Anisotropy in embankments

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Introduction

Laboratory tests on stratified materials usually reveal values for 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 scale of laboratory tests is readily understandable. Layering can easily extend from one side of the sample to other, as in illustrated in the Figure 1. The horizontal conductivity of such a sample could be significantly higher than the vertical conductivity.

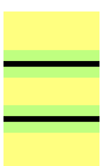

Figure 1. Illustration of a stratified laboratory sample.

The significance of laboratory measured anisotropy in field flow systems is, however, questionable. The purpose of this document is to explore this issue and to make some recommendations on using the anisotropic feature in SEEP/W. The example included three analyses: a homogenous embankment; an anisotropic embankment; and a homogeneous embankment with anisotropic layers.

Numerical Simulation

Let us start by considering seepage through a homogeneous embankment, as shown in Figure 2. The embankment is 20 m high with 2:1 side slopes. The downstream face is protected from seepage erosion with a toe under-drain.

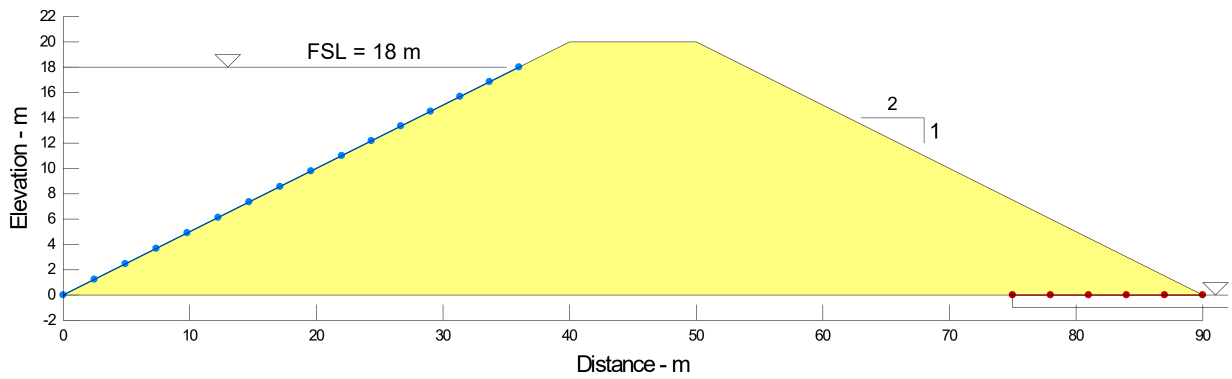

Figure 2. Homogeneous dam configuration.

SEEP/W has the capability of considering an anisotropic coefficient. The effect is specified as:

$$K_y = ratio * K_x \quad \text{Equation 1}$$

K_x is **always** specified and K_y is **always** computed from K_x and the specified ratio. A ratio of 2, for example, means K_y is two times greater than K_x, while a ratio of 0.1 means K_x is 10 times greater than K_y.

In SEEP/W, using the anisotropy ratio physically means that the material is perfectly stratified; that is, all layering extends from the left side to the right side of the model domain and that the layering is the same throughout the embankment. It is important to understand the physical significance of this ratio (Figure 3).

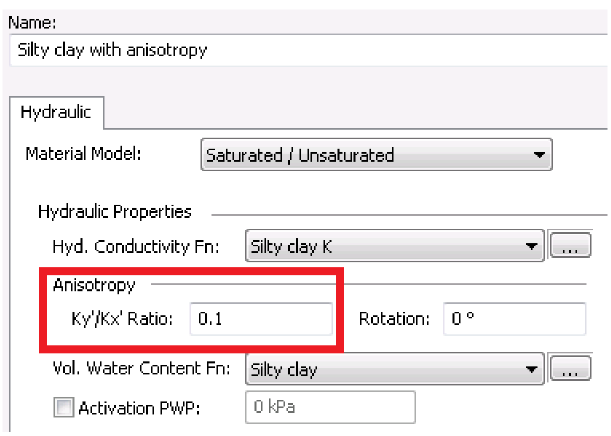

Figure 3. Applying anisotropy to the silty clay material.

