APPRAISAL OF SEDIMENT TRANSPORT EQUATIONS

By

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This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

as partial fulfillment of the requirements for the degree of

BACHELOR OF ENGINEERING (CIVIL ENGINEERING)

School of Civil Engineering
Universiti Sains Malaysia

April 2006

ACKNOWLEDGEMENTS

I want to give my gratitude to my final year project supervisor Dr. Aminuddin bin Abdul Ghani. Without his help, it is impossible for me to finish this thesis. Besides that, he had shown me the way to the completion of my project with a lot of guidance and help. I also want to give my gratitude to my final year project fasilator, Mr. Chang Chun Kiat for his help in completion of my project with help in clearing all my doubt that I encounter during this work. I also want to thank all REDAC staff who helped me during the period of my project.

Further, I want to show my special thank to my fellow course mates who have assisted me in field data collection with me. They are Chew Teck Yeow, Nicholas Lim and Noorazlan Bin Amat Sihab. With their help, I was able to complete my project. Besides all above, I also want to give my gratitude to Assoc. Prof. Dr. Mohamad Sanusi S. Ahamad, Assoc. Prof. Dr. Meor Othman Hamzah and Assoc. Prof. Dr. Ir. Mohamad Razip Selamat for giving briefing me on the final year project so i can make my project more complete.

Finally, I would like to say that without support, guidance and cooperation from all peoples, this study would be impossible to be complete in time. Everything needs cooperation from many sides and it is hard to complete anything without help from other peoples. So i want to thank you all.

ABSTRACT

For history, we know that river is a foundation in building and expanding a civilization. River is not just a source for water, food and transportation but also contributing many other advantages to human activities such as agricultural, industrial, electricity power and other. However, it also can cause massive destruction during floods. This happens when equilibrium becomes unstable with human activities. So, human should think of ways and means to save the river from pollution, erosion and sedimentation. In order to control and prevent erosion and sedimentation, studies should be carried out on sediment transport in rivers. By these ways of control and prevention, flood disasters will be under control and should not occur in the future. Therefore, this study is carried out on Kulim River in Kedah. This study also involves in collecting raw data which concerns about erosion and sedimentation like bed load, suspended load and bed material. Measurements carried out include the geometry data of depth, river cross section, slope, sediment size, viscosity and water discharge are collected too. These data are used for further calculation and evaluvation with bed load transport equations and total bed material load transport equations. The results show that Eugelund – Hansen and Graf equation are able to predict satisfactorily the measured load.

ABSTRAK

Jika lihat daripada sudut sejarah, kita dapat mengetahui sungai merupakan salah lokasi pertapakan dan permulaan sesebuah tamadun. Sungai bukan merupakan sumber air minuman, makanan dan pengangkutan bagi manusia tetapi ia juga memberi manusia banyak manfaat kepada kegiatan manusia seperti pertanian, perindustrian, penjanaan kuasa hidroelektik dan sebagainya. Walaubagaimana pun, sungai juga memberi kesan buruk kepada kehidupan manusia semasa berlakunya banjir. Kejadian bencana alam ini berlaku apabila kestabilan sungai terganggu disebabkan oleh kegiatan – kegiatan kemanusiaan. Oleh itu, manusia mesti memikirkan cara dan kaedah untuk menyelamatkan sungai daripada pencemaran, hakisan dan pengendapan sungai. Untuk mengawal dan menghalang hakisan dan pengendapan sungai, kajian – kajian seharusnya dijalankan ke atas pengangkutan endapan sungai. Dengan cara pengawalan dan pencegahan, kejadian banjir akan berada dalam kawalan dan sepatutnya tidak akan berlaku lagi pada masa hadapan. Tempat kajian ini Sungai kulim yang berlokasi di Kedah Darul Aman. Kajian ini juga mempunyai kegiatan pencerapan data lapangan yang berkaitan tentang hakisan dan pengendapan seperti beban dasar, beban terampai dan bahan dasar. Dengan beberapa pengukuran yang diperolehi daripada sungai seperti kedalaman sungai, keratan rentas sungai, kelerengan sungai, saiz endapan, kelikatan air sungai dan kadaralir sungai. Data – data tersebut akan digunakan dalam pengiraan persamaan pengangkutan beban dasar dan persamaan pengangkutan jumlah beban bahan dasar. Keputusan menunjukkan persamaan Eugelund – Hansen dan Graf dapat meramalkan dengan baik jumlahan beban endapan yang dicerap.

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CHAPTER 1

INTRODUCTION

1.0 Introduction

Stable, equilibrium river channels erode and move in the landscape, but have the ability, over time and in an unchanging climate, to transport the flow, sediment, and debris of their watersheds in such a manner that they generally maintain their dimension (width and depth), pattern (meander length), and profile (slope) without aggrading (building up) or degrading (scouring down) (Rosgen, 1996; Leopold et. al, 1964). Stable, equilibrium rivers are considered a reasonable and sustainable management objective in consideration of the repeated and catastrophic flood damages experienced in Vermont. Many rivers are in major vertical adjustment due to human imposed changes in the condition of their bed and banks, slope and meander pattern, and/or watershed inputs (see Lane's Balance in Figure 1.1).

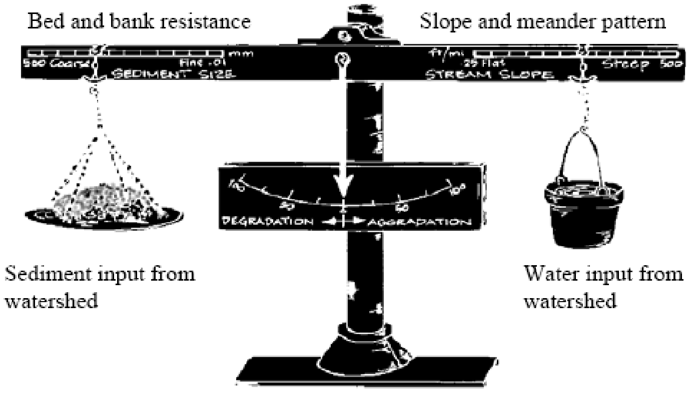

Figure 1.1 : Stable Channel Equilibrium (Lane, 1955)

1.1 Problem Statement

Alluvial rivers and reservoirs frequently adjust their geometry and conveyance patterns through natural processes of sediment transport. If left uncontrolled, however, excessive scour of a streambed will induce major shifts in boundary geometry and can threaten stability of in-stream structures, such as bridges or underground utilities. Likewise, continued deposition of bed sediment will cause reduced storage capacities in stream channels and in conservation and flood control reservoirs. This decline in storage eventually eliminates the intended capacity for flow regulation and water supply, and reduces the hydroelectric power generation, navigation and recreation benefits that are dependent on reservoir storage.

