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Sediment Source and Transport in River Channels: Implications for River Structures

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ABSTRACT
Rivers are important resources that play the role of life sustenance in nature by providing environmental, cultural and economic benefits including municipal water use, irrigation, hydropower, navigation, fishing and recreation. Since they are the corridors connecting terrestrial environment to the ocean realm, they always transport and accumulate sediments. Knowledge and understanding of sediment characteristics, channel processes, process of sediment source and transport in river channels is vital in modeling and managing rivers in terms of how they both transport and impact engineering structures erected on rivers. Although, ongoing research is beginning to fill in some of these gaps through the use of laboratory experiments and mathematical models, this has not been matched by sufficient progress in measuring and quantifying the bifurcation process in natural river channels, very often because natural rivers are far harder to study and the technology required still remains unavailable. When the rate of sediment influx is high along river channels, reservoirs in dams are filled up with sediment which might need dredging to remove the sediments. Also turbine blades of power plants are considerably disturbed as a result of sediment particles deposited on the blades; flow in culverts and around bridge piers are exposed to erosion of the bed thereby exposing the foundation. Problems arising from sediment transport and deposition can be mitigated by selecting suitable cross sections for the measurement of sediment flow rate parameters and removal of the sediment which would lead to the reduction of negative impacts on the river structures.

Key Words: *River Sediment, River Channel, Engineering structures, Reservoir Sedimentation, bridge piers.*

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I. Introduction

The ultimate source of sediments on lands and in the oceans is the continental realm, where weathering and erosion generate the sediment that is carried as bedload in suspension or as dissolved salts to environments of deposition (Gary, 2009). Thermal and tectonic processes in the earth's mantle and crust generate regions of uplift and subsidence, which respectively act as sources and sinks for sediment. Weathering and erosion processes acting on bedrocks exposed in uplifted regions are strongly controlled by climate and topography. In river bodies, sediments erode into regoliths and bedrocks as the turbulent flow scours at the floor and margins of the channel, until pieces fall off into the stream. (Anderson, 1990). Transported sediments may be carried away in the river flow as bedload in suspension, or in solution.

Sediment transport is important in the fields of sedimentary geology, geomorphology, civil engineering and environmental engineering. It is the movement of solid particles, typically due to a combination of gravity acting on the sediment, and/or the movement of the fluid in which the sediment is entrained (Wiberg et al., 1989). Knowledge of sediment transport is most often used to determine whether erosion or deposition will occur, the magnitude of this erosion or deposition, and the time and distance over which it will occur (Huber, 2004).

II. Mechanism of Sediment Transport and Deposition in River

2.1 Sources and Movement of Sediments in River Channels

Movement of sediment particles may be purely due to gravity but more commonly it is the result of flow in water, air ice or dense mixture of sediments and water (Gary, 2009). Sediment transport occurs in natural systems where the particles are clastic rocks (sand, gravel, boulders, etc.), mud or clay. Sediment transport due to fluid motion occurs in rivers, oceans, lakes, seas, and other bodies of water due to currents and tides (Walker et al., 2009). It is also caused by glaciers as they flow, on terrestrial surfaces under the influence of wind. Sediment transport due to gravity can occur on sloping surfaces, including hillslopes, scarps, cliffs, and the continental shelf to continental slope boundary.

In water bodies like river, ocean and sea, fluvial processes which relate to flowing water in natural systems are the most prevalent (Ferguson et al., 2006). Sediment moved by water can be larger than that moved by air because water has both a higher density and viscosity (Allen, 1997). In typical rivers the largest carried sediment is of sand and gravel size, but larger floods can carry cobbles and even boulders. Fluvial sediment transport can result in the formation of ripples and dunes, in fractal-shaped patterns of erosion, in complex patterns of natural river systems, and in the development of floodplains (Milliman et al., 1984).

Sediment is transported by the flow in one of three principal modes: as bedload transport, suspended-load transport or as dissolved-load transport (Martin et al., 1979). Bedload transport refers to the particles or grains of sediment moved along the bed of a river which is at all times wholly supported by the bed itself. In other words, bedload are sediment material which moves by sliding and rolling, largely as a result of the shear stress exerted on the boundary by the flowing water. As you might expect, bedload consists largely of the coarser fraction, the sand and gravel, of the sediment available to the river.

