SEDLIB Multiple Grain Sized Mixed Sediment Library: Technical Manual

Corresponding to SEDLIB v.1.2

Gary L Brown, Corey Trahan, Jennifer N Tate, Gaurav Savant

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SEDLIB Multiple Grain Sized Mixed Sediment Library

Purpose

SEDLIB is a sediment transport library. It is capable of solving problems consisting of multiple grain sizes, cohesive and cohesionless sediment types, and multiple layers. It calculates erosion and deposition processes simultaneously, and simulates such bed processes as armoring, consolidation, and discrete depositional strata evolution.

The SEDLIB library system is designed to link to any appropriate hydrodynamic code. The hydrodynamic code must be capable of performing advection diffusion calculations for a constituent. SEDLIB interacts with the parent code by providing sources and sinks to the advection diffusion solver in the parent code. The solver is then used to calculate both bedload and suspended load transport, for each grain class. The sources and sinks are passed to the parent code via a source/sink bed sediment flux, for both suspended load and bedload.

Organization

SEDLIB is designed to be both robust and adaptable. To this end, an organizational scheme for SEDLIB was developed such that the parts of the library that are most likely to be changed and/or updated are also the parts that are the least integral to the function of the library as a whole. Figure 1 gives a schematic description of this organization.
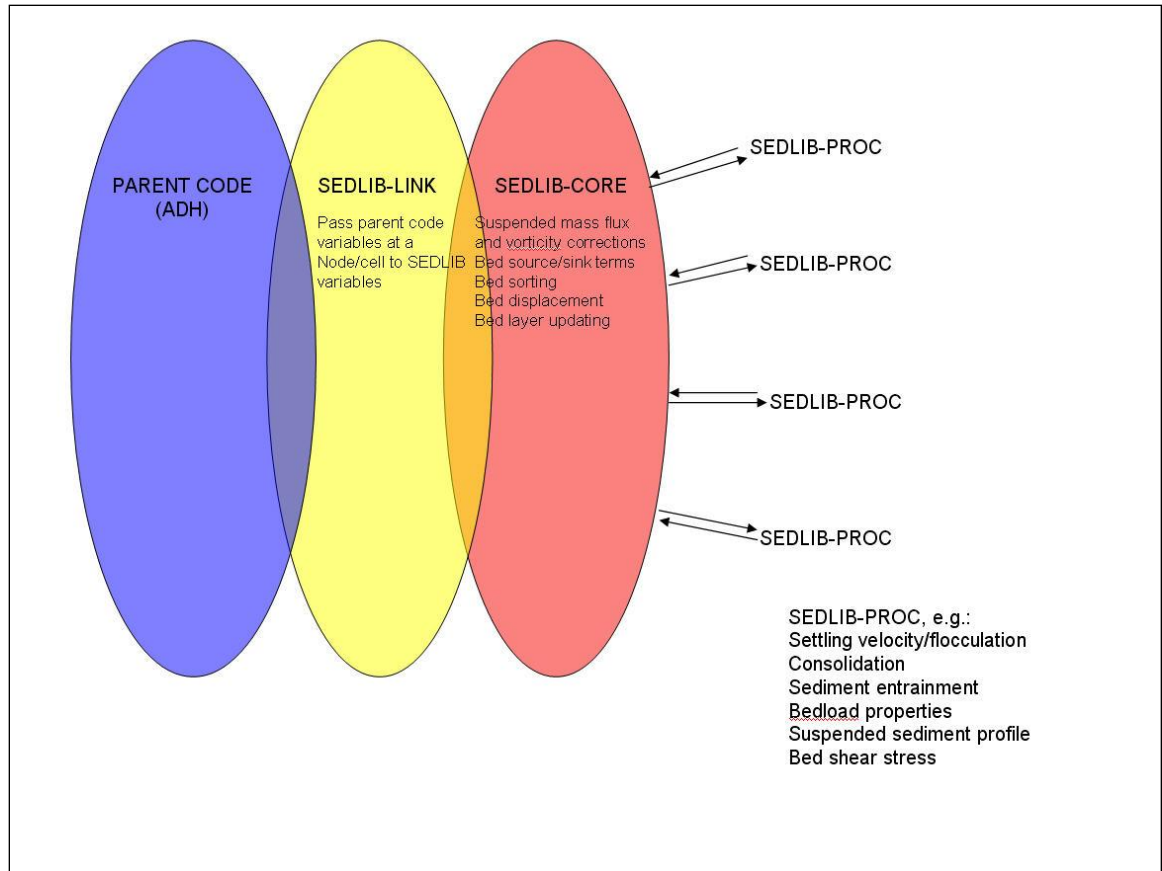
Figure 1: SEDLIB organizational chart

In Figure 1, the colored ovals represent common variable spaces – that is, those subroutines within a given oval share a set of common variables. Where the ovals overlap represent subroutines that share multiple sets of common variables.

The parent code shares a set of common variables with the SEDLIB-LINK routines. The parent code calls the SEDLIB-LINK at each computational point. So, for example, if the computational point in the parent code is a set of nodes, the parent code will have a nodal loop and *within that loop* the parent code will call the SEDLIB-LINK routine. SEDLIB performs all of its calculations at a single point. All spatial gradients and fluxes are calculated in the parent code via the advection-diffusion calculations.

The purpose of the SEDLIB-LINK routines is merely to pass information to and from the SEDLIB library. This message passing is facilitated by sharing two sets of common variables across the SEDLIB-LINK – one set that is associated with the parent code, and one set that is associated with SEDLIB.

When the SEDLIB-LINK is called, all of the relevant hydrodynamic and sediment information is passed from the parent code variables to the corresponding SEDLIB variables. The SEDLIB-LINK then calls one or more of the SEDLIB-CORE routines. Upon completion of the execution of the SEDLIB-CORE routines, the SEDLIB-LINK passes the updated sediment information

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from the SEDLIB common variables back to the corresponding variables in the parent code.

The SEDLIB-CORE routines perform the fundamental sediment transport calculations. These include such things as the development of source and sink terms, erosion and deposition, bed sorting, and bed layer accounting. These routines contain very little specific information concerning the physics of individual processes – that information is contained in the SEDLIB-PROC routines. Rather, these routines are the basic computational engines that are used to combine all of the various physical processes into a coherent framework.

The SEDLIB-PROC routines are a set of subroutines with no common variables whatsoever. That is, all information passing to and from these routines is passed through the call statements. Each of these routines represents an individual physical process.

It is expected that most of the future development of the code will consists of adding new and updated content to the SEDLIB-PROC routines. Since each of these is completely independent of the rest of the code, they can be tested independently and then inserted into the code with relative ease. Hence, the whole library system is optimized for both adaptability and consistency by organizing it such that those aspects of the library that are the most mutable are also those aspects of the library that are the most modular.

SEDLIB-CORE

The SEDLIB-CORE routines contain the fundamental sediment transport calculations. The routines are given as follows:

sedlib_core_bed.c – this the main subroutine for sediment bed calculations

sedlib_core_suspended_transport.c – this is the main subroutines for passing information to the parent code needed for suspended sediment calculations

sedlib_core_bedload_transport.c – this is the main subroutines for passing information to the parent code needed for bedload sediment calculations

sedlib_core_bed_shear_stress.c – this calculates the bed shear stress.

sedlib_core_critical_shear_stress.c – this calculates the critical shear stress for noncohesive grains

sedlib_core_noncoh_erosion_deposition_flux.c- this calculates the erosion and deposition potentials for noncohesive grains.

sedlib_core_coh_deposition_flux.c – this calculates the depositional flux potentials for cohesive grains

sedlib_core_mixed_sed_erosion_flux.c – this calculates the erosion and deposition potentials for mixed sediment beds

sedlib_core_limit_erosion.c – this is called to address the special case where erosion switches to deposition in the middle of a sediment time step

sedlib_core_active_strata_source.c – this calculates the sediment information associated with the active strata

sedlib_core_bed_sorting_and_displacement.c – this calculates the bed displacement and active layer grain distribution

sedlib_core_active_layer_properties.c – this calculates the active layer porosity and cohesive parameters

sedlib_core_bed_layer_update.c – this updates the bed layer information at the end of the time step

The following documentation gives a detailed description of each of these subroutines.

SEDLIB-CORE

These are the SEDLIB core routines. Although these routines can be modified, it is expected that they will change much less frequently than the SEDLIB-PROC routines. The SEDLIB-CORE routines share set of common variables (share_sedlib.h). These are for convenience in sharing information between routines.

sedlib_core_bed.c

Purpose

This is the main subroutine for performing bed calculations. It accomplishes the following tasks:

- Generates erosion and deposition potentials for use in calculating erosion and deposition fluxes

- Calculates displacement, active layer sorting, and new active layer properties (i.e. porosity and cohesive erosion properties)

- Calculates the updated suspended and bedload source/sink terms, to be applied as bed fluxes in the parent code.

- Updates the bed layers and consolidates the bed layers (if consolidation is activated).

The following is a pseudo-code flow chart of the subroutine:

Allocate and initialize variables

Call sedlib_core_bed_shear_stress to calculate the shear stresses (both the grain shear stress resulting from skin friction, and the total shear stress resulting from both skin drag and form drag associated with bedforms, etc.)

Call sedlib_core_critical_shear_stress to calculate the critical shear stresses associated with noncohesive sediment classes. There are 2 separate values of critical shear stress used in these calculations:

- critical_shear_stress_plane_bed is the critical shear stress computed using the Shields criterion, as given by van Rijn
- critical_shear_stress is the critical shear modified for the effects of bed slope, and for the effects of the sediment mixture on the shear stress (i.e. the hiding factor)

Calculate the settling velocity of each grain

Call sedlib_core_noncoh_erosion_deposition_flux to get values of the erosion and deposition potentials for noncohesive grains only

Call sedlib_core_coh_deposition_flux to get values of the deposition potentials for cohesive grains only.

Find the appropriate type classification for each bed layer. Any bed layer containing more than 10% cohesive sediment behaves as a cohesive layer. Otherwise, the layer behaves as a noncohesive layer.

Calculate the active layer thickness. If the top bed layer is either a cohesive layer or a sedflume layer, the active layer thickness is set equal to 1.E-4 m. Otherwise, the active layer thickness is determined as a function of the grain sizes in the top bed layer, the shear stress, and the critical shear stress (minimum value = 1.E-4 m).

Perform a check to see if the new active layer will grab multiple bed layers. If the new active layer is thicker than the old active layer, it will include the material in the bed that is contained in that difference in thickness. If this material is composed of multiple bed layers, it is convenient to go ahead and just combine them into the active layer. This avoids eroding through multiple layers, which is a nonlinear problem that does not converge well (the erosion properties become a discontinuous function of the displacement, and the solution can ring).

Save the old information so we can reload it at the beginning the next concentration iteration.

There are 2 concentration iterations. The first iteration computes a solution, and uses this solution to calculate the active layer porosity. The second iteration then re-computes the solution using the new value of the porosity.

Concentration iteration loop

Load old values from saved old values and initialize the erosion fluxes

Erosion loop

Set the active strata ceiling equal to the old active strata ceiling minus the active layer thickness and call sedlib_core_active_strata_source.

Call sedlib_core_mixed_sed_erosion_flux to get the final erosion and deposition potentials.

For the first concentration iteration only, call sedlib_proc_sl_near_bed_correction_brown to compute the near-bed suspended sediment correction factor (for depth-averaged computations only)

Call sedlib_core_bed_sorting_and_displacement, and solve only for displacement: this is done to determine whether erosion or deposition is occurring.

IF

This is not the first erosion iteration and deposition is indicated, this means that the bed has switched from erosional to depositional within a single sediment time step. This is undesirable: therefore we just assume the sediment computations are finished after the last erosion iteration and end the computations.

Else…

Using the new value of the active stratum ceiling associated with the new displacement computation, Call sedlib_core_active_strata_source to get the active stratum properties. If deposition is occurring, these are just the active layer properties (since in this case the

active stratum is a sediment sink). If erosion is occurring, these are the properties of the bed layer below the active layer. Active_strata_source also determines the maximum allowable thickness of the erosion, which is the distance between the bottom of the active layer and the bottom of the bed layer that is currently being eroded (total_erodable_thickess)

Call sedlib_core_mixed_sed_erosion_flux to get the final erosion and deposition potentials.

If there is net deposition, the active strata properties are part of the solution (i.e. they appear on the left-hand side of the grain fraction equations). This is because, in deposition, the active layer donates material to the bed, so the properties of that material are the active layer properties. Call sedlib_core_bed_sorting_and_displacement and exit the erosion loop

If there is net erosion, the active stratum properties are equal to the properties of the bed layer just below the active layer. Solve for displacement and the active layer fraction by calling sedlib_core_bed_sorting_and_displacement

If the erosion is greater than the total_erodable_thickness, we wish to limit the erosion to the thickness of the layer. However, calculating the time step required to erode this thickness is a nonlinear calculation. Therefore, we simplify the problem by just eroding some portion of the layer in successive erosion iterations until it is thin enough to be included in the active layer. This is done with the following procedure.

