21- Anisotropic Material Models

The anisotropic models in RS2 and RS3 are major extensions of the Jointed Rock Model. The jointed rock model that is described in section 9 could utilize a Mohr Coulomb or a Generalized Hoek Brown criterion for the matrix and up to 3 different criteria for joints. The shear strength of joints or weak planes could be described by any of the three criteria of Coulomb, Barton-Bandis and Hyperbolic. The jointed material models, described in section 9, are kept in the library of anisotropic model, but the new models are far more versatile.

Further motivation for the development of these models arise from Rocscience's intention to extend the compatibility between their slope stability tools. Slide and Slide3, two of the slope stability analysis tools developed by Rocscience, take advantage of the Limit Equilibrium approach in calculations of the Factor of Safety. The library of anisotropic failure criteria in this two software is very extensive. The Finite Element method with association with the Shear Strength Reduction (SSR) method provides a very powerful method for analysis of slope stability problems and evaluation of factor of safety as well. RS2 and RS3, the two Rocscience's finite element software, offer the SSR method. With the addition of Anisotropic Material Models, an equivalent anisotropic material models library in RS2 and RS3 is develop in a way to provide equivalents of all the failure criteria as in Slide and Slide3.

The Anisotropic Material Models use the multi-yield plasticity formulation that takes one failure criterion for the matrix and virtually unlimited number of joints. The criteria to choose form for the matrix and joints could be any of the criteria that are available in the Elastic/Plastic and Slide Material models lists. Note that in general the matrix or the base material is stronger than the joints.

The Anisotropic Material Models, their formulations and special considerations are presented below. These models can take advantage of various elastic (stiffness) options in RS2 and RS3 that are included linear and nonlinear isotropic, transversely isotropic and orthotropic elasticity.

21.1- Anisotropic Linear

The Anisotropic Linear strength model (Snowden, 2007) allows you to define a material with the following anisotropic strength characteristics:

- Bedding plane cohesion and friction angle
- Rock mass cohesion and friction angle
- Angle of bedding plane from horizontal

It is assumed that the joints are present within the range of parameters A around the main orientation of the bedding planes defined above, and there is a linear transition from bedding planes strength to rock mass strength that happens in range B.

The relationship between shear strength and alpha angle is illustrated in the Figure 21.1.

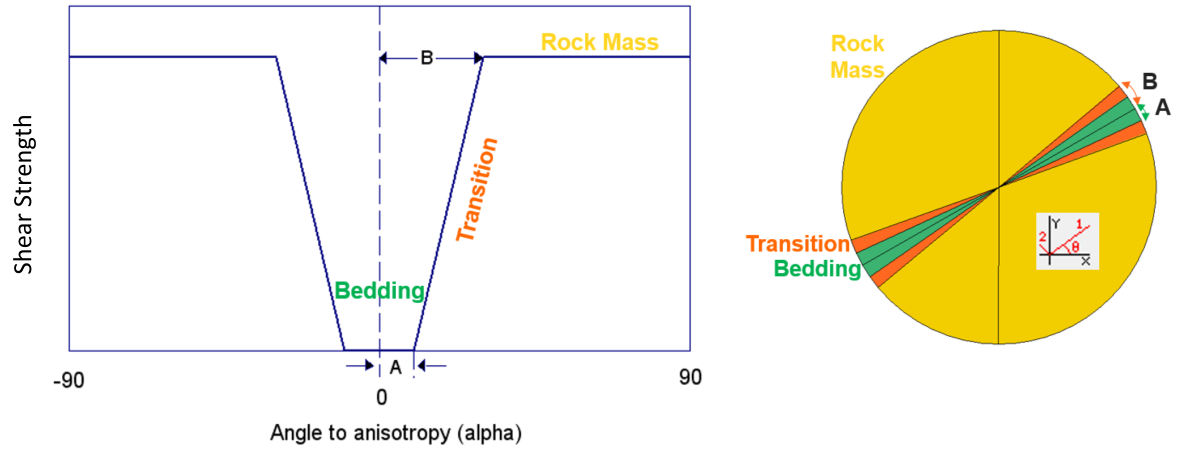

Figure 21.1- Symmetric anisotropy function for Anisotropic Linear model

For the Anisotropic Linear strength model there are two methods of defining the direction of the anisotropy:

1- Angle
2- Surface

If the Anisotropy Definition is set to Angle, then the direction of anisotropy is constant and defined by a single angle which is entered in the Angle (ccw to 1) edit box. If the Anisotropy Definition is set to Surface, then the direction of anisotropy can be variable and defined by an Anisotropic Surface.

An Anisotropic Surface (see Figure 21.2) is used to determine the local orientation of anisotropy. The orientation for each Gaussian integration point will be the tangent to anisotropic surface at anode on the surface that is closest to the gaussian integration point.

The multi-yield model of the Anisotropic Linear model consists of a matrix that uses a Mohr Coulomb criterion for the rock mass strength and at least a Coulomb joint that takes the bedding strength. If the A range is greater than zero, more joints with the same strength characteristics are populated within this range. If the B range is greater than zero two more joints will be generated at midpoint of this range on both sides of the main anisotropy orientation.

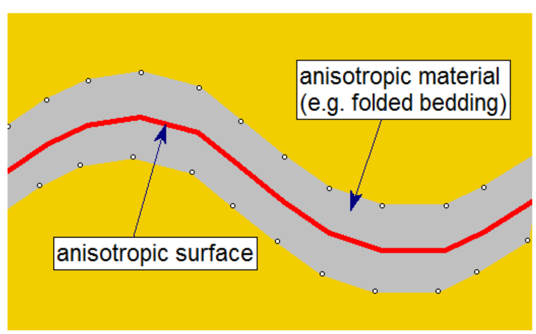

Figure 21.2- Using the Surface option in definition of beddings orientation

The residual values can be considered for the strength of rock mass and beddings. Peak and residual tensile strengths can be applied to the rock mass and beddings. The dilation angle is set to zero for all the mechanisms of this multi-yield model.

