Consolidation with wick drain

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Introduction

This example is about modeling the behavior of a wick drain in a consolidation analysis. The primary purpose here is to illustrate how interface elements can conveniently be used to include the effects of a wick drain, and to discuss some of the analysis issues relevant to wick drains.

Numerical Simulation

For illustrative purposes, only one wick drain cell is analyzed (Figure 1). The drain spacing is 4 m and the drain length is 6 m. The excess pore-water pressure is induced by a surface pressure equal to 100 kPa.

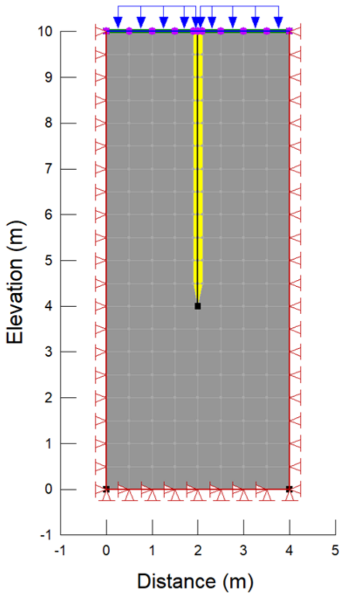
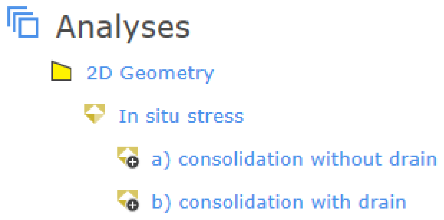


Figure 1. Configuration of wick drain cell.

This type of study requires a consolidation analysis, which means it is necessary to specify both of the stress/strain and hydraulic material properties and boundary conditions. There are three analyses in the Project (Figure 2) to compare the same soil column with and without the wick drain present, with the initial stresses and pore-water pressure conditions defined in the "Parent" In Situ analysis.



Analyses

- 2D Geometry
  - In situ stress
    - a) consolidation without drain
    - b) consolidation with drain

Figure 2. Analysis Tree for the Project.

The surface pressure is applied with the step-function in Figure 3. The first time step (Δt) is 1 day. The increment change in pressure from t = 0 to t = 1 is 100. For all other time steps, the incremental change is zero. Physically, the load can only be applied once. Using the boundary function achieves this.

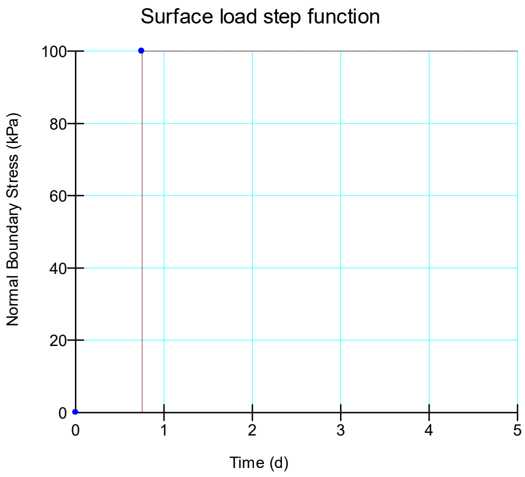


Figure 3. Boundary function defining the surface pressure.

The hydraulic boundary condition on the ground surface is set to zero pressure, inferring that the water table is at the ground surface and any water outflow will not change the position of the water table.

The soil is treated as an Isotropic Elastic material with effectives stress parameters. The E-modulus is 50,000 kPa and the Poisson's ratio (ν) is 0.334 (1/3). From a structural point of view, the drain soil is assigned the same properties as the surrounding clay, inferring that the drain itself has no effect on the compression behavior of the soil.

The soil and drain will at all times remain saturated and be under positive pore-water pressures. This means that the Saturated Only material model can be used in the Hydraulic tab for positive pore-water pressure conditions. The saturated hydraulic conductivity (K) is equal to 1 x 10^{-9} m/sec, with a saturated volumetric water content of 0.3.

The conductivity of the drain is also be specified by the Saturated Only material model, with an anisotropy ratio. The same K-value used for the clay is used for the saturated hydraulic conductivity of the drain. A saturated K value in GeoStudio defines the conductivity in the x-direction or the x′-direction (transverse direction). The conductivity in the orthogonal direction (y in this case) is the x-conductivity times the specified ratio. The specified ratio is 1000. This means that the conductivity in the longitudinal direction is 1000 x 1e-9 = 1e-6 m/sec; that is, K_l is 1000 times greater than K_t.