Another way of looking at anisotropy is to consider a series of layers as shown in Figure 4. Each layer is 0.2 m thick with a horizontal conductivity 10 times greater than the homogeneous conductivity and an anisotropic ratio of 0.1 (i.e. $K_x = 10*K_y$).

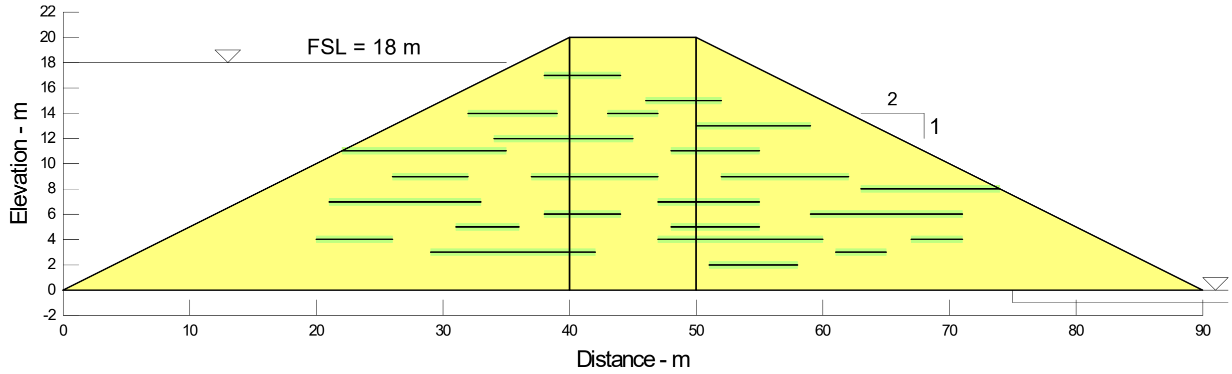

Figure 4. Embankment with highly conductive layers.

Although all three of the analyses were steady-state simulations that do not require a volumetric water content function, a function was created for use in estimating the hydraulic conductivity functions. The same volumetric water content function was applied to all materials used in each of these analyses. The volumetric water content function was defined using the internal estimation algorithms within SEEP/W, with the silty clay material and a saturated water content of 0.5 (Figure 5).

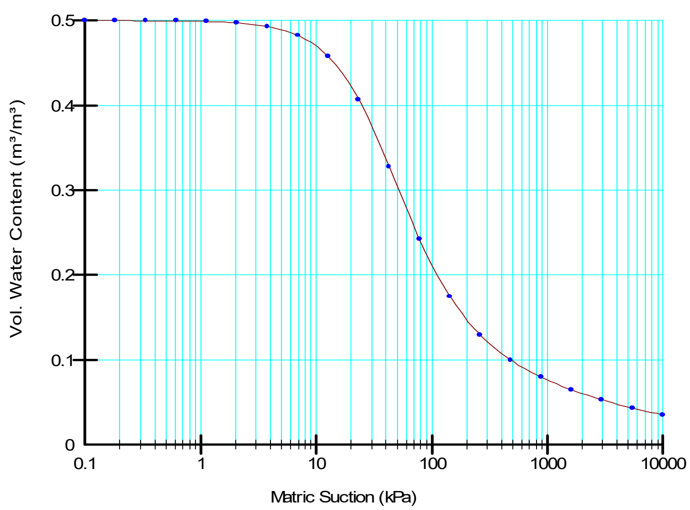

Figure 5. Volumetric water content function for silty clay material.

Three material types were defined. The first was the homogeneous material, with the silty clay volumetric water content and a hydraulic conductivity function with a saturated hydraulic conductivity of $1x10^{-4}$ m/sec (Figure 6). The second analysis used a clone of this homogeneous material, with only the anisotropy ratio varying from 0.01 to 0.5. The third analysis defines a second hydraulic conductivity function with the saturated hydraulic conductivity defined as $1x10^{-3}$ m/sec, with the anisotropy ratio set to 0.1.

