TECHNICAL
REPORT

ISO/TR
11651

First edition
2015-08-15

Estimation of sediment deposition in reservoir using one dimensional simulation models

Estimation du dépôt de sédiments dans le réservoir en utilisant des modèles de simulation à une dimension

Reference number
ISO/TR 11651:2015(E)

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Foreword

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The committee responsible for this document is ISO/TC 113, *Hydrometry*, Subcommittee SC 6, *Sediment transport*.

Introduction

Storage reservoirs built across rivers or streams lose their capacity on account of deposition of sediment. Surveys indicate that world-wide reservoirs are losing their storage capacity, at an annual rate of about one percent, due to accumulation of sediments. The impacts of sedimentation on the performance of the reservoir project are manifold. Some of the important aspects are the following:

a) reduction in live storage capacity of the reservoir;

b) accumulation of sediment at or near the dam may interfere with the functioning of water intakes and hence is an important parameter in deciding the location and level of various outlets;

c) increased inflow of sediment into the water conveyance systems and hence to be considered in the design of water conductor systems, desilting basins, turbines, etc;

d) sediment deposition in the head reaches may cause rise in flood levels;

e) the location and quantity of sediment deposition affects the performance of the sediment sluicing and flushing measures used to restore the storage capacity.

Hence, prediction of sediment distribution in reservoirs is essential in the following:

a) feasibility studies during planning and design of various components of new projects;

b) performance assessment of existing projects.

The most simple and earliest models to predict the sedimentation processes in reservoirs are the empirical ones. The trap-efficiency curves derived from records of existing reservoirs are among the most commonly used empirical methods. Recently, due to better understanding of the fundamentals of reservoir hydraulics and morphology, along with the rapid growth of computational facilities, development and application of mathematical models have become a normal practice.

Compared to empirical methods, the mathematical approach of the sediment distribution enables more time and space dependent and more accurate modelling. A large number of mathematical models have been developed during the past few decades. Flow in the reservoir can be represented by the basic equations for conservation of momentum and mass of water and sediment.

Estimation of sediment deposition in reservoir using one dimensional simulation models

1 Scope

This Technical Report describes a method for estimation/prediction of sediment deposition within and upstream of a reservoir using numerical simulation techniques through one-dimensional flow and sediment transport equations.

Numerical simulation models for predicting sediment distribution are applicable for reservoirs, where the length of the reservoir greatly exceeds the depth and width and the reservoir has a significant through flow.

This Technical Report includes the theoretical basis and fundamental assumptions of the technique and provides a summary of some numerical methods used to solve the unsteady flow and sediment transport equations. Also provided are details on the application of the model, including data requirements, procedures for model calibration, validation, testing, applications and identification of uncertainties associated with the method. This Technical Report does not provide sufficient information for the development of a computer program for solving the equations, but rather is based on the assumption that an adequately documented computer program is available.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 748, *Hydrometry — Measurement of liquid flow in open channels using current-meters or floats*

ISO 772, *Hydrometry — Vocabulary and symbols*

ISO 1100-2, *Hydrometry — Measurement of liquid flow in open channels — Part 2: Determination of the stage-discharge relationship*

ISO 2425, *Hydrometry — Measurement of liquid flow in open channels under tidal conditions*

ISO 2537, *Hydrometry — Rotating-element current-meters*

ISO 3454, *Hydrometry — Direct depth sounding and suspension equipment*

ISO 4363, *Measurement of liquid flow in open channels — Methods for measurement of characteristics of suspended sediment*

ISO 4364, *Measurement of liquid flow in open channels — Bed material sampling*

ISO 4365, *Liquid flow in open channels — Sediment in streams and canals — Determination of concentration, particle size distribution and relative density*

ISO 4373, *Hydrometry — Water level measuring devices*

ISO 6416, *Hydrometry — Measurement of discharge by the ultrasonic (acoustic) method*

ISO 18365, *Hydrometry — Selection, establishment and operation of a gauging station*

ISO/TS 3716, *Hydrometry — Functional requirements and characteristics of suspended-sediment samplers*

ISO/TR 9212, *Methods of measurement of bedload discharge*

3 Definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Units of measurement

The units of measurement used in this Technical Report are SI units.