The *in situ* conditions are simulated using the same materials as the child analyses. The water table is specified at the surface of the model domain to define the initial conditions of the In Situ analysis.

Results and Discussion

Figure 4 shows the pore-water pressure distribution in the drain with time (Analysis 2). Initially, there is some excess pore-water pressure in the drain, but then it dissipates and eventually becomes hydrostatic.

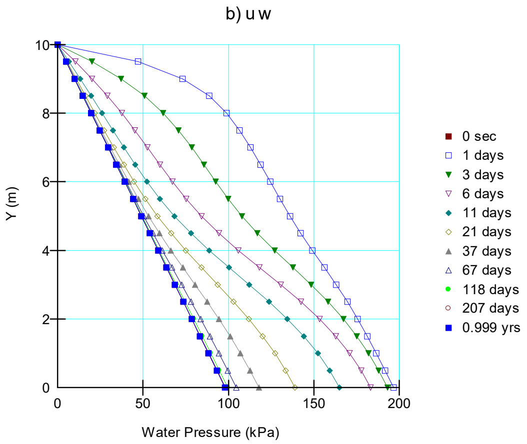


Figure 4. Pore-water pressure distributions in the drain.

The fact that the pressure is not hydrostatic immediately means that the drain is offering some resistance to flow in the vertical or longitudinal direction.

An easy and convenient way of modeling a perfectly free-flowing drain is to define a Head-type boundary condition along the center of the drain. In this case, a boundary condition of H = 10 m would ensure that the pressure in the drain is hydrostatic at all times.

Figure 5 shows the pore-water pressure distributions at Day 1 and at Day 6.

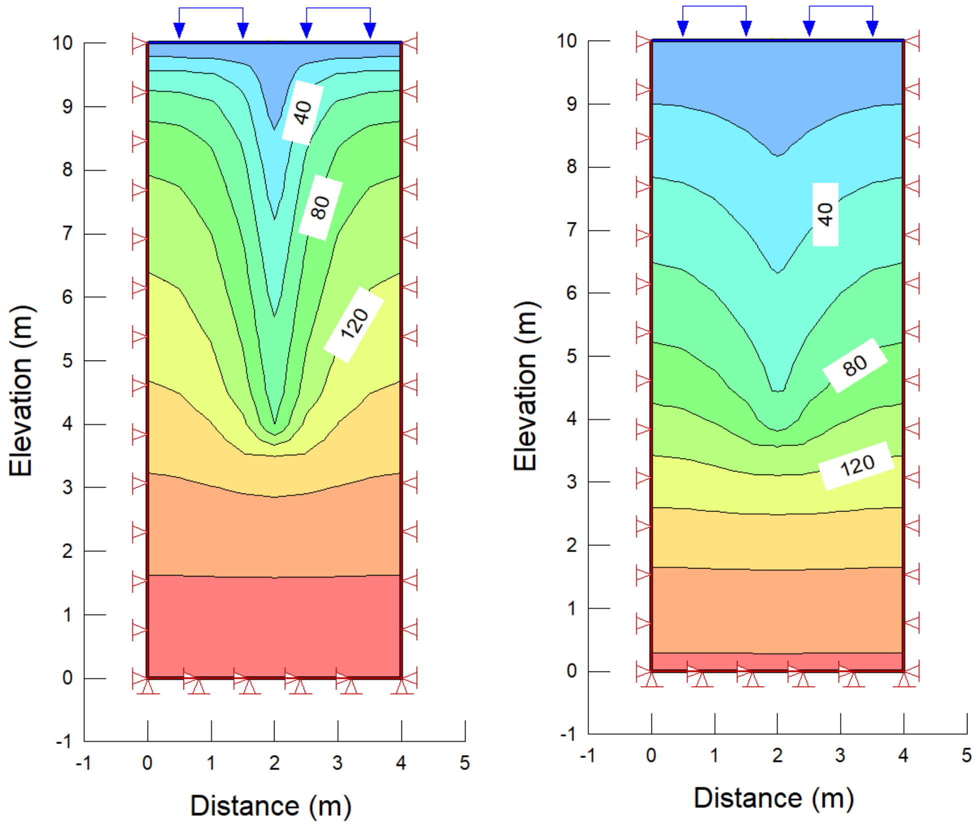


Figure 5. Pore-water pressure distributions on Day 1 (left) and Day 6 (right).

