HYDRAULICS OF TWO-PHASE FLOWS: WATER AND SEDIMENT

G R Basson
Dept. of Civil Engineering, University of Stellenbosch, South Africa.

Keywords: sediment, sediment transport, turbulence, river regime, stream power, density currents, stream forms. meandering channels, braiding channels, scour and deposition, energy dissipation, equilibrium channels

Contents

Summary

The flow of water with sediment content is important to the hydraulic engineer involved with water supply and flood control projects. Seen as a two-phase flow phenomenon, water and sediment in motion is described as an energy-coupled process, giving rise to erosion and scour, suspension, transport, advection, dispersion and deposition of sediment.

These processes can affect the stream-flow regimen, giving rise to various bed forms such as ripples, submerged dunes, flat beds or anti-dunes. They also affect the plan-form of natural stream flow channels, causing such forms as stream-braiding and meandering, depending on the stream power, total sediment load and rate of energy dissipation in the flow. A number of bed-form concepts and sediment transport formulae are given, for calculation purposes.

The sediment behavior characteristics, such as bed load and suspended load, bed forms and roughness effects, stream power, non-equilibrium and equilibrium regimes are dealt with.

Critical conditions for entrainment and deposition are outlined. The role of density currents in advective transport, and turbulence in suspension and dispersion is described.

The importance of analyzing the inter-relationship of water and sediment, seen as a two-phase system, and its bearing on the stable behavior and maintenance of natural and dredged channels, and its importance in the sedimentation of reservoirs is concluded with.

1. Introduction

The interrelationship between water and sediment determines the equilibrium shape of a river. The plan form, river width, flow depth and longitudinal slope depends on the sediment characteristics, the discharge and the related sediment transport capacity of the stream. The sediment could consist of very fine clay and silt sizes (less than 30 micron in diameter) as found in the Yellow River, China, to large boulders of more than 2 m in diameter in mountain rivers (Figure 1).

Figure 1. Mountain River

While ancient populations were aware of the engineering problems related to water and sediment dynamics, many of their hydraulic structures suffered from scour or sediment deposition. Some hydraulic works are however still in operation after thousands of years due to the good knowledge their designers had on the sediment-water interrelationship (see Large Dams).

2. Historical sustainable design for river sedimentation

On the upper Yangtze River in China, an engineer designed a 300 m^3/s irrigation canal, joining it to the main river by excavating through a ridge. He also proposed operating rules to minimize sediment transport into the canal and predicted how the diversion would operate: divert 40% of the river flow during summer and divert 60% during winter (low flow period). The engineer made use of various techniques to control the sediment such as river curvature enhanced by artificial islands in the stream. Today we understand these principles, but this river diversion was designed and constructed more than 2000 years ago! In the 1970s Chinese engineers verified the operating rules of the diversion to within 3 percent accuracy as predicted by its original designer.

3. The importance of water-sediment two phase flow

A sound understanding of the mechanics of sediment transport is important in the design of hydraulic structures to address the following aspects:

- general scour (re-entrainment of sediment from the bed) of an alluvial (sand bedded) river.
- local scour at a hydraulic structure, such as at bridge piers
- deposition of sediment in flow zones where the available sediment concentration exceeds the sediment transport capacity of the stream, thereby reducing the useful capacity of a storage reservoir for example
- the equilibrium width-depth relationship of a river, in order to design stable channels/canals (see Fluid Mechanics)..

Apart from the above possible impacts of sediment transport on hydraulic structures, sediment is important for the environment :

- nutrients are attached to fine sediments and the maintenance of equilibrium sediment transport in a river system is therefore very important for the ecology. In this regard relatively small dams compared to large dams could be beneficial, if flushing of water and sediments during floods are maintained.
- In a natural river system cohesive sediments are removed regularly from coarser sub-layers of sediment during floods, thereby providing the required environment for fish breeding. Hydraulic structures should therefore not impact on the floods severely by flood peak attenuation, except in cases where social requirements and risk of flooding play a major role (see Storm Water Drainage and Effluent Disposal).

4. Sediment characteristics

Natural sediment can vary considerably in size based on the local geology and stream power. Sediment transport equations normally predict in the range of particle sizes of 0,03 mm to 2 mm. Clay fractions (smaller than 4 micron) and silt, are however quite common in rivers and are often found on flood plains, while in the main channel fine sediments are often washed through the river system during a flood. In mountainous rivers bed sediment could be large boulders up to 2 to 3 m in diameter. **Sediment size** is an important variable to consider since it determines, with the specific gravity of the sediment, the settling (fall) velocity of the sediment.

Specific gravity of sediment is typically 2 650 kg/m^3. The viscosity of the fluid, which is temperature dependant, also plays a role in settling velocities of sediment.

Fine sediments (less than 0,03 mm) often has **cohesive** characteristics due to inter-particle forces and are therefore more difficult to entrain from the bed than non-cohesive sediments of the same size (see Sediment Phenomena).

