DISSERTATION

TRANSPORT VELOCITIES OF BEDLOAD PARTICLES IN ROUGH OPEN CHANNEL FLOWS

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY **BOUNTHANH BOUNVILAY** ENTITLED **TRANSPORT VELOCITIES OF BEDLOAD PARTICLES IN ROUGH OPEN CHANNEL FLOWS** BE ACCEPTED AS FULFILLLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT OF DISSERTATION

TRANSPORT VELOCITIES OF BEDLOAD PARTICLES IN ROUGH OPEN CHANNEL FLOWS

This dissertation aims at defining the bedload particle velocity in smooth and rough open channels as a function of the following variables: bed slope S_f, flow depth y, viscosity of the fluid ν, particle size d_s, bed roughness k_s, particle specific gravity G, and gravitational acceleration *g*.

Sets of aluminum plates were placed on the bottom of an experimental plexiglass-tilting flume, with trapezoidal cross-section, to form a smooth bed. A layer of sand or gravel was glued onto aluminum plates to form bed roughness. Bedload particles used in the experiments were stainless steel ball bearings, glass marbles, and natural quartz particles. The experiments were performed to provide 529 average bedload particle velocities. The analysis of the laboratory measurements showed that: (1) for a smooth bed ($k_s = 0$), the rolling bedload particle velocity V_p increases with particle sizes d_s; (2) for a rough bed ($k_s > 0$), particle velocity decreases with particle density G, thus lighter particles move faster than heavier ones; and on a very rough boundary V_p decreases with particle sizes; (3) bedload particles move at values of the Shields parameter $\tau_{*ds} = u_*^2/(G-1)gd_s$ below the critical Shields parameter value of $\tau_{*dsc} = 0.047$; (4) few of the observed particles moved at values of Shields roughness parameter $\tau_{*ks} = u_*^2/(G-1)gk_s$ less than 0.01; (5) particles are observed to move at values of the Shields roughness parameter 0.01

$< \tau_{*ks} < 0.15$; (6) the ratio of particle velocity V_p to mean flow velocity u_f lies in the range of 0.2 to 0.9, while Kalinske (1942) suggested 0.9 to 1.0; and (7) the ratio of particle velocity V_p to shear velocity u_* lies in the range of 2.5 to 12.5, compared to the values cited in the literature $6.0 < V_p/u_* < 14.3$.

New methods for predicting transport velocity of bedload particles in rough and smooth open channels are examined. Two approaches for transport velocities of bedload particles were considered. The first approach combines dimensional analysis and regression analysis to define bedload particle velocity as a power function of the Shields parameter τ_{*ds}, boundary relative roughness k_s/d_s, dimensionless particle diameter d_*, and excess specific gravity (G-1). The second approach considers the transport velocity of a single particle on a smooth bed. The reduction in particle velocity due to bed roughness is then examined through a theoretical and empirical analysis. Results show that the bedload particle velocity on smooth beds is approximately equal to the flow at the center of the particle; and the bed roughness gradually decreases the transport velocity of the rolling bedload particles. Comparatively, The first approach gives satisfactory results, except when k_s equals 0, then V_p goes to ∞; and when k_s is large, V_p does not stop (unbounded); for the second approach $V_p = V_{pmax}$ when k_s equals 0, and when V_p equals 0 (no motion), then k_s follows the criteria a and b described in Chapter 5 (section 5.4).

The analysis shows that the proposed formula, Eq. (5.34) provides much better predictions than the existing formulas. The discrepancy ratio distributions using Eq. (5.34) are normally distributed and have higher density (close to perfect agreement) than all other formulas. In addition, the proposed formula, Eq. (5.34) is also verified with the

devastating flood of the Avila Mountain in Venezuela in December 1999. The results give realistic estimates of particle velocities.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Symbol	Description
A	area of the stream cross-section (m^2), A = ½ (T_w + B_w)y;
b	constant parameter;
B_w	width of the plate, which also defined the bottom width of the channel (mm);
c	constant parameter;
c_c	$\rho/4\mu$ (s/m^2);
C_D	drag coefficient;
C_L	lift coefficient;
c_a, c_b, c_d, c_e	constant parameters;
c_α	proportionality constant;
c_μ	sliding friction coefficient;
d_s	diameter of the rolling particles (mm);
d_*	dimensionless particle diameter, $d_* = d_s\left[\frac{(G-1)g}{\nu^2}\right]^{1/3}$;
f	collision coefficient;
F_D	drag force;
F_L	lift force;
F_f	friction force;
F_N	support force of the plane;
Fr	Froude number;
g	gravitational acceleration (m/s^2);

G specific gravity of the particles;

H energy grade line elevation (m) at the two point gages;

$H_{u.s.} = y_{u.s.} + (S_o \Delta X) + (V_{u.s.})^2/2g$;

$H_{d.s.} = y_{u.s.} + (V_{u.s.})^2/2g$;

k_s bed roughness, average diameter of the particles of gravel glued to the plates (see Table 3.1), in mm;

m constant parameter;

m_μ static friction coefficient;

n number of trials for each particle (between 15 and 21 trials per particle type and size);

n_a $(0.014 k_s/u_*)^{0.26}$;

n_μ bulk friction coefficient;

P wetted perimeter of the stream cross-section (mm);

$$P = B_w + 2\sqrt{y^2 + \left(\tfrac{1}{2}(T_w - B_w)\right)^2} \; ;$$

Q flow rate in liters/s, $Q = 6.45632$ (manometer reading / 12)$^{0.503}$;

Re Reynolds number;

Re_* Shear Reynolds number;

R_h hydraulic radius of the stream cross-section (m), $R_h = A/P$;

R_i discrepancy ratio (%);

S_f friction slope $\Delta H / \Delta X$;

S_o bed slope (m/m);

T_{avg} average water temperature in ^oC (measured at start and end of each run);

T_w	top width of the channel (mm); measured at each point gage along the flume;
u_c	critical velocity (m/s);
u_f	average stream flow velocity (m/s); $u_f = Q/A$;
u_1	flow velocity at the height of the particle center (m/s);
u_{1c}	critical velocity at the threshold motion (m/s);
u_*	Shear velocity (m/s), $u_* = \sqrt{gR_hS_f}$;
u_{*c}	critical shear velocity (m/s);
V_p	average velocity over n trials for each particle (mm/s);
w	settling velocity of the rolling particles (m/s);
W_s	submerged weight of the sphere;
y	flow depth in mm (measured at three location with point gages);
y/k_s	relative submergence, ratio of average stream depth to bed roughness;
ΔX	distance between two point gages in the test section (1.62 m);
ΔH	energy loss or head loss (m) between the two point gages; $H_{u.s}$– $H_{d.s.}$;
ν	kinematic viscosity in mm^2/s or $m^2/s \times 10^{-6}$; $\nu = 0.0003625 (T_{avg})^2 - 0.038775 (T_{avg}) + 1.6345$;
δ	laminar sub-layer thickness (m), $\delta = 11.6\frac{\nu}{u_*}\times 10^{-6}$ if ν in mm^2/s;
σ	standard deviation of particle velocities (m/s);
ΔB	roughness function;

ΔB_c	calculated rough ness function;
τ	mean bed shear stress (kg/m^2);
τ_c	shear stress at threshold of motion (kg/m^2);
τ_{oc}	critical bed shear stress required for the particle to roll (kg/m^2);
τ_{*ds}	Shields parameter;
τ_{*ks}	Shields roughness parameter;
ρ_s	particle density (kg-sec^2/m^4);
ρ_f	fluid density (kg-sec^2/m^4);
θ	bed slope angle;
μ	dynamic viscosity of water (kg-sec/m^2);
ν	kinematic viscosity (m^2/s);
τ_o	bed shear stress (kg/m^2);
$\tan\alpha$	dynamic friction coefficient;
α, β, χ	particle velocity coefficients;
Pump setting	for major adjustment of the flow (slow, medium, fast);
Valve setting	for fine adjustment of the flow;
Reach length	length of test section (2000 mm);
Slope reading	reading of vertical displacement (mm) for a ruler attached to the flume near the upstream end, the ruler is 7145 mm upstream of the pivot point of at flume support;
Manometer readings	manometer height in inches of water to compute flow rates;
u.s.	upstream -- generally refer to the position of the upstream point gage in the test section;

d.s.	downstream – generally refer to the position of the downstream point gage in the test section;
$V_{u.s.}$	average flow velocity at the upstream point gage;
$V_{d.s.}$	average flow velocity at the downstream point gage;

CHAPTER 1

INTRODUCTION

1.1. PROBLEM STATEMENT

The study of rolling bedload particle velocity in rough open channel flows is a basic subject in the field of river mechanics and sediment transport. This study aims at the determination of the velocity of rolling bedload particles in rough open channel flows.

1.2. BACKGROUND

Three major approaches for the study of bedload transport are often found in the literature: (1) deterministic approach; (2) empirical approach; and (3) statistical-mechanical approach. The deterministic approach, which is based on some physical laws, studies the relation between bedload transport rates and the corresponding stream power, flow momentum, or other flow properties. The results are expressed in terms of average

flow conditions. A representative of this type of work is the Bagnold stream power function (Chien and Wan, 1983). The empirical approach relates measured bedload rates with their corresponding flow conditions. The results of many observations provide the basis for engineering applications, but sometimes give conflicting estimates when applied to rivers. The statistical-mechanical approach proposed by Einstein (1950), is a combination of the above two approaches. It considers both flow stochastic and deterministic properties of particle motion. The Einstein bedload function (Einstein 1950) shows that individual particle mechanics is one important aspect in this type of approach. Since bedload particle movement can be divided into rolling, sliding and saltation, this proposed research concentrates on the rolling motion, i.e., the motion of a single particle rolling over a rough open channel bed. The primary interest of this research has been to quantitatively examine the velocity of individual particles moving as rolling bedload on rough beds.

1.3. OBJECTIVES

The specific objectives address in this study are: (1) to compile a large database including observed bedload particle velocity measurements on smooth and rough beds; (2) to analyze the database using existing bedload particle velocity formulas; (3) to develop new functions that computes bedload particle velocity in rough open channel flows using dimensional and regression analysis, and theoretical analysis; (4) to determine threshold conditions; and (5) to test the new functions with laboratory measurements and select the best function for field applications representative of very large floods.

1.4. METHODS

To achieve the objective, an extensive compilation of existing laboratory measurements at CSU and other laboratory data from literature has been done. The theoretical and empirical analyses have been studied, and new theoretical and empirical equations were developed and tested with a database including data from Meland and Norrman (1966), Fernandez Luque and van Beek (1976), Steidtmann (1982), Bridge and Dominic (1984), CSU (1995), and Bigillon (2001).

1.5. OUTLINE

This dissertation includes 7 chapters. Chapter 1 briefly introduces the subject and states the objective. Chapter 2 includes a literature review, presented as a highlight of a few of the major papers written on the particle velocity approximations. Chapter 3 describes the CSU experimental set-up and data analysis. Chapter 4 provides a dimensional and regression analyses and testing of empirical formulas. Chapter 5 describes the theoretical development leading to a particle velocity formula. Chapter 6 describes laboratory and field applications of the proposed formulas. Finally, Chapter 7 summarizes the main results of this research.

CHAPTER 2

LITERATURE REVIEW

The purpose of this chapter is to review the pertinent information available from experimental studies on this subject. This material is presented as a highlight of a few of the major papers written on the bedload particle velocity on smooth and rough beds.

2.1. EARLIER STUDIES

Krumbein (1942) studied the effect of particle shape on sediment transportation with experiments conducted in flumes. Krumbein related the observed behavior to the settling velocities of particles. His experiments were confined to the bed movement of single particles of different shapes, over a hydraulically smooth bed, for turbulent flow conditions. Through dimensional analysis, Krumbein determined a relationship between sphericity and the ratio of particle velocity to mean flow velocity, V_p / u_f, as a function

of the Froude number. Krumbein noticed that the curves followed an exponential type of equation, and proposed:

$$\frac{V_p}{u_f} = \left(\frac{V_p}{u_f}\right)_0 \left(1 - \exp(-bFr)\right) \tag{2.1}$$

where: V_p = particle velocity (m/s); u_f = mean flow velocity (m/s); b = constant; Fr = Froude number. In a discussion of Krumbein's paper, Kalinske (1942) noted that all of Krumbein's experiments were made at a constant flow depth of 131 mm, which allowed the Froude number to be written as a function of mean flow velocity:

$$Fr = \frac{u_f}{\sqrt{9.81 \times 0.131}} = 0.88 u_f$$

For the case of spheres, Eq. (2.1) can then be written as:

$$\frac{V_p}{u_f} = 0.88\left[1 - \exp(-1.85 u_f)\right] \tag{2.2}$$

Therefore, Krumbein's equation is not more than a plot of V_p / u_f vs. u_f. He did not make any attempts either to correlate against variables other than *Fr*, or to find a physical basis for his empirical equation. Moreover, the nominal diameter of all particles tested was kept constant, so that size effects were not taken into account. Finally, even though the flow was turbulent, all of Krumbein's experiments were done over a smooth bed, and therefore have less applicability to real world situations.

Kalinske (1942) reported that the Froude number Fr has no physical significance in regard to the movement of particles on the bed. Kalinske proposed that the particle

velocity V_p should be equal, or at least proportional to $u'–u_c$. where: u' = the velocity of the fluid acting on the particle (m/s); u_c = critical velocity for that particle. As u' is proportional to u_f, Kalinske obtained the following expression

$$V_p = c_a\left(u_f - u_c\right) \tag{2.3}$$

where: c_a = constant; u_f = mean flow velocity (m/s); V_p = particle velocity (m/s); u_c = critical velocity (m/s). Kalinske applied his model to Krumbein's data and found the best agreement for $0.9 < c_a < 1.0$. No mention is made regarding how to obtain the critical velocity for a given particle.

Ippen and Verma (1955) analyzed the motion of small spheres over beds of different roughness in flume experiments, for turbulent flow conditions. Upon plotting the ratio u_f / V_p against the Reynolds number, Re, they found that after a transition of variable length (proportional to grain density), u_f / V_p reached an ultimate value that remained constant over a wide range of Re and that the particle velocity increased directly with size, and attributed this to the fact that larger particles protrude into higher velocities than smaller ones. Assuming that the nearly constant ratio u_f / V_p is governed by the following variables: (G -1), k_s / d_s, and $1/S$, they obtained the following equation as a best fit to the data:

$$\frac{u_f}{V_p} = 1 + \frac{1}{12}(G-1)\left(\frac{k_s}{d_s}\right)\left(\frac{1}{\sqrt{S}}\right) \tag{2.4}$$

where: G = the specific gravity of grains; d_s = particle size (mm); k_s = roughness size (mm); S = energy grade line; Eq. (2.4) is explicitly dependent on the particle size, and shows an increase in particle velocity with size. From the definition of shear velocity u_* and mean bed shear stress τ_o:

$$u_* = \sqrt{\frac{\tau_o}{\rho}} \tag{2.5}$$

$$\tau_o = \gamma h S \tag{2.6}$$

one can obtain:

$$S = \frac{u_*^{\,2}}{gh} \tag{2.7}$$

and replacing Eq. (2.7) into Eq. (2.4) leads to:

$$\frac{u_f}{V_p} = 1 + c_b \left(\frac{k_s}{d_s}\right)\left(\frac{1}{u_*}\right) \tag{2.8}$$

where: $c_b = \frac{1}{12}(G-1)\sqrt{gh}$, a constant for a given flow depth and grain material (m/s); u_* = shear velocity (m/s); V_p = particle velocity (m/s); u_f = mean flow velocity (m/s); Eq. (2.8) clearly shows that particle velocity is directly related to both particle size and shear velocity, while inversely related to roughness size.

Meland and Norrman (1966) represent the most complete up-to-date approach to generate information about single grain transport velocities. Most recent theoretical papers on sediment transport rates rely heavily on Meland and Norrman for data in order

to validate their models. Meland and Norrman investigated the interactive effects of water velocity, bed roughness, and particle size on the transport rate of single particles over rough beds by turbulent flows, keeping particle shape, density and bed packing constant. Meland and Norrman used glass beads only, rolling on top of a bed made from the same beads. Upon analyzing their results, in which particle velocity is plotted against particle size for different values of shear velocity, it can be clearly seen that, for a given bed roughness and shear velocity, larger particles move faster than smaller ones, as concluded by Ippen and Verma (1955). Meland and Norrman give two main reasons for this behavior: First, larger particles ride higher off the bed, being thus exposed to the greater velocities; and second, the rolling resistance decreases when the ratio of particle size to roughness size is increased. They also found that the influence of size upon transport velocity decreases with increasing shear velocity and with decreasing bed roughness size. In other words, at high shear velocities and small bed roughness, the particle velocity tends to be constant with size.

$$\frac{V_p}{k_s^{\,m}} = a_m u_* \frac{d_s^{\,n_a}}{k_s} - b_m \tag{2.9}$$

where: u_* = shear velocity (m/s); V_p = particle velocity (m/s); k_s = roughness size (mm); $m = 0.75;\ n_a = \left(\frac{0.014 k_s}{u_*}\right)^{0.26}$; a_m = 7.05; and b_m = 5.1. This empirical equation applies only to Meland and Norrman's experiments; the constants appearing in the equation are of no particular importance. V_p is directly related to u_* and d_s, and inversely related to k_s. In other words, V_p is directly related to the ratio k_s / d_s of particle size, i.e., larger particles roll easier than smaller ones over a given bed, or a given particle rolls more

easily over a smooth than a rough bed. They also observed that transport velocities were lower on beds of loosely packed glass beads than in corresponding fixed, solid beds. This effect was most noticeable at high transport stages, and decreased, or was even reversed for low shear velocities. Eq. (2.9) gives a better results when applied the constants $a_m = 4$, and $b_m = 5.8$ (see Figs. 2.1 and 2.2).

Parson (1972) reported measurements on the rates of travel of several sizes of sand grains and glass beads in laminar sheet flow (i.e., overland flow) at different discharges and slopes, over a smooth bed. Parson found that particles moving in contact with the bed (i.e., rolling and sliding motion) travel at speeds approximately one-half the velocity of water in unobstructed flow, at a distance from the bed equal to the radius of a sphere of equal volume. For some tests with a large number of grains thrown at the same time, Parson overlooked a significant difference in speed. For glass beads, he found good agreement with the following equation:

$$V_p = \frac{\tau_o d_s}{4\mu}\left(1 - \frac{\tau_{oc}}{\tau_o}\right) \tag{2.10}$$

where: V_p = particle velocity (m/s); μ = fluid dynamic viscosity (kg-s/m^2); d_s = grain diameter (mm); τ_o = bed shear stress (kg/m^2); τ_{oc} = critical bed shear stress required for the glass beads to roll (kg/m^2). Using Eq. (2.5), one can express τ_o and τ_{oc} as:

$$\tau_o = \rho u_*^{\,2} \tag{2.11}$$

$$\tau_{oc} = \rho u_{*_c}^{\,2} \tag{2.12}$$

replacing (2.11) and (2.12) into Eq. (2.10), and defining $c_c = \frac{\rho}{4\mu}$ (s/m^2), results in:

$$V_p = c_c d_s \left({u_*}^2 - {u_{*c}}^2 \right) \tag{2.13}$$

where: u_* = shear velocity (m/s); u_{*c} = critical velocity (m/s). Eq. (2.13) not only shows that V_p depends directly on d_s, but also that V_p is proportional to the difference between a velocity and a critical velocity. In this case, it is shear velocity squared.

Ikeda (1971) made a theoretical analysis of the mechanics of the motion of a single spherical grain rolling on the bed, by considering the four main forces acting on the particle: drag, lift, gravity and friction with the bed. The resulting equation is as follows:

$$\frac{V_p}{u_*} = \frac{u_f}{u_*} - \left[\frac{4}{3} c_\mu \frac{(G-1)}{(c_\mu C_L + C_D)} \frac{g d_s}{{u_*}^2} \right]^{1/2} \tag{2.14}$$

where: V_p = particle velocity (m/s); u_* = shear velocity (m/s); u_f = fluid velocity at the center of the spherical grain (m/s); c_μ = sliding friction coefficient; G = particle specific gravity; g = gravitational acceleration (m/s^2); C_D and C_L = the drag and lift coefficients respectively; However, Ikeda did not give a method to specify the values of c_μ, C_D and $C_{L,}$ which makes this formula inapplicable in practice. Besides, Ikeda assumed that the particle velocity is always behind the fluid velocity. This is not true for the case of steep slopes at very low fluid velocities.

Francis (1973) studied the motion of solitary grains along the bed of a flume. Francis' investigation was limited to particles moving over a fixed-plane bed made out of particles of the same type as those being transported, and he did not consider the effects

of grain size relative to roughness size. Francis found a satisfactory correlation between V_p (m/s) and the particle settling velocity, w (m/s). He also found a considerable difference in V_p for grains of different shapes. Specifically, he concluded that rounded particles always roll faster than angular ones.

The effect of grain size on V_p was always accounted for by using the regression with w, but shape effects could not be reduced. Francis performed the experiments with spherical particles traveling over a bed consisting of cylinders of the same diameter as the grains laid perpendicular to the flow. In this case, spherical particles traveled faster than any natural grains. Finally, he observed marked grains moving in the company of many other grains, in order to test the applicability of results derived from single grain experiments. In this case, speed was reduced 5% on average below that corresponding to solitary grains. This effect was most noticeable for low transport stages, and disappeared altogether for very high shear velocities.