Suspended-sediment transport refers to the particles or grains of sediment moved along a river within and wholly supported by the flow (Goudie et al., 2001) In order for sediment grains to remain in suspension the upward-directed forces associated with turbulence in the flow must be strong enough to overcome the downward force of gravity acting on the grains (Kecureck et al., 2005) An additional mode of transport, transitional between that moved as bedload and that forming the suspended load is called the saltation load. In most rivers the bulk of transported sediment, often 90 per cent or more, moves as suspended-sediment load.

Dissolved load transport involves that component of the total load carried in solution. From a geomorphic perspective it is generally unimportant because it exerts little if any control over the form and pattern of the channel. Nevertheless, the total mass of material moved by rivers in this way can be a major component of the sediment budget of a drainage basin. It can be particularly significant in basins formed in highly soluble rocks such as limestones and marls. Generally, for sediment to flow in river channels, certain variables must be in place (Nestmann, 1999) as shown in table 1.

Table 1. Variables for sediment flow (Nestmann, 1999).

Flow Variables	Water discharge, Sediment Discharge, Mean Velocity, Average Depth, Water Surface slope.
Sediment Variables	Mean Diameter, Difference in Spec. weight of sediment and water.
Fluid Variables	Mass Density, Dynamic Viscosity
Channel Geometry	Average Width

2.2 Characteristics of fluids and sediments in fluid

For fluid to move sediment that is currently at rest on a surface, the boundary shear stress exerted by the fluid must exceed the critical shear stress for the initiation of motion of grains at the bed (Walker et al., 2009). Fluid flowing exhibits two types of flow viz: **laminar flow** and **turbulent flow**. In laminar flow, all molecules within the fluid move parallel to each other in the direction of transport while in turbulent flow, molecules in the fluid move in all directions but with a net movement in the transport direction (fig. 1).

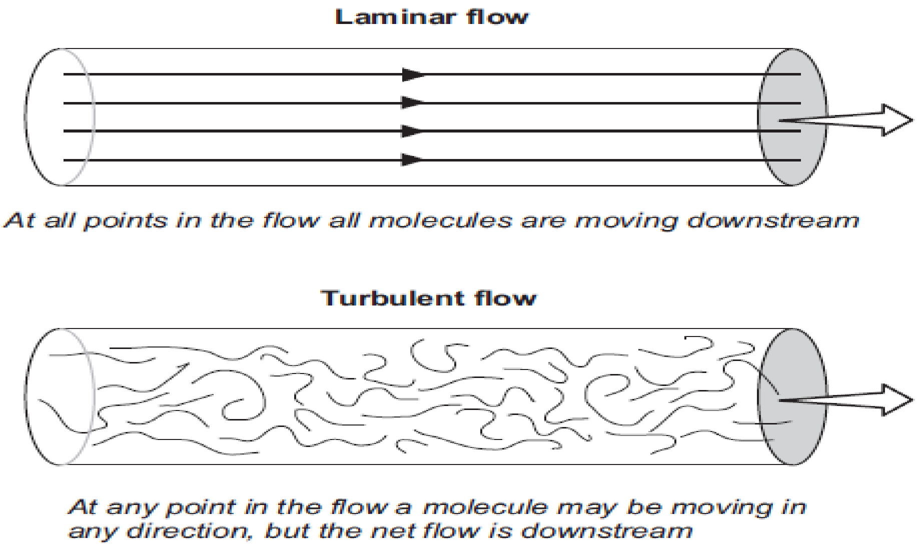

Fig. 1 Laminar and Turbulent flow of fluid through a tube.

However, a dimensionless quantity/parameter known as **Reynolds number** is required for the initiation of motion as a function of a particular form of the particle. It is a quantity that indicates the extent to which a flow is laminar or turbulent. Reynolds number is represented thus:

$$Re = V.L/V^* \qquad (1)$$

Where V is the velocity of flow, V* is fluid kinematic viscosity and L is the diameter of a pipe or depth of flow in an open channel. Fluid flow in pipes and channels is said to be laminar when the Reynolds value is low (< 500) and turbulent at higher values (> 2000). Laminar flow occurs in debris flows, in moving ice and in lava flows, all of which have high kinematics viscosity (Leeder, 1999). Fluids with low kinematics viscosity, such as air, are turbulent at low velocities, so all natural flows in air that can transport particles are turbulent. Water flows are only laminar at very low velocities or very shallow water depths, so turbulent flows are much more common in aqueous sediment transport and deposition processes. Most flows in water and air that are likely to carry significant volumes of sediment are turbulent (Pye, 1994).

