USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) in HEC-RAS User Manual - Draft v 1.1[1]

Background

HEC-RAS has included mobile bed capabilities since version 4.0. These capabilities have followed the HEC-6 approach that computes vertical bed changes in response to dynamic sediment mass balance and bed processes. However many riverine sediment problems involve lateral bank erosion that do not fit in this computational paradigm. There are a number of published methodologies for computing bank failure. These span a spectrum from basic angle of repose methods that require very few parameters but simplify bank processes considerably, to full blow geotechnical bank stability models that require a full suite of geotechnical parameters yet lack a framework for hydraulic toe feedbacks. The Bank-Stability and Toe Erosion Model (BSTEM) developed by the National Sediment Laboratory of the USDA's Agricultural Research Station is a physically based model that accounts for the dominant stream bank processes but requires an intermediate level of complexity and parameterization. This method was selected for implementation in HEC-RAS.

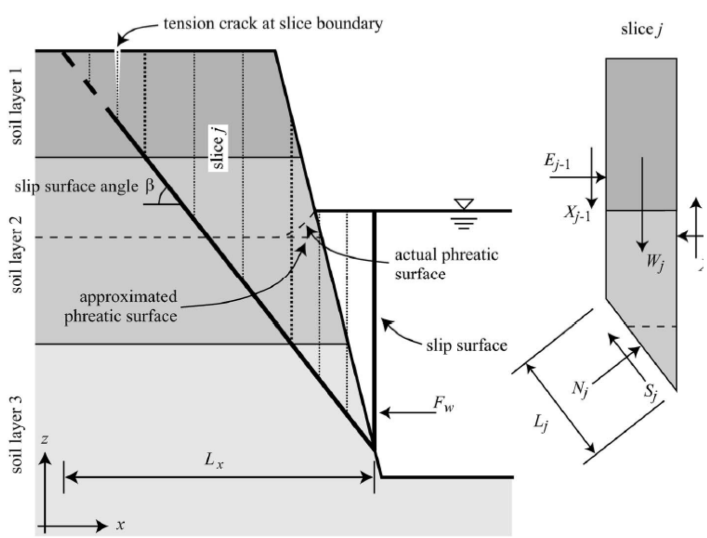


Figure 1: Schematic of the "vertical slice" method from Langendoen and Simon (2008) used in the current version of BSTEM in HEC-RAS.

BSTEM (Simon et al, 2000, Langendoen and Simon, 2008, Simon et al, 2010) couples iterative, planer bank failure analysis based on a fundamental force balance (Figure 1) with a toe scour model that allows feedback between the hydraulic dynamics on the bank toe which could

[1] This DRAFT document reflects interface and capabilities as of March 2013,

exacerbate failure risk (in the case of toe scour) or decrease failure risk (in the case of toe protection). The goal of coupling HEC-RAS with BSTEM is to build a model that simulates feedbacks between bed and bank processes. For example, if HEC-RAS computes decreases in the regional base level or local channel scour it will decrease bank stability and increase the risk of a failure. Similarly, when a bank does fail, the bank material will be added to the sediment mass balance of the mobile bed model which will simulate the river's capacity to 'metabolize' and transport these point sources.

Getting Started

BSTEM toe erosion and bank failure analysis will be performed as part of a sediment transport analysis on any cross section bank that has all the necessary parameters. Computing bank failure at every bank will increase run times. Therefore, it may be advantageous to only specify BSTEM parameters for banks that have a probability of failure.

To enter BSTEM Data open the **Sediment Data** editor. Bank failure analysis is currently only computed as part of a sediment transport analysis. So you will have to specify all of the standard sediment transport data by entering the **Initial Conditions and Transport Parameters** and **Boundary Conditions** tabs. Then move on to the third tab in the **Sediment Data** editor: **BSTEM Bank Failure Methods**.

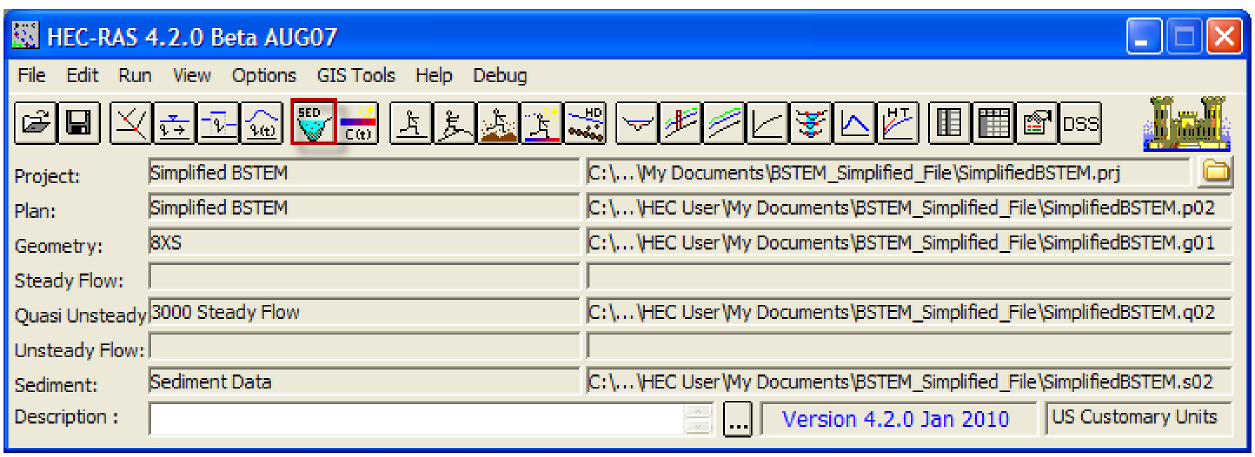


Figure 2: Sediment edit button on the main HEC-RAS editor.

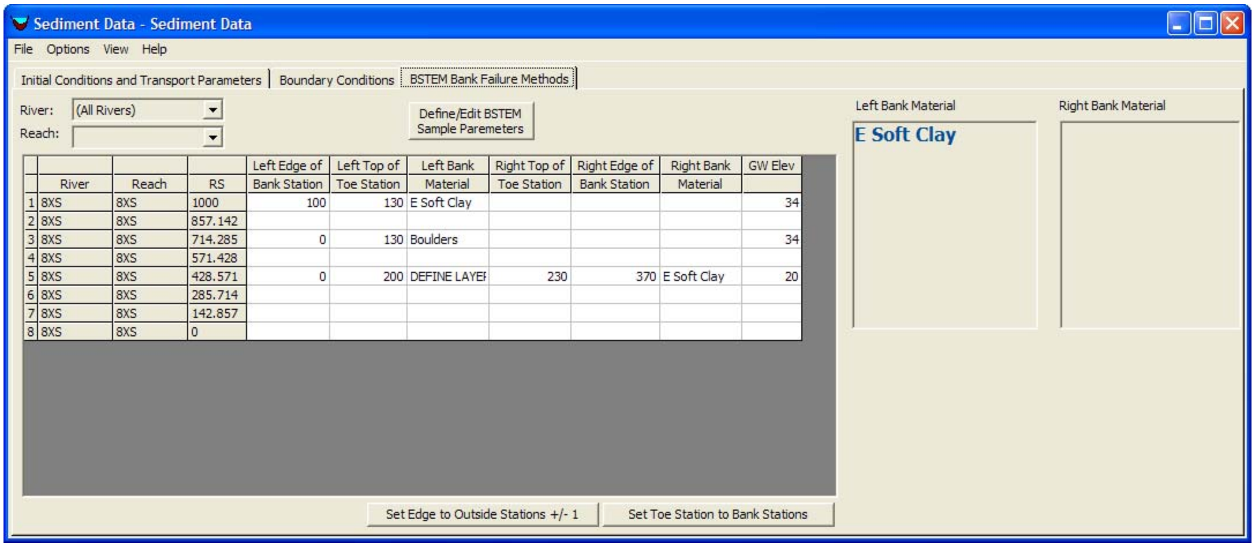


Figure 3: BSTEM parameter editor in HEC-RAS.

