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MODELISATION DES APPORTS HYDRIQUES ET TRANSFERTS HYDRO-SEDIMENTAIRES

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# SISYPHE 6.0 User Manual

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| <p>This manual is part of the documentation on the TELEMAC hydro-informatic finite elements system (release 6.0). It describes the sediment transport processes which are programmed in the morphodynamic model SISYPHE as well as the method of coupling with the hydrodynamics model. SISYPHE can be applied to calculate the medium to long term bed evolutions in rivers, coastal or estuarine conditions. Physical processes as well as details on the numerical scheme and computational procedure are explained in full details.</p> |            |  |  |

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## Executive Summary

This manual is part of the documentation on the TELEMAC hydro-informatic finite element system (release 6.0). It describes the sediment transport processes which are programmed in the morphodynamic model SISYPHE as well as the method of feedback between the hydrodynamics and the sediment transport model.

SISYPHE is a process-based model: sediment transport rates, decomposed into bed-load and suspended load, are calculated as a function of the time-varying flow field and sediment properties at each node of the triangular grid. The resulting bed evolution is determined by solving the Exner equation using either finite element or finite volume techniques.

Different processes can be accounted for, including the effect of combined waves and currents, non-equilibrium flow conditions, the presence of rigid beds, tidal flats, cohesive and non-cohesive sediment properties, ... SISYPHE can be either chained or internally coupled to the hydrodynamic models (TELEMAC-2D, -3D) or to the wave propagation model (TOMAWAC). It can be applied to diverse flow conditions including rivers, coastal and estuarine environments. Optimization of numerical schemes and use of parallel processors allow to calculate medium to long-term bed evolution of the order of decades, in basin scale models (10-100 km).

We describe in this manual sediment transport processes as well as their implementation (numerical schemes, numerical and physical parameters, input data files). After a general introduction in Part 1, the different steps required for a sedimentological computation are explained in Part 2, including the methods of coupling between the hydrodynamic and morphodynamic models. The sediment and flow parameters, including the bottom shear stress calculation, are presented in Part 3. Part 4 is devoted to the bed-load transport, and Part 5 to the suspended load. Part 6 and 7 present respectively a model description of sand grading effects, and cohesive sediment properties as well as a preliminary treatment of sand-mud mixtures. The effect of waves is discussed in Part 8. Part 9 gives a description of numerical methods and computer time optimization. Finally, Part 10 presents a brief discussion on the morphodynamic model limitation and accuracy.

We recall here that SISYPHE, as well as other modules of the TELEMAC system, are open source since July 2010 and can be downloaded on the internet site ([www.telemacsystem.com](http://www.telemacsystem.com)). Difficulties related to installation, bug reports as well as suggestions for future development are welcome and need to be submitted through the forum to the development team.

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## Summary

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# 1. Introduction

## General overview of SISYPHE

SISYPHE is a sediment transport and morphodynamic model which is part of the hydro-informatic finite elements system TELEMAC. In this model, sediment transport rates, decomposed into bed-load and suspended load, can be calculated at each grid point as a function of various flow (velocity, water depth, wave height...) and sediment parameters (grain diameter, relative density, settling velocity...). The bed-load is calculated by using one of the classical sediment transport formulae from the literature. The suspended load is determined by solving an additional transport equation for the depth-averaged suspended sediment concentration. The bottom evolution equation (the Exner equation) can be solved, by using either a finite element or a finite volume method.

SISYPHE is applicable to sand (uniform or graded) as well as to cohesive sediments or sand-mud mixtures. The sediment composition is represented by a finite number of classes, each characterized by its mean diameter, grain density and settling velocity. Sediment transport processes also include the effect of bottom slope, rigid beds, secondary currents, sliding beds... For cohesive or mixed sediments, the effect of bed consolidation can be accounted for.

SISYPHE can be applied to a large variety of hydrodynamic conditions from rivers, estuaries to coastal applications, where the effects of waves superimposed to a tidal current can be included. The bed shear stress, decomposed into skin friction and form drag, can be calculated either by imposing a friction coefficient (Strickler, Nikuradse, Maning or Chézy) or predicted by a bed-roughness predictor.

## Coupling with hydrodynamics

SISYPHE does not calculate the flow field: the relevant hydrodynamic variables can be either imposed in the model or calculated by a hydrodynamic computation ('chaining method' or 'internal coupling'). It is more convenient to use one of the hydrodynamic modules of the TELEMAC system (namely TELEMAC-2D, -3D and TOMAWAC for waves) for compatibility reasons (same grid, same pre- and post-processor...), but the user can also choose a different hydrodynamic model.

The different methods which can be used to prescribe the hydrodynamics, are described in Part 2.

## Numerical software

The model can be run using either supercomputers and workstations with Unix, Linux operating system or Windows PCs. The SISYPHE release is the same in all machines ; the activation procedures as well as the pre- and post-processors, however, may be different. SISYPHE V6.0 uses the versions 6.0 of the BIEF finite element library (TELEMAC system library).

Like for any morphodynamic model, the user should have a sufficient knowledge of the morphodynamic issues, both for selecting the input data (e.g. the transport formulae) and for assessing the results being achieved.

## Outline of the manual

We present in Chapter 2 the computation processes and methods of coupling between hydrodynamics and morphodynamics. Chapter 3 is a description of the main sediment and hydrodynamics parameters (total bed shear stress/skin friction). Chapter 4 deals with the bed-load, and Chapter 5 with the suspended load. Chapter 6 is devoted to sand grading effects, Chapter 7 to cohesive and mixed sediment properties, and Chapter 8 to the effects of waves. Chapter 9 presents the numerical schemes and methods to reduce CPU time, for long term morphodynamics simulations (of the order of decades) and medium scale basins. Chapter 10 is a brief discussion on the morphodynamic model accuracy and limitation.

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## 2. Computation processes

### 2.1. Sequence of operations

#### Mesh generation

The mesh generation is a preliminary step which is common to all the Telemac modules.

Digitisation of bottom and domain boundaries on a map, using a digitising pad :

- Domain meshing using a finite element mesh generator. The computation domains are discretized through triangular, 3-node finite elements. An interface software (FUDAA) is provided for reading the files from various mesh generators, possibly interpolating a bathymetry and generating a TELEMAT-readable geometry file.
- Input of boundary conditions, either at the mesh generator or through a file.

Different mesh generators can be used. The user will find in the next sections some practical information for operating SISYPHE.

This document however does not provide any detailed description of the Mesh generator, the FUDAA post-processor. The reader is invited to refer to the following documents :

- ✓ documentation of SINUSX software [03],
- ✓ documentation of mesh generator [04],
- ✓ documentation of FUDAA

#### Sequence of operations

The sequence of operations required for a sedimentological computation is as follows :

- ✓ Data processing
- ✓ Input of computational parameters (duration, time step, )
- ✓ Input of physical parameters (processes to be taken into account, etc.)
- ✓ Adaptation of boundary conditions (condim file)
- ✓ Computation activation (type: *Sisyphe name\_of\_steering\_file*)
- ✓ Result analysis using graphical software FUDAA.

*The tables in Appendix display the links among the various items of the processing sequence at a workstation for the TELEMAT system.*

*The different options for running SISYPHE and sequence of operations are explained in the Appendix1.*

*For explanations on the installation at workstation, see also Appendix 1.*

### 2.2. Input data files

#### List of files

A number of files are specific to each of the cases. The software in the processing chain and the SISYPHE procedure create most of them, but the user may also create or modify some files.

The *GEOMETRY FILE* and *BOUNDARY CONDITION FILE* are the binary files issued from the grid generator (MATISSE or STBTTEL). They contain a full description of the (three-node) triangular grid as well as the initial sediment bed level. This initial configuration is obtained from the interpolation of bathymetric data file (format sinus x) on each node of the triangular grid.

The *FORTTRAN FILE* contains those subroutines which the user may modify in order to adapt them to

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his/her own case.

The *HYDRODYNAMIC FILE* contains the hydrodynamic results of a previous hydrodynamic computation (TELEMAC-2D or -3D). The hydrodynamic computation is made on the same grid as the SISYPHE in the TELEMAC system. When a results file from a finite differences hydrodynamic model needs to be read, the hydrodynamic results file shall be transformed beforehand and interpolated on the SIYPHE triangular mesh.

The hydrodynamics will be given either by the last time step of that file in steady mode, or by the time steps related to the period of the tide or flood being considered in unsteady mode.

That file should contain current data, and also wave data (when the effects of wave is considered) as required for the computation.

The *WAVE FILE* contains the hydrodynamic results of a previous wave computation (TOMAWAC).

Only the last record will be read if the key word ('*WAVE EFFECTS*' is activated)

The *PREVIOUS SEDIMENTOLOGICAL COMPUTATION FILE* is provided for implementing a computational sequence, it contains the results of a previous sedimentological computation made using SISYPHE on the same grid. If that file exists, then the initial sedimentological conditions of the computation will be given by the last time step in the file. This data set will be read only if the key word '*COMPUTATION CONTINUED*' is activated.

The *REFERENCE FILE* is for validating the results of the computation at the last time step, the results file of an identical computation being taken as a reference.

All the files are either binary (Selafin format) or formatted (ASCII format). Details of the input data and output results are given in this part. Examples can be found in the Appendix 2.

### **Geometry file**

This binary file contains information of the triangular grid and can be used as input file for all hydrodynamic and wave propagation models (TELEMAC-2D, -3D or TOMAWAC ). The mesh can be generated by MATISSE, STBTTEL or other grid generator.

Interpolation of bathymetric file and quality of the data is a crucial step for morphodynamic modelling.

### **Boundary condition file**

The format of the boundary condition file is the same as for TELEMAC-2D or -3D: the same layout standard was adopted. This file is automatically filled up by the STBTTEL/MATISSE (grid generator) interface, but it can also be prepared or modified through a text editor.

Each line in this file is dedicated to a point along the edge of the grid. The edge points are numbered like the file lines; the numbering first describes the domain outline in the counterclockwise direction from lower left point (X+Y minimum), then the islands in the clockwise direction. The boundary condition about the bottom depth is imposed at the specific place of the tracer boundary condition in TELEMAC-2D (see example in the Appendix).

### **Steering file/fortran file**

As well as in other modules of the TELEMAC system, the model parameters can be either specified in the SISYPHE steering file or by modifying some of the user subroutines in the Fortran file.

The steering file should specify:

- ✓ The names of input /output files (a complete list is given in Appendix 1)
- ✓ Sediment parameters (sand diameter, cohesive or not, settling velocity , ...),
- ✓ Selected transport processes (skin friction, bed load, suspended load, transport formulae, ...).
- ✓ Numerical options (finite elements or finite volumes...)

More details can be found in the Appendix.

### **keywords**

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Names of principal input/output files (other files are optional):

- ✓ 'BOUNDARY CONDITIONS FILE'
- ✓ 'GEOMETRY FILE'
- ✓ 'FORTRAN FILE',
- ✓ 'RESULTS FILE'

For restart only:

- ✓ 'COMPUTATION CONTINUED' (=No :default option)
- ✓ 'PREVIOUS SEDIMENTOLOGICAL COMPUTATION FILE'

## 2.3. Coupling hydrodynamics/morphodynamics

We describe here two possibilities to link the hydrodynamic and the morphodynamic models: chaining (the flow is obtained from a previous hydrodynamic simulation assuming fixed bed) or internal coupling (both the flow and bed evolution are updated at each time steps).

### 2.3.1. Chaining method

#### Principle

Both models (hydrodynamics and morphodynamics) are run independently: in the previous hydrodynamics simulation, the bed is assumed to be fixed. Then, in the next morphodynamics run, the flow rate and free surface are read from previous hydrodynamics results file.

This 'chaining method' is only justified for relatively simple flows, due to the difference of time-scales between the hydrodynamics and the bed evolution. For unsteady tidal flow, SISYPHE can be used in an unsteady mode: the flow field is linearly interpolated between two time steps of the hydrodynamic file. For steady flow, the last time step of the hydrodynamic file is used and the flow rate and free surface assumed to stay constant while the bed evolves.

#### Flow updating

At each time step, the flow velocity is updated by assuming simply that both the flow rate and the free surface elevation are conserved, such that, in the case of deposition, the flow velocity is locally increased, whereas in the case of erosion, the flow velocity decreases.

This rather schematic updating does not take into account any deviation of the flow. It is only suitable for simple flows (2D processes) and assuming relatively small bed evolutions. However it can be responsible for numerical instabilities (cf. [01b], Hervouet and Villaret, 2004).

The morphodynamic computation is stopped when the bed evolution reaches a certain percent of the initial water depth. This simple updating of the flow field is no longer valid when the bed evolution becomes greater than a significant percentage of the water depth, specified by the user. At this point, it is recommended to stop the morphodynamic calculation and to recalculate the hydrodynamic variables.

#### Mass continuity

It should be noted that with this simple method, the **sediment mass continuity** may not be satisfied because of potential losses due to changes in the flow depth as the bed evolves.

In the SISYPHE steering file, The keyword 'HYDRODYNAMIC FILE' gives the name of the previous hydrodynamic results file (TELEMAC-2D or combined TOMAWAC/TELEMAC-2D).

When the flow is **steady** ('STEADY CASE' = YES), only the last record will be used. Otherwise ('STEADY CASE' = NO), the 'TIDE PERIOD' and 'NUMBER OF TIDES OR FLOODS' will be used to specify the sequence to be read on the hydrodynamic files. Hydrodynamic records are interpolated at each time step of the sedimentological computation.

Note: an error may occur when the 'TIDAL PERIOD' is not a multiple of the graphical time steps of the



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hydrodynamic file ('*Hydrodynamic file is not long enough*').

In an **unsteady case**, the keyword '*STARTING TIME OF THE HYDROGRAM*' gives the first time step to be read. If the starting time is not specified, the last period of the hydrogram will be used for sedimentological computation.

### **Steering/fortran files**

**For uncoupled mode**, the SISYPHE steering file should specify:

- ✓ The time steps, graphical or listing output, duration ...
- ✓ The hydrodynamic file as yielded by TELEMAC-2D, -3D ('*HYDRODYNAMIC FILE*') or even by user-subroutine (*condim\_sisyphe.f*).
- ✓ For waves only: the wave parameters can be either calculated by a wave propagation code (TOMAWAC), or defined directly in SISYPHE (*condim\_sisyphe.f*). The effect of waves on bed forms and associated bed roughness coefficient can be accounted with keyword: *EFFECT OF WAVES = 'YES'*.
- ✓ a restart from a previous SISYPHE model run, by setting '*COMPUTATION CONTINUED = YES*' and specification of sedimentological results in '*PREVIOUS SEDIMENTOLOGICAL COMPUTATION*'
- ✓ Flow options: steady or unsteady options, flow period...

### **Keywords**

For time step, duration and output:

- ✓ '*TIME STEP*', *NUMBER OF TIME STEPS*
- ✓ '*GRAPHIC PRINTOUT PERIOD*', *LISTING*
- ✓ '*VARIABLES FOR GRAPHIC PRINTOUTS*'

For hydrodynamics (imposed flow and updated):

- ✓ '*HYDRODYNAMIC FILE*', ...
- ✓ '*STEADY CASE*' (=NO, default option)
- ✓ '*TIDE PERIOD*' (= 44640, default option)
- ✓ '*STARTING TIME OF THE HYDROGRAM*' (=0., default option)
- ✓ '*NUMBER OF TIDES OR FLOODS*' (= 1, default option)
- ✓ '*CRITICAL EVOLUTION RATIO*' (=0.1, default value)

For waves:

- ✓ '*WAVE FILE*', '*WAVE EFFECTS*'...

## **2.3.2. Internal coupling**

### **Principle**

For a more realistic simulation, SISYPHE can be automatically coupled (internally) with the hydrodynamic model, TELEMAC-2D or -3D. SISYPHE is called inside the hydrodynamic model without any exchange of data files. The data to be exchanged between the two programs is now directly shared in the memory, instead of being written and read in a file.

At each time step, the hydrodynamics variables (velocity field, water depth, bed shear stress,...) are transferred to the morphodynamic model, which sends back the updated bed elevation to the hydrodynamics model.

### **Time step and coupling period**

The internal coupling method is more CPU time consuming than the chaining method. Various techniques can be set up to reduce the CPU time (e.g. parallel processors, ... see §9). In certain

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cases, the use of a *COUPLING PERIOD* >1 allows the **bed load** transport rates and resulting bed evolution not to be re-calculated at every time step.

For the **suspended load**, a diffusion/transport equation needs to be solved. This transport equation obeys the same Courant number criteria on the time step than the hydrodynamics, and therefore needs to be solved at each time-step (*COUPLING PERIOD* = 1').

The time step of SISYPHE is equal to the time step of TELEMAC-2D or -3D multiplied by the '*COUPLING PERIOD*'. The graphic/listing printout periods are the same as in the TELEMAC computation.

The TELEMAC-2D/3D steering file must specify the type of coupling, the name of the SISYPHE steering file, and the coupling period. In addition, the Fortran file of SISYPHE must be sometimes specified in the TELEMAC steering file (if there is no Fortran file for TELEMAC). Some of the keywords of the SISYPHE steering file become obsolete.

### **Keywords**

For internal coupling, the following keywords need to be specified in the TELEMAC-2D (or -3D) steering files:

- ✓ *COUPLING WITH* = '*INTER-SISYPHE*'
- ✓ '*COUPLING PERIOD*' (=1, default value)
- ✓ '*NAME OF SISYPHE STEERING FILE*'

All computational parameters (time step, duration, printout, option for friction) need to be specified in the TELEMAC steering file, but are no longer used by SISYPHE. The values of time step, bottom shear stress... are transferred directly from TELEMAC to SISYPHE.

Discarded keywords (SISYPHE):

- ✓ '*TIME STEP*',
- ✓ '*GRAPHIC PRINTOUT PERIOD*',
- ✓ '*LISTING PRINTOUT PERIOD*',
- ✓ '*LAW OF BOTTOM FRICTION*',
- ✓ '*FRICTION COEFFICIENT*'

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### 3. Flow-sediment interactions

#### 3.1. Sediment/fluid properties

##### Non cohesive/cohesive sediment

Fine sediment particles of diameters less than 60  $\mu\text{m}$  present complex cohesive properties which affect the sediment transport processes.

For **non-cohesive sediments** ( $D_{50} > 60 \mu\text{m}$ ), the grain diameter and grain density  $\rho_s$  are the key parameters which determine its resistance to erosion and sediment transport rate.

For **cohesive sediments** ( $D_{50} < 60 \mu\text{m}$ ), the grain diameter is no longer the key sediment parameter: The settling velocity now depends on the concentration and other physico-chemical properties of the suspension due to flocculation, whereas the critical bed shear strength depends on the consolidation state of the sediment bed.

We consider in the following chapters (3-5), the simpler case of uniform, non-cohesive sediments, characterized by one single value for the grain size  $D_{50}$  and grain density (with  $\rho_s = 2650 \text{ kg/m}^3$  for quartz particles), which can be transported both as bed-load and suspended load. Sand grading effects and cohesive sediment properties are discussed in chapters 6 and 7.