The sediments entrained in a flow can be transported along the bed as bed load in the form of sliding and rolling grains, or in suspension as suspended load by the main flow. Some sediment materials may also come from the upstream reaches and be carried downstream in the form of wash load. However, for sediment to move upwards from the base of the flow, a force known as **Bernoulli Effect** is required to drive the sediment (Fig 2). This is the phenomenon that allows bird and aircraft to fly and yachts to sail. This effect is similar to that of squeezed and constricted end of a garden hose; the water comes out as a faster jet when the end of the base is partly closed off. This effect is presented in form of an equation as

$$\text{Total energy} = pgh + pv^2/2 + P \qquad (2)$$

Where *p* is the density of the fluid, v is the velocity, g is the acceleration due to gravity, h is the height difference and p is the pressure. Equation 2 assumes no loss of energy due to frictional effects, so in reality the relationship is

$$\text{Total energy} = pgh + pv^2/2 + p + E_{loss} \qquad (3)$$

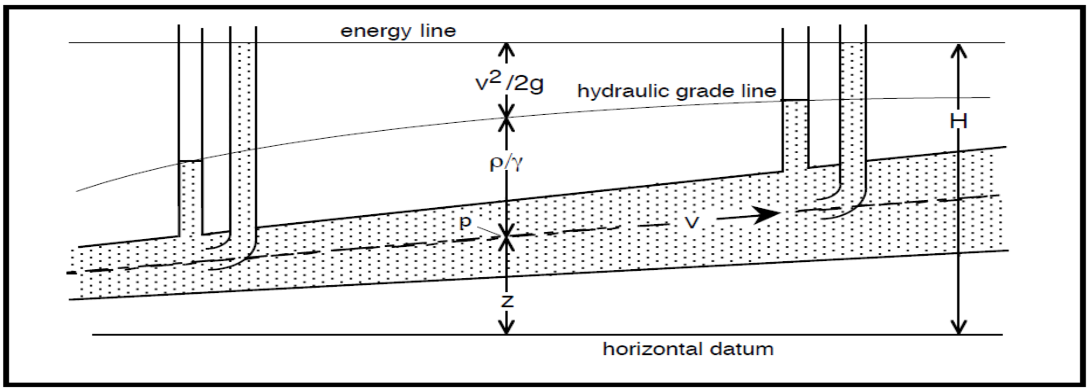

Fig. 2. Definition diagram for the Bernoulli energy equation terms as they apply to flow through a pipe (Henderson, 1966)

The fluid velocity at which a particle becomes entrained in the flow can be refered to as the **critical velocity**. If the forces acting on a particle in a flow are considered then a simple relationship between the critical velocity and the mass of the particle would be expected. If this principle is applied to flow along a channel, a clast in the bottom of the channel will reduce the cross section of the flow over it. This reduction provides temporary **lift force** that moves the clast of the bottom of the flow. A simple linear relationship between the flow velocity, the drag and the lift forces can be applied to sand, gravel and fine grain sizes. This relationship is illustrated in **Hjulstrom's diagram** (fig 3). It demonstrates some important features of sediment movement in currents. The lower line on the graph displays the relationship between flow velocity and particles that are already in motion. This shows that a pebble will come to rest at around 20 to 30 cms-1, a medium sand grain at 2 to 3 cm-1 and a clay particle when the flow velocity is effectively zero.