Defining Cross Section Configuration

Setting up a half-HEC-RAS cross section (for the left or right bank) in such a way that it is also compatible with BSTEM is an extremely important step in getting physically appropriate failures from the BSTEM computations. The conceptual BSTEM half cross section (Figure 4) is composed of four segments (green labels in Figure 4) with unique slopes:

i. The **Top of Bank** which is the relatively flat portion of the cross section above the bank.
ii. The **Bank** which is the steepest part of the cross section.
iii. The **Toe** which is a mild slope between the bank and the channel, presumably composed of blocks of material that have fallen and accumulated at the base of the bank and are protecting the toe or some sort of rip rap or toe protection.
iv. The **Channel** which is the region between the toe and the thalweg.

HEC-RAS divides a cross section at the thalweg and uses the station-elevation points to the left of the thalweg for the left BSTEM half-cross section and those to the right of the thalweg for the right BSTEM geometry. There are at least four important current considerations for setting up an HEC-RAS cross section to get good performance from the BSTEM routines.

1. The **Top of Bank** point should be either the first point in the cross section (for a Left Bank) or the last point in the cross section (for a Right Bank). This point should be far enough to the left or right (depending on which bank is being modeled) of the **Edge of Bank** to accommodate the full range of possible failure slopes (Figure 5).
2. There should be no station-elevation points between the **Top of Bank** and the **Edge of Bank**.

3. There should be a number of relatively evenly spaced points between the **Edge of Bank** and the **Top of Toe**. BSTEM starts its failure plane search method at each station elevation point between the **Edge of Bank** and the **Top of Toe** (Figure 5). The spacing of nodes between these points will affect the precision of the failure plane computations.
4. HEC-RAS will automatically select the lowest station-elevation point in the cross section to be the **Thalweg**.

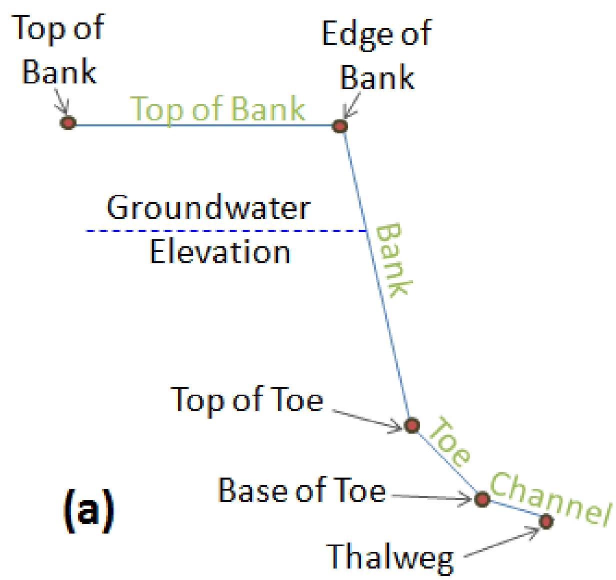


Figure 4: Definition of Station points for BSTEM half cross sections.

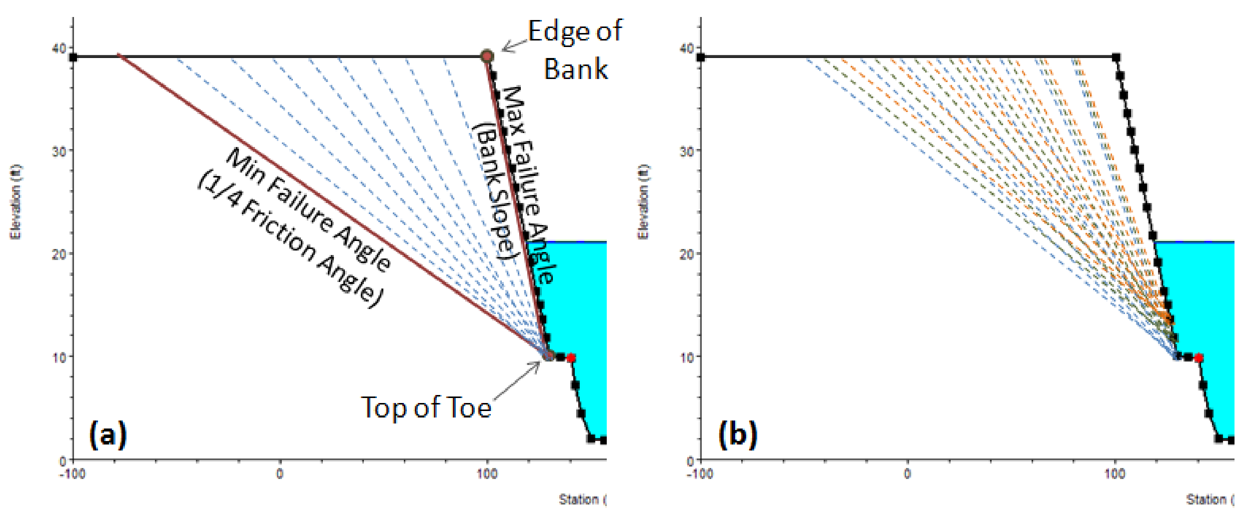
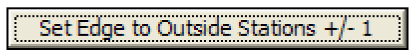


Figure 5: (a) The maximum, minimum and incremental angles evaluated (b) at each node between the "Top of Toe" and "Edge of Bank."

Note: As BSTEM development proceeds we plan to internalize these steps in the HEC-RAS code to make them transparent to the user. However, in the alpha version there is a greater burden on the user to create HEC-RAS cross sections that are compatible with the BSTEM code.

Each bank of each cross section analyzed requires two user defined points, an **Edge of Bank** Station and a **Top of Toe** Station. It should be noted that these points are defined by their station across the cross section and not their elevation. These points are depicted in Figure 6 and described below.

<u>Left Edge of Bank Station</u>: This should be the second station-elevation point and should be far enough to the right of the first point to allow the potential failure plane to develop between them. This can be set to the second cross section station for every left bank with a selected Bank Material by pressing the **Set Edge to Outside Stations +/- 1** button.



<u>Right Edge of Bank Station</u>: Analogous to the Left Bank Top Station, this is the next to last cross section station that should be far enough left of the last station that the distance between them would reliably include any shear surface computed through the bank. This can be set to the next to last cross section station for every left bank with a selected Bank Material by pressing the **Set Edge to Outside Stations +/- 1** button.