##### Keywords

In the SISYPHE steering file, the physical properties of the sediment are defined:

- ✓ 'COHESIVE SEDIMENT' (= NO , default option)
- ✓ 'NUMBER OF SIZE CLASSES OF BED MATERIAL' (NSICLA= 1, default option)
- ✓ 'SEDIMENT DIAMETERS' ( $D_{50} > 0.00006 \text{ m}$ , for non-cohesive sediment)
- ✓ 'SEDIMENT DENSITY' ( $\rho_s = 2650 \text{ Kg/m}^3$ , default value)
- ✓ 'SETTLING VELOCITIES'

The fluid physical properties are defined by:

- ✓ 'VISCOSITY OF THE FLUID' ( $\nu = 10^{-6} \text{ m}^2/\text{s}$  , by default)
- ✓ 'DENSITY OF THE FLUID' ( $\rho_0 = 1000 \text{ kg/m}^3$  , by default)
- ✓ 'GRAVITY ACCELERATION' ( $g = 9.81 \text{ m.s}^{-2}$ )

#### 3.2. Bed shear stress

##### Hydrodynamic models

The current-generated bed shear stress enters both the St Venant's momentum equation as well as the bottom boundary condition for the velocity profile.

When SISYPHE is coupled with TELEMAC-2D, the bed shear stress  $\tau_0$  is calculated at each time step, from the depth-averaged mean flow velocity, by use of a quadratic friction coefficient  $C_d$  (see chapter below for the determination of the friction coefficient):

$$\tau_0 = \frac{1}{2} \rho C_d U^2 \quad (1)$$

where  $\rho$  is the fluid density, and  $U$  the depth-averaged velocity.

When SISYPHE is coupled with TELEMAC-3D, the bed shear stress is aligned with the near bed velocity in order to account for possible veering of the flow in the vertical. The magnitude of the bed shear stress is still related to the depth-averaged velocity, except if a Nikuradse friction law is applied.

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In the case of Nikuradse, the friction velocity  $u_*$  defined by  $\tau_0 = \rho u_*^2$  is related to the near bed flow velocity  $u(z_1)$  assuming a logarithmic velocity profile:

$$u(z_1) = \frac{u_*}{\kappa} \ln\left(\frac{z_1}{z_0}\right) \quad (2)$$

where  $\kappa=0.4$  is the Karman constant and  $z_0$  is related to the Nikuradse bed roughness ( $z_0=k_s/30$ ).

### Role of bed forms

A natural sediment bed is generally covered with bed forms (length  $\lambda$  and height  $\eta$ ). The presence of bed forms greatly modify the boundary layer flow structure, with the formation of recirculation cells and depression in the lee of bed forms.

Depending on the flow rate and sediment transport rate, the size of bed forms ranges from a few cm for ripples to a few tens of meter for mega-ripples. The dimensions of dunes scale with the water depth ( $\eta_D \approx 0.4 h$ ,  $\lambda_D \approx 6-10h$ ).

In most cases, large scale models do not resolve the small to medium scale bed forms (ripples, mega-ripples) which need therefore to be parameterized by an increased friction coefficient.

### Sediment transport applications

The bed shear stress is the most important hydrodynamics parameter, regarding sand transport applications.

In the presence of bed forms, the total bed shear stress (averaged along bed forms) is increased and made of two components: a **form drag**  $\tau''$  component in addition to the local **skin friction**  $\tau'$  component:

$$\tau_0 = \tau' + \tau'' \quad (3)$$

The local **skin friction** component determines the **bed-load** transport rate and the **equilibrium concentration** for the suspension. The **total friction** velocity determines the (spatially averaged along bed forms) turbulence eddy viscosity/diffusivity vertical distribution in 3D models, and therefore determines both velocity vertical profile and mean concentration profile.

## 3.3. Sediment transport

### Bed-load/suspended load

When the current-induced bed shear stress increases above the critical threshold value, sediment particles start to move as bed load, while the finer particles are transported in suspension.

The **bed-load** occurs in a very thin high concentrated near-bed layer, where collisions and particle-particle interactions occur.

The **suspended load** is defined as the depth-integrated flux of sediment concentration, from the top of the bed-load layer up to the free surface. For dilute suspension, clear flow concepts (turbulence diffusion, eddy viscosity, logarithmic velocity profile) are considered to be valid.

The **total sediment load**  $Q_t$  includes both a **bed-load**  $Q_b$  and a **suspended load**  $Q_s$  components:

$$Q_t = Q_b + Q_s \quad (4)$$

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### Shields parameter

Most sand transport formulae assume a critical value of the bed shear stress, noted  $\tau_c$ , for the onset of erosion:

$$Q_s=0 \text{ for } \tau_0 < \tau_c$$

The Shield parameter or non-dimensional critical shear stress  $\theta_c$  is defined by:

$$\theta_c = \frac{\tau_c}{(\rho_s - \rho)gD_{50}} \quad (5)$$

can be either specified in the SISYPHE steering file by use of keyword 'SHIELD PARAMETER' (AC), or calculated by the model as a function of non-dimensional grain diameter.

The Van Rijn formula has been programmed (cf. [31]).

$$\begin{array}{ll} D_* \leq 4 & \theta_c = 0.24.D_*^{-1} \\ 4 < D_* \leq 10 & \theta_c = 0.14.D_*^{-0.64} \\ 10 < D_* \leq 20 & \theta_c = 0.04.D_*^{-0.1} \\ 20 < D_* \leq 150 & \theta_c = 0.013.D_*^{0.29} \\ 150 \leq D_* & \theta_c = 0.045 \end{array}$$

where the non-dimensional diameter  $D_*$  is defined by :

$$D_* = \left( \frac{g(s-1)}{v^2} \right)^{1/3} \cdot D_{50} \quad (6)$$

### keywords

- ✓ 'BED-LOAD' (= YES : default option)
- ✓ 'SUSPENDED LOAD' (=NO : default option)
- ✓ 'SHIELDS PARAMETER' (default option: Van Rijn formula)

## 3.4. Friction laws

### Differences between 2D and 3D models

The **intensity** of bed shear stress is calculated by use of same friction laws in both –2D and –3D models: the bed shear stress is related to the depth-averaged flow velocity, except when the **Nikuradse friction law** is applied. In 3D-models, the bed shear stress is directly related to near bed velocity assuming a log profile (eq. 2), whereas in 2D-models, the log profile is assumed to be valid up to the free surface (eq. 7.e).

The **direction** of the bed shear stress and resulting sand transport rate is assumed to be **in the direction of the depth-averaged velocity** in SISYPHE (alone or internally coupled with TELEMAC-2D). When SISYPHE is internally coupled to TELEMAC-3D, the bed shear stress and resulting transport rate are assumed to be **in the direction of the near bed velocity**. The 3D model gives a more accurate estimate of the bottom friction, since it accounts for a possible veering of the current in the vertical.

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### **Coupling with TELEMAC-2D**

The bed shear stress and resulting sand transport rates are assumed to be in the direction of the mean flow velocity, except when the sediment transport formulation accounts for:

- deviation correction due to sloping bed effects,
- secondary currents due to river meandering.

### **Coupling with TELEMAC-3D**

Both bed shear stress and bed load transport rate are aligned with the near bed velocity. This 3D approach is more physical, and takes into account possible recirculation and veering of the flow, such that corrections for secondary currents for example are no longer necessary.

### **Uncoupled model**

The quadratic friction coefficient  $C_d$  which is used to calculate the total bed shear stress (cf. eq. 1.b) can be calculated based on the selected friction law. Different options which are consistent with the TELEMAC-2D options, are available in SISYPHE and depend on the choice of the '*LAW FOR BOTTOM FRICTION*' (KFROT) and on the value of the '*FRICTION COEFFICIENT*'.

- ✓ Chézy coefficient  $C_h$  (KFROT =2):

$$C_d = \frac{2g}{C_h^2} \quad (7a)$$

- ✓ Strickler coefficient  $S_t$  (KFROT =3):

$$C_d = \frac{2g}{S_t^2} \frac{1}{h^{1/3}} \quad (7b)$$

- ✓ Manning friction (KFROT =4):

$$C_d = \frac{2g}{h^{1/3}} M_a^2 \quad (7d)$$

- ✓ Nikuradse bed roughness  $k_s$  (KFROT =5):

$$C_d = 2 \left[ \frac{\kappa}{\text{Log}\left(\frac{12h}{k_s}\right)} \right]^2 \quad (7e)$$

where  $g$  is gravity,  $h$  the water depth and  $\kappa=0.4$  is the von Karman constant.

The last relation can be derived by depth-integrating the mean velocity profile, assuming the velocity to follow a logarithmic profile up to the free surface.

### **Keywords**

In the SISYPHE steering file, the total bed shear stress is calculated based on:

*'LAW OF BOTTOM FRICTION'* (KFROT =3, default option)

*'BOTTOM FRICTION COEFFICIENT GRAVITY'* ( $S_t=50$ , default value)

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'GRAVITY' (g=9.81 m/s<sup>2</sup>)

Similar keywords are available in both TELEMAC-2D and -3D in the case of internal coupling.

### 3.5. Skin friction correction

#### Total bed shear stress decomposition

Sand transport rates are calculated as a function of the local skin friction component  $\tau'$ . The total bed shear stress issued from the hydrodynamics model needs to be corrected in the morphodynamics model.

$$\tau' = \mu \tau_0$$

Physically, the skin bed roughness should be smaller than the total bed roughness (i.e.  $\mu \leq 1$ ). However, in most cases the hydrodynamic friction does not represent the physical bottom friction: the coefficient is generally used as a calibration coefficient in hydrodynamics models. It is determined in order to represent observations of the time-varying free surface and velocity field. Therefore, its model value integrates various neglected processes (side wall friction, possible errors in the bathymetry and input data...).

Under those conditions, a correction factor  $\mu > 1$  can be admitted.

#### Different options

Different methods are programmed in SISYPHE in order to calculate the ripple correction factor  $\mu$ , according to the keyword 'SKIN FRICTION CORRECTION' (ICR):

- ICR = 0: no correction: the total friction issued from TELEMAC, is directly used for sand transport calculations ( $\mu=1$ ).
- ICR = 1: the skin roughness is assumed to be proportional to the sand grain diameter like in the case of flat beds ( $k_s' \sim D_{50}$ ). The proportionality coefficient is specified by the keyword 'RATIO BETWEEN SKIN FRICTION AND MEAN DIAMETER' (KSPRATIO).

$$\mu = \frac{C_d'}{C_d} \quad (8)$$

where  $C_d$  et  $C_d'$  are both quadratic friction coefficients related respectively to total friction and skin friction:  $C_d$  is issued from TELEMAC and  $C_d'$  is calculated from  $k_s'$ :

$$C_d' = 2 \left[ \frac{\kappa}{\text{Log}\left(\frac{12h}{k_s'}\right)} \right]^2 \quad (9)$$

- ICR = 2: we use a bed ripple predictor to calculate the ripple bed roughness  $k_r$  (as explained below (see eq.12)). Both  $k_r$  and  $k_s'$  should influence the transport rates. Here we assume:

$$\mu = \frac{(C_d')^{0.75} (C_r)^{0.25}}{C_d} \quad (10)$$

where the quadratic friction  $C_r$  due to ripples is calculated as a function of  $k_r$  according to eq.(9)

#### Keywords

The selected option for the skin friction correction is based on keywords:

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'SKIN FRICTION CORRECTION' (ICR=0, default option)

'RATIO BETWEEN SKIN FRICTION AND MEAN DIAMETER' (KSPRATIO=3 , default value)

### 3.6. Bed roughness predictor

#### Total bed roughness (uncoupled mode)

Different options are programmed in SISYPHE to predict the total bed roughness. It is recalled that the bed friction option of SISYPHE is not used in the case of internal coupling with TELEMAC.

- For  $KFROT = 0$  : the bed is assumed to be flat  $k_s = k_s' = \alpha D_{50}$
- For  $KFROT = 1$ : the bed roughness is decomposed into different components (skin, ripples...) and each component is calculated by SISYPHE depending on the flow regime.

For **waves** and combined waves and currents, ripple dimensions are calculated as a function of wave parameters following the method of Wiberg and Harris (1994) (see chapter 8 on wave effects). The wave-induced ripple bed roughness  $k_r$  is calculated as a function of the wave-induced ripple height  $\eta_r$  :  $k_r = \max(k_s', \eta_r)$ .

For **currents only**, the Van Rijn (2007) predictor has been implemented (cf. Huybrechts, 2010). The total bed roughness can be decomposed into a grain roughness  $k_s'$ , a small-scale ripple roughness  $k_r$ , a mega-ripple component  $k_{mr}$ , and a dune roughness  $k_d$ :

$$k_s = k_s' + \sqrt{k_r^2 + k_{mr}^2 + k_d^2} \quad (11)$$

Both small scale ripples and grain roughness have an influence on the sediment transport laws, while the mega-ripples and dune roughness only contribute to the hydrodynamic model (total friction).

#### Ripple correction factor

In order to account for the effect of ripples on the skin friction, the keyword 'SKIN FRICTION CORRECTION' should be set to  $ICR = 2$ . For currents only, the ripple bed roughness is a function of mobility number, according to Van Rijn (2007):

$$\left. \begin{aligned} k_r &= D_{50} \{85 - 65 \tanh [0.015 (\psi - 150)]\} \\ k_r &= 20 D_{50} \text{ for } \psi \geq 250 \end{aligned} \right\} (12)$$

$$\text{with } \psi = \frac{U^2}{(s-1)gD_{50}} \quad (13)$$

#### Keywords

'LAW OF BOTTOM FRICTION' (KFROT =0 or 1, flat bed or rippled bed for total friction)

'SKIN FRICTION CORRECTION' (ICR=1 or 2 flat bed or rippled bed , for skin friction correction)



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## 4. Bed-load transport

### 4.1. Exner equation

#### Equilibrium conditions

Bed-load occurs in a thin near-bed high-concentrated region. The bed-load layer therefore adapts very rapidly to any changes in the flow conditions, such that **equilibrium conditions** can be considered to be valid. The bed-load transport rate can then be calculated by use of some equilibrium sediment transport formula, as a function of various flow and sediment parameters, assuming that the transport rate corresponds to saturation conditions (see §4.2).

#### Bed evolution

To calculate the bed evolution, SISYPHE solves the Exner equation:

$$(1-n) \frac{\partial Z_f}{\partial t} + \text{Div} \left( \vec{Q}_b \right) = 0 \quad (14)$$

where :  $n$  is the bed porosity ( $n \sim 0.4$  for non cohesive sediment),

$Z_f$  the bottom elevation,

$Q_b$  ( $\text{m}^2/\text{s}$ ) the solid volume transport (bed-load) per unit width.

Equation (14) states that the variation of sediment bed thickness can be derived from a simple mass balance. It is only valid for equilibrium conditions. Equation (14) is strictly valid for bed-load only. However, it can be extended to total load (including the suspended load) assuming quasi-steady and uniform flow conditions. Otherwise, a different treatment should be applied to both bed load and suspended load, in order to take into account properly for non-equilibrium flow conditions.

#### General form

For currents only (no wave effects), a large number of semi-empirical formulae can be found in the literature to calculate the bed-load transport rate. SISYPHE offers the choice between 10 different bed-load formulas including the widely used Meyer-Peter and Müller 'MPM' [27], Engelund-Hansen 'EH' [20] and Einstein-Brown's [19] formulae.

Most sediment transport formulae assume threshold conditions for the onset of erosion (MPM, Van Rijn, Hunziker...). Other formulae are based on similar energy concept (eg. EH) or can be derived from a statistical approach (EB, Bijker,...). The non-dimensional current-induced sand transport rate, noted  $\Phi_s$ , can be expressed as a function of the non-dimensional skin friction or Shields parameter, noted  $\theta'$ , as defined by:

$$\theta' = \frac{\mu \tau_0}{(\rho_s - \rho) g D_{50}} \quad (15)$$

$$\Phi_s = \frac{Q_s}{\sqrt{g(s-1)D_{50}^3}}$$

$\mu$ , the correction factor for skin friction

#### Keywords

- 'BED-LOAD'=YES (default option)
- 'SUSPENDED LOAD'=NO (default option)

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- 'COEFFICIENT FUNCTION OF THE POROSITY' ( $XKV=1/(1-n)=1.6$ , default value)

where  $C_{bed}=1-n$  is the sediment bed volume concentration ( $n \approx 0.4$ )

- 'BED-LOAD TRANSPORT FORMULA' (default option is MP formula, ICF=1)

## 4.2. Sediment transport formulae

### Choice of formulae

The choice of a transport formula depends on the selected value of the model parameter ICF, as defined in the steering file by the keyword 'BED-LOAD TRANSPORT FORMULA' (ICF).

The user can program a specific transport formula through the `Qsform.f` (user-subroutine), by setting ICF=0.

Other sediment transport formulae, described in chapters 8 and 9, have been programmed in SISYPHE to account for the effects of waves (cf. Bijker, Bailard, Dibajnia and Watanabe...) or sand grading (cf. Hunziker). They can nevertheless be used for currents only and uniform grain size.

- ✓ ICF= 1: Meyer-Peter formula

This classical bed-load formula has been validated for coarse sediments in the range ( $0.4\text{mm} < D_{50} < 29\text{mm}$ ). It is based on the concept of initial entrainment:

$$\begin{aligned}\Phi_b &= 0 \quad \text{if} \quad \theta' < \theta_c \\ \Phi_b &= 8(\theta' - \theta_c)^{3/2}\end{aligned}\tag{16}$$

where :

$\theta_c$  is the critical Shields parameter ( $\theta_c \sim 0.047$ , cf. §3.3),

- ✓ ICF = 2: Einstein-Brown formula

This bed-load formula is recommended for coarse sand ( $D > 2\text{mm}$ ) and large bed shear stress  $\theta > \theta_c$ . The solid transport rate (see [19]) is expressed as:

$$\begin{aligned}\Phi_b &= F(D_*) f(\theta) \\ F(D_*) &= \left( \frac{2}{3} + \frac{36}{D_*} \right)^{0.5} - \left( \frac{36}{D_*} \right)^{0.5} \\ f(\theta) &= 2.15 \exp(-0.391/\theta) \quad \text{if} \quad \theta \leq 0.2 \\ f(\theta) &= 40\theta^3 \quad \text{if} \quad \theta > 0.2\end{aligned}\tag{17}$$

where the non-dimensional diameter  $D_*$  is defined according to (6).

- ✓ ICF= 3 or 30: Engelund-Hansen formula

The Engelund-Hansen formula [20] predicts the total load (bed load plus suspended load). It is recommended for fine sediments, in the range ( $0.2\text{mm} < D_{50} < 1\text{mm}$ ) but beware that the use of a total load formula is only suitable under equilibrium conditions (quasi steady and uniform flow). Two different forms of the same equation are programmed in SISYPHE:

- ICF = 30 corresponds to the original formula, where the transport rate is related to the skin friction without threshold:

$$\Phi_s = 0.1(\theta')^{5/2}\tag{18}$$

- ICF = 3 corresponds to the version modified by Cholley and Cunge ([15], 1981)

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in order to account for the effects of sand dunes formation. The transport rate is here related to the total bed shear stress :

$$\Phi_s = \frac{0.1}{C_d} \theta^{5/2} \quad (19)$$

the dimensionless bed shear stress  $\theta$  is calculated as a function of the dimensionless skin friction  $\theta'$  :

$$\begin{cases} \theta = 0 & \text{if } \theta' < 0.06 \quad (\text{flat bed regime - no transport}) \\ \theta = \sqrt{2.5(\theta' - 0.06)} & \text{if } 0.06 < \theta' < 0.384 \quad (\text{dune regime}) \\ \theta = 1.065\theta'^{0.176} & \text{if } 0.384 < \theta' < 1.08 \quad (\text{transition regime}) \\ \theta = \theta' & \text{if } \theta' > 1.08 \quad (\text{flat bed regime - upper regime}) \end{cases}$$

Notice: in the case of coupling between bed-load and suspended load (*SUSPENSION* = YES), a total load formula (N°3 and 30) should not be used, in order to avoid the suspended load to be calculated twice.

