Total head and porewater pressure reduction in adjacent clay basin constrain tunnel design

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Abstract: Tunnel or cavern leakage in bedrock hills, surrounded by clay basins, may cause a reduction of porewater pressure and subsequent sediment subsidence.

Key words: Subsidence, Porewater pressure, Groundwater, Total head, Tunnel

INTRODUCTION

Geotechnical and engineering analyses have often focused primarily on sediment subsidence in cases where underground tunnels passed directly beneath regions with sensitive sediments. As society and engineers become increasingly conscious of the environmental and civil infrastructural consequences to changes in the groundwater system, less noticeable effects from underground excavation become important. This paper focuses on the effects of the groundwater table drawdown and porewater pressure reduction in clay basins adjacent to tunnels in exposed bedrock (Figure 1).

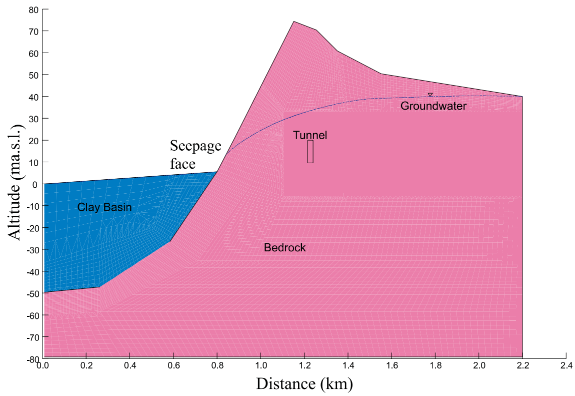

Figure 1. Vertical profile of 2-D model showing bedrock, tunnel, clay basin and groundwater table.

ANALYSES

A 2-D finite element groundwater model (SEEP/W by Geo-slope, 1998) is employed to simulate leakage scenarios in a parameter study to quantify changes in total head and porewater pressures at an analogous field site. The simulations are kept simple with a homogeneous, continuum model including a hydraulic conductivity value for the bedrock ($8\cdot10^{-7}$ m/s) and a hydraulic conductivity value for the clays ($4.8\cdot10^{-10}$ m/s). A constant recharge is applied to the model in areas with exposed bedrock, corresponding to 30 % of the annual precipitation at the recharge sites. There is a seepage face at the foot of the

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exposed bedrock, as well as in the upper right hand corner of the model. The seepage faces are modelled with constant head nodes at these sites. These nodes do not feed water into the model. A hydrostatic constant head boundary makes up the left edge of the model, while the right edge and bottom of the model are no-flow boundaries. Constant head nodes are also placed at the top of the clay basin, corresponding to a groundwater level just below ground surface. These constant head nodes do not feed water into the model, even after steady-state simulations. Tunnel leakage is simulated with nodes that extract a pre-determined leakage volume. Input data are based on field measurements from the future tunnel site, including artesian pressures at the base and mid-depth of the clay basin. The tunnel is situated some 400 metres from the clay basin.

Porewater pressure changes from SEEP-simulations are analysed, using both conventional analytical 1D methods and a 2D finite element model in PLAXIS, to estimate time dependent settlements in the soft, normally consolidated marine clay. In both the analytical 1D model and the PLAXIS model a stress dependent oedometer modulus $E_{oed}=m\times\sigma_1'$ is applied where σ_1' is the major effective main stress and m is a modulus number equal to 12. A vertical coefficient of consolidation c_v between 0.5-3.7 m^2/year is applied in the analytical 1D model. In PLAXIS, the coefficient of consolidation is given by the formula $c_v=k\times E_{oed}/\gamma_w$ where γ_w is the unit weight of water equal to 10 kN/m^3 and k is the coefficient of permeability. Thus, both E_{oed} and c_v increase with depth in the PLAXIS model. In Figure 1, the horizontal scale is significantly compressed compared to the vertical scale. In reality, the problem is almost one-dimensional. To achieve the same development of the settlement over time with use of the two models, a coefficient of permeability k=0.031 m/year had to be applied in PLAXIS. The results from these calculations are shown in Figure 6.

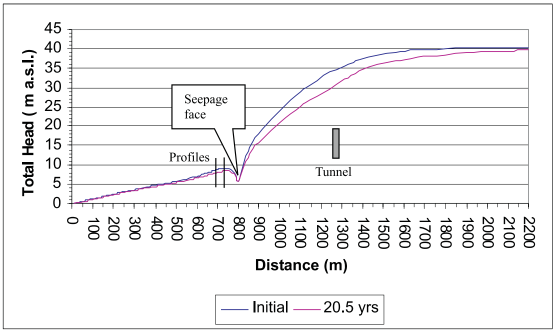


Figure 2. Total head values under initial conditions and after 20.5 years with a tunnel leakage of 10 l/min/100 m tunnel. The values represent the total head at the interface between the clay basin and the bedrock surface from the left edge of the model to the seepage face, then horizontally from the seepage face to the right edge of the model (see Figure 1). Profiles are at Distance = 700 m and 740 m. Seepage face at X=800 m, Tunnel at X=1230 m.

