GeoStudio Example File
Anisotropy in embankments

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Introduction

Laboratory tests on stratified materials usually reveal values of hydraulic conductivity that are different in the horizontal and vertical directions. This can occur in lacustrine or marine deposits, or in materials compacted in layers, such as in embankment dams. The higher conductivity tends to occur parallel to the stratification. This makes the hydraulic conductivity anisotropic; that is, the conductivity is not the same in all directions. Anisotropy at the laboratory scale is readily understandable. As illustrated in Figure 1, layering can easily extend from one side of the sample to the other. The horizontal conductivity of such a sample can be significantly higher than the vertical conductivity.

Figure 1. Illustration of a stratified laboratory sample.

The significance of laboratory measurements of anisotropy at the field scale is, however, questionable. The purpose of this document is to explore this issue and make recommendations on using the anisotropic feature in SEEP/W. The example includes four analyses: a homogeneous and isotropic embankment dam, a homogeneous and anisotropic embankment dam, a heterogeneous embankment dam with continuous layers, and a heterogeneous embankment dam with discontinuous layers.

Numerical Simulations

Let us start by considering seepage through a homogeneous and isotropic embankment dam. Figure 2 shows the 20-meter-high silty clay embankment dam with 2:1 side-slopes in which the downstream face is protected from seepage erosion by a toe drain.

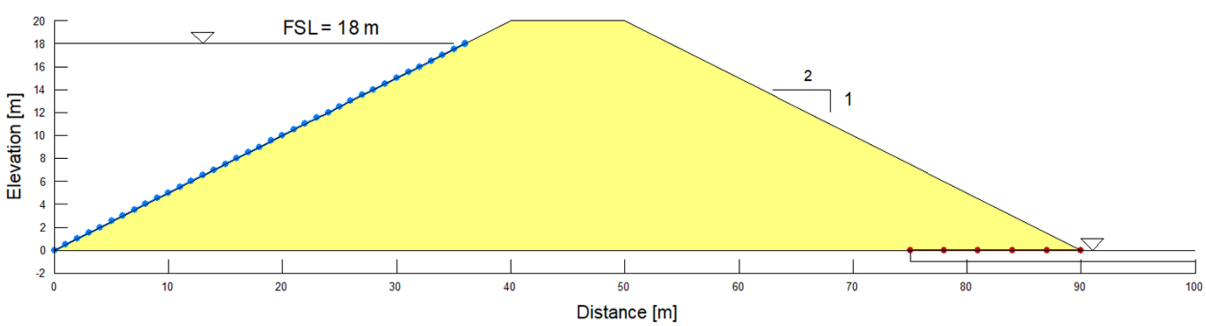

Figure 2. Homogeneous and isotropic dam.

SEEP/W has the capability of considering hydraulic conductivity anisotropy. The effect is specified as:

$$K_{y'} = K_{y'}/K_{x'} \times K_{x'} \qquad \text{Equation 1}$$

where $K_{x'}$ is always specified and $K_{y'}$ is always computed from $K_{x'}$ and the specified anisotropy ratio ($K_{y'}/K_{x'}$). Figure 3 shows the dialog box for the anisotropy ratio in the saturated/unsaturated material model. A ratio of two means $K_{y'}$ is two times greater than $K_{x'}$ while a ratio of one-tenth means $K_{x'}$ is ten times greater than $K_{y'}$. It is important to understand the physical significance of this ratio as it implies that the material is perfectly stratified; that is, all layering extends from the left to the right-hand side of the domain and that the layering is the same throughout the embankment.

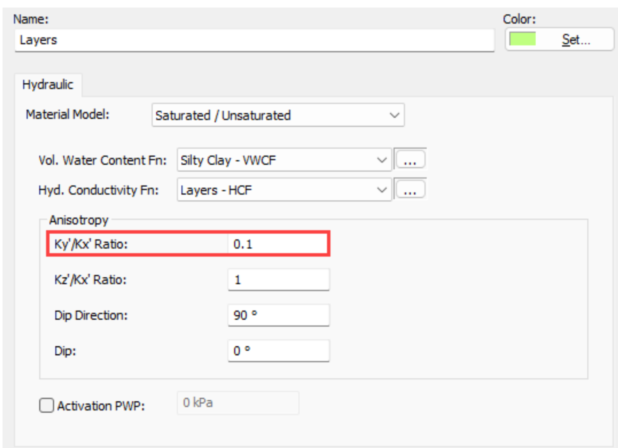

Figure 3. Applying anisotropy to the saturated/unsaturated material model.