✓ ICF = 7: Van Rijn formula

This formula was proposed by Van Rijn (1984a) in order to calculate the bed-load transport rate for particles :  $0.2\text{mm} < D < 2\text{ mm}$ :

$$\Phi_b = 0.053 D_*^{-0.3} \left( \frac{\theta_p - \theta_{cr}}{\theta_{cr}} \right)^{2.1} \quad (20)$$

### Validity range

Most sediment transport formulae are based on experiments performed under steady-flow conditions. They demonstrate rapid variation of the bed-load transport rates as a function of the mean flow intensity: an increase of the current velocity by 10% will result, depending on the formula being used, in an increase of the transport rate by over 30% (Meyer-Peter), 60% (Engelund-Hansen) or almost 80% (Einstein-Brown). Therefore, any error made when calculating the hydrodynamics will be significantly amplified by the sediment transport rates estimates. On the other hand, under variable flow conditions (e.g. in tidal regime), the average transport will be highly influenced by the stronger currents and will not be directly related to the mean flow.

The validity range of the different formulae can be summarized in the table below:

| Sand transport Formula | Meyer-Peter<br>ICF = 1 | Einstein-Brown<br>ICF = 2 | Engelund-Hansen<br>ICF = 3 or 30 | Van Rijn<br>ICF = 7 |
|------------------------|------------------------|---------------------------|----------------------------------|---------------------|
| Mode of transport      | Bed-load               | Bed-load                  | Total load                       | Bed-load            |
| Sand diameter          | > 1 mm                 | From 0.2 mm to 3 mm       | From 0.2 mm to 4 mm              | From 0.2 to 2 mm    |
| Rippled bottoms        | Yes                    | Yes                       | Yes                              |                     |
| Low bed-load flows     | Yes                    | Yes                       | No                               |                     |
| High bed-load flows    | Yes                    | Yes                       | Yes                              |                     |

**Table 1:** Validity range of the sand transport formulae programmed in SISYPHE (for currents only)

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### 4.3. Sloping bed effect

The effect of a sloping bottom is to increase the sand transport rate in the downslope direction, and to reduce it upslope. In SISYPHE, we apply a correction factor to both the magnitude and direction of the solid transport rate, before solving the bed-evolution equation. This sloping bed effect is only activated if the keyword '*SLOPE EFFECT*' is activated.

Two different formulations for both effects are available depending on the choice of '*FORMULA FOR SLOPE EFFECT*' (*SLOPEFF*) and '*FORMULA FOR DEVIATION*' (*DEVIA*).

#### Magnitude of sand transport rate

- For *SLOPEFF*=1. The first correction method is based on the Koch and Flokstra's formula (1981) [26]. The solid transport rate intensity is multiplied by a factor :

$$Q_b = Q_{b0} \left( 1 - \beta \frac{\partial Z_f}{\partial s} \right) \quad (21)$$

where  $s$  is the co-ordinate in the current direction,

$\beta$  is an empirical factor, which can be specified by keyword '*BETA*' (recommended default value = 1.3). This effect of bed slope is then similar to adding a diffusion term in the bed-evolution equation. It tends to smooth the results and reduces instabilities.

- For *SLOPEFF*=2, the method of Soulsby (1997) is programmed: The threshold bed shear stress is modified as a function of bed slope and depends on the '*FRICTION ANGLE OF THE SEDIMENT*' ( $\phi_s$ )

$$\frac{\theta_c}{\theta_{co}} = \frac{\cos \psi \sin \beta + \left( \cos^2 \beta \tan^2 \phi_s - \sin^2 \psi \sin^2 \beta \right)^{0.5}}{\tan \phi_s} \quad (22)$$

Where  $\beta$  is the angle of the bed to the horizontal plan,

$\psi$ , the angle of the current to the upslope direction.

#### Direction of sand transport rate

The change in the direction of solid transport is taken into account by the formula:

$$\tan \alpha = \tan \delta - T \frac{\partial Z_f}{\partial n} \quad (23)$$

where:  $\alpha$  is the direction of solid transport in relation to the flow direction,

$\delta$  the direction of bottom stress in relation to the flow direction and

$n$  the co-ordinate along the axis perpendicular to the flow.

- *DEVIA* = 1: According to Koch and Flokstra, the coefficient  $T$  now depends on the Shields parameter:

$$T = \frac{4}{6\theta}$$

- *DEVIA* = 2, the deviation is calculated based on Talmon et al. (1995) and depends on empirical coefficient  $\beta_2=0.85$ .

$$T = \frac{1}{\beta_2 \sqrt{\theta}}$$

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This default value can be modified by changing the keyword: 'PARAMETER FOR DEVIATION' =  $\beta_2$ .

#### **Keywords**

- 'SLOPE EFFECT' (=YES, default option)
- FORMULA FOR SLOPE EFFECT' (SLOPEFF=1, default option)
- 'FORMULA FOR DEVIATION' (DEVIA=1, default option)
- 'FRICTION ANGLE OF THE SEDIMENT' ( $\phi_s=40^\circ$ , default value)
- BETA: ( $\beta = 1.3$ , default value)
- PARAMETER FOR DEVIATION ( $\beta_2 = 0.85$ , default value)

### **4.4. Sediment slide**

#### **Sediment Slide**

An iterative algorithm prevents the bed slope to become greater than the maximum friction angle ( $\phi_s \sim 32^\circ - 40^\circ$ ). This option is activated by use of key word 'SEDIMENT SLIDE'.

Further developments are needed to introduce the bed stability, in order to represent mud slides.

$$\|\overrightarrow{\text{grad}(Z_f)}\| < \tan(\phi_s) \quad (24)$$

#### **Keywords**

- ✓ 'SEDIMENT SLIDE' (= NO, default option)
- ✓ 'FRICTION ANGLE OF SEDIMENT' ( $\phi_s=40^\circ$ , default value)

### **4.5. Secondary currents**

In meandering streams, centrifugal inertial forces are induced by the curvature  $R$  of the streamlines. The depth-averaged mean pressure gradient due to the cross-sectional variation of the free surface balances the depth -averaged centrifugal force, noted  $F$ :

$$\begin{aligned} \overline{F_y} &= -\frac{1}{\rho} \frac{\partial P}{\partial y} \\ \overline{F_y} &= \rho \frac{\overline{U}^2}{R} \\ -\frac{1}{\rho} \frac{\partial P}{\partial y} &= -g \frac{\partial Z_s}{\partial y} \end{aligned}$$

where  $y$  is the cross-sectional axis, and  $\frac{\partial Z_s}{\partial y}$  the cross-sectional variation in the free surface. The mass balance in the  $y$ -direction gives a zero-depth averaged cross-sectional velocity.

$$\rho \frac{\overline{U}^2}{R} = -g \frac{\partial Z_s}{\partial y}$$

However, in the vertical, the centrifugal force increases with distance from the bed whereas the pressure gradient is constant.  $P$  and  $F$  are therefore out of balance ( $P$  greater in the lower part of the flow, whereas  $F$  is greater in the upper part). This results in a cross-sectional circulation, with a cross-velocity directed near the inner bank and

The flow velocity therefore follows a spiral motion which is cannot be represented by a 2D depth averaged hydrodynamic model.

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The correction method, based on Engelund (1974), has been programmed in Sisyphe, in order to account for the effect of these radial stresses on the sand transport rates. This method is based on the following assumptions:

- the bottom shear stress is constant in a cross-section,
- the bed roughness is also constant,
- the mean water depth  $h$  is constant.

The near bed angular deviation of the main flow  $\delta$  can be shown to be proportional to  $h/R$ , as explained in Yalin and Ferreira da Silva (2001). We use here:

$$\tan \delta = 7 \frac{h}{R}$$

The radius bend  $R$  is generally unknown, but can be inferred from the cross sectional variation in the free surface

$$R = -\rho \alpha' \frac{\overline{U}^2}{g \frac{\partial Z_s}{\partial y}}$$

where  $\alpha'$  is a correction factor ( $\alpha' \sim 0.75$  for bed and  $\alpha' \sim 1$  for smooth bed conditions).

### **Keywords**

- 'SECONDARY CURRENTS' (=NO, default option)

Uses the correction method in order to account for the effect of secondary currents in meandering channels.

This option should only be activated when the flow is calculated by a depth-averaged model.

## **4.6. Treatment of rigid beds**

### **Different methods**

The effect of rigid beds is to reduce the sand transport rate, and to let the incoming sand pass over the bed. The problem of rigid beds is conceptually trivial but becomes tricky numerically. In finite elements the new algorithm for minimum water depth allows a natural treatment of rigid beds (cf. Hervouet et al. 2011), such that previous methods are now obsolete. In release 6.0, the sediment is basically seen as a layer with a depth that must remain positive, and the Exner equation is seen as a continuity equation similar to Saint-Venant continuity equation.

With finite volumes, two methods are still implemented in SISYPHE, depending on the 'OPTION FOR THE TREATMENT OF NON ERODABLE BEDS':

- Option (0, default option), the bed is movable everywhere. The new algorithm for minimum water depth is used
- Options (4) are mass-conservative and avoid erosion of the rigid beds.
- **Keywords**
  - ✓ 'OPTION FOR THE TREATMENT OF NON ERODABLE BEDS' (=0, default option)
  - ✓ 'FINITE VOLUMES' (=NO, default option)
  - ✓ 'MASS-LUMPING' (=YES, default option)

### **User-subroutine**

The position of the rigid bed is set by default to a very large negative value and can be changed in subroutine `noerod.f`.

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## 4.7. Effect of tidal flats

Tidal flats, where the depth can be equal to 0, may be treated by 2 approaches:

In the default option ( $OPTBAN = 1$ ), equations are solved everywhere. The water depth is set to a minimum value  $HMIN$  (key-word *MINIMAL VALUE OF THE WATER HEIGHT*, default value 1.D-3) in order to avoid divisions by zero. However, in case of coupling with Telemac-2D or 3D, the original depth is kept for suspension, because a strict compatibility with Saint-Venant continuity equation is required, that would be spoiled by clipping. This is the recommended option.

Another option ( $OPTBAN = 2$ ), removes from the computation elements with points that have a depth less than a minimum  $HMIN$ . This option must be considered obsolete, it is actually not exactly mass-conservative and does not work properly in parallel mode.

### Keywords

- 'TIDAL FLATS' (=YES , default option)
- 'MINIMAL VALUE OF THE WATER HEIGHT' ( $HMIN = 10^{-3}$  ,default value)
- 'OPTION FOR THE TREATMENT OF TIDAL FLATS' ( $OPTBAN = 1$ , default option)

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## 5. Suspended load

### 5.1. Suspended load transport equation

#### Passive scalar hypothesis

For non-equilibrium flow conditions, the bed-load and the suspended-load need a separate treatment. The interface between the bed-load and suspended load is located at  $z=Z_{ref}$ .

- In the thin high-concentrated bed-load layer ( $z < Z_{ref}$ ) particle-particle interactions and flow-turbulent interactions strongly modify the flow structure. Equilibrium conditions are however a reliable assumption to relate the bed-load to the current induced bed shear stress.
- In the upper part of the flow, for dilute suspension ( $z > Z_{ref}$ ), clear flow concepts still apply, and the sediment grains can be regarded as a passive scalar which follows the mean and turbulent flow velocity, with an additional settling velocity term.

#### Settling velocity

The settling velocity  $W_s$  is an important parameter for the suspension. It can be either specified, and if not, it is calculated by the model as a function of grain diameter, by use of a semi-empirical formula. The Van Rijn formula which is valid for non-cohesive spherical particles and dilute suspensions, has been programmed in SISYPHE (cf. Van Rijn, 1993, cf. [31], p. 3.13):

$$\left. \begin{aligned} W_s &= \frac{(s-1)gD_{50}^2}{18\nu} & \text{if } D_{50} \leq 10^{-4} \\ W_s &= \frac{10\nu}{D_{50}} \left( \sqrt{1 + 0,01 \frac{(s-1)gD_{50}^3}{18\nu^2}} - 1 \right) & \text{if } 10^{-4} \leq D_{50} \leq 10^{-3} \\ W_s &= 1,1\sqrt{(s-1)gD_{50}} & \text{if } 10^{-3} \leq D_{50} \end{aligned} \right\}$$

Where  $s=\rho_s/\rho_0$  is the relative density, and  $g$  is gravity.

Outside the bed-load layer sediment particles are assumed to follow the mean flow velocity, noted  $\vec{U}$ , with an additional vertical settling velocity, noted  $W_s$ . The particle velocity can be expressed as:

$$\vec{U}_p = \vec{U} + \vec{W}_s$$

#### 3D transport equation

The 3D advection-diffusion equation for the suspended sediment concentration is:

$$\frac{\partial C}{\partial t} + \text{div}(\vec{U} + \vec{W}_s)C = \text{div}(\varepsilon_s \cdot \vec{\nabla} C) \quad (26)$$

where  $\varepsilon_s$  the sediment diffusivity coefficient.

The following boundary conditions must be satisfied both at the free surface ( $Z_s$ ) and at the interface between the bed-load and the suspended load ( $z=Z_{ref}$ ):

$$\left. \begin{aligned} z = Z_s & \quad \varepsilon_s \frac{\partial C}{\partial z} + W_s C = 0 \\ z = Z_{ref} & \quad -\varepsilon_s \frac{\partial C}{\partial z} - W_s C = (E - D)_{Z_{ref}} \end{aligned} \right\} \quad (27)$$



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where  $Z_s$  is the free surface elevation  $Z_{ref}$  the position of the interface between the bed-load layer and the suspension.  $E-D$  is the net erosion minus deposition flux of sediment. The 3D transport equation (26) and boundary conditions (27) can be solved in the 3D sediment transport model of TELEMAC-3D.

## 2D transport equation

The 2D transport equation for the depth-averaged mean concentration  $C$  is obtained by depth-integration of eq. (27):

$$\frac{\partial}{\partial t}(hC) + \frac{\partial}{\partial x}(h\bar{u}C) + \frac{\partial}{\partial y}(h\bar{v}C) = \frac{\partial}{\partial x}(h\varepsilon_s \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y}(h\varepsilon_s \frac{\partial C}{\partial y}) + E - D \quad (28)$$

with:

$$X = \bar{x} = \frac{1}{h} \int_{Z_{ref}}^{Z_s} x(z) dz$$

where  $h = Z_s - Z_f \approx Z_s - Z_{ref}$  is the water depth, assuming the bed-load layer thickness to be small.

After simplification of the advection terms and using the continuity equation, the following approximate depth-averaged transport equation can be solved in its non-conservative form:

$$\underbrace{\frac{\partial C}{\partial t} + U_{conv} \frac{\partial C}{\partial x} + V_{conv} \frac{\partial C}{\partial y}}_{Adv} = \underbrace{\frac{1}{h} \left[ \frac{\partial}{\partial x} \left( h\varepsilon_s \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( h\varepsilon_s \frac{\partial C}{\partial y} \right) \right]}_{Diff} + \frac{(E - D)_{z=Z_{ref}}}{h} \quad (29)$$

where  $U_{conv}$  and  $V_{conv}$  are the depth-averaged convective flow velocities in the x and y directions

### Convection

The convective velocity differs can be corrected from the depth-averaged mean velocity in order to account for the fact that most sediments is transported near the bed (see §5.4).

### Diffusion

The diffusion terms can be set to zero ('DIFFUSION' = NO)

According to the choice of the parameter 'OPDTRA' (key word), the diffusion terms in (29) can be simplified and equation (29) becomes :

$$\frac{\partial C}{\partial t} + U_{conv} \frac{\partial C}{\partial x} + V_{conv} \frac{\partial C}{\partial y} = \left[ \frac{\partial}{\partial x} \left( \varepsilon_s \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( \varepsilon_s \frac{\partial C}{\partial y} \right) \right] + \frac{(E - D)_{z=Z_{ref}}}{h} \quad (29b)$$

The value of the dispersion coefficient  $\varepsilon_s$  depends on the choice of the parameter OPTDIF and different possibilities are offered (constant coefficient, by default). The Elder model (OPTDIF=2) allows to calculate both the longitudinal and transversal components as a function of the friction velocity. ( $\varepsilon_s = 6 u_* h$  and  $\varepsilon_s = 0.3 u_* h$ )

Different schemes are available for solving the non-linear advection terms depending on the choice of the parameter the classical characteristics schemes (to the diffusive schemes SUPG and PSI, it is recommended to use the conservative schemes

## Keywords

- ✓ 'SUSPENSION' (=NO by default)
- ✓ 'DIFFUSION' (= YES, by default)
- ✓ 'OPTION FOR THE DIFFUSION OF TRACER' (OPDTRA=1, the default option corresponds to the simplified expression of the diffusion term)
- ✓ 'OPTION FOR THE DISPERSION' (=1, default option)
- ✓ 'DISPERSION ALONG THE FLOW' ( $\varepsilon_s = 10^{-2} \text{ m}^2/\text{s}$ , default value)
- ✓ 'DISPERSION ACROSS THE FLOW' ( $\varepsilon_s = 10^{-2} \text{ m}^2/\text{s}$ , default value)

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- ✓ 'TYPE OF ADVECTION' (RESOL=1 , method of characteristics by default)

It is recommended in the presence of tidal flats to use the conservative scheme based on the calculation of flux per segments (14). Scheme 14 should be used if the convection velocity differs from the depth-averaged velocity and no longer satisfy the St Venant's continuity equation of §5.4 ('CORRECTION ON CONVECTION VELOCITY' =YES ).

## 5.2. Bed evolution

### Bed evolution due to the suspension

The bottom-evolution equation due to the suspension accounts for the vertical fluxes at the interface between the bed-load and the suspended load. The bed-evolution equation becomes:

$$(1-n) \frac{\partial Z_f}{\partial t} + (E-D) = 0 \quad (30)$$

where  $Z_f$  is the bottom elevation,  $Z_{ref}$  the interface between the bed-load and suspended-load, and  $n$ , the bed porosity ( $n \sim 0.4$ ). Erosion and deposition fluxes are calculated at the bed-load/suspended load interface ( $z = Z_{ref}$ ) as explained in § 5.3.

### Consistency in the units

In equation (30), the net sediment flux  $E-D$  is in m/s.

For consistency with the bed-load units ( $m^2/s$ ), concentrations and bed porosity are dimensionless.

However, the user can choose mass concentration for graphic printouts, by use of key word 'MASS CONCENTRATION'.

The relation between volume concentration and mass concentration is :  $C (Kg/m^3) = \rho_s C$

### Keywords

- ✓ 'MASS CONCENTRATION' (NO, default option).
- ✓ 'BED LOAD' =NO (YES, default option)
- ✓ 'SUSPENDED LOAD' =YES (NO, default option)
- ✓ 'COEFFICIENT FUNCTION OF THE POROSITY' ( $XKV = 1 / (1-n) = 1.6$ , this default value corresponds to a bed porosity  $n \approx 0.4$ )
- ✓ 'SEDIMENT DENSITY' ( $\rho_s = 2650 \text{ Kg/m}^3$ )

## 5.3. Equilibrium concentrations

### Erosion/Deposition rate

For non-cohesive sediments, the net erosion minus deposition flux is determined based on the concept of equilibrium concentration (see [14b] Celik and Rodi, 1988):

$$(E-D)_{Z_{ref}} = W_s (C_{eq} - C_{Z_{ref}}) \quad (31)$$

where  $C_{eq}$  is the equilibrium near-bed concentration and  $C_{Z_{ref}}$  is the near-bed concentration, calculated at the interface between the bed-load and the suspended load,  $z = Z_{ref}$ .