Fernandez Luque and van Beek (1976) used a different approach than the one in previous studies, by using a loose bed for all of their experiments. They measured particle velocities as a function of bed shear stress in a closed-flow rectangular flume. The measured grains were scoured from the bed and then rolled on top of it. The average transport velocity of particles, which were saltating, or even in suspension, for most of the time was found to be equal to the average fluid velocity for turbulent flow without bed load at about three particle diameters above the bed surface minus a constant proportional to u_{*_c}, as shown below:

$$V_p = c\left(u_* - 0.7u_{*_c}\right) \tag{2.15}$$

where: u_{*_c} = critical shear velocity at Shields condition for entrainment (m/s); V_p = particle velocity (m/s); u_* = shear velocity (m/s) and c = constant (11.5). Eq. (2.15) is valid over a wide range of slopes. The form of this equation is quite misleading, since it seems that V_p will decrease with size (because u_{*_c} is higher for larger particles), but this is not the case because the points through which the equation was plotted correspond to all different experiments. Thus, in Eq. (2.15), u_* is also a function of size; because in experiments with larger particles, larger shear velocities were required not only to entrain grains, but also to keep them moving. As in Francis (1973), the particles were rolling on top of a bed made from the same material, so that the effect of size cannot be described.

Romanovskiy (1977) not only shows his own experimental results, but he also discusses previous approaches to the problem of modeling grain transport velocity. In particular, he presents Goncharov's (1938) empirical equation:

$$V_p = u_1 - u_{1c} \tag{2.16}$$

where: V_p = particle velocity (m/s); u_1 = flow velocity at the height of the particle center (m/s); u_{1c} = critical value at the threshold of motion (m/s). Assuming a logarithmic velocity profile, it is possible to relate u_1 to the mean flow velocity, u_f, through a constant, so that one obtains:

$$V_p = c_a\left(u_f - u_c\right) \tag{2.17}$$

where: c_a = constant; u_f = mean flow velocity (m/s); u_c = critical velocity (m/s). This is identical to Kalinske' Eq. (2.3). One considers the shear velocity as:

$$u_* = \sqrt{\frac{f}{8}} u_f \tag{2.18}$$

where: f = Darcy-Weisbach coefficient; u_* = shear velocity (m/s); we can write Eqs. (2.3) and (2.17) in terms of shear velocities:

$$V_p = c(u_* - u_{*c}) \tag{2.19}$$

where: $c = (f/8)^{1/2}$, which is assumed constant; u_{*c} = critical shear velocity (m/s). The later equation is quite similar to the form of Fernandez Luque and van Beek's (1976) Eq. (2.15). Romanovskiy (1977) made a simplified analysis of the forces acting on a rolling grain and proposed:

$$V_p = c_e \left(u_f - u_c \sqrt{\frac{\tan\alpha}{m_\mu}} \right) \tag{2.20}$$

where: $\tan\alpha$ = dynamic friction coefficient; m_μ = static friction coefficient; u_f = mean flow velocity (m/s); c_e = constant; u_c = critical velocity (m/s). For a particle at repose, $\tan\alpha = m_\mu$; and if u_f is allowed to increase slowly from zero, at a certain velocity $u_f = u_c$, the particle will be entrained. From his experimental work he concluded that the form of Eq. (2.20) adequately represents the data.

Abbott and Francis (1977) continued the investigations reported by Francis (1973). More experiments were carried out and the following equation was found to represent all data sets with very low scatter:

$$V_p = c(u_* - u_{*c}) \tag{2.21}$$

where: u_* = shear velocity (m/s); u_{*_c} = critical shear velocity (m/s); and c = constant parameter ($13.5 < c < 14.5$); A particle riding on top of the bed has a far lower threshold of motion than one nested into it. Abbott and Francis obtained u_{*_c}, based on actual measurements of overriding grains. Thus, instead of using Shields' criterion, the critical shear velocity was derived assuming a Shields parameter value of $\theta_o = 0.02$.

Bridge and Dominic (1984) made an extensive analysis of bed load grain transport velocity data in order to calibrate their proposed physically based model to estimate sediment transport rates. On theoretical grounds they showed that:

$$V_p = c\left(u_* - u_{*_c}\right) \tag{2.22}$$

where: $cu_{*_c} = w\sqrt{\tan\alpha}$; w = the settling velocity of particles (m/s); $\tan\alpha$ = dynamic friction coefficient; $6 < c < 14.3$; u_* = shear velocity (m/s); u_{*_c} = critical shear velocity (m/s); Application of this model to the existing data sets on single grain transport velocities yielded good results.

Wiberg and Smith (1987) developed an expression for the critical shear stress in non-cohesive sediment derived from the balance of forces on individual particles at the surface of a bed. The resulting equation, for a given grain size and density, depends on near bed drag force, the lift force to drag force ratio, and the particle angle of repose. Calculated values of the critical shear stress for uniformly sized sediment correspond closely to those determined from Shields' diagram. The initial motion problem for mixed grain sizes additionally depends on the relative protrusion of the grains into the flow and the particle angle of repose. The latter decreases when the diameter of a moving grain, d_s,

is larger than the length scale of the bed roughness, k_s $(d_s / k_s > 1)$, and increases when $d_s / k_s < 1$, producing a corresponding decrease or increase in critical shear stress. Using the Miller and Byrne (1966) experimental relationship between d_s / k_s, and particle angle of repose, which is consistent with Shields' definition of initial motion, Wiberg and Smith obtain results that are in good agreement with the available experimental critical shear stress data for heterogeneous beds. Wiberg and Smith used a physically based model of bedload sediment transport and data sets from Francis (1973), Fernandez Luque and van Beek (1976) and Abbott and Francis (1977) to derive the semi-empirical equation:

$$\frac{V_p}{u_*} = 4.2 \frac{\left[\frac{(\tau - \tau_c)}{\tau_c}\right]^{1/2}}{\left(\frac{\tau}{\tau_c}\right)} + 2.4 \qquad (2.23)$$

where: τ = mean bed shear stress (kg/m^2); τ_c = shear stress at threshold of motion (kg/m^2); V_p = particle velocity (m/s); and u_* = shear velocity (m/s).

Jan (1992) addressed the relative contribution of the stresses developed in granular fluid flows (viscosity, collision and friction stresses). Jan determined how much each of the examined stresses contributed to the total stress acting on a rolling sphere. Experiments were conducted for the steady movement of a sphere rolling down smooth and rough inclines in air, water and salad oil. An equation was derived expressing the velocity of a sphere rolling down a roughened incline without acceleration or deceleration based on the principle of conservation of momentum. Jan 's average terminal velocity V_p was derived as the following:

$$V_p = \sqrt{\frac{(\rho_s - \rho_f) g d_s (\sin\theta - n_\mu \cos\theta)}{f_c \rho_s + \frac{3}{4} C_D \rho_f}} \tag{2.24}$$

where: ρ_s, ρ_f = particle and fluid densities (kg-s^2/m^4); C_D = drag coefficient; θ = bed slope angle; d_s = particle diameter (mm); g = gravitational acceleration (m/s^2); f_c = collision coefficient (0.667); and n_μ = bulk friction coefficient (0.13). Both f and n_μ were determined via regression analysis using experiment data. Jan' experiments were performed for situations where the tested particle was identical to those comprising the roughness over which it rolled. Roughness particles were tightly spaced in a single layer on a smooth wooden bed of a tilting flume. Several conclusions were made as a result of the experiments and analysis. First, velocity is independent of rolling particle density. Second, collision stresses increase with increased bed inclination. Third, side wall friction from particles interacting with the side boundaries of the flume is negligible.

Meier (1995) completed the literature review on the existing formulas of transport velocity, in which he analyzed seventeen equations. Most of the equations can be written in the following form:

$$V_p = c_\alpha (u_* - u_{*c}) \tag{2.25}$$

where: V_p = particle velocity (m/s); u_* = shear velocity (m/s); u_{*_c} = critical shear velocity (m/s); and c_α = proportionality constant. The differences between various investigators is how they correlate c_α and u_{*_c} with the flow parameters. A shortcoming of this type of equation is that it does not apply for a steep bed slope.

Steidtmann (1982) conducted an experiment to assess the effects of size and density, with sand-size spheres of two densities being transported and deposited under controlled flume conditions. Observations on the motion of discrete particles show that grains smaller than bed roughness grains move continuously and have the same transport velocities regardless of density. For grains near and slightly larger than the roughness, movement is intermittent; and, for a given size, heavy particles move more slowly than light particles. For grains much larger than bed roughness grains, movement is continuous over the rough surface, and light and heavy grains have nearly the same transport velocities. Steidtmann's analysis of bulk sediment deposited from plane-bed transport, show that the size and proportion of heavy grains decrease and that of light grains increase with distance transported. For ripple bed transport, the size relations between associated light and heavy grains remains essentially unchanged with transport distance and the proportion of light and heavy grains is extremely variable. The results suggest that size-density sorting in plane-bed transport is a function of the transportability identified in the discrete grain studies but that sorting in ripple-bed transport is related to deposition on, and recycling through, the bed forms.

Bigillon (2001) conducted an experiment in a tilted, narrow, glass-sided channel, 2m in length and 20 cm in height. The channel inclination ranged from 0° to 12°. Two types of spherical particles were used in the experiments: glass beads and steel beads, the particle density was 2500 and 7750 kg/m^3 respectively. The water supply at the channel entrance was controlled by an electromagnetic flow meter provided by Krohne (France). The flow depth was a few particle diameters. Most of the time, channel slope was in excess of 1°, the water flow regime was supercritical, that is the Froude number exceeded

unity. The channel bed was made up of regularly juxtaposed half-cylinders of equal size. Bigillon selected three sizes of cylinder: their radius are 1.5 mm, 3 mm, and 4 mm. The motion of mobile beads was recorded using the Pulnix camera. A single particle was dropped from above into the water stream 1 m upstream from the measuring window. Bigillon filmed the motion of the particle with the Pulnix camera. For each flow condition (u_f,θ), the variability of the results was evaluated by repeating the run between three and five times, and only the average value was reported. The standard deviation was low relative to the mean (less than 5%) when the particle rolled. Bigillon noted that, these mean velocities cannot be rigorously assimilated to asymptotic velocities V_p, they provide a reasonable approximation of V_p. Fifty experimental data points were collected and the variability for hydraulic and particle parameters include: the range of shear velocity $u_* = 0.018\text{-}0.038$ m/s, $T_{water} = 20°C$, $\nu_{water} = 1.004\times10^{-6}$ m^2/s, particle diameter d_s = 1.5 mm and 3 mm, G = 2.5 (glass bead) and 7.75 (steel bead), k_s = 1.5 mm and 3 mm, bed slope $S_f = 0.02$ and 0.05, mean flow velocity $u_f = 0.223\text{-}0.492$ m/s, flow depth y = 2.13-28.65 mm, and observed bedload particle velocity $V_{pobs} = 0.076\text{-}0.496$ m/s.

2.2. DATA COMPILATION

A complete set of the experimental and data measurements is provided in Chapter 3. It includes the laboratory data of Meland and Norrman (1966), Fernandez Luque and van Beek (1976), Steidtmann (1982), Bridge and Dominic (1984), CSU (1995), and Bigillon (2001). A summary of this database is given in Table 2.1. It is comprised of 6 data sets containing a total of 1038 data points. These data are limited to the particle sizes

with median diameters in the range of 0.21 to 29.3 mm, bed roughness in the range of 0.19 to 7.76 mm, average flow velocity in the range of 0.22 to 1.00 m/s, shear velocity in the range of 0.0097 to 0.1108 m/s, flow depth in the range of 2.13 to 180 mm, and slope in the range of 0.00073 to 0.05. Details on the variability of hydraulic and bedload particle parameters are given in the appendices. Table 2.2 to 2.4 provides the summary of literature review, including existing equations, data sources and previous and recent studies.

Table 2.1: Variability of Hydraulic and Bedload Particle Parameters

Variables	Existing Experiments Data				Recent Experiments Data	
	Meland and Norrman (1966)	Fernandez Luque and van Beek (1976)	Steidtmann (1982)	Bridge and Dominic (1984)	CSU (1995)	Bigillon (2001)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Number	120	85	330	77	356	50
S_f	-	-	-	-	0.00073-0.011	0.02-0.05
T (°C)	20	22	18-22	20	17.25-21.5	20
$\nu \times 10^{-6}$ (m^2/s)	1.004	1.26	0.98-1.095	1.004	0.968-1.08	1.004
y (mm)	-	-	180	-	50.3-71.15	2.13-28.65
u_* (m/s)	0.0172-0.1108	0.0122-0.0641	0.0172-0.0277	0.0122-0.0641	0.0097-0.0641	0.018-0.038
u_f (m/s)	0.25-1.0	-	0.29-0.44	-	0.25-0.89	0.22-0.49
k_s (mm)	2.09-7.76	0.9-3.3	0.35	0.19-3.5	1.2-3.4	1.5-3
d_s (mm)	2.09-7.76	0.9-3.3	0.21-1.25	0.19-3.5	2.4-29.3	1.5-3
d_s/k_s	1.0	1.0	0.6-3.57	1.0	2.02-24.4	1.0
Shape of Particles	Spherical	Angular	Spherical	Spherical Angular	Spherical Angular	spherical

Table 2.2: Summary of Literature Review

Sources	Equations	Notes
Krumbein (1942)	$\frac{V_p}{u_f} = 0.88\left(1 - \exp(-1.85u_f)\right)$	where: V_p = particle velocity; u_f = mean flow velocity; b = constant; Fr = Froude number
Kalinske (1942)	$V_p = c_a\left(u_f - u_c\right)$	where: c_a = constant; u_f = mean flow velocity; V_p = particle velocity; u_c = critical velocity; Kalinske applied his model to Krumbein's data and found the best agreement for $0.9 < c_a < 1.0$
Ippen and Verma (1955)	$\frac{u_f}{V_p} = 1 + c_b\left(\frac{k_s}{d_s}\right)\left(\frac{1}{u_*}\right)$	Where: $c_b = \frac{1}{12}(G-1)\sqrt{gh}$, k_s = roughness size, d_s = grain size, u_* = shear velocity, V_p =particle velocity and u_f = mean flow velocity
Meland and Norrman (1966)	$\frac{V_p}{k_s{}^m} = 7.05u_* \frac{d_s{}^n}{k_s} - 5.1$	Where: u_* = shear velocity, V_p = particle velocity, k_s = roughness size, m = 0.75 and $n = \left(\frac{0.014k_s}{u_*}\right)^{0.26}$
Ikeda (1971)	$\frac{V_p}{u_*} = \frac{u_f}{u_*} - \left[\frac{4}{3}c_\mu \frac{(G-1)}{\left(c_\mu C_L + C_D\right)}\frac{gd_s}{u_*{}^2}\right]^{1/2}$	where, V_p = particle velocity, u_* = shear velocity, u_f = fluid velocity

		at the center of the spherical grain, c_μ = sliding friction coefficient, G = the particle specific gravity, g = gravitational acceleration, and C_D and C_L = drag and lift coefficients
Parson (1972)	$V_p = c_c d_s \left(u_*^{\,2} - u_c^{\,2}\right)$	where, u_* = shear velocity, u_c = critical velocity, d_s = grain size and $c_c = \rho/4\mu$.
Fernandez Luque and van Beek (1976)	$V_p = c\left(u_* - 0.7u_{*c}\right)$	Where: u_{*c} = critical shear velocity at Shield's condition for entrainment, V_p = particle velocity and u_* = shear velocity, and c = 11.5;
Romanovskiy (1977)	$V_p = c_e\left(u_f - u_c\sqrt{\frac{\tan\alpha}{m_\mu}}\right)$	Where: $\tan\alpha$ = dynamic friction coefficient, m_μ = static friction coefficient, u_f = mean flow velocity, c_e = constant and u_c = critical velocity
Abbott and Francis (1977)	$V_p = c\left(u_* - u_{*c}\right)$	Where: u_* = shear velocity, u_{*c} = critical shear velocity and $13.5 < c < 14.3$, c = constant parameter.
Bridge and Dominic (1984)	$V_p = c\left(u_* - u_{*c}\right)$	$c_h u_{*c} = w\sqrt{\tan\alpha}$, w = the settling velocity of particles, $\tan\alpha$ = the dynamic coefficient

		friction, 6< c <14.3, u_* = shear velocity and u_{*c} = critical shear velocity
Wiberg (1987)	$\frac{V_p}{u_*} = 4.2\frac{\left[\frac{(\tau-\tau_c)}{\tau_c}\right]^{1/2}}{\left(\frac{\tau}{\tau_c}\right)} + 2.4$	Where: τ = mean bed shear stress, τ_c = shear stress at threshold of motion, V_p = particle velocity and u_* = shear velocity
Jan (1992)	$V_p = \sqrt{\frac{(\rho_s - \rho_f) g d_s (\sin\theta - n_\mu \cos\theta)}{f\rho_s + \frac{3}{4} C_D \rho_f}}$	Where: ρ_s, ρ_f = particle and fluid density, C_D = drag coefficient, θ = bed slope angle, d_s = particle diameter, g = gravitational acceleration, f = collision coefficient, and n_μ = bulk friction coefficient
Meier (1995)	$V_p = c_\alpha (u_* - u_{*c})$	Where: V_p = particle velocity, u_* = shear velocity, u_{*c} = critical shear velocity, and c_α = proportionality constant

Table 2.3: Existing Database

Sources	Number of Data Points	Bed-load Particle Size	Notes
Meland and Norrman (1966)	120	d_s=2.09, 3.15, 3.93, 5.1, 5.95, 7.0 and 7.76mm; k_s=2.09 and 7.76mm	Glass spheres G=2.65
Fernandez Luque and van Beek (1976)	85	d_{walnut}=1.5mm 0.9mm<d_{sand}<1.8mm d_{gravel}=3.3mm $d_{magnetite}$=1.8mm	Walnut, sand (I), sand (II), gravel and magnetite; G=2.64 and 4.58 Shape, density,…
Steidtmann (1982)	330	0.21mm<d_{sand}<1.25mm k_s=0.35mm(Glass sphere)	Sand-size spheres (d_s) Glass spheres (k_s) 154 with G_s=4.5 176 with G_s=2.5
Bridge and Dominic (1984)	77		Glass spheres G=2.56
Wiberg (1987)	115	d_s = 0.35, 0.5, 0.8, 1.5, 2.0, 2.5, 5, 10, 28.6mm	Shape, density,…
Rakoczi (1991)	100	d_{s1}=5-10mm, d_{s2}=10-15mm, d_{s3}=15-20mm; d_{s4}=20-25mm and d_{s5}=25-36mm	Gravel G=2.65
Jan (1992)	158	13.5mm<d_{glass} <24.1mm d_{steel} = 13.5mm d_{golf} = 42.5mm 13.5mm<k_s<42.5mm	Golf, steel balls; water, air and salad oil
CSU (1995)	356	1.57mm<d_{steel}<19.04mm d_{tin}=4.375mm	Glass, natural and steel spherical and angular

		$14.48mm<d_{glass}<29.3mm$ $1.2mm<d_{natural}<13.6mm$ k_s=1.2,1.7,2.4 and 3.4mm	shapes
Bigillon (2001)	50	$1.5mm<d_{steel}<3mm$ $1.5mm<d_{glass}<3mm$ k_s=1.5 and 3mm	Glass and steel spherical shape

Table 2.4: Summary of Previous and Recent Studies

Author	Equation	Data	Particle Size	Particle Shape	Particle Density	Smooth Bed	Rough Bed	Still Fluid	Flowing Fluid
Meland and Norrman (1966)	Yes	Yes	Yes	Spherical			Yes		Yes
Fernandez Luque and van Beek (1976)	Yes	Yes	Yes	Angular	Yes		Yes		Yes
Steidtman (1982)		Yes	Yes	Spherical	Yes	Yes	Yes		Yes
Bridge and Dominic (1984)	Yes	Yes	Yes	Spherical, Angular			Yes		Yes
Wiberg (1987)	Yes	Yes	Yes	Spherical, Angular	Yes		Yes		Yes
Jan (1992)	Yes	Yes	Yes	Spherical	Yes	Yes	Yes	Yes	
CSU (1995)	Yes	Yes	Yes	Spherical, Angular	Yes	Yes	Yes	Yes	Yes
Bigillon (2001)	Yes	Yes	Yes	Spherical	Yes		Yes		Yes

2.3. APPLICATION OF EXISTING METHODS

Figs. 2.1 to 2.6 show the application of the equations of Meland and Norrman (1966), Fernandez Luque and van Beek (1976), and Bridge and Dominic (1984) to their own database. The results show that the equations of Meland and Norrman, Fernandez Luque and van Beek, and Bridge and Dominic predict very well with their own data.