Another way of looking at anisotropy is to consider a series of layers. As shown in Figure 4, each layer (in green) is 0.33 meters-thick with a horizontal conductivity ten times greater than the vertical conductivity, which is equal to that of the silty clay (in yellow).

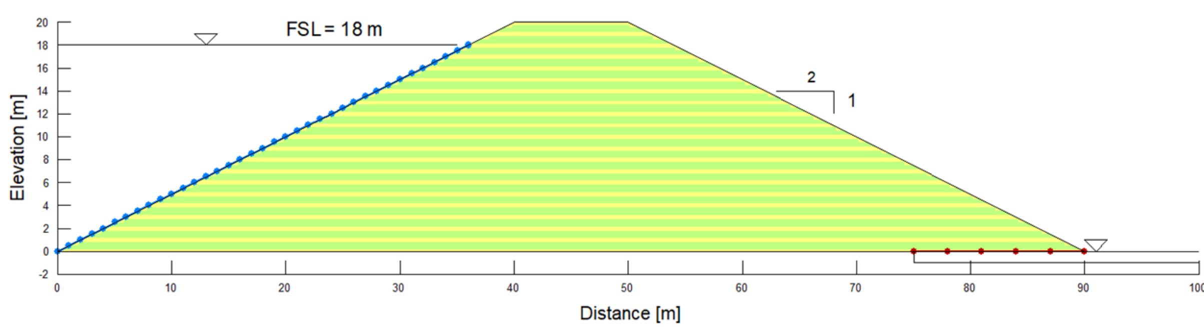

Figure 4. Heterogeneous embankment dam with continuous conductive layers.

Although solution to these steady-state problems does not require a volumetric water content function, a function is created for use in estimating the hydraulic conductivity functions. Figure 5 shows the volumetric water content function which is estimated using the sample silty clay material with a saturated volumetric water content of 0.5. The hydraulic conductivity functions of the silty clay and pervious layers, shown in Figure 6, are estimated using van Genuchten's model with a saturated hydraulic conductivity of 1×10^{-4} and 1×10^{-3} m/s, respectively.

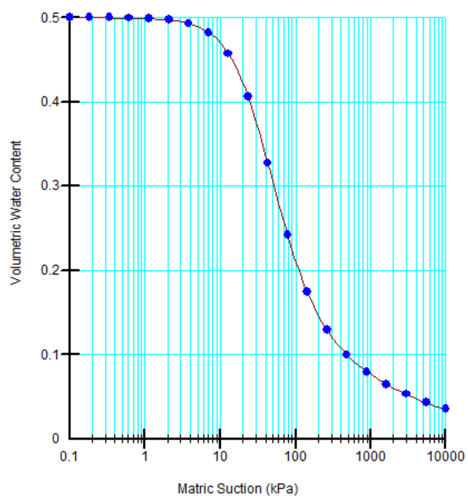

Figure 5. Volumetric water content function of the silty clay material.

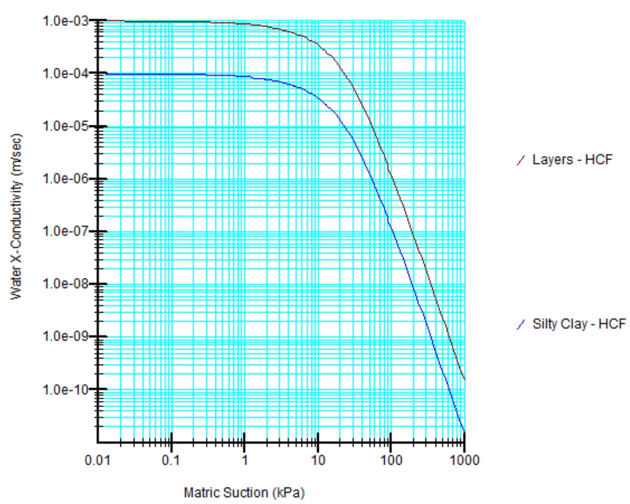

Figure 6. Hydraulic conductivity functions of the silty clay and pervious layer materials.