Ever since man started tilling the soil, cutting trees for building material, building roads, and performing the many other activities of our modern civilization, the rate of soil erosion had being increased and grossly affected the physical and biological character of fresh and estuarine aquatic habitats. The increase in sediment transport from the land to the rivers and streams is not always obvious to the casual observer peaks of soil movement occur during storm events of wind and water. The fluvial process of sediment transport moves soil and rock particles at different rates for different sizes, gradient of streams, and volume of flow. When the sediment-carrying capacity of a stream is exceeded, deposition takes place in the lower-velocity reaches and aquatic habitat is frequently altered or destroyed for the indigenous species.

1.2 Objective

Objective of this study are mainly for research, which is described such as follows:

1. Data collection at Kulim River, Kedah.
2. Analysis data using sediment transport equation.
3. Determination what sediment transport equation is suitable for sediment transport prediction.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Sediment is defined as fragmented material formed by physical and chemical weathering of rocks. Sediment transport study includes movement of huge boulders down mountain sides, to diffusion of colloid-sized material in groundwater systems. Transport is driven by gravity, and drag forces between the sediment and surrounding fluid (air or water). Transport of sediment is usually divided into three types: bedload, saltation, and suspension. (Harris, 2003)

2.1 River Morphology

River morphology is the shape or form of a river along its length and across its width. Rivers flow in *channels*, the area within the banks of the river show in the figure below.

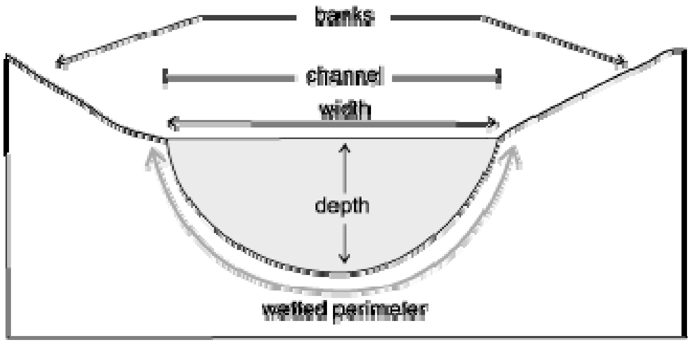

Figure 2.1 : Cross section of a river channel.

A river floods when it carries more water than the channel can accommodate (referred to as the bankfull discharge), and the river spills over its banks onto the floodplain. The *wetted perimeter* of a stream is the surface of the bed and banks covered by water and is the zone where erosion and deposition can occur. The *floodplain* is the relatively flat-lying part of the valley next to the channel. The greater the flood discharge, the larger the area of the floodplain that is inundated. A commonly used concept for floodplain planning and zoning is the *100-year floodplain.* This is the area that would be inundated by the largest flood that hydrologists estimate has a 1 in 100 probability of occurring in any given year. This is based on previous years' flow records. A common misconception is that the 100-year flood will happen once every 100 years; however, such a flood has a 1 in 100 chance of happening this year or any other year. It could occur in two consecutive years.

Sediment is important to determining the morphology of river systems (Figure 2.2). Rivers naturally evolve and change their shapes by eroding, transporting, and depositing sediment. The movement of sediment in rivers and their valleys determines the course of the river, the shape of the channel bottom, the locations of pools and riffles (light rapids) along the river, and the materials that make up the bed of the river. These factors influence the types of wildlife habitat available in the river system. One of the most important functions of rivers from a biological standpoint is sediment and nutrient (carbon) transport in a watershed. Another important functions of a river is to erode and carry sediment. Rivers carry sediment, but also natural debris, most commonly branches and logs from fallen trees. The total amount of sediment that a river is capable of carrying is the capacity of the river, which depends on the speed and volume of the flow of the river. The greater this volume and speed, the more sediment the river can carry. The more sediment a river carries, the higher the erosive force of the river. Rivers move a lot of sediment during floods when a river's flow is powerful and thus capable of moving very large objects, including boulders. Rivers alter their channels within the floodplain by scouring sediment from the bed and banks and transporting it downstream. The sediment removed from any one stretch of the river is replenished by sediment from upstream (Figure 2.3).

Major factors that affect the speed of the flow of a river include the river's channel shape, slope, and the roughness of the riverbed. The *slope* of the river's surface is its gradient, usually expressed as the drop in feet per mile along the river. Generally, the steeper the gradient of the river, the faster the flow. The thalweg is the part of the stream channel with the fastest flow. The natural stream channel will assume a geomorphological form which will be compatible with the sediment load and discharge history which it has experienced over time.