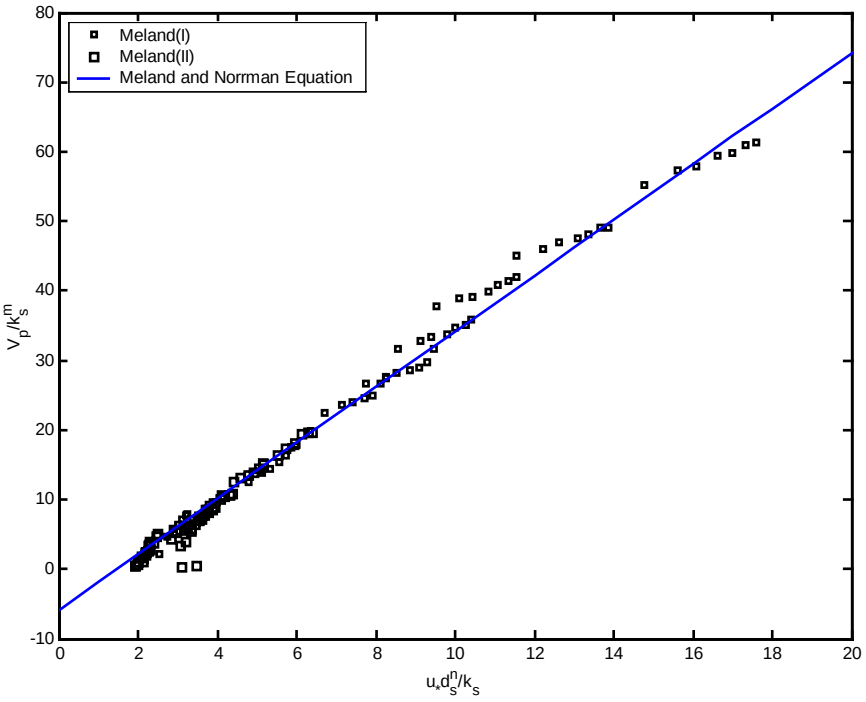

Figure 2.1: V_p/k_s^m vs. $u_*d_s^n/k_s$

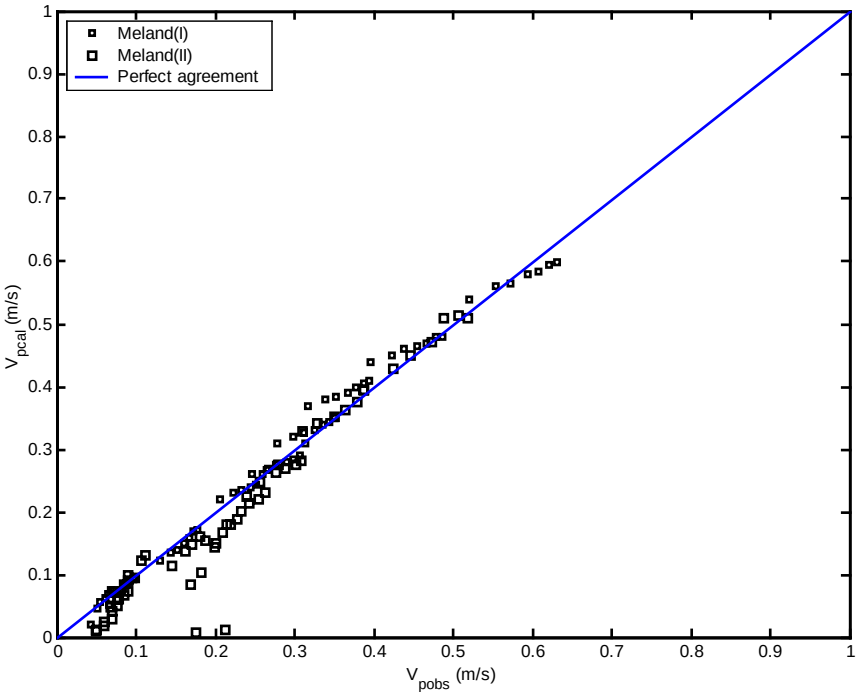

Figure 2.2: Comparison between Calculated and Observed V_p using Eq. (2.9)

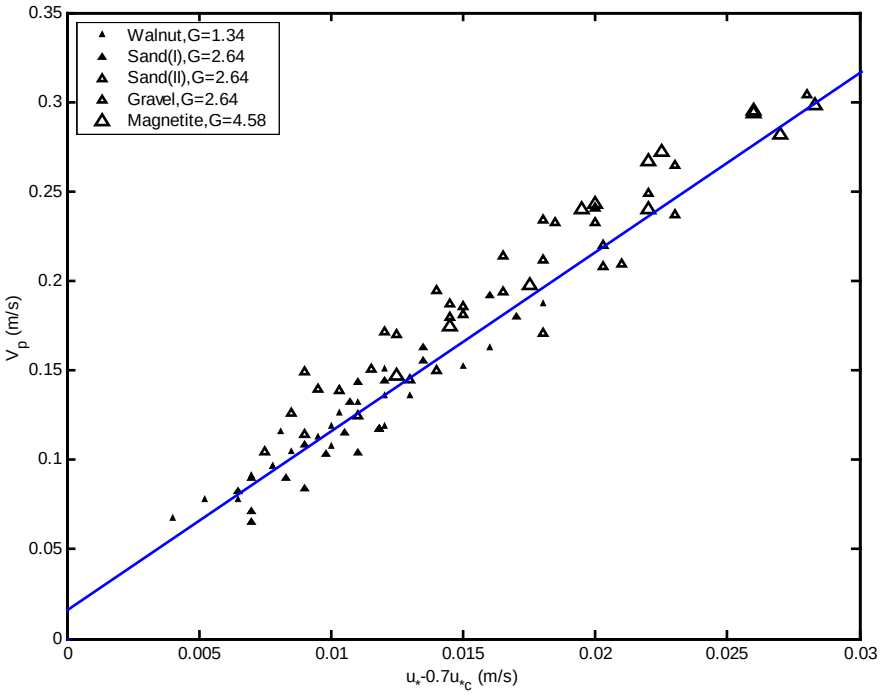

Figure 2.3: V_p vs. (u_*-0.7u_{*c})

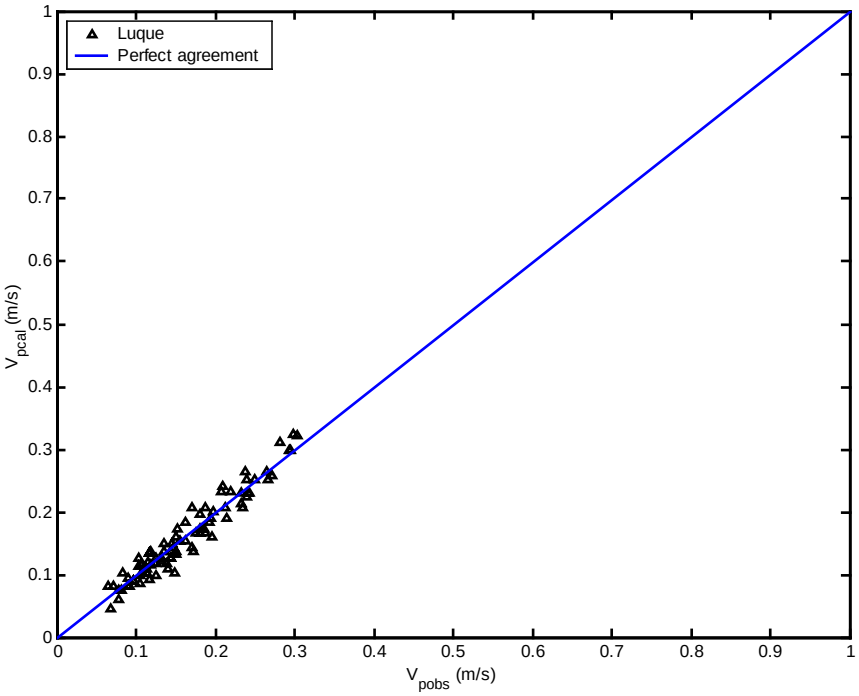

Figure 2.4: Comparison between Calculated and Observed V_p using Eq. (2.15)

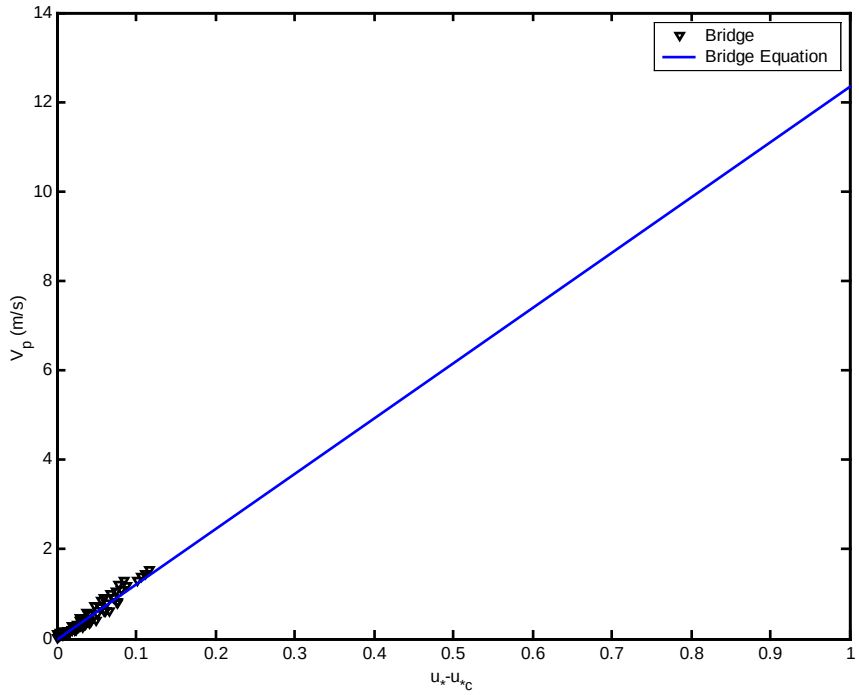

Figure 2.5: V_p vs. (u_*-u_{*c})

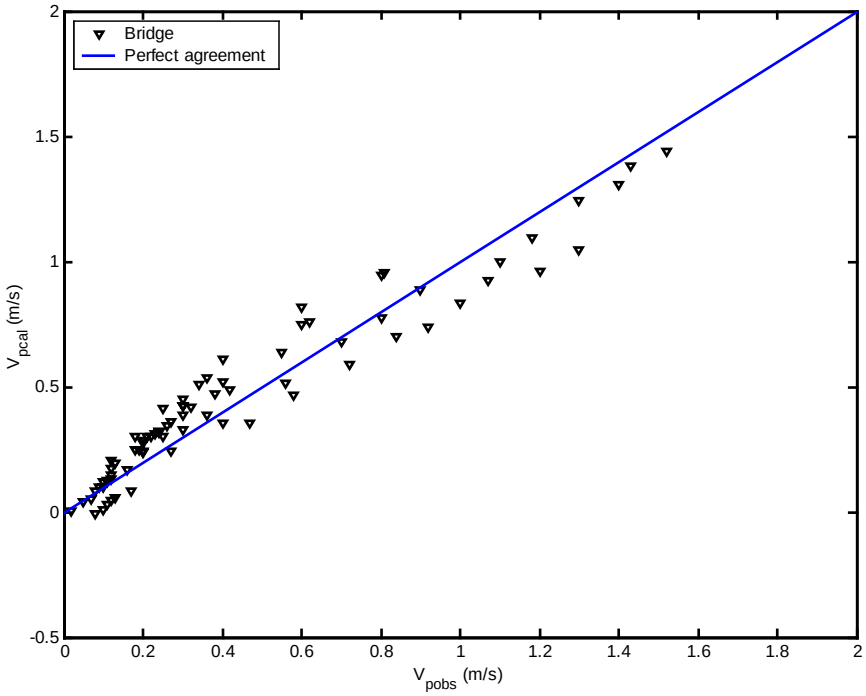

Figure 2.6: Comparison between Calculated and Observed V_p using Eq. (2.22)

2.4. SUMMARY

The existing methods, i.e., Meland and Norrman, Fernandez Luque and van Beek, and Bridge and Dominic compare well with their own data. There is a shortage of laboratory data on particle specific gravity G (density), particle shape, bed roughness k_s, particle size d_s, etc., therefore more extensive physical experiments are needed to cover a greater range of variability for hydraulic and particle parameters.

CHAPTER 3

DATA COMPILATION

Julien, Meier, and Blackard (1995) conducted experiments at the Engineering Research Center (ERC) of Colorado State University on transport velocities of bedload particles in smooth and rough open channel flows. This chapter represents the descriptions of the flume, plates, particles, set up, experiments, and methodology used in the experiments.

3.1. THE FLUME

A 9.77m long plexiglass tilting flume shown in Fig. 3.1, with trapezoidal cross-section was used for the experiment. The bed slope has a range of approximately 0% to 4%, although 1% was the largest slope used (run 18, 20, 28 and 37). The side walls of the flume are adjustable, allowing for the channel cross-section to be varied. In these experiments the side walls were kept fixed at a 3 H to 1 V ratio, in order to minimize

their influence on the flow. A 2 m long test reach near the downstream end of the flume was used to measure particle velocities.

The location of the test reach was chosen by visual inspection as that portion of the flume with most uniform flow conditions. An adjustable weir located at the downstream end of the flume was used in some of the runs to control the test reach water levels. Many runs with higher flow rates were performed with the weir removed as long as the flow was steady and uniform in the test section. The system re-circulated water collected at the downstream end of the flume in a stilling tank with a pump driven by an electric motor.

The motor has three speed settings (slow, medium, and fast) and the return pipe has a valve for fine adjustment of the flow rate. Three point gages were used to measure flow depths. Two gages were located at the beginning and end of the test section, the third was used to record flow depth over the weir. Flow rates were measured using an orifice plate located in the water return pipe. Pressure taps on each side of the construction were connected to two manometers in parallel, with water and mercury as manometric fluids. The mercury manometer was needed for the higher flow rates.

Figure 3.1: Three Point Gages used to Measure Water Depth.

3.2. THE PLATES

Sand or gravel was glued to aluminum plates to achieve various bed roughnesses. Four sets of plates with rounded sand and gravel were used, one set with angular gravel and one smooth aluminum plate (bed roughness k_s=0). Grain sizes used as bed roughness are shown in Table 3.1. Two 12-ft long plates were used for each bed roughness condition. The upstream plate used the same roughness as the downstream plate in order to establish the velocity profile of the stream. The test reach was located over the downstream plate.

Table 3.1: Gravel Gradations for Roughened Plane Surfaces

Sieve Retained (mm)	Sieve Passed (mm)	Bed Roughness (mm)
No gravel	No gravel	0
1.0	1.4	1.2
1.4	2.0	1.7
2.0	2.8	2.4
2.0	2.8	2.4(angular)
2.8	4.0	3.4

Various adhesives were used to bond the sand and gravel to the plates. The first set of plates was produced using a spray lacquer made by Krylon to glue 2.4 mm (angular) gravel particles. This attempt failed as the gravel did not stick to the plates well. A vanish substitute called “EnviroTex Lite pour-on” made by Environmental Technology, Inc. was then used; the particles of gravel adhered much better. A contact cement from DAP was also used. It performed as well as the EnviroTex and the contact cement avoided the difficulty in producing a uniform layer of gravel without having “clumps” on the plates. For the 1.2 mm sand, a waterproof paint was used (Tile Clad II from Sherwin Williams). This held the sand in place very well, although clumping was difficult to prevent with this paint as well.

In the early runs, particles had a tendency to roll off the sides of the plates. To solve this problem extra sand/gravel was glued to the sides, creating small ridges that acted as “guard rails” to keep the particles on the plate. The roughened plates are shown in Fig. 3.2, 3.3, 3.4, 3.5 and 3.6