- If the total erodable thickness is less than the active layer thickness, just add the material to the active layer and recalculate. This takes place over a time step = 0, since it is just redistributing bed material

- If the total erodable thickness if greater than the active layer thickness, keep cutting the time step in half and re-solve until the thickness is less than the total erodible thickness.

Using this new time step, solve for the displacement and the active layer fractions

Update the old values with the new values

Call sedlib_core_active_layer_properties to calculate values for the porosity and cohesive erosion properties of the active layer

Decrement the total time step by the time required to erode this portion of the layer

Repeat the erosion loop until the erosion no longer exceeds the total erodable thickness

If a very thin deposit beneath the active layer is created, mix it into the active layer to avoid creating thin bed layers.

For the first concentration iteration, update the active layer porosity and the active layer cohesive properties. These are then used to recalculate everything (in the second concentration iteration) with this updated estimate of these active layer properties.

End concentration loop

The old variable values are reinitialized to the saved old values. This is needed in order to calculate the bed layer updates correctly.

The bed layers are then updated by calling sedlib_core_bed_layer_update, and, if consolidation is activated, the bed layers are consolidated by calling sedlib_proc_consolidate_layer.

Calculate the net suspended load and bedload fluxes to be passed back to the parent code, for use in transport calculations.

Calculate the bed_mass_change for use in mass conservation check calculations.

sedlib_core_suspended_transport.c

Purpose

This is the subroutine that acquires the correction factors necessary to modify the 2D advection diffusion equation such that 3D effects are accounted from in an approximate sense. This routine is only called for depth averaged calculations.

The 2D advection diffusion equation, modified to include these correction factors, is given as follows:

$$\frac{\partial(hC)}{\partial t} + \frac{\partial\left(\left(\alpha_{VC.X}+u\right)\alpha_{FC}hC\right)}{\partial x} + \frac{\partial\left(\left(\alpha_{VC.Y}+v\right)\alpha_{FC}hC\right)}{\partial y} +$$
$$\frac{\partial}{\partial x}\left(hD_X\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(hD_Y\frac{\partial C}{\partial y}\right) - E_{SS} + D_{SS}R_{CP}C = 0 \tag{1}$$

R_{cp} is a near bed correction factor, which gives an approximate value of the near bed concentration as a function of the depth averaged concentration. This correction factor is taken from a Rouse type concentration profile, that has been modified to account for nonequilibrium effects (Brown, 2008).

α_{FC} is the mass flux correction factor. This factor is analogous to a momentum correction factor in the hydrodynamic depth-averaged equations. It arises from the integration of the product of the concentration and the velocity over the depth; hence, it is a function of both the theoretical velocity profile and the theoretical concentration profile. Figure 2 gives typical values of this coefficient, as a function of relative roughness (β_{RH}) and the exponent of the concentration profile (K).

α_{VC} is the vorticity correction factor. It is only applicable when vorticity transport is activated (i.e. bendway angular momentum correction). It corrects the direction of the transport to account for these vorticity effects. It is a function of the mass flux correction factor (and hence the concentration profile). Note that the vorticity correction factor is a vector quantity. Figure 3 gives typical values of the magnitude of this correction factor, as a function of the exponent of the concentration profile (K).

The sedlib_core_suspended_transport routine sets a value for the bulk roughness height (i.e. the "velocity profile forming" roughness height, that includes both grain and form roughness) and then calls sedlib_proc_transport_correction_factors to acquire values for the correction factors.
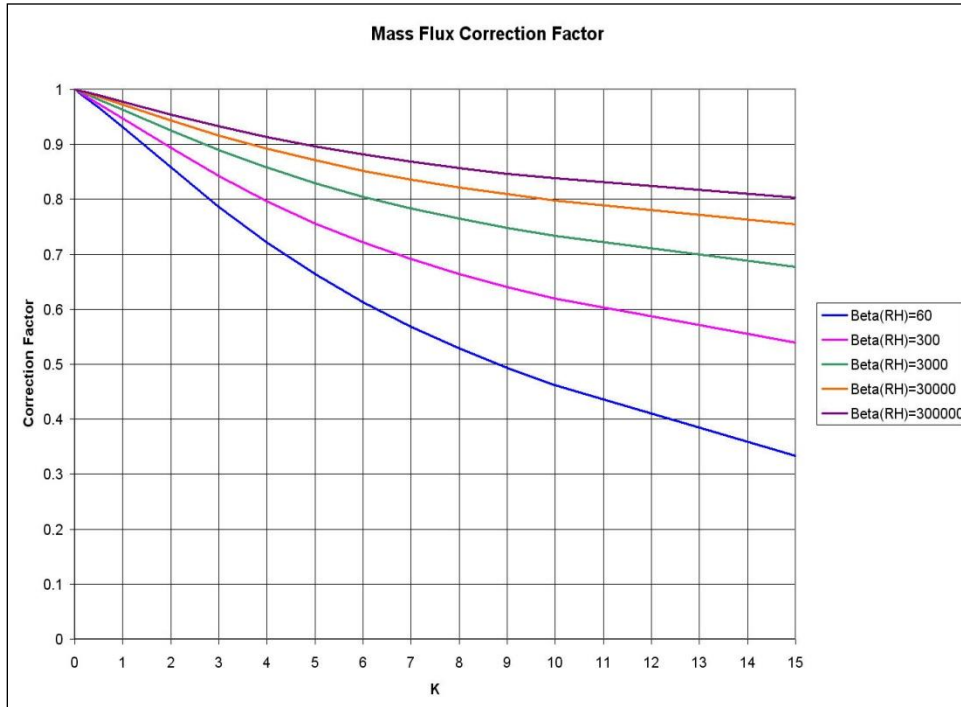
Figure 2: The mass flux correction factor
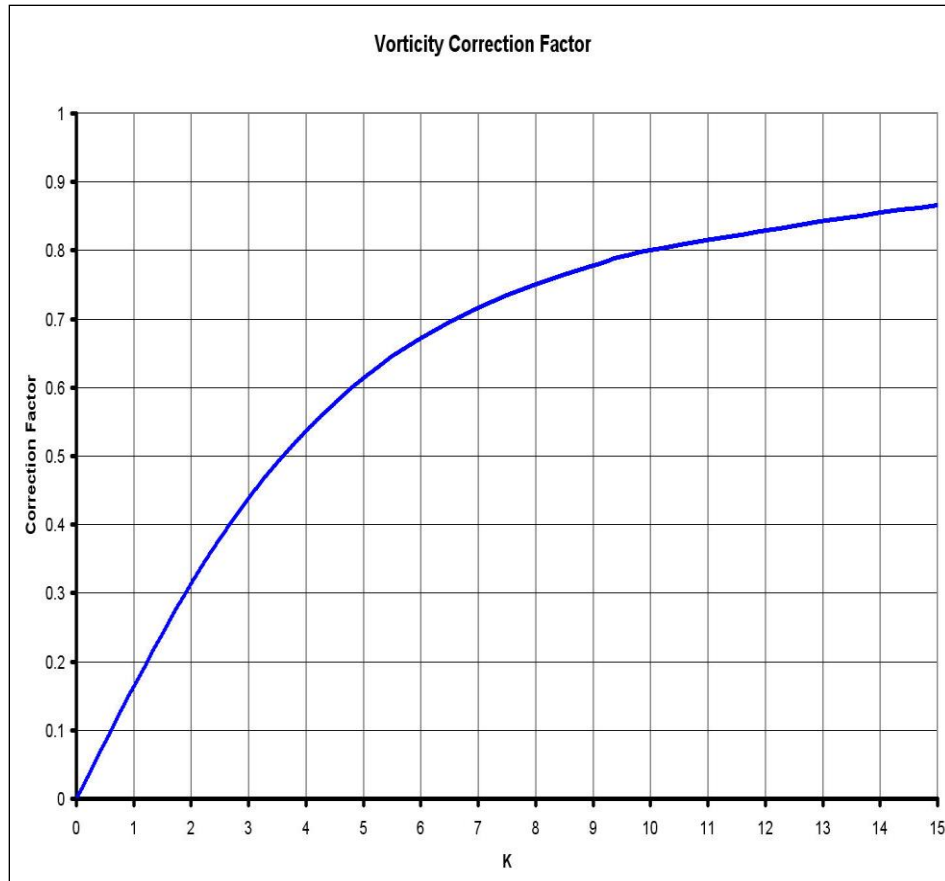
Figure 3: The vorticity correction factor

sedlib_core_bedload_transport.c

Purpose

This is the subroutine that acquires the bedload velocity and thickness. These values are needed in order to compute bedload transport using the advection diffusion equation.

Note that the source and sink terms for the bedload are computed in sedlib_core_bed. They do not need to be computed in this subroutine.

Sedlib_core_bedload_transport performs the following functions:

- Call sedlib_proc_bedload_velocity_philips_and_sutherland to calculate the bedload velocity

- Call sedlib_proc_bedload_direction_correction to acquire the vector components of the bedload direction.

sedlib_core_bed_shear_stress.c

Purpose

This subroutine returns the bed shear stress values. These include both the bulk bed shear stress induced by both grain and form drag (total_shear_stress_mag) and the shear stress induced by the grains only (grain_shear_stress_mag). The total_shear_stress_mag is used for processes associated with the suspension, such as the concentration profile. The grain_shear_stress_mag is used for processes associated with the bed, such as entrainment.

Sedlib_core_bed_shear_stress performs the following functions:

Determine the roughness height that is representative of the total drag (i.e. grain and bedform drag). If this is given as an equivalent roughness height, the value is used as is. If the value is given as Manning's n, the Manning's n is converted to a roughness height using the following expression (Christensen, 1970).

$$k_s = \left(8.25 \sqrt{g} \; \frac{n}{K_n} \right)^6 \tag{2}$$

Call sedlib_proc_find_percent_finer to determine the d_{90} for the bed material at the bed surface.

Set the grain roughness height = 3*d90 (Van Rijn, 1984a). Set a minimum roughness height of 0.001 m.

Call sedlib_proc_bedshear_current_only_christensen to calculate the grain drag coefficient associated with the steady (or quasi-steady) current induced shear stress.

If ice cover is present, call sedlib_proc_bedshear_under_ice_savant_brown to calculate the grain drag coefficient.

If the parent model is 3D (not depth averaged), the velocity is a near bed velocity. Therefore, an approximate equivalent depth-averaged velocity is computed, to be used in the friction calculations.

Determine the flow velocity magnitude as the vector sum of the depth averaged velocity and the transverse near-bed velocity due to vorticity (bendway) effects.

Solve for the grain_shear_stress_mag

Call sedlib_proc_bedshear_current_only_christensen to calculate the grain-plus-form drag coefficient associated with the steady (or quasi-steady) current induced shear stress.

If ice cover is present, call sedlib_proc_bedshear_under_ice_savant_brown to calculate the grain-plus-form drag coefficient.

Solve for the total_shear_stress_mag

If the parent model is a depth-averaged model, calculate the correction factor to estimate near-bed velocities from depth-averaged velocities.

Set the grain shear direction as the vector sum of the near-bed streamwise velocity and the near-bed vorticity induced transverse velocity.

Determine the wave-current shear stress magnitude if desired. If wave-current induced shear is invoked, the shear stress obtained from the current only calculation is overwritten: the wave-current analysis yields the combined wave current shear.

sedlib_core_critical_shear_stress.c

Purpose

This is the subroutine that calculates the critical shear stress for each noncohesive grain.

Sedlib_core_critical_shear_stress performs the following functions:

- Calculate the d50 and the geometric mean diameter (dgm) by calling sedlib_proc_find_percent_finer. These are used in subsequent calculations.

- Call sedlib_proc_critical_shear_correction to calculate the reduction factor to be applied to the critical shear stress value as a function of the streamwise bed slope and/or the transverse bed slope.

- If the sediment type is noncohesive, then

  - Call sedlib_proc_critical_shear_stress_van_rijn to calculate the critical shear stress of the grain for a horizontal bed by the method of Shields. Save this as critical_shear_stress_plane_bed

  - Depending on the hiding factor method invoked, calculate the critical shear stress for either d50 or dgm by calling sedlib_proc_critical_shear_stress_van_rijn

  - Determine the hiding factor by calling the appropriate sedlib_proc function.

  - Determine the critical shear stress for each grain by multiplying the critical shear stress for the d50 (or dgm) by the ratio of the grain size to d50 (or dgm), the hiding factor, and the reduction factor for the bed slope. Save this as critical_shear_stress.

sedlib_core_noncoh_erosion_deposition_flux.c

Purpose

This subroutine calculates the erosion and deposition flux potential terms for noncohesive sediment. These terms can be calculated independently of the layer being eroded, since they are only a function of shear stress and grain properties.