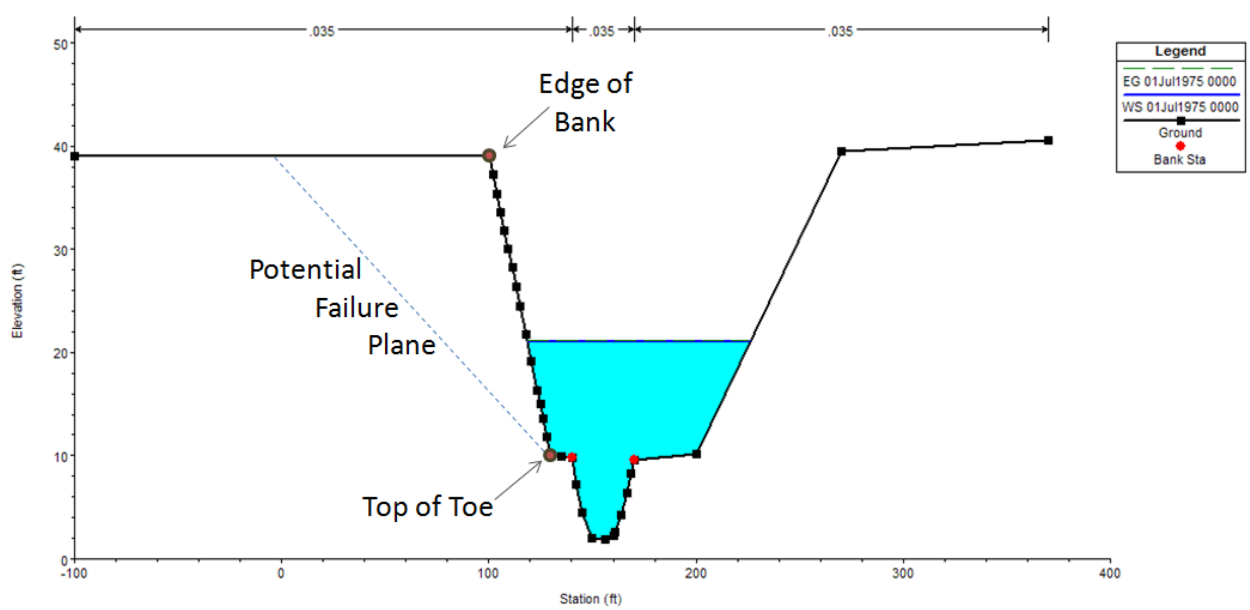


Figure 6: Reasonable location for Edge of Bank and Top of Toe definitions on an HEC-RAS cross section.

Left Top of Toe Station: BSTEM divides the bank into two sections, the Bank and the Toe (Figure 4). Conceptually, the toe is a material composed of blocks of failed material or engineered toe protection. Therefore, failure planes are only computed through the bank surface *above* the **Top of Toe**. The **Top of Toe** often corresponds to a break in slope or material type but it does not have to (Figure 4). In future versions users will be able to select a separate material type for the toe but in the first alpha version it adopts the material type of the bank or layer associated with it. This parameter can be automatically set to the HEC-RAS left bank station for every cross section that has a Left Bank Material specified by pressing the **Set Toe Station to Bank Stations** button at the bottom of the editor.

Right Top of Toe Station: The **Right Top of Toe** is analogous to the Left (see above) and can be set to the left bank station for every bank that has a **Right Bank Material** by pressing the **Set Toe Station to Bank Stations** button.

GW Elev: In order to compute bank failure on either side of any cross section a Groundwater Elevation must be specified. Results will be very sensitive to this parameter. BSTEM does not yet have a physical limit to negative pore water pressure so a very low groundwater table could generate nearly infinite bank stability. In this alpha version a single static groundwater elevation can be specified for each cross section. Dynamic ground water options are a very high developmental priority.

Defining Cross Section Materials

Right/Left Bank Material: HEC-RAS requires at least one set of material properties to be specified for each bank it performs bank failure analysis on.   Three levels of detail are available for specifying this parameter including:

1) Selecting From a List of Pre-Defined Default Parameters
2) Select a Single Set of User Defined Material Parameters for a Bank
3) Define Layers of Unique Material at a Bank

The material specification approach is bank-specific, so different approaches can be used for different banks within the same model.

1. Selecting From a List of Pre-Defined Default Parameters

The stand alone version of BSTEM includes 16 default material types that are also included in HEC-RAS. These default material types are each populated with characteristic soil properties distilled from a database of field data collected by the USDA's Agricultural Research Service ().

The unit weight, friction angle (ϕ'), cohesion, ϕ^b, critical shear stress (τ_c), and erodibility are listed in Table 1. (See the description of these parameters in the next section)

It is worth noting, however, that these parameters are extremely site specific, and the default parameters are central tendencies of very noisy data sets, particularly for cohesive material types. Therefore, default parameters will often generate substantial errors.

Coupling these bank failure algorithms with the mass balance computations in the mobile bed capabilities in HEC-RAS introduced one additional parameter requirement. Any mass that is 'failed' into the channel requires a gradation so HEC-RAS can partition it into grain classes for transport. Therefore, idealized gradations were selected for each material type based on their description. These gradations are depicted in Figure 7.

Table 1: Default materials and material parameters.

Default Material Type	Saturated Unit Weight (lbf/ft^3)	Friction Angle (ϕ')	Cohesion (lb/ft2)	ϕ^b	Critical Shear (lb/ft2)	Erodibility ($ft^3/lbf\text{-}s$)
Boulders	127.3	42	0	15	10.4	7.04E-07
Cobbles	127.3	42	0	15	2.59	1.41E-06
Gravel	127.3	36	0	15	0.23	4.74E-06
Coarse Angular Sand	117.8	32.3	8.354	15	0.0106	2.21E-05
Coarse Round Sand	117.8	28.3	8.354	15	0.0106	2.21E-05
Fine Angular Sand	117.8	32.3	8.354	15	0.00267	4.40E-05
Fine Round Sand	117.8	28.3	8.354	15	0.00267	4.40E-05
Erodible Silt	114.6	26.6	89.81	15	0.00209	4.94E-05
Moderate Silt	114.6	26.6	89.81	15	0.1044	7.07E-06
Resistant Silt	114.6	26.6	89.81	15	1.0443	2.20E-06
Erodible Soft Clay	112.7	26.4	171.26	15	0.00209	4.94E-05
Moderate Soft Clay	112.7	26.4	171.26	15	0.1044	7.07E-06
Resistant Soft Clay	112.7	26.4	171.26	15	1.0443	4.94E-05
Erodible Stiff Clay	112.7	21.1	263.16	15	14.6	4.94E-05
Moderate Stiff Clay	112.7	21.1	263.16	15	0.1044	7.07E-06
Resistant Stiff Clay	112.7	21.1	263.16	15	1.0443	4.94E-05