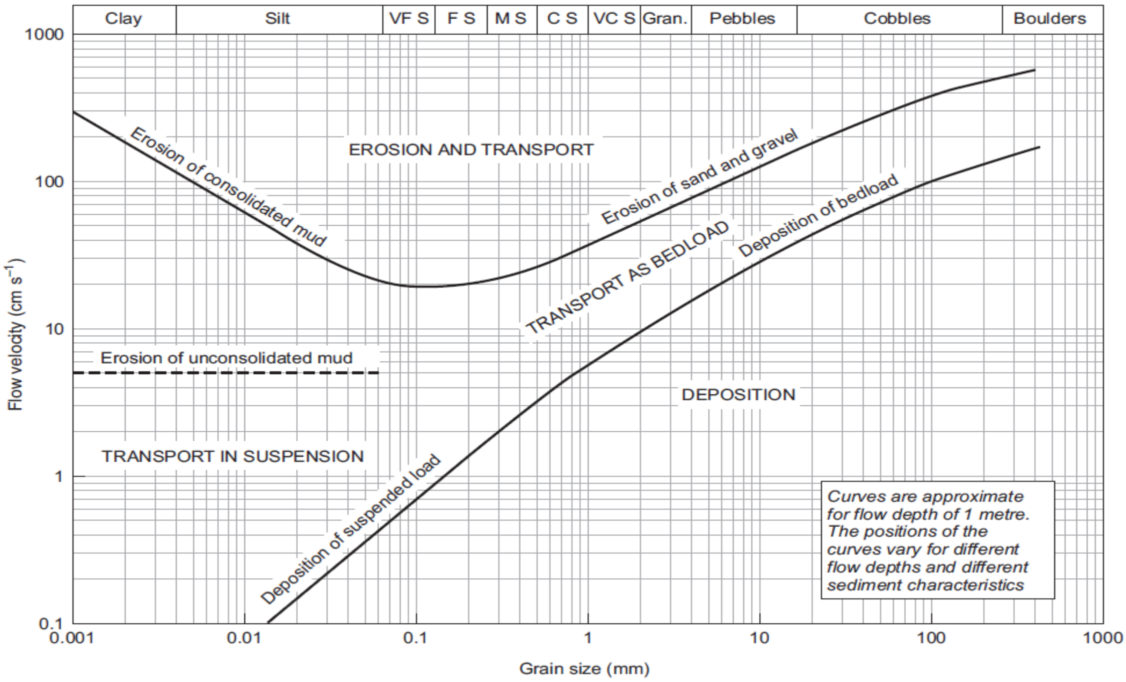

Fig 3. Hjulstroms Diagram showing the relationship between the velocity of a water flow and the transport of loose grains (Gary, 2009).

2.3 Modes of entrainment of sediments

The sediments entrained in a flow can be transported along the bed as bed load in the form of sliding and rolling grains, or in suspension as suspended load advected by the main flow. Some sediment materials may also come from the upstream reaches and be carried downstream in the form of wash load. The location in the flow in which a particle is entrained is determined by the Rouse number.

$$P = \frac{w_s}{\kappa u_*} \qquad (4)$$

Here, the Rouse number is given by *P*. The term w_s in the numerator is the sediment settling velocity. The upwards velocity on the grain is given as a product of the von Kármán constant, $\kappa = 0.4$, and the shear velocity, u_*.

Table 2 below gives the approximate required Rouse numbers for transport as bed load, suspended load, and wash load.

Mode of Transport	**Rouse Number**
Initiation of motion	>7.5
Bed load	>2.5, <7.5
Suspended load: 50% Suspended	>1.2, <2.5
Suspended load: 100% Suspended	>0.8, <1.2
Wash load	<0.8

The settling velocity (also called the "fall velocity" or "terminal velocity") is a function of the particle Reynolds number. Generally, for small particles (laminar approximation), it can be calculated with Stokes' Law. For larger particles (turbulent particle Reynolds numbers), fall velocity is calculated with the turbulent drag law. Dietrich (1982) compiled a large amount of published data to which he empirically fit settling velocity curves. Ferguson and Church (2006) analytically combined the expressions for Stokes flow and a turbulent drag law into a single equation that works for all sizes of sediment, and successfully tested it against the data of Dietrich. Their equation is

$$w_s = \frac{RgD^2}{C_1\nu + (0.75C_2RgD^3)^{(0.5)}} \quad (5)$$

In equation 5, w_s is the sediment settling velocity, g is acceleration due to gravity, and D is mean sediment diameter. V is the kinematic viscosity of water, which is approximately 1.0 x 10^{-6} m^2/s for water at 20 °C.

C_1 and C_2 are constants related to the shape and smoothness of the grains.

Constant	Smooth Spheres	Natural Grains: Sieve Diameters	Natural Grains: Nominal Diameters	Limit for Ultra-Angular Grains
C_1	18	18	20	24
C_2	0.4	1.0	1.1	1.2

III. Impacts of Sediment Transport on River structures

Sediment transport is relevant in sedimentary geology and solution of problems related to environmental, geotechnical, and geological problems (Garde et al., 1977). Measuring or quantifying sediment transport or erosion is therefore important for coastal engineering. Several sediment erosion devices have been designed in order to quantify sediment erosion (e.g., Particle Erosion Simulator (PES)). One such device, also referred to as the BEAST (Benthic Environmental Assessment Sediment Tool) has been calibrated in order to quantify rates of sediment erosion (Grant et al., 2013). Geologists can use inverse solutions of transport relationships to understand flow depth, velocity, and direction, from sedimentary rocks and young deposits of alluvial materials (Nestmann, 1999).