5. Modes of sediment transport

There are three modes of transport:

Colloidal suspended sediment transport: Fine sediment (particle diameter $< 1\mu m$) is transported with the stream due to inter-particle forces. This mode of sediment transport however plays a minor role in rivers and at reservoirs it is estimated to contribute to less than 3% of the total sediment transport.

Turbulent sediment transport: This is often the dominant mode of transport. A specific river/canal has an equilibrium (saturated) sediment transport capacity, based on local hydraulic characteristics such as bed roughness, flow depth and width, longitudinal slope of the river and the sediment characteristics : particle size and specific gravity.

Density current (gravity/turbidity current) sediment transport

Under specific hydraulic conditions as rivers flow into the ocean or a reservoir, the density difference between the river water due to sediment transport and clear water of the reservoir, creates conditions for the mode of sediment transport to change, from turbulent river conditions to a density current which dives to the bed and transports mainly fine sediment fractions < 10μm in diameter. Density currents have been observed to travel over distances of more than 100 km through a reservoir such as Lake Mead in the USA (see Sediment Data Acquisition).

6. Turbulent sediment transport

6.1. Vertical sediment concentration distribution

The vertical suspended sediment concentration distribution is generally found relatively uniform for small size sediments, while for larger sediment sizes the highest sediment transport is closer to the bed. The latter is known as so-called bed load transport. When sediment is also suspended higher above the bed, it is known as suspended sediment transport. This distinction between bed load and suspended load, is however unnecessary, since hydraulic theory can accurately describe the vertical distribution of sediment:

$$\frac{C}{C_a} = \left(\frac{D-y}{y} \cdot \frac{a}{D-a} \right)^z \qquad (1)$$

with D = flow depth
y = height above bed where sediment concentration is C
a = height above bed where sediment concentration is C_a
z = function of the shear velocity and settling velocity

Sediment transport equations have been developed to describe bed load, suspended load or total load by integration over depth and width of velocity and sediment concentration.

Wash load consist of fine particles in a river system, flushed through the system during floods, and often not considered to influence the sediment transport capacity or hydraulic characteristics. This is however a misconception since the fine sediments often changes the momentum exchange in the turbulent eddies at the bed, which increases the vertical velocity gradient and the mean velocity, compared to clear water flow. Furthermore the fine sediments react mathematically the same as coarse sediments, although at smaller settling velocities.

-
-
-

Bibliography

Ackers, P. and White, W.R. (1973). Sediment Transport : New Approach and Analysis. JHD, Proc. Am. Soc. Civ. Engrs., 99 (HY-11). [A comprehensive theoretical and practical analysis base on hydraulic principles]

Basson, G.R. and Rooseboom, A. (1997). Dealing with Reservoir Sedimentation. South African Water Research Commission, Report no. TT 91/97. [An analysis of the extent of the sediment problem in water storage reservoirs in South Africa, China and elsewhere, based on observations and first-hand experience, and discussion of methods of alleviating the rate of loss of storage]

Engelund, F. and Hansen, E. (1967). A Monograph on Sediment Transport in Alluvial Streams. Tehnish Forlag, Denmark. [An early attempt at quantifying sediment transport rates, with a fairly good predictability]

Lane, E.W. (1957). A study of the Shape of Channels Formed by Natural Streams Flowing in Erodible Material. Missouri River Div. Sediments Series No. 9, U.S. Army Engineer Div., Missouri River, Corps of Engineers, Omaha, Nebraska. [A landmark paper presenting the concept of stable channels in equilibrium, based on field observations and laboratory data]

Van Rijn, L.C. (1984). Sediment Transport, Parts I and II. J. Hydr. Engrg. 110 (10) and 110 (11). [A later development in formulating sediment transport with good predictability in the laboratory and under field conditions]

Yang, C.T. (1973). Incipient Motion and Sediment Transport. Proc. Am. Soc. Civ. Engrs., 99 (HY-10). [Presents a stream-power basis for sediment transport with a high predictability in the laboratory, but poor in the field]

Biographical Sketch

Gerrit Basson is Professor and Head of the Water Division at the Department of Civil Engineering of the University of Stellenbosch, Republic of South Africa. He obtained the degrees B.Eng. (cum laude) and B.Eng.(Hons.) Civil from the University of Pretoria, South Africa, and the degrees M.Eng. and Ph.D. from the University of Stellenbosch, South Africa. He is a registered Professional Engineer in South Africa, Member of the South African Institution of Civil Engineers (SAICE) and Member of the International Association of Hydraulic Engineering and Research (IAHR).

He has fifteen years' experience in consulting engineering, mainly in the fields of Hydraulic Engineering and Water Resources Planning. He is a specialist in the subjects of reservoir sedimentation and its control and the dredging of reservoirs, on which he has co-authored several publications. His other technical publications number about twenty. He is also active in research and data analysis on the hydraulic roughness of tunnels.

He serves on the SAICE Water Division Committee since 1999. He is the representative for the International Association of Hydrological Sciences (IAHS), on the International Commission on Continental Erosion (ICCE). He is a member of the South African National Committee of the IAHS (SANCIAHS) for 2000 to 2003.