Sedlib_core_noncoh_erosion_deposition_flux performs the following functions:

- find the D_{50} , D_{90} and the σ_ϕ (the standard deviation of the grain size on the sedimentary scale) of the bed surface material by calling sedlib_proc_find_percent_finer

- Loop on all of the grain classes and search for noncohesive classes

  - Only solve for suspended load if the grain size is less than a specified gravel limit (0.0025 m). The suspended process equations are generally not valid for gravel classes.

  - find the suspended near-bed equilibrium concentration by calling any one of several suspended entrainment functions

  - Limit suspension such that it only occurs if the shear velocity is at least ½ of the settling velocity

  - Convert the near bed concentration from a concentration by volume to a concentration by mass

  - Calculate the suspended sediment erosion flux potential and deposition flux potential for the grain class as follows:

$$E_S = v_S C_{NB.EQ} \tag{3}$$

$$D_S = v_S \tag{4}$$

> where:
>
> E_s = the suspended erosion potential
>
> D_s = the suspended deposition potential
>
> v_s = the settling velocity
>
> $C_{NB.EQ}$ = the near bed equilibrium suspended concentration

  - Call sedlib_proc_bedload_velocity_philips_and_sutherland to calculate the bedload velocity

  - Set the bedload thickness equal to 1 (we are solving for the product of the bedload concentration time the bedload thickness, so we set the thickness to 1 and bundle the other terms into the bedload concentration)

- Find the bedload thickness and equilibrium concentration by calling any of several bedload entrainment functions.

- Convert the equilibrium bedload concentration potential from a concentration by volume to a concentration by mass

- Find the bedload adaption length by calling sedlib_proc_bed_load_adaption_length_jain.

- Solve for the bedload erosion and deposition potentials as follows:

$$E_B = \frac{u_B T_B C_{BL.EQ}}{L_B} \tag{5}$$

$$D_B = \frac{u_B T_B}{L_B} \tag{6}$$

where:

E_B = the bedload erosion potential

D_B = the bedload deposition potential

u_B = the bedload velocity magnitude

T_B = the bedload thickness

L_B = the bedload adaption length

$C_{BL.EQ}$ = the equilibrium bedload concentration

- find the partition fraction for bedload and suspended load by calling sedlib_proc_transport_mode_allocation_van_rijn

- If the bedload erosion potential exceeds this partition fraction of the total load, limit the bedload erosion potential to this fraction.

- End the grain class loop

sedlib_core_coh_deposition_flux.c

Purpose

This is the subroutine that calculates the deposition flux potential for cohesive grains. It calls sedlib_proc_coh_deposiiton_krone and loads the result into sed_sl_deposition_flux.

sedlib_core_mixed_sed_erosion_flux.c

Purpose

This subroutine returns the final erosion and deposition potentials to be used in the bed displacement and grain sorting calculations. They are potentials, and not actual fluxes, because the fluxes are determined by the product of these terms and the fraction of the sediment that is available for transport. For erosion, this is the bed fraction; for deposition, this is the suspended (or bedload) concentration.

Sedlib_core_mixed_sed_erosion_flux determines the flux potentials differently, depending on whether the bed layer being eroded is behaving as a noncohesive layer or as a cohesive layer. If the layer is behaving as a noncohesive layer, the noncohesive grains erode according to the noncohesive flux values (determined previously in sedlib_core_noncoh_erosion_deposition_flux). The cohesive grains are then eroded at a rate equal to the grain fraction weighted average of the noncohesive erosion rates. If the layer is behaving as a cohesive layer, all grains that are erodable erode at the cohesive erosion rate. If the layer is a SEDFLUME layer, it erodes according to the prescribed erosion rate as determined by the SEDFLUME data.

Sedlib_core_mixed_sed_erosion performs the following functions:

- If the bed layer is noncohesive, assign each noncohesive grain an erosion rate equal to the noncohesive erosion rate for that grain, and assign an erosion rate for the cohesive grains equal to the grain class weighted average of all of the noncohesive erosion rates.

- If the bed layer is cohesive

    - Call sedlib_proc_erosion_alishahi_and_krone to determine the erosion rate for the layer

    - If the grain is a cohesive grain and the bed shear stress exceeds the critical erosion shear for the grain, the grain erodes at the cohesive erosion rate for the layer. If the shear stress does not exceed the critical erosion shear for the grain, the erosion rate is 0.

    - If the grain is a noncohesive grain and the bed shear stress exceeds the critical shear stress for the grain, the grain erodes at the cohesive erosion rate for the layer. The erosion flux is then divided between suspended load and bedload flux by calling sedlib_proc_transport_mode_allocation_van_rijn. Note that the erosion rate of the noncohesive grains as a function of the cohesive erosion is not permitted to exceed the erosion rate associated with the noncohesive grains alone. If the shear stress does not exceed the critical shear stress for the grain, the erosion rate is 0.

If the layer is a sedflume layer, the erosion rate is found by calling sedlib_proc_sedflume_erosion. The erosion flux for the noncohesive grains is then divided between suspended load and bedload flux by calling sedlib_proc_transport_mode_allocation_van_rijn. Note that the erosion rate of the noncohesive grains as a function of the cohesive erosion is not permitted to exceed the erosion rate associated with the noncohesive grains alone. If the shear stress does not exceed the critical shear stress for the grain, the erosion rate is 0.

sedlib_core_limit_erosion.c

Purpose

This subroutine is only called for the special case when erosion switches to deposition in the middle of a time step. This can happen, for example, when one erodes to a layer that erodes much more slowly than the layer above it.

This circumstance is not properly handled by the bed bookkeeping scheme. Therefore, this subroutine is designed to force the model to continue to erode thoughout the time step.

This is done by setting the active strata properties equal to the properties of a non-erodable layer. This forces the model to continue erosion down to the non-erodable surface (i.e. the bottom of the active layer)

A non-erodable layer is a layer that consists entirely of an immobile grain class i.e. a grain class that is never present in the erosion or deposition terms. This "immobile" grain class is a convenient numerical device for allowing the model to continue to sort sediment in the active layer without eroding though non-erodable surfaces. This class of grains is invisible to the user, since they never appear in the sediment bed, but only appear in the active layer calculations.

For more on the immobile grain class and its use in SEDLIB, see the descriptions of sedlib_core_bed_sorting_and_displacement, and sedlib_core_active_strata_source.

sedlib_core_active_strata_source.c

Purpose

This subroutine returns the active stratum information. This includes the grain size distribution, porosity, and cohesive sediment properties (such as critical shear stress, erosion rate constant, etc.).

The active stratum is defined as the "window" of the sediment bed between the bottom of the active layer (the active stratum ceiling), and the bottom of the active layer from the previous time step (the old active stratum ceiling). If the active stratum ceiling is rising over a time step, the active layer is donating material TO the bed, and hence the active stratum properties are determined by the active layer itself. If the active stratum ceiling is falling over a time step, the active layer is receiving material FROM the bed, and hence the active stratum properties are given by the properties of the bed.

SEDLIB is designed to erode layers discretely. That is, each layer is eroded according to its own properties. This means that, during erosion, sedlib_core_active_strata_source will always return the properties of only one bed layer.

In order to ensure that this occurs, it is necessary to ensure that the "window" between the new and old active stratum ceiling values never contains more than one bed layer.

SEDLIB is also designed such that it will not penetrate non-erodable surfaces. This includes surfaces that are always non-erodable (such as a solid boundary) and surfaces that are temporarily non-erodable (such as a cohesive layer where the critical shear stress of the layer is not exceeded by the bed shear stress for the current time step).

This is accomplished though the use of an immobile grain class. This immobile grain class is a convenient numerical device for allowing the model to continue to sort sediment in the active layer without eroding though non-erodable surfaces. The immobile grain class is invisible to the user, since these grains never appear in the sediment bed, but only appear in the active layer calculations. If a solid boundary or a non-erodable layer is encountered, sedlib_core_active_strata_source returns only grains in the immobile grain class to the active layer computations.   The immobile grains never appear in the erosion or deposition terms, so they behave exactly like armoring grains, and prevent the erosion from penetrating the non-erodable surface.   If, during a subsequent time step, the hydraulic conditions change such that the layer is no longer non-erodable, sedlib_proc_active_strata_source will return the layer properties and real grain distribution, so that the erosion process can proceed into the layer.

Sedlib_proc_active_strata_source performs the following functions:

- Determine is the active stratum ceiling is rising or falling. If it is rising, let the active stratum properties equal the active layer properties and return.

- If the active stratum ceiling is falling, then active stratum properties must be determined.

- If oald_resolve flag = 0, then the active stratum includes more than one bed layer. If the bed layers are very thin, and if the active layer thickness expands between time steps, it is possible to include more than one layer within the active stratum just by the expansion of the active layer thickness. Therefore, the active stratum source consists of the mass weighted average of the properties of each bed layer included in the active stratum. (Note that this special case active stratum is combined with the active layer without allowing any erosion or deposition to take place (i.e. over a time step = 0). This allows the material to be mixed into the active layer without introducing the numerical instabilities associated with eroding through multiple layer properties).

- If oald_resove_flag = 1, a single layer is being included in the active stratum. If the layer is erodable, the layer properties are returned, and the total erodable thickness is returned as well. The total erodable thickness is the thickness required to erode to the bottom of the layer.

- If the layer is non-erodable, or if the solid boundary is encountered, an active stratum consisting only of grains from the immobile grain class is returned, and the total erodable thickness is set to a very large number (this ensures that sediment time step will go to completion).

sedlib_core_bed_sorting_and_displacement.c

Purpose

This subroutine solves the system of equations that are used to determine the updated suspended and bedload concentrations, the bed displacement, and the active layer grain fraction distribution.   The equations for the concentration values are merely implicit formulations of mass balance for the water column (or bedload thickness). The equations for the bed properties are based on the system of equations first proposed by Spasojevic and Holly (1993) and implemented into the CH3D model.   The equations used in SEDLIB are modified from these original equations, to account for layers of different porosity and sediment classes of different specific gravity.

The equations are given as follows: For an active layer consisting of n grain classes, there are 3n+4 unknowns. These include:

- n+1 suspended concentration values
- n+1 bedload concentration values
- n+1 equations active layer grain fractions
- 1 equation for the displacement.

The extra grain class is the immobile grain class. The immobile grain class is a numerical convenience used to represent nonerodable layers or surfaces. The immobile grain class never appears in the erosion or deposition terms: it only appears in the active stratum source/sink terms.

The solution requires 3n+4 equations. These equations are given here.

For each grain class in the active layer, a mass conservation equation can be written as follows:

$$\frac{\partial\left((1-p_{AL})\beta_i\varepsilon_m\right)}{\partial t} + \frac{\beta_i E_{SL.i} + \beta_i E_{BL.i} - D_{SL.i} C_{SL.i} - D_{BL.i} C_{BL.i}}{\rho_w s_i}$$
$$+ (1-p_{AS})\beta_{AS.i}\frac{\partial(\eta-\varepsilon_m)}{\partial t} = 0 \tag{7}$$

where:

ρ_w = density of water (kg m^{-3})

$\beta_{AS.i}$ = active stratum fraction for grain size class i

s_i = specific gravity for grain size class i

p_{AS} = porosity of the active stratum

η = bed elevation (m)

β_i = grain size distribution of the active layer

p_{AL} = porosity of the active layer

ε_m = active layer thickness (m)

$E_{SL.i}$ = the suspended erosion flux potential (kg m^{-2} s^{-1})

$D_{SL,i}$ = the suspended deposition flux potential (kg m^{-2} s^{-1})

$E_{BL,i}$ = the bedload erosion flux potential (kg m^{-2} s^{-1})

$D_{BL,i}$ = the bedload deposition flux potential (kg m^{-2} s^{-1})

$C_{SL,i}$ = suspended concentration for grain class i (kg kg^{-1})

$C_{BL,i}$ = bedload concentration for grain class i (kg kg^{-1})

By summing these n+1 equations and enforcing the condition that the sum of the grain class fractions in the active layer and the active stratum must equal 1, a global mass conservation equation for bed sediment can be written as follows:

$$\left(1-p_{AS}\right)\frac{\partial\left(\eta\text{-}\varepsilon_m\right)}{\partial t}+\frac{\partial\left(\left(1-p_{AL}\right)\varepsilon_m\right)}{\partial t}$$
$$+\sum_{i=1}^{i=ngc}\frac{\left(\beta_i E_{SL,i}+\beta_i E_{BL,i}\text{-}D_{SL,i}C_{SL,i}\text{-}D_{BL,i}C_{BL,i}\right)}{\rho_w s_i}=0 \tag{8}$$

The water column mass balance equation for the suspended load is given as follows:

$$C_{SL,i}=\frac{\beta_i E_{SL,i}\text{-}hC_{SL,i.old}}{h+D_{SL,i}R_i\Delta t} \tag{9}$$

R_i = the suspended profile correction factor

The mass balance equation for the bedload is expressed in terms of the bedload thickness instead of the water depth:

$$C_{BL,i}=\frac{\beta_i E_{BL,i}\text{-}\lambda_{BL,i}C_{BL,i.old}}{\lambda_{BL,i}+D_{BL,i}\Delta t} \tag{10}$$

$\lambda_{BL,i}$ = the bedload thickness (m)

These 3n+4 equations can be solved simultaneously. If the active layer ceiling is falling (i.e. erosion is occurring) the active stratum properties are taken from the eroding bed layer, and the solution of the system of equations can be found exactly from algebraic substitution.