RESULTS AND DISCUSSION

The results of steady state and transient simulations of a tunnel leaking 10 litres/minute for every 100 m of tunnel are depicted in the figures below. The transient simulation approaches steady state results after approximately 20 years. Figure 2 illustrates the change in total head from the initial conditions to 20.5 years later. The groundwater drawdown above the tunnel is approximately 5 metres, and reduces to an unnoticeable amount just upstream of the seepage

face. The drawdown increases again to a maximum in the clay basin only 60 metres from the seepage face, showing a reduction of total head of c. 1.1 m. From this point and further to the left boundary of the model, the total head change reduces to 0 m as the model is feed from the constant head at the left representing the "sea", approximately 700 m away.
The groundwater table directly over the tunnel has its greatest drawdown within the first 15 years after construction (Figure 3). The total head values at the base and within the clay sediments also show near steady state levels after 15 years (Figure 4).

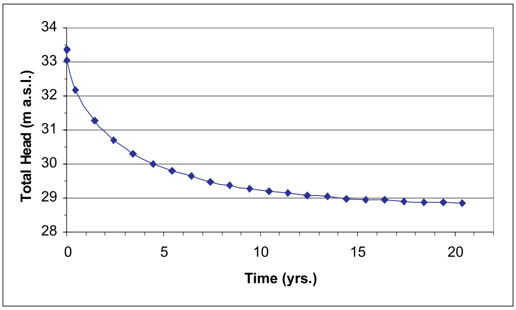


Figure 3. Groundwater table drawdown directly over the tunnel.

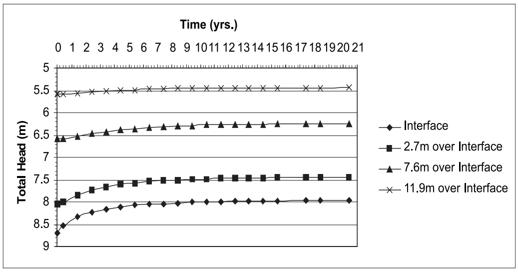
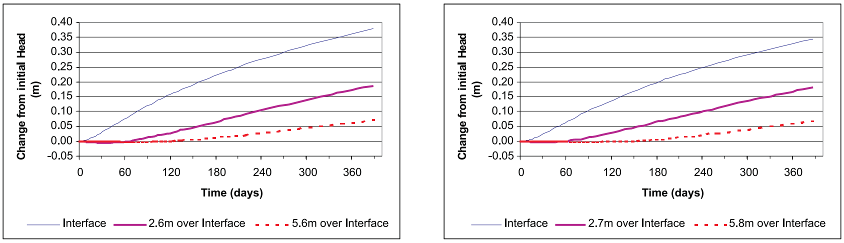


Figure 4. Vertical profile 100 m downstream of the seepage face (X=700 m). Total thickness of sediments at this profile is 14.7 m. The "Interface" is between the clay and the bedrock.

Figure 4 illustrates the total head values for different levels within the clay sediments 100 m downstream of the seepage face. At this profile X=700 m, the potentiometric surface is 3.7 m over the ground level. At 60 m downstream of the seepage face (X=740 m, max. total head within clay basin), the potentiometric surface is 4.1 m over the ground surface.
Values change almost instantaneously at the interface between the clay sediments and the bedrock, while a slight delay is seen at the shallower levels of the vertical profile (Figure 5). Figures 5a and b illustrate the delay in total head reduction that migrates through the sediment thickness with time, for vertical profiles X= 700 m and X= 740 m respectively. Piezometers 2.5 metres above the interface do not react until 2 months after the heads have begun to decline at the base.
When calculating settlement, it is assumed that pressure changes take place instantaneously through the clay layer, and as a result there will be an error in the estimated time for consolidation in very thick clay layers. This is of less significance in Figure 6 (see also Figure 4), where the clay layer is between 8.6 – 31 m thick. Settlements show a sharp increase, from zero at X=800 to a maximum value of 130 mm at X=740. From X=580 the settlements decrease almost linearly to zero at the boundary where X=8.
The settlement results from the analytical calculations agree closely with the results from the finite element model. At x=740 the value in the finite element model is the same as the analytical value. The development of settlement over time, is however slower in PLAXIS as shown in Figure 6.



a) *b)*

Figure 5a and b. Total head values for vertical profiles at X=700 m and X=740 m, respectively. Note time resolution (days).

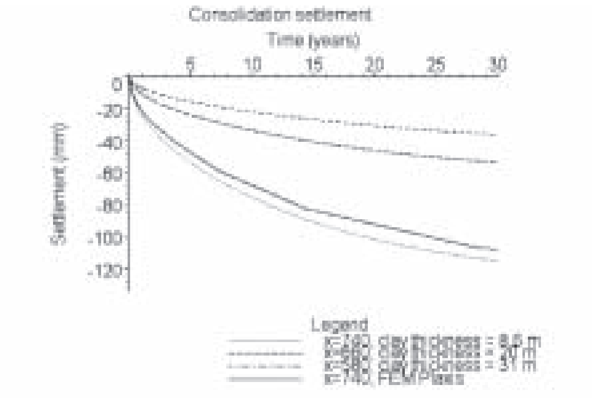


Figure 6. Consolidation settlements with 3 analytical and one PLAXIS curve at X=580, X=660, and X=740 m, respectively. Settlements from SEEP pressure changes with a tunnel leakage of 10 l/min/100 m tunnel.

CONCLUSIONS

Tunnel or cavern leakage in bedrock hills, surrounded by clay basins, may cause a reduction of porewater pressure and subsequent sediment subsidence several hundreds of metres away. Changes in total head can be registered shortly after leakages are initiated at the base of the clay sediments, while piezometers 2.5 m above the clay base may not register a change until after a couple months of tunnel leakage.

Acknowledgements

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