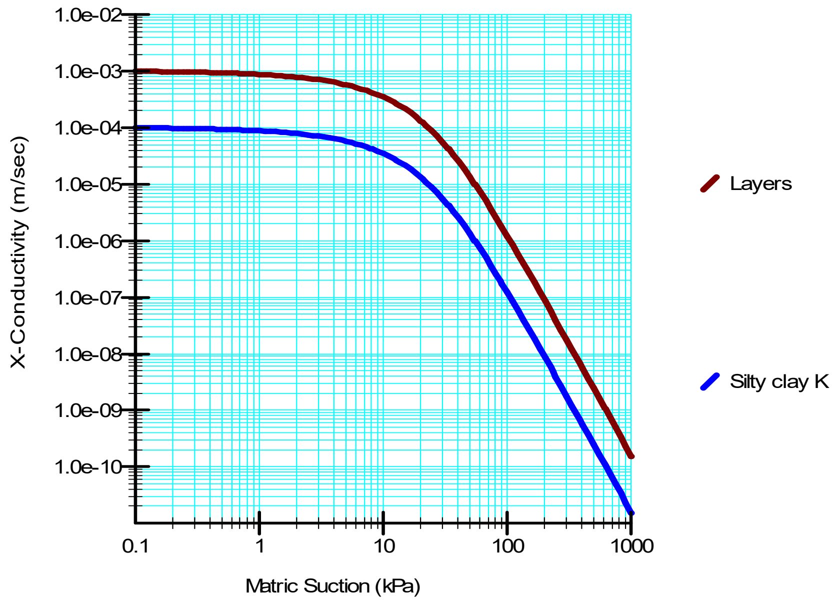

Figure 6. Hydraulic conductivity functions for the silty clay and layer materials.

Results and Discussion

The classic solution for flow through a homogeneous dam is shown in Figure 7. The total head contours or equipotential lines (labelled) are nearly vertical. Several flow paths are also shown on the figure. These are the paths a droplet of water would follow from the reservoir to the drain. Note, these are not flow lines as in a flow net.

The dashed line is a contour of zero pressure or what is often referred to as the piezometric line. Notice that one of the flow paths crosses the piezometric line, which confirms that the zero pressure line is not a flow boundary in a saturated-unsaturated flow system.

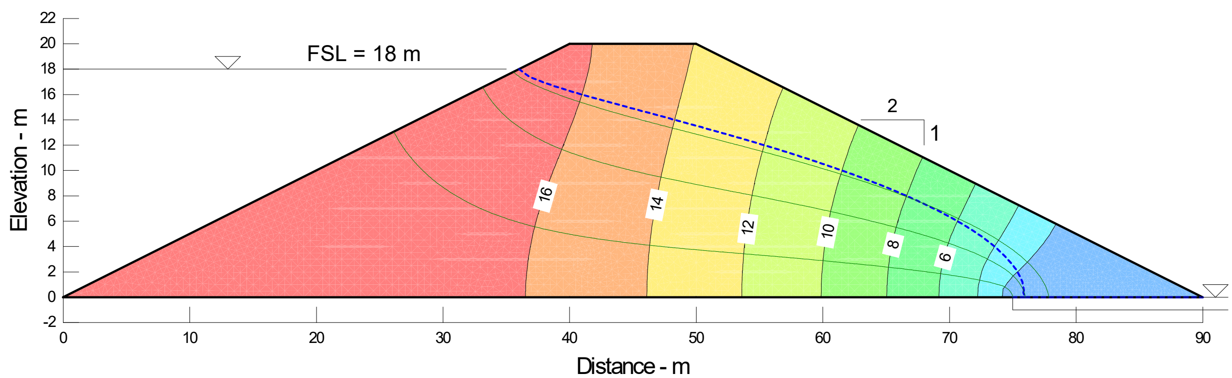

Figure 7. Flow through a homogeneous dam.

Now let's consider how the flow regime might change if the homogenous material became anisotropic. The following diagrams show the effect of various anisotropic ratios used in the Define Materials window. It is evident that the flow tends to be more lateral as the horizontal conductivity increases relative to the vertical conductivity. The flow is almost totally horizontal as the ratio becomes 0.01 (i.e. K_x is 100*K_y; Figure 12).