If the active layer ceiling is rising (i.e. deposition is occurring) the active stratum properties are the same as the active layer properties. This makes the system of equations nonlinear (due to the product of the displacement and the active stratum

distribution in equation 7). Therefore, the displacement must be solved iteratively, by using the value of the displacement from the previous iterate in the active stratum source terms.

The following table and equations demonstrate the solution process for 2 grain classes.

Table 2: System of Bed Equations, Given for 2 Grain Classes.

	η	β_1	$C_{SL.1}$	$C_{BL.1}$		β_2	$C_{SL.2}$	$C_{BL.2}$		RHS
1=η	$L_{0,0,0,0}$	$L_{0,0,0,1}$	$L_{0,0,0,2}$	$L_{0,0,0,3}$		$L_{0,1,0,1}$	$L_{0,1,0,2}$	$L_{0,1,0,3}$		$R_{0,0}$
2=β_1	$L_{0,0,1,0}$	$L_{0,0,1,1}$	$L_{0,0,1,2}$	$L_{10,0,1,3}$						$R_{0,1}$
3=$C_{SL.1}$		$L_{0,0,2,1}$	$L_{0,0,2,2}$							$R_{0,2}$
4=$C_{BL.1}$		$L_{0,0,3,1}$		$L_{0,0,3,3}$						$R_{0,3}$
5=β_2	$L_{1,0,1,0}$					$L_{1,1,1,1}$	$L_{1,1,1,2}$	$L_{1,1,1,3}$		$R_{1,1}$
6=$C_{SL.2}$						$L_{1,1,2,1}$	$L_{1,1,2,2}$			$R_{1,2}$
7=$C_{BL.2}$						$L_{1,1,3,1}$		$L_{1,1,3,3}$		$R_{1,3}$

1) Solve 3 and 4 for $C_{SL.1}$ and $C_{BL.1}$ and 6 and 7 for $C_{SL.1}$ and $C_{BL.1}$

2) Substitute into 1, 2 , 5 so those equations are cast in terms of η and β only

3) Solve 2 and 5 for β_1 and β_2.

4) Substitute into 1 so it is cast in terms of η only

5) Solve 1 (directly for erosion, iteratively for deposition)

6) Solve the equations developed in step 3 for β_1 and β_2.

7) Solve the equations developed in step 1 for $C_{SL.1}$, $C_{BL.1}$, $C_{SL.1}$ and $C_{BL.1}$

sedlib_core_active_layer_properties.c

Purpose

This subroutine generates values of the porosity and the cohesive erosion properties for the active layer. It is necessary to assign these values to the active layer in order to save it as a bed layer at the end of the time step. Also, the active layer porosity is partly responsible for governing the net displacement.

The active layer properties are assigned using a mass weighted average of the properties associated with the various sediment sources to the active layer. The bed sources are assigned the properties associated with the active stratum. The depositional sources are assigned properties associated with the individual grains.

The mass weighed average equation for a generic property X is given as follows:

$$\sum_{i=1}^{ngc} \left\{ \begin{array}{l} \left(\dfrac{\partial \left(X_{AL} \left(1 - p_{AL}\right) \varepsilon_m \right)}{\partial t} \right) + \\[2ex] X_{AS} \left(\left(1 - p_{AS}\right) \beta_{AS.i} \dfrac{\partial \left(\eta - \varepsilon_m \right)}{\partial t} \right) + \\[2ex] X_{AL} \left(\dfrac{\beta_i E_{SL.i} + X_{AL} \beta_i E_{BL.i} - X_{D.i} D_{SL.i} C_{SL.i} - X_{D.i} D_{BL.i} C_{BL.i}}{\rho_w s_i} \right) \end{array} \right\} = 0 \qquad (10)$$

where:

ρ_w = density of water (kg m^{-3})

$\beta_{AS.i}$ = active stratum fraction for grain size class i

s_i = specific gravity for grain size class i

p_{AS} = porosity of the active stratum

η = bed elevation (m)

β_i = grain size distribution of the active layer

p_{AL} = porosity of the active layer

ε_m = active layer thickness (m)

$E_{SL.i}$ = the suspended erosion flux potential (kg m^{-2} s^{-1})

$D_{SL.i}$ = the suspended deposition flux potential (kg m^{-2} s^{-1})

$E_{BL.i}$ = the bedload erosion flux potential (kg m^{-2} s^{-1})

$D_{BL.i}$ = the bedload deposition flux potential (kg m^{-2} s^{-1})

$C_{SL.i}$ = suspended concentration for grain class i (kg kg^{-1})

$C_{BL.i}$ = bedload concentration for grain class i (kg kg^{-1})

sedlib_core_bed_layer_update.c

Purpose

This subroutine is called after all bed sorting and displacement calculations are complete. It updates the bed to account for the change in mass associated with the net erosion or deposition that occurs within the time step.

The bed layering algorithm is designed to optimize the available storage space in the bed (i.e. the total number of bed layers) by storing new depositional events as discrete layers, while retaining the unique information associated with existing layers at depth.

Sedlib_core_bed_layer_update performs the following functions:

- Remove the "immobile" grains from the active layer, and (if deposition is occurring) the active stratum. The immobile grain class is a numerical device that is used to represent non-erodable layers and surfaces. It must be removed from the active layer before the active layer is mixed back into the bed. This is done by increasing the fraction of each of the other grains by the inverse of the immobile grain fraction, and then removing the thickness of the active layer (and active stratum if deposition is occurring) that corresponds to the fraction of the distribution represented by the immobile grains.

- Determine the elevation of the active layer relative to the elevation of the bed layers, and what action is required in order to maintain a constant number of bed layers in the bed.

  - If the active layer is located above the existing bed (as with deposition) it is necessary to combine 2 of the existing layers in order to add the deposition layer as a separate layer.

  - If the active layer penetrates just the top 2 layers, no combining or splitting of layers is required to add the active layer as a separate layer and still maintain the same number of layers.

  - If the active layer is located beneath the top 2 bed layers, one or more of the existing layers must be split to add the active layer as a separate layer.

- If only one bed layer exists, combine the active layer and active stratum into the existing bed layer and exit

- If layers must be combined, combine the top two existing layers and the active stratum, and then add the active layer as the top bed layer. Note that if both of these existing layers are of finite thickness, the unique information in each layer is lost in the combining process. Therefore, this protocol works best when there are one or more layers of zero thickness at the bed surface. The user can specify as many of these zero thickness "depositional" layers as they wish, and these will be filled by deposition.

- If no layers need to be combined or split, then the active layer is made into the top bed layer, and any layers of finite thickness located above layers of zero thickness are shifted deeper into the bed to fill these layers. This

process allows discrete depositional layers to be preserved at depth in the bed, while shifting existing zero thickness layers to the top of the bed so they can be filled by future deposition. Since this step is only invoked when the bed is at near equilibrium conditions (e.g. when deposition has slowed to near zero), this protocol effectively stores discrete depositional events as separate layers.

- If layers need to be split, the top existing layer is split by creating a zero thickness layer at the top of the bed. This splitting is repeated until the total number of layers needed for the full compliment of layers has been obtained. Then, the active layer is made into the top bed layer. Note that this process creates zero thickness layers near the bed surface (just below the top layer), which can be used as depositional layers.

- Very thin layers (layers less than 1.E-16 m thick) are zeroed out to avoid numerical errors.

  Any SEDFLUME layers that are completely eroded are flagged as non-SEDFLUME layers, so they can be used as standard layers after all the material in the SEDFLUME layer is eroded.

SEDLIB-CORE References

Brown, Gary L. "Approximate Profile for Nonequilibrium Suspended Sediment" Vol. 134, No. 7, July 2008, pp. 1010-1014

Christensen, B. A. 1970. Manning's n For Cast-In-Place Concrete Pipe; Discussions by Bent A. Christensen, and R. Sakthivadivel, S. Seetharaman and M.V. Somasundara. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 96(HY3).

Spasojevic, M. and Holly, F. M. Jr. (1993) "Three-Dimensional Numerical Simulation of Mobile Bed Hydrodynamics, IIHR Report # 367, December.

Van Rijn, Leo C. 1984. Sediment transport, Part I: Bed load transport. Journal of Hydraulic Engineering ASCE, 110(10), 1431-1456.

SEDLIB-PROC

These are the SEDLIB process routines. Any new routines submitted to SEDLIB should be documented here.

sedlib_proc_active_layer_thickness

Purpose

Sedlib_proc_active_layer_thickness will compute the thickness of the active layer – the depth of bed surface sediment that is available for erosion. This formulation is based on the expression given by Van Rijn (1984). It is modified from Van Rijn's original formulation to reduce the active layer thickness as a function of the fraction of nonerodable grains in the active layer. It also includes a minimum thickness limit of 0.0001 m.

The active layer thickness is computed as follows:

$$\varepsilon_m = \text{MAX}\left[\left(2\left(1-\frac{\sum\beta_{AL.nonerode}}{\sum\beta_{AL.all}}\right)+\frac{\sum\beta_{AL.nonerode}}{\sum\beta_{AL.all}}\right)D_{90},0.0001\text{m}\right]$$

Where ε_m is the thickness of the active layer, D_{90} is the 90% grain size diameter, β_{AL} is the active layer distribution for each grain. This computation includes the ratio of the grain size distribution sum for the nonerodable grains to that of all the grains.

Calling Sequence

CALL sedlib_proc_active_layer_thickness ()

Variable	Type	Definition
ngs	Integer Input	The number of grain sizes
diameter [ngs]	Real Input	The grain size diameter (L)
active_layer_fraction[ngs]	Real Input	The active layer fractions
shear_stress	Real Output	The bed shear stress ($M/(LT^2)$)
critical_shear_stress	Real Input	The critical shear stress for erosion ($M/(LT^2)$)

Notes

Van Rijn, L.C., (1984a) "Sediment Transports, Part I: Bed load transport" Journal of Hydraulic Engineering, ASCE, 110(10), 1431-1456.

sedlib_proc_consolidate_layer

Purpose

Sedlib_proc_consolidate_layer will determine the consolidation of the bed based on a simple interpolation from empirically derived rates. These rates are given as a function of the age of the bed, which is inferred from the current porosity value relative to the porosity values given in the consolidation table.

The bed layer consolidation is computed as follows:

First, the age of the layer is inferred from the porosity of the layer. Then, the age is incremented by the time step, and the bed properties are interpolated from the consolidation table. The layer thickness is then adjusted to account for the change in porosity.

For example, assume the following consolidation table

Age	Porosity	Critical Erosion shear	Erosion rate constant	Erosion rate exponent
0	0.5	0.1	.001	1
10000	0.4	0.2	.002	1.5
20000	0.3	0.3	.003	2

And assume that the porosity of the bed layer is 0.45, the thickness of the bed layer is 0.01 m, and the time step is 100 seconds.

The consolidation is computed as follows:

1) Infer the age of the layer from the porosity through interpolation from the table. In this case, 0.45 is midway between 0.5 and 0.4, so the age of the layer is 5000 seconds.

2) Increment the age of the bed by the time step. This results in a layer age of 5100 seconds.

3) Interpolate the new bed layer properties.

       Porosity = 0.449

       Critical erosion shear = 0.151

       Erosion rate constant = .00151

       Erosion rate exponent = 1.255

4) Adjust the layer thickness:

$$t_n = t_o \frac{(1-p_o)}{(1-p_n)}$$

Where t_n is the new thickness, t_o is the old thickness, p_n is the new porosity, and p_o is the old porosity.