Two different semi-empirical formula from the literature are programmed in SISYPHE:

- ✓ ICQ= 1: Zyserman and Fredsoe (1994)

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According to the Zyserman and Fredsoe ([35], 1994) formulation (ICQ=1):

$$C_{eq} = \frac{0.331(\theta' - \theta_c)^{1.75}}{1 + 0.72(\theta' - \theta_c)^{1.75}} \quad (32)$$

where  $\theta_c$  is the critical Shields parameter and  $\theta' = \mu\theta$ , the non-dimensional skin friction which is related to the Shields parameter, by use of the ripple correction factor.

✓ ICQ= 2: Bijker (1992) formula:

The equilibrium concentration corresponds to the volume concentration at the top of the bed-load layer. It can be related to the bed load transport rate:

$$C_{eq} = \frac{Q_s}{bZ_{ref} u_*} \quad (33)$$

with empirical factor  $b = 6.34$

For ICQ= 2, both bed-load and suspended load should be calculated at each time step. The 'PERIOD OF COUPLING' should be set to 1(coupled mode) and 'BED-LOAD' = YES.

### **Reference level**

The reference elevation  $Z_{ref}$  corresponds (in theory) to the interface between bed-load and suspended-load. For flat beds, the bed-load layer thickness is proportional to the grain size, whereas when the bed is rippled, the bed-load layer thickness scales with the equilibrium bed roughness ( $k_r$ ).

The definition of the reference elevation needs also to be consistent with the choice of equilibrium bed-concentration formula.

- ICQ= 1: According to Zyserman and Fredsoe, the reference elevation should be set to  $Z_{ref} = 2D_{50}$ . In SISYPHE we take  $Z_{ref} = k'_s$ , where  $k'_s$  is the skin bed roughness for flat bed ( $k'_s \sim D_{50}$ , the default value of proportionality factor is KSPRATIO =3).
- ICQ= 2: According to Bijker,  $Z_{ref} = k_r$

### **Vertical concentration profile**

We assume here a Rouse profile for the vertical concentration distribution, which is theoretically valid in uniform steady flow conditions:

$$C(z) = C_{Z_{ref}} \times \left[ \frac{z-h}{z} \frac{a}{a-h} \right]^R \quad (34)$$

where R is the Rouse number defined by:

$$R = \frac{W_s}{\kappa u_*} \quad (35)$$

and  $\kappa$ , the von Karman constant ( $\kappa=0.4$ ), and  $u_*$  the friction velocity corresponding to the total bed shear stress as commented before (see §3.2).

### **Ratio between the reference and depth-averaged concentration**

By depth-integration of the Rouse profile (eq. 34), the following relation can be established between the mean (depth-averaged) concentration and the reference concentration:

$$C_{Z_{ref}} = F C$$

where:

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$$F^{-1} = \left( \frac{Z_{ref}}{h} \right)^R \int_{Z_{ref}/h}^1 \left( \frac{1-u}{u} \right)^R du$$

In SISYPHE, we use the following approximate expression for F:

$$\left. \begin{aligned} F^{-1} &= \frac{1}{(1-Z)} B^R [1 - B^{(1-R)}] & \text{for } R \neq 1 \\ F^{-1} &= -B \text{Log} B & \text{for } R = 1 \end{aligned} \right\} (36)$$

with  $B = Z_{ref}/h$

### **Keyword**

*'REFERENCE CONCENTRATION FORMULA (ICQ)'*

## **5.4. Convection velocity**

A straightforward treatment of the advection terms would imply the definition of an advection velocity and replacement of the depth-averaged velocity U in (29) by:

$$U_{conv} = \overline{UC} / C$$

A correction factor is introduced in Sisyphe, defined by:

$$F_{conv} = \frac{U_{conv}}{U} \quad (37)$$

The convection velocity should be smaller than the mean flow velocity ( $F_{conv} \leq 1$ ) since sediment concentrations are mostly transported in the lower part of the water column where velocities are smaller. We further assume an exponential profile concentration profile which is a reasonable approximation of the Rouse profile, and a logarithmic velocity profile, in order to establish the following analytical expression for  $F_{conv}$ :

$$F_{conv} = - \frac{I_2 - \text{Ln}\left(\frac{B}{30}\right) I_1}{I_1 \text{Ln}\left(\frac{eB}{30}\right)} \quad (38)$$

with :  $B = k_s/h = Z_{ref}/h$

$$I_1 = \int_B^1 \left( \frac{(1-u)}{u} \right)^R du \quad \text{and} \quad I_2 = \int_B^1 \text{Ln} u \left( \frac{(1-u)}{u} \right)^R du$$

(cf. [23] Huybrechts et al., 2010).

### **keyword**

➤ *'CORRECTION ON CONVECTION VELOCITY'* (= NO, default option)

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## 5.5. Initial concentrations, boundary conditions

### Initial conditions

The initial concentration for the suspended load can be either imposed within `condim_susp.f` or specified in the steering file through the keyword '*INITIAL SUSPENSION CONCENTRATIONS*' initializes the value of the volume concentration for each class.

### Boundary conditions

For the boundary conditions, the concentration of each class can be specified in the steering file through keyword: '*CONCENTRATION PER CLASS AT BOUNDARIES*'. It may be also convenient to use keyword '*EQUILIBRIUM INFLOW CONCENTRATION =YES*': the concentration at the entrance of the domain and at  $t=0$  is set to its equilibrium value, according to the choice of the '*REFERENCE CONCENTRATION FORMULA*'. Input concentrations can be also directly specified (user subroutines: `conlit.f`).

### Equilibrium conditions

The concentrations at the entrance of the domain can be calculated by SISYPHE assuming equilibrium conditions in order to avoid unwanted bed-evolution at the entrance of the domain, and also at the first time step, it is possible to impose the concentration to its equilibrium value, by activating the keyword '*EQUILIBRIUM INFLOW CONCENTRATION*'.

The equilibrium (depth-averaged) concentration is then calculated assuming equilibrium concentration at the bed and a Rouse profile correction for the F factor.

### Keywords

- ✓ '*INITIAL SUSPENSION CONCENTRATIONS*' ( $C_{S0}=0$ , default value)
- ✓ '*EQUILIBRIUM INFLOW CONCENTRATION*' (=NO, default option)
- ✓ '*CONCENTRATION PER CLASS AT BOUNDARIES*' (=0, default value)

### User subroutines

The subroutine `condim_susp.f` can be used to specify the initial conditions for the sediment concentration (see § V.4.2).

The subroutine `conlit.f` can be used to specify the concentration at the entrance of the domain.

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## 6. Sand grading effects

### 6.1. Sediment bed composition

#### Granulometry distribution

The number of classes of bed material is specified in the steering file and limited to ( $NSICLA < 10$ ). This condition should be relaxed in the next version (6.1).

For uniform sediment, the granulometry distribution is represented by one single value ( $NSICLA = 1$ ) for the whole domain. The mean grain diameter and corresponding settling velocity are defined in the steering file.

For sediment mixtures, the granulometry distribution is discretized in a number of classes. Each class of sediment noted  $j$  ( $1 < j \leq NSICLA$ ) is defined by its mean diameter  $D_{50}(j)$  and volume fraction in the mixture at every node, noted  $AVAI(j)$ . The characteristics of each class of sediment (mean diameter, Shields number  $\theta_c(i)$ , settling velocities  $W_s(i)$ ) of each class can be specified in the steering file or calculated by the model (same Van Rijn formulae than for single class sediment).

The percent of each class of material need to verify:

$$\sum_{j=1, NSICLA} AVAI(j) = 1 \quad \text{and} \quad 0 \leq AVAI(j) \leq 1$$

The initial bed composition can be defined in the steering file for simple configuration (uniform bed). For a more complex bed configuration (spatial variation, vertical structure), the user\_subroutine `init_compo.f` must be used to define the initial state.

The mean diameter ( $D_m$ , noted `ACLADM`) is calculated based :

$$D_m = \sum_{j=1, NSICLA} AVAI(j) D(j)$$

#### Bed structure

The bed is stratified into a number of layers (`NOMBLAY`) that enables vertical variations of the sediment bed composition. The percentage of each class  $j$  of material (noted  $AVAI(i, j, k)$ ) as well as the thickness of each layer  $E_s$  are defined at each point  $i$  and for each layer  $k$ .

The composition of transported material is computed using the composition of the upper layer (see below the definition of an 'active layer').

The initial composition of the bed (Number of layers, thickness of each layer  $E_s$ , composition of each layer  $AVAI$ ) are specified in user-subroutine `init_compo.f`.

The subroutine `init_avail.f` checks that the structure of the initial bed composition compatible with the position of the rigid bed (as defined in user subroutine `noerod.f`):

$$Z_f(i) - Z_r(i) = \sum_{k=1, NOMBLAY} E_s(k)$$

In general, the thickness of the bed is very large (by default, 100 m), so the bottom layer thickness need to be increased.

Assuming the porosity of each class to be identical (parameter  $XKV = 1/(n-1)$  is a constant), the total mass of sediments per unit area is:

$$M_s(i) = \sum_{k=1, NOMBLAY} \rho_s E_s(k) (n-1)$$

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In each layer, the *AVAI* (percent of each class) which are defined as the volume of each class of material per the total volume of material, are considered to be constant. In each layer (and at each point) the constraints on the *AVAI* need to be satisfied :

$$\sum_{j=1, NSICLA} AVAI(i, k, j) = 1 \quad \text{and} \quad 0 \leq AVAI(i, k, j) \leq 1$$

### **Keywords**

Initial sediment bed composition is defined by:

- ✓ *NUMBER OF SIZE CLASSES OF BED MATERIAL* (*NSICLA* = 1, by default)
- ✓ *SEDIMENT DIAMETERS* (.01; .01; ... by default)
- ✓ *SETTLING VELOCITIES* (if not specified calculated by SISYPHE)
- ✓ *SHIELDS PARAMETER*
- ✓ *INITIAL FRACTION FOR PARTICULAR SIZE CLASS* (*AVA0* = 1; 0; 0. ..., , by default)

For more than one size-classes, the user should specify *NSICLA* values for the mean diameter, initial fraction... For example, for a mixture of two sands:

- ✓ *NUMBER OF SIZE-CLASSES OF BED MATERIAL* = 2
- ✓ *INITIAL FRACTION FOR PARTICULAR SIZE CLASS* = .5; .5
- ✓ *MEAN DIAMETER OF THE SEDIMENT* = .02; .01
- ✓ *SHIELDS PARAMETERS* = .045; .01
- ✓ *SETTLING VELOCITIES* = .10; .05

If not specified the settling velocities and Shield parameters are calculated as a function of grain size for each particles.

## **6.2. Transport of sediment mixtures**

The method programmed in SISYPHE for the treatment of mixtures of sediment with variable grain sizes is classical and based on previous models from the literature (as for example the 1D model Sedicoup developed at Sogreah [13b]). The active layer model is based on Hirano's concept [22a,b,c].

### **Active layer/Active stratum**

Since only a thin upper layer will be transported, the upper layer is therefore subdivided into a thin 'active layer' (*k*=1) and an 'active stratum' (*k*=2).

The composition of the active layer is used to calculate the composition of transported material and the intensity of transport rates for each class of sediments

$$Q_s = \sum_{j=1, NSICLA} AVA0(j) Q_s(j)$$

where *AVA0(j)* are the percentage of class *j* in the active layer.

The active stratum is the layer that will exchange sediment with the active layer in order to keep the active layer to a fixed size. When there is a lot of erosion and when this active stratum becomes too thin, the stratum lying underneath will be merged with it.

The active layer thickness is not well defined and depend on the flow and sediment transport parameters (cf. Van Rijn, 1987). According to Yalin (1977), it is proportional to the sand diameter of the upper layer (1,2 \* *d*<sub>90</sub>). The active later thickness generally scales with the bed roughness, which is typically of the order of a few grain diameters for flat beds up to a few cm in the case of rippled

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beds. In the presence of dunes, the active layer thickness should be half the dune height (cf. Ribberink, 1987).

In Sisyphe, the active layer thickness is an additional model parameter (noted *ELAY0*) which can be estimated by calibration and specified by the user in the steering file by keyword '*ACTIVE LAYER THICKNESS*'. With the option '*CONSTANT ACTIVE LAYER THICKNESS*' = NO, it is possible to use a time- and spatially varying active layer thickness during the simulation. In Sisyphe, we simply assume  $ELAY0 = 3 D_m$  ( $D_m$  is the mean diameter of the upper layer) .

The erosion rate is restricted by the total amount of sediments in the active layer, which therefore acts as a rigid bed. The same methods applied for rigid beds are applicable for active layer formulation.

In order to avoid numerical problems such as negative sediment fractions, it is advised to use finite elements combined with the positive depth algorithm – as explained in § 4.5 for the treatment of rigid bed - when dealing with graded sediment and a thin-sized active layer.

The error message '*TIME STEP SHOULD BE REDUCED*' also appears in the listing file when the erosion is greater than half of the active layer thickness. It is strongly recommended to follow the message.

### **General formulation**

Bed-load transport rates are computed separately for each class using classical sediment transport formulae, corrected for sand grading effects (see below). The Exner equation is solved for each class of material. The individual bed evolutions due to each class of bed material are then added to give the global evolution due to bed-load.

Similarly, the suspended transport equation is solved for each class of material and the resulting bed evolutions for each class are added to give the global evolution due to the suspended load. The concentration of each class of sediments is computed, with the corresponding settling velocity, erosion and deposition flux.

At each time step, the bed evolution (due to bed load and to suspension) is used to compute the new structure (composition and layer thickness) of the new sediment bed mixture. The algorithm which determines the new bed composition considers two possibilities (deposit or erosion) and ensures mass conservation for each individual class of material. The algorithm is explained in Gonzales (2002).

### **Hiding-exposure**

In order to calculate the bed-load transport rate for each class of sediment, it is necessary to take into account the effect of hiding-exposure: in a mixture, the big particles will be more exposed to the flow than the smaller ones which will be protected. Classical sand transport formulae (for uniform sand) need to be corrected by use of a "hiding-exposure" correction factor (*HIDFAC*, as defined below in §6.4).

### **Keywords**

Sand grading effects are defined by:

- ✓ *HIDING FACTOR FORMULA* (*HIDFAC*=0, by default)
- ✓ *ACTIVE LAYER THICKNESS* (*ELAY0*=, by default)
- ✓ '*CONSTANT ACTIVE LAYER THICKNESS*' (= YES, by default)
- ✓ '*NUMBER OF BED LOAD MODEL LAYERS*' (*NOMBAY*= 2, by default)

### **Remarks**

- The number of layers has to be less than 10. The user has to compare the bed layers thickness in comparison to the total bed thickness (given in *noerod.f*) to ensure that there will be no more than 10 layers during the computation. The composition of the sediment *AVAIL* is defined at each point and for each layer:



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AVAIL(NPOIN,10,NSICLA) . The sum of AVAIL on the classes must be equal to one everywhere.

- The number of layers is allowed to vary spatially and with time as the sediment bed undergoes erosion (empty sediment layers are suppressed) or deposition (sediment layers can be added).
- A new procedure will be developed in release 6.1 with a constant number of layers which will be compatible with the consolidation algorithm.

### 6.3. New sediment transport formula

The formula of Hunziker ([24], 1995) is an adaptation of the Meyer-Peter Müller formula for fractional transport. The volumetric sediment transport per class is given by:

$$\Phi_{b,i} = 5 p_i [\zeta_i (\mu \theta_i - \theta_{cm})]^{3/2} \quad \text{si} \quad \mu \theta_i > \theta_{cr} \quad (39)$$

with :

|  |   |
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| $p_i$  | fraction of class $i$ in the active layer |
| $\theta_i$   | Shields parameter                         |
| $\theta_{cm} = \theta_{cr} \cdot \left( \frac{D_{mo}}{D_m} \right)^{0.33}$ | corrected critical Shields parameter      |
| $\theta_{cr}$  | critical Shields parameter (=0.047)       |
| $\zeta_i = \left( \frac{D_i}{D_m} \right)^{-\alpha}$                       | hiding / exposure factor                  |
| $D_i$  | grain size of class $i$                   |
| $D_m$  | mean grain size of the surface layer (m)  |
| $D_{mo}$   | mean grain size of the under layer (m)    |

Here the critical Shields parameter is calculated, as a function of the dimensionless mean grain size  $D_m$ . It should be noted that according to Hunziker, stability problems may occur outside the parameter range:

$$\alpha \leq 2.3 \quad \text{and} \quad \frac{D_i}{D_m} \geq 0.25$$

#### Keywords

- ✓ BED-LOAD TRANSPORT FORMULA ( ICF = 6)
- ✓ HIDING FACTOR FORMULA (not used if ICF = 6)

### 6.4. Hiding/exposure factors

Sediment transport rates of each class can be calculated using classical sediment transport formulae. Those formulation are initially valid for uniform particles and need to be modified to account for sand grading effects: in a mixture, big particles are more exposed to the flow than if they are alone, and small particles more protected. The bed-load formulae can be modified by use of a hiding/exposure

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factor.

Different formulations have been implemented in SISYPHE, depending on the choice of '*HIDING FACTOR FORMULA*' (*HIDFAC*).

Two formulae (Egiazaroff [18] and Ashida & Michiue [12]) have been written in association with the Meyer-Peter and Müller formula. The third formula (Karim et al [25] ) can be associated with any bed-load predictor. The first two formulae modify the critical Shields parameter that will be used in the Meyer-Peter formula, whereas the third formula modify directly the bed-load transport rate.

➤ Formulation of Egiazaroff (*HIDFAC*=1)

$$\theta_{cr} = \zeta_i \cdot 0.047 \quad \text{critical Shields parameter}$$

with:

$$\zeta_i = \left[ \frac{\log(19)}{\log(19 \cdot D_i / D_m)} \right]^2 \quad \text{hiding/exposure factor}$$

➤ Formulation of Ashida & Michiue (*HIDFAC*=2)

$$\theta_{cr} = \zeta_i \cdot 0.047 \quad \text{critical Shields parameter}$$

with:

$$\zeta_i = \begin{cases} \left[ \frac{\log(19)}{\log(19 \cdot D_i / D_m)} \right]^2 & \frac{D_i}{D_m} \geq 0.4 \\ 0.85 \cdot \frac{D_m}{D_i} & \frac{D_i}{D_m} < 0.4 \end{cases} \quad \text{hiding/ exposure factor}$$

➤ Formulation of Karim et al. (*HIDFAC*=4)

$$Q_{s,i} = \zeta_i \cdot Q_{s,i}^* \quad \text{corrected bed load transport rate}$$

with:

$$\zeta_i = \left( \frac{D_i}{D_m} \right)^{0.85} \quad \text{hiding/exposure factor}$$

**Keywords**

'*HIDING FACTOR FORMULA*' (*HIDFAC*=0, by default)

'*HIDING FACTOR FOR PARTICULAR SIZE CLASS*' (=1, by default)

(sets the value of hiding factor for particular size class if *HIDFAC* =0)

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## 7. COHESIVE SEDIMENTS

### 7.1. Erosion, deposition fluxes

The classical Krone and Partheniades formulation is applied for cohesive sediments which is assumed to be uniform:

$$\left. \begin{aligned} E &= M \left[ \left( \frac{u_*}{u_{*e}} \right)^2 - 1 \right] \quad \text{for } u_* > u_{*e} \\ D &= W_s C \left[ 1 - \left( \frac{u_*}{u_{*d}} \right)^2 \right] \quad \text{for } u_* < u_{*d} \end{aligned} \right\} \quad (40)$$

where  $u_*$  is the friction velocity related to skin friction,  $u_{*e}$  and  $u_{*d}$  are the critical shear stress velocities for erosion and deposition. The empirical coefficient  $M$  is a dimensional coefficient and its unit must be consistent with the choice of the concentration unit. In order to calculate volume concentrations,  $M$  is converted by SISYPHE in m/s, from the steering file (in Kg/m<sup>2</sup>/s ).

