TRANSPORT OF SEDIMENTS

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Summary

The study of flow in a watercourse is a particularly difficult task, since the channel bed usually varies in space and time. The movement of the sediments, which make up the mobile bed, represents a complex phenomenon.

Herein we define: a *watercourse* may be an artificial one, such as a laboratory channel or a artificial canal, both of well-defined dimensions, or a natural one, such as gullies, streams or rivers. A *mobile bed* is defined as a channel bed made up of loose solid particles of different sizes.

The different modes of the transport of (non-cohesive) sediments as bed load and as suspended load will be presented. The formulae for the calculations of the transport of

the total load will be exposed, as well as their domain of application.

1. Introduction

1.1. Water-Sediment Mixture

The flow of water over a mobile bed has the ability to entrain the sediments (solid particles); a water-sediment mixture displaces itself in the water-course. The movement of sediments — *erosion, transport, deposition* — modifies the flow, but also the channel bed, its elevation, slope and roughness. The interaction between water and sediments makes the problem a coupled one. When the bed is a *mobile* one, the hydraulics must concern itself with both the flow of the liquid phase, namely the mixture, and the movement of the solid phase, namely the sediments in the mixture.

A characterization of the liquid and the solid phase of a water-sediment mixture is a difficult task.

i) The *liquid* phase is rather well described by: its density, ρ , its viscosity, μ , the average velocity of the flow, U , and the friction velocity, u_*.

ii) The *solid* phase is more difficult to characterize; considered should be: the size of the solid particles, given by its granulometric curve, which includes different types of diameters such as d_{50} , d_{90} , d_{35} , etc., the form of these particles, the density of the particles, ρ_s , together, these parameters can be defined by the settling velocity of the particles, v_{ss} , and possibly, the cohesion between the particles.

All these parameters could vary along the watercourse. Since the dimensions of the sediments are relatively small compared to the ones of the flow, the *turbulence* will play an essential role in all flows of a water-sediment mixture.

The transport of sediments plays an important role in many problems of fluvial hydraulics. This phenomenon is complex and consequently a theoretical study can only be performed in simplified cases.

The formulae, developed for the quantitative determination of the transport of sediments, are based on limited experimental results and thus should be used with caution. While such formulae are of great value for the hydraulic engineer, they must be applied within hydraulic conditions under which they have been established.

1.2. Flow of a Mixture

For gravitational flow of a water-sediment mixture, one may distinguish three types of movement:

i) The mixture may be considered Newtonian, if the volumetric concentration of the particles is very small, $C_s \ll 1\,\%$. The difference between the density of the mixture and of the water, $\Delta\rho = (\rho_m - \rho) = (\rho_s - \rho)\, C_s$, remains also small,

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$\Delta\rho \ll 16$ [kg/m^3]. The *transport of sediments* (Graf and Altinakar, 1998, Chapter 6), as bed load and as suspended load, falls into this category. This type of transport of solid particles is most often encountered in artificial and natural watercourses.

ii) The mixture behavior is quasi-Newtonian, if the volumetric concentration is small, $C_s \ll 8$ %. The difference between the density of the mixture and of the water becomes important if $\Delta\rho < 130$ [kg/m^3]. The transport of sediments as *concentrated suspension* (Graf, 1971, p. 182-186) notably close to the bed, as well as the *turbidity currents* (Graf and Altinakar, 1998, Chapter 7) fall into this category.

iii) The mixture behavior is non-Newtonian if the volumetric concentration gets important, $C_s > 8$%. The difference between the density of the mixture and of the water is also large, $\Delta\rho > 130$ [kg/m^3]. The flow of a non-Newtonian fluid modifies all concepts of Newtonian hydraulics. The transport of sediments as *hyperconcentrated suspension* (Wan and Wang, 1994), the *debris flow* (Takahashi, 1991), as well as *hyperconcentrated turbidity currents* (Wan and Wang, 1994) fall into this category.

The above schematic classification is a simplification of the reality, where limits can often not readily be defined and where different cases may coexist.