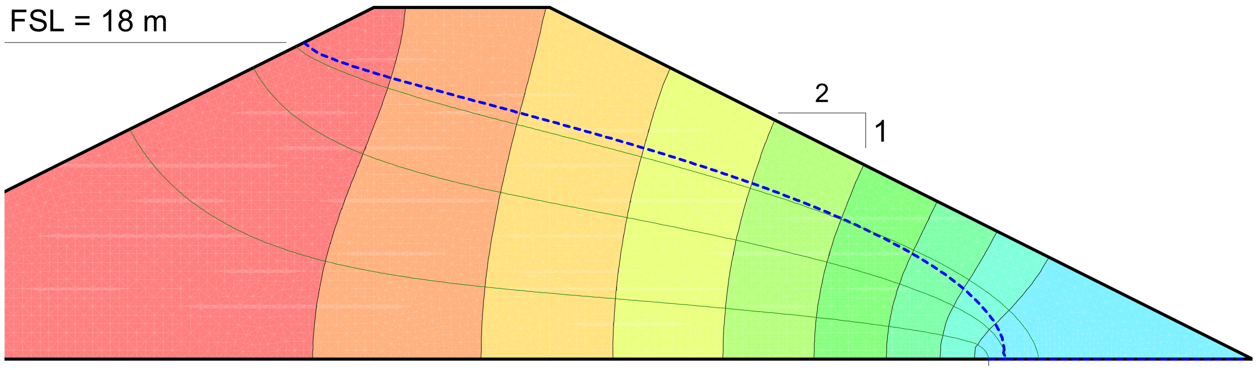

Figure 8. Flow with anisotropic ratio equal to 1.0 (homogeneous case).

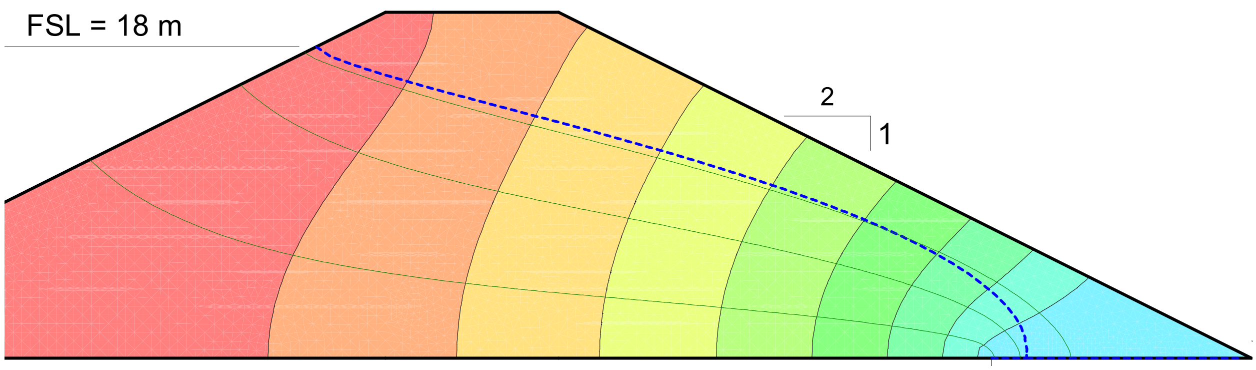

Figure 9. Flow with specified anisotropic ratio equal to 0.5; $K_y = 0.5\ K_x$ or $K_x = 2\ K_y$.