21.2- Snowden Modified Anisotropic Linear Strength

The Snowden Modified Anisotropic Linear strength model is based on the Anisotropic Linear strength model, with the following additional features (Snowden, 2011):

1- allows you to define non-linear stress dependent strength envelopes for the rock mass and bedding material in a tabular format
2- allows non-symmetric anisotropy.

The Snowden Modified Anisotropic Linear model allows you to define a non-symmetric anisotropy function as shown in Figure 21.3, using four parameters A1, A2, B1 and B2. Compare this with the symmetric function for the Anisotropic Linear model in Figure 21.1 which only uses two variables A and B.

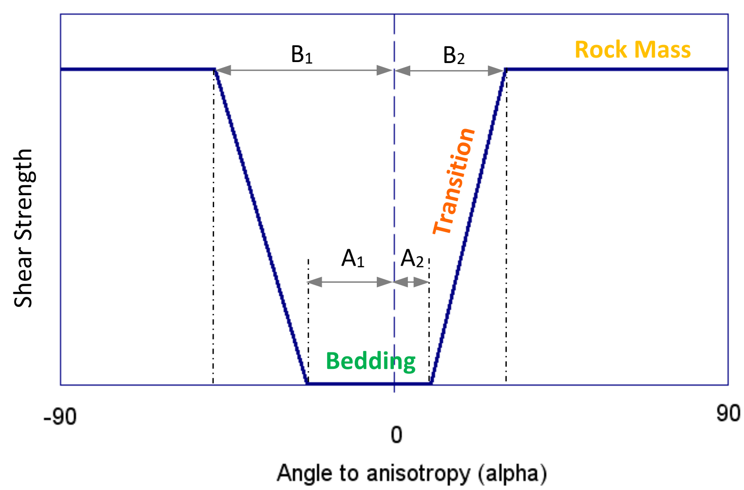

Figure 21.3 Non-symmetric anisotropy function for Snowden Modified Anisotropic Linear model

Both the Snowden Modified Anisotropic Linear model and the Anisotropic Linear model assume a linear transition between the bedding plane strength and the rock mass strength.

The original Anisotropic Linear model assumes constant values of cohesion and friction angle for the bedding and rock mass. For the Snowden Modified Anisotropic Linear model, non-linear strength functions can be defined for the bedding and rock mass using one of these two options:

1- Shear-Normal function
2- Cohesion-Friction function

Residual shear strength, peak and residual tensile strength are also considered for beddings and the rock mass.

There are two methods of defining the direction of the anisotropy:

1- Angle
2- Surface

If the Anisotropy Definition is set to Angle, then the direction of anisotropy is constant and defined by a single angle which is entered in the Angle (ccw to 1) edit box. If the Anisotropy Definition is set to Surface, then the direction of anisotropy can be variable and defined by an Anisotropic Surface.

An Anisotropic Surface is used to determine the local orientation of anisotropy. The orientation for each Gaussian integration point will be the tangent to anisotropic surface at anode on the surface that is closest to the gaussian integration point.

The yield functions in the mutli-yield model use the nonlinear functions defined for rock mass and beddings to calculate equivalent Mohr-Coulomb criteria with instantaneous friction angles and cohesions calculated based on the current stress state. The plastic flow rules take advantage of dilation ratios.

If the A1 and A2 ranges are greater than zero, more joints with the same strength characteristics are populated within these ranges. If the B1 and B2 ranges are greater than zero two more joints will be generated at midpoint of these range on the corresponding side of the main anisotropy orientation.

21.3- Generalized Anisotropic Strength

The Generalized Anisotropic Strength option allows you to create a composite material model in which you can assign any of the failure criteria in the Elastic/Plastic and Slide Material models lists. For example, as illustrated in Figure 21.4, you could create a material with Hoek-Brown properties over a range of orientations, and Mohr-Coulomb properties over another range of orientations.

The Generalized Anisotropic Strength option allows you to assign any combination of strength models to any ranges of orientation.

The first angular range always starts at –90 degrees (this is the default value of the FIRST Angle From value and cannot be edited by the user). The angular ranges must be ordered counter-clockwise, from –90 to +90. The last angular range always ends at +90 degrees (this must be entered by the user, as the LAST Angle To value). As the data is entered, the chart at the right of the dialog, will be updated to display the Generalized Anisotropic Function that is being defining.

Any range could be assigned for each material included in the definition of General Anisotropic model. Since the formation is based on the Jointed Rock, it is required to distinguish the rock mass and joints. Joints will be populated within the specified ranges in the definition of the Generalized Anisotropic model.

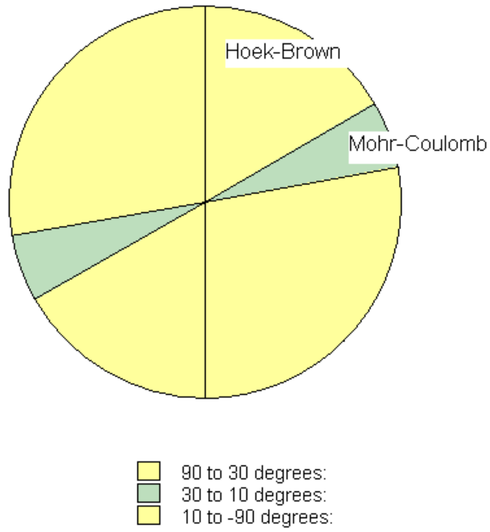

Figure 21.4- Example of Generalized Anisotropic Strength model

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