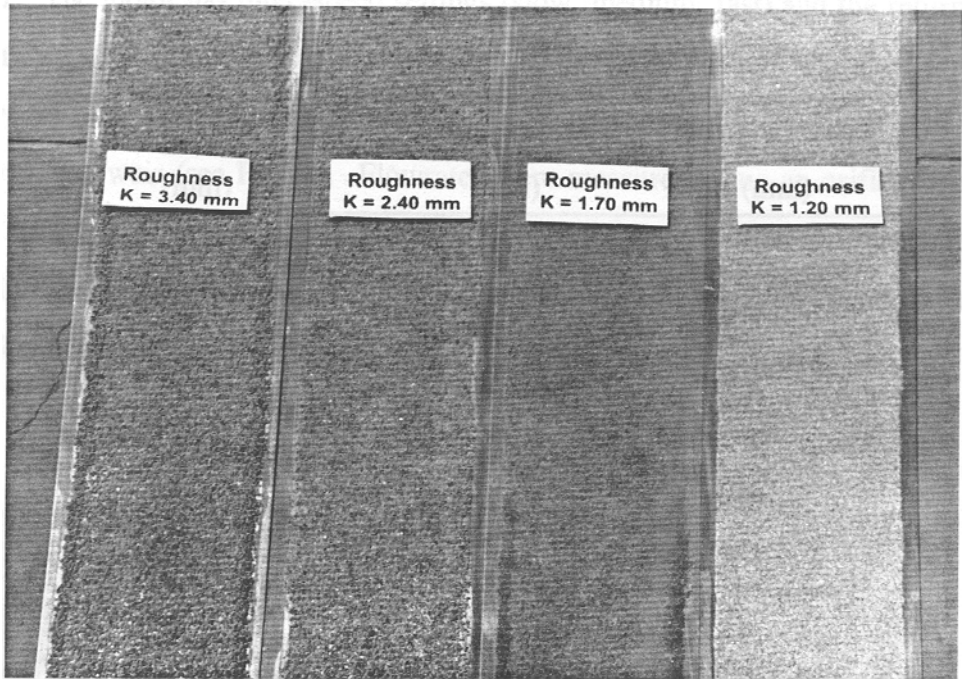

Figure 3.2: Form Roughened Plates

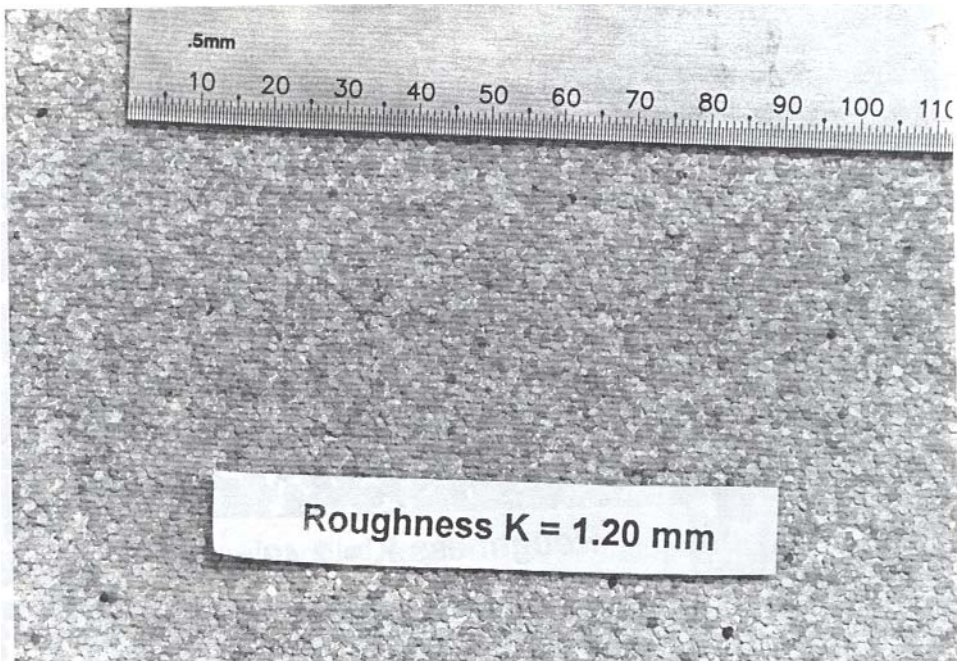

Figure 3.3: Plate at Roughness k_s = 1.2 mm

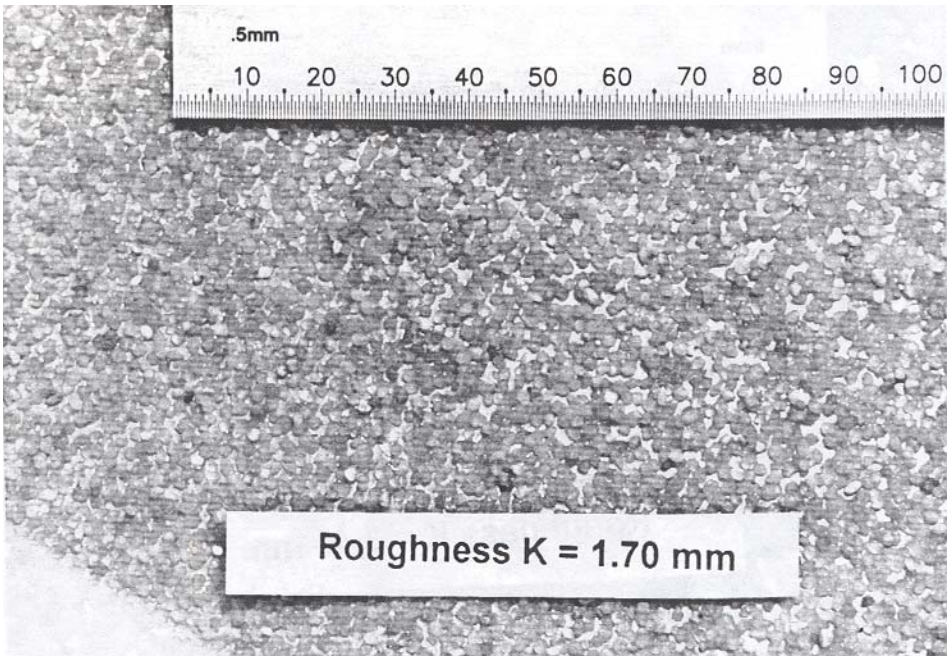

Figure 3.4: Plate at Roughness k_s = 1.7 mm

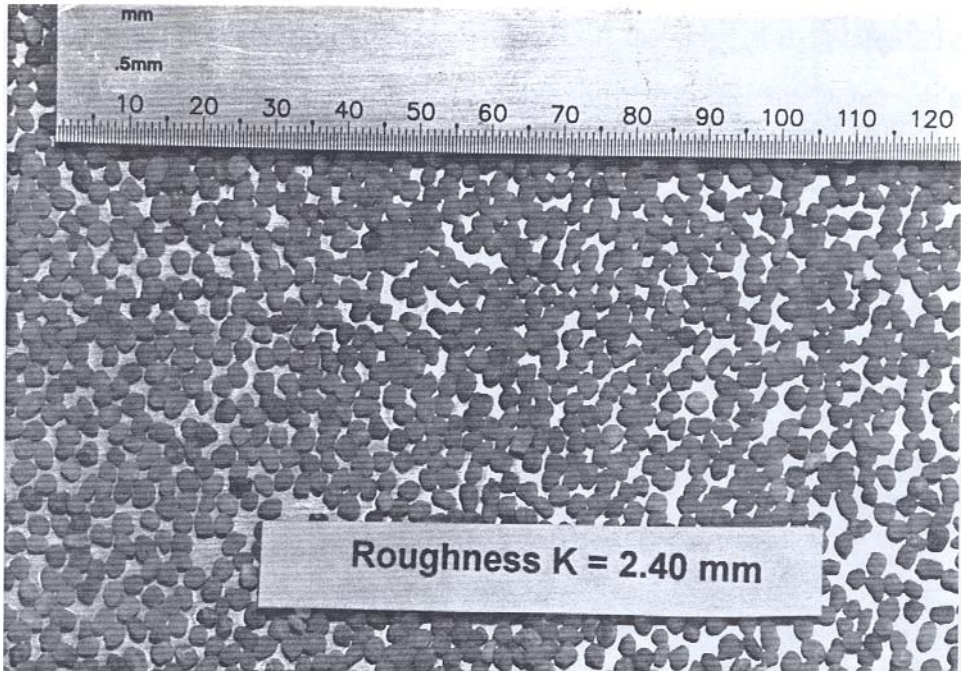

Figure 3.5: Plate at Roughness k_s = 2.4 mm

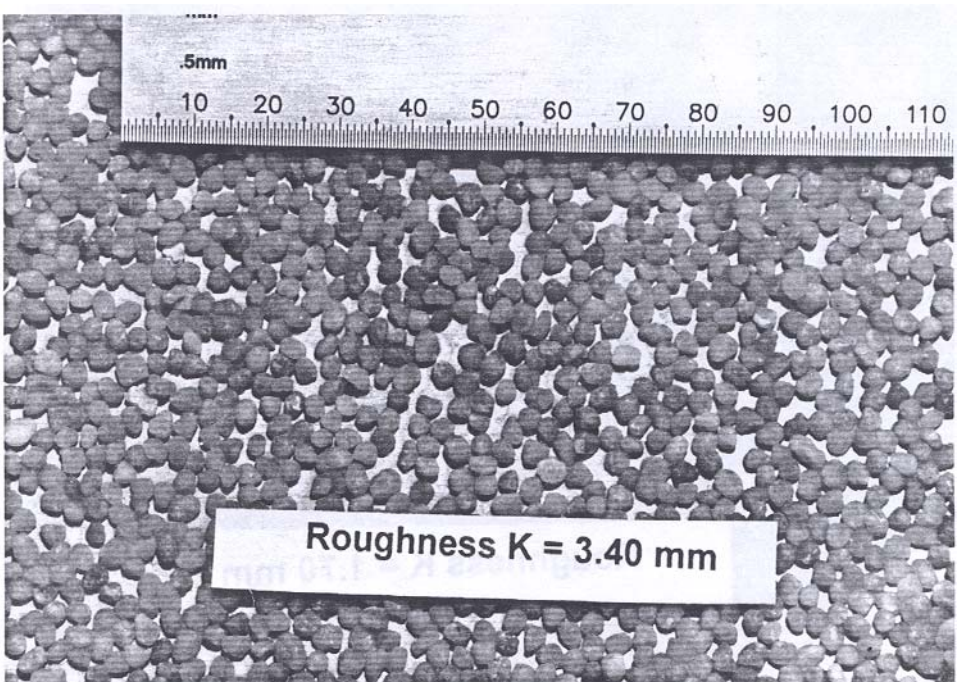

Figure 3.6: Plate at Roughness k_s = 3.4

3.3. THE PARTICLES

Three types of particles were run in the experiment: stainless steel ball bearings, glass marbles and natural quartz particles. The steel ball bearing and glass marbles were used because of their precise spherical shape. Using steel and glass also gave results for particles of two different densities. The quartz particles were used to emulate conditions closer to natural conditions for slope and density, and also to examine the effects of particle angularity.

As can be seen from Fig. 3.7 and Table 3.2, a large number of particle types and diameters were tested. Not all of them moved in every run. For the lower transport rates, most steel particles didn't move at all, or did so only for short distances before halting, because of their high density. The natural particles also rolled very little at low transport

stages, tending to sit on their flatter sides. For the higher transport stages the smaller steel and natural particles simply disappeared when dropped in the water, presumably whisked away in suspension. The glass marbles were the most consistent across all transport stages. Almost every run used all five marbles. Many different particles were used for each size. The particles were sieved and categorized accordingly. For example, the 3.4 mm diameter “particle” was in fact a set of particles, all passing though the 4.00 mm sieve and retained in the 2.8 mm sieve.

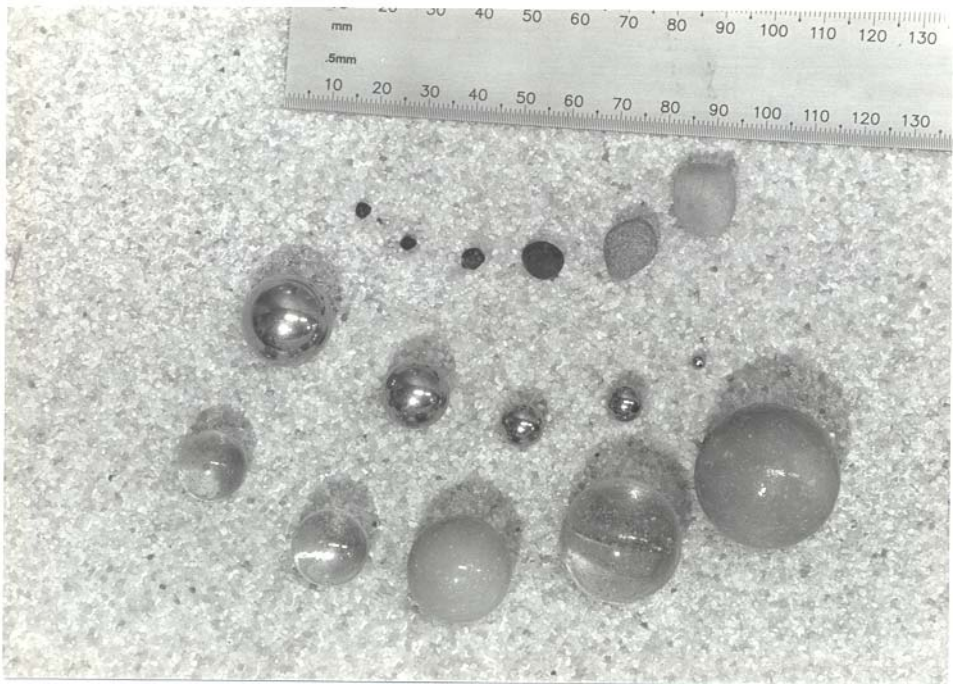

Figure 3.7: Particles used in the Experiment

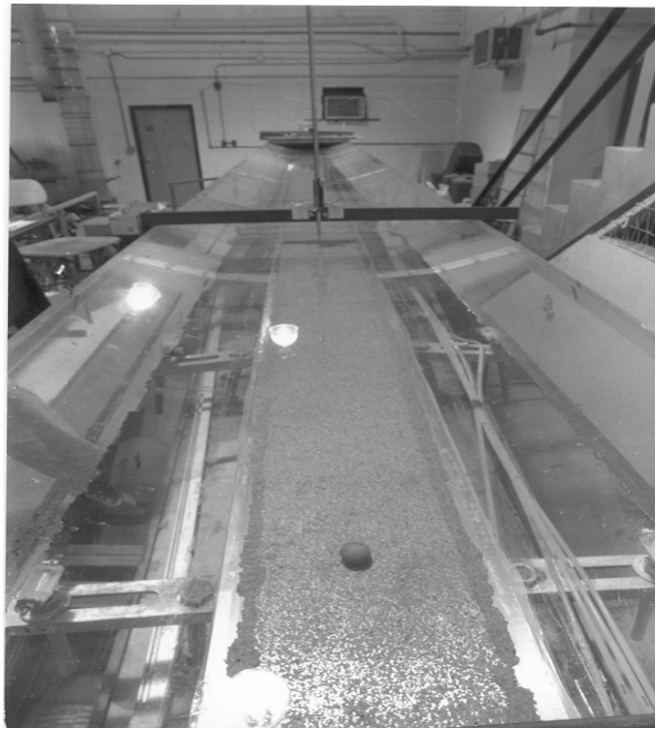

Figure 3.8: The Experiment

Table 3.2: Particle Size used in the Experiments

Type	G	Diameter (mm)	Sieve Retained (mm)	Sieve Passed (mm)
Steel	8.02	19.04		
		15.88		
		14.28		
		9.50		
		7.90		
		6.34		
		4.75		
		3.14		
		1.57		
Glass	2.60	29.30		
		25.17		
		21.70		
		15.97		
		14.48		
Natural	2.65	13.60	11.2	16.0
		9.60	8.0	11.2
		6.80	5.6	8.0
		4.80	4.0	5.6
		3.40	2.8	4.0
		2.40	2.0	2.8
		1.70	1.4	2.0
		1.20	1.0	1.4

3.4. EXPERIMENTAL SET UP

Establishing the desired hydraulic conditions for each run involved setting the bed slope, pump, valve and (optionally) adjusting the weir in order to reach a predetermined value of shear velocity u_*. In general, a bed slope and pump setting were selected, then the valve and weir adjusted until the two point gages in the test section indicated approximately the same flow depth. If the flow depth was too shallow (<50 mm), or if the value of u_* undesirable, bed slope and/or pump setting were changed and the process started over. Adjustments were made until the difference in flow depths between point gages was smaller than 15% of the drop in bed elevation between the point gages (due to the bed slope).

After the hydraulic conditions were set (and recorded) for a given run, the particles were released upstream and their times measured over the 2 m test section. Notes were taken on any non-uniform particle motion, such as surging of particles, suspension or halting. If a particle ran off the plate, that measurement was discarded and repeated. Each particle was run at least 15 times. Hydraulic conditions were measured and recorded at the middle and end of each run, allowing an average over three readings for flow depths, top flow widths, and manometer readings. A total of 49 runs have been completed on plates with six different roughness. For each roughness, a range of values of shear velocity $u_* = (\tau_o/\rho)^{1/2}$ were used in the range where the particles are expected to be in motion and in contact with the bed. A summary of the runs is presented in Tables 3.3 and Table 3.4. One set of plates had no roughness and the experiments for the 2.4 mm gravel were repeated using rounded versus angular material to identify possible differences owing to the angularity of the surface material. Fig. 3.9 Shows a linear relationship

between settling velocity *w*, and $[(G-1)gd_s]^{1/2}$, the plot indicated that $w \cong 0.9423\ [(G-1)gd_s]^{1/2}$ with $R^2 = 1.0$.

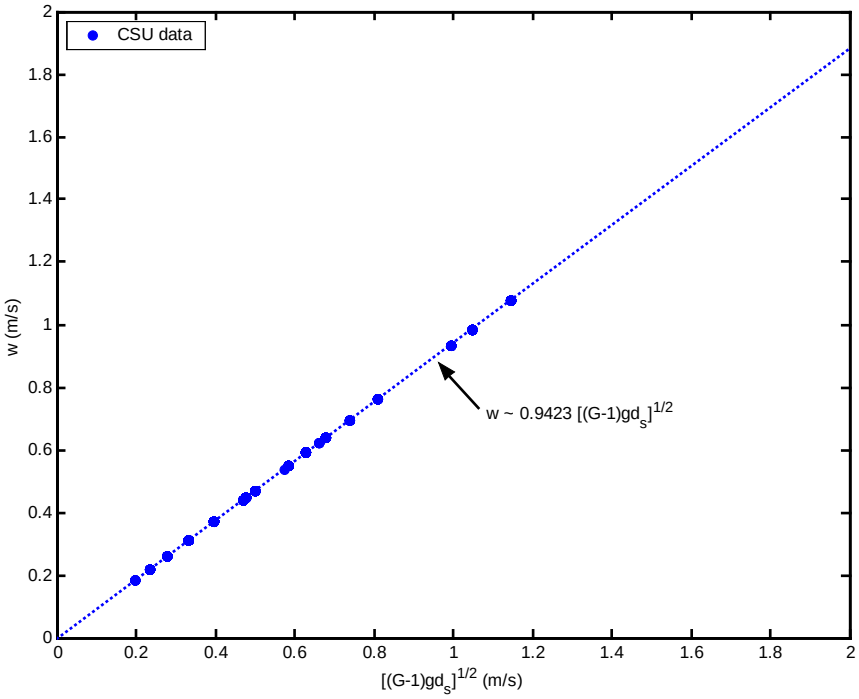

Figure 3.9: w vs. $[(G-1)gd_s]^{1/2}$

Table 3.3: Classification of Experimental Runs

Run Number	u_* (m/s)	Roughness (mm)	Run Number	u_* (m/s)	Roughness (mm)
1	0.0111	0	26	0.0501	3.4 (rounded)
2	0.0176	0	27	0.055	3.4 (rounded)
3	0.016	0	28	0.0625	1.7 (rounded)
4	0.0119	0	29	0.0593	1.7 (rounded)
5	0.0141	0	30	0.0516	1.7 (rounded)
6	0.0152	0	31	0.048	1.7 (rounded)
7	0.0194	0	32	0.0419	1.7 (rounded)
8	0.0249	0	33	0.0359	1.7 (rounded)
9	0.0299	0	34	0.0242	1.7 (rounded)
10	0.0176	0	35	0.0285	1.7 (rounded)
11	0.0356	0	36	0.0186	1.7 (rounded)
12	0.0097	0	37	0.0616	2.4 (rounded)
13	0.0301	2.4 (angular)	38	0.0558	2.4 (rounded)
14	0.0386	2.4 (angular)	39	0.0514	2.4 (rounded)
15	0.025	2.4 (angular)	40	0.0467	2.4 (rounded)
16	0.0339	2.4 (angular)	41	0.0378	2.4 (rounded)
17	0.0506	2.4 (angular)	42	0.0317	2.4 (rounded)
18	0.0641	2.4	43	0.019	2.4 (rounded)
19	0.0424	0	44	0.0248	2.4 (rounded)
20	0.0623	3.4 (rounded)	45	0.019	1.2 (rounded)
21	0.024	3.4 (rounded)	46	0.027	1.2 (rounded)
22	0.0231	3.4 (rounded)	47	0.036	1.2 (rounded)
23	0.0298	3.4 (rounded)	48	0.044	1.2 (rounded)
24	0.0362	3.4 (rounded)	49	0.051	1.2 (rounded)
25	0.0438	3.4 (rounded)			

The voluminous data set in Appendix A provides a substantial compilation of particle velocity information for each size fraction for plane surfaces of different roughnesses and particles of different size, density and angularity.

3.5. PRELIMINARY RESULTS

The data set shows the following overall characteristics: (1) under given hydraulic and surface roughness conditions, coarse particles generally roll faster than fine particles; (2) exceptions to (1) were observed, either when smaller particles were partly in saltation, or when the standard deviation of repeated particle velocity measurements were large compared to the mean velocity; (3) the most convincing results are found on runs 3 and 5 for a smooth plate, and runs 34, 36, and 44 for rough plates; (4) at a given roughness size, particles roll slightly faster on a plane boundary of rounded particles as opposed to angular particles; and (5) as shear velocity u_* increases, the smaller particles enter saltation and tend to move faster than coarse particles.

A plot of particle velocity against particle diameter for a smooth bed ($k_s = 0$) is shown in Fig. 3.10. where larger particles move faster than smaller ones for all values of shear velocity. Larger particles protrude higher into the flow, in regions with higher flow velocities. There are no clear differences in transport velocities for particles of different densities; Fig. 3.11 shows that lighter particles move faster than heavier particles, and particle velocity tends to decrease with the increase of the particle size; for natural particles, the variability of particle velocity with respect to particle size is high, this may

be the effect of particle shape; and for glass particles, larger particles move faster than smaller ones.

Fig 3.12 shows the ratio of particle velocity V_p to shear velocity u_* lies in the range of 2.5 to 12.5; Fig. 3.13 shows, for glass and natural particles (lighter), $V_p \cong 9.14u_*$, and for steel particles (heavier), $V_p \cong 3.94u_*$; Fig. 3.14 shows the variation of particle velocity, V_p against Shields parameter, τ_{*ds}. Fig. 3.15 shows the ratio of particle velocity V_p to mean flow velocity u_f lies in the range of 0.2 to 0.9; Fig. 3.16 shows that spherical particles move faster than angular particles at the same $u_*/[(G-1)gd_s]^{1/2}$.

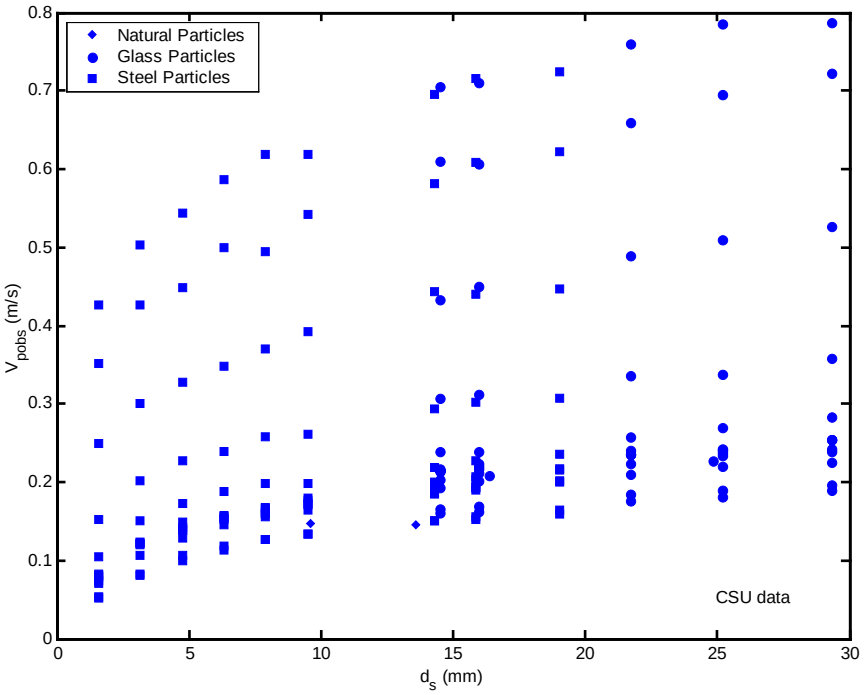

Figure 3.10: V_{pobs} vs d_s for $k_s = 0$

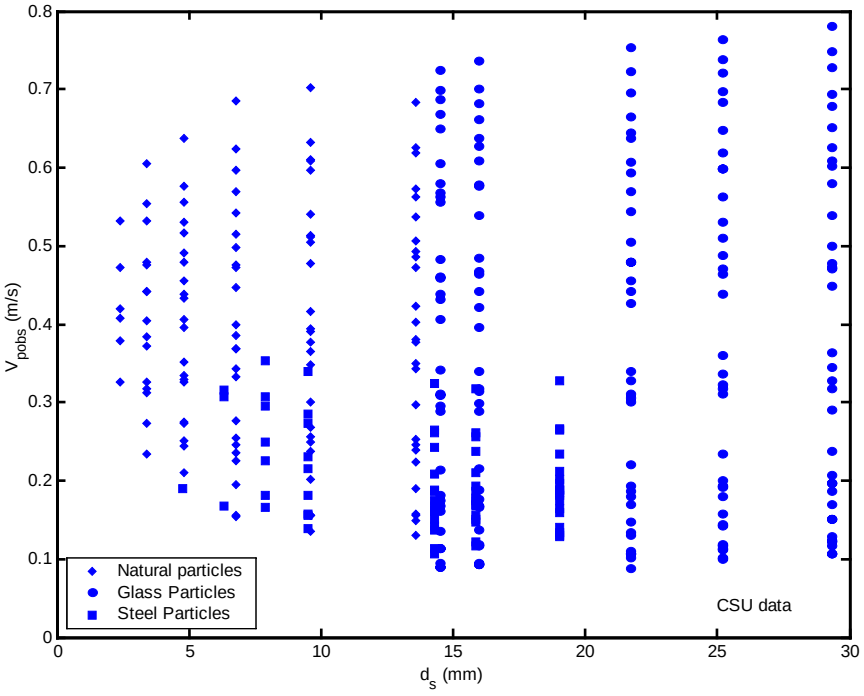

Figure 3.11: V_{pobs} vs d_s for $k_s > 0$

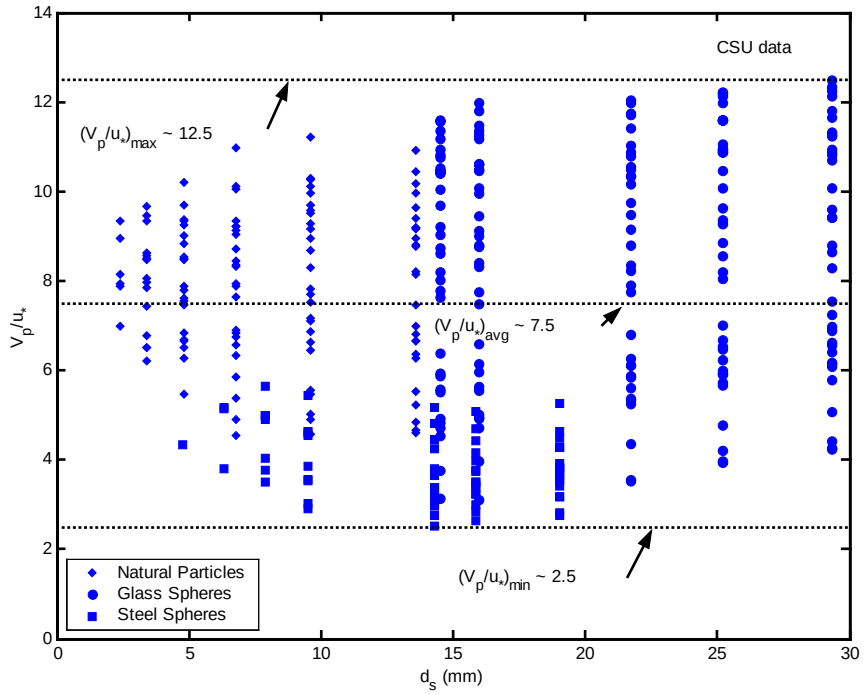

Figure 3.12: V_p/u_* vs d_s

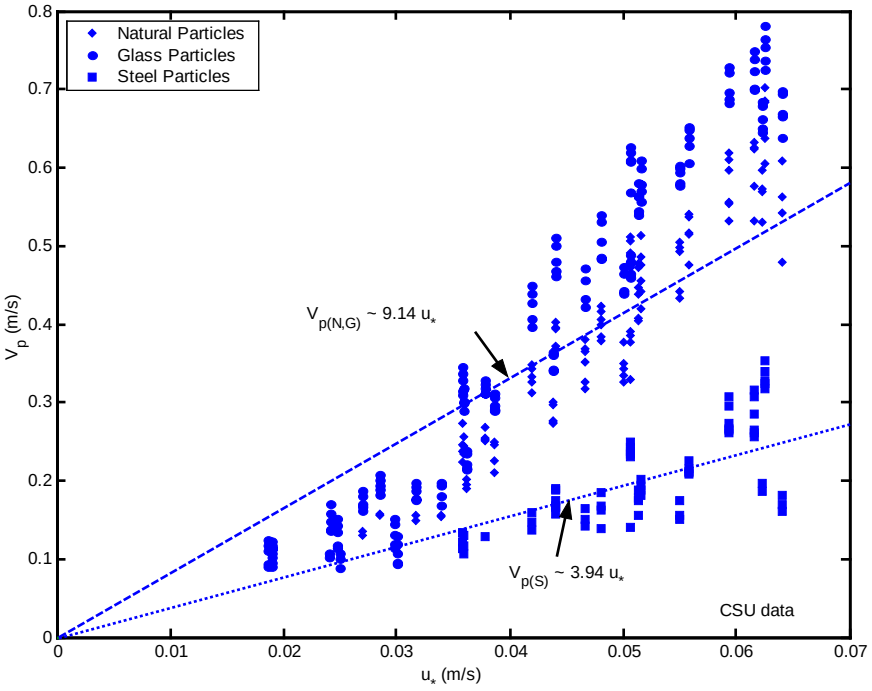

Figure 3.13: V_p vs u_*, a) $V_{p(N,G)} \sim 9.14u_*$, and b) $V_{p(S)} \sim 3.94u_*$