5 Principles of quasi-unsteady sediment modelling

Many early and contemporary sediment models simplify hydrodynamics of sediment transport models by invoking a “quasi-unsteady” flow assumption. Instead of solving the Saint-Venant equations explicitly or implicitly, the hydrodynamics are represented by a series of steady flow backwater computations and associated with temporal durations. Most generalized sediment transport models still utilize this approach. Because sediment transport and hydraulic processes respond on different time and distance scales and because of the inherent uncertainties associated with sediment simulations, the simplification provided by this approximation often justify the error introduced. However, because the quasi-unsteady approach does not route water, it can be difficult to implement for reservoir modelling. Quasi-unsteady models have been used successfully to model reservoir sedimentation but they require external hydrologic routing computations to define reservoir stage. This process often has to be iterative because the hydrologic routing parameters change in time as the capacity of the reservoir changes with sediment deposition. Therefore, an unsteady approach can be advantageous.

6 Principles of unsteady flow models

6.1 General

Numerical models are used to solve sedimentation problems in river engineering, especially for long-term simulation of long river reaches. The modelling cycle is schematically represented in Figure 1. The prototype is the reality to be studied and is defined by data and by knowledge. The data represents boundary conditions, such as bathymetry, water discharges, sediment particle size distributions, vegetation types, etc. The knowledge contains the physical processes that are known to determine the system’s behaviour, such as flow turbulence, sediment transport mechanisms and mixing processes. Understanding the prototype and data constitute the first step of the cycle.

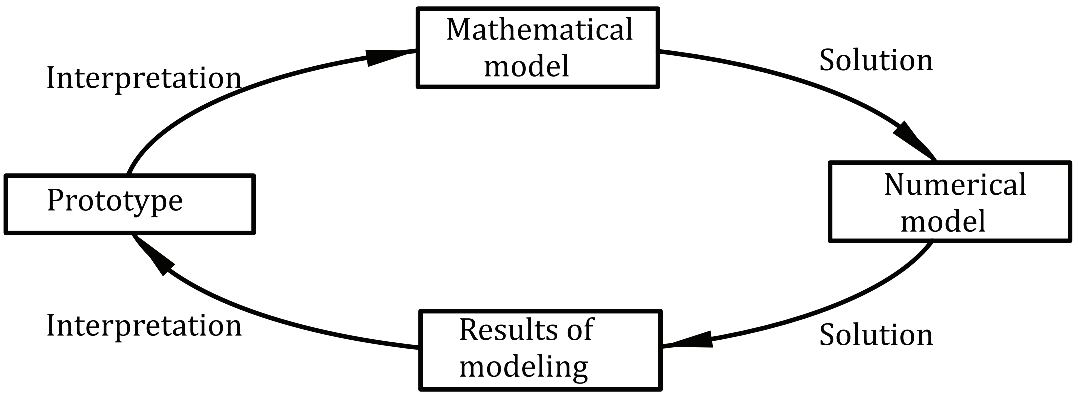

Figure 1 — Modelling cycle

In the first interpretation step, all the relevant physical processes that were identified in the prototype are translated into governing equations that are compiled into the mathematical model.

A mathematical model therefore constitutes the first approximation to the problem. It is the prerequisite for a numerical model. At this time, many simplifying approximations are made, such as steady versus unsteady and one- versus two- versus three-dimensional formulations, simplifying descriptions of turbulence, etc. In water resources, one usually (but not always) arrives to the set-up of a boundary value problem whose governing equations contain partial differential equations and nonlinear terms.

Next, a solution step is required to solve the mathematical model. The numerical model embodies the numerical techniques used to solve the set of governing equations that forms the mathematical model. In this step, one chooses, for example, finite difference versus finite element versus finite volume discretization techniques and selects the approach to deal with the nonlinear terms. This is a further approximating step because the partial differential equations are transformed into algebraic equations, which are approximate but not equivalent to the former.