#### Keywords

- ✓ 'COHESIVE SEDIMENTS' = YES ( NO; default option),
- ✓ 'PARTHENIADES CONSTANT' (  $M = 10^{-3}$  Kg/m<sup>2</sup>/s, by default),
- ✓ 'CRITICAL SHEAR VELOCITY FOR MUD DEPOSITION' (VITCE:  $u_{*e} = .01$  m/s , by default),
- ✓ 'CRITICAL EROSION SHEAR VELOCITY OF THE MUD' (VITCD :  $u_{*d} = 1000$  m/s , by default).

### 7.2. Consolidation effects

#### Vertical structure of the mud deposit

The concentration of cohesive sediment deposit increases with time and vertical stratification takes place as sediment concentrations become higher at the bottom.

We so far implemented a simple semi-empirical multi-layer model (*NCOUCH\_TASS* is the number of layers in the bed, with a maximum of 10 layers). The number of layers is selected by the user in the steering file. It is assumed to be constant : empty layers may occur, while the sediment bed is eroded. During deposition, the surface layer thickness increases.

For each layer, the concentration is assumed constant. The bed concentration increases vertically from the top surface layer to the bottom.

In a pure mud regime, the bed shear strength increases as the mud concentration increases while consolidation is taking place.

$$\tau_{ce} = \rho u_{*ce}^2 \approx C^\beta$$

The bed structure (number of layers, concentration per layer and erosion shear strength) can be specified by the user in the SISYPHE steering file. The initial layer thicknesses are specified in the user subroutine: *init\_mixte.f*.

The thickness of the various mud layers are specified in the user\_subroutine : *init\_mixte.f*.

#### Time evolution

The consolidation effect is reproduced by assuming that the vertical flux of sediment from layer  $n$  to underneath layer  $n+1$  is proportional to the mass of sediments contained in the layer.

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$$\frac{dm_i}{dt} = a_i m_i \quad (41)$$

The transfer mass coefficients  $a_i$  are specified in the steering file ('*MASS TRANSFER PER LAYER*')

This multilayer consolidation algorithm, however simplistic, qualitatively reproduces an increase of mud bed deposit with time, while ensuring mass conservation (transfer coefficient of the last bottom layer is zero). Model results are highly sensitive to the specified values of the mass transfer coefficients  $a_i$  which are difficult to calibrate. The development of a more physically based consolidation algorithm is under progress.

### **Keywords**

- '*COHESIVE SEDIMENTS*' = YES (default , NO; NO; ...)
- '*MUD CONSOLIDATION*' (=NO, default)
- '*NUMBER OF LAYERS OF THE CONSOLIDATION MODEL*' (*NCOUCH\_TASS* =10, default )'
- '*MUD CONCENTRATION PER LAYER*' in Kg/m<sup>3</sup> (*CONC\_VASE*= 50.; 100.;...,by default )
- '*MASS TRANSFER PER LAYER*' (*TRANS\_MASS* = 5.10-5, .....0., by default)
- '*CRITICAL EROSION SHEAR STRESS OF THE MUD PER LAYER*': in N/m<sup>2</sup>  
(*TOCE\_VASE*= 0.01; 0.02 ....., by default)

## **7.3. Mixed sediments**

A two classes sand-mud mixture can be represented in SISYPHE. It is composed of two classes of bed sediments (*NSICLA*= 2). This fairly recent development available in release 6.9, requires further testing and improvement.

The first class (noted 1) is non-cohesive and represented by its grain diameter  $D_1$  and can be transported as bed-load or suspended load. The settling velocity  $W_{s1}$  is a function of the relative sediment density ( $s=1.65$ ) and grain diameter  $D_1$ .

The second class (noted 2) is cohesive and represented by its settling velocity  $W_{s2}$  which is a function of flocs properties. The vertical structure and consolidation algorithm are the same as for pure mud: we use the same multi-layer model for consolidating bed as described in §7.2. The bed is discretized in a constant number of layers (*NCOUCH\_TASS* <10), each characterized by a constant value of the mass concentration for the mud, which can be specified in the steering file ( $C_{si}$  for  $i=1$ , *NCOUCH\_TASS*). The time and spatial variation in the sediment composition is obtained by variation in the composition of each layers (mass of mud and mass of sand per layers, for a given mass concentration).

Note: the mass concentration of the mud component is defined for the mud only (i.e. mass of sediments per volume of mud).

### **Scheme of sand mud mixture**

The sediment bed is discretized into vertical layers, each layer is characterized by the **mass percent**  $P_i$  of each class:

$$P_i = \frac{C_{si} V_i}{M_t}$$

where  $V_i$  is the volume occupied by component  $i$ , and  $M_t$  the total mass of the sand-mud mixture:

$$M_t = C_{s2} V_2 + C_{s1} V_1$$

$$V_t = V_2 + V_1$$

With  $C_{s1} = \rho_s = 2650 \text{ Kg/m}^3$  (sand density), while for the mud,  $C_{s2}$  depends on the consolidation state

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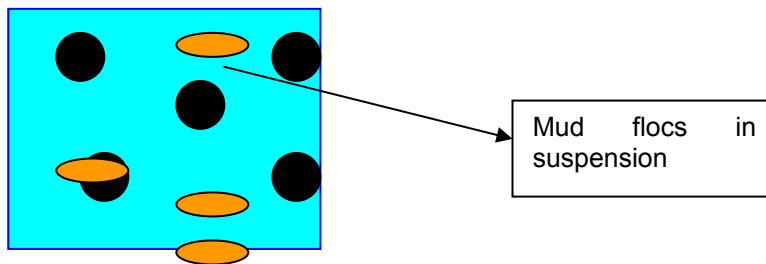
(and is constant for each vertical layer).

The erosion/deposition rates now depends on the mass % of each class in the surface layer (Panagiotopoulos et al., 1997). If the mass percent of the mud class is greater than 50% the bed is considered as pure 'cohesive' and the erosion/deposition laws follow the Partheniades classical law. (see below for the calculation of the bed shear strength in a sand/mud mixture).

If the mud percentage is less than 30 %, the bed is considered as non cohesive, and has little effect on the bed shear strength.

Once sediment particles have been put in suspension, they are transported independently, by solving for each class, a transport equation for the volume **concentration of the individual sediment particles (deflocculated)** defined as:

$$C_i = \frac{C_{mi}}{\rho_s}$$



### Erosion law for sand mud mixture

The rate of erosion is based on the Partheniades erosion law, where the critical bed shear strength of the mud class depends on the consolidation state.

The bed shear strength of the sand mud mixtures depends on the % of mud ( $P_2$  at the surface top layer). We follow here the method of Waeles (2005, [36]).

The erosion rate  $E_{(1+2)}$  is calculated for the mixture and then for each class  $E_i$ .

$$E_i = P_i E_{(1+2)}$$

➤  $C > 50\%$ : mud dominant

We apply the Krone erosion law:

$$E_{(1+2)} = M \left[ \left( \frac{u_*}{u_{*e}} \right)^2 - 1 \right] \quad \text{for} \quad \tau_b = \rho u_*^2 > \tau_{ce} = \rho u_{*e}^2$$

$$E_{(1+2)} = 0 \quad \text{if} \quad \tau_b < \tau_{ce}$$

➤  $C < 30\%$ : sand dominant

We apply the Zyserman and Fredsoe equilibrium concentration:

$$E_{(1+2)} = W_{s1} C_{eq} \quad \text{for} \quad \tau_b = \rho u_*^2 > \tau_{ce} = \rho u_{*e}^2$$

➤  $30\% < C < 50\%$ : intermediate range.

We assume a linear interpolation of erosion rates for each class.

### keywords

➤ 'MIXED SEDIMENT' (default MIXTE = No)

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➤ If MIXTE =YES:

- 'COHESIVE SEDIMENTS' (SEDCO) =YES, NO
- 'NUMBER OF SIZE-CLASSES OF BED MATERIAL' (NSICLA) = 2

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## 8. Wave effects

### 8.1. Theoretical background

#### Wave effects

In the coastal zone, the effect of waves, superimposed to a mean (wave-induced or tidal) current modifies the bottom boundary layer structure. Due to the reduced thickness of the bed boundary layer, bottom shear stresses are largely enhanced and resulting sand transport rates are an order of magnitude greater than in the case of currents alone. In addition, the wave-generated ripples also have a strong effect on the bed roughness and sand transport mechanisms.

These effects will only be accounted for when the keyword 'EFFECT OF WAVES' is activated.

#### Linear wave theory

The wave orbital velocity is calculated by SISYPHE, assuming linear theory:

$$U_0 = \frac{H_s \omega}{2 \sinh(kh)} \quad (42)$$

where  $\omega = 2\pi/T_p$  is the wave pulsation,  $k = 2\pi/L$ , where  $L$  is the wave length

The wave number is calculated from the wave dispersion relation:

$$\omega^2 = gk \tanh(kh) \quad (43)$$

#### Wave propagation

The wave parameters (wave height, wave period, wave direction) need to be specified. They can be simply imposed in the Fortran file (user subroutine: `condim_sisyphe.f`) or calculated by a previous TOMAWAC simulation [10].

The 'HYDRODYNAMIC FILE' can contain all the wave parameters (which is recommended for the non-steady case). The waves can also be specified from an independent wave field. The 'WAVE FILE' gives the name of a previous wave (TOMAWAC) results file. Only the last record will be read.

#### Wave parameters

The wave-parameters, required as input parameters for the morphodynamic computation, are the significant wave height  $H_s$  and the peak wave period  $T_p$ . The wave-angle  $\theta_w$  needs also to be specified in some particular applications, e.g. when using for example the Bailard's formula. (If not, the default value is  $90^\circ$ , which means that the direction of propagation of the wave is parallel to the x-axis).

If the wave field is calculated by TOMAWAC, the results hydrodynamic file should contain the following variables:

- ✓ HM0: significant wave height (corresponds to  $H_s$ )
- ✓ TPR5: peak period (corresponds to  $T_p$ )
- ✓ DMOY: mean wave direction, relative to y axis (corresponds to  $\theta_w$ )

The (last time record of the) 'WAVE FILE' issued from previous TOMAWAC computation is read by SISYPHE. In addition, the mean current issued from previous TELEMAC computation is read from the 'HYDRODYNAMIC FILE'.

For unsteady flow conditions (time-varying velocity and wave field), the user should run Tomawac in an unsteady mode, and store all the wave and hydrodynamic relevant variables on the same input 'HYDRODYNAMIC FILE'.

#### Keywords

- ✓ 'WAVE EFFECTS' (=NO, by default)

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✓ 'WAVE FILE'

### User-subroutine

condim\_sisyphe.f

## 8.2. Wave-induced bottom friction

### Wave-induced bottom friction

The maximum stress due to waves is calculated at each time step as a function of the wave-orbital velocity  $U_w$  by use of a quadratic friction coefficient  $f_w$  due to waves:

$$\tau_w = \frac{\rho}{2} f_w U_w^2$$

The wave friction factor  $f_w$  is calculated as a function of relative density:

$$f_w = f_w(A_0/k_s)$$

where  $A_0$  is the orbital amplitude on the bed ( $A_0 = U_w/\omega$ ), and  $k_s$  the bed roughness.

In SISYPHE, we use the Swart ([29], 1974) formula:

$$\begin{aligned} f_w &= \exp(-6.0 + 5.2 \left(\frac{A_0}{k_s}\right)^{-0.19}) \quad \text{if } \left(\frac{A_0}{k_s}\right) > 1.57 \\ f_w &= 0.3 \quad \text{if } \left(\frac{A_0}{k_s}\right) \leq 1.57 \end{aligned} \quad (44)$$

### Wave-current interaction

For combined waves and currents, the wave-induced (mean and maximum) bottom stresses are an order of magnitude larger than in the case of currents alone. Different models can be found in the literature to calculate the wave and current bottom stress, noted  $\tau_{cw}$ , as a function of the bottom shear stress due to currents only,  $\tau_c$ , and the maximum shear stress due to waves only,  $\tau_w$ .

In Bijker [14]:

$$\tau_{cw} = \tau_c + \frac{1}{2} \tau_w \quad (45)$$

The mean ( $\tau_{\text{mean}}$ ) and maximum ( $\tau_{\text{max}}$ ) shear stress can also be calculated following Soulsby's method [28]. Non-dimensional variables are defined:

$$X = \frac{\tau_0}{\tau_0 + \tau_w} ; Y = \frac{\tau_{\text{moy}}}{\tau_0 + \tau_w} ; Z = \frac{\tau_{\text{max}}}{\tau_0 + \tau_w}$$

They can be parameterized based on different turbulence models:

$$Y = X \left[ 1 + bX^p (1 - X)^q \right]$$

$$Z = 1 + aX^m (1 - X)^n$$

The various model coefficients (a, b, m, n, p, q) are empirical functions of friction coefficients  $f_w$ ,  $C_D$  and also of the wave-current angle  $\phi$ :

$$a = (a_1 + a_2 |\cos \phi|^l) + (a_3 + a_4 |\cos \phi|^l) \log_{10} \left( \frac{2f_w}{C_D} \right)$$



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$$b = (b_1 + b_2 |\cos \phi|^J) + (b_3 + b_4 |\cos \phi|^J) \log_{10} \left( \frac{2f_w}{C_D} \right)$$

with similar expressions for m, n, p, and q.

The 26 (!) fitted constants ( $a_i$ ,  $b_i$ ,  $m_i$ ,  $n_i$ ,  $p_i$ ,  $q_i$ , I et J) depend on the turbulence model selected. The coefficients which have been used in Sisyphe correspond to the model of Huynh-Thanh et Temperville (1991) [24b]:

I=0.82 - J=2.7

|   | $a_i$ | $b_i$ | $m_i$ | $n_i$ | $p_i$ | $q_i$ |
|---|-------|-------|-------|-------|-------|-------|
| 1 | -0.07 | 0.27  | 0.72  | 0.78  | -0.75 | 0.89  |
| 2 | 1.87  | 0.51  | -0.33 | -0.23 | 0.13  | 0.40  |
| 3 | -0.34 | -0.10 | 0.08  | 0.12  | 0.12  | 0.50  |
| 4 | -0.12 | -0.24 | 0.34  | -0.12 | 0.02  | -0.28 |

**Table 2:** constants issued from turbulence model HT91, in Soulsby (1997, p 91).

#### **Friction coefficient under combined waves and current:**

The characteristic shear-stress to represent wave current interactions, noted  $\left\langle \overrightarrow{\tau_{cw}}(t) \right\rangle$ , is related to the time averaged mean-velocity:

$$\left\langle \overrightarrow{\tau_{cw}}(t) \right\rangle = \rho f_{cw} \left\langle \left| \overrightarrow{U}(t) \right|^2 \right\rangle$$

where:

$$\left\langle \left| \overrightarrow{U}(t) \right|^2 \right\rangle = U_c^2 + \frac{1}{2} U_w^2$$

According to Camenen ([14a], 2002, page 60),  $\left\langle \overrightarrow{\tau_{cw}}(t) \right\rangle$  is taken as a weighted average between  $\tau_{moy}$  and  $\tau_{max}$ :

$$\left\langle \overrightarrow{\tau_{cw}}(t) \right\rangle = X \tau_{moy} + (1 - X) \tau_{max}$$

which is equivalent to:

$$\left\langle \overrightarrow{\tau_{cw}}(t) \right\rangle = Y \tau_c + Z \tau_w$$

The final expression for the wave-current interaction factor is:

$$f_{cw} = \frac{Y \tau_c + Z \tau_w}{U_c^2 + \frac{1}{2} U_w^2} \quad (46)$$

This expression of the wave and current friction factor is used in Bailard [13] and in Dibajnia and Watanabe [17] sand transport formulae.

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### 8.3. Wave-induced ripples

Equilibrium ripples are generally observed outside the surf zone. Their dimensions can be predicted as a function of waves (orbital velocity  $U_0$  and wave period  $T=2\pi/\omega$ ), for a given uniform sediment diameter  $D_{50}$ . We follow in Sisyphe the procedure of Wiberg and Harris ([34b], 1994). This formulation is only applicable for oscillatory flow conditions and does not account for the effect of a superimposed mean current.

Ripples can be classified into three types depending on the value of the ratio of wave orbital diameter to mean grain diameter,  $D_0/D_{50}$ , where  $D_0 = 2U_0/\omega$ . The ripples dimensions, namely their wave length  $\lambda$  and height  $\eta$ , could be calculated as follows:

In the orbital ripples regime, under moderate wave conditions, ripples dimensions are simply proportional to  $D_0$ :

$$\begin{aligned}\lambda &= 0.62 D_0 \\ \eta &= 0.17 \lambda\end{aligned}$$

For larger waves, in the anorbital ripple regime, ripples dimensions scale with the sand grain diameter:

$$\left. \begin{aligned}\lambda &= 535 D_{50} \\ \eta &= \lambda \exp \left( -0.095 \left( \log \frac{D_0}{\eta} \right)^2 + 0.042 \log \frac{D_0}{\eta} - 2.28 \right)\end{aligned} \right\} \quad (47)$$

The effect of ripples is to increase the bed roughness. As in Bijker's formula, we assume in SISYPHE:

$$k_s = \max(\eta, 3D_{50}) \quad (48)$$

The effect of the mean current superimposed to the waves is accounted for by introducing a correction factor, noted  $\alpha$ , to the orbital excursion, following Tanaka and Dang ([29b], 1996):

$$\alpha = 1 + 0.81 * \left( \tanh(0.3 S_*^{2/3}) \right)^{2.5} \left( \frac{U}{U_w} \right)^{1.9}$$

with:

$$S_* = D_{50} \frac{\sqrt{(s-1)gD_{50}}}{4\nu}$$

#### Keywords

✓ 'BOTTOM FRICTION LAW' : KFROT= 1 (3, default option)

### 8.4. Wave-induced sand transport

The main effect of waves is to increase the sand transport rates in comparison to the case of currents alone. This effect can be accounted for by using one of the wave sand transport formula which have been programmed in SISYPHE: the Bijker's [14], the Soulsby – Van Rijn formula [28], Bailard's [13] and the Dibajnia and Watanabe formulae [17]. In SISYPHE, the solid flow is assumed to be oriented in the direction of the mean current. The possible deviation of the transport in the direction of waves, which can be important in the near shore zone due to non-linear effects, is not accounted for.

#### Bijker formula [14]

The Bijker formula (1968) can be used for determining the total transport rate  $Q_s$  (bed-load + suspension), with its two components, the bed-load  $Q_{sc}$  and the suspended-load  $Q_{ss}$  being determined

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separately. The development is made on the scalar variables, since Bijker's formula is an extension of a steady flow formula to account for the effect of the wave enhanced shear stress.

The suspended load transport is treated in a simplified manner: the concentration profile is assumed to be continuously in equilibrium. The inertia effects related to the water column loading and unloading will then in no way be modelled. In addition, no exchange takes place with the bed load layer, only the continuity of concentration is ensured in that case.

### **Bed-load transport**

Bijker extended the steady bed-load formula proposed by Frijlink (1952), adding the effect of the wave into it. In non-dimensional variables, the bed-load transport rate is:

$$\Phi_b = b\theta_c^{0.5} \exp\left(-0.27 \frac{1}{\mu\theta_{cw}}\right) \quad (49)$$

where  $\theta_c$  is the non-dimensional shear stress due to currents alone,  $\theta_{cw}$  the non-dimensional shear stress due to wave-current interaction, and  $\mu$  is a correction factor which accounts for the effect of ripples. The shear stress under combined wave and current is calculated by eq. (45).