1.3. Modes of Transport (see Figure 1)

The transport of sediments by flow of water is the entire solid transport which passes through a cross section of a watercourse. Traditionally (but a bit artificially) the transport of sediments is classified in different modes of transport which correspond to different physical mechanisms.

In a watercourse the sediments, namely the solid phase, are transported as:

i) *bed load*, q_{sb}, — volumetric solid discharge per unit width [m^3/sm] — when the particles stay in close contact with the bed and displace themselves by gliding, rolling or (shortly) jumping ; this type of transport concerns the larger particles ;

ii) *suspended load*, q_{ss} , when the particles stay occasionally in contact with the bed and displace themselves by making more or less large jumps remaining surrounded by water; this type of transport concerns the smaller particles;

iii) bed load + suspended load, being the (total) *bed-material load*, $q_s = q_{sb} + q_{ss}$, when the particles stay more or less in continuous contact with the bed;

iv) *wash load*, q_{sw}, when the particles are almost never in contact with the bed and are washed through the cross section by the flow ; this type of transport concerns the finest particles.

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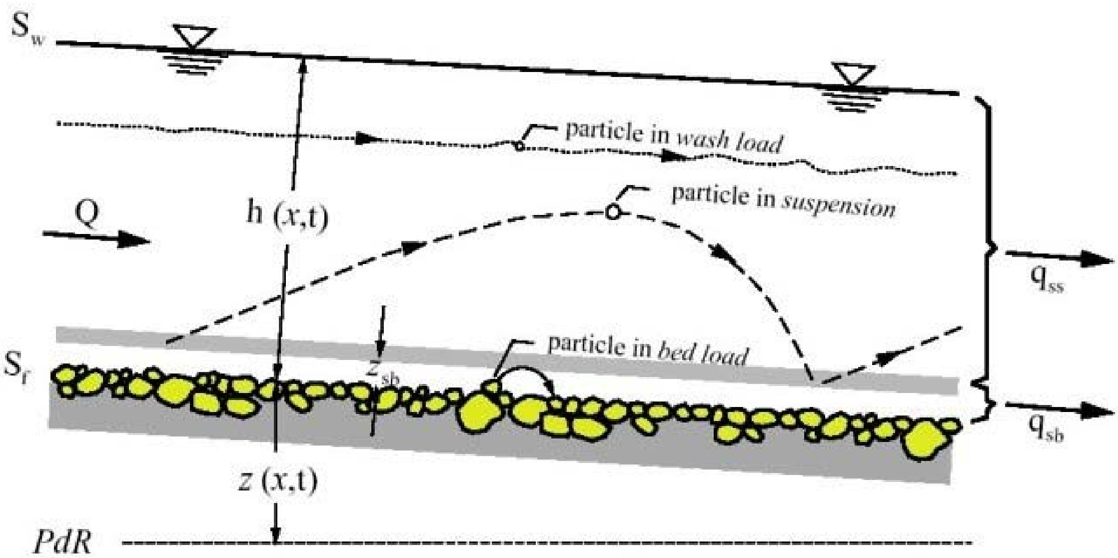

Figure 1: Scheme of modes of transport.

The transport of sediments, namely the erosion of the bed, commences upon attainment of a certain critical value, which can be parameterized, for example, by the critical shear stress, τ_{ocr} .

It will be useful, but it is also rather imprecise, to give limiting values for the separation of the different modes of transport. Given are purely indicative values using the ratio of the shear velocity of the flow, u_* , and the settling velocity of the particles, v_{ss} (Graf, 1971) :

- $u*/v_{ss} > 0.10$ beginning of bed-load transport,
- $u*/v_{ss} > 0.40$ beginning of suspended load transport.

To determine quantitatively the transport of sediments, there are three possibilities available, namely :

- using existing formulae (see Sections 2, 3 and 4),
- obtaining field measurements with adequate instruments (Graf, 1971,Chapter 13),
- performing physical models (Graf, 1971,Chapter 14).