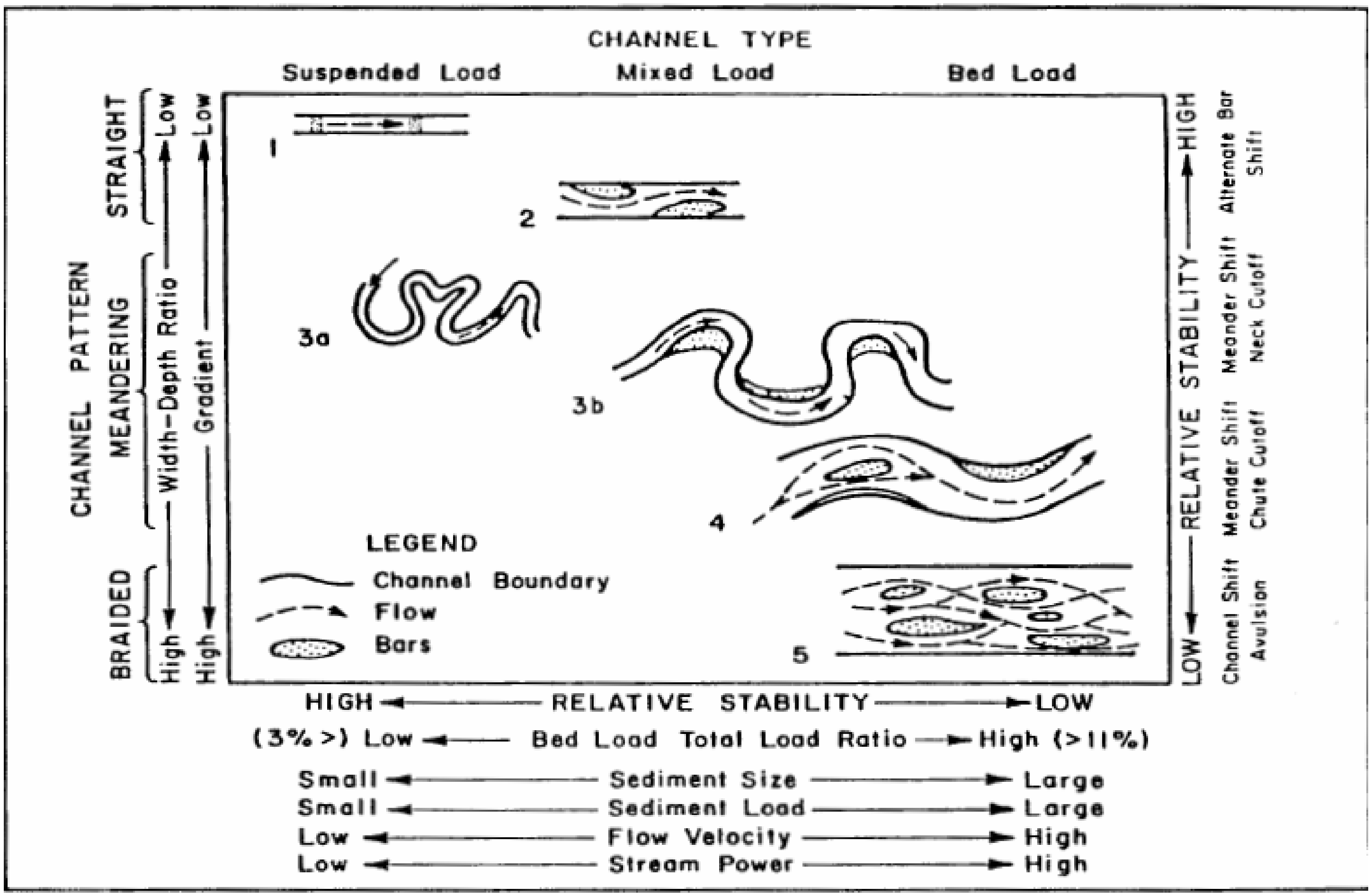

Figure 2.2 : Channel Classification And Relative Stability As Hydraulic Factors Are Varied