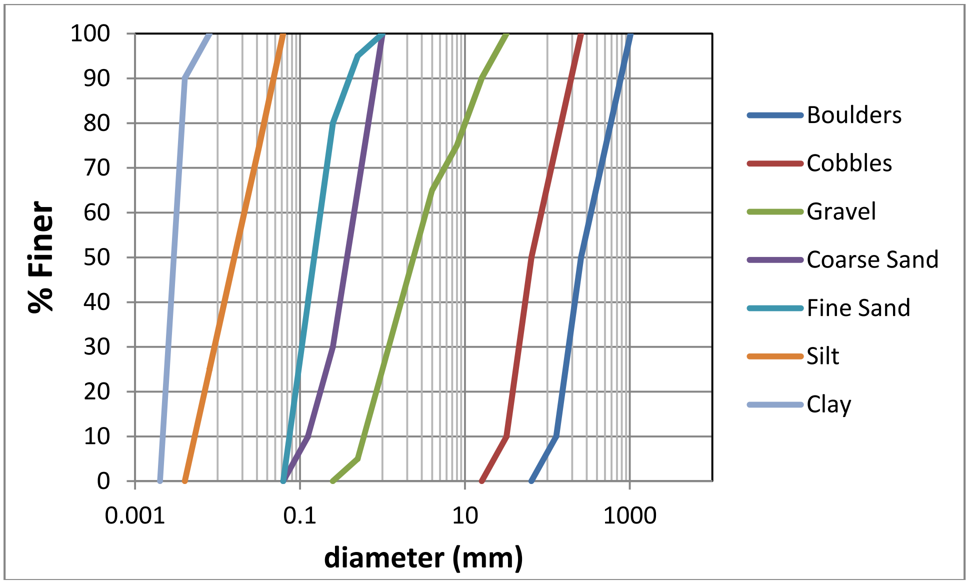


Figure 7: Idealized gradations selected for the default material types.

In order to select one of the default material types, simply click on the column labeled **Left Bank Material** or **Right Bank Material** at the cross section of interest. This will give you a drop down box populated with the default material types. Ignore the first option "**DEFINE LAYERS**" if you want to use this method, scroll down the list and click the desired material type and it will associate it with that bank (Figure 8). A new material type can be selected by re-clicking the type and selecting and new one.

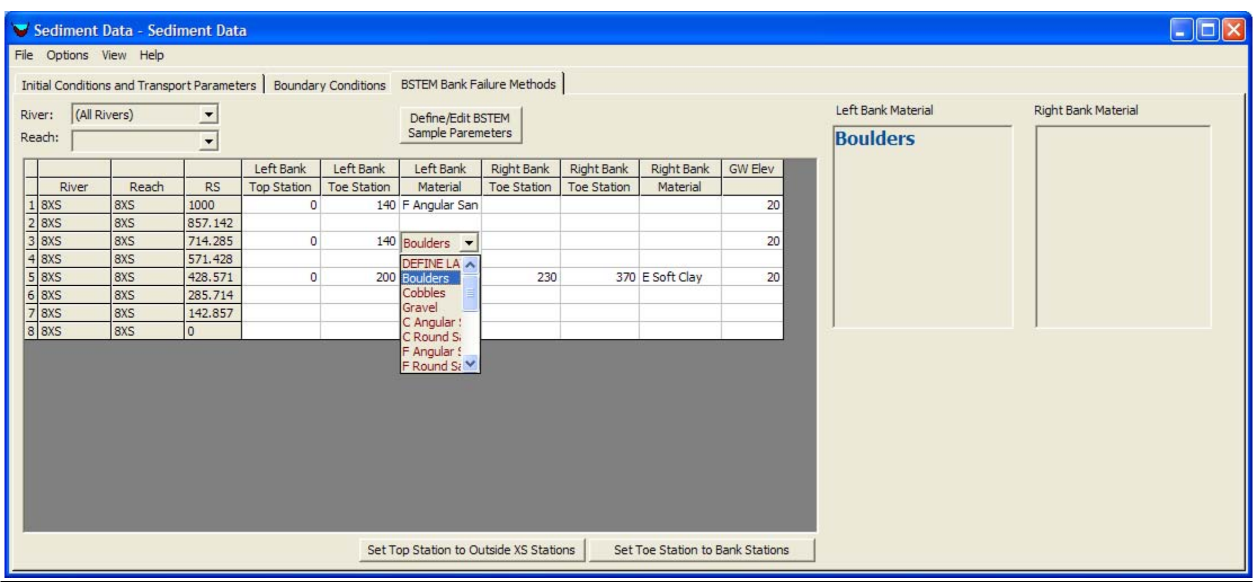


Figure 8: Select a default material type by clicking on the Left or Right Bank Material columns at the Cross Section of Interest. This will give you a drop down list of the default material types.

2. **Select a Single Set of User Defined Material Parameters for a Bank**

Because of the inherent variability of these parameters, site specific measurements are recommended. If data are available, customized material types can be associated with a bank. This is analogous to the process for defining sediment gradations in the **Initial Conditions and Transport Parameters** Tab, where gradation records are defined and then associated with the appropriate cross section.

Before a customized material type can be associated with a cross section it must be defined by pressing the **Define/Edit BSTEM Sample Parameters** button. This will activate the **BSTEM Material Parameter** editor (Figure 9). To create a new BSTEM material press the **New Record** button and specify the name. HEC-RAS will reject any names that are identical to existing or default material names. Five mandatory intrinsic soil strength parameters (used to compute the failure plane and factor of safety), two mandatory erodibility parameters (used to compute toe scour) and one optional parameter can then be entered.

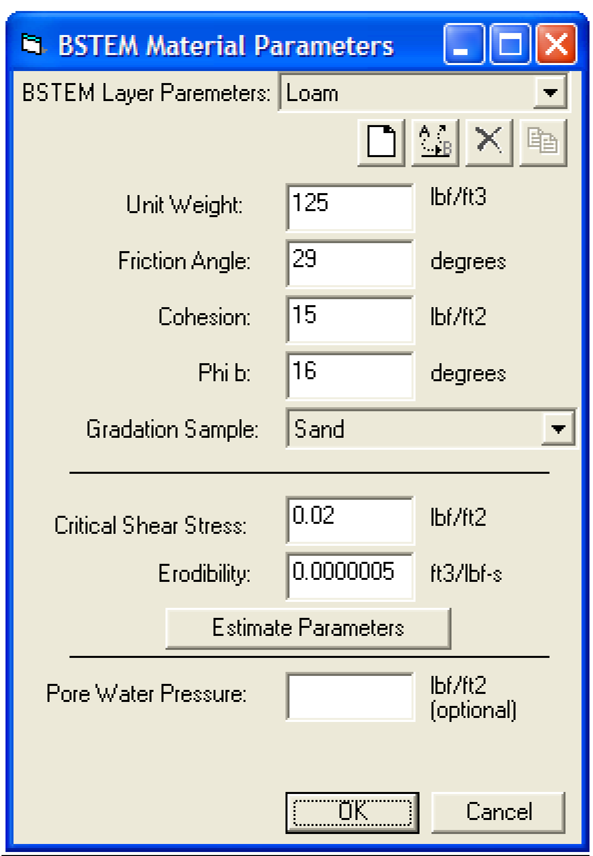


Figure 9: Customized material type editor.

Soil Strength Parameters

The first five parameters are intrinsic soil strength parameters and are associated with the computation of a critical failure plane and the factor of safety associated with that failure plane. They emerge from classical geotechnical measurements that most soils labs would be able to handle. Four user defined parameters, including cohesion (c'), saturated unit weight (W), the angle of internal friction (ϕ'), and the angle representing the relationship between shear matrix suction and apparent cohesion (ϕ^b) are used with hydrodynamic and geometry data from HEC RAS to compute a factor of safety for a range of possible failure planes by computing the ratio of the resisting forces to the driving forces. These four user defined parameters are entered in the **Material Parameter** editor (Figure 9) and are described below.