In the original formulation [18], we have  $b=5$ . Recent studies [17] showed that  $b=2$  provides better results in comparison to field data and other engineering models. Then the formula is programmed in Sisyphe with  $b=2$ .

The ripple correction factor  $\mu$  is calculated in the same way as in the Meyer Peter formula.

### **Suspended load transport**

The suspended load transport is obtained by vertically integrating, from a reference level corresponding to the thickness of the bed load layer, the product of the volume concentration by the mean horizontal velocity.

After depth-integration and assuming a Rouse profile for the concentration and a logarithmic velocity profile for the mean velocity profile, the suspended load can be written as:

$$Q_{ss} = Q_{sc} I \quad (50)$$

with:

$$I = 1.83 \times 0.216 \frac{B^{A-1}}{(1-B)^A} \int_B^1 \left(\frac{1-y}{y}\right)^A \ln\left(\frac{33y}{B}\right) dy$$

$$\begin{cases} A = \frac{W_s}{\kappa u_{*cw}} \\ B = \frac{k_s}{h} \end{cases} \quad \text{and} \quad u_{*cw} = \sqrt{\frac{\tau_{cw}}{\rho}}$$

### **Keywords**

- ✓ 'BED-LOAD TRANSPORT FORMULA': ICF= 4
- ✓ 'WAVE EFFECTS' = YES

### **The Soulsby - Van Rijn formula [28]**

The transport rate  $Q_s$  (volume/volume) due to the combined action of waves and current is provided by the following equation :

$$Q_{b,s} = A_{b,s} U \left[ \left( U^2 + 2 \frac{0.018}{C_D} U_0^2 \right)^{0.5} - U_{cr} \right]^{2.4} \quad (51)$$

This formula can be applied to estimate both components of the total sand transport rate (bed-load +

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suspension), and it is suitable for rippled bed regimes.

$A_{b,s}$  are the bed-load/suspended load coefficients, calculated by:

$$\left. \begin{aligned} A_b &= \frac{0.005 h (D_{50} / h)^{1.2}}{[(s-1)gD_{50}]^{1.2}} \\ A_s &= \frac{0.012 D_{50} D_*^{-0.6}}{[(s-1)gD_{50}]^{1.2}} \end{aligned} \right\} \quad (52)$$

where:

- ✓  $U$ , the depth-averaged current velocity,
- ✓  $U_0$ , the RMS orbital velocity of waves,
- ✓  $C_D$  is the quadratic drag coefficient due to current alone.

This formula has been validated assuming a rippled bed roughness:  $k_s = 0.18 \text{ m}$ .

The critical entrainment velocity,  $U_{cr}$ , is given by:

$$U_{cr} = 0.19 D_{50}^{0.1} \log_{10} \left( \frac{4h}{D_{90}} \right) \quad \text{if } 0.1 \text{ mm} \leq D_{50} \leq 0.5 \text{ mm}$$

$$U_{cr} = 8.5 D_{50}^{0.6} \log_{10} \left( \frac{4h}{D_{90}} \right) \quad \text{if } 0.5 \text{ mm} \leq D_{50} \leq 2 \text{ mm}$$

Validity range:

$$h = 1 - 20 \text{ m}$$

$$U = 0.5 - 5 \text{ m.s}^{-1}$$

$$D_{50} = 0.1 - 2 \text{ mm}$$

### **Keywords**

- ✓ *BED-LOAD TRANSPORT FORMULA = 5*
- ✓ *WAVE EFFECTS = YES*

In the Van-Rijn-Soulsby formula, the diameter  $D_{90}$ , characteristic of the coarser grains, should also be specified by use of the keyword:

- ✓ *'D90'*

### **Bailard's formula [13]**

The Bailard's formula is based on an energetic approach. The bed-load and the suspended-load components of the sand transport rate are expressed respectively as the third- and fourth-order momentum of the near-bed time-varying velocity field  $\vec{U}(t)$ .

$$Q_b = \frac{f_{cw}}{g(s-1)} \frac{\varepsilon_c}{\tan \varphi} \left\langle |\vec{U}|^2 \vec{U} \right\rangle \quad (53)$$

$$Q_s = \frac{f_{cw}}{g(s-1)} \frac{\varepsilon_s}{W_s} \left\langle |\vec{U}|^3 \vec{U} \right\rangle \quad (54)$$

with  $f_{cw}$ : friction coefficient which accounts for wave-current interactions

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$\varepsilon_s, \varepsilon_c$ : empirical factors ( $\varepsilon_s=0.02$ ,  $\varepsilon_c=0.1$ )

$\varphi$ : sediment friction angle ( $\tan \varphi=0.63$ )

$\langle \rangle$  time-averaged over a wave-period

Under combined wave and currents, the time-varying velocity vector  $\vec{U}(t)$  is made of a mean component  $U_c$  and an oscillatory component of amplitude  $U_0$ , assuming linear waves.  $\phi$  is the angle between the current and the wave direction,  $\phi_c$  is the angle between the mean current direction and the x-axis,  $\phi_w$  is the angle between the wave direction of propagation and the x-axis.

The time-varying velocity field verifies:

$$\vec{U}(t) = U_c e^{i\phi_c} + U_0 \cos \omega t e^{i\phi_w}$$

For the third-order term, one can derive an analytical expression in the general case, whereas for the fourth-order momentum, we have to assume the waves and currents to be co-linear ( $\phi=0$ ), in order to find an analytical expression. (For the general case of a non-linear non-colinear wave, we would have to integrate numerically the fourth-order velocity term (cf. Camenen, 2002 [14a]). This method is however not efficient.

Third-order term:

$$\begin{aligned} \left\langle \left| \vec{U} \right|^2 \vec{U} \right\rangle &= \vec{U}_c (U_c^2 + \frac{1}{2} U_0^2) + \vec{U}_0 (\vec{U}_c \cdot \vec{U}_0) \\ \left\langle \left| \vec{U} \right|^2 \vec{U} \right\rangle_x &= \left[ U_c^3 + U_c U_0^2 (1 + \frac{1}{2} \cos 2\phi) \right] \cos \phi_c - \frac{1}{2} U_c U_0^2 \sin 2\phi \sin \phi_c \\ \left\langle \left| \vec{U} \right|^2 \vec{U} \right\rangle_y &= \left[ U_c^3 + U_c U_0^2 (1 + \frac{1}{2} \cos 2\phi) \right] \sin \phi_c + \frac{1}{2} U_c U_0^2 \sin 2\phi \cos \phi_c \end{aligned}$$

Fourth-order term:  $\left\langle \left| \vec{U} \right|^3 \vec{U} \right\rangle_x = \frac{1}{8} (24 U_0^2 U_c^2 + 8 U_c^4 + 3 U_0^4) \cos \phi_c$

$$\left\langle \left| \vec{U} \right|^3 \vec{U} \right\rangle_y = \frac{1}{8} (24 U_0^2 U_c^2 + 8 U_c^4 + 3 U_0^4) \sin \phi_c$$

### **Keywords**

- ✓ 'BED-LOAD TRANSPORT FORMULA' = 8
- ✓ 'WAVE EFFECTS' = YES

### **Dibajnia and Watanabe formula [17]**

The Dibajnia and Watanabe (1992) formula is an unsteady formula, which accounts for inertia effects. The sand transport rate is calculated by:

$$\frac{\vec{Q}_s}{W_s D_{50}} = \alpha \frac{\vec{\Gamma}}{|\vec{\Gamma}|^{1-\beta}} \quad (55)$$

with:  $\alpha=0.0001$  and  $\beta=0.55$ , empirical model coefficients.

$\vec{\Gamma}$  represents here the difference between the amounts of sediments transported in the onshore and offshore directions. This formula is used to estimate the intensity of the solid transport rate, the direction is assumed to follow the mean current direction.

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#### Time-varying velocity field

In the wave direction, the time-varying velocity is given by:

$$U(t) = U_c \cos \phi + U_0 \sin \omega t$$

r is defined here as the asymmetry parameter:

$$r = \frac{U_0}{U_c \cos \phi}$$

The wave cycle is decomposed into two parts:

- (1) During the first part of the wave-cycle ( $0 < t < T_1$ ), the velocities are directed onshore ( $U(t) > 0$ ),
- (2) During the second part ( $T_2 = T - T_1$ ), the velocities are negative ( $U(t) < 0$ ).

The sand transport rate in the wave direction is:

$$\Gamma_{X'} = \frac{u_1 T_1 (\Omega_1^3 + \Omega_2'^3) - u_2 T_2 (\Omega_2^3 + \Omega_1'^3)}{(u_1 + u_2) T} \quad (56)$$

where  $\Omega_1$  and  $\Omega_2$  represent the amount of sand transported respectively in the onshore and offshore directions which will be deposited before flow reversal;  $\Omega_1'$  et  $\Omega_2'$  represent the remaining part which stays in suspension after flow reversal. The inertia of sediment depends on the ratio  $D_{50}/W_s$ , and represented by parameter  $\omega_i$  defined by:

$$\omega_i = \frac{u_i^2}{2(s-1)gW_s T_i} \quad \text{with} \quad u_i^2 = \frac{2}{T_i} \int_{u>0 \text{ or } <0} u^2 dt$$

Case 1: all sediment is deposited before flow reversal.

$$\begin{aligned} \omega_i \leq \omega_{crit} : \quad \Omega_i &= \omega_i \frac{2W_s T_i}{D_{50}} \\ \Omega_i' &= 0 \end{aligned}$$

Case 2: part of the sediment stays in suspension after flow reversal.

$$\begin{aligned} \omega_i \geq \omega_{crit} : \quad \Omega_i &= \omega_{crit} \frac{2W_s T_i}{D_{50}} \\ \Omega_i' &= (\omega_i - \omega_{crit}) \frac{2W_s T_i}{D_{50}} \end{aligned}$$

The critical value of  $\omega_{crit}$  is calculated as a function of the wave-current non-dimensional friction:

$$\Theta_{cw} = \frac{\langle \tau_{cw} \rangle}{\rho} \cdot \frac{1}{(s-1)gD_{50}}$$

According to Temperville et Guiza (2000):

$$\begin{cases} \omega_{crit} = 0.03, & \text{si } \Theta_{cw} \leq 0.2 \\ \omega_{crit} = 1 - \sqrt{1 - ((\Theta_{cw} - 0.2)/0.58)^2}, & \text{si } 0.2 \leq \Theta_{cw} \leq 0.4 \\ \omega_{crit} = 0.8104\sqrt{\Theta_{cw}} - 0.4225, & \text{si } 0.4 \leq \Theta_{cw} \leq 1.5 \\ \omega_{crit} = 0.7236\sqrt{\Theta_{cw}} - 0.3162, & \text{si } 1.5 \leq \Theta_{cw} \end{cases}$$

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### **Keywords**

- ✓ 'BED-LOAD TRANSPORT FORMULA' = 9
- ✓ 'WAVE EFFECTS' = YES

## 9. Numerical schemes

### 9.1. Numerical methods

Both finite elements and finite volumes are programmed in SISYPHE.

#### Finite-elements

The computational domain is meshed into unstructured triangular finite elements (SISYPHE uses the same mesh as being used for computing the hydrodynamics).

All variables are decomposed on a set of basis functions:

$$f = \sum_{i=1}^{N_{poin}} f_i \Psi_i$$

Where NPOIN number of discretization points

$f_i$  value of function  $f$  at point  $i$

$\Psi_i$  point-related basic function.

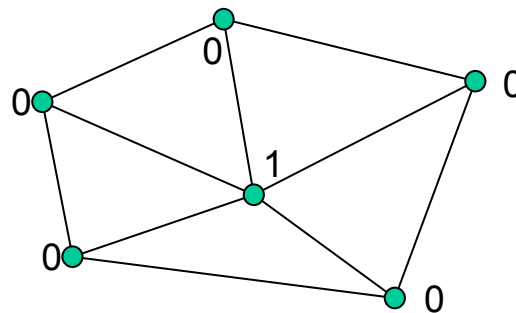
Its value is 1 at that point and 0 at all the others

The functions are only evaluated at the discretization points. A function is interpolated, within a given element, from the values at the nodes.

The interpolation functions are simple only over a reference element; each actual element is the image through a simple geometrical transformation (there is one transformation for each element).

Equations are discretized by application of the variational principle and projected on test functions.

- Definition of test functions



$$\sum_{i=1}^{N_{poin}} \Psi_i = 1$$

- Application of the variational principle

$$f = 0 \longrightarrow \iint_{\Omega} f \Psi_i d\Omega = 0$$

- decomposition on basis functions

$$\sum_{j=1}^{N_{poin}} f_j \iint_{\Omega} \Psi_i \Psi_j d\Omega = 0$$

- Definition of mass matrix:

$$M_{ij} = \iint_{\Omega} \Psi_i \Psi_j d\Omega$$



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### **Mass-lumping**

Mass-lumping consists of adding all the term of each line of the mass-matrix on the diagonal term in order to create a diagonal matrix. The mass matrix is replaced by the diagonal matrix:

$$D_i = \int_{\Omega} \Psi_i d\Omega = \sum_j M_{ij}$$

Time-derivatives are then computed as in finite-differences method. The solution can be computed faster but is smoothed.

### **Finite volumes**

Equations are integrated on a control volume (use of Ostro-Gradsy theorem) prior discretization. This is well adapted for the treatment of transport term (tracer equation). The main advantage is for the treatment of discontinuities. The Courant number condition on the time step (CFL) needs to be verified.

### **Equivalence between finite elements/finite volumes**

The segments defining control volumes around nodes are built between the gravity centres of the triangles and the centres of the segments of the triangles. Then the normal of the segments on each side of the segments of the triangles are added.

The results obtained with this method are in the general case the same as those obtained with finite elements with mass-lumping. For the user, the main difference with the finite elements methods concerns the treatment of non-erodable bed. In finite volumes, an algorithm is implemented that will reduce the bed-load transport rate according to the quantity of sediment available, so as to prevent erosion of more sediment than there is.

### **Keywords**

- ✓ 'FINITE VOLUMES' = ("NO", default option)
- ✓ 'MASS\_LUMPING ( YES, default option)
- ✓ 'OPTION FOR THE TREATMENT OF NON ERODABLE BEDS' = 4

## **9.2. Discretization of the Exner equation**

### **Finite elements**

The variational principle can be applied to the Exner equation (14):

$$\int_{\Omega} \frac{Z_f^{n+1} - Z_f^n}{\Delta t} \cdot \Psi_j \cdot d\Omega + \int_{\Omega} \text{div} \left( \vec{Q}_s^n \right) \cdot \Psi_j \cdot d\Omega = 0$$

note : The porosity factor (1/(1-n)) has been omitted (included in the transport rate).

Decomposition of all variables on the set of basis functions leads to the following system:

$$M \tilde{Z}_f^{n+1} = M Z_f^n - \Delta t \cdot \int_{\Omega} \text{div} \left( \vec{Q}_s^n \right) \cdot \Psi_i \cdot d\Omega$$

|       |                     |   |
|-------|---------------------|---|
| Where | $Z_f^n$             | Bottom depth at the time $n\Delta t$                    |
|       | $\Delta t$          | Time step   |
|       | $\tilde{Z}_f^{n+1}$ | Assessment of bottom depth at the time $(n+1) \Delta t$ |
|       | M                   | Mass matrix   |
|       | $\Psi_i$            | Basis function  |

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That system can be solved either through conventional methods (refer to the keyword *SOLVER* in the reference manual) or by replacing the mass matrix with the mass matrix as condensed along the diagonal (*MASS-LUMPING* = *YES*). Mass lumping means replacement of the mass matrix *M* (symmetrical) by the diagonal volume matrix :

In finite elements, the calculation of the divergence term  $\text{div}(\vec{Q}_s)$  can be done analytically for a given triangular element. For a given triangular element *i*, let us call  $\vec{n}_i$  the vector normal exterior to the side:

$$\int_{\Omega} \text{div}(\vec{Q}_s) \cdot \Psi_i \cdot d\Omega = \frac{1}{6} \sum_{i=1}^3 \vec{Q}_{s_i} \cdot \vec{n}_i$$

### **Finite volumes** (*FINITE VOLUMES* = *YES*)

The finite elements and finite volumes approaches are equivalent, by replacing the mass matrix by the volume matrix: The finite volume cell control is defined as the cell passing through the center of gravity of the finite elements.

The Stokes theorem can be applied to calculate directly the divergence for a given finite volume cell:

$$\int_{\Omega_i} \text{div}(\vec{Q}_s) \cdot d\Omega = \int_{\Gamma_i} \vec{Q}_s \cdot \vec{n} \, d\Gamma$$

For compatibility with the finite element, we use here the finite volume cell centered on the node, and passing through the center of gravity of each surrounding triangular element:

$\vec{Q}_s$  is linearly interpolated and assumed constant per segment on the boundary of the finite volume cell

$$\int_{\Gamma_i} \vec{Q}_s \cdot \vec{n} \, dl = \sum_{AB} \left( \frac{\vec{Q}_{sA} + \vec{Q}_{sB}}{2} \right) \cdot \vec{n}_{AB}$$

$$|\vec{n}_{AB}| = 1$$

Here  $\vec{n}_{AB}$  is the vector normal to segment AB and normalized

### **Recommendation**

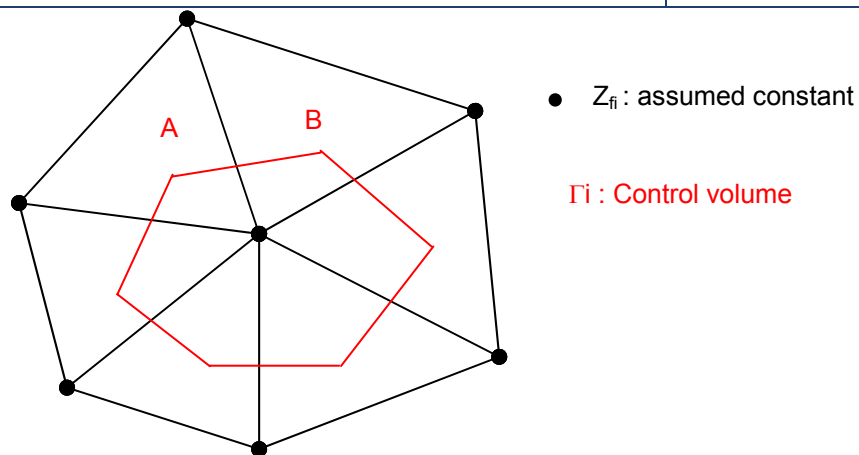
The results obtained using finite volumes method are in general the same as those obtained with finite elements with mass-lumping. For the user, the main difference with the finite elements methods concerns the treatment of rigid bed.

For the user, the main difference with the finite elements methods concerns the treatment of rigid bed, which is done naturally in finite elements using the positive water depth algorithm as explained in Hervouet et al. (2011). This new finite elements algorithm is based on segments by segments fluxes. In finite volumes, different options are available : an algorithm is implemented that will reduce the bed-load transport rate according to the quantity of sediment available, in order to prevent erosion of more sediment than there is. Option 4 for the treatment of rigid beds is recommended when finite volumes are selected.