1.4. Types of Problems

Many hydraulic problems, which require some knowledge of the transport of sediments, can usually be put into one of the following categories:

- determination of a sedimentological rating curve, $q_s = f(q)$, for a given cross section of the channel (see Figure 2);
- determination of the stability of the bed in a given cross section (Graf and Altinakar, 1998, Section 3.4.4);

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- determination of the stability of the channel slope (aggradation and degradation) in a given reach of the channel (Graf and Altinakar, 1998, Section 2.4).

The different modes of transport of sediments, quantified in form of solid discharge, q_{sb}, q_{ss} and q_s, should be related to the liquid discharge, q. It gives the relation of the "sedimentological" rating curve (see Figure 2) for a given cross section of the channel. This curve together with the "liquid" rating curve (Graf and Altinakar, 1998, Figure 3.8) give a rather complete hydraulic description for a given cross section of a channel having a mobile bed.

The formulae used to calculate the solid discharge q_s, estimate the *capacity* of the transport of sediments for a given flow. Under such conditions, the transport is said to be in equilibrium. However, it could happen that the supply of solid discharge is not equal to the capacity of the transport. The transport of sediments is then not in equilibrium.

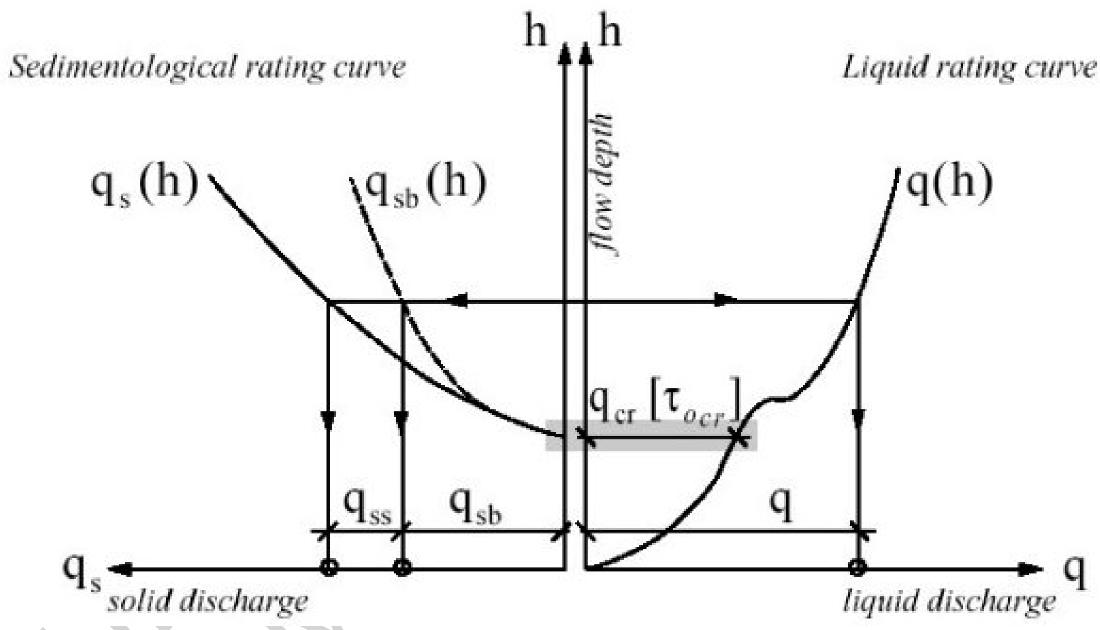

Figure 2: Rating curves for liquid discharge and solid discharge.

1.5. Equations of Saint-Venant and Exner

The hydrodynamic equations, and some solutions, for flow in an open channel over a mobile bed, when entrainment of sediments is possible, are presented in Graf and Altinakar, 1998,Chapter 6.2. These are the equations of Saint-Venant over a *mobile bed* supplemented by the relation of Exner.