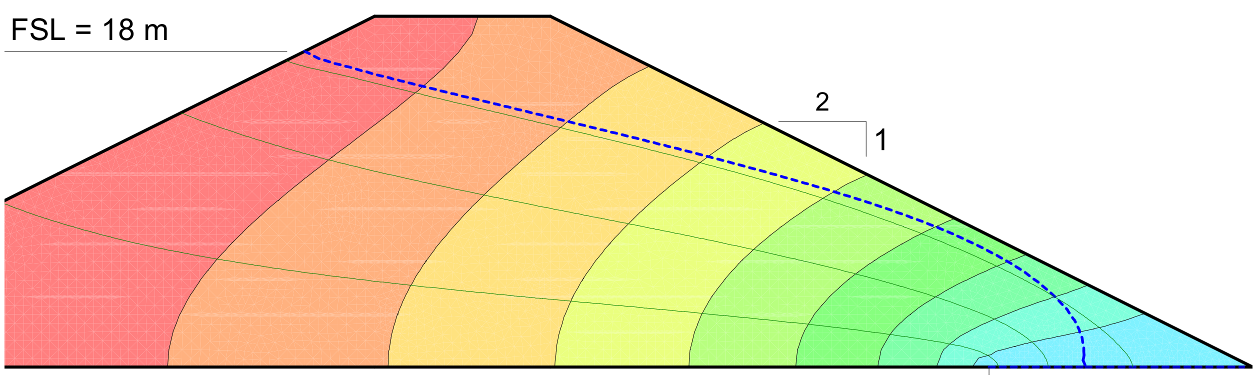

Figure 10. Flow with specified anisotropic ratio equal to 0.2; $K_y = 0.2\ K_x$ or $K_x = 5\ K_y$.

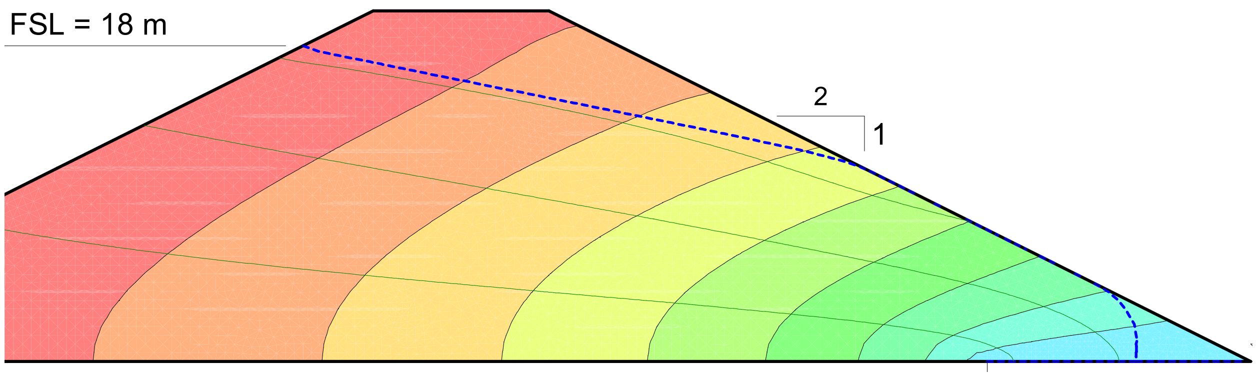

Figure 11. Flow with specified anisotropic ratio equal to 0.1; $K_y = 0.1\ K_x$ or $K_x = 10\ K_y$.

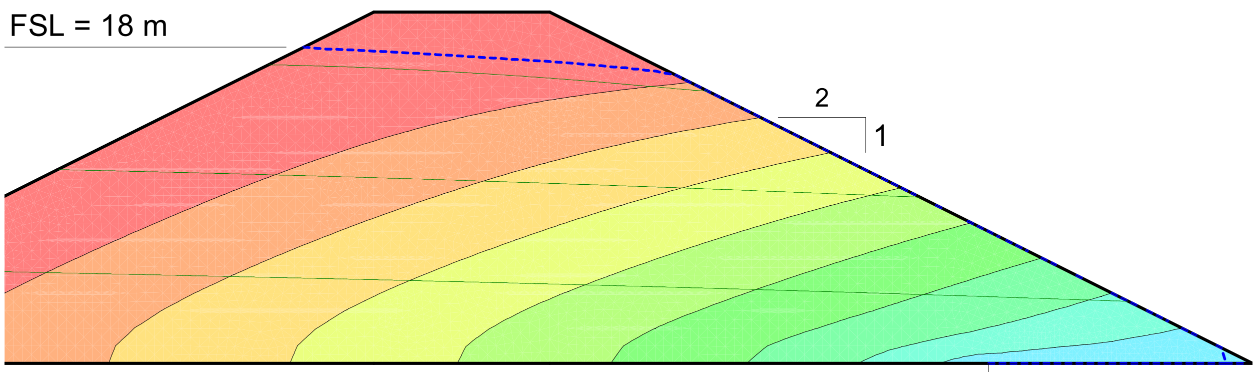

Figure 12. Flow with specified anisotropic ratio equal to 0.01; $K_y = 0.01\ K_x$ or $K_x = 100\ K_y$.