### **Keywords**

- ✓ *MASS-LUMPING* (*YES*, by default)
- ✓ *FINITE VOLUMES* (*NO*, by default)
- ✓ 'OPTION FOR THE TREATMENT OF NON ERODABLE BEDS' = 0
  - 0 (no particular method for finite elements)
  - 4 for finite volumes

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### 9.3. Suspended sand transport equation

#### Conservative/non-conservative form

The transport-diffusion equation can be written in conservative form (28) or non-conservative form (29). The conservative form (28) is better for numerical discretization (suitable for the treatment of discontinuities). The non-conservative form (29) is not mathematically correct because the continuity equation of the Saint-Venant continuity equation is no longer satisfied for the corrected convection velocity.

$$\bar{U}_{conv} < \bar{U}$$

The conservative form is also better for numerical discretization (suitable for the treatment of discontinuities):

The transport equation can be solved by using either finite elements or finite volumes method. Different options are available for the treatment of the advection terms which is the trickiest part, and the numerical methods are similar as the one used in the former water-quality module SUBIEF-2D [11].

#### Treatment of advection terms

The choice of the numerical scheme is based on keyword ('*TYPE OF ADVECTION*').

The following finite elements methods available are:

- 1. Method of characteristics (the most classical)
  - Main advantages : unconditionally stable and monotonous
  - Diffusive for small time steps
  - Not mass conservative
- 2. Method Streamline Upwind Petrov Galerkin (SUPG)
  - Courant number criteria
  - Not mass conservative
  - Less diffusive for small time steps
- 3 or 4. Conservative N-scheme (similar to finite volumes)
  - solves the continuity equation under its conservative form
  - (recommended when the correction on convection velocity is accounted for)
  - Courant number limitation (sub iterations are included to reduce the time step)
- 13, 14 are the same as 3 and 4 but here adapted to the presence of tidal flats based on positive water depth algorithm

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- 5. Distributive schemes (PSI): like N scheme 4, but non-linear ie the fluxes are corrected according to the tracer value itself. This relaxes the courant number criteria and it is also less diffusive than scheme 4 and 14. The CPU time is however increased. This method does not apply for tidal flats.

It is therefore recommended to use scheme 4 or 14 (if tidal flats) as a good compromise (accuracy/computational time)

### **Keywords**

The following keywords determine the numerical scheme options, choice of advection scheme, accuracy of solver, coefficient of implicitation ....

- ✓ 'TETA SUSPENSION'(TETA\_SUSP = 1, by default)
- ✓ 'TYPE OF ADVECTION' (=1, default option: characteristics)
- ✓ 'SOLVER FOR SUSPENSION' (=3, conjugate gradient, by default)
- ✓ 'PRECONDITIONING FOR SUSPENSION'
- ✓ 'SOLVER ACCURACY FOR SUSPENSION' (=  $10^{-8}$ , by default)  
It is important to have a small value here, when working with volume concentration  $\lll 1$
- ✓ 'MAXIMUM NUMBER OF ITERATIONS FOR SOLVER FOR SUSPENSION' (=50, per default)  
It is important to have a small value here, when working with volume concentration  $\lll 1$
- ✓ OPTION FOR THE DISPERSION( =1, constant dispersion coefficient per default)
  - ✓ DISPERSION ALONG THE FLOW =  $10^{-2}$
  - ✓ DISPERSION ACROSS THE FLOW =  $10^{-2}$

See also :

- ✓ 'MATRIX-VECTOR PRODUCT', 'MATRIX STORAGE...'

The user is invited to look in the dictionary for detailed instructions if he wants to modify some numerical parameters. Refer to Hervouet (2007, chapter 6).

## **9.4. Computer time optimization**

### **Long term simulations**

Extrapolation methods (linear extrapolation, lengthening of the tide...) are no longer needed for 2D simulations due to large gain in computer time, such that simulation on medium term (order of decades) or medium scales (10-100 km) domains are possible within reasonable time.

### **Optimization of internal coupling**

It is possible to take advantage of the fact that bed evolutions are quite small and the time step of the bed-load transport model can be an order of magnitude greater than for the hydrodynamic model. The time step of SISYPHE is the time step of TELEMAC multiplied by the coupling period.

This method is only applicable to the bed-load: the suspended load is determined by solving a transport equation and the criteria on time step is the same as in the hydrodynamics model.

Remark: when the Bijker equilibrium concentration formula has been selected, the coupling period must be set to one (the erosion flux is calculated from the bed-load transport rate).

### **Parallel processors**

SISYPHE or SISYPHE coupled with TELEMAC-2d can also be run in parallel, but only with internal coupling.

To run SISYPHE with more than one processor, key-word PARALLEL PROCESSORS must be used. In case of coupling with Telemac-2D or 3D, this keyword in Sisyphé is discarded and taken from the

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calling programme.

Parallelism uses the parallel library MPI, that must of course be installed.

### **Keyword**

Telemac steering file:

- 'COUPLING PERIOD'
- '*PARALLEL PROCESSORS*'
- ...

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## 10. Discussion: model accuracy and limitation

The accuracy of morphodynamic model results (sediment transport rate and resulting bed evolution) is limited by numerous sources of errors/uncertainties:

- \* the accuracy of empirical sediment transport formulae;
- \* the sensitivity of sediment transport rate estimates to hydrodynamic variables including current velocity and friction coefficient;
- \* The quality of the morphodynamic model results crucially depends on the quality of the initial bathymetry and interpolation of the data on the triangular mesh.
- \* In the coastal zone: the tidal-averaged mean sediment transport results from flood tide and ebb tide transports that are generally equivalent to each other. Under natural conditions, it is a rather small effect that can be easily covered by cumulated numerical errors and other sources of uncertainties
- \* the evolution of bottoms that does not result from the transport, but from its spatial variation, which is lower in accuracy;
- \* the high empiricism of sand-grading effects (hiding-exposure correction factors);
- \* the high-empiricism in the erosion-deposition fluxes calculations for the suspended load calculations.

The user should be aware of all these difficulties, and perform some sensitivity analysis to the choice of input parameters. It is highly recommended to validate model results by comparison with data, if available. A calibration over past evolutions is necessary, to know whether, and how accurately, the model can predict the future evolutions.

On the other hand, when newly built structures disturb the flow, the quick sedimentary evolutions being involved are caused by first order effects (such as high current gradient) and a better prediction of the impact of bottoms can be ensured, provided that other factors which are not simulated by the model do not exceedingly affect the evolution of bottoms.

Conclusion: it is recommended not to use the morphodynamics model as a “black box” !

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## 11. References

### System Telemac

Updated versions of the documentation are on [www.systemtelemac.com](http://www.systemtelemac.com))

- [01] Hervouet, J.M. 2007. Hydrodynamics of free surface flow, finite elements system. Wiley
- [01b] Hervouet J.M., Villaret C., 2004: Integrated approaches for modeling sediment transport, Second International Conference on Fluvial Hydraulics, River flow 2004, Naples June 23-25 2004.
- [01c] Hervouet J.M., Razafindrakoto E., Villaret C., 2011: dealing with dry zones in free surface flows, a new class of advection scheme. IAHR conference, july 2011.
- [02] TELEMAC 2D Version 5.2. – User Manuals. EDF reports HP-75/04/033/A, HP-75/04/035/A, HP-75/04/037/A
- [03] SINUSX version 2.0. - Manuel de l'utilisateur Rapport EDF
- [04] MATISSE Version 1.0. – User's guide. EDF report HE-42/98/04/A
- [05] STBTTEL Version 4.1 – Manuel utilisateur, EDF report 1998
- [06] RUBENS Version 5.0. – User manual. EDF report 1998
- [07] EDAMOX Version 1.0. - Manuel Utilisateur. Rapport EDF
- [08] SISYPHE Version 5.2 - Manuel d'initiation. *Rapport EDF, HP-75/2002/021*
- [09] SISYPHE Version 5.4. – Validation Document. *Rapport EDF, HP-75/2004/21.*
- [9b] SISYPHE Release 5.5 - User Manual EDF-LNHE *Report HP-75/03/023.*
- [09c] SISYPHE Version 5.4. – Manuel de référence. *Rapport EDF, HP-75/2004/17.*
- [10] TOMAWAC software for finite element sea state modelling. Release 5.2 . Theoretical note , *Rapport EDF – LNHE HP-75/02/065/A*
- [11] SUBIEF-2D Version 5.0. - Descriptif informatique. Manuel utilisateur, Manuel d'initiation, manuel de référence, *Rapport HP-72/2000/002/A.*

### Other references

- [12] Ashida K., Mishiue M., 1973: Studies on bed load transport rate in alluvial streams, *Trans JSCE*, Vol.4.
- [13] Bailard J., 1981: An energetics total load transport model for a plane sloping beach, *Journal of Geophysical Research*, 86, C11, 10938-10954.
- [13b] Belleudy P., 2000: Numerical simulation of sediment mixture deposition, part 1: analysis of a flume experiment, *Journal of Hydraulic Research*, Vol.38, N°6.
- [14] Bijker E.W., 1968: Mechanics of sediment transport by the combination of waves and current In Design and Reliability of Coastal Structures, *23<sup>rd</sup> Int. Conf. on Coastal Engineering*, 147-173.
- [14a] Camenen B., 2002: Modélisation numérique du transport sédimentaire sur une plage sableuse, *Thèse de Doctorat*, Université Joseph Fourier, Grenoble 1.
- [14b] Celik I., Rodi W., 1988: Modelling Suspended Sediment Transport in non- equilibrium situations, *Journal of Hydraulic Eng.*, Vol. 114, N°10.
- [15] Chollet J.P., Cunge J.A., 1980 : New interpretation of some headloss - flow velocity relationship for deformable bed, *J. Hydr. Eng.*, 17 (1).

|     |  |         |
|-----|--|---------|
| ... |  | Version |
|-----|--|---------|

- [16] Davies A.G., Villaret C., 2004: Modelling the effect of wave-induced ripples on littoral sand transport, *EDF-LNHE Report HP-75/03/029/A*.
- [17] Dibajnia M., Watanabe A., 1992: Sheet flow under non-linear waves and currents, *Proc. of the Intl. Conf. on Coast Eng.*, 2015-2029.
- [18] Egiazaroff I.V., 1965: Calculation of non-uniform sediment concentrations, *J of Hydr. Div. ASCE*, Vol. 91, N°4, pp. 225-248.
- [19] Einstein H.A (1950) : *The bed load function for sediment transportation in open channel flow*. US Dep. Of Agriculture, Techn. Bull. N°126.
- [20] Engelund F., Hansen E., 1967: *A monograph on sediment transport in alluvial streams*, 3<sup>ième</sup> édition Techn. Univers. Of Denmark, Copenhagen, Denmark.
- [20b] Engelund, F.: Flow and Bed Topography in Channel Bends, *Journal of the Hydraulics Division*, Vol. 100, No. HY11, 1974.
- [21] Gonzales de Linares M., 2002 : Graded sediment in SISYPHE, *Rapport EDF-LNHE*, HP-75/2002/68.
- [22a] Hirano, M.: On phenomena of river-bed lowering and armouring below reservoirs, in *Proc. 14th Hydraul. Lecture Meeting*, 13-14 Feb., Civ. Eng. Ass. Hydr. Committee, Hatsumei Kaikan, 1970
- [22b] Hirano, M.: River bed degradation with armouring, *Transactions Jap. Soc. Civ. Eng.*, 3, 194-195, 1971
- [22c] Hirano, M: Studies on variation and equilibrium state of a river bed composed of nonuniform material, *Transactions Jap. Soc. Civ. Eng.*, 4, 128-129, 1972
- [23] Huybrechts N., Villaret C., Hervouet JM, 2010: Comparison between 2D and 3D modelling of sediment transport: application to the dune evolution, *Riverflow Proceedings*.
- [24] Hunziker R.P., 1995: *Fraktionsweiser Geschiebetransport*, Ph.D. thesis, Mitteilungen Nr 138 der Versuchsanstalt fur Wasserbau, Hydrologie und Glaziologie, ETH Zurich, Switzerland.
- [24b] Huynh-Thanh, Temperville A., 1991: A numerical model of the rough turbulent boundary layer in combined wave and current interaction, in *Sand Transport in Rivers Estuaries and the Sea*, eds RL Soulsby and R. Bettess, pp. 93-100, Balkema, Rotterdam.
- [25] Karim M.F., Kennedy J.F., 1982: A computer based flow and sediment routing IIR *Report N°250* Modelling for streams and its application to the Missouri River, University of Iowa, Iowa City, IA.
- [26] Koch F.G., Flokstra C., 1981: Bed level computations for curved alluvial channels, XIXth Congress of the International Association for Hydraulic Research, New Delhi India.
- [27] Meyer-Peter E., Muller R., 1948: *Formulae for bed-load transport*. Sect. Int. IARH Congress, Stockholm, Sweden.
- [28a] Ribberink J., 1987: Mathematical modelling of one-dimensional morphological changes in rivers with non-uniform sediment, *PhD thesis*, Delft University.
- [28b] Soulsby R., 1997: *Dynamics of marine sands* Thomas Thelford Edition
- [29] Swart D.H., 1976 : Offshore sediment transport and equilibrium beach profiles. *Delft Hydraulics Publi.* 131, Delft University, The Netherlands.
- [29b] Tanaka, H., Dang, V.T., 1996. Geometry of sand ripples due to combined wave-current flows. *J. of Waterway, Port, Coastal and Ocean Engineering, ASCE*, 122 (6), 298-300.
- [30] Van Rijn L.C., 1984: Sediment transport - Part I : bed load - Part II: suspended load, *J. of Hydraulic Division, Proc. ASCE*, **110**, HY10, 1431-56, HY11, 1613-41.
- [30 b] Van Rijn L.C., 1987: Mathematical modelling of morphological processes in the case of suspended sediment transport, *Doctoral Thesis*, Faculty of civil engineering, Delft University of technology).



|     |  |         |
|-----|--|---------|
| ... |  | Version |
|-----|--|---------|

- [31] Van Rijn L.C., 1993: *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*, Aqua Publications.
- [32] Villaret C., 2001: Prise en compte des fonds non-érodables dans le logiciel Sisyphe, *Rapport EDF-LNH*, HP-75/02/045/B.
- [33] Villaret C., 2001: Modélisation du transport solide par la formule de Bijker-Etude de sensibilité et tests validation . *Rapport EDF R&D LNHE* HP-75/2001/66/A.
- [34] Villaret C., Davies A.G., 2004 : Numerical modeling of littoral sand transport, ICCE Conference (Portugal, Sept).
- [34b] Wiberg P.L., Harris C.K., 1994: Ripple geometry in wave-dominated environments. *Journal of Geophysical Research* 99 (C1), 775-789.
- [35] Zyserman J.A., Fredsoe J. 1994: Data analysis of bed concentration of suspended sediment, *Journal of Hydraulic Engineering*, ASCE, Vol. **120**, N°9, pp 1021-1042.
- [36] Waeles B., 2005: Detachment and transport of clay sand gravel mixtures by channel flows, Ph. D. Thesis University of Caen.
- [37] Yalin, MS, 1977: *Mechanics of sediment transport*, Pergamon Press, Oxford.
- [37b] Yalin M.S., Ferrera da Silva A.M.F., 2001: *Fluvial Processes*, IAHR monograph Delft Hydraulics.

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## 12. Appendix 1: Running SISYPHE

### Different steps

- \* mesh generation and interpolation of bathymetric data file
- \* Modification/preparation of boundary condition files
- \* Preliminary hydrodynamic computation
- \* Preparation of Steering and Fortran files
- \* Activation of SISYPHE
- \* Analysis of results file (FUDAA post processor)

### Activation

The activation procedure is called "sisyphe", with the following syntax :

sisyphe [-D] [-b|n|d|s time] [steering file]

The sign [ ] denotes options or optional arguments that are listed hereinafter :

- \* -h or -H option: short- or long-lasting assistance. Provides more or less long instructions for implementing the procedure.
- \* -D option: Selection of the compilation mode. Option D activates the FORTRAN debugger.
- \* -b, -n, or -d heure option: provides for a delayed program execution.
  - \* -b: batch activation (immediate start-up), logon is possible.
  - \* -n: night-time activation (start-up at 8.00 p.m.), logoff is possible.
  - \* -d time: activation with start-up delayed to a specified time, logoff is possible. The format for specifying the time is: 'xxhxx'. 2 digits for hour, followed by letter 'h' and 2 digits for minutes (other standards compatible with the UNIX 'at' control may be used as explained in the manual of that control).
- \* -s option: execution is interactive, with a listing output.

In the absence of these options, execution is interactive, but the listing is only displayed on screen.

Note: in order to interrupt a computation being executed, the file delete\_cas\_numberofprocess.bat that is generated upon the activation should be run.

### Sequence of operations

- \* Confirmation of the existence of the file 'steering\_file'.
- \* Creation of a working directory '\*.tmp'. This temporary directory contains all that is needed for running the model. When the steering file being used is called 'cas1', this directory is called e.g. 'cas1\_22100.tmp' and is located in the same directory as file 'cas1'. The process number is given by the system.
- \* Fetching, using the DAMOCLES software, of those computer parameters required for compilation and execution of the model.
- \* Allocation of the files on preselected channels (FORT.xx) in the working directory after confirming their existence.
- \* Compilation of the user-supplied main routine and linking with the relevant libraries.
- \* Execution of SISYPHE

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- \* Retrieval of the RESULTS FILE in positions as specified by the user in his STEERING FILE.

If the results file already exists, the latter is renamed by adding the suffix .old.

Retrieval of the case output file: '\*\_sortie.txt' (for the -b,-n, -d and -s activation options).

### **Installation at workstation**

The implementation of the running procedure (see in Section VIII) assumes that the user has declared the PROJECT variable in his environment, that variable being provided for indicating the path to the 'LIB' and 'BIN' directories in which all the adequate files (libraries, keyword dictionary, etc.) for running SISYPHE are located. In order to declare the PROJECT variable, e.g. in Bourne Shell, the following lines should be added into the '.profile' user's file :

```
PROJECT=/home/systel5
PATH=$PATH:$PROJECT/BIN
```

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## 13. Appendix 2: Input files

### 13.1. List of files

The structure of the set of input/output files for SISYPHE is summarised below. All the files are either binary (Selafin format) or formatted (ASCII file). The data or results files associated to each case are listing in the following Table.

|                                 |                                |   |                               |
|---------------------------------|--------------------------------|---|-------------------------------|
| <b>GEOMETRY FILE</b>            | Binary                         | Input data file<br>Output of MATISSE (grid generator)       |                               |
| <b>BOUNDARY CONDITIONS FILE</b> | Formatted                      | Input for SISYPHE<br>Output of MATISSE (grid generator)     |                               |
| <b>STEERING FILE</b>            | Formatted                      | Input for SISYPHE<br>Use DAMOCLES                           |                               |
| <b>RESULTS FILE</b>             | Binary                         | Output of SISYPHE<br>Input for FUDAA (post processor)       |                               |
| FORTRAN FILE                    | Formatted<br>(use_subroutines) | Input for SISYPHE   | Only if changes are necessary |
| HYDRODYNAMIC FILE               | Binary                         | Input for SISYPHE<br>Output of TELEMAT (hydrodynamic model) | No coupling with TELEMAT      |
| WAVE FILE                       | Binary                         | Input for SISYPHE<br>Output of TOMAWAC (wave model)         | 'EFFECT OF WAVES'             |
| PREVIOUS SEDIMENTOLOGICAL FILE  | Binary                         | Input/Output of SISYPHE                                     | 'COMPUTATION CONTINUED'       |
| REFERENCE FILE                  | Binary                         | Input for SISYPHE   | 'VALIDATION'                  |

**Table 1:** List of files, format and options. Only the first four files (in bold) are required, the other ones are optional depending on the choice of selected keywords (last column).

### 13.2. Boundary condition file

The format of the boundary condition file is the same as for TELEMAT-2D or -3D: the same layout standard was adopted. This file is automatically filled up by the STBTET/MATISSE (grid generator) interface, but it can also be prepared or modified through a text editor.