For this example, the new thickness is given as follows

$$t_n = 0.05 \frac{(1-0.45)}{(1-0.449)} = 0.049909$$

Calling Sequence

CALL sedlib_proc_consolidate_layer ()

Variable	Type	Definition
ncti	Integer Input	The number consolidation time intervals
t_step	Real Input	The time step length (T)
layer_por	Real Input	The porosity of the layer
layer_thick	Real Input	The layer thickness (L)
Cbp [ncti][5]	Real Input	The consolidation properties
c_param[5]	Real Output	The output consolidation properties

Notes

sedlib_proc_bed_load_adaption_length_jain

Purpose

Sedlib_proc_bed_load_adaption_length_jain will calculate the bed load adaption length using the method of Jain (1992)

The bl_l is computed as follows:

If the shear stress magnitude is less than the critical shear stress

$$bl_l = 100 \times bl_{thick}$$

Otherwise

$$bl_l = 1.82 \frac{\tau - \tau_c}{(s\text{-}1)\rho g D} l_{jump}$$

$$l_{jump} = u_{sed} t_{burst}$$

$$u_{sed} = 8.5 u_* \sqrt{1 - \frac{u_{*.c}}{u_*}}$$

$$t_{burst} = 6 \frac{d}{u_w}$$

$$u_w = 2.5 u_* \ln(\beta + 1)$$

$$\beta = 29.7 \times 0.368 \frac{d}{k}$$

$$k = 3 d_{90}$$

$$u_* = \sqrt{\frac{\tau}{\rho}}$$

$$u_{*.c} = \sqrt{\frac{\tau_c}{\rho}}$$

Where: bl_l is the bed load adaption length, bl_{thick} is the bed load thickness length, d is the water depth, D is the grain diameter, τ_c is the critical shear stress, τ is the bed shear stress, u_w is the depth-averaged flow velocity u_{sed} is the sediment velocity, $u_{*.c}$ is the critical velocity, u_* is the bed shear velocity, ρ is the water density, s is the specific gravity of the grain, l_{jump} is the jump length for the grain, k is the equivalent sand roughness, and t_{burst} is the grain burst period.

Calling Sequence

CALL sedlib_proc_bed_load_adaption_length_jain ()

Variable	Type	Definition
s(spg)	Real Input	Specific gravity of sand grain
g(g)	Real Input	Acceleration due to gravity
ρ(rho)	Real Input	Density f fluid
D(diameter)	Real Input	Grain diameter
τ(shear mag)	Real Input	Shear stress imposed by fluid flow
τ_c(critical shear stress)	Real Input	Critical shear stress for erosion
d(depth	Real Input	Fluid depth
k(esrh)	Real Input	Equivalent sand grain roughness
Bl_{thick}(sed bl thick)	Real Input	Bed load thickness
bl_l(bed load adaption length)	Real Output	Bed load adaption length

Notes

Jain, S.C. (1992). "Note on lag in bedload discharge," *Journal of Hydraulic Engineering*, ASCE, Vol. 118, No. 6, pp. 904-917.

sedlib_proc_bed_load_direction_correction

Purpose

Sedlib_proc_bed_load_direction_correction will correct the bed load for bed slope.

If the bed has no horizontal slope, the bedload vector will point in the same direction as the shear stress vector (note that the direction of the shear stress vector has been corrected for vorticity effects, so therefore the direction of the bedload vector is implicitly corrected for these effects as well). If the bed has any horizontal slope, the trajectory of the grains moving in bedload will include a gravitational component

This formulation is the same as that given by Struiksma et al (1985), with a shape factor corresponding to spherical particles, which (by their definition) is = 1.5.

The u_{BLx} and u_{BLy} are computed as follows:

$$u_{BL.x} = \frac{\tau_x - K_{bs}\dfrac{\partial z}{\partial x}}{\sqrt{\left(\tau_x - K_{bs}\dfrac{\partial z}{\partial x}\right)^2 + \left(\tau_y - K_{bi}\dfrac{\partial z}{\partial y}\right)^2}}$$

$$u_{BL.y} = \frac{\tau_y - K_{bs}\dfrac{\partial z}{\partial y}}{\sqrt{\left(\tau_x - K_{bs}\dfrac{\partial z}{\partial x}\right)^2 + \left(\tau_y - K_{bs}\dfrac{\partial z}{\partial y}\right)^2}}$$

$$K_{bs} = \frac{2}{3}\rho g(s-1)D$$

Where $u_{.BLx}$ is the x-component of the unit direction vector, $u_{.BLy}$ the y-component of the unit direction vector, τ_x is the x-direction shear stress, τ_y is the y-direction shear stress, $\delta z/\delta x$ is the gradient of z in the x-direction, $\delta z/\delta y$ is the gradient of z in the y-direction.

Calling Sequence

CALL sedlib_proc_bed_load_direction_correction ()

Variable	Type	Definition
s(spg)	Real Input	Specific gravity of grain
gravity(g)	Real Input	Acceleration due to gravity
ρ(rho)	Real Input	Fluid(water) density
d(diameter)	Real Input	Grain diameter
τ_x	Real Input	X-direction shear stress
τ_y	Real Input	Y-direction shear stress
$\dfrac{\partial z}{\partial x}$	Real Input	Gradient of z in x-direction
$\dfrac{\partial z}{\partial y}$	Real Input	Gradient of z in y-direction
u_{BLx} and u_{BLy} (*bldcf)	Real Output	Bed load correction: 1 by 2 Array

Notes

Struiksma, N., Olesen, K. W., Flokstra, C. & Vriend, H. J. De 1985. Bed deformation in curved alluvial channels. Journal of Hydraulic Research 23(1): 57–79.

sedlib_proc_bed_load_velocity_phillips_and_sutherland

Purpose

Sedlib_proc_bed_load_velocity_phillips_and_sutherland will calculate the bedload velocity (u_b)

The bedload velocity is computed as follows:

$$u_b = 8.5\left(\frac{\tau}{\rho}\left(1-\left(\frac{\tau_{cr}}{\tau}\right)^{1/2}\right)\right)^{1/2}$$

Where u_b is the bedload velocity, τ is the grain shear stress, τ_{cr} is the critical shear stress and ρ is the water density.

Calling Sequence

CALL sedlib_proc_bed_load_velocity_phillips_and_sutherland ()

Variable	Type	Definition
ρ(rho)	Real Input	Fluid(water) density
τ	Real Input	The grain shear stress
τ_{cr}	Real Input	The critical shear stress

Notes

Phillips, B. C. , and Sutherland, A. J. (1989). "Spatial lag effects in bed load sediment transport." *J. Hydraul. Res.* , **27** (**1**), 115–133.

sedlib_proc_bed_load_flux_van_rijn

Purpose

Sedlib_proc_bed_load_flux_van_rijn will calculate the bedload flux using the formulation proposed by Van Rijn (1984). The formulation is modified for use with multiple grain classes and sloping beds according to Kleinhans and van Rijn (2002).

The bedload flux (q_b) is computed as follows:

$$q_b = u_b t_b c_b$$

The bed particle velocity (u_b) is computed as follows:

$$u_b = 1.5 \left[(s-1)gD \right]^{0.5} T^{0.6}$$

The bedload thickness (t_b) is computed as follows:

$$t_b = 0.3 D D_*^{0.7} T^{0.5}$$

The bed load concentration (c_b) is computed as follows:

$$c_b = c_0 0.18 \frac{T}{D_*}$$

$$D_* = D_{50} \left[\frac{(s-1)g}{v^2} \right]^{\frac{1}{3}}$$

$$T = \frac{\tau - \tau_{cr}}{\tau_{cr.h}}$$

Where, s is the grain specific gravity, D is the particle diameter, D_{50} is the median diameter of all of the cohesionless grains, c_0 is the maximum bed load volumetric concentration (0.65), T is the transport stage parameter, D_* is the dimensionless particle diameter, g is the acceleration due to gravity, u is the mean flow velocity, τ is the bed shear stress, τ_{cr} is the critical shear stress, and $\tau_{cr.h}$ is the critical shear stress for a horizontal bed

Calling Sequence

CALL sedlib_proc_bed_load_flux_van_rijn ()

Variable	Type	Definition
s	Real Input	Specific Gravity
g	Real Input	Acceleration due to gravity
d	Real Input	Diameter of particle
ν	Real Input	Kinematic Viscosity
τ	Real Input	Shear Stress
τ_{cr}	Real Input	Critical Shear Stress
$\tau_{cr.h}$	Real Input	Critical shear stress for a horizontal bed
q_b	Real output	Bedload flux

Notes

Kleinhans, M.G. and van Rijn, L.C.,2002, "Stochastic Prediction of Sediment Transport in Sand-Gravel Bed Rivers", *Journal of Hydraulic Engineering,* Vol. 128, No. 4, April 2002.

van Rijn ,L.C. 1984, Sediment Transport, Part I: Bed Load Transport, J. Hydr. Engrg. 110, 1431 DOI:10.1061/(ASCE)0733-9429(1984)110:10(1431)

sedlib_proc_bed_load_flux_meyer_peter_mueller

Purpose

Sedlib_proc_bed_load_flux_meyer_peter_mueller will calculate the bedload flux using the formulation proposed by Meyer-Peter and Mueller (1948).

The bedload flux is computed as follows:

$$q_b = \left(\frac{8}{g(s-1)}\right)\left(\frac{\tau\left(\frac{D_{90}}{k}\right)^{0.25} - \tau_{cr}}{\rho}\right)^{1.5}$$

Where, s is the grain specific gravity, ρ is the water density, D_{90} is the 90th percentile diameter of all of the cohesionless grains, k is the total bed roughness height (form plus skin drag), g is the acceleration due to gravity, τ is the bed shear stress, τ_{cr} is the critical shear stress for the grain size under consideration

Calling Sequence

CALL sedlib_proc_bed_load_flux_meyer_peter_mueller ()

Variable	Type	Definition
s	Real Input	Specific Gravity
g	Real Input	Acceleration due to gravity
ρ	Real Input	Density of water
k	Real Input	The total bed roughness height
D_{90}	Real Input	The 90% percentile grain size for the active layer
τ	Real Input	Shear Stress
τ_{cr}	Real Input	Critical Shear Stress
Q_b	Real output	The bedload flux

Notes

Meyer-Peter, E., and Müller, R. (1948). "Formulas for bed-load transport." *Proc.*, *2nd Meeting*, IAHR, Stockholm, Sweden, 39-64.

sedlib_proc_bed_load_flux_wong_parker

Purpose

Sedlib_proc_bed_load_flux_wong_parker will calculate a correction to the Meyer-Peter Mueller bedload flux, so that it is applicable to plane bed conditions.

The bedload flux is computed as follows:

$$q_b = \left(\frac{3.97}{g(s-1)} \right) \left(\frac{\tau - \tau_{cr}}{\rho} \right)^{1.5}$$

Where, s is the grain specific gravity, ρ is the water density, g is the acceleration due to gravity, τ is the bed shear stress, τ_{cr} is the critical shear stress for the grain size under consideration

The bedload flux computed here is compared to the bedload flux computed by Meyer-Peter and Mueller. The minimum of the two computed values is used.

Calling Sequence

CALL sedlib_proc_bed_load_flux_meyer_peter_mueller ()

Variable	Type	Definition
s	Real Input	Specific Gravity
g	Real Input	Acceleration due to gravity
ρ	Real Input	Density of water
τ	Real Input	Shear Stress
τ_{cr}	Real Input	Critical Shear Stress
Q_b	Real output	The bedload flux

Notes

Wong, M. and Parker, G. (2006). "Reanalysis and Correction of Bed-Load Relation of Meyer-Peter and Müller Using Their Own Database." *J. Hydraul. Eng.*, 132(11), 1159–1168.

sedlib_proc_bedshear_current_only_christensen

Purpose

Sedlib_proc_bedshear_current_only_christensen will calculate a coefficient of friction, c_f, for the depth averaged hydrodynamic model.

The c_f is computed as follows:

$$c\_f = 2\phi$$

$$\phi = \left(\frac{0.4\beta}{(\beta+1)(\ln(\beta+1)-1)+1} \right)^2$$

$$\beta = 29.7 \frac{d}{k}$$

Where, d is the water depth, and k is the roughness height.

Calling Sequence

CALL sedlib_proc_bedshear_current_only_christensen ()

Variable	Type	Definition
depth	Real Input	Depth of flow
roughness_height	Real Input	Roughness height
c_f	Real Output	Coefficient of friction

Notes

sedlib_proc_coh_deposition_krone

Purpose

Sedlib_proc_coh_deposition_krone will calculate the deposition potential by the method of Krone(1962)

The deposition potential is computed as follows:

$$D = v_s \left(1 - \frac{\tau}{\tau_{c.d}} \right)$$

Where, v_s is the settling velocity, τ is the shear stress and $\tau_{c.d}$ is the critical shear stress for deposition.

Calling Sequence

CALL sedlib_proc_coh_deposition_krone ()

Variable	Type	Definition
τ	Real Input	Fluid imparted shear stress magnitude
$\tau_{c.d}$	Real Input	Critical shear stress for deposition
v_s	Real Input	Settling velocity

Notes

Krone, R. 1962, Flume studies of the transport of sediment in estuarial shoaling process, Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California, Berkeley

sedlib_proc_coh_erosion_alishahi_and_krone

Purpose

Sedlib_proc_coh_erosion_alishahi_and_krone will calculate an erosion flux potential (E_s) based on the formulation of Alishahi and Krone (1964).

The E_s is computed as follows:

If the applied shear stress is greater than the critical shear stress for erosion

$$E_s = M\left(\frac{\tau}{\tau_{ce}} - 1\right)^n$$

Otherwise, $E_s = 0.0$;

Where, M is the erosion rate constant for the grain class, τ is the applied shear stress, τ_{ce} is the critical shear stress for erosion and n is an exponent.