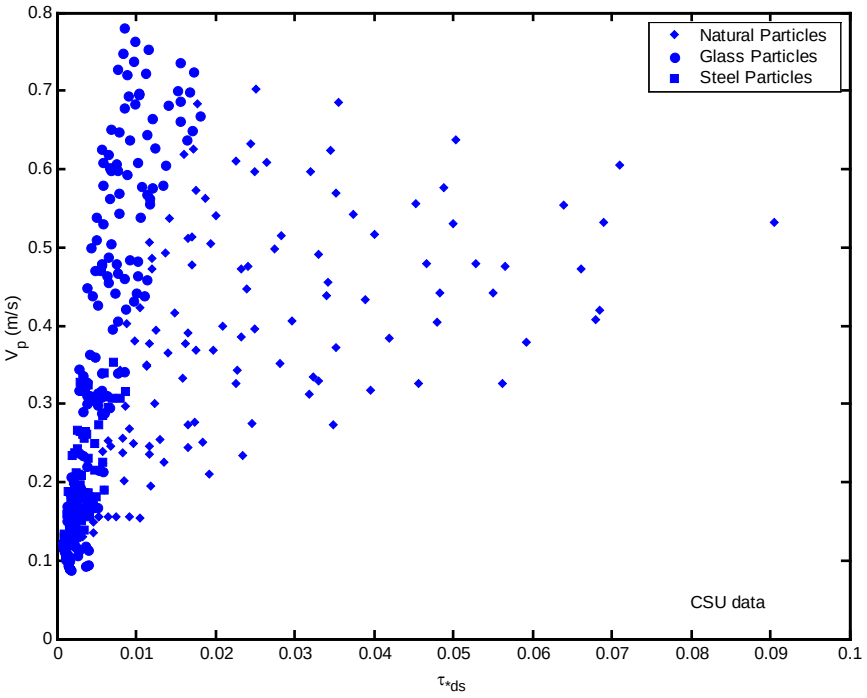

Figure 3.14: V_p vs τ_{*ds}

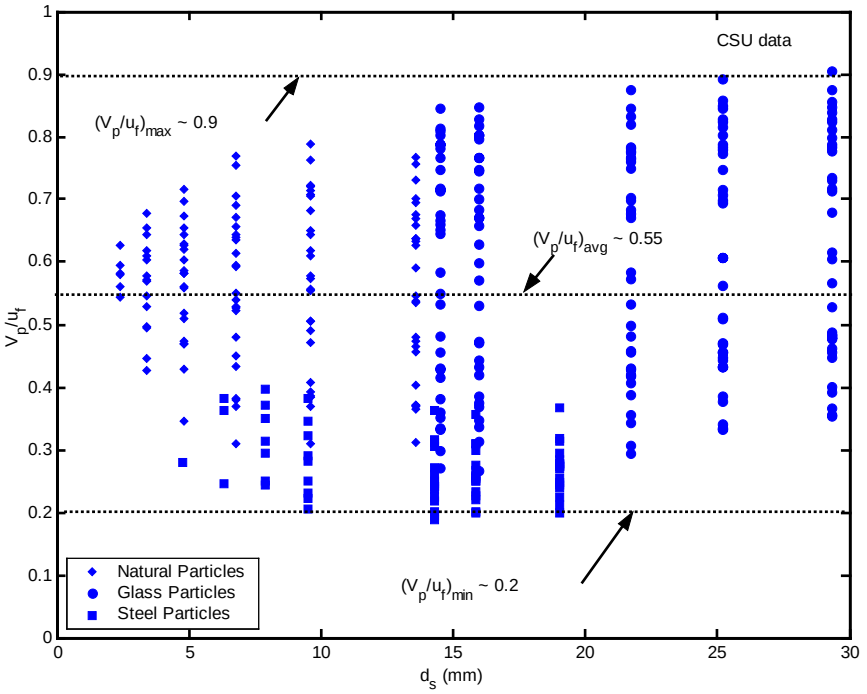

Figure 3.15: V_p/u_f vs d_s

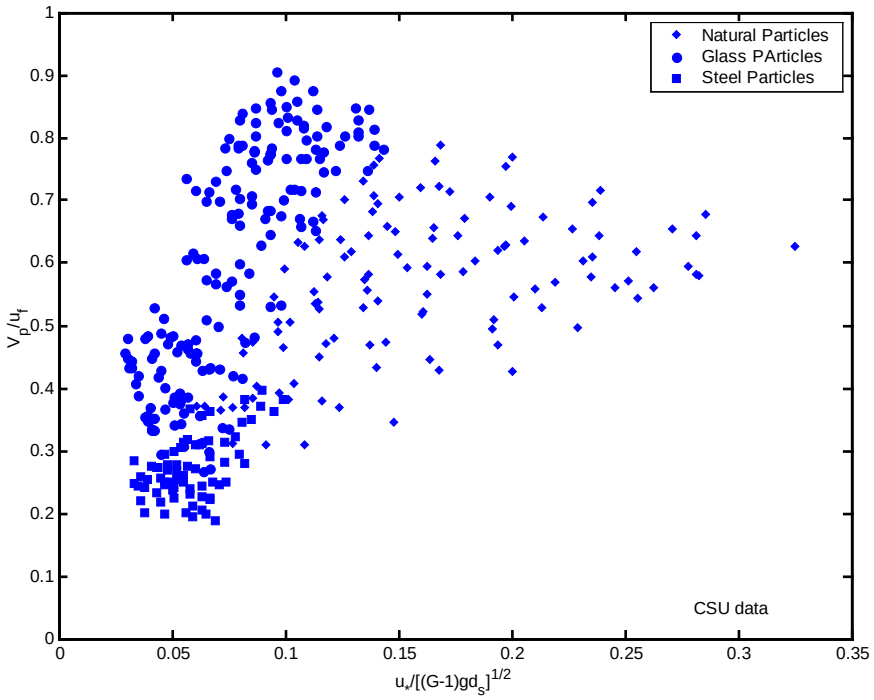

Figure 3.16: V_p/u_f vs $u_*/[(G-1)gd_s]^{1/2}$

From Fig. 3.13, we generated linear equations of the following form, for each bed roughness and particle type:

$$V_p = C_1 + C_2 u_* \tag{3.1}$$

where: C_1 and C_2 are constants, these equations were then reduced to the form of Eq. (2.19) by introducing the absolute value of C_1/C_2 as a new positive constant:

$$V_p = C_2\left(u_* - \left|C_1 / C_2\right|\right) \tag{3.2}$$

where: $c = C_2$ and $\left|C_1/C_2\right| = u_{*c}$. The computed values of c and u_{*c} for different bed roughness and particle types is shown in Table 3.4.

Table 3.4. Computed Values of c and u_{*c} for different k_s and Particle type

Particle Type	k_s (mm)	c	u_{*c} (m/s)	R^2
Natural	0	NA	NA	NA
(G = 2.6)	1.2	15.51	0.0192	0.98
	1.7	14.83	0.0197	0.97
	2.4	14.03	0.0212	0.93
	3.4	14.83	0.0244	0.95
Glass	0	18.61	0.0033	0.94
(G = 2.65)	1.2	16.29	0.0145	0.98
	1.7	15.39	0.0143	0.99
	2.4	15.87	0.0187	0.95
	3.4	16.33	0.0214	0.98
Steel	0	15.08	0.0044	0.85
(G = 8.02)	1.2	7.93	0.0213	0.93
	1.7	8.21	0.0251	0.89
	2.4	5.08	0.0152	0.42
	3.4	4	0.0147	0.77

3.6. STATISTICAL ANALYSIS

In the statistical analysis, the discrepancy method is adopted to indicate the goodness of fit between the calculated and observed results. The discrepancy ratio, R_i

$$R_i = \frac{V_{pcal(i)}}{V_{pobs(i)}} \tag{3.1}$$

in which $V_{pcal(i)}$, $V_{pobs(i)}$ = calculated and observed bedload particle velocity corresponding to data point number in a data set. For a perfect fit, $R_i = 1.0$.

3.7. PARAMETRIC ANALYSIS OF CSU DATA

Fig. 3.17, 3.19, and 3.20 show that $\tau_{*ds}/0.047 \approx 0.01$ ($\tau_{*ds} \approx 0.00047$), when $k_s<d_s$, bedload particles move at values of shear stress below the threshold value given by the Shields diagram, and $\tau_{*ds} = 0.047$ when $d_s = k_s$. Fig. 3.18 shows the values of τ_{*ks} is in the range of 0.01 to 0.15; Fig. 3.20 shows values of $Re_* > 100$; Fig. 3.21 shows $V_p/[(G-1)gd_s]^{1/2} < 2$, then combined with Fig. 3.9, resulted in $V_p/w < 2$, and therefore $V_p < 2w$; and Figs. 3.22 and 3.23 show the values of V_p/u_* is in the range of 2.5 to 12.5, and the threshold value for τ_{*ks} is 0.01; Figs. 3.24 and 3.25 show the values of $u_*/w < 0.5$, which is in agreement with the criterion for bedload sediment transport in Julien (1995, p.187, Figure 10.4).