Unit Weight: This is the *saturated* unit weight of the soil.

Friction Angle: (ϕ') The friction angle is a classic geotechnical parameter that is a measurement of the soil strength. It quantifies the friction shear resistance of soil. The 'angle' of 'friction angle' comes from the Mohr-Coulomb failure criterion and is the angle of inclination in the classical Mohr diagram. It is a theoretical angle[2] used to compute soil strength and should not be confused with physically intuitive angles like the angle of repose. This also is not the minimum angle of the failure plane. In cases where ground water elevation is higher than the water surface elevation the bank can lose frictional strength and be left only with cohesion, allowing for a shallower failure plane angle. This parameter can be determined by collecting 'undisturbed' cores for triaxial testing in a soils lab or it can be measured *in situ* with a borehole shear test. The Iowa Borehole Shear device (Thorne, 1981) is a hand held instrument that is commonly used to collect this parameter from hand augured 8 cm boreholes for BSTEM studies.

Cohesion: Cohesion is the attractive force of particles in a soil mixture, usually as a result of electrochemical or biological bonding forces. These forces increase the strength of a soil matrix. Cohesion is generally a minor consideration in granular soils but can account for a substantial amount of soil strength in cohesive materials. Cohesion is computed from the same data as the friction angle and, therefore, must be measured either by triaxial laboratory tests or *in situ* borehole shear measurements.

Phi b: (ϕ^b) As soil drains, capillary tension induces negative pore water pressure or matrix suction. Suction resists bank failure and increases the shear strength of the soil matrix. In the bank failure algorithms, suction is quantified as an 'apparent cohesion' or the equivalent increase in cohesion required to generate the same increase in shear strength (Figure 10). ϕ^b is

[2] the rate of increasing strength with increasing normal force

a function of soil moisture and maxes out at the friction angel (ϕ') at saturation. For most materials ϕ^b is generally between 10 to 30 degrees depending on soil type. It is very difficult to go out and fundamentally measure this parameter. It has been measured a handful of times in research settings. Most applications start between 10 and 15 but it goes to a maximum of the friction angle when the material is saturated (Fredlund). Because of the estimated nature of this parameter it can be used as a calibration factor.

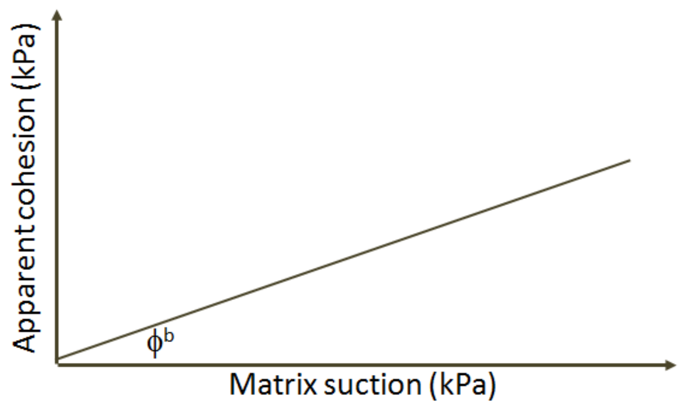


Figure 10: ϕ^b, the slope of the relationship between matrix suction and apparent cohesion.

<u>Gradation Sample</u>: There is a fifth bank material parameter that is required but is not used in the failure calculation. In order to partition any failed material into grain classes for transport by the sediment transport model, the bank material has to have a bed gradation associated with it. Bed gradations are defined by pressing the **Define/Edit Bed Gradation** button on the main **Initial Conditions and Transport Parameters** tab of the **Sediment Data Editor** (Figure 11).

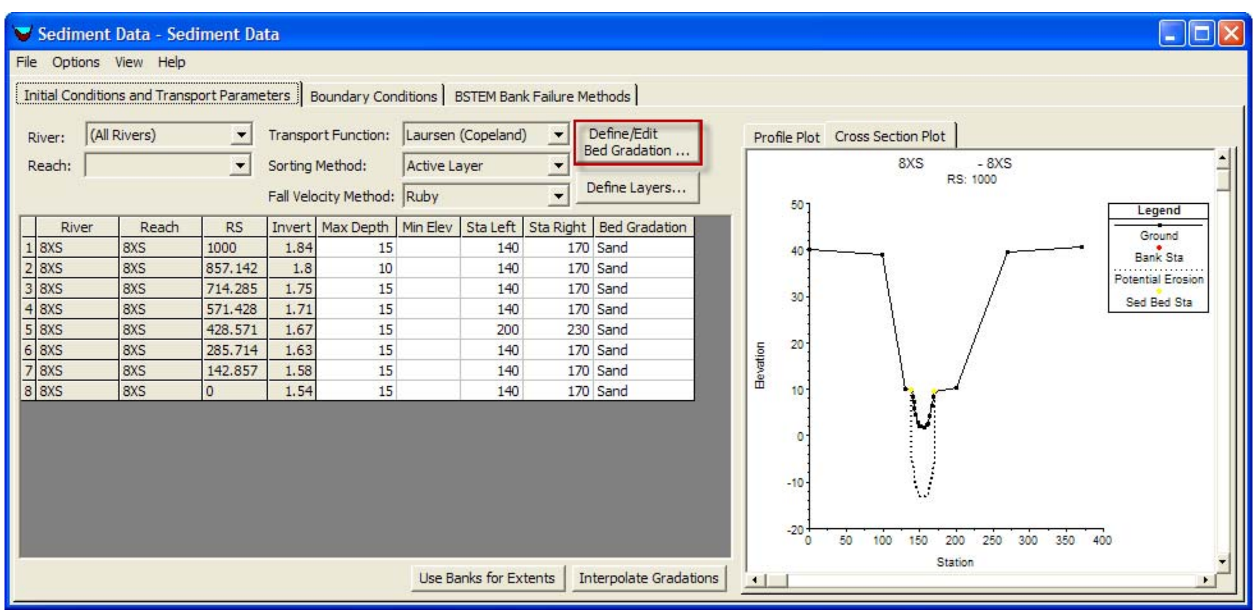


Figure 11: Defining bed gradations.

Any gradations defined here become automatically available in the drop down **Gradation Sample** menu on the **Material Parameter** editor. Select a gradation to associate with this sample.

Erodibility Parameters

The second set of parameters are more specialize to bank failure analysis. They are measurements of the erodibility of the soils in response to hydrodynamic forcing. Standard soil testing laboratories are not likely to have the capabilities to collect these parameters. However, there are several facilities in the Corps, other federal agencies, and universities that can quantify these parameters. Bank jet tests (Hansen) and sedflume laboratory tests (ERDC, Briard) are the best ways to estimate these parameters.

Critical Shear Stress: The critical shear is the stress at which the bank begins to scour.

Erodibility: The rate of sediment removal in response to a unit shear stress.