Each line in this file is dedicated to a point along the edge of the grid. The edge points are numbered like the file lines; the numbering first describes the domain outline in the counterclockwise direction from lower left point (X+Y minimum), then the islands in the clockwise direction. The boundary condition about the bottom depth is imposed at the specific place of the tracer boundary condition in

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TELEMAC-2D.

The following thirteen variables for each edge point are first read out of the boundary conditions file:

X1, X2, X3, X4, X5, X6, X7, **LIEBOR**, **EBOR**, X10, X11, **N**, **K**.

The first seven variables (X1, X2, X3, X4, X5, X6, X7), as well as X10 and X11, are specific to the Telamac-2d model. They are read in Sisyphe, but remain unused.

**LIEBOR** is an integer providing the type of boundary conditions along the edges :

- = KENT (numerical value 5): bottom evolution imposed to EBOR value at a liquid boundary,
- = KSORT (numerical value 4): free evolution at a liquid boundary,
- = KLOG or KADH (numerical value 2 or 0) : solid boundary.

**EBOR** provides the values of sedimentary evolutions when they are imposed.

**LIEBOR** and **EBOR** are **NPTFR**-dimensioned arrays, where NPTFR is the number of boundary points of the domain.

A fixed bottom depth is usually imposed at the boundaries with an inflow (**EBOR** = 0; **LIEBOR** = **KENT**), whereas a free evolution is imposed at the boundaries with an outflow (**LIEBOR** = **KSORT**).

**N** is the global number of the edge point.

**K** is the local number of boundary points.

The boundary conditions file (see example ) makes it possible to impose both types and values of boundary conditions when the latter do not change in time. Upon simulations in non-permanent conditions, however, this file is not always sufficient for imposing the boundary conditions. The `conlit.f` subroutine shall then be resorted to.

BOUNDARY CONDITION FILE

| HYDRODYNAMIC   |      |      |        | L<br>I<br>E<br>B<br>O<br>R | E<br>B<br>O<br>R |      |      |    |    |  |
|----------------|------|------|--------|----------------------------|------------------|------|------|----|----|--|
| BOUNDARY COND. |      |      |        |                            |                  |      |      |    |    |  |
| !-----!        |      |      |        | !-----!                    |                  |      |      |    |    |  |
| 5 4 4          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 56 | 1  | From edge point 1 to edge point 2 :<br>free evolution.                         |
| 5 4 4          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 1  | 2  |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 2  | 3  |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 3  | 4  |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 4  | 5  |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 5  | 6  |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 6  | 7  |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 7  | 8  |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 8  | 9  |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 9  | 10 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 10 | 11 | From edge point 21<br>to edge point 30 :<br>free evolution<br>liquid boundary. |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 11 | 12 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 12 | 13 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 13 | 14 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 14 | 15 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 15 | 16 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 16 | 17 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 17 | 18 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 18 | 19 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 19 | 20 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 20 | 21 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 21 | 22 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 22 | 23 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 23 | 24 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 24 | 25 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 25 | 26 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 26 | 27 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 27 | 28 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 28 | 29 |  |
| 4 0 6          | .000 | .000 | .000.0 | 4                          | .000             | .000 | .000 | 29 | 30 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 30 | 31 |  |
| 2 2 2          | .000 | .000 | .000.0 | 2                          | .000             | .000 | .000 | 31 | 32 |  |

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### 13.3. Steering file

#### Principle

This text file is created either directly by a text editor or through a user interface. In a way, it is the computation instrument panel. It contains a set of keywords to which values are ascribed (an exemplary steering file can be found in the Appendix). If a keyword does not occur in this file, SISYPHE will allocate the default values as defined in the dictionary file. If no such default value is defined in the dictionary, the computation will be interrupted with an error message. For instance, the command *TIME STEP* = 10. is for specifying that the time step value of the computation is 10 seconds.

SISYPHE reads the steering file at the beginning of computation.

Both dictionary and steering files are read by a so-called DAMOCLES utility included in SISYPHE. Then upon the creation of the steering file, the DAMOCLES syntactical rules that are described below should be observed (as it takes place automatically if the file is created using EDAMOX).

#### Writing rules

The writing rules are as follows :

- \* The keywords may be of the Integer, Real, Logical value or Character type.
- \* The keyword sequence order in the steering file is unimportant.
- \* The number of characters will not exceed 72.
- \* For keywords in the form of an array, the successive values are separated by a semi-colon. The number of values to be given will not necessarily be equal to the array dimension ; if it happens, DAMOCLES will return the number of values being read. For example :

*TYPE OF ADVECTION* = 1; 3

(that keyword, which is a keyword in Telemac-2d, not in Sisyphe is declared as a 4-valued array)

- \* Symbols ":" or "=" are used equally for separating a keyword name from its value. Any number of blanks can be entered either before or after them. The value itself may occur on the next line. For example:

*TIME STEP* =    10.

or                      *TIME STEP* : 10.

or else                *TIME STEP* =10.

- \* The characters located between two "/" on one line are considered as comments. Likewise, the characters occurring between a "/" and a line ending are considered as comments. For example :

*TIME STEP* = 10.    /time step

- \* A line beginning with a "/" in the first column is wholly considered as a comment, even though there is another "/" in the line. For example :

- \* Writing the integers : The maximum size made possible by the machine shall not be exceeded. No blank shall be inserted between the sign (optional for +) and the number. A point at the end of the number is tolerated.

- \* Writing the real numbers: both point and comma are accepted as a decimal separator, as well as the Fortran E and D formats ( 1.E-3 0.001 0,001 1.D-3 denote the same value).

- \* Writing the logical values : Values 1 OUI YES .TRUE. TRUE VRAI on the one hand, and 0. NON NO .FALSE. FALSE FAUX on the other hand are accepted.

- \* Writing the strings of characters : The strings including blanks or dedicated symbols ("/", ":", "=", "&") should be placed between apostrophes ('). The value of a character keyword may include up to 144 characters. As in Fortran, the apostrophes included within one string should be

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doubled.

\* In addition to the keywords, a number of instructions or meta-commands that are interpreted during the sequential reading of the steering file can also be used :

- *&FIN* indicates the file end (even though the file is not completed, so that some keywords can be deactivated merely by placing them after that command for their easy subsequent reactivation). However, the computation proceeds.
- *&ETA* prints the list of keywords and the associated values at the time when DAMOCLES meets that command. That display will take place at the beginning of output listing.
- *&LIS* Prints the list of keywords. That display will take place at the beginning of output listing.
- *&IND* prints the detailed list of keywords. That display will take place at the beginning of output listing.
- *&STO* causes the interruption of program, the computation will not proceed.



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## STEERING FILE

```

/*****
/
/          KEYWORD DECLARATION FILE OF THE SISYPHE MODEL
/
/*****
/
/-----/
/          FICHIERS D'ENTREE
/-----
/
FORTRAN FILE           : 'princi'
STEERING FILE          : 'cas'
BOUNDARY CONDITIONS FILE : 'conlim'
GEOMETRY FILE          : 'geo'
/
PREVIOUS COMPUTATION FILE : ''
RESULTS FILE            : 'bosse.res'
REFERENCE FILE          : 'bosse.ref'
/
/-----
/          GENERAL OPTIONS
/-----
/
TITLE = 'bosse'
/
GRAPHIC PRINTOUT PERIOD = 1
VARIABLES FOR GRAPHIC PRINTOUTS : 'U,V,S,Z,H,B,N,P,D,K'
LISTING PRINTOUT PERIOD = 10
MASS-BALANCE = OUI
VALIDATION = OUI
/
STEADY CASE = OUI
TIME STEP = 1800.
NUMBER OF TIME STEPS = 100
/
/-----
/          COMPUTATION METHOD AND PARAMETERS
/-----
/
BED-LOAD TRANSPORT FORMULA = 3
/
CRITICAL EVOLUTION RATIO = 0.5
/
/-----
/          PHYSICAL CONSTANTS AND PARAMETERS
/-----
/
MEAN GRAIN DIAMETER = 0.0003
/
FRICTION COEFFICIENT = 80.

```

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```
/
/-----
/      NUMERICAL VARIABLES
/-----
/
MINIMUM H VALUE = 0.1
/
ZERO = 1.E-12
/ IMPLICITNESS COEFFICIENT  ( 0 < TETA < 1 )
TETA = 0.5
&
```

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## 14. Appendix 3 : User subroutines (Fortran file)

### Role of the Fortran file

Programming can be necessary for particular applications. The user subroutines are described in this section. When one of these subroutines is necessary for the case being handled, a FORTRAN file (keyword '*FORTRAN FILE*') including the subroutine(s) required by the user, needs to be associated with that computational case.

### Amendment of coordinates: *corrxy.f*

This subroutine was designed for carrying out, at the beginning of a computation, an amendment of the grid point coordinates, e.g. for a scaling-up (shifting from a small-scale model to a full size), a rotation or a translation.

This subroutine is empty by default and provides, in the form of a comment, an example of programmed change of scale and origin.

### Input conditions

#### ✓ Hydrodynamic variables: *condim\_sisyphe.f*

The user can impose the values of the following variables in each point of the domain :

- \* liquid flow component,
- \* water depth,
- \* bottom, depth,
- \* free surface elevation,
- \* cumulative evolution,
- \* wave height,
- \* wave period,
- \* wave angle.

Among others, this subroutine is used for defining the initial conditions.

This subroutine is activated at the beginning of a computation in permanent conditions and at each time step in unsteady conditions.

#### ✓ *condim\_susp.f*

The user can impose the initial values of the concentration for each class of sediments for the suspension. This subroutine is activated at the beginning of a computation.

#### ✓ *conlit.f*

The user can modify the boundary conditions within the time loop. This subroutine is called up at each computation time step.

A bed-load transport rate can also be imposed at the liquid boundaries. To that purpose, *LIEBOR = KENT* is imposed at that boundary either in the boundary conditions file or in the *Conlit.f* subroutine.

The sediment transport rate is defined in the *conlit.f* subroutine.

*LIQBOR* is set to *KENT*, i.e. a sediment flow is imposed, then the *QBOR* array containing the sediment flow values at the nodes is initialised. (Warning : if *LIQBOR* is not set to *KENT*, *QBOR* is ignored).

### Input parameters

#### ✓ *init\_constant.f*,

The values of  $\kappa$  (Karman constant),  $\pi$ ..., can be changed in *init\_constant.f*.

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The following subroutines can also be modified for specific applications:

- `gf_user.f`: can be used to specify the feeding rate (cf §III.4)
- `init_compo.f`: can be used to specify the initial bed composition (cf § III.2)
- `hiding_factor.f`: can also be modified to compute a different hiding factor formula

#### **Time variable or space variable friction: strche.f**

Strche.f is used for defining a space-variable or time variable friction coefficient. By default, the value given for the *FRICTION COEFFICIENT* keyword in the steering file is imposed throughout the domain.

The corstr subroutine is for imposing a time-variable friction coefficient, which can be computed as a function of liquid flow, water depth...

#### **New sand transport formula: qsform.f**

Through this subroutine, the user can program a sediment transport formula that is different from those already implemented in Sisyphe for imposing a transport formula that better suits his/her study. The keyword '*BED-LOAD TRANSPORT FORMULA*' should be set to 0.

#### **Definition of rigid areas: noerod.f**

This subroutine is used for specifying the rigid areas. The depths of non-erodable areas ( $Z_r$  array) are imposed in this subroutine. To that purpose, the keyword '*OPTION FOR THE TREATMENT OF NON ERODABLE BEDS*' should be set to a 0 with finite element method and to 4 with finite volumes.

#### **Use of private variables: nomvar.f and predes.f**

SISYPHE standard version makes it possible to output a number of computed variables. In some cases, the user may want to compute variables and write them into the results file (so far, the number of these variables is limited to four).

Likewise, each variable is identified by one or several letters in the keyword '*VARIABLES FOR GRAPHIC PRINTOUTS*'. The new variables are then identified by letters A, G, L and O which, respectively, correspond to numbers 23, 24, 25 and 26.

In the software data structure, these four variables correspond to the  $PRIVE\%ADR(1)\%P\%R(X)$ ,  $PRIVE\%ADR(2)\%P\%R(X)$ ,  $PRIVE\%ADR(3)\%P\%R(X)$  and  $PRIVE\%ADR(4)\%P\%R(X)$  arrays (where X is the number of grid points) that can be used in several programming stages.

The new variables are programmed in two steps:

\* Firstly, the names of these new variables should be set by completing the `nomvar.f` subroutine, which consists of two equivalent structures for English and French languages. Each structure sets the names of variables of the results file to be generated, then the names of variables to be read again in the previous computation file in case of a reactivation. This subroutine can also be amended when, for instance, the French version of SISYPHE being used, one wants to make a reactivation on a file generated by the English version. If so, the TEXTPR array of the subroutine French part shall contain the English names of the variables.

\* Secondly, the PREDES subroutine is to be amended for entering the computation(s) of the new variable(s) therein. Besides, the LEO and IMP variables are provided for determining whether, at the time step being considered, the variable should be printed in the monitoring listing or in the results file.

FORTRAN FILE

```
C          *****
C          SUBROUTINE CONDIM
C          *****
C
C          * (U      , V      , QU      , QV      , H      , ZF      , Z      ,
C          *   ESOMT   , C      , Q      , HW      , TW      ,
C          *   X      , Y      , NPOIN  , AT      , PMAREE )
C
C          FUNCTION   : IMPOSED VALUES
C
C                      - OF VECTORIAL FLOWRATE QU, QV
C                      - OF WATER DEPTH          H
C                      - OF BOTTOM DEPTH          ZF
C                      - OF FREE SURFACE          Z
C                      - OF TOTAL EVOLUTION      ESOMT
C                      - OF FLOWRATE              Q
C                      - OF WAVE HEIGHT           HW
C                      - OF WAVE PERIOD           TW
C
C-----
C
C                      ARGUMENTS
C
C-----
C |      NAME      | MODE |      ROLE
C |-----|-----|-----|
C | U , V          | <--  | CO-ORDINATES DE VELOCITY VECTORS
C | QU , QV        | <--  | VECTORIAL FLORATE ALONG X AND ALONG Y
C | H              | <--> | WATER DEPTH
C | ZF             | <--> | BOTTOM DEPTH
C | Z              | <--> | FREE SURFACE ELEVATION
C | ESOMT          | <--> | TOTAL EVOLUTION OF BOTTOMS
C | C              | <--> | CELERITY
C | Q              | <--> | FLOWRATE
C | HW             | -->  | WAVE HEIGHT
C | TW             | -->  | WAVE PERIOD
```

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```

C |   X,Y           | --> | GRID CO-ORDINATES
C |   NPOIN         | --> | NUMBER OF GRID POINTS
C |   AT            | --> | TIME
C |   PMAREE        | --> | TIDE TIME
C | _____|_____|_____
C MODE : -->(UN-MODIFIED DATA) , <--(RESULT) , <-->(MODIFIED DATA)
C-----
C CALLING ROUTINE : SISYPH
C CALLED ROUTINES :
C*****
C
C      IMPLICIT NONE
C      INTEGER LNG,LU
C      COMMON/INFO/LNG,LU
C
C      INTEGER NPOIN , I
C
C      DOUBLE PRECISION  U(NPOIN) , V(NPOIN)      , H(NPOIN)
C      DOUBLE PRECISION  QU(NPOIN), QV(NPOIN)      , Q(NPOIN)
C      DOUBLE PRECISION  C(NPOIN) , ESOMT(NPOIN), HW(NPOIN), TW(NPOIN)
C      DOUBLE PRECISION  Z(NPOIN) , ZF(NPOIN)
C      DOUBLE PRECISION  X(NPOIN) , Y(NPOIN)
C      DOUBLE PRECISION  AT          , PMAREE , PI
C
C-----
C
C-----
C  INITIALISATION OF ARRYS THAT ARE NON READ IN THE RESULTS FILE :
C-----
C
C      DO 1 I=1,NPOIN
C          QU(I)=.25D0
C          Q(I)=.25D0
C          ESOMT(I)=0.D0
C          QV(I)=0.D0
C          Z(I)=.6D0
C          ZF(I)=0.D0
1  CONTINUE
PI=3.1416D0

```

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```
      DO 2 I=1,NPOIN
        IF (X(I) .GE. 2.D0 .AND. X(I) .LE. 10.D0) THEN
          ZF(I)=.1D0*DSIN(PI*(X(I)- 2.D0)/ 8.D0)
          ,      *SIN(PI*(X(I)- 2.D0)/ 8.D0)
        END IF
        H(I)=Z(I)-ZF(I)
2    CONTINUE
C-----
      RETURN
      END
```

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## 15. Appendix 4: Output files

### 15.1. Listing

The computation process can be monitored on a listing that is created automatically by SISYPHE.

The keywords provided for acting upon the listing are as follows:

*'LISTING PRINTOUT PERIOD'*

*'VARIABLES TO BE PRINTED'*

*'MASS-BALANCE'*

*'VALIDATION'*

In case of a delayed (or "batch") initiation of the computation, that listing is written into a file having the standard name 'cas\*\_sortie.txt', where cas is the name of the computation parameters file. It can be scanned using either a text editor or the command "more cas\*\_sortie.txt". That file can be consulted at any time during the computation and makes it possible to monitor the evolution of the latter.

If the computation is initiated interactively, the listing scrolls down on the screen unless the *–s* option is used (a listing file listing 'cas\*\_sortie.txt' is then created).

The following are displayed, in the indicated sequence order, in the listing:

- \* data about the computation inputs;
- \* the parameters of the case file that was activated;
- \* the values of all the keywords are recapitulated in order to monitor the initiated computation.
- \* data about the geometry file being used : number of points in the grid, number of elements, number of edge points.
- \* data about reading of the previous file-type files (*PREVIOUS COMPUTATION FILE* and possibly *PREVIOUS SEDIMENTOLOGICAL COMPUTATION FILE*) : file name, time step, names of read variables, record from which the file reading begins...
- \* data about the computations made by SISYPHE:
- \* the period of these printouts is then the *LISTING PRINTOUT PERIOD*. Thus, the following can be found upon the printout:
  - \* the maximum and minimum values of evolutions,
  - \* the value of cumulated evolution integral (if *MASS-BALANCE* is true).
- \* The values, in each grid point, of some variables selected through the keyword *'VARIABLES TO BE PRINTED'*. It is rather a debugging function offered by SISYPHE, to be handled carefully in order to prevent a too bulky output listing from being created.

In addition, the result of the validation procedure is given at the last computation time step (if the keyword *'VALIDATION'* is true). The user also can make a validation at each time step by amending the *VALIDA* subroutine.

The last line printed by SISYPHE is :    NORMAL END OF PROGRAM

### 15.2. Results file

The *RESULTS FILE* is a binary file, the name and standard of which have been defined in the steering file (binary SELAFIN format).

This file first includes all the data about grid geometry, then the names of stored variables.



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Furthermore, for each time step, it contains the time and, for each grid point, the values of several variables. The printouts are made by the subroutine **ECRGeo** (that sets the SELAFIN options and fills up the initial part of the file), then by **DESIMP** that writes the results upon each time step.

The *RESULTS FILE* is provided for display purposes through the RUBENS post-processor. It can also be re-used for initialising the sedimentological variables in case of a sedimentological computation sequence (refer to the keyword '*PREVIOUS SEDIMENTOLOGICAL COMPUTATION FILE*' in the reference manual).

The keywords for acting upon the content of that RESULTS FILE are as follows:

*'GRAPHIC PRINTOUT PERIOD'*

*'VARIABLES FOR GRAPHIC PRINTOUTS'*

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# SISYPHE MODEL COMPUTING ENVIRONMENT (TELEMAC CHAIN)