Results and Discussion

Figure 7 shows the classic solution for flow through a homogeneous dam. In this case, the flow paths cross the near vertical total head contours (or equipotential lines) at ninety degrees. These flow paths correspond to the trajectories that water particles would follow from the reservoir to the toe drain and should not be confused with the flow lines that appear in a flow net. The dashed line corresponds to the phreatic surface, and more specifically, the zero pressure contour. As shown in the figure, one of the flow paths crosses the phreatic surface and thereby confirms that the phreatic surface is not a flow boundary in the saturated/unsaturated flow system. In this case, the flow rate through the centerline of the dam is equal to 3.83×10^{-4} $m^3/s/m^2$.

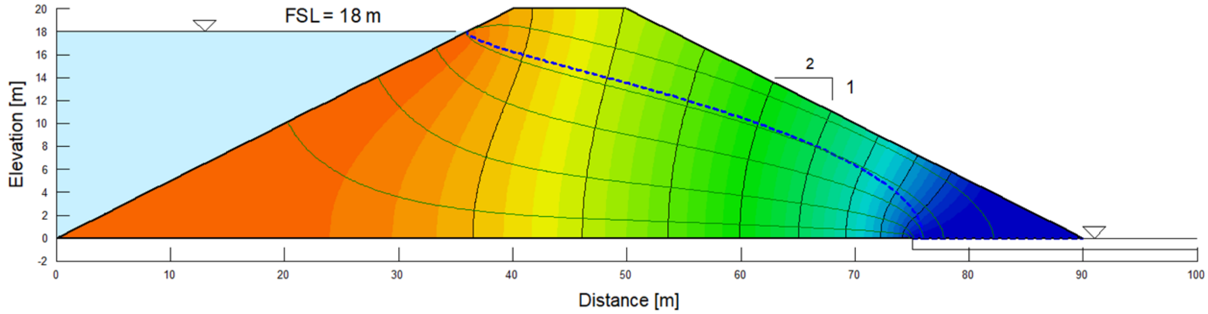

Figure 7. Flow through the homogeneous and isotropic embankment dam.

Let us now consider how the flow regime changes in the presence of a series of continuous layers. As shown in Figure 8, the flow is much more lateral as water moves through the more pervious layers. The total head contours are no longer near vertical, and the flow paths no longer cross the contours at ninety degrees. The pervious layers also increase the flow rate through the centerline of the dam, which is now equal to 1.33×10^{-3} m³/s/m².

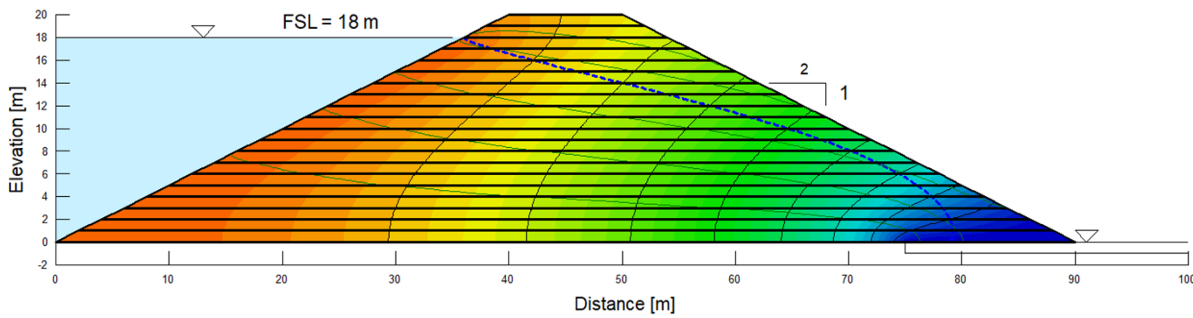

Figure 8. Flow through the heterogeneous embankment dam with continuous conductive layers.

In this case, the effective hydraulic conductivity parallel to the continuous layers can be computed using a weighted arithmetic mean:

$$K_{x'} = \sum_{i=1}^{N} A_i K_{x'i} \qquad \text{Equation 2}$$

where A_i and $K_{x'i}$ are the cross-sectional area and hydraulic conductivity of the ith layer, respectively. Adopting this equation results in a hydraulic conductivity of 4×10^{-4} m/s and an anisotropic ratio of 0.25. Solving the analysis with these hydraulic properties results in a phreatic surface and equipotential lines that are nearly identical to those of the heterogenous embankment dam with continuous layers. As shown in Figure 9 the flow paths are slightly different due to the absence of layers. The flow rate through the centerline of the dam, which is equal to 1.33×10^{-3} m³/s/m², is nearly identical to that found in the presence of continuous layers. These results highlight the equivalency of both scenarios. In this case, the field scale anisotropy can be captured in the laboratory using one-meter-thick samples. This is somewhat prohibitive and suggests that common (small scale) laboratory tests may not be representative of actual field conditions.