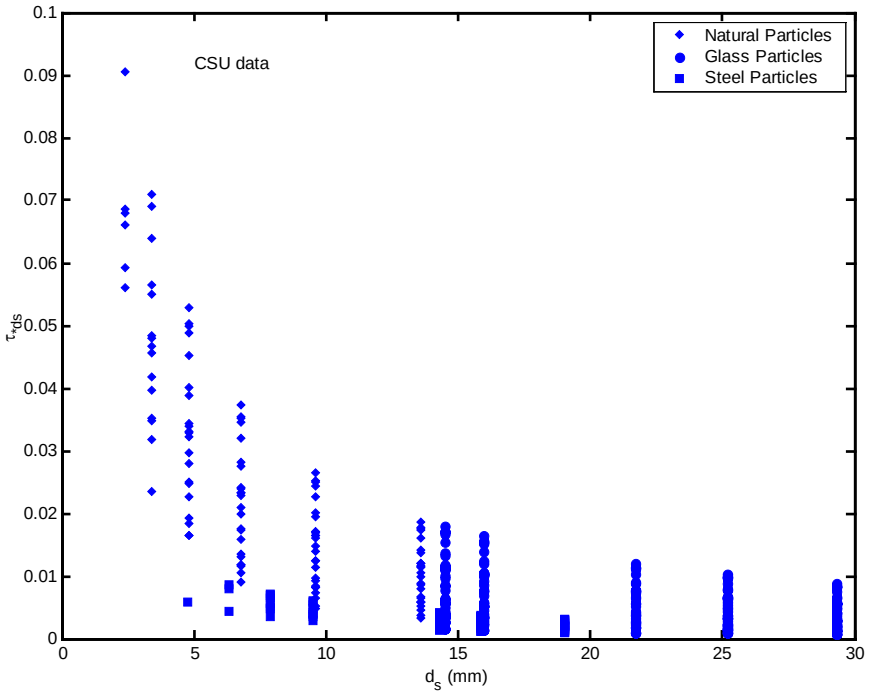

Figure 3.17: τ_{*ds} vs d_s

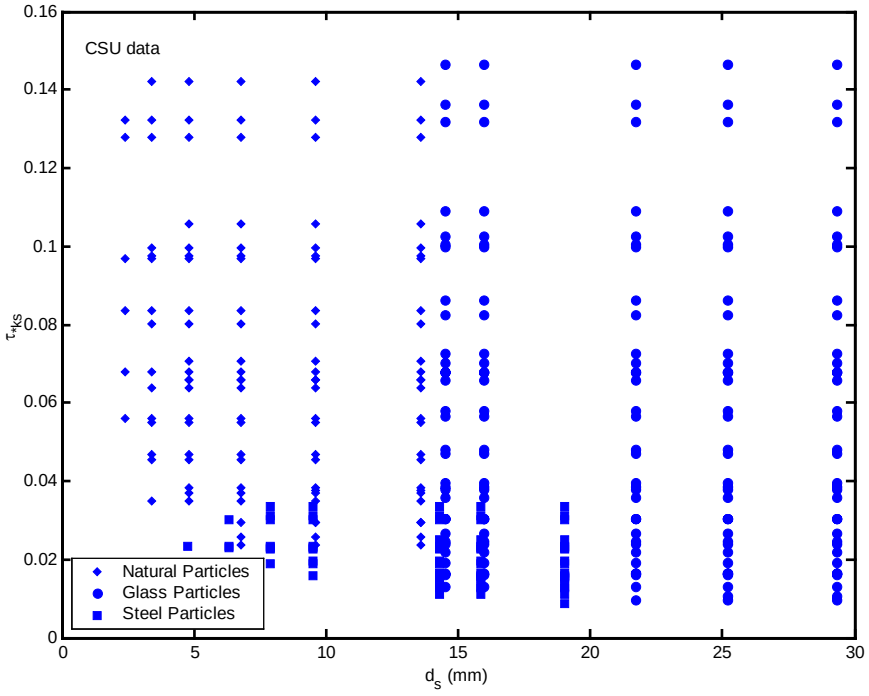

Figure 3.18: τ_{*ks} vs d_s

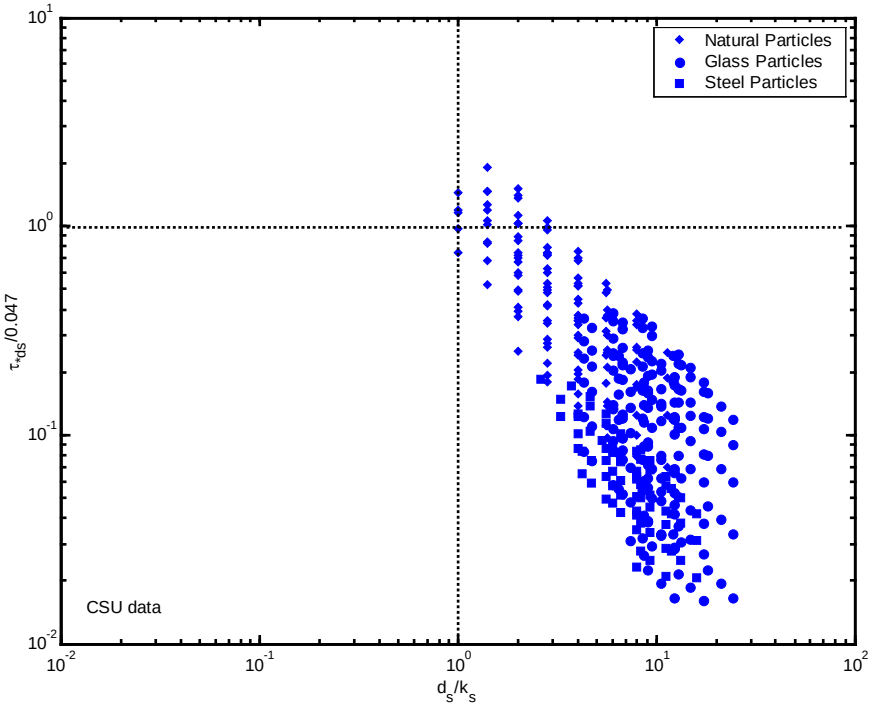

Figure 3.19: $\tau_{*ds}/0.047$ vs d_s/k_s

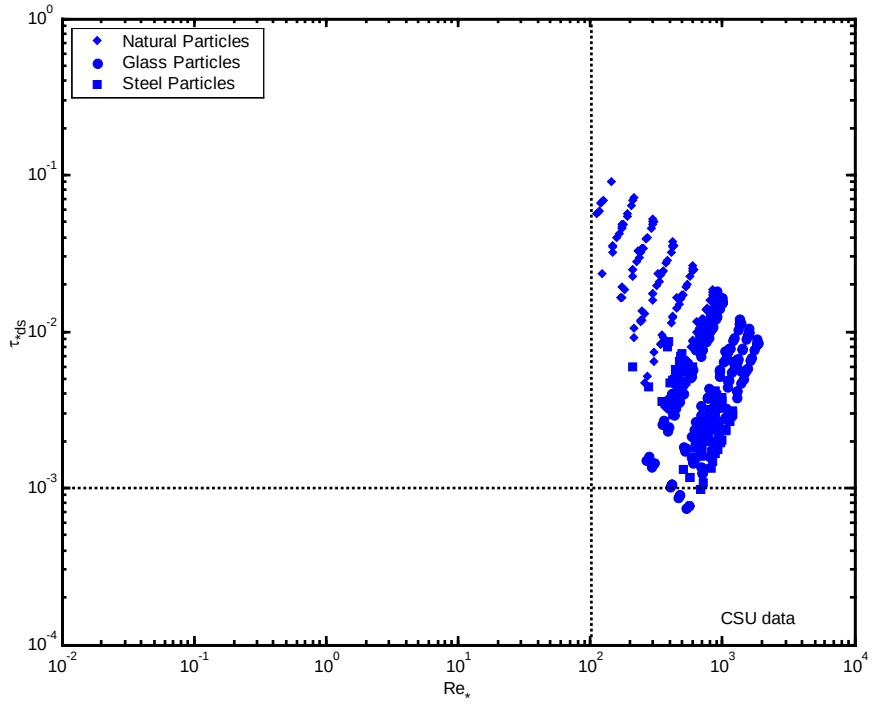

Figure 3.20: τ_{*ds} vs Re_*

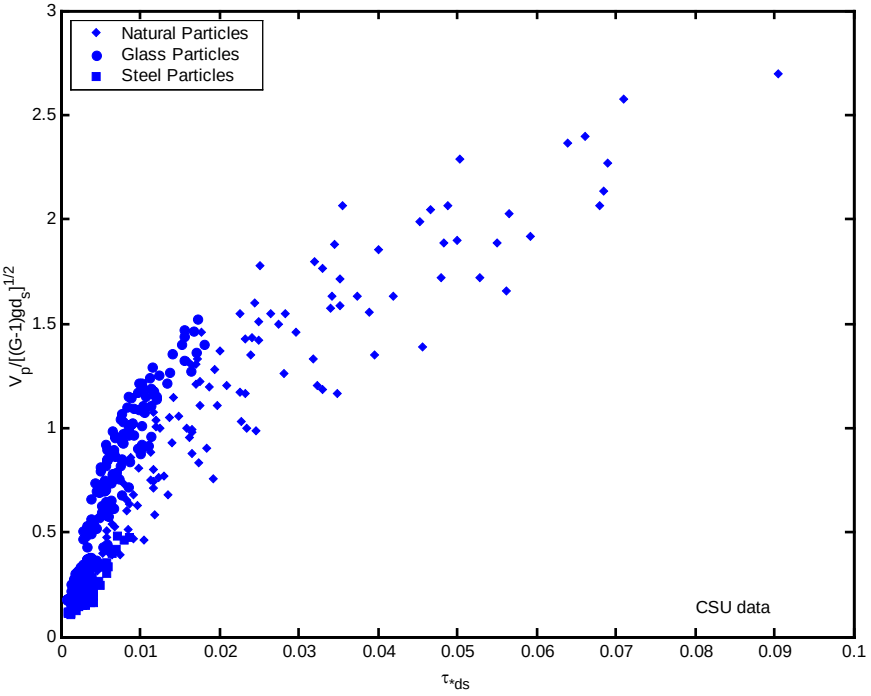

Figure 3.21: $V_p/[(G-1)gd_s]^{1/2}$ vs τ_{*ds}

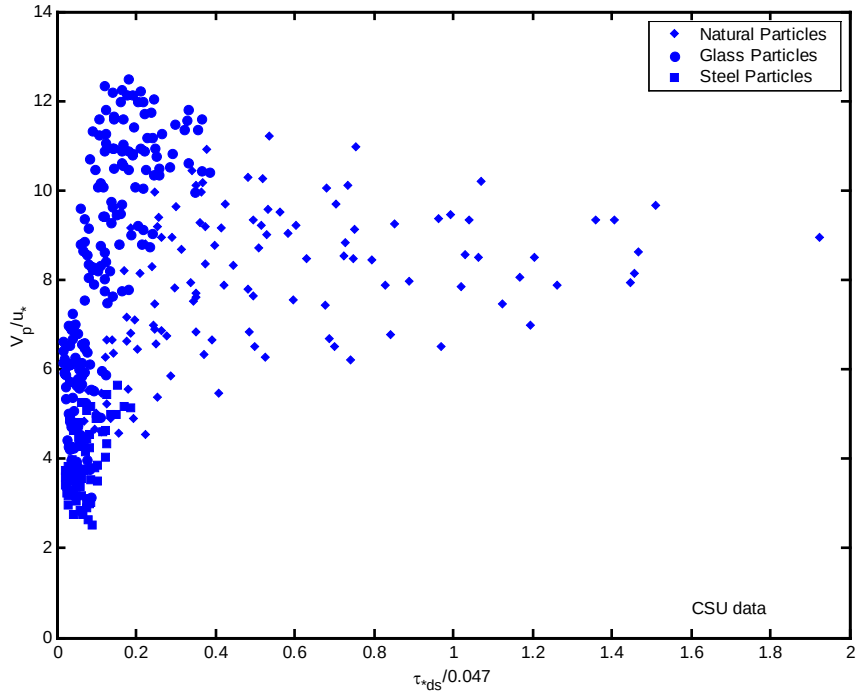

Figure 3.22: V_p/u_* vs $\tau_{*ds}/0.047$

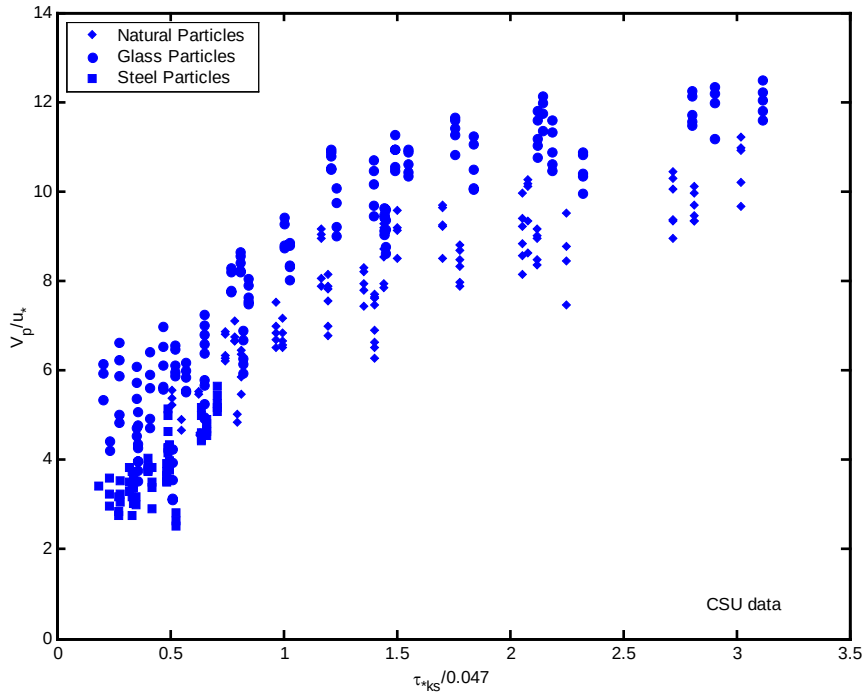

Figure 3.23: V_p/u_* vs $\tau_{*ks}/0.047$

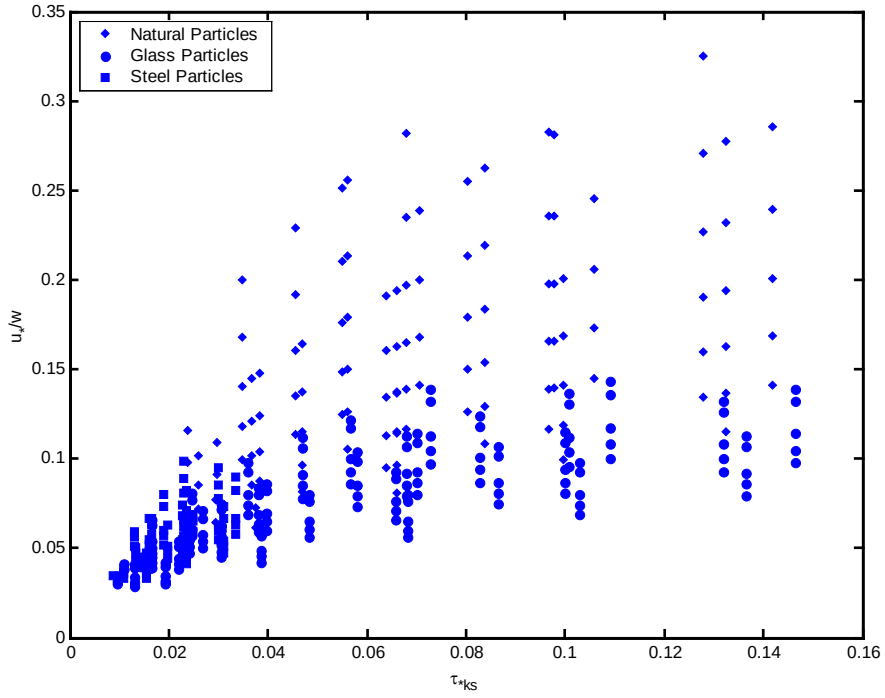

Figure 3.24: u_*/w vs τ_{*ks}

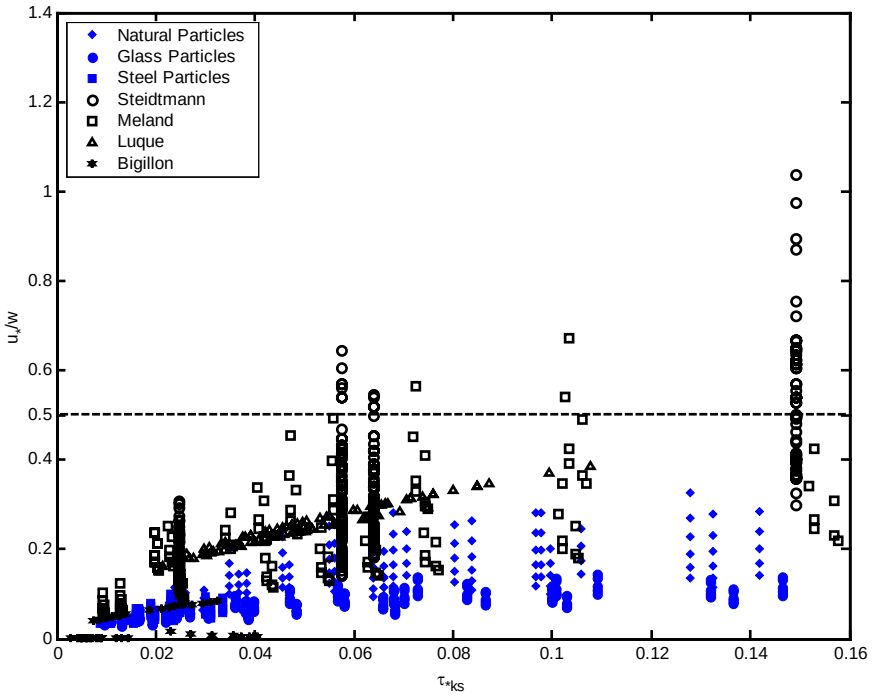

Figure 3.25: u_*/w vs τ_{*ks}, for different database

3.8. SUMMARY

Analysis of the data showed that: (i) for a smooth bed ($k_s = 0$) larger particles move faster than smaller ones. In other words, rolling bedload particle velocity increases with particle sizes; (ii) for a rough bed ($k_s > 0$) lighter particles move faster than heavier ones; (iii) bedload particles move at values of the Shields parameter $\tau_{*ds} < 0.047$ when $d_s > k_s$; (iv) the ratio of particle velocity V_p to mean flow velocity u_f lies in the range of 0.2 to 0.9, while Kalinske (1942) suggested 0.9 to 1.0; (v) the ratio of particle velocity V_p to shear velocity u_* lies in the range of 2.5 to 12.5, while Kalinske (1947) suggested 11.0, Bagnold (1956, 1973) suggested 8.5, Francis (1973) suggested 8.3 to 11.8, Fernandez Luque and van Beek (1976) suggested 11.5, Engelund and Fredsoe (1976, 1982)

suggested 6.0 to 10.0, Fleming and Hunt (1976) suggested 9.0, Abbott and Francis (1977) suggested 13.5 to 14.3, Mantz (1980) suggested 9.2, and Naden (1981) suggested 11.8; (vi) $0.01 < \tau_{*ks} < 0.15$; (vii) $Re_* > 100$; (viii) $V_p < 2w$; (ix) the threshold value for τ_{*ks} appears to be 0.01; (x) $u_*/w < 0.5$.

CHAPTER 4

DIMENSIONAL AND REGRESSION ANALYSIS

The subject of transport velocity of a single particle over rough open channel flow is complicated since it involves several unknown parameters, such as the drag coefficient and the friction coefficient. To date, theoretical solutions of particle velocities are uncertain at best. The approach of this Chapter is to combine the methods of dimensional and regression analysis. Roughness and rolling particle interactions have been proven to be highly dependent on geometrical constraints such as: particle sizes (both roughness and rolling), relative roughness, and bed slope.

The challenge becomes one of deriving an equation that encompasses the correct variables without being too awkward to use. Ideally, the derived equation should predict the desired output relatively well, without the inclusion of empirical coefficients. This Chapter first examines the CSU data and particularly the Shields parameter in term of

rolling particle diameter d_s and boundary roughness k_s. The dimensional and regression analyses are then presented. An empirical equation is finally tested with data from CSU, other laboratories and field measurements.

4.1. EXAMINATION OF SHIELDS APPROACH

The simplest empirical form of estimated bedload particle velocity based on analysis of CSU data is shown in Fig. 4.1, and is a variation of $V_p/[(G-1)gd_s]^{1/2} \sim u_*^2/(G-1)gk_s$.

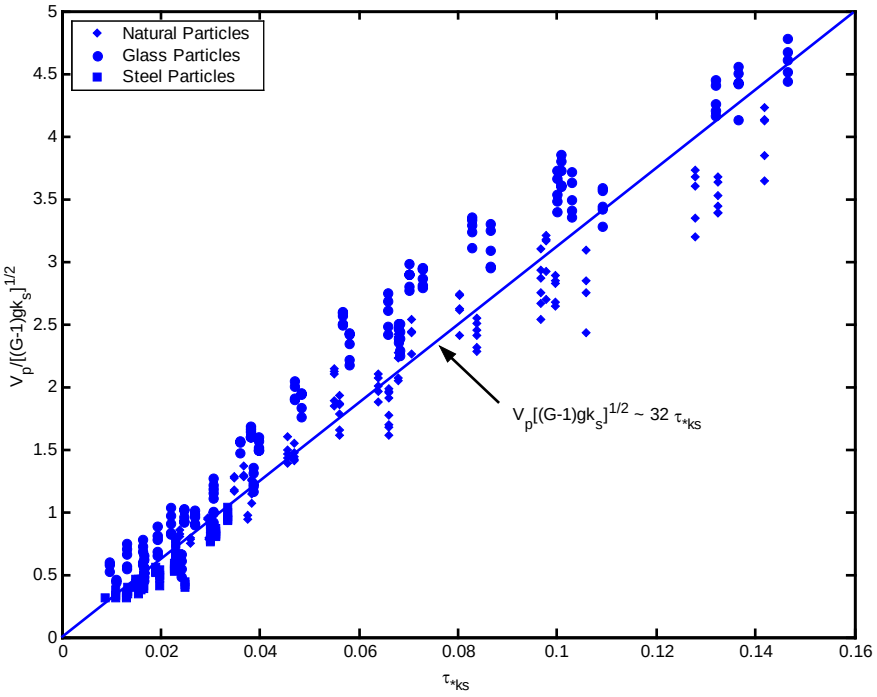

Figure 4.1: $V_p/[(G-1)gk_s]^{1/2}$ vs τ_{*ks}

From Fig. 4.1, we have

$$\frac{V_p}{\sqrt{(G-1)gd_s}} \sim 32\frac{u_*^{\,2}}{(G-1)gk_s} \tag{4.1}$$

or

$$\frac{V_p}{u_*} \sim 32\frac{u_*}{\sqrt{(G-1)gk_s}} \tag{4.2}$$

or

$$\frac{V_p}{u_*} \sim 32\tau_{*ks}^{\,1/2} \tag{4.3}$$

The bedload particle velocity can be estimated by

$$V_p \cong 32u_*\tau_{*ks}^{\,1/2} \tag{4.4}$$

Since the Shields parameter is usually written in term of d_s, a three-parameter empirical model is introduced. The variation of $V_p/[(G\text{-}1)gd_s]^{1/2}$ with Shields parameter $\tau_{*ds} = u_*^{\,2}/[(G\text{-}1)gd_s]$, and (k_s/d_s), then transforms (4.4) into power form equation as shown below

$$\frac{V_p}{\sqrt{(G-1)gd_s}} = a\left[\frac{u_*^{\,2}}{(G-1)gd_s}\right]^b\left(\frac{d_s}{k_s}\right)^c \tag{4.5}$$

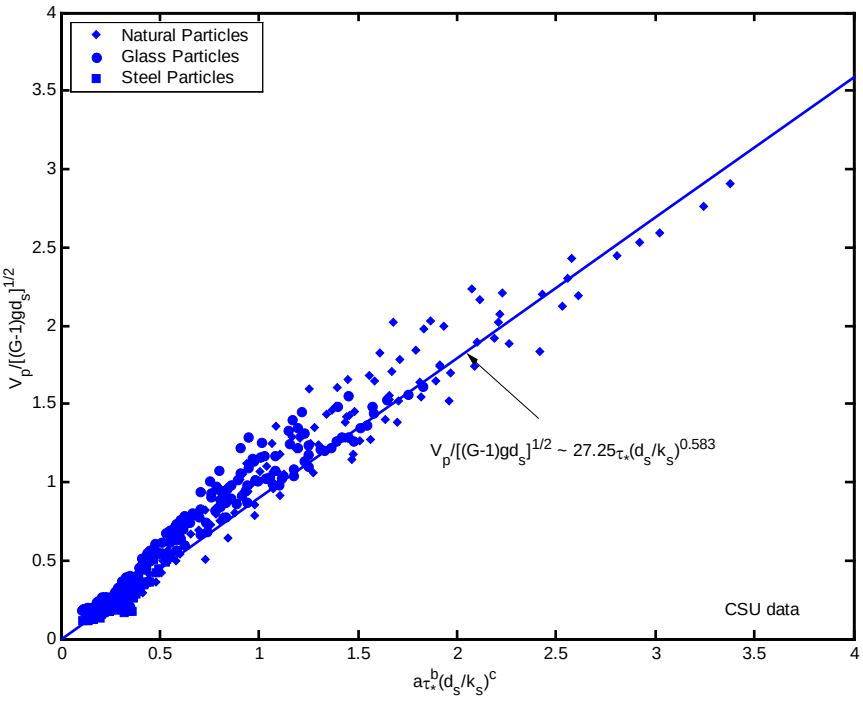

Figure 4.2: $V_p/[(G-1)gd_s]^{1/2} \sim 30.5\tau_{*ds}^{1.0}(d_s/k_s)^{0.583}$

Using EXCEL multiple regression analysis toolbox, the coefficients *a*, *b*, and *c* can be determined using:

$$\log \frac{V_p}{\sqrt{(G-1)gd_s}} = \log a + b \log \tau_{*ds} + c \log\left(\frac{d_s}{k_s}\right) \tag{4.6}$$

Applied to CSU's (1995) database, one obtains

$$V_p = 30.5\left[\frac{u_*^{\,2}}{(G-1)gd_s}\right]^1\left(\frac{d_s}{k_s}\right)^{0.583}\sqrt{(G-1)gd_s} \tag{4.7}$$

Similarly, when applied to the entire database, one obtains

$$V_p = 6.59\left[\frac{u_*^{\,2}}{(G-1)gd_s}\right]^{0.94}\left(\frac{d_s}{k_s}\right)^{1.1}\sqrt{(G-1)gd_s} \tag{4.8}$$

The rolling bedload particle velocity can be estimated by Eqs. (4.7) and (4.8), where: shear velocity $u_* = [gR_hS_f]^{1/2}$ (m/s), d_s = particle size (mm), k_s = bed roughness (mm), G = particle specific gravity, and g = gravitational acceleration (m/s^2). The comparison between calculated and observed rolling bedload particle velocity V_p is shown in Figs. 4.3 and 4.5; Figs 4.4 and 4.6 show a discrepancy ratio distribution using Eqs. (4.7), and (4.8). Since the empirical regression coefficients b and c are quite close to unity, the basic form of Eq. (4.1) is found to be representative of laboratory conditions. It is concluded that the Shields roughness parameter $\tau_{*ks} = u_*^2/[(G-1)gk_s]$ can be useful to determine bedload particle velocity.

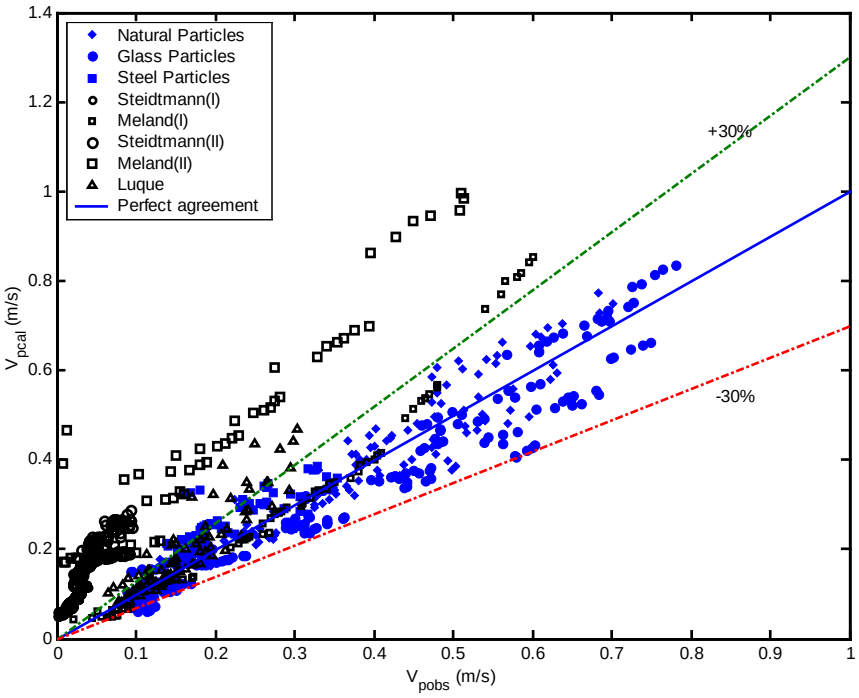

Figure 4.3: Comparison between Calculated and Observed V_p using Eq. (4.7)

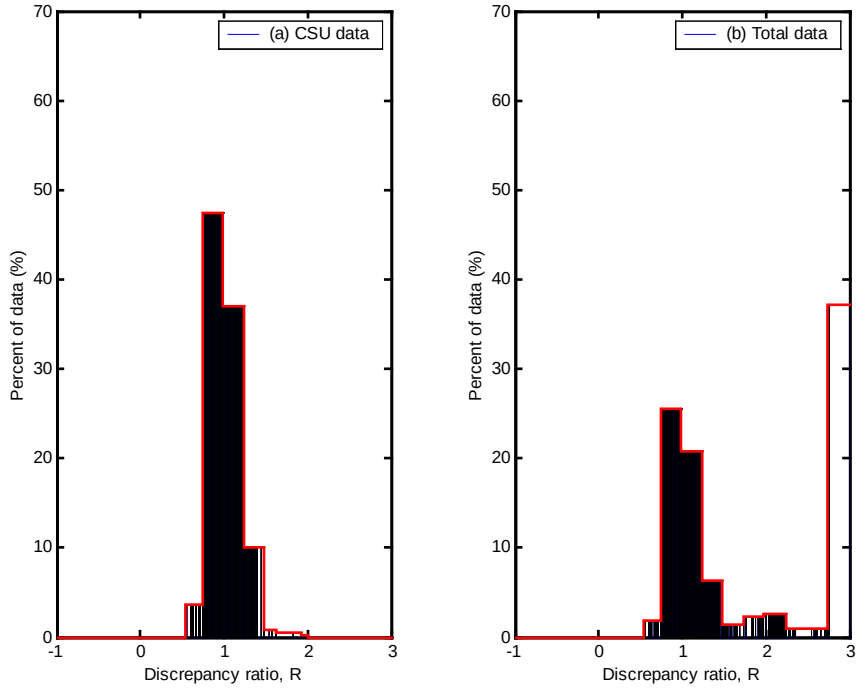

Figure 4.4: Discrepancy Ratio Distribution of V_p using Eq. (4.7)