Calling Sequence

CALL sedlib_proc_coh_erosion_alishahi_and_krone ()

Variable	Type	Definition
τ (shear_mag)	Real Input	Applied Shear Stress
τ_{ce} (ces)	Real Input	Shear stress for erosion
M (erc)	Real Input	Erosion rate constant
n (ere)	Real Input	Erosion rate exponent

Notes

Alishahi, M.R., and Krone, R.B. .1964. "Suspension of cohesive sediments by wind-generated waves," *Technical Report HEL-2-9*, Hydraulic Engineering Laboratory, University of California, Berkeley.

sedlib_proc_coh_fall_velocity_hwang_and_mehta

Purpose

Sedlib_proc_coh_fall_velocity_hwang_and_mehta will compute a settling velocity for the cohesive flocs based on the formulation of Hwang and Mehta (1989)

The w_s is computed as follows:

$$w_s = \frac{aS^n}{\left(S^2 + b^2\right)^m}$$

Where, w_s is the floc settling velocity (in mm/s) , S is the bulk cohesive sediment concentration (in ppt), a, b, m, n are coefficients of fit.

Based on their analysis of Lake Okeechobee sediment, Hwang and Mehta used the following values for these coefficients:

a = 33.38

b = 4.39

m = 1.48

n = 1.02

Calling Sequence

CALL Sedlib_proc_coh_fall_velocity_hwang_and_mehta ()

Variable	Type	Definition
w_free	Real Input	The free settling velocity of the grain class
s_i	Real Input	The bulk suspended concentration (of all cohesive sediment classes)
a_i	Real Input	Coefficient a
b_i	Real Input	Coefficient b
m_i	Real Input	Coefficient m
n_i	Real Input	Coefficient n

Notes

Hwang, K.-N, and A. J. Mehta, 1989: Fine sediment erodibility in Lake Okeechobee. Coastal and Oceanographic Engineering Department, University of Florida, Report UFL/COEL-89/019, Gainesville, FL.

sedlib_proc_critical_shear_correction

Purpose

Sedlib_proc_critical_shear_correction will calculate a correction to be applied in the presence of longitudinal as well as lateral slope.

The $\tau_{c.i}$ (critical_shear_correction) is computed as follows:

$$\tau_c = K_L K_B \tau_{ch}$$

$$K_L = \cos(\theta_L) - \sin(\theta_L)\left(\frac{1}{\tan(\Phi_R)}\right)$$

$$K_B = \cos(\theta_B)\sqrt{1 - \frac{\tan^2(\theta_B)}{\tan^2(\Phi_R)}}$$

$$\theta_L = \tan^{-1}\left(-\frac{\tau_x \frac{\partial z}{\partial x} + \tau_y \frac{\partial z}{\partial y}}{\sqrt{\tau_x^2 + \tau_y^2}}\right)$$

$$\theta_B = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2 - \tan^2\theta_L}$$

Where τ_{ch} is the critical shear stress of the size class, θ_L is the longitudinal bed slope, θ_T is the transverse bed slope, and Φ_R is the angle of repose of the sediment (default = 30°) Note that θ_L and are θ_T are defined here as positive for down slope.

If the longitudinal bed slope is negative (i.e. the bed is sloping upward) K_L is set equal to $K_L(\theta_L)$ X $(1 - \tan(-\theta_L))$. This is done because, although a positive slope will theoretically make $K_L >> 1$, this is physically unrealistic. These equations are derived assuming a constant shear stress, but the real shear stress is constantly fluxuating due to turbulence. Therefore, the real criteria for incipient motion is a stability criteria, rather than a constant net force criteria.

The correction given here for positive slope is approximate. It accounts for the fact that, for a positive slope, normal stresses begin to act on the grains. This upward slope correction is not quantitatively justified. Therefore, the inclusion of a more rigorous development of this process would be beneficial.

Calling Sequence

CALL Sedlib_proc_critical_shear_correction ()

Variable	Type	Definition
shear_vect_x	Real Input	Shear stress in x-direction
shear_vect_y	Real Input	Shear stress in y-direction
dz_dx	Real Input	Gradient of z in x-direction
dz_dy	Real Input	Gradient of z in y-direction

Notes

Lane, E. W. (1955). "Design of Stable Channels" Transactions, American Society of Civil Engineers, 120(2776), pp1,234-1279.

U.S. Department of the Interior, Bureau of Reclamation, Sediment Section (1958). Interim report, "Total Sediment Transport Program, Lower Colorado River Basin", 175p.

sedlib_proc_critical_shear_stress_shields_van_rijn

Purpose

Sedlib_proc_critical_shear_stress_shields will calculate a critical shear stress for noncohesive particles based on the method of Shields (1936) using values of the mobility number given by van Rijn (1984).

The critical shear stress is calculated as follows:

$$\tau_{ch} = \varphi \rho \, g \, (s\text{-}1) D$$

Where, $\tau_{ch,i}$ is the horizontal critical shear stress of the size class, ρ is the density of water; s is the specific gravity of the sediment size class, D is the grain diameter of the sediment size class, and φ is the mobility number. The mobility number is given in terms of the dimension grain diameter, D_*

$$D_* = D \left[\frac{(s\text{-}1)g}{v^2} \right]^{1/3}$$

For $D_* \leq 4.469 : \phi = 0.24 D_*^{-1}$

For $4.469 < D_* \leq 10.17 : \phi = 0.14 D_*^{-0.64}$

For $10.17 < D_* \leq 17.85 : \phi = 0.04 D_*^{-0.1}$

For $17.85 < D_* \leq 144.57 : \phi = 0.013 D_*^{0.29}$

For $144.57 < D_* \leq : \phi = 0.55$

Calling Sequence

CALL Sedlib_proc_critical_shear_stress_shields_van_rijn ()

Variable	Type	Definition
diameter	Real Input	Diameter of the grain class
density	Real Input	Density of water
gravity	Real Input	Acceleration due to gravity
specific_gravity	Real Input	Specific gravity of the grain class
kinematic_viscosity	Real Input	The kinematic viscosity of water

Notes

Shields A. (1936) "Application of similarity principles and turbulence research to bed-load movement" Translated by W. P. Ott and J.C Van Uchelen, Soil Conservation Service Cooperative Laboratory, California Institute of Technology, Pasadena, California.

van Rijn ,L.C. 1984, Sediment Transport, Part I: Bed Load Transport, J. Hydr. Engrg. 110, 1431 DOI:10.1061/(ASCE)0733-9429(1984)110:10(1431)

sedlib_proc_find_percent_finer

Purpose

Sedlib_proc_find_percent_finer will find the fraction of sediment finer than any fraction (between 0 and 1).

The fraction finer is computed as follows:

First, the sediment classes are sorted such that they are in order from finest to coarsest class. Then, the fraction finer than the specified fraction is found by interpolation between classes.

Calling Sequence

CALL Sedlib_proc_find_percent_finer ()

Variable	Type	Definition
ngs	Integer Input	The number of grain classes
diameter	Real Input	The array containing the diameter of each grain class
bed_fraction	Real Input	The array containing the fraction of each grain class in the sample
fraction_needed	Real Input	The fraction desired (between 0 and 1)

Notes

sedlib_proc_hiding_factor_karim_holly_yang

Purpose

Sedlib_proc_hiding_factor_karim_holly_yang will account for the effects of the near bed grain size distribution on the exposure of each grain class to the flow, and hence the availability of each grain class for potential erosion. It is used to modify the critical shear stress of the grain.

The hiding factor is computed as follows:

$$\varsigma_h = \left(\frac{D}{D_{50}} \right)^{-0.85}$$

Where ς_h is the hiding factor to be applied to the critical shear stress, D is the grain diameter of the sediment size class, and D_{50} is the 50 percent finer grain size.

Calling Sequence

CALL Sedlib_proc_hiding_factor_karim_holly_yang ()

Variable	Type	Definition
D	Real Input	The specific grain size diameter (L)
D_{50}	Real Input	The 50% finer grain size diameter (L)

Notes

Karim, M.F., Holly, F.M., and Yang, J.C. (1987). "IALLUVIAL: Numerical simulation of mobile-bed rivers: Part I, Theoretical and numerical principles." Report No. 309, Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa.

sedlib_proc_hiding_factor_egiazaroff

Purpose

Sedlib_proc_hiding_factor_egiazaroff will account for the effects of the near bed grain size distribution on the exposure of each grain class to the flow, and hence the availability of each grain class for potential erosion. It is used to modify the critical shear stress of the grain.

A maximum value is set for grain ratios less than 0.4, as suggested by Ashida and Michiue (1972).

The hiding factor is computed as follows:

$$\varsigma_h = 8.67 \left(\ln \left(19 \frac{D}{D_{GM}} \right) \right)^{-2}$$

$$if \ \frac{D}{D_{GM}} < 0.4; \varsigma_h = 0.8431 \frac{D}{D_{GM}}$$

Where ζ_h is the hiding factor to be applied to the critical shear stress, D is the grain diameter of the sediment size class, and D_{GM} is the geometric mean grain diameter for the active layer.

Calling Sequence

CALL Sedlib_proc_hiding_factor_egiazaroff ()

Variable	Type	Definition
D	Real Input	The specific grain size diameter (L)
D_{GM}	Real Input	The geometric mean grain diameter (L)

Notes

Egiazaroff L. V. (1965) "Calculation of Non-Uniform Sediment Concentration" Journal of Hydraulics Division, ASCE, 91(HY4), 225-248.

Ashida and Michiue (1972) " Study on Hydraulic resistance and bedload transport rate in alluvial streams" *Transactions, Japan Society of Civil Engineering*, 206, 59-69.

sedlib_proc_hiding_factor_wu_wang_jia

Purpose

Sedlib_proc_hiding_factor_wu_wang_xia will account for the effects of the near bed grain size distribution on the exposure of each grain class to the flow, and hence the availability of each grain class for potential erosion.   It is used to modify the critical shear stress of the grain.

The hiding factor is computed as follows:

$$\varsigma_h = \left(\frac{f_{\text{HID.i}}}{f_{\text{EXP.i}}} \right)^{0.6}$$

$$f_{\text{HID.i}} = \sum_{j=1}^{ngc} \frac{\beta_j D_j}{\left(D_i + D_j \right)}$$

$$f_{\text{EXP.i}} = \sum_{j=1}^{ngc} \frac{\beta_j D_i}{\left(D_i + D_j \right)}$$

Where ς_h is the hiding factor to be applied to the critical shear stress, D_i is the grain diameter of the ith sediment size class, D_j is the grain diameter of the jth sediment size class, and β_j is the active layer grain fraction for the jth sediment size class.

Calling Sequence

CALL Sedlib_proc_hiding_factor_karim_holly_yang ()

Variable	Type	Definition
i	Integer Input	The sediment size class to be evaluated
D	Real Input	The grain size diameters for all grain classes (L)
β	Real Input	The active layer grain fraction distribution(L)

Notes

Wu, W. M., Wang, S. S. Y., and Jia, Y. F., 2000, Nonuniform sediment transport in alluvial rivers, J. Hydr. Res., IAHR, Vol. 38, No. 6, pp. 427-434.

sedlib_proc_noncoh_entrainment_rate_garcia_parker

Purpose

Sedlib_proc_noncoh_entrainment_rate_garcia_parker will compute the near bed equilibrium volumetric concentration for noncohesive grains. Noncohesive sediment behavior is governed primarily by granular properties. Noncohesive sediment particles erode if the critical shear stress for erosion is exceeded for that particle. Once the particle is eroded, it begins to settle and is subject to redeposition. Hence, the erosion/deposition flux is a balance between particle erosion and suspension due to shear and turbulence, and particle deposition due to settling.

The noncohesive sediment flux is computed as follows:

$$S_{ss} = v_s \left(\beta_{AL} C_{eq} - rC \right)$$

$$C_{eq} = \frac{K_a Z_u^5}{\left(1 + \dfrac{10}{3} K_a Z_u^5 \right)}$$

$$Z_u = \frac{u_*}{v_s} \left(\frac{D}{\nu} \sqrt{gD(s-1)} \right)^{\frac{3}{5}}$$

where S_{SS} is the suspended sediment source/sink term for the size class, K_a is a constant equal to $1.3XE^{-7}$, r is the near bed concentration factor for the size class, C is the depth-averaged concentration for the size class, and β_{AL} is the grain fraction in the active layer, C_{eq} is the near bed equilibrium volumetric concentration.