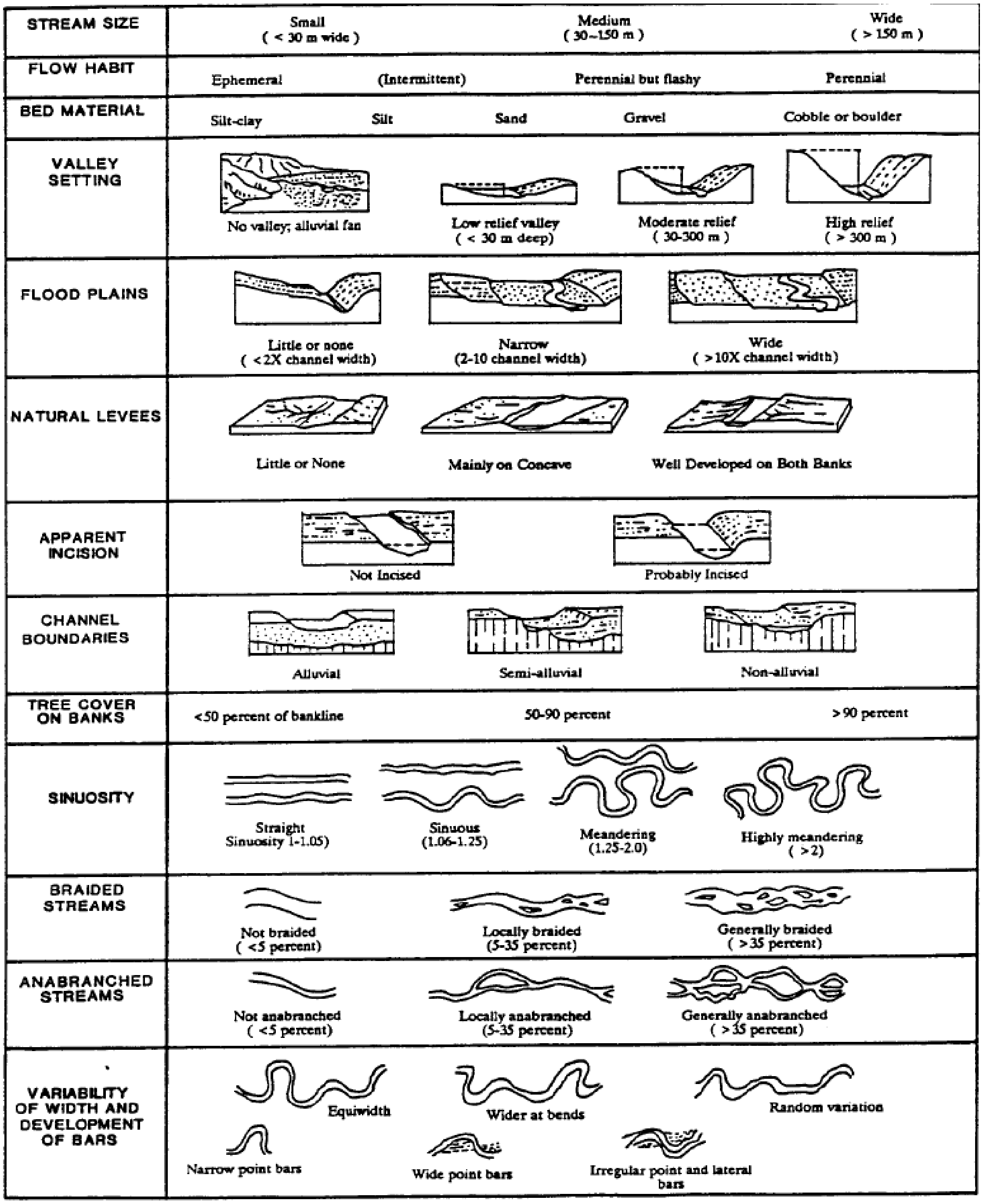

Figure 2.3 : Geomorphic Factors That Affect Stream Stability

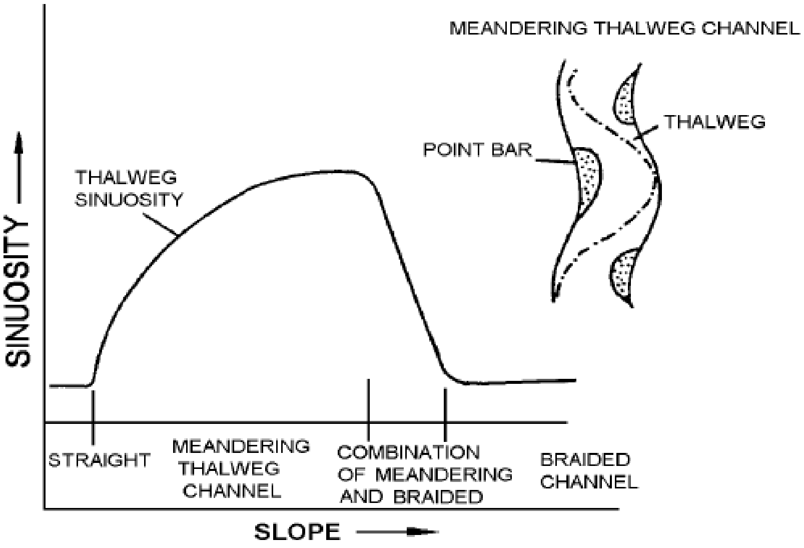

Figure 2.4 : Sinuosity Versus Slope With Constant Discharge

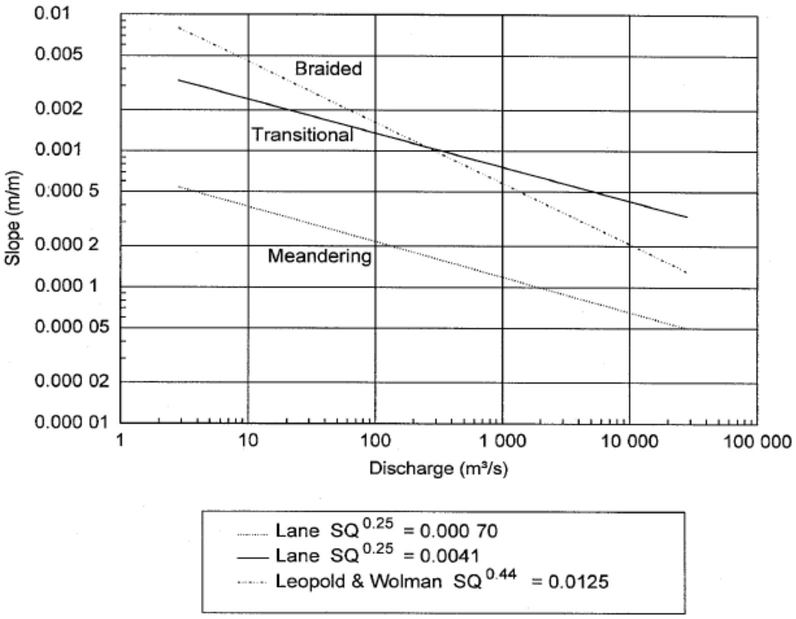

Figure 2.5 : Slope-Discharge For Braiding Or Meandering Bed Streams

2.2 Bed Forms

There is a strong interrelationship between resistance to flow, bed configuration, and rate of sediment transport. In order to understand the variatition of resistance to flow under different flow and sediment conditions, it is necessary to know the definitions and the conditions under which different bed exist. (Yang, 1996)

2.2.1 Terminology

The commonly used terms for forms in the literature can be summarized as follows:

1. Plane bed is a plane bed surface without elevation or depression larger than the largest grains of bed material. (Yang, 1996)
2. Rippples are small bed forms with wavelengths less than 30 cm and heights less than 5 cm. Ripple profiles are approximately triangular, with long gentle upstream slopes and short, steep downstream slopes. (Yang, 1996) . Ripples also are characteristic of very low transport rates in rivers with sediment size D less than about 0.6 mm. Typical wavelengths λ are on the order of 10's of cm and and wave heights $\eta\Delta$ are on the order of cm. Ripples migrate downstream and are asymmetric with a gentle stoss (upstream) side and a steep lee (downstream side). Ripples do not interact with the water surface. (Parker, 2004)
3. Bars are bed forms having lengths of the same orderas the channel width or greater, and heights comparable to the mean depth of the generating flow (Yang, 1996).