Another way of inspecting the changes is to look at a section across the cell. Figure 6 shows the changes in pore-water pressure with time along a cross-section at Elevation 7 m.

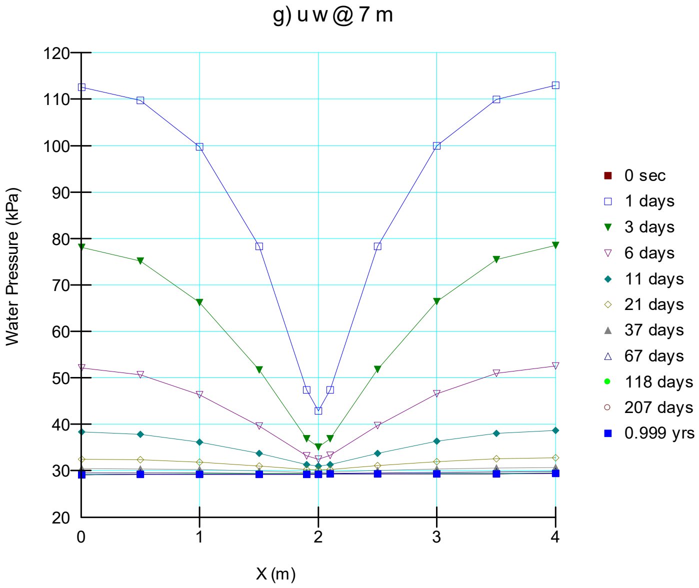


Figure 6. Pore-water pressure changes at elevation 7 m.

Wick drains are usually only about 100 mm wide, and are installed on a square or triangular pattern. They act somewhat like closely spaced wells in plan view, with overlapping radial flow to the wells. Research has been done by several people on how to convert the 3-D radial flow into an equivalent flow for a 2-D finite element analysis. A reasonably good summary of the research has been presented by Indraratna and Redana (2000). In the end, they come to the conclusion that for a 2-D finite element analysis, the effective thickness can be taken as the average of the drain thickness and the width. In equation form, the effective thickness d_e is:

$$d_e = \frac{(t+w)}{2}$$

Equation 1

In the SIGMA/W formulation, the hydraulic conductivity of the drain itself comes into the calculations, and the solutions are much more sensitive to the conductivity than to the actual thickness (cross-sectional area). So, in this sense, d_e is not all that significant to the solution – the K values are usually more important.

Resistance to flow within the wick drain (sometimes described as well resistance) can be accounted for in a SIGMA/W analysis with a longitudinal conductivity. Usually wick drains are vertical. A hydraulic conductivity function in SIGMA/W by default gives K_x . K_y is obtained by specifying a conductivity ratio. For a vertical drain, K_l or K_y then is K_x times the specified ratio.

Sometimes it is convenient to make the interface elements thicker than d_e. This makes it easier to see the elements, to select the elements for assigning material properties, and to select nodes along the interface elements for graphing.

The true longitudinal drain conductivity (K_l) can be adjusted for an artificially thick interface element. The amount and resistance to flow in the artificial drain size must be the same as the actual drain. Keeping the hydraulic gradient (i) constant, the conductivity must be adjusted in proportion to the ratio of the areas (thicknesses). If the artificial thickness is 2 times the actual thickness, the artificial conductivity needs to be divided by 2, for example.

It is rather difficult to create elements that represent the smear zone. It is more convenient to model the effect of a smear zone by treating the soil as a layered system with a blended horizontal conductivity.

With flow across a layered system, the less permeable layer can quickly dominate the head loss and, in turn, govern the flow behavior. Consider the simple layered system in Figure 7. Each segment is 1 m long. A total head (H) of 10 m is applied on the left end, and a total head of 1.0 m on the right end. The conductivity of the right segment is 10 times less than on the left. The head loss distribution across the system is as shown in Figure 8. Note that most of the head loss occurs in the less conductive material, and also that the gradient is much higher in the less conductive material. In other words, the less conductive material on the right essentially governs the flow.

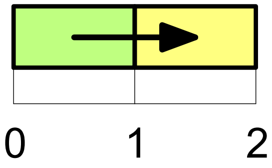


Figure 7. Flow in a layered system.