A little calculator is available which will help estimate these parameters. Press the **Estimate Parameters** button to access this calculator. The critical shear stress can be computed for cohesionless materials base on a representative grain size. It should be noted, however, that this is a highly variable and site specific parameter and the value computed by the calculator does not account for cohesion and, therefore, should not be used for cohesive soils. To compute erodibility a relationship was developed (Figure 12) between this parameter and the critical shear such that:

$$E = 0.09\ \tau_c^{-0.5}$$

This relationship however is based on the regression depicted in Figure 12 which includes a lot of scour in log space. This underscores the variable and site specific nature of these parameters therefore local measurement of these parameters is highly recommended.

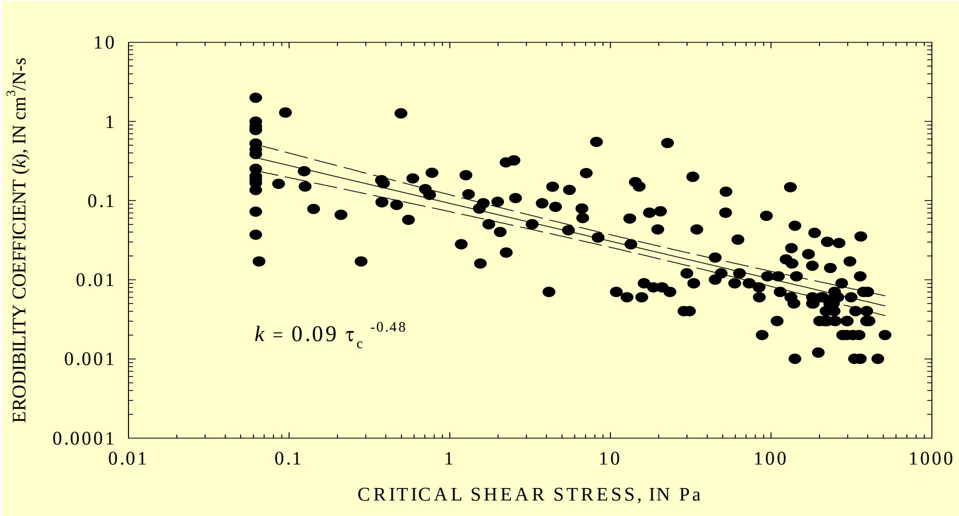


Figure 12: Relationship between erodibility and critical shear stress.

3. Define Separate Parameters for Multiple Layers for Each Cross Sections

Finally, it is often advantageous to define several layers of bank material. The bank might have a distinct stratigraphy with contrasting layers, it may be consolidated and, therefore, stronger at depth or sometimes vegetation is modeled by introducing a surface layer with the same friction angle as the parent material but higher cohesion. To specify layers, select the **Define Layers** option, which will always be the first choice in the **Bank Material** drop down menu. If the **Define Layers** option is selected, a new grid will appear on the right side of the dialogue (Figure 12).

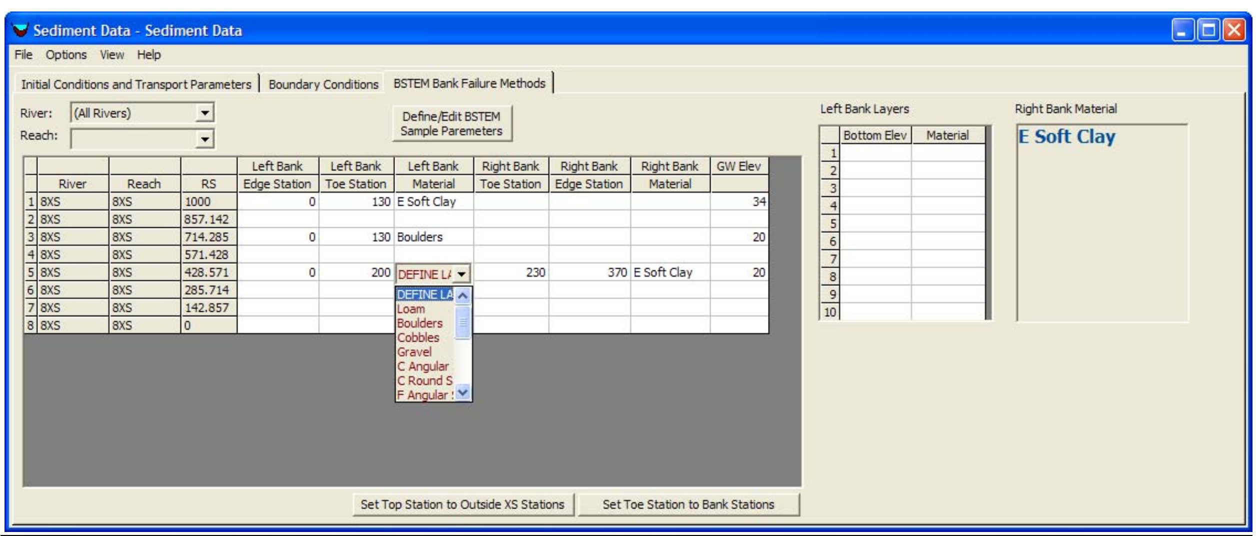


Figure 13: Selecting the layer mode for a bank failure.

The layer window requires two parameters for each layer: a bottom elevation and a material. Input layers from the top to the bottom. Therefore, the first layer will extend from the highest point on the half-cross section to the specified **Bottom Elevation**. Then, just like the **Bank Material Type** option in the main BSTEM editor, a list of bank materials can be accessed by clicking on the **Material** column. Each layer has to have its own material specified, but the materials do not have to be unique and can be any combination of default or user specified material types. Add layers until the last **Bottom Elevation** extends below the conceivable bottom of the model (i.e. the elevation the model is likely to scour to). The bottom of the deepest layer has to at least extend to the thalweg elevation for the model to run.

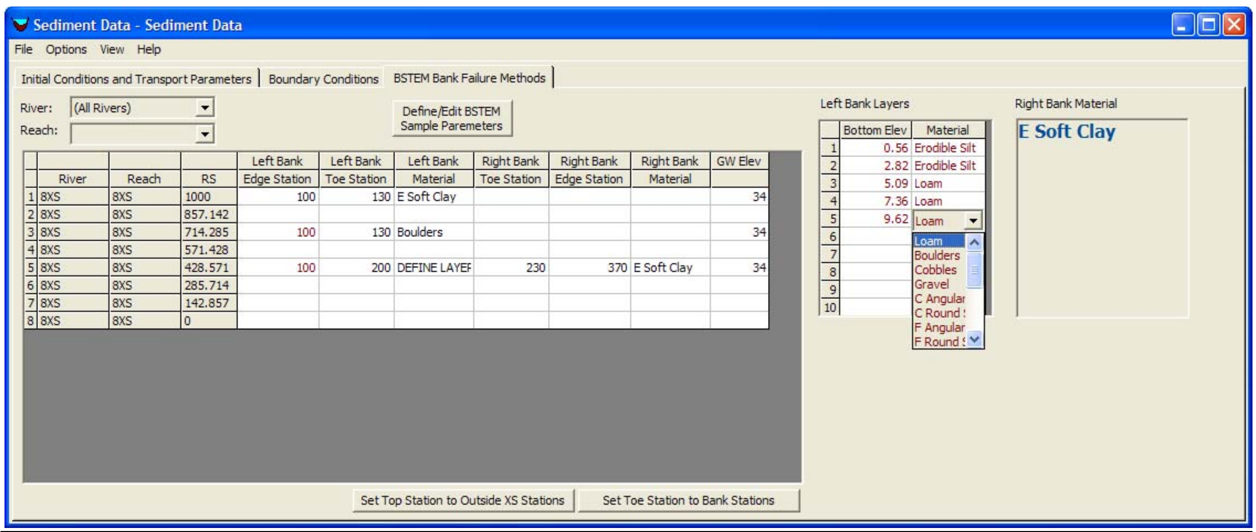


Figure 14: Defining layers and layer material types.