Calling Sequence

CALL Sedlib_proc_noncoh_entrainment_rate_garcia_parker ()

Variable	Type	Definition
sg	Real Input	The specific gravity ()
g	Real Input	The gravitation acceleration (L/T^2)
ρ	Real Input	The density (M/L^3)
ν	Real Input	The kinematic viscosity (L^2/T)
D	Real Input	The diameter of the grain (M)
τ	Real Input	The shear stress magnitude ($M/(LT^2)$)
τ_{cr}	Real Input	The critical shear stress of the grain ($M/(LT^2)$)
v_s	Real Input	The settling velocity of the grain (L/T)

Notes

Garcia, M., and Parker, G. (1991)."Entrainment of bed sediment into suspension," Journal of Hydraulic Engineering, 117(4),414.

sedlib_proc_noncoh_entrainment_rate_wright_parker

Purpose

Sedlib_proc_noncoh_entrainment_rate_wright_parker will compute the near bed equilibrium volumetric concentration for noncohesive grains. This expression is an improvement of the Garcia-Parker method, offering corrections for the interaction of multiple-grain sized sediments and introducing an energy slope term that renders the method useful in large rivers.

Noncohesive sediment behavior is governed primarily by granular properties. Noncohesive sediment particles erode if the critical shear stress for erosion is exceeded for that particle. Once the particle is eroded, it begins to settle and is subject to redeposition. Hence, the erosion/deposition flux is a balance between particle erosion and suspension due to shear and turbulence, and particle deposition due to settling.

The noncohesive sediment flux is computed as follows:

$$S_{ss} = v_s \left(\beta_{AL} C_{eq} - rC \right)$$

$$C_{eq} = \frac{K_a \left(\lambda Z_u \right)^5}{\left(1 + \frac{10}{3} K_a \left(\lambda Z_u \right)^5 \right)}$$

$$Z_u = \frac{u_*}{v_s} \left(\frac{D}{\nu} \sqrt{gD(s\text{-}1)} \right)^{\frac{3}{5}} \left(S_{EGL} \right)^{\frac{2}{25}} \left(\frac{D}{D_{50}} \right)^{\frac{1}{5}}$$

$$\lambda = 1 - 0.28\sigma$$

where S_{SS} is the suspended sediment source/sink term for the size class, K_a is a constant equal to 7.8XE^{-7}, r is the near bed concentration factor for the size class, C is the depth-averaged concentration for the size class, and β_{AL} is the grain fraction in the active layer, C_{eq} is the near bed equilibrium volumetric concentration, S_{EGL} is the slope of the energy grade line, D_{50} is the median bed surface sediment grain diameter, and σ is the standard deviation of the bed surface sediment on the phi scale.

Calling Sequence

CALL Sedlib_proc_noncoh_entrainment_rate_wright_parker ()

Variable	Type	Definition
sg	Real Input	The specific gravity ()
g	Real Input	The gravitation acceleration (L/T^2)
ρ	Real Input	The density (M/L^3)
D	Real Input	The diameter of the grain (M)
D_{50}	Real Input	The median diameter of the bed surface grains (M)D
ν	Real Input	The kinematic viscosity (L^2/T)
τ	Real Input	The shear stress magnitude ($M/(LT^2)$)
τ_{cr}	Real Input	The critical shear stress of the grain ($M/(LT^2)$)
v_s	Real Input	The settling velocity of the grain (L/T)
σ	Real Input	The standard deviation of the bed surface sediment on the phi scale

Notes

Wright, S., and Parker, G. (2004)."Flow resistance and suspended load in sand-bed rivers: simplified stratification model," Journal of Hydraulic Engineering, 130(8),796.

sedlib_proc_noncoh_entrainment_rate_van_rijn

Purpose

Sedlib_proc_noncoh_entrainment_rate_van_rijn will compute the near bed equilibrium volumetric concentration for noncohesive grains using the formulation proposed by Van Rijn (1984). The formulation is modified for use with multiple grain classes and sloping beds according to Kleinhans and van Rijn (2002).

The near bed equilibrium volumetric concentration (C_{eq}) is computed as follows:

$$C_{eq} = 0.015 \left(\frac{D_{50}}{a} \right) \left(\frac{T^{1.5}}{D_*^{0.3}} \right)$$

$$D_* = D_{50} \left[\frac{(s-1)g}{\nu^2} \right]^{\frac{1}{3}}$$

$$T = \frac{\tau - \tau_{cr.h}}{\tau_{cr.h}}$$

Where, s is the grain specific gravity, D_{50} is the median diameter of all of the cohesionless grains, a is the reference height (=1/2 the total bed roughness height), T is the transport stage parameter, D_* is the dimensionless particle diameter, g is the acceleration due to gravity, τ is the bed shear stress, and $\tau_{cr.h}$ is the critical shear stress for a horizontal bed

Calling Sequence

CALL sedlib_proc_noncoh_entrainment_rate_van_rijn ()

Variable	Type	Definition
s	Real Input	Specific Gravity
g	Real Input	Acceleration due to gravity
a	Real Input	The reference height (= ½ the total bed roughness height)
D_{50}	Real Input	The median particle diameter
ν	Real Input	Kinematic Viscosity
τ	Real Input	Shear Stress
$\tau_{cr.h}$	Real Input	Critical shear stress for a horizontal bed
C_{eq}	Real output	The near bed equilibrium concentration

Notes

Kleinhans, M.G. and van Rijn, L.C.,2002, "Stochastic Prediction of Sediment Transport in Sand-Gravel Bed Rivers", *Journal of Hydraulic Engineering,* Vol. 128, No. 4, April 2002.

van Rijn, L. C. _1984b_. "Sediment transport. Part II: Suspended load transport." *J. Hydraul. Eng.*, 110_11_, 1613–1641.

sedlib_proc_noncoh_fall_velocity_cheng

Purpose

Sedlib_proc_noncoh_fall_velocity_cheng will calculate the settling velocity for noncohesive grains using the formulation of Cheng (1997)

The w_s is computed as follows:

$$D_* = \left(\frac{(s\text{-}1)g}{\upsilon^2} \right)^{\frac{1}{3}} D$$

$$w_s = \frac{\upsilon}{D} \left(\sqrt{25 + 1.2 D_*^2} \text{-} 5 \right)^{1.5}$$

Where, D_* is the dimensionless particle number, g is the acceleration due to gravity, υ is the kinematic viscosity, and D is the grain diameter

Calling Sequence

CALL Sedlib_proc_noncoh_fall_velocity_cheng ()

Variable	Type	Definition
diameter	Real Input	Diameter of particle
specific gravity	Real Input	Specific gravity of particle
kinematic viscosity	Real Input	Kinematic viscosity of fluid
grav	Real Input	Acceleration due to gravity

Notes

Nian-Sheng Cheng (1997), Simplified Settling Velocity Formula for Sediment Particle, J. Hydr. Engrg. 123, 149 , DOI:10.1061/(ASCE)0733-9429(1997)123:2(149)

sedlib_proc_sedflume_erosion

Purpose

Sedlib_proc_sedflume_erosion will compute erosion rates as prescribed by the results of a SEDFLUME core analysis.

Sedflume erosion rate data is given as a table of values sorted by bed layer and shear stress. For a given bed layer, the erosion rate can be found by interpolating between the shear stress values to find the appropriate value for the applied bed shear stress.

This function performs this shear stress interpolation. Erosion rate data for a specific bed layer is passed to the function, together with the applied bed shear stress. The function perfoms an interpolation and returns the appropriate erosion rate.

Calling Sequence

CALL Sedlib_proc_sedflume_erosion ()

Variable	Type	Definition
nssi	Integer Input	Number of sedflume shear stress intervals
bshear	Real Input	The applied bed shear stress (Pa)
sss	Real Array Input	The array containing the sedflume shear stress values (Pa)
ser	Real Array Input	The array containing the sedflume erosion rate values corresponding to the sss values ($M/(L^2 T)$)

Notes

sedlib_proc_sl_near_bed_correction_brown

Purpose

Sedlib_proc_sl_near_bed_correction_brown will computes a correction factor which converts a depth-averaged suspended sediment concentration to a near-bed suspended sediment concentration. The correction factor is a modified form of the Rouse profile, modified to account for nonequilibrium effects (Brown, 2008).

The correction factor is computed as follows:

$$R_{CP} = \frac{C_a}{C_{AVG}} = \frac{K}{\left(1 - e^{-K}\right)}$$

$$K = \frac{6}{\beta_{ss}\kappa} \frac{\left(1 + F_{v.a}\right)}{\left(\dfrac{u_*}{v_s} + F_{v.a}\right)}$$

Where C_a is the near-bed suspended sediment concentration, C_{AVG} is the depth-averaged suspended sediment concentration, v_s is the settling velocity, u_* is the friction velocity, $F_{v.a}$ is the dimensionless net near bed vertical sediment flux, β_{ss} is the sediment turbulent mixing correction factor

The dimensionless net near bed vertical sediment flux is given as follows

$$F_{v.a} = \frac{S_{SS}}{v_s C_a}$$

Where $F_{v.a}$ is the net near bed vertical sediment flux (erosion flux is positive)

The sediment turbulent mixing correction factor (β_{ss}) is given as follows (Van Rijn, 1984b).

$$\text{For silts and clays,} \beta_{ss} \cong 1.$$

$$\text{For sands,} \beta_{ss} = 1 + 2\left(\frac{v_s}{u_*}\right)^2$$

Calling Sequence

CALL Sedlib_proc_sl_near_bed_correction_brown ()

Variable	Type	Definition
sedtype	Integer value	Type of sediment (cohesive or noncohesive)
con	Real Value	Depth-averaged concentration (g/g)
ustar	Real Value	Friction velocity (L/T)
settling_vel	Real Value	Settling velocity (L/T)
erosion flux	Real value	The erosion flux (L/T)
deposition potential	Real value	The deposition potential (L/T)
snbcf_old	Real value	The value of the near-bed-concentration factor from the previous iterate (for use in convergence)

Notes

Brown, Gary L. "Approximate Profile for Nonequilibrium Suspended Sediment" Vol. 134, No. 7, July 2008, pp. 1010-1014

Van Rijn, L.C., (1984b) "Sediment Transports, Part II: Suspended load transport" Journal of Hydraulic Engineering,., ASCE, 110(11), 1613-1641

sedlib_proc_transport_correction_factors

Purpose

Sedlib_proc_transport_correction_factors will calculate the transport correction factors necessary to approximate 3-dimensional sediment flux behavior with 2-dimensional vertically averaged model equations. The mass flux correction factor is used to account for the fact that the depth average of the convective flux must be corrected for the bias introduced by the products of the sediment and velocity profiles (i.e. the flux is somewhat less than one would calculate if one assumed uniform profiles). The vorticity correction factors account for the correction in the direction of the flux due to vorticity.

The transport correction factor for the horizontal sediment mass flux is computed as follows:

$$\alpha_{FC} = \left(\frac{e^{\left(\frac{K}{\beta_{RH}}\right)}}{\left(1 - e^{-K}\right)} \right) \left(\frac{\ln(\beta_{RH})\left(1 - e^{-K}\right) + \text{POLY}(-K)}{\left(\ln(\beta_{RH}) - 1\right)} \right)$$

With

$$\beta_{RH} = \frac{29.7d}{r}$$

Where r is the bottom roughness height, POLY is a polynomial expansion which proceeds as follows:

$$POLY(-K) = \frac{-K}{1 \times 1!} + \frac{K^2}{2 \times 2!} - \frac{K^3}{3 \times 3!} + \frac{K^4}{4 \times 4!} \cdots$$

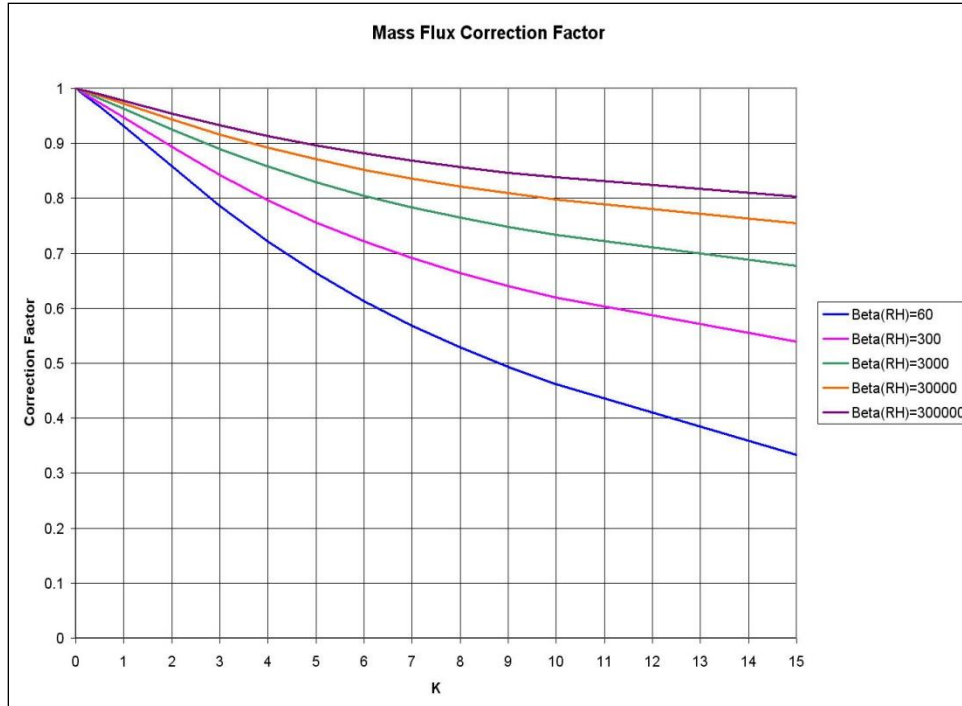A lookup table can be created using the following values:

K	POLY(-K)
0.0001	-0.0001
0.001	-0.0010
0.01	-0.0100
0.1	-0.0976
0.2	-0.1904
0.5	-0.4438
1	-0.7966
2	-1.3193
3	-1.6889
4	-1.9673
5	-2.1878
6	-2.3693
7	-2.5232
8	-2.6567
9	-2.7745
10	-2.8798
15	-3.2853

Since r is being used to describe the velocity profile in this equation, this value of the roughness height should indicate the total roughness (i.e. sand roughness and form roughness). It can be obtained from Manning's n by using the following formula

$$r = \left(8.25 \sqrt{g} \; \frac{n}{K_M} \right)^6$$

Where g is the gravitational acceleration, n is the Manning's n, and K_M is the Manning's constant (1.0 in metric units and 1.486 in English units).