4. Dunes are bed forms smaller than bars but larger than bars ripples. Their profiles is oput of phase with water surface profile. (Yang, 1996) Dunes are also the most common bedforms in sand-bed rivers; they can also occur in gravel-bed rivers. Wavelength λ can range up to 100’s of m, and wave height ηΔ can range up to 5 m or more in large rivers. Dunes are usually asymmetric, with a gentle stoss (upstream) side and a steep lee (downstream) side. They are characteristic of subcritical flow . Dunes migrate downstream. They interact weakly with the water surface, such that the flow accelerates over the crests, where water surface elevation is slightly reduced. (That is, the water surface is out of phase with the bed.) (Parker, 2004)
5. Transition is the transitional bed configuration is generated by flow condition intermediate between those producing dunes and plane bed. In many cases, part of the bed is covered with dunes while a plane bed covers the remainder. (Yang, 1996)
6. Antidunes are also called standing waves. The bed and water surface profiles are in phase. While the flows is moving in the downstream direction, the sand waves and water surface waves are actually moving I the upstream direction (Yang, 1996). Antidunes occur in rivers with sufficiently high (but not necessarily supercritical) Froude numbers. They can occur in sand-bed and gravel-bed rivers. The most common type of antidune migrates upstream, and shows little asymmetry. The water surface is strongly in phase with the bed. A train of symmetrical surface waves is usually indicative of the presence of antidunes. (Parker, 2004)
7. Chutes and pools occurs at relatively large slopes with high velocities and sediment concentrations. They consist of large elongated mounds of sediment (Yang, 1996).

Trains of cyclic steps occur in very steep flows with supercritical Froude numbers. They are long-wave relatives of anti dunes. The steps are delineated by hydraulic jumps (immediately downstream of which the flow is locally subcritical). The steps migrate upstream. These features are also called chute-and-pool topography. (Parker, 2004)

2.3 Bed Load And Suspended Load

Sediment transport is often separated into two classes, based on the mechanism by which grains move. These are bed load, wherein grains move along or near the bed by sliding, rolling, or hopping, and suspended load, wherein grains are picked up off the bed and move through the water column in generally wavy paths defined by turbulent eddies in the flow. In many streams, grains smaller than about 1/8 mm tend to always travel in suspension, grains coarser than about 8 mm tend to always travel as bed load, and grains in between these sizes travel as either bed load or suspended load, depending on the strength of the flow. It is useful to divide transport into these categories because the distinction helps to develop an understanding of how transport works and what controls it.

Sediment transport in streams can also be divided into two other classes, based on the source of the grains. These are *bed material load*, which is composed of grains found in the stream bed, and *wash load*, which is composed of grains found in only small (less than a percent or two) amounts in the bed. The sources of wash load grains are either the channel banks or the hillslope area contributing runoff to the stream. Wash load grains tend to be very small (clays and silts and sometimes fine sands) and, hence have a very small settling velocity. Once introduced into the channel, wash-load grains are kept in suspension by the flow turbulence and essentially pass straight through the stream with negligible deposition or interaction with the bed. (Palmer, 2005)

2.3.1 MODES OF SEDIMENT TRANSPORT

Bed material load is that part of the sediment load that exchanges with the bed (and thus contributes to morphodynamics). Wash load is transported through without exchange with the bed. In rivers, there are variety sizes of material, but for material which finer than 0.0625 mm (silt and clay) is often approximated as wash load. Bed material load is further subdivided into bed load and suspended load.

2.3.1.1 Bed Load:

The sediments are sliding, rolling or saltating in ballistic trajectory just above bed. Role of turbulence is indirect.

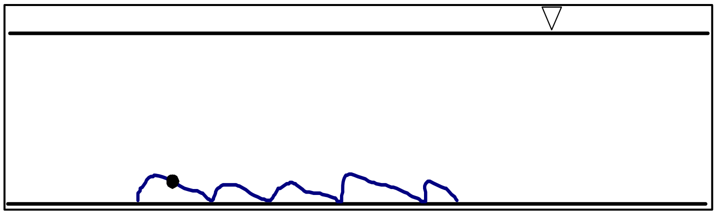

Figure 2.6 : Flow for bed load (Parker, 2004)

2.3.1.2 Suspended Load:

The sediments are under direct dispersive effect of eddies and may be wafted high into the water column.

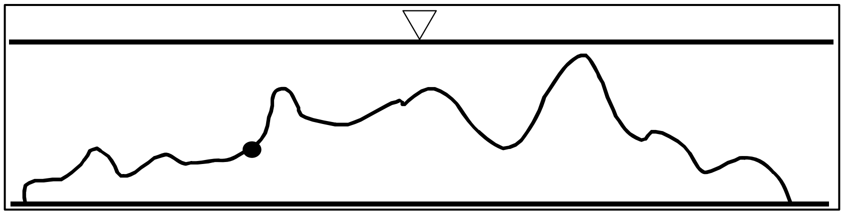

Figure 2.7 : Flow for suspended load (Parker, 2004)

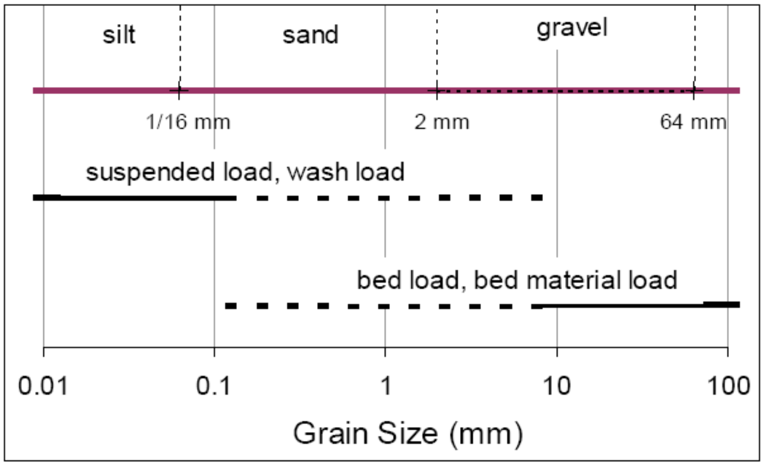

Figure 2.8 : Classification types of load based on grain size (Palmer, 2005)

2.3.2 Bed Load Transport Motion

When the bed shear stress exceeds a critical value, sediments are transported in the form of bed-load and suspended load. For bed-load transport, the basic modes of particle motion are rolling motion, sliding motion and saltation motion.