Another solution step involves the solution of the numerical model in a computer and provides the results of modelling. This step embodies further approximations and simplifications, such as those associated with unknown boundary conditions, imprecise bathymetry, unknown water and or sediment discharges and friction factors.

Finally, the data needs to be interpreted and placed in the appropriate prototype context. This last step closes the modelling cycle and ultimately provides the answer to the problem that drives the modelling efforts.

The choice of model for each specific problem should take into account the requirements of the problem, the knowledge of the system, and the available data. On one hand, the model must take into account all the significant phenomena that are known to occur in the system and that will influence the aspects that are being studied. On the other hand, model complexity is limited by the available data. There is no universal model that can be applied to every problem. The specific requirements of each problem should be analysed and the model chosen should reflect this analysis in its features and complexity.

6.2 Governing equations

The governing equations are the one-dimensional, cross-sectionally averaged expressions for (1) the conservation of mass (or equation of continuity), (2) conservation of linear momentum and (3) continuity of the bed material.

The following one-dimensional flow equations are solved to get the hydraulic parameters such as energy slope, velocity and depth of flow at each cross-section at each time step. The sediment transport capacities at each cross-section are then computed and compared with the sediment inflow. The scour or deposition at each section is computed using sediment continuity equation and new cross-section bed levels are determined accordingly. The computations then proceed to the next time step and the cycle is repeated with the updated geometry.

Conservation of mass (or equation of continuity),

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

Conservation of linear momentum

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\beta \frac{Q^2}{A}\right) + gA\frac{\partial y}{\partial x} + gA(S_\mathrm{f} - S_0) = qu' \tag{2}$$

Equation of Continuity of the Bed Material

$$\frac{\partial G_\mathrm{b}}{\partial x} + \frac{\partial G_\mathrm{s}}{\partial x} + \frac{\partial}{\partial t}\left(C_\mathrm{s} A\right) + \rho_* \frac{\partial}{\partial t}\left(B_\mathrm{d} z\right) = 0 \tag{3}$$

where

A	is the cross-sectional area of the channel, and varies with x, t, and z;
t	is the time;
Q	is the discharge, and varies with x and t;
u'	is longitudinal component of the lateral inflow velocity and varies with x and t;
x	is the longitudinal position along the channel axis;
y	is the depth of flow, and varies with x and t;
g	is the acceleration of gravity;
β	is the momentum coefficient and varies with x, z, and t;
q	is the lateral inflow per unit length of channel, and varies with x and t;
S_0	is the bed slope, and varies with x;
S_f	is the friction slope, and varies with x, t and z;
G_b	is the bed load;
G_s	is the suspended load;
C_s	is the average spatial sediment concentration in the cross-section;
ρ_*	is the density of sediment in the bed;
B_d	is the deformable bed width and varies with t;
z	is the bed elevation and varies with t.

The momentum coefficient may be computed using Formula (4):

$$\beta = \int \frac{u^2 dA}{U^2 A} \tag{4}$$

where

u is the velocity in some elemental area dA;

U is the mean velocity in the same cross-section having a total area A.

The friction slope, S_f, accounts for the resistance due to external boundary stresses. The friction slope is generally represented by Chezy or Manning's equations.

For the Chezy equation, the bed resistance term in the momentum formula is described as:

$$S_f \frac{gQ|Q|}{C^2 AR} \tag{5}$$

where

Q is the discharge;

A is the flow area;

R is the resistance or hydraulic radius.

For the Manning description, the term is:

$$S_f = \frac{gQ|Q|}{M^2 AR^{4/3}} \tag{6}$$

The Manning number, M, is equivalent to the Strickler coefficient. Its inverse is the more conventional Manning's, n. The value of n is typically in the range 0,01 (smooth channel) to 0,10 (thickly vegetated channel). The corresponding values for M are from 100 to 10.