The following figure is a plot of α_{FC} for various values of K and β_{RH}.

Mass Flux Correction Factor

Correction Factor (y-axis): 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1

K (x-axis): 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15

Legend:
Beta(RH)=60
Beta(RH)=300
Beta(RH)=3000
Beta(RH)=30000
Beta(RH)=300000

The transport correction factor for the direction of the horizontal suspended sediment flux influenced by vorticity currents is computed as follows:

$$\text{For } u_T = u_{T.MAX}\left(2\frac{z}{h} - 1\right)$$

$$\alpha_{VC.X} = U\frac{\left(\alpha_{FC}u + \psi_{VC}u_{T.MAX}\right)}{\sqrt{\alpha^2_{FC}U^2 + \psi^2_{VC}U^2_{T.MAX}}} - u$$

$$\alpha_{VC.Y} = U\frac{\left(\alpha_{FC}v + \psi_{VC}v_{T.MAX}\right)}{\sqrt{\alpha^2_{FC}U^2 + \psi^2_{VC}U^2_{T.MAX}}} - v$$

with

$$\psi_{VC} = \frac{\left(1 + e^{-K}\left(\dfrac{2}{K} + 1\right) - \dfrac{2}{K}\right)}{\left(1 - e^{-K}\right)}$$

Where u is the depth averaged X-velocity. v is the depth averaged Y-velocity, α_{FC} is the correction factor for horizontal suspended sediment mass flux, $U_{T.MAX}$ is maximum transverse velocity magnitude, U is the depth-averaged streamwise velocity magnitude, $u_{T.MAX}$ is the X-component of the transverse velocity at the bed, and $v_{T.MAX}$ is the Y-component of the transverse velocity at the bed.

The following figure is a plot of ψ_{VC} for various values of K.
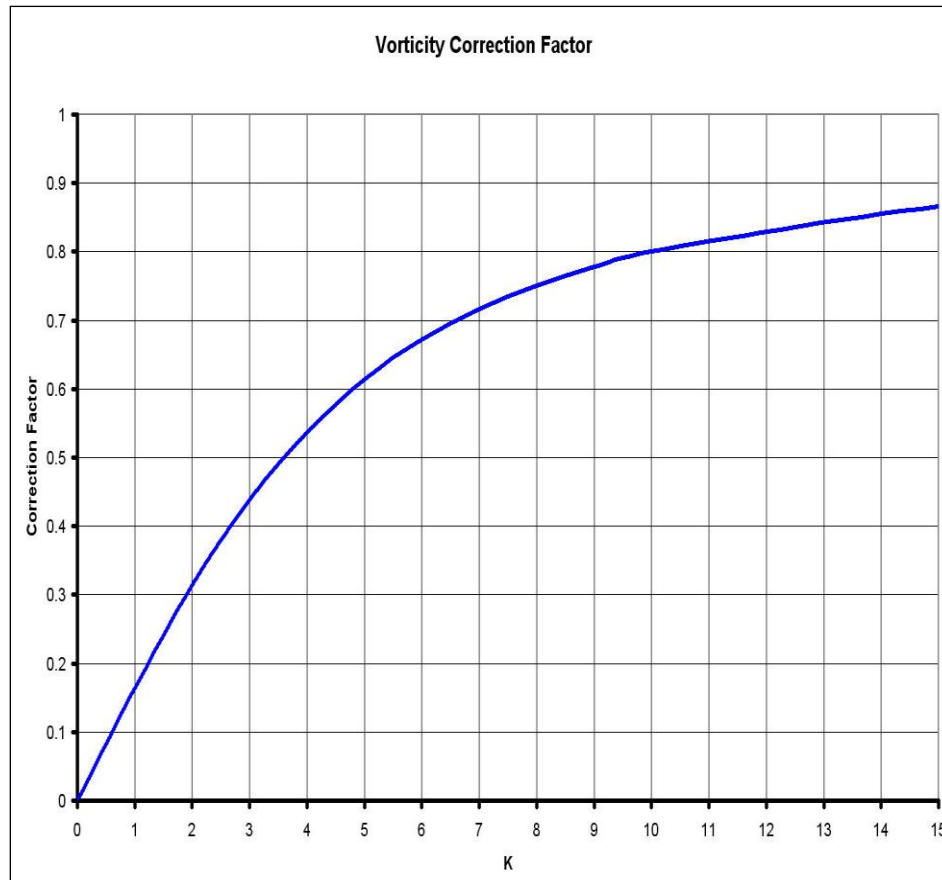
Calling Sequence

CALL Sedlib_proc_transport_correction_factors ()

Variable	Type	Definition
esrh	Real Input	Equivalent sand roughness height (accounting for the total hydrodynamic drag) (L)
d	Real Input	Depth (L)
u	Real Input	X component of velocity (L/T)
v	Real Input	Y component of velocity (L/T)
u_T	Real Input	X component of transverse velocity (L/T)
v_T	Real Input	Y component of transverse velocity (L/T)
rdf	Real Input	The near bed correction factor for the suspended sediment profile
scf []	Real Array Output	The output correction factors

Notes

sedlib_proc_transport_mode_allocation_van_rijn

Purpose

Sedlib_proc_transport_mode_allocation_van_rijn will account for the limiting of the equilibrium concentration at lower shear stresses, which is done to account for the fraction of the eroded material that is transported as bedload. This parameter is essentially the partition between suspended and bed load.

The transport mode allocation parameter is computed as follows:

$$\gamma = 0.75 - 0.325 \ln\left(\frac{u_*}{v_s}\right)$$

Where γ is the transport mode allocation parameter for the grain, u_* is the friction velocity, and v_s is the settling velocity of the grain.

Calling Sequence

CALL Sedlib_proc_transport_mode_allocation_van_rijn ()

Variable	Type	Definition
τ	Real Input	The shear stress of the flow ($M/(LT^2)$)
τ_{cr}	Real Input	The critical shear stress for the grain ($M/(LT^2)$)
v_s	Real Input	The settling velocity for the grain (M/L)
ρ	Real Input	The density (M/L^3)

Notes

Van Rijn, L.C., (1984a) "Sediment Transport, Part I: Bed load transport" Journal of Hydraulic Engineering, ASCE, 110(10), 1431-1456.

sedlib_proc_wave_current_shear_grant_madsen

Purpose

Sedlib_proc_wave_current_shear_grant_madsen will compute a combined wave-current shear stress magnitude at the sediment bed using the Grant Madsen formulation.

The τ_m is calculated as follows:

$$\tau_m = \tau_{wm}\sqrt{1+2\mu\left|\cos\phi_{wc}\right|+\mu^2}$$

$$\mu = \frac{\tau_c}{\tau_{wm}}$$

$$\frac{1}{4\sqrt{f_{cw}/C_\mu}} + \log_{10}\left[\frac{1}{4\sqrt{f_{cw}/C_\mu}}\right] = \log_{10}\left[\frac{C_\mu A_{bm}}{k_r}\right] - 0.17 + 0.24\left(4\sqrt{f_{cw}/C_\mu}\right)$$

f_{cw} is computed using a Newton iterative solver.

$$C_\mu = \sqrt{1+2\mu\left|\cos\phi_{wc}\right|+\mu^2}$$

$$\mu = \frac{\tau_c}{\tau_{wm}}$$

$$u_{*w.m} = u_{*o.m}\sqrt{\frac{f_{cw}}{2}}$$

$$u_{*m} = C_\mu u_{*w.m}$$

$$\delta_{cw} = \kappa\frac{u_{*m}}{\omega}$$

$$u_{*c} = u_{*m} \frac{\ln\left(\dfrac{z_r}{\delta_{cw}}\right)}{\ln\left(\dfrac{\delta_{cw}}{z_o}\right)} \left(-\frac{1}{2} + \sqrt{\kappa \frac{u_c(z_r)}{u_{*m}} \frac{\ln\left(\dfrac{\delta_{cw}}{z_o}\right)}{\left(\ln\left(\dfrac{\delta_{cw}}{\delta_{cw}}\right)\right)^2}} \right)$$

$$z_o = \frac{k_r}{30}$$

$$z_r = k_r$$

Where τ_m is the maximum wave-current shear stress, τ_{wm} is the maximum wave shear stress, τ_c is the maximum current shear stress, ϕ_{wc} is the angle between waves and flow current direction, μ is the ratio of maximum current to maximum wave shear stress, ρ is the fluid Density, ν is the time invariant eddy viscosity, C_μ is the Wave-Current angle correction, f_{cw} is the composite current-wave friction coefficient, u_{*wm} is the wave shear velocity, u_{*c} is the current shear velocity

Calling Sequence

CALL Wave_Current_Shear_Grant_Madsen ()

Variable	Type	Definition
u_vel	Real Input	The flow x-velocity
v_vel	Real Input	The flow y-velocity
depth	Real Input	The depth
w_angle	Real Input	Significant wave Angle
w_height	Real Input	Significant wave height
w_period	Real Input	Significant wave period
equi_sand_grain_rough	Real Input	Equivalent sand grain roughness
density	Real Output	Density of fluid
gravity	Real Input	Gravitational acceleration
max_shear	Real output	Maximum wave-current shear stress

Notes

Grant, W. D. and O. S. Madsen (1979): Combined wave and current interaction with a rough bottom. *J. Geophysical. Research*, **84**, 1797–1808.

sedlib_proc_wave_current_shear_teeter

Purpose

Sedlib_proc_wave_current_shear_teeter will compute a combined wave-current shear stress at the sediment bed using the formulation of Teeter. This formulation assumed fully developed waves in shallow water, and infers wave properties from the wind speed. It is combined with the current shear via simple vector summation.

The τ_m is computed as follows:

$$C_{d.w} = \left(\frac{0.4}{16.11 - 0.5\ln(d) - 2.48\ln(u_w)} \right)^2$$

$$\tau_w = \left(1.225 \ C_{d.w} u_w^2 \right) \left(2.38 \frac{k_w}{1 - k_w} \right) \left(e^{-0.6 d_{lim}} \right)$$

$$k_w = \frac{1.118}{u_{w.lim}^{1/2}}$$

$$u_{w.lim} = \text{MAX}(u_w, 5.0628)$$

$$d_{lim} = \text{MAX}(d, \ 2.001) - 2$$

$$\tau_m = \sqrt{\left(|\tau_{cx}| + |\tau_{wx}| \right)^2 + \left(|\tau_{cy}| + |\tau_{wy}| \right)^2}$$

$$\tau_{wx} = \tau_w \frac{u_{wx}}{u_w}$$

$$\tau_{wy} = \tau_w \frac{u_{wy}}{u_w}$$

Where, d is the depth, τ_{wc} is the combined wave-current shear stress, τ_{cx} and τ_{wx} are the x-direction components of current and wave shear stress, τ_{wy} and τ_{wy} are the y-direction components of current and wave shear stress, u_w is the wind speed.

Calling Sequence

CALL Sedlib_proc_wave_current_shear_teeter ()

Variable	Type	Definition
uw_x	Real Input	Wave X-direction velocity
vw_y	Real Input	Wave Y-direction velocity
tc_x	Real Input	Current X-direction shear stress
tc_y	Real Input	Current Y-direction shear stress
depth	Real Input	Flow depth excluding the wave perturbation.

Notes

TEETER Allen M. ; JOHNSON Billy H. ; BERGER Charlie ; STELLING Guus ; SCHEFFNER Norman W. ; GARCIA Marcelo H. ; PARCHURE T. M. ; *Hydrodynamic and sediment transport modeling with emphasis on shallow-water, vegetated areas (lakes, reservoirs, estuaries and lagoons) : Modelling sediment resuspension, water quality and submersed aquatic vegetation* Hydrobiologia 2001, vol. 444, pp. 1-23 (2 p.1/4)