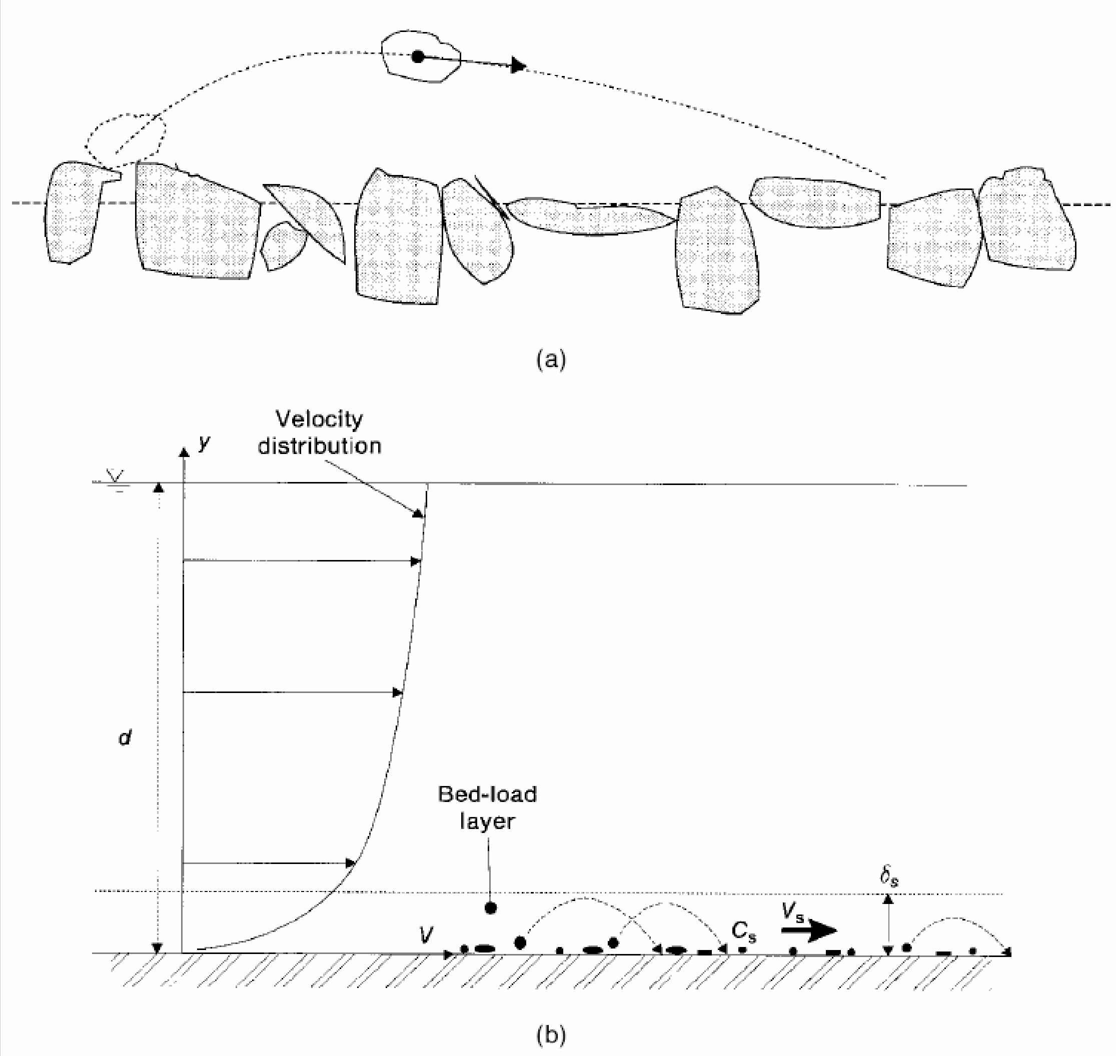

Figure 2.9 : Bed-load motion. (a) Sketch of saltation motion.

(b) Dentitions sketch of the bed-load layer. (Chanson, 2004)

Bed-load transport is closely associated with inter-granular forces. It takes place in a thin region of fluid close to the bed (sometimes called the bed-load layer or saltation layer) (Fig. 10.1, 10.4). Visual observations suggest that the bed-load particles move within a region of less than 10 to 20 particle-diameter heights. During the bed-load motion, the moving grains are subjected to hydrodynamic forces, gravity force and inter-granular forces. Conversely the (submerged) weight of the bed load is transferred as a normal stress to the (immobile) bed grains.

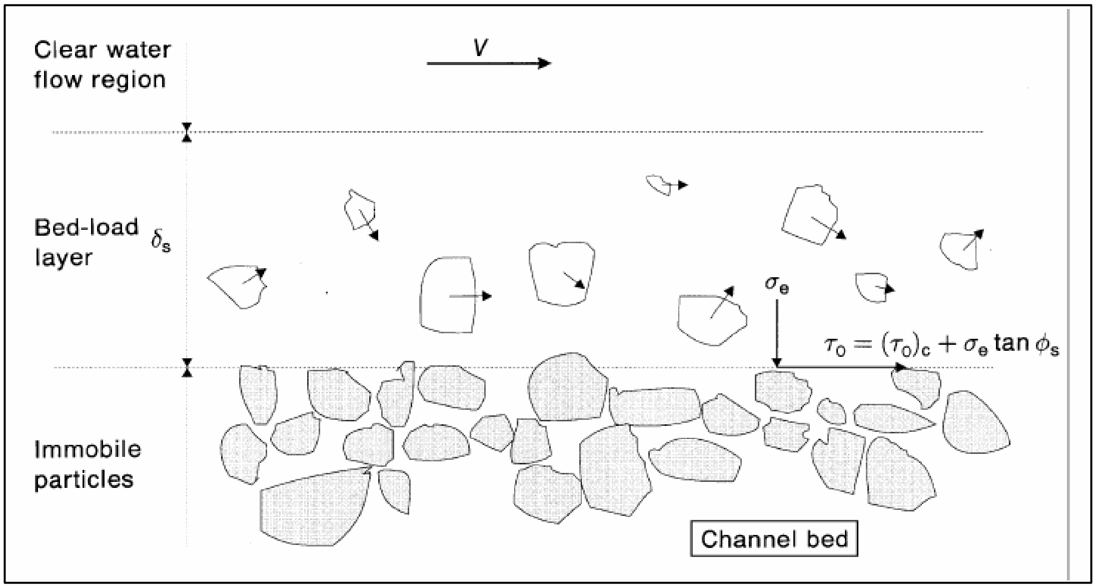

Figure 2.10 : Sketch of bed-load motion at equilibrium. (Chanson, 2004)