The Chezy coefficient is related to Manning's n by

$$C = \frac{R^{1/6}}{n} = MR^{1/6} \tag{7}$$

Both R and n can vary as a function of x, z, and t. Formula 6 is based on the assumption that the Manning equation for steady, uniform flow provides a reasonable approximation for S_f in unsteady, non uniform flow.

Formula (2) can be modified to include a term accounting for the momentum imparted to the water by a temporally and spatially varying wind. Formulae (1) and (2) also can be written with (1) depth and velocity, (2) stage and velocity, or (3) stage and discharge as the dependent variables.

Formulae (1) and (2) apply to the unsteady, spatially varied, turbulent free-surface flow of an incompressible, viscous fluid in an open channel of arbitrary cross-section and alignment. The equations are solved simultaneously for the unknowns, z (depth of flow) and Q (discharge) as a function of time *(t)* and longitudinal position *(x).*

Formula (3) accounts for the sediment transport and thus the changes in bed levels. Various equations are available for the calculation of sediment transport rate and alluvial roughness, e.g. the Meyer-Peter and Muller and the DuBoys' transport function for the calculation of bed load; the Engelund and Hansen model, the Ackers and White model, the Yang model and the Smart and Jaeggi model for determination of the total load and the Engelund and Fredsoe and van Rijn models for the computation of bed load and suspended load separately. All these models/equations can be applied using a single representative grain size or using a number of grain sizes representing grain size fractions in graded material.

Formulae (1) and (2) are derived from first principles and may be obtained directly from the three dimensional equation of mass continuity and the Navier-Stokes equations, which are general, three dimensional statements of the conservation of momentum for any fluid flow. A number of assumptions are required to derive Formulae (1) and (2). An unsteady flow model should generally be applied to those conditions in which none of the major assumptions is severely violated. The assumptions are as follows:

a) flow is approximately one-dimensional, meaning that the predominant spatial variation in dynamic conditions of hydraulic parameters (discharge, velocity and stage) is in the longitudinal direction;

b) fluid density is homogeneous throughout the modelled reach;

c) vertical accelerations are negligible, i.e. the hydrostatic pressure distribution is applicable;

d) velocity is uniformly distributed in a given cross-section. Inclusion of the momentum coefficient in Formula (2) allows this assumption to be violated somewhat, however, there should be no flow separation and streamlines should not be highly curvilinear;

e) neither aggradation nor degradation of the river bed occurs during computational time step;

f) turbulence and energy dissipation can be described by resistance laws formulated for steady, uniform flow [required for Formula (4)];

g) there are no abrupt changes in channel shape or alignment;

h) velocity is zero at the channel boundary;

i) there is no super elevation of the water level at any cross-section;

j) surface tension and density of air at the free surface are negligible.

6.3 Numerical techniques for solution of governing equations

No known analytical solutions exist for Formulae (1) and (2). Consequently, numerical techniques are used to convert Formulae (1) and (2) into algebraic equations that may be solved for z and Q at finite, incremental values of x and t. This solution depends on the proper description of the cross-sectional area as a function of x and t, and on the availability of accurate boundary condition data.

A variety of numerical techniques have been proposed and used to solve the unsteady flow equations. The techniques of interest are those based on some type of gridded discretization of the problem at hand, in which the continuous variables for which the solution is sought are solved only at specific discrete locations of the physical domain. The algebraic equations that form the numerical model are functions of those discrete quantities. For the same problem (i.e. the same set of differential governing formulae and boundary conditions), it is possible to obtain very distinct sets of algebraic numerical equations, depending on the technique used to discretize the equations. The broad categories of numerical techniques are method of characteristics, finite differences, finite elements and finite volumes. Generally, finite-difference techniques are preferred for the solution of the one-dimensional partial differential equations describing unsteady open-channel flow. The finite difference method includes

a) explicit finite-difference methods, and

b) implicit finite-difference methods.

Numerous variations of each of these general categories of techniques exist. The methods are briefly reviewed to provide some perspective on advantages and disadvantages of each method.