3.1 Reservoir Sedimentation in Dams

Sediment discharge into a reservoir formed by a dam forms a reservoir delta (Basson et al., 2008). This delta will fill the basin, and eventually, either the reservoir will need to be dredged or the dam will need to be removed (fig. 4). Knowledge of sediment transport can be used to properly plan to extend the life of a dam (Ashton et al., 2001). Generation of hydroelectric power commonly necessitate construction of dams across rivers. The entire bed load and a part of the suspended sediment load are usually deposited in the reservoir. This reduces with time the usable water storage. A secondary effect of reservoir silting is an increase in the spread area for a given storage volume and may apply to a larger loss due to evaporation (Saniya et al., 2006). The rate of silting of the reservoir will depend on the amount of sediment load coming into the reservoir and the amount of the sediment load being transported with spilled water through sluices (Sweet et al., 2003). Problems related to silting of reservoirs that need consideration and research are trap efficiency of the reservoir and its relation to the characteristics of the pond, the distribution of the deposition in the reservoir and passage of density current through sluices (Cheng, 2002). To permanently preserve the storage capacity, the pool is lowered as much sediment is let out of the reservoir as possible during the flood season, but the reservoir filled afterwards in the dry season when the flow contains much less sediment.

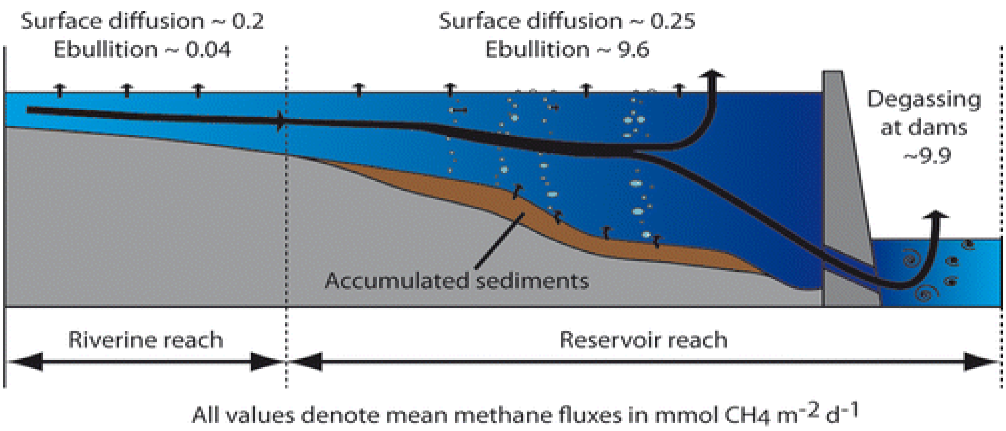

Fig. 4. Sedimentation in dam (Environmental science technology, 2013)

IV. Case History of Impacts of sediment transport and deposition on river structures

4.1 Dams

Many of the world's rivers provide evidence of reduced sediment loads resulting from dam construction (Nestmann, 1999). For example, the River Nile has been widely cited as a river where the pre-dam sediment load discharged into the Mediterranean Sea of circa 100 Mt per year has been effectively reduced to zero by the construction of the Aswan dam. The magnitude of the reduction in the sediment load of a river caused by the construction of a dam will depend on a number of factors including the location of the dam within the river basin, the trap efficiency of the associated reservoir, and the proportion of the flow withdrawn for use and the nature of that use (Dey, 1999). In general, the greatest reductions in sediment loads occur where the annual runoff passing through the river system is also reduced because of water abstraction for irrigation and other uses. In dams constructed along river channels for the purpose of hydroelectric generation (power plant), the sediment-laden water flows through the power plants vanes and turbine blades. This causes considerable disturbance in the flow, thereby reducing the efficiency and damage to the turbines. One way to solve this problem would be to increase the size of the reservoir above the power plant, which would at the same time increase the energy output (Chen et al., 2006). Case history is in the Kraka River in Northern Iceland which has created problems in the operation of the turbines in the power plant as a result of sediment transport.