Degradation (erosion) and aggradation (deposition), which are long-term processes of the evolution of the channel bed, can be described with the equations of Saint-Venant and Exner (Graf and Altinakar, 1998, Section 6.2.4). Under reasonable assumptions analytical solutions are possible. *Degradation* (or *aggradation*) in a reach of a watercourse is encountered if the entering solid discharge is smaller (or larger) than the capacity for the transport of sediments. The sediments of the bed will be eroded (or deposited) and as a consequence the elevation of the channel bed decreases (or increases). Different scenarios to be encountered are shown in Figure 3.

Analytical solutions of the equations of Saint-Venant and Exner are only possible when the hypothesis of quasi-steadiness but also quasi-uniformity of the flow is justified. However, these assumptions are *no* longer possible, if the temporal variation of the discharge and the one of the elevation of the bed are of the same order of magnitude, namely relatively rapid. Under such conditions no analytical solutions, which are reasonably simple, are available. The system of the equations of Saint-Venant and Exner can be resolved — without making too severe assumptions — by numerical methods; this may be achieved with the use of computers. The numerical methods are essentially the same as the ones used to solve the equations of Saint-Venant over a *fixed* bed (Graf and Altinakar, 1998, Section 5.2). They become however rather complicated, if they are applied for the modelisation of flow over a *mobile* bed. The *implicit* methods (Graf and Altinakar, 1998, Section 5.2.4) using finite differences are the ones which are at the present frequently used to solve the equations of Saint-Venant and Exner.

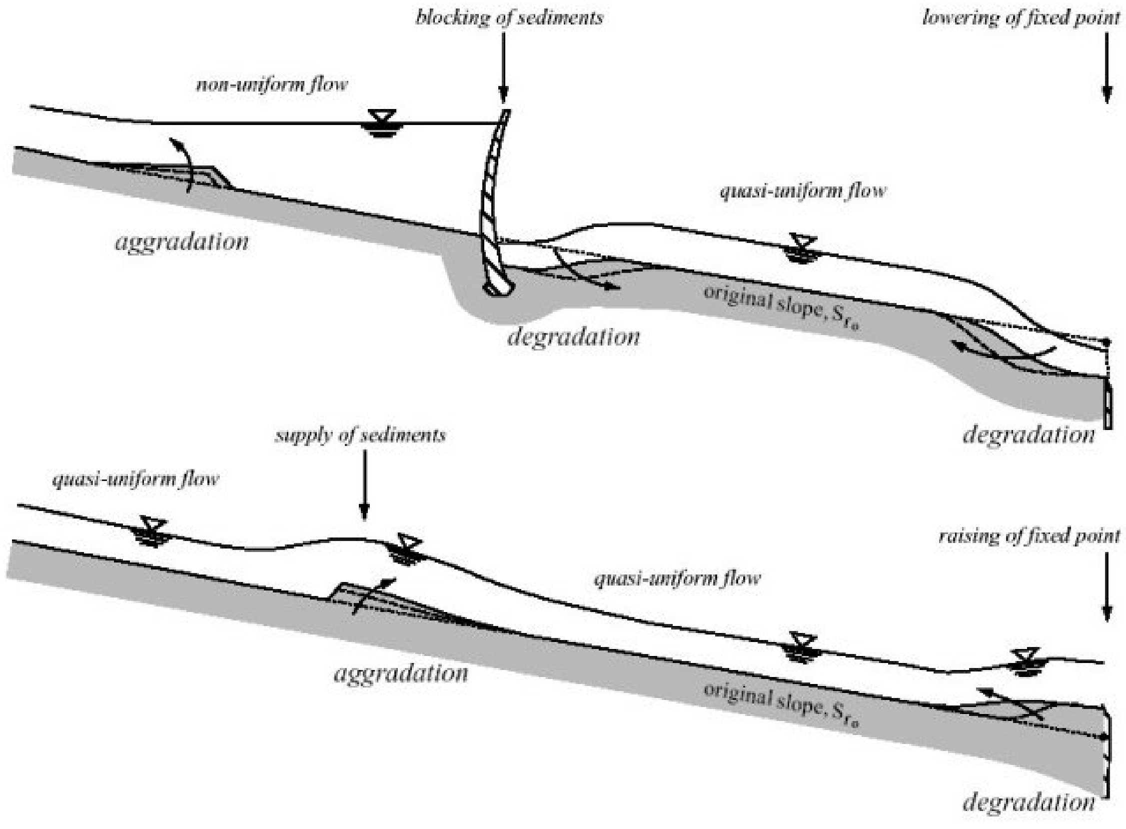

Figure 3: Scheme of a degradation or an aggradation.