Output

HEC-RAS will modify the cross sections in response to bed elevation change in the sediment model and bank failure in BSTEM. Cross section output files can get very large, so they must be requested. In the Sediment Analysis window go to **Options→Sediment Output Options**. This will access the **Sediment Output Options** window where cross section output can be requested and the increment can be specified.

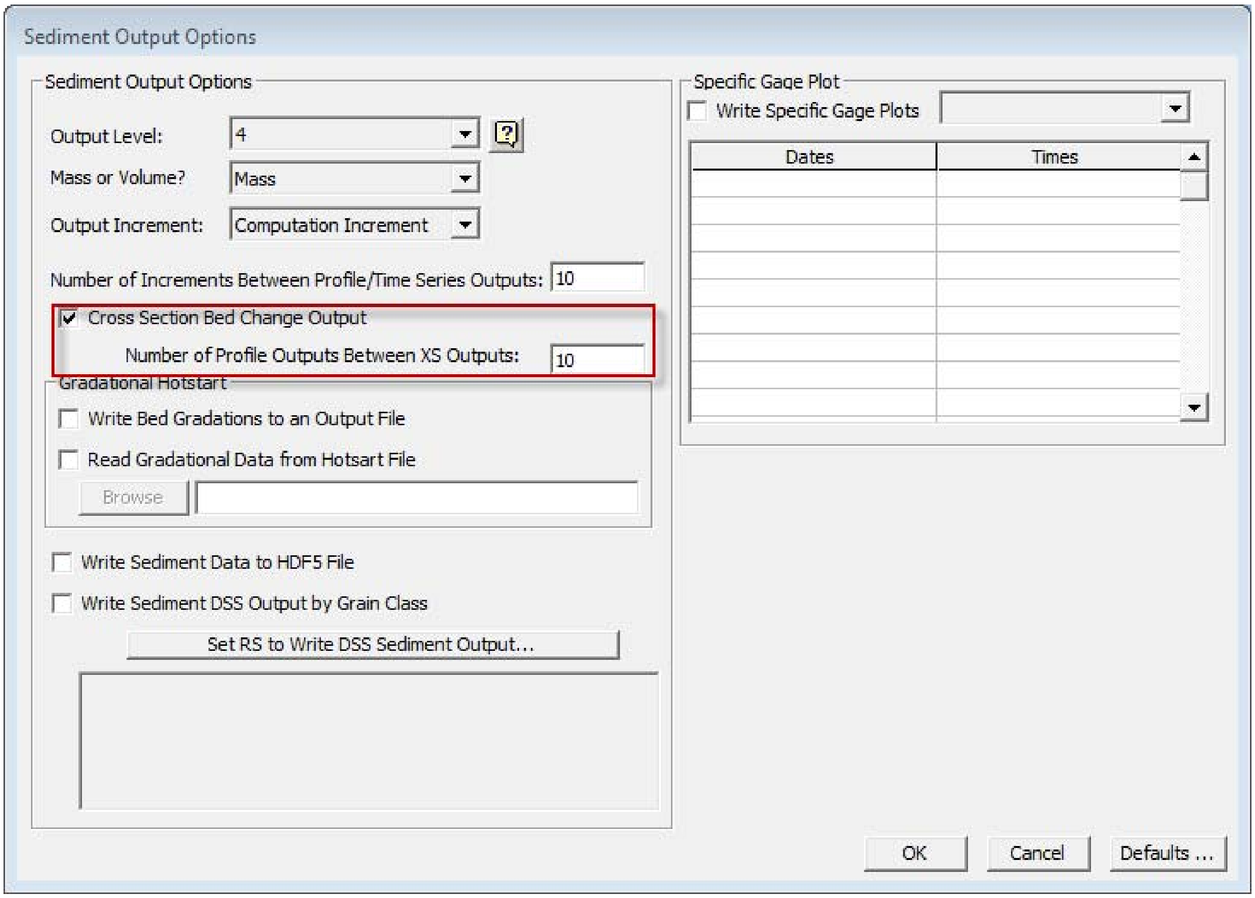


Figure 15: Requesting and specifying the frequency of sediment cross section output in the Sediment Output Options window.

To access this output, select **View→Sediment - XS Bed Change Plot…** (all the way at the bottom) from the main HEC-RAS window. This will activate the XS output editor where you can look at the shape of each cross section at various points in the simulation and even animate the bed and bank change. The example in

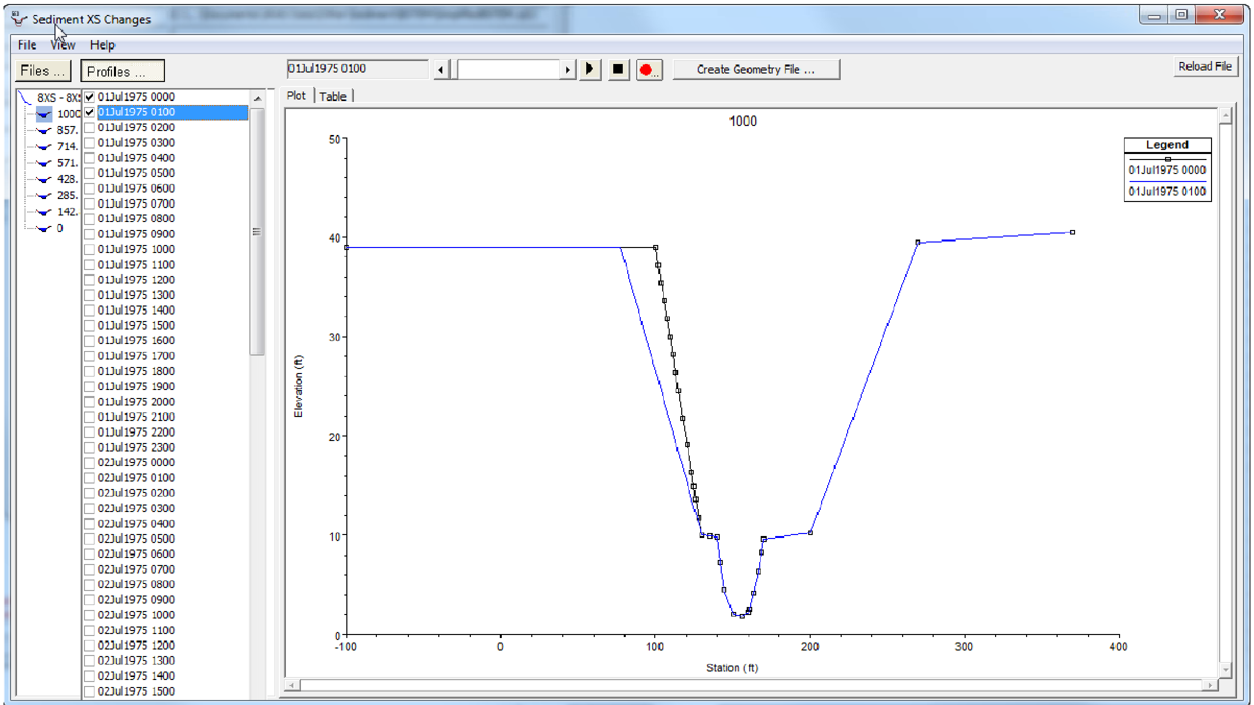


Figure 16: Example cross section output before and after a bank failure computed in HEC-RAS.