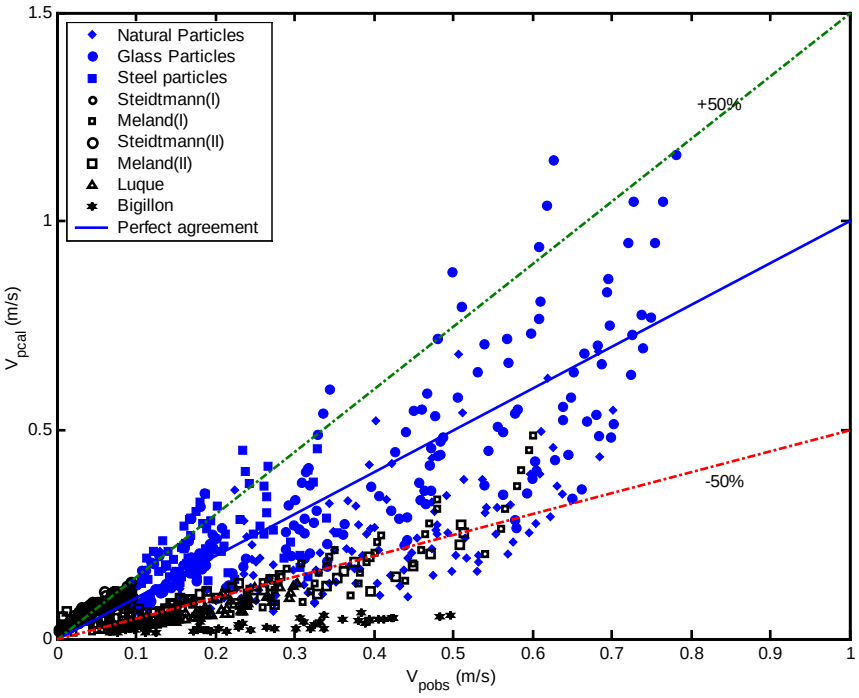

Figure 4.5: Comparison between Calculated and Observed V_p using Eq. (4.8)

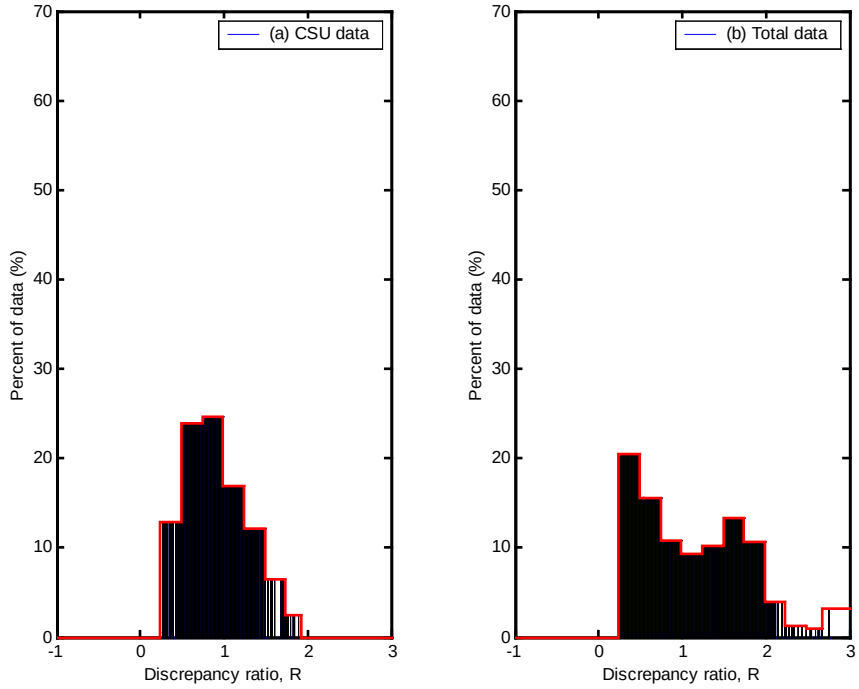

Figure 4.6: Discrepancy Ratio Distribution of V_p using Eq. (4.8)

4.2. DIMENSIONAL ANALYSIS

Dimensional analysis is adopted to find a functional relationship between the parameters affecting bedload particle velocity. The dependent variable is a function of six independent variables, with a total n = 7 variables:

$$V_p = f\left(u_*, (G-1), \nu, d_s, k_s, g\right) = 0 \tag{4.9}$$

in which f represents an unspecified function of the shear velocity u_*, particle specific gravity (G-1), kinematic viscosity of the fluid ν, bedload particle diameter d_s, bed roughness k_s, and gravitational acceleration g. After d_s, and g are selected as repeating variables, the two fundamental dimensions (j = 2) are rewritten in terms of repeating variables:

$$\left.\begin{aligned} d_s &= L \\ g &= \frac{L}{T^2} \end{aligned}\right\} \text{thus} \begin{cases} L = d_s \\ T = \sqrt{\dfrac{d_s}{g(G-1)}} \end{cases}$$

After the relationships for L, T are substituted into the non-repeating variables, five π terms (n-j = 7-2 = 5) are obtained, respectively, from V_p, u_*, ν, (G-1), and k_s

π_1:

$$\frac{V_p T}{L} = \frac{V_p}{d_s}\sqrt{\frac{d_s}{g(G-1)}} = \frac{V_p}{\sqrt{(G-1)g d_s}} \tag{4.10}$$

π_2:

$$\frac{u_* T}{L} = \frac{u_*}{d_s}\sqrt{\frac{d_s}{g(G-1)}} = \frac{u_*}{\sqrt{(G-1)g d_s}} \tag{4.11}$$

π_3:

$$\frac{\nu T}{L^2} = \frac{\nu}{{d_s}^2}\sqrt{\frac{d_s}{g(G-1)}} = \frac{\nu}{{d_s}^{3/2}[g(G-1)]^{1/2}} \tag{4.12}$$

$${\pi_3}^2 = \frac{\nu^2}{{d_s}^3(G-1)g} = \frac{1}{{d_*}^3} \tag{4.13}$$

π_4:

$$\frac{k_s}{L} = \frac{k_s}{d_s} \tag{4.14}$$

$$\pi_5 = (G-1)$$

From π_1 to π_5, the five dimensionless parameters can thus be written

$$\frac{V_p}{\sqrt{(G-1)gd_s}} = F\left\{\frac{u_*}{\sqrt{(G-1)gd_s}}, \frac{1}{{d_*}^3}, \frac{k_s}{d_s}, (G-1)\right\} \tag{4.15}$$

The results from this dimensional analysis indicate that the dimensionless bedload particle velocity parameter is a function of the Shields parameter τ_{*ds}, boundary relative roughness k_s/d_s, dimensionless particle diameter d_*, and excess particle specific gravity (G-1). Further progress can be achieved only through physical understanding or an analysis of laboratory or field experiments. The bedload particle velocity is assumed to be proportional to the product of the powers of the dimensionless parameters

$$\frac{V_p}{\sqrt{(G-1)gd_s}} = a\left[\frac{u_*}{\sqrt{(G-1)gd_s}}\right]^b {d_*}^c\left(\frac{d_s}{k_s}\right)^d (G-1)^e \tag{4.16}$$

in which *a*, *b*, *c*, *d*, and *e* are coefficients to be determined from the multiple regression analysis.

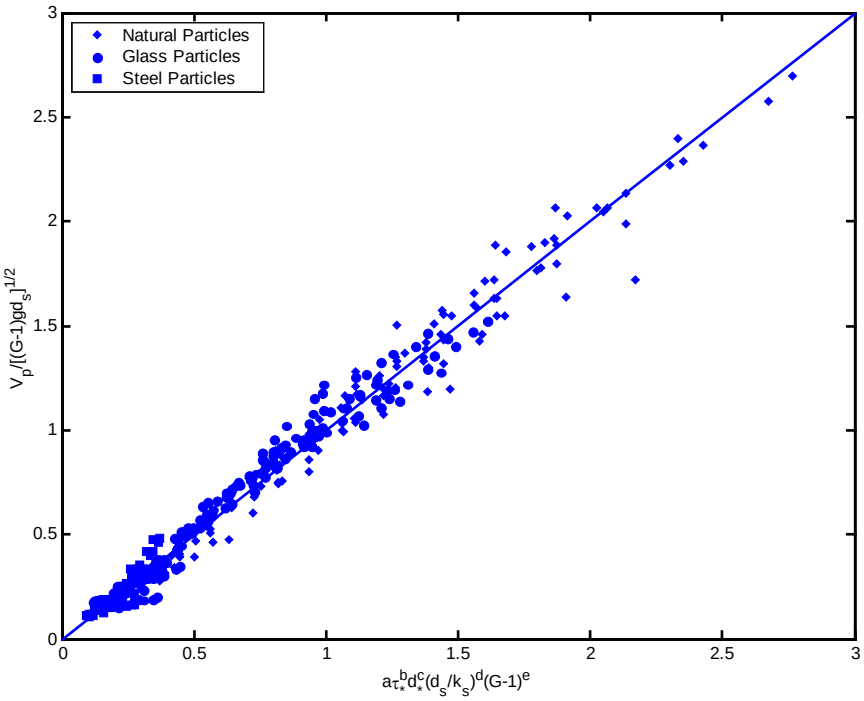

Figure 4.7: $V_p/[(G-1)gd_s]^{1/2}$ vs $11.5\tau_{*ds}^{0.95} d_*^{0.21} (d_s/k_s)^{0.36} (G-1)^{-0.28}$

Using EXCEL multiple regression analysis toolbox, the coefficients *a*, *b*, *c*, *d*, and *e* can be determined as follow

$$\log\frac{V_p}{\sqrt{(G-1)gd_s}} = \log a + b\log\left[\frac{u_*}{\sqrt{(G-1)gd_s}}\right] + c\log d_* + d\log\left(\frac{d_s}{k_s}\right) + e\log(G-1) \quad (4.17)$$

Applied to CSU's (1995) database we have

$$V_p = 11.5\left[\frac{u_*}{\sqrt{(G-1)gd_s}}\right]^{1.9} d_*^{0.21}\left(\frac{d_s}{k_s}\right)^{0.36}(G-1)^{-0.28}\left[(G-1)gd_s\right]^{0.5} \quad (4.18)$$

Similarly, applied to the total database, one obtains

$$V_p = 2.2\left[\frac{u_*}{\sqrt{(G-1)gd_s}}\right]^2 d_*^{0.5}\left(\frac{d_s}{k_s}\right)^{0.57}(G-1)^{-0.4}\left[(G-1)gd_s\right]^{0.5} \tag{4.19}$$

or

$$V_p = 2.2\tau_{*ds} d_*^{0.5}\left(\frac{d_s}{k_s}\right)^{0.57}(G-1)^{-0.4}\left[(G-1)gd_s\right]^{0.5} \tag{4.20}$$

The comparison between calculated and observed bedload particle velocity using Eqs. (4.18) and (4.20) is shown in Figs. 4.8 and 4.10; Figs. 4.9 and 4.11 show a discrepancy ratio distribution using Eqs. (4.18) and (4.20).

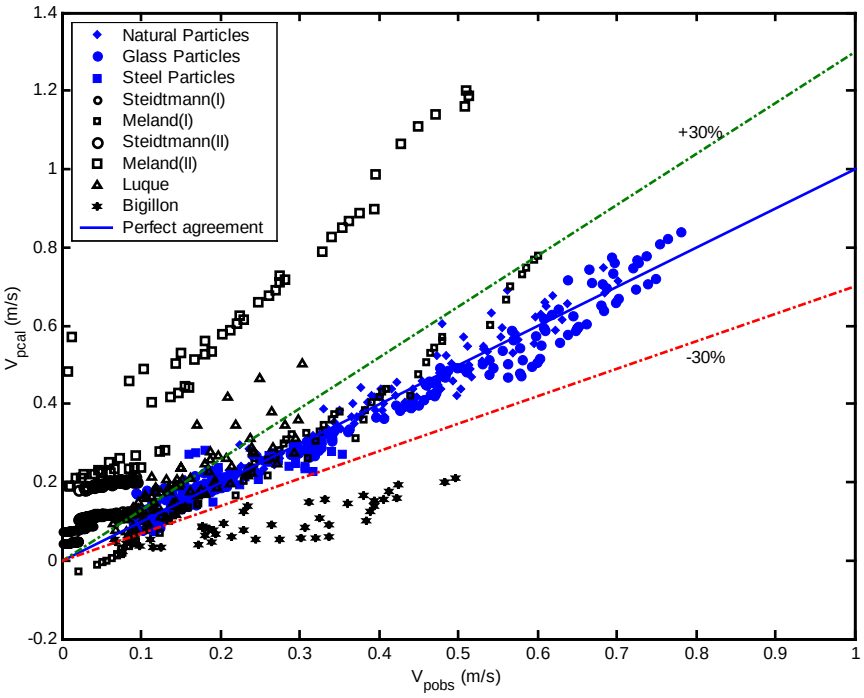

Figure 4.8: Comparison between Calculated and Observed V_p using Eq. (4.18)

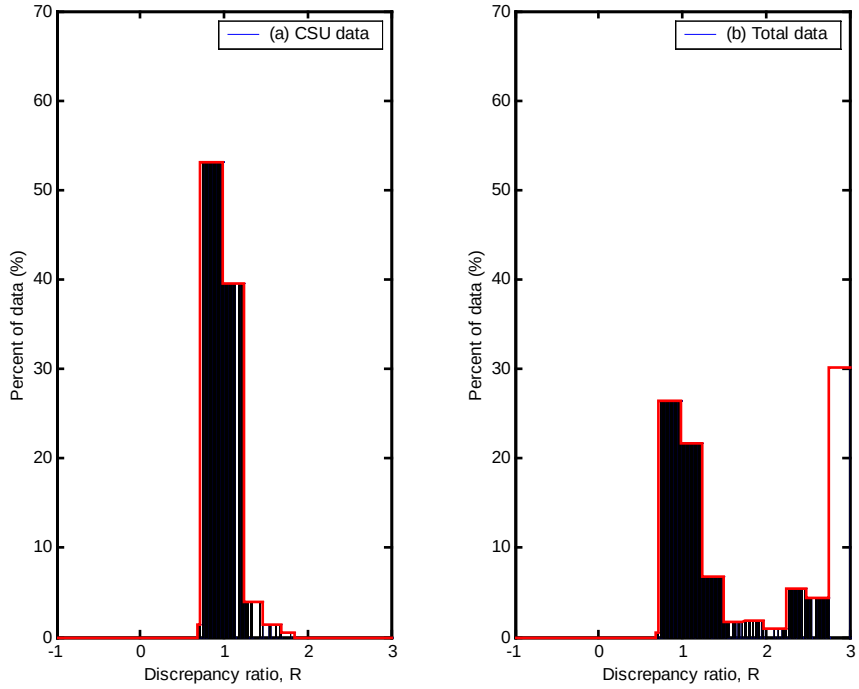

Figure 4.9: Discrepancy Ratio Distribution of V_p using Eq. (4.18)

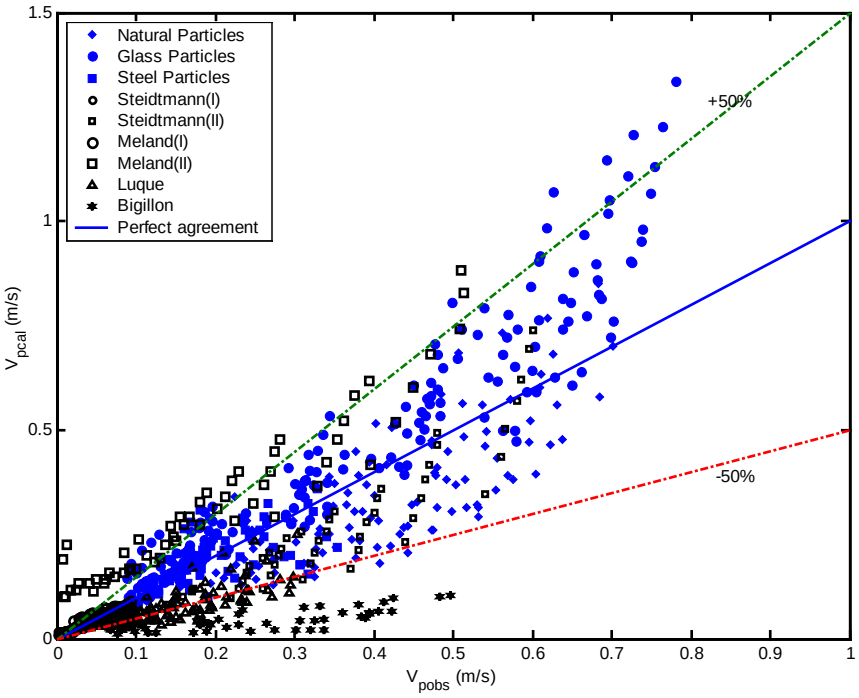

Figure 4.10: Comparison between Calculated and Observed V_p using Eq. (4.20)

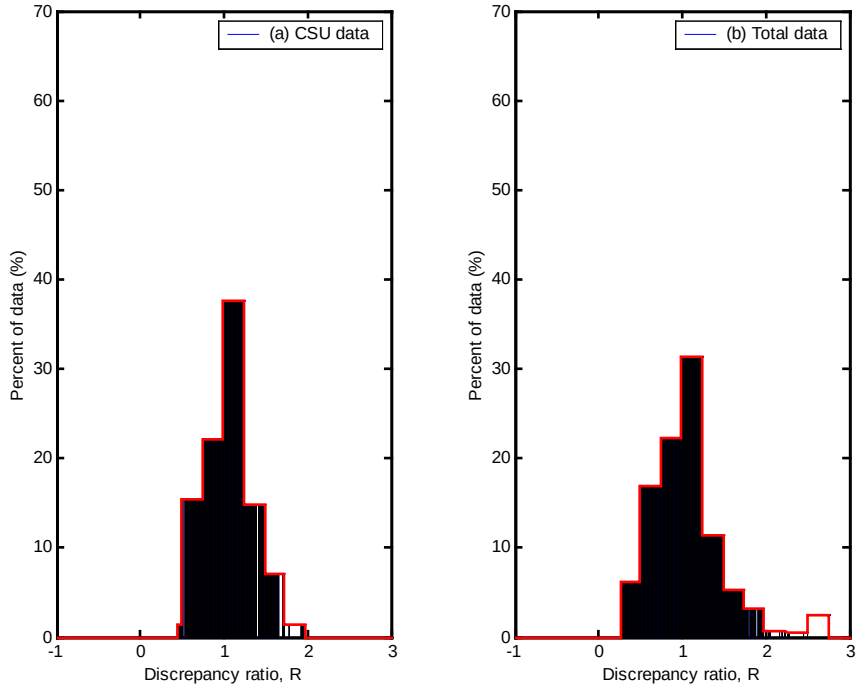

Figure 4.11: Discrepancy Ratio Distribution of V_p using Eq. (4.20)

The comparison between calculated and observed particle velocity using the proposed formula and the values is summarized in Table 4.1. A discrepancy ratio method is used to indicate the goodness of fit between calculated and observed results. It can be seen that for Eqs. (4.7) and (4.8) the percentages of data falling within the range of discrepancy ratios between 0.75 to 1.25 were in the range of 42.5 to 84.5% using the CSU database and 22.5 to 47.5% using the Total database; and for Eqs. (4.18) and (4.20) the percentages of data falling within the range of discrepancy ratios between 0.75 to 1.25 were in the range of 60 to 93% using the CSU database and 49 to 56% using the Total database.

Table 4.1: Comparison between Calculated and Observed V_p using Proposed Formulas

Equation	Data Sources	Data in Range of Discrepancy Ratio, R_i (%)				No. of Data Points	R^2
		0.75-1.25	0.5-1.5	0.25-1.75	0-2.0		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Eq. (4.7)	CSU	84.5	98.5	100	100	356	0.9
	Total	47.5	58	63.5	100	1018	0.7
Eq. (4.8)	CSU	42.5	79	98	100	356	0.54
	Total	22.5	49.5	84.5	100	1018	0.69
Eq. (4.18)	CSU	93	96.75	100	100	356	0.96
	Total	49	56.5	59	100	1018	0.7
Eq. (4.20)	CSU	60	92	98.5	100	356	0.77
	Total	56	85	97.5	100	1018	0.84

Eqs. (4.7), (4.8), (4.18), and (4.20) can be reduced to a simple form shown in Eq. (4.21); From Eq. (4.8), the exponents *b* and *c* are close to unity, one can approximate with

$$\frac{V_p}{\sqrt{(G-1)gd_s}} = a\left(\frac{u_*^{\,2}}{(G-1)gk_s}\right)$$

or

$$\frac{V_p}{u_*} = f\left[\left(\frac{u_*^{\,2}}{(G-1)gd_s}\right)^x\left(\frac{d_s}{k_s}\right)^y\right] \tag{4.21}$$

Notice that $V_p \rightarrow \infty$ when $k_s \rightarrow 0$; and there is no threshold for $V_p \rightarrow 0$ other than $k_s \rightarrow \infty$. Also, when $k_s = d_s$ at τ_{*ds} =0.047, Eq (4.21) does not reduce to $V_p = 0$.

4.3. SUMMARY

This proposed bedload particle velocity function, Eq. (4.20) is derived through the combination of dimensional analysis and regression analysis with a proposed formula in power form. Eq. (4.20) accounts for various flow and particle parameters, such as bed slope S, flow depth *y* (mm), viscosity of the fluid ν (m^2/s), particle size d_s (mm), bed roughness k_s (mm), specific gravity of the particles G, and gravitational acceleration *g* (m/s^2). Results showed that calculated and observed rolling bedload particle velocity fit very well when applied to both CSU and the total database.

The proposed rolling bedload particle velocity Eq. (4.20) predicts very well when $k_s \neq 0$, but when $k_s \rightarrow 0$ (smooth bed), then bedload particle velocity $V_p \rightarrow \infty$ (unbounded); when $d_s = k_s$, there is no value of τ_{*ds} (no threshold) as $V_p \rightarrow 0$. The following Chapter provides further analysis to define the maximum bedload particle velocity on smooth bed, and also the threshold condition for beginning of motion when $k_s \neq d_s$.

CHAPTER 5

BEDLOAD PARTICLE VELOCITY

The results of the dimensional and regression analysis in Chapter 4 indicate that: (i) when $k_s \rightarrow 0$ (smooth bed), then the bedload particle velocity $V_p \rightarrow \infty$; and (ii) there is no threshold value ($V_p \rightarrow 0$) when $k_s = d_s$. This Chapter examines the maximum bedload particle velocity over smooth beds. A theoretical analysis of particle velocity on smooth and rough surfaces are presented. The theoretical equation is then tested with laboratory and field databases. Sections 5.1 and 5.2 were modified from Guo (1997).