4.2 Culverts and bridge piers

Flow in culverts, over dams, and around bridge piers can cause erosion of the bed (Parker et al., 1982). This erosion can damage the environment and expose or unsettle the foundations of the structure. Therefore, good knowledge of the mechanics of sediment transport in any environment is important for civil and hydraulic engineers. Scour around the foundations of bridge piers is one of the major causes of serious damage to bridges (Tsujimoto et al., 1987). Local scour at a bridge pier principally results from the down flow along the upstream face of the pier and the resulting horseshoe vortex which forms at the base of the pier aids the phenomenon (Kumar et al., 1999) (fig 5). Most of the scour investigators mainly focused on the scour around piers with uniform horizontal cross-section geometry and did not consider the effects of foundation geometry. The foundations of bridge pier usually are used for transferring the loads on bridge to safe place like earth.

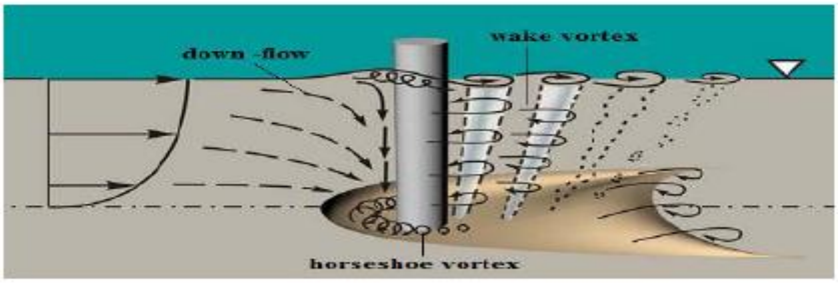

Fig. 5 Flow and scour pattern at a circular bridge pier (Parvin, 2013)

4.3 Solution to sediment transport problems

4.3.1 Measurement of relevant parameters

Measurement of hydraulic and morphodynamic impacts are often needed to determine and predict future developments (Nikora et al., 2001). This include surveys of the river bottom, the form and composition of the riverbed, changes in the discharge pattern and transport rate for bed load material.

The first step in the methodology of controlling sediment transport is the selection of suitable cross sections for the measurements that are representative for the river according to certain criteria, like condition of the bed surface, changes in the river gradient, dredging operation etc

Problems arising from sediment transport and deposition can be mitigated by stopping upstream erosion. But stopping erosion completely is not always possible, or economically feasible in solving specific downstream problems (Leo, 1993). However, the solution of one problem in this manner may lead to the creation of other problems such as erosion down river. To reduce the sediment transport upstream, methods such as trapping sediment in a sedimentation pond, allowance for storage of sediment in structure design, sediment bypassing and other methods can be used separately or in combination (Bailard, 1981).

4.3.2Point Diversion

Construction of diversion canal has been recognized as a way to eliminate sediment from the main water stream. Proper selection of the point where the water is to be diverted from a river course is essential for its efficiency in reducing sediment transport (Miller et al., 1977). The flow is diverted into two main streamflows. Flow into the side of the vane and flow into the river stream. Between these flows builds up a secondary current. The current sweeps the bottom load towards the inside of the curve.

4.3.3 Settling Pezo

By using vanes and a settling pond together, the downstream sediment transport in the can be greatly reduced without causing great erosion from the vanes (fig 6). A settling pond is one of the most effective devices for removing sediment paticles as fine as 0.07mm from flowing water. The reduction of flow velocity in the settling pond is caused by an expansion of the channel cross section over the length of the pond. Such reduction in velocity also reduces the bed shear and the turbulence. The bed material settles in the pond from which it can be removed by mechanical means.