Validation

Finally, model testing was conducted to demonstrate the reliability of the HEC-RAS/BSTEM algorithms. Several test scenarios were constructed and modeled with HEC-RAS, the stand alone version of BSTEM 5.4 and the stand alone Fortran version of BSTEM used in the integration (which was subjected to rigorous independent validation against BSTEM 5.4 (Simon et al., 2010)). The before and after cross sections for a bank failure event are included in Figure 17. HEC-RAS is replicating the fortran version and is very close to BSTEM 5.4 (which can be explained by a couple algorithm differences between the fortran version and BSTEM 5.4).

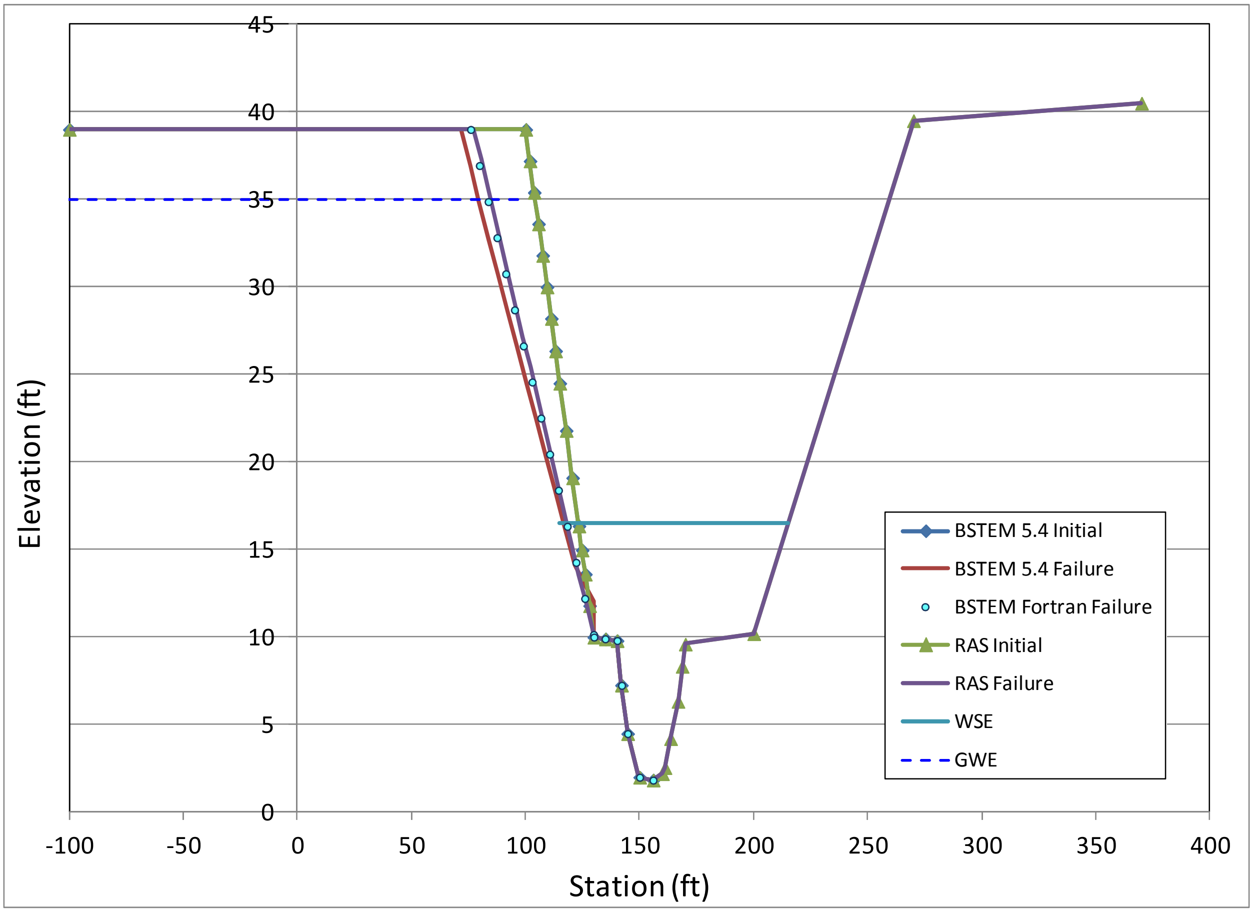


Figure 17: Output from a validation test of the HEC-RAS implementation of the bank failure capabilities and the stand alone models.

<u>References</u>:

Langendoen, E. J., and Simon, A. _2008_. "Modeling the evolution of incised streams. II: Streambank erosion." *J. Hydraul. Eng.*, 134(7),2008.

Simon, A., Ozeren, Y., and Thomas, R. E. (2012) Comparison of the Bank-Stability Sub Model with in the Visual Basic and FORTRAN Versions of (BSTEM), 18p.

Simon, A., Curini, A., Darby, S.E., and Langendoen, E.J. (2000). "Bank and near-bank processes in an incised channel", Geomorphology, 35, pp. 193-217.

Thorne, C.R. (1981) Field measurements of rates of bank erosion and bank material strength. *Erosion and Sediment Transport Measurement*. Proceedings of the Florence Symposium, IAHS Publication 133, 503-512.

SI Table

Default Material Type	Saturated Unit Weight (kN/m^3)	Friction Angle (ϕ')	Cohesion (kPa)	ϕ^b	Critical Shear (Pa)	Erodibility ($cm^3/N\text{-}s$)
Boulders	20	42	0	15	498	0.004
Cobbles	20	42	0	15	124	0.009
Gravel	20	36	0	15	11	0.030
Coarse Angular Sand	18.5	32.3	0.4	15	0.506	0.141
Coarse Round Sand	18.5	28.3	0.4	15	0.506	0.141
Fine Angular Sand	18.5	32.3	0.4	15	0.128	0.141
Fine Round Sand	18.5	28.3	0.4	15	0.128	0.141
Erodible Silt	18	26.6	4.3	15	0.1	0.316
Moderate Silt	18	26.6	4.3	15	5	0.045
Resistant Silt	18	26.6	4.3	15	50	0.014
Erodible Soft Clay	17.7	26.4	8.2	15	0.1	0.316
Moderate Soft Clay	17.7	26.4	8.2	15	5	0.045
Resistant Soft Clay	17.7	26.4	8.2	15	50	0.316
Erodible Stiff Clay	17.7	21.1	12.6	15	699.1	0.316
Moderate Stiff Clay	17.7	21.1	12.6	15	5	0.045
Resistant Stiff Clay	17.7	21.1	12.6	15	50	0.316