2. Bed-Load Transport

2.1. Notions

Transport as bed-load is the mode of transport of sediments (see Figure 1) where the moving solid particles stay very close to the bed, $0 < z < z_{sb}$, which they may leave only temporarily. The displacement of the particles is intermittent; the turbulence plays an important role.

There exist a number of formulae, which have been proposed for the prediction of the bed-load transport (Graf, 1971,Chapter 7, Yalin, 1972,Chapter 5, and Raudkivi,1976,Chapter 7). These formulae are empirical in nature, but often have incorporated dimensionless numbers. This allows us to make experiments in the laboratory; subsequently it is possible to use such formulae for field conditions.

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Biographical Sketches

Walter H. Graf Professor at the Swiss Federal Institute of Technology in Lausanne (EPFL) since 1973, Walter H. Graf concentrated his research activities on the open-channel hydraulics and hydrodynamics of lakes and reservoirs. Previously W. H. Graf had teaching engagements at the University of California-Berkeley, at Cornell University and at Lehigh University in the USA. In 1995, he was named a "Guest Professor" at the Tsinghua University in Beijing, China. He holds a Dr. h.c., conferred by the University of Graz, Austria, in 1999. He was the Miller Visiting Professor at the University of Illinois in 2001/2002. Over the years he served also as a visiting professor in various institutions worldwide.

W. H. Graf is the author or editor of four books on Hydraulics of Sediment Transport (1971, McGraw Hill, USA), Hydrodynamics of Lakes (1979, Elsevier, NL), Lake and Reservoir Hydraulics (1987, Water Res. Publ., USA) and Hydrodynamique (1991, Ed. Eyrolles, F.). More recently the two volumes of Hydraulique Fluviale (1993, 1996, 2000, Presses polytechniques et universitaires romandes, CH) were produced; the last books were done with the collaboration of M. S. Altinakar, they are translated into English and Chinese.

In 1987, the XXII Congress of the International Association of Hydraulic Research (IAHR) was held in Lausanne, under the direction of W. H. Graf with the participation of M. S. Altinakar; together six volumes of proceedings were edited.

Mustafa S. Altinakar After completing his doctoral thesis in 1988 at the Hydraulic Research Laboratory (LRH) of the Swiss Federal Institute of Technology in Lausanne (EPFL), Dr. Mustafa S. Altinakar joined Bonnard and Gardel Consulting Engineers Ltd. in Lausanne, where he worked until 1997 as a Senior Design Engineer and Project Manager. He participated in the design and construction of several large-scale hydro projects including dams, hydroelectric power plants, water supply and distribution projects, river training and flood protection works, and other hydraulic structures. He also specialized in tunnel aerodynamics and numerical simulation of fire and smoke propagation in tunnels. During the period 1989-1997, Dr. Altinakar also maintained a part-time position in the LRH at the EPFL. During this time he co-authored two books: Hydrodynamique (Eyrolles, 1991; PPUR, 1995) and Hydraulique Fluviale (PPUR 1993, 1996, 2000 in French; Wiley and Sons 1998 in English; Chengdu University Press 1998 in Chinese).

In 1997, M.S. Altinakar returned to the LRH as a full-time Research Associate and head of the fluvial hydraulics research group. He also participated in teaching fluid mechanics and of fluvial hydraulics courses.

M. S. Altinakar is currently the acting Director of the Hydraulic Research Laboratory at the Swiss Federal Institute of Technology in Lausanne (EPFL). His research activities are concentrated on environmental hydraulics with a particular emphasis on fluvial hydraulics and sediment transport, mixing and transport phenomena, and stratified flows.

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