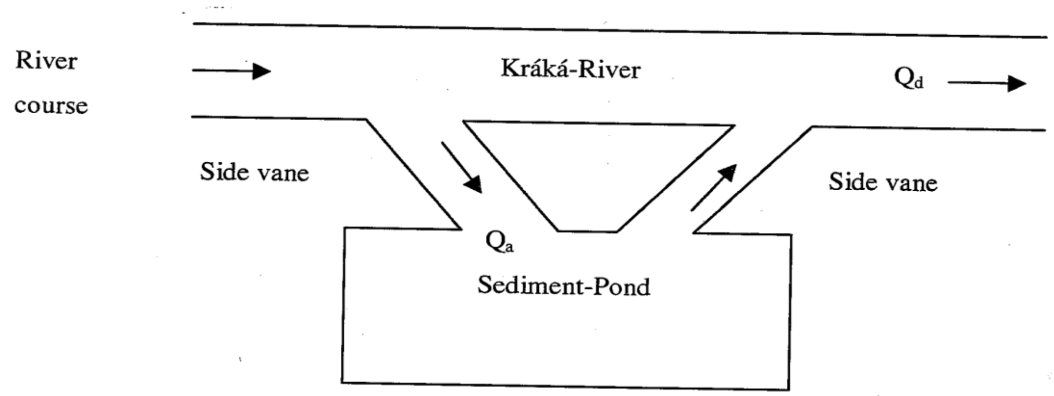

Fig 6 Skech of a Vane and Settling Pond

4.3.4 Use of vegetative cover

The movement of soil may be caused by high wind velocity. Vegetative measures are effective in reducing this this kind of erosion by improving the protective cover on the exposed soil surface to eroding forces and by increasing infiltration rates (Nestmann, 1999). Land treatment such as grass and meal seeds prevents the erosion of the soil. Meal seeds are especially suitable because they gather up sand and prevent it from further erosion. Such practices increase the infiltration capacity of the soil and retard the water flow. This takes hower some time before any progress can be seen.

V. Conclusion

The general understanding of sediment transport in river channels is of great importance in construction of engineering structures like dams, power plants, bridge piers, culverts, bridges etc. The life span of these structures depends on the amount of sediment carried by the river as the water flow. High sediment influx into the river affects the efficiency of dam, turbine blades, foundation of culverts and bridge piers. As a result of this, concerted efforts are required to understand the mechanics of movement of sediment in running water. Channel structures such as side vanes, reservoir and land treatment complement each other to prevent damage to engineering structures. These structures are designed to divert sediment in designated compactment. Also trapping of sediment in a settling pond with side vanes have been recommended as a good solution to decrease the sediment transport in river. Also vegetation of the land is another solution to soil erosion which will decrease sand erosion by wind that deposit sediment into the river.

References

[1] Allen, P.A. (1997) Earth Surface Processes. Blackwell Science, Oxford, 404 pp.
[2] Ashton, Andrew; Murray, A. Brad; Arnault, Olivier (2001). "Formation of coastline features by large-scale instabilities induced by high-angle waves". Nature 414 (6861): 296–300.
[3] Anderson, R (1990). "Eolian ripples as examples of self-organization in geomorphological systems". Earth-Science Reviews 29: 77.
[4] Bailard, James A. (1981). "An Energetics Total Load Sediment Transport Model For a Plane Sloping Beach". Journal of Geophysical Research 86: 10938.
[5] Basson, G. 2008. Reservoir sedimentation – an overview of global sedimentation rates, sediment yield and sediment deposition prediction. The International Workshop on Erosion, Transport and Deposition of Sediments. University of Bern,UNESCO ISI.
[6] Chen, X., Zhou, O. and Zhang, E. (2006). In-channel sand extraction from the mid- lower Yangtze channels and its management: Problems and challenges.
[7] Journal of Environmental Planning and Management, Vol. 49. Oxford, UK, Routledge, pp. 309–20.
[8] Cheng, Nian-Sheng (2002). "Exponential Formula for Bedload Transport". Journal of Hydraulic Engineering 128 (10): 942.
[9] Dey S. (1999) Sediment threshold. Applied Mathematical Modelling, Elsevier, Vol. 23, No. 5, 399-417.
[10] Dietrich, W. E. (1982). "Settling Velocity of Natural Particles" (PDF). Water Resources Research 18 (6): 1615–1626.
[11] Fanz. N (1999). Sediment Transport in River Kraka. Institute of hydraulic structures and Agricultural Engineering, University of Karlsruhe Vol 30
[12] Ferguson, R. I., and M. Church (2006), A Simple Universal Equation for Grain Settling Velocity, Journal of Sedimentary Research, 74(6) 933-937.

[13] Garde R.J, Ranga R.K.G (1977) . Mechanics of sediment transportation and alluvial stream problems. University of Roorkee, India.

[14] Grant, J., Walker, T.R., Hill P.S., Lintern, D.G. (2013) BEAST-A portable device for quantification of erosion in intact sediment cores. Methods in Oceanography. DOI: 10.1016

[15] Goudie, A; Middleton, N.J. (2001). "Saharan dust storms: nature and consequences". Earth-Science Reviews 56: 179

[16] Gomez, B., and Church, M., 1989, An assessment of bed load sediment transport: formulae for gravel bed rivers: Water Resources Research, v. 25, p. 1161- 1186.