2.4 Size of Sediment Particles

The entrainment, transportation, and subsequent deposition of a sediment depend not only on the characteristic of the flow involved, but also on the properties of the sediment itself. Those properties of most importance in the sedimentation processes can be divided into properties of the particles and of the sediment as a whole. The most important property of the sediment particles is its size. In much of river sediment studies of the past, average size alone has been used even to describe the sediment as a whole. This procedure can give reasonable results only if the shape, density, and size distribution of natural sediment do not have major varistions between river systems. To obtain more accurate results, a more precise description of the sediment is necessary. Because the size and shape of grains making up a sediment vary over wide ranges, it is meaningless to consider in detail the properties of an individual particle, and it is necessary to determine averages or different size class or grades. Because such classifications are essentially arbitrar, many grading system are to be found in the engineering and geologic literature. Table 2 below shows a grade scale proposed by the subcommittee on Sediment Terminology of the American Geophysical Union. (Vanoni, 1977)

2.5 Sediment Transport Equations

Sediment transport equations are equations used to predict sediment transport rate.

Example of relation between Einstein number(q_b^*) Versus Shields Number(τ_c^*) For

Bedload Transport shown in Figure 2.12

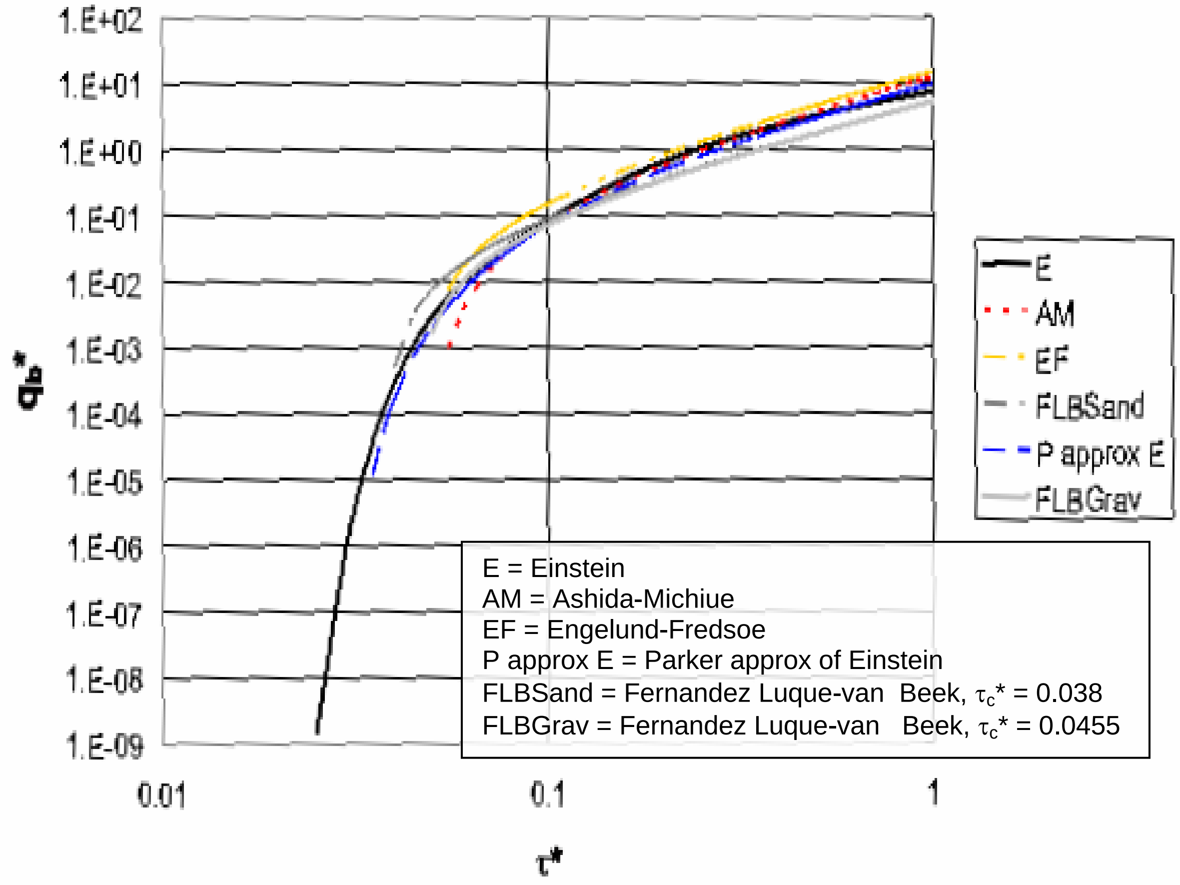

Figure 2.12 : Plots of Bedload Transport Relatons (Parker, 2004)

Bedload Transport Equation For Figure Above

Einstein (1950)

$$1-\frac{1}{\sqrt{\pi}}\int_{-(0.143/\tau^*)-2}^{+(0.143/\tau^*)-2} e^{-t^2}dt = \frac{43.5q_b^*}{1+43.5q_b^*} \qquad (2.1)$$

Ashida & Michiue (1972) $$q_b^* = 17\left(\tau^* - \tau_c^*\right)\left(\sqrt{\tau^*} - \sqrt{\tau_c^*}\right), \quad \tau_c^* = 0.05 \tag{2.2}$$