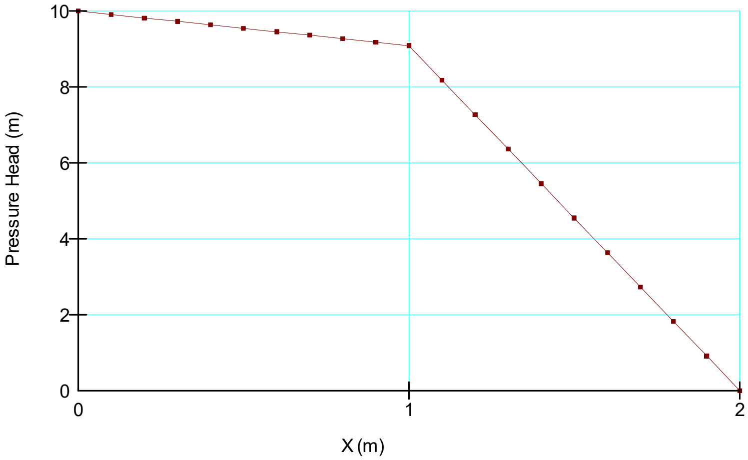


Figure 8. Head loss distribution in a layered system.

For a layered system like this we can compute an equivalent conductivity as follows (Freeze and Cherry; 1979):

$$K = \frac{d}{\left(\frac{d_1}{K_1} + \frac{d_2}{K_2}\right)}$$

Equation 2

Say d_1 is 1 m, d_2 is 1 m, K_1 is 10 m/sec and K_2 is 1 m/sec. The blended equivalent K then is 1.818 m/sec.

We can use this information to represent the conductivity of the native clay together with the smear zone, rather than create separate geometric regions for the two different zones. This makes numerical modeling easier.

The implication for our analysis here is that the smear zone around the drain dominates the dissipation of the pore-water pressures and, in turn, the rate of consolidation.

If you are going to model the effects of a wick drain, we strongly recommend that you start with one cell, as illustrated by the example presented here. This allows you to refine all of the input and understand the influence of the various parameters before moving on to a 2-D field case.

In a real field case, a drainage blanket is usually placed on the surface after the drains have been installed to allow the water coming from the drains to flow laterally to some discharge point. There are several ways to model this. One way is to actually include a region with sand properties, as shown in Figure 9. Another way is to include a horizontal interface layer with sand properties, as in Figure 10.

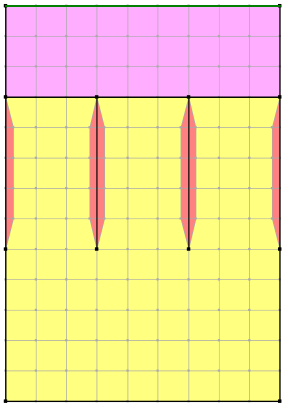


Figure 9. Layout with granular layer above the drains.

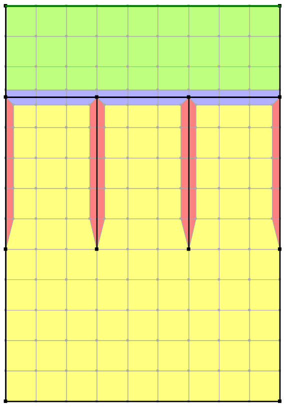


Figure 10. Layout with horizontal interface layer for lateral drainage.

A third way is to specify a head-type or pressure-type boundary condition along the region edges at the top of the drains, if it is considered that there is no or very little resistance to lateral flow at the original ground surface. This is what was done in the wick drain cell analyzed here. The interface regions are actually made up of rectangular elements along most of the length, and triangular elements at the ends.

Numerically, the triangular elements at the ends are perfectly acceptable for a case like this. All finite element equations are formed at the nodes, and therefore the flow (Q) is computed at the nodes. Numerically, flow does not cross the element edges; all edge flows are converted into nodal flow in a finite element formulation. So, while the triangular elements perhaps do not fully represent the physically reality, they are nonetheless mathematically acceptable for this application.

Looking at it another way, the pointed ends of the interface elements do not impede the longitudinal flow exiting the drain. At the top, often the head is specified, and at the bottom, it is highly unlikely that the end of the wick drain remains unclogged after the installation.

Summary and Conclusions

This example is intended to present procedures and techniques that should allow you to create your own models of actual cases. The material properties selected here are totally arbitrary, for demonstration purposes. It is up to you to select and use appropriate properties suitable for your particular project.

References

Freeze, R.A. and Cherry, J.A. (1979); *Groundwater*, Prentice-Hall, pp. 32-34.

Indraratna, B. and Redana, I.W. (2000); Numerical modelling of vertical drains with smear and well resistance installed in soft clay. Canadian Geotechnical Journal, No. 37, pp. 132-145.