[17] Henderson, F.M., 1966, Open Channel Flow, Macmillan, New York Hubert. C (2004). The Hydraulics of Open Channel Flow: An Introduction.

[18] Butterworth-Heinemann, 2nd edition, Oxford, UK, 630 pages.

[19] Kocurek, Gary; Ewing, Ryan C. (2005). "Aeolian dune field self-organization – implications for the formation of simple versus complex dune-field patterns". Geomorphology 72: 94.

[20] Kuhnle, R. A.; Wren, D. G.; Langendoen, E. J.; Rigby, J. R. (2013). "Sand Transport over an Immobile Gravel Substrate". Journal of Hydraulic Engineering 139 (2)

[21] Kumar V., Ranga Raju K.G. and Vittal N. (1999). Reduction of local scour around bridge piers using slots and collars. Journal of Hydraulic Engineering, ASCE, 125(12): 1302-1305

[22] Leeder, M.R. (1999) Sedimentology and Sedimentary Basins: from Turbulence to Tectonics. Blackwell Science, Oxford.

[23] Leo C. Van Rijn, (1993). Principle of sediment transport in rivers, estuaries and coastal seas, Holland. Vol 3

[24] Martin, J-M and Meybeck, M. 1979. Elemental mass balance of material carried by major world rivers. Marine Chemistry, Vol. 7. Amsterdam, Elsevier, pp.173–206.

[25] Miller, M.C.; McCave, I.N.; Komar, P.D. (1977). "Threshold of sediment motion under unidirectional currents.". Sedimentology 24 (4): 507–527.

[26] Milliman, J. D., Quraishee, G.S. and Beg, M.A.A. 1984. Sediment discharge from the Indus River to the Ocean: Past, present and future. In B.U. Haq and J.D.

[27] Milliman (eds), Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan. New York, Van Nostrand Rheinhold, pp. 65–70

[28] Nakato, T., 1990, Tests of selected sediment-transport formulas: Journal of Hydraulic Engineering, v. 116, p. 362-379.

[29] Nestmann F.H.C, (1999). Sediment transport in Rivers, with example from Kraka River North Iceland. Institute of hydraulic structures and Agricultural Engineering, University of Karlsruhe. Vol 30. pp. 1-20.

[30] Nikora, V; Goring, D; McEwan, I; Griffiths, G (2001). "Spatially averaged open- channel flow over rough bed". J. Hydraul. Eng. 127 (2).

[31] Parvin E, AmirAhmad. D, Hadi A, Maryam. M. (2013). The Effect of Geometric Parameters and Foundation Depth on Scour Pattern around Bridge Pier.

[32] Journal of Civil Engineering and Urbanism. Volume 3, Issue 4: 156-163 Parker, G, Klingeman P.C Mclean, D.G. (1982). Bedload and size distribution in paved Gravel-Bed streams. Journal of the Hydraulics Division (ASCE) 108 (4): 544-571

[33] Pye. K. (Ed) (1994) Sediment Transport and Depositional Processes. Blackwell scientific publications, Oxford.

[34] Roering, J, Kirchner, James W.; Dietrich, William E. (1999). "Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology". Water Resources Research 35 (3): 853

[35] Saniya Sharmeen and Garry R. Willgoose1, (2006) The interaction between armouring and particle weathering for eroding landscapes, Earth surface Processes and Landforms 31, 1195–1210 Sweet, R.J., Nicholas, A.P., Walling, D.E. and Fang, X. (2003).Morphological controls on medium-term sedimentation rates on British lowland river floodplains. Hydrobiologia Vol. 494. Dordrecht, Netherlands, Springer, pp. 177–183.

[36] Tsujimoto T., Murakami S., Fukushima T, and Shibata R. (1987). Local scour around bridge piers and its protection works. Mem. Fac. Technol. Kanazawa Univ., Japan, Kanazawa, 20(1) : 11-21.

[37] Wiberg, Patricia L.; Dungan Smith, J. (1989). "Model for Calculating Bed Load Transport of Sediment". Journal of Hydraulic Engineering 115: 101.

[38] Walker, T.R., Grant, J. (2009) Quantifying erosion rates and stability of bottom sediments at mussel aquaculture sites in Prince Edward Island, Canada. Journal of Marine Systems. 75: 46-55