Engelund & Fredsoe (1976) $$q_b^* = 18.74\left(\tau^* - \tau_c^*\right)\left(\sqrt{\tau^*} - 0.7\sqrt{\tau_c^*}\right), \quad \tau_c^* = 0.05 \tag{2.3}$$

Fernandez Luque & van Beek (1976) $$q_b^* = 5.7\left(\tau^* - \tau_c^*\right)^{1.5}, \tau_c^* = 0.037 - 0.0455 \tag{2.4}$$

Parker (1979) fit to Einstein (1950) $$q_b^* = 11.2\left(\tau^*\right)^{1.5}\left(1 - \frac{\tau_c^*}{\tau^*}\right)^{4.5}, \tau_c^* = 0.03 \tag{2.5}$$

2.5.1 Bed Load Transport Equation

There are many equations had been develop due to the important of sediment transport. Below are list of bed load equation and total bed load equation:

1) Einstein Equation

$$\Phi = \frac{q_b}{D\sqrt{(S-1)gD}} \tag{2.6}$$

$$\Omega = \frac{\tau_b U_*}{\rho\left[(S-1)gD\right]^{3/2}}$$

$$\Phi = C\Omega$$

$$S = \Theta / \Theta_C - 1$$

$$\Theta = U_*^{\,2} / \left[(S-1)gD\right]$$

Θ = Dimensionless shear stress

Θ_C = Dimensionless critical shear stress

q_b = Volumetric bed load transport rate

Φ = Einstein dimensionless transport rate

C = Constant

a = Coefficient

D = Diameter of particle

U_* = Shear velocity

τ_b = Bed shear stress

ρ = Fluid density

g = Acceleration of gravity

(Cheng, 2002)

2) Ashida & Michiue Equation

$$q_b^* = 17\left(\tau^* - \tau_c^*\right)\left(\sqrt{\tau^*} - \sqrt{\tau_c^*}\right) \quad , \quad \tau_c^* = 0.05 \qquad (2.7)$$

q_b^* = $q_b / (\sqrt{RgD}\,D)$, Einstein number for bed load transport

τ^* = $\tau_b/(\rho RgD)$ or $\tau_b/(\rho RgD_{50})$, Shields number

τ_c^* = critical Shields number at the threshold of motion

(Parker, 2004)

3) Fernandez Luque & van Beek Equation

q_b^* = $5.7\left(\tau^* - \tau_c^*\right)^{1.5}$, $\tau_c^* = 0.037 \sim 0.0455$ (2.8)

q_b^* = $q_b /(\sqrt{RgD}\,D)$, Einstein number for bed load transport

τ^* = $\tau_b/(\rho RgD)$ or $\tau_b/(\rho RgD_{50})$, Shields number

τ_c^* = critical Shields number at the threshold of motion

(Parker, 2004)

4) Shields Method

$\frac{q_b\Delta}{qS_o}$ = $\frac{10(\tau_o - \tau_c)}{\rho g\Delta d_{50}}$ (2.9)

q_b = volume bedload transport rate per unit width

q = Unit of flow rate

ρ_S = Sediment density

ρ = Fluid density

τ_O = Tractive force on channel bottom

τ_C = Critical tractive force

d_{50} = Mean grain diameter

Δ = $S_S - 1$

S_S = Relative density of the sand

(Ab. Ghani, 2003)

5) Meyer-Peter Muller (MPM) Method

$$\phi = \left[\left(\frac{4}{\psi}\right) - 0.188\right]^{3/2} \qquad (2.10)$$

$$\phi = 8\left[\frac{1}{\psi} - 0.047\right]^{3/2} \qquad (2.10a)$$

Sediment transport parameter:

$$\phi = \frac{C_V V R}{\sqrt{g\left(S_S - 1\right) d_{50}{}^{3}}} \qquad (2.11a)$$

Flow parameter:

$$\psi = \frac{\left(S_S - 1\right) d_{50}}{R S_O} \qquad (2.11b)$$

S_S = 2.65

S_S = Relative density of the sand

ϕ = Sediment transport parameter

g = Acceleration of gravity

C_V = Volumetric sedimentation concentration

d_{50} = Mean grain diameter

ψ = Flow parameter

V = Flow velocity

R = Hydraulic radius

(Ab. Ghani, 2003)

6) Einstein-Brown Method

$$\phi = 40\left(\frac{1}{\psi}\right)^3 \qquad (2.12)$$

ψ = Flow parameter

ϕ = Sediment transport parameter

(Ab. Ghani, 2003)

7) Bagnold Equation

$$\Phi = \Theta\left(\sqrt{\Theta} - \sqrt{\Theta_C}\right)\frac{1}{k}\left[5.75\log\left(30.2\frac{mD}{K_S}\right) - \frac{w}{U_*}\right] = (13.2 - 19.3)\Omega \qquad (2.13)$$

k = 0.63

K_S/D = 1

$m = 1.4\left(\theta/\theta_C\right)^{0.3}$

$\frac{w}{U_*} = 4.5\left(\theta_C/\theta\right)^{0.5} \quad for\, D > 0.7mm$

$\Phi = C\Omega$

$\Theta = U_*^{\,2}/\left[(S-1)gD\right]$

Θ = Dimensionless shear stress

Θ_C = Dimensionless critical shear stress

Φ = Einstein dimensionless transport rate

C = Constant

k = Dynamic friction factor

m = Coefficient

n = Exponent

U_* = Shear velocity

D = Diameter of particle

w = Settling velocity

(Cheng, 2002)

8) Engkund –Fredsoe Equation

$$\Phi = 9.3\frac{(\Theta-\Theta_C)\left(\sqrt{\Theta}-0.7\sqrt{\Theta_C}\right)}{k} = 11.6\Omega \qquad (2.14)$$

k = 0.8

Φ = $C\Omega$

C = Constant

Φ = Einstein dimensionless transport rate

Θ = ${U_*}^2 / \left[(S-1)gD\right]$

Θ = Dimensionless shear stress

Θ_C = Dimensionless critical shear stress

(Cheng, 2002)