Anisotropic ratios from laboratory tests as high as 10 or even approaching 100 are not uncommon. Such high values when applied to field situations, however, can result in unrealistic solutions. It is doubtful that even a modest ratio of 10 will create a seepage face on the downstream slope, as depicted in Figure 11. This suggests that laboratory measured anisotropic ratios are not representative of actual field conditions. Stated another way, the stratification or layering is likely not perfect or not continuous in the field.

The result of considering the anisotropy as layers is shown in Figure 13. Although the equipotential lines and flow paths have kinks, the overall pore-water pressure distribution is similar to the homogeneous case presented above in Figure 8. The zero pressure contour or piezometric line, in particular, is nearly the same as for the homogenous case.

The pressure distribution is not altered significantly because the layers are not all connected and continuous. Considering the anisotropy as highly conductive but discontinuous layers is likely much closer to the actual field conditions than specifying an anisotropic ratio.

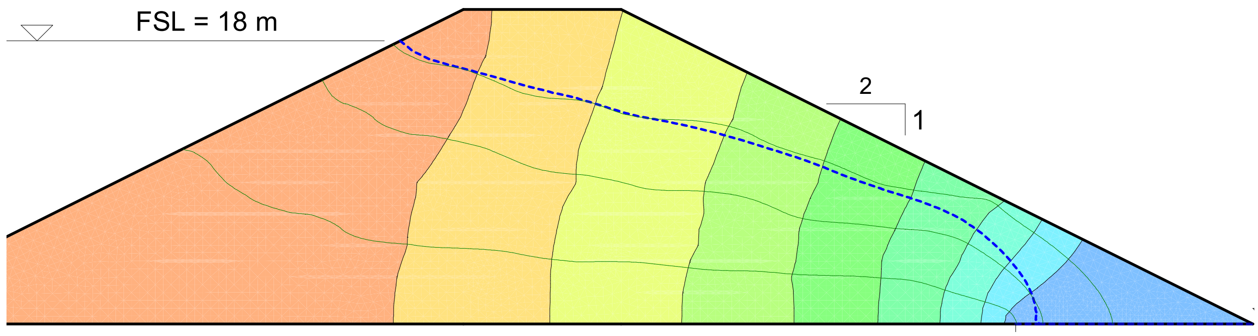

Figure 13. Flow system with conductive layers.

Summary and Conclusions

The results presented here demonstrate that great care needs to be exercised when anisotropic ratios are specified in a seepage analysis. Laboratory measured anisotropy may not be representative of the actual field conditions. If anisotropy is considered to be an issue, then it is mandatory that you start with no anisotropy to firmly establish the flow regime. The results should be reasonable and logical with no anisotropy.

Once the non-anisotropic condition has been firmly established, you should investigate the effect of anisotropy in a series of steps. For example, start with a ratio of 2 (or 0.5), then maybe increase the ratio to 5 (or 0.2), then increase the ratio to 10 (or 0.1) and so forth. By the time you reach a ratio of 10 or 0.1, the results may already be unreasonable, as above in Figure 11.

If you specify a ratio of 100 (or 0.01) on the very first run, you will, in all likelihood, not be able to interpret the results. Good modeling practice dictates that you must always start with the non-anisotropic case to establish a clear reference point and then apply the anisotropic ratio in small gradual steps.

If using laboratory measured anisotropic ratios do not give reasonable results, then in all likelihood, the laboratory measured values are not representative of actual field conditions.

In conclusion, the anisotropic ratio in SEEP/W must be specified with careful thought and caution.