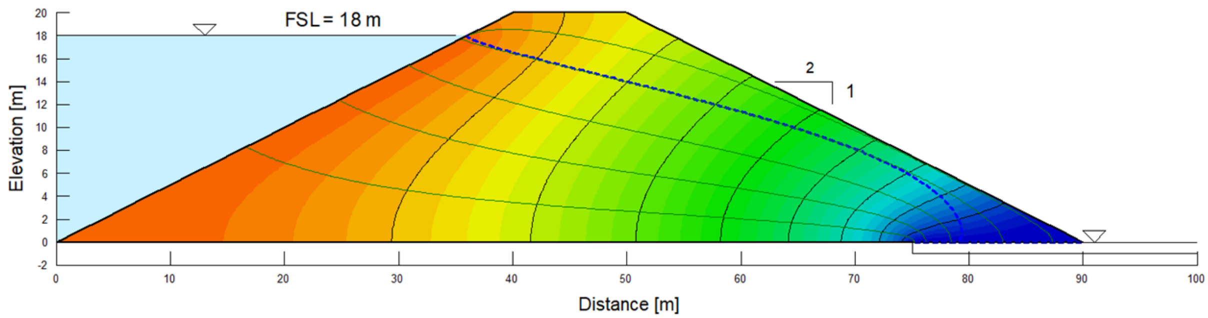

Figure 9. Flow through the homogeneous and anisotropic embankment dam.

Although more related to heterogeneity than anisotropy, the continuity of the layers may also have a significant impact on the results. Figure 10 shows the layer segments as well as the total head contours, flow paths, and phreatic surface. The total head contours and flow paths are jagged, but similar to those found in the homogeneous and isotropic dam. This similarity is also reflected in the flow rate through the centerline of the dam, which is equal to 5.57×10^{-4} $m^3/s/m^2$. The discontinuity of the layers basically removes most of the effect of anisotropy. This imperfect layering, or stratification, is likely to occur in the field and suggests that laboratory measurements may not be representative of field conditions.

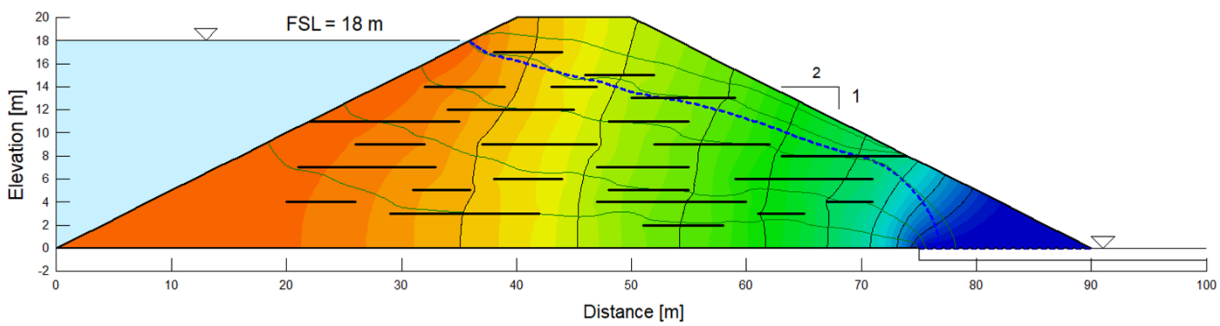

Figure 10. Flow through the heterogenous embankment dam with discontinuous conductive layers.

Summary and Conclusions

The results presented here demonstrated that great care needs to be exercised when using anisotropy ratios in seepage analyses. This mostly stems from a general misunderstanding of anisotropy and the fact that laboratory measurements of anisotropy may not be representative of actual field conditions. It was also found to be preferable to start with an isotropic scenario that provides a baseline understanding of the flow field and then gradually introduce anisotropy to account for real-world complexities.