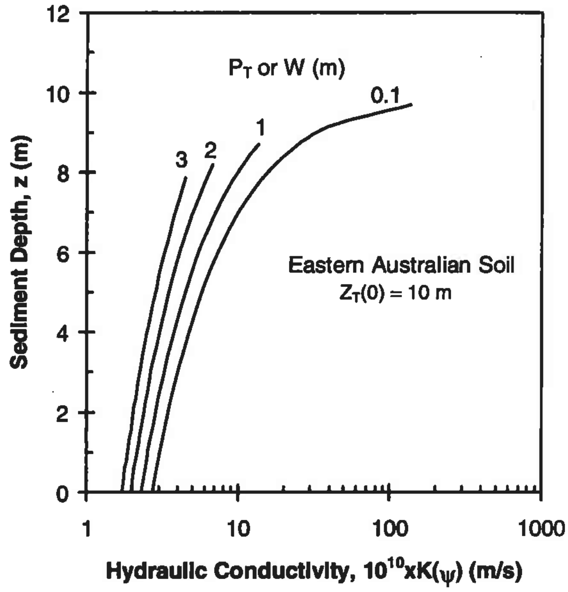

Figure 6. Groundwater hydraulic conductivity profiles. Numbers on curves are the depth to watertable or surface load.

The solution of (12) for the dewatering of sediments shows that the cumulative outflow of water, i (volume per unit area of sample) is:

$$i = -S_0 t^{1/2} \quad (13)$$

Here $S_0 = S(\psi_0, \psi_n)$ is the sorptivity, which depends on electrolyte concentration [Smiles et al., 1985] and is related to the hydraulic properties of the sediment.

One method of dewatering these soft coastal sediments is to use closely spaced, vertical wick drains together with surface loads. Because gravity effects are negligible, the time to dewater the soils can be estimated from [Smiles, 1973]:

$$\frac{\vartheta - \vartheta_n}{\Delta\vartheta} = erfc\left[\frac{S_0}{2\Delta\vartheta\, L}\sqrt{\pi\, t}\right] \quad (14)$$

Here $\Delta\vartheta = \vartheta_0 - \vartheta_n$ and L is the half-spacing between vertical drains. A realistic goal is to drain the sediment to $(\vartheta - \vartheta_n)/\Delta\vartheta = 0.5$. Figure 7 shows the predicted time for dewatering as a function of the drain half spacing. Here we have assumed a total overburden load of 5 m.

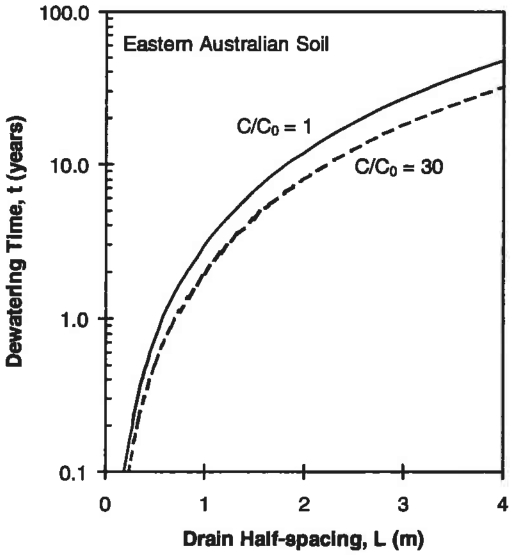

Figure 7. Dependence of the dewatering time on the half-spacing between vertical wick-drains. Dashed line shows the impact of a 30-fold increase in electrolyte concentration.

With a typical value of L of 1.5 m, Figure 6 shows that it will take 10 years to drain these sediments using vertical wick drains and consolidation. Also shown in Figure 6 is the impact of changing the groundwater concentration 30-fold (to about seawater concentration). This results in over a 40% decrease in the dewatering time.

5. 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, watertable 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.

6. ACKNOWLEGEMENTS

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