5.1. VELOCITY PROFILE NEAR SMOOTH BED

Since the particle moves near the smooth bed, the determination of the particle velocity profile is important. A turbulent flow over a smooth bed is composed of two regions: an inner and an outer region. The inner region is influenced by viscous shear, while the outer region is influenced by turbulent shear. The inner region is further divided

into three layers: the viscous sub-layer, the buffer layer and the log layer. Since the bedload movement always occurs near the bed, it relates to the velocity profile in the inner region. In the viscous sub-layer, the velocity distribution is

$$u^+ = y^+ \tag{5.1}$$

in which $u^+ = u_f / u_*$, $y^+ = u_* y / \nu$, u_f is the velocity at distance y from the bed, u_* is the shear velocity, and ν is the water kinematic viscosity. In the log layer, the velocity distribution is

$$u^+ = \frac{1}{\kappa} \ln y^+ + 5.5 \tag{5.2}$$

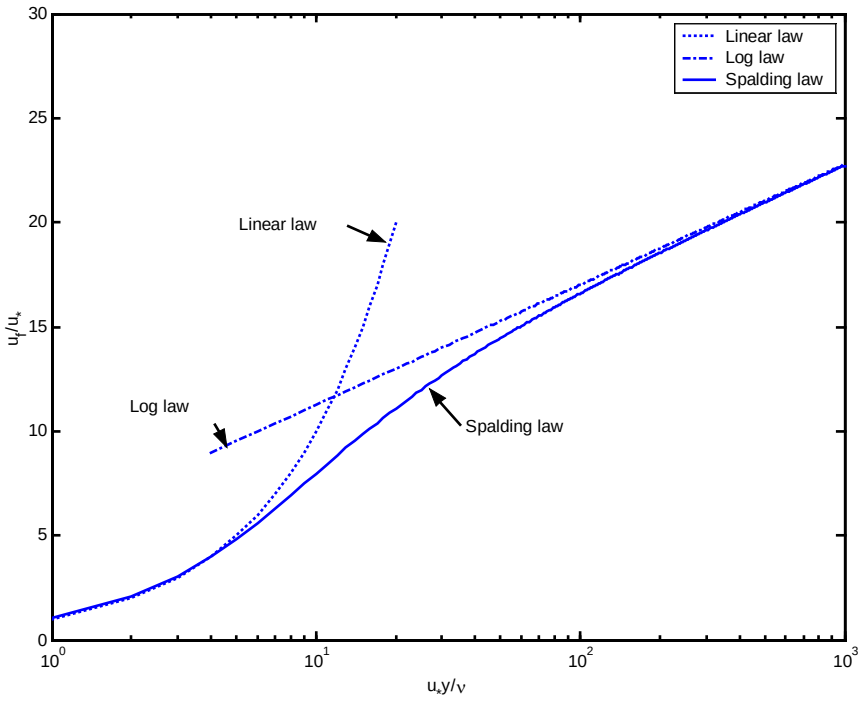

Figure 5.1: Velocity Profile In The Inner Region

In the buffer layer, Spalding's equation can be used (White, 1991, p.415), which is

$$y^+ = u^+ + \exp(-\kappa B)\left[\exp(\kappa u^+) - 1 - \kappa u^+ - \frac{(\kappa u^+)^2}{2} - \frac{(\kappa u^+)^3}{6}\right] \tag{5.3}$$

in which κ = 0.4 and B = 5.5. From equations (5.1) and (5.2), one has

$$\frac{du^+}{dy^+} = 1, \text{ for } y^+ \to 0 \tag{5.4a}$$

$$\frac{du^+}{dy^+} = \frac{1}{\kappa y^+}, \text{ for } y^+ \to \infty \tag{5.4b}$$

From the above expression, a general velocity gradient may be approximated by

$$\frac{du^+}{dy^+} = \frac{\kappa a^2 + y^+}{\kappa a^2 + \kappa y^{+2}} \tag{5.5}$$

The above equation satisfies the two asymptotic expressions. The integration of the Eq. (5.5) with the boundary condition $u^+ = 0$ at $y^+ = 0$ gives

$$u^+ = a\tan^{-1}\left(\frac{y^+}{a}\right) + \frac{1}{2\kappa}\ln\left[1 + \left(\frac{y^+}{a}\right)^2\right] \tag{5.6}$$

When $y^+ \to \infty$, the above equation reduces to

$$u^+ = \frac{1}{\kappa}\ln y^+ + \frac{\pi}{2}a - \frac{1}{\kappa}\ln a \tag{5.7a}$$

Comparing (5.7) with (5.2) gives

$$\frac{\pi}{2}a - \frac{1}{\kappa}\ln a = 5.5 \tag{5.7b}$$

Solving for *a* gives

$$a = 6.47 \tag{5.7c}$$

A plot of Eqs. (5.1) and (5.5) with a = 6.47 is shown in Figure 5.1.

5.2. MAXIMUM VELOCITY OF A PARTICLE ON SMOOTH BED

Consider that, for a sphere of diameter d_s, the slope angle of the plane is θ. The forces acting on the sphere include drag force, F_D, lift force, F_L, submerged weight of the sphere W_s, and resistance to the movement of the sphere F_f.

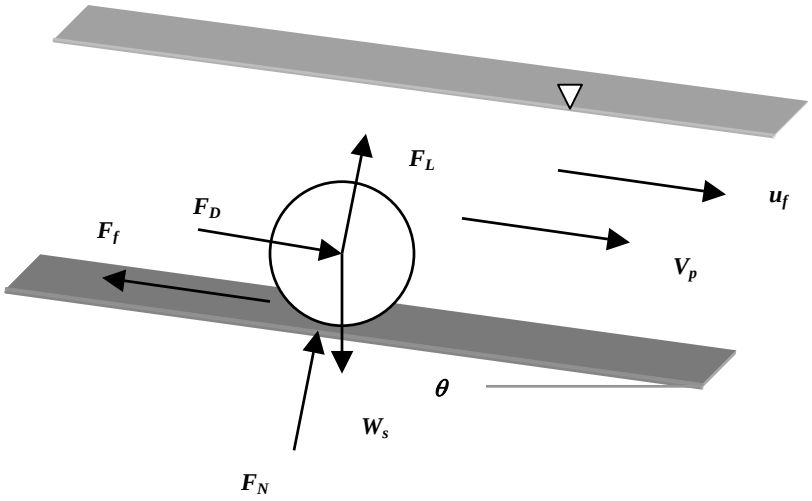

Figure 5.2: Forces Acting on a Sphere Rolling down an Inclined Smooth Bed

Considering the steady state, one can write the following equilibrium equations

$$W_s \sin\theta = F_D - F_f \tag{5.8}$$

$$W_s \cos\theta = F_N + F_L \tag{5.9}$$

The submerged weight is

$$W_s = \frac{1}{6}\pi\rho(G-1)g{d_s}^3 \tag{5.10}$$

Assumed that the fluid moves faster than the particle, the drag force in the flowing fluid can be used

$$F_D \approx \frac{1}{2}C_D\rho\left(u_f - V_p\right)^2 \frac{\pi{d_s}^2}{4} \tag{5.11}$$

in which α is an experimental coefficient. The lift force points upward and can be calculated

$$F_L = \frac{2}{3}\pi\rho{d_s}^2\left(u_f - V_p\right)V_p \tag{5.12}$$

The frictional force is

$$F_f \le \mu F_N \tag{5.13}$$

considering the equilibrium in the *z*-direction, one has

$$F_N = W_s\cos\theta - F_L = \frac{1}{6}\pi\rho(G-1)g{d_s}^3\cos\theta - \frac{2}{3}\pi\rho{d_s}^2\left(u_f - V_p\right)V_p \tag{5.14}$$

similarly, considering the equilibrium in the *x*-direction, one obtains

$$\frac{1}{6}\pi\rho(G-1)g{d_s}^3\sin\theta + \frac{1}{2}C_D\rho\left(u_f - V_p\right)^2\frac{\pi{d_s}^2}{4} \le \mu\left[\frac{1}{6}\pi\rho(G-1)g{d_s}^3\cos\theta - \frac{2}{3}\pi\rho{d_s}^2(u_f - V_p)V_p\right] \tag{5.15}$$

which shows that the particle accelerates all the time and a steady state is achieved when the equal sign is used in (5.15). The above equation can be rearranged in terms of $(u_f - V_p)$, i.e.

$$\left(1-\frac{16}{3}\frac{\mu}{C_D}\right)\left(u_f-V_p\right)^2+\frac{16}{3}\frac{\mu}{C_D}u_f\left(u_f-V_p\right)+\frac{4}{3C_D}(G-1)gd_s(\sin\theta-\mu\cos\theta)=0 \quad (5.16)$$

solving for $(u_f - V_p)$ gives

$$u_f - V_p = \frac{-b \pm \sqrt{b^2-4ac}}{2a} \quad (5.17)$$

in which

$$a = 1-\frac{16}{3}\frac{\mu}{C_D} \quad (5.18)$$

$$b = \frac{16}{3}\frac{\mu u_f}{C_D} \rangle 0 \quad (5.19)$$

$$c = \frac{4}{3C_D}(G-1)gd_s(\sin\theta-\mu\cos\theta) \quad (5.20)$$

since the fluid goes faster than the particle, the positive value of $(u_f - V_p)$ is the required solution, since b>0, the particle velocity is

$$V_p = u_f - \frac{\sqrt{b^2-4ac}-b}{2a} \quad (5.21)$$

For an experimental study, assume μ constant, C_D function of a Reynolds number $\mathrm{Re}_* = u_* d_s / \nu$, then the second term on the right hand side of (5.21) has the following function form

$$\frac{\sqrt{b^2-4ac}-b}{2a} = u_* f\left(\mathrm{Re}_*, \frac{u_f}{u_*}, (G-1)\frac{gd_s}{{u_*}^2}, \theta, \mu\right) \quad (5.22)$$

Considering u_f / u_* at $y = d_s$ is also a function of Re_* from the velocity profile equation in a smooth bed, and θ has been merged into the shear velocity u_*, the above relation should become primarily dependent on Re_* and to a lesser degree depend on θ, μ, and d_*

$$\frac{V_p}{u_*} = f\left(\mathrm{Re}_*, d_*, \mu, \theta\right) \tag{5.23}$$

As approximation, one can plot V_p/u_* vs Re_* as shown in Fig. 5.3. Applying Eq. (5.6) with a correction factor β, one obtains

$$\frac{V_p}{u_*} = a\tan^{-1}\left(\frac{\mathrm{Re}_*}{\beta a}\right) + \frac{1}{2\kappa}\ln\left[1+\left(\frac{\mathrm{Re}_*}{\beta a}\right)^2\right] \tag{5.27}$$

in which $\kappa = 0.4$ and $a = 6.47$, as for Eq. (5.6), Guo (1997) used the Matlab Nonlinear Optimization Toolbox to determine that $\beta = 4$. The rolling bedload particle velocity for smooth bed can be estimated by

$$V_p = \left\{6.47\tan^{-1}\left(\frac{\mathrm{Re}_*}{25.88}\right) + \frac{1}{2\kappa}\ln\left[1+\left(\frac{\mathrm{Re}_*}{25.88}\right)^2\right]\right\} \times u_* \tag{5.28}$$

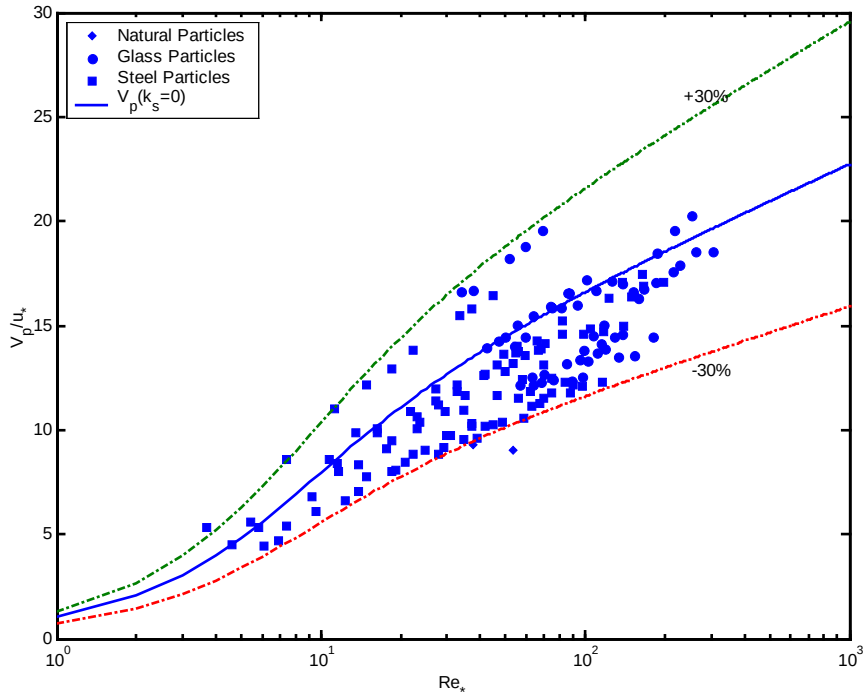

Figure 5.3: V_p/u_* vs Re_* using Eq. (5.28)

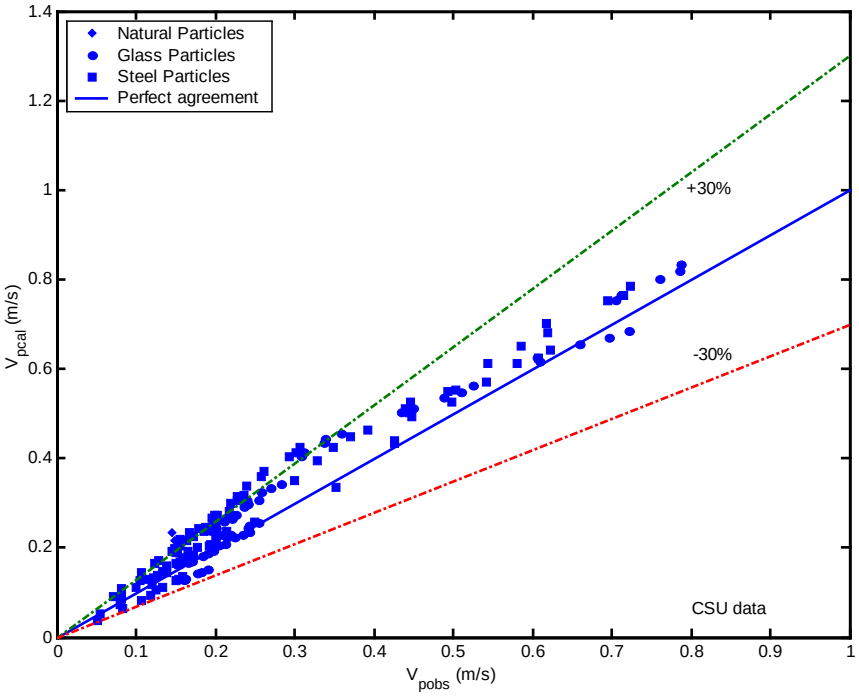

Figure 5.4: Comparison between Calculated and Observed V_p using Eq. (5.28)

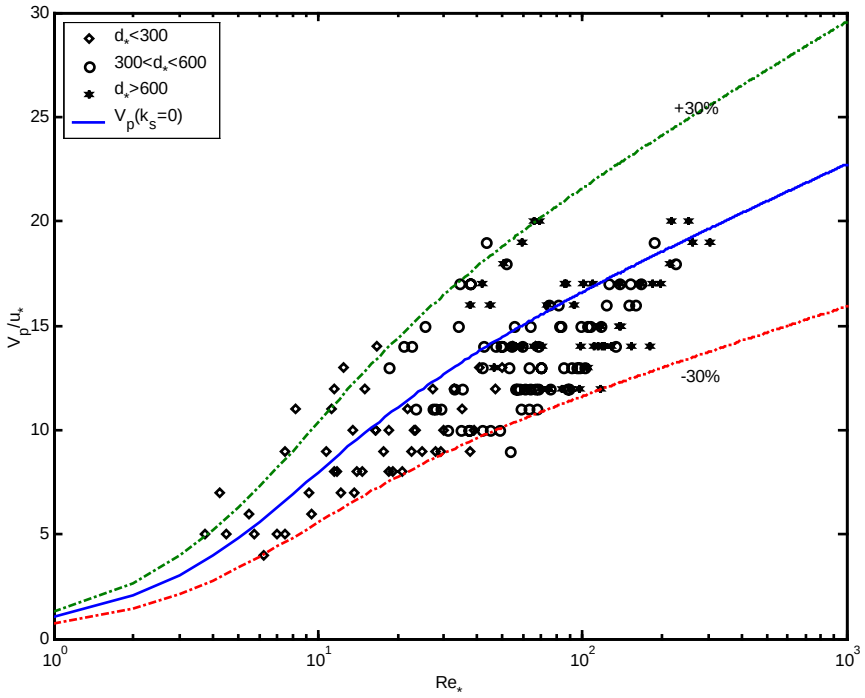

Figure 5.5: V_p/u_* vs Re_* using Eq. (5.28) for different values of d_*

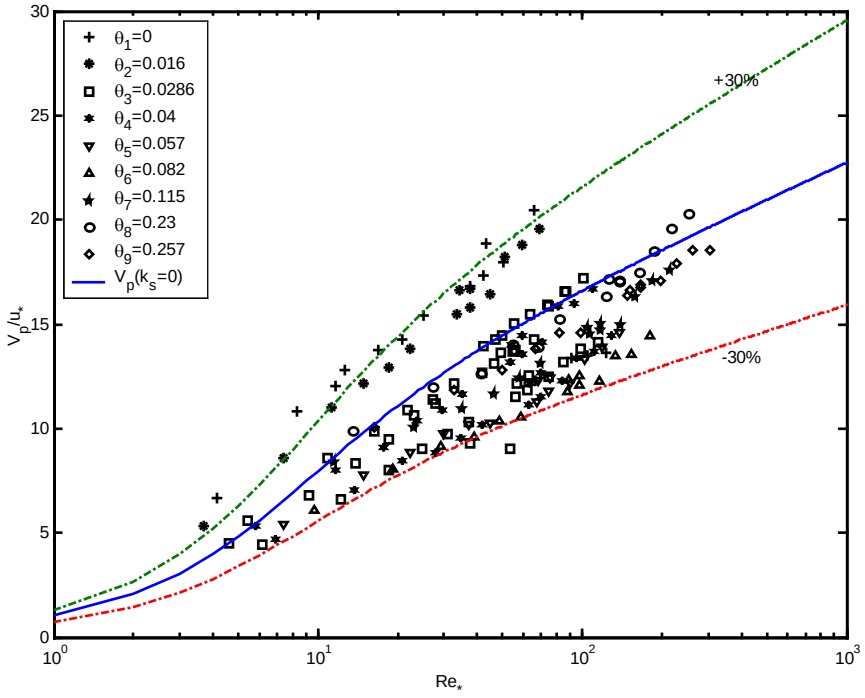

Figure 5.6: V_p/u_* vs Re_* using Eq. (5.28) for different values of θ

5.3. SINGLE PARTICLE ROLLING DOWN AN INCLINED ROUGH BED

Consider a sphere of diameter d_s rolling in a flowing fluid over an inclined bed of roughness. The slope angle of the plane is θ. The forces acting on the sphere include drag force, F_D, lift force, F_L, submerged weight of the sphere W_s, and resistance to the movement of the sphere from boundary F_f.

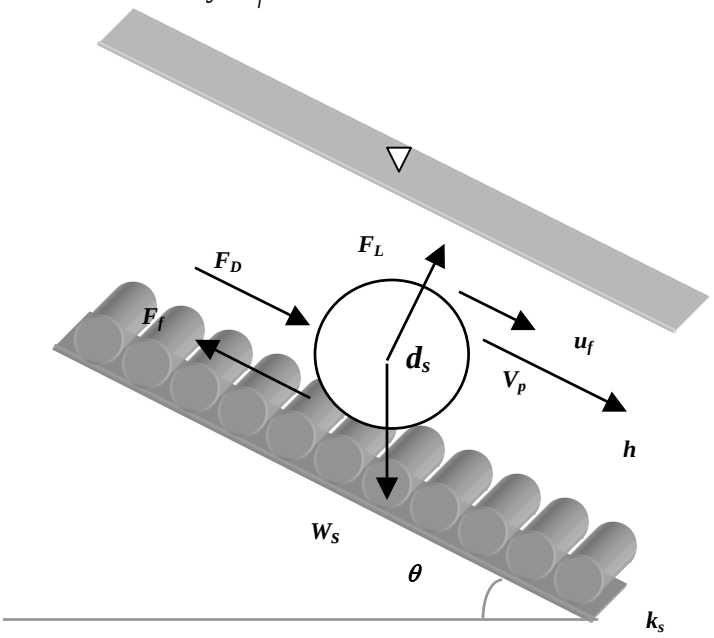

Figure 5.7: Forces Acting on a Sphere Rolling down an Inclined Bed of Roughness

$$\frac{V_p}{u_*} = \frac{V_{psmooth}}{u_*} - \Delta B \tag{5.29}$$

where the boundary roughness function $\Delta B = f(k_s, \tau_{*ds}, d_*)$. A plot of V_p / u_* as a function of Re_* and ΔB for both smooth and rough beds is shown in Fig. 5.9. After substituting Eq. (5.29) to particle velocity on smooth bed, Eq. (5.29) reduces to

$$\frac{V_p}{u_*} = 6.47 \tan^{-1}\left(\frac{\mathrm{Re}_*}{25.88}\right) + \frac{1}{2\kappa}\ln\left[1 + \left(\frac{\mathrm{Re}_*}{25.88}\right)^2\right] - \Delta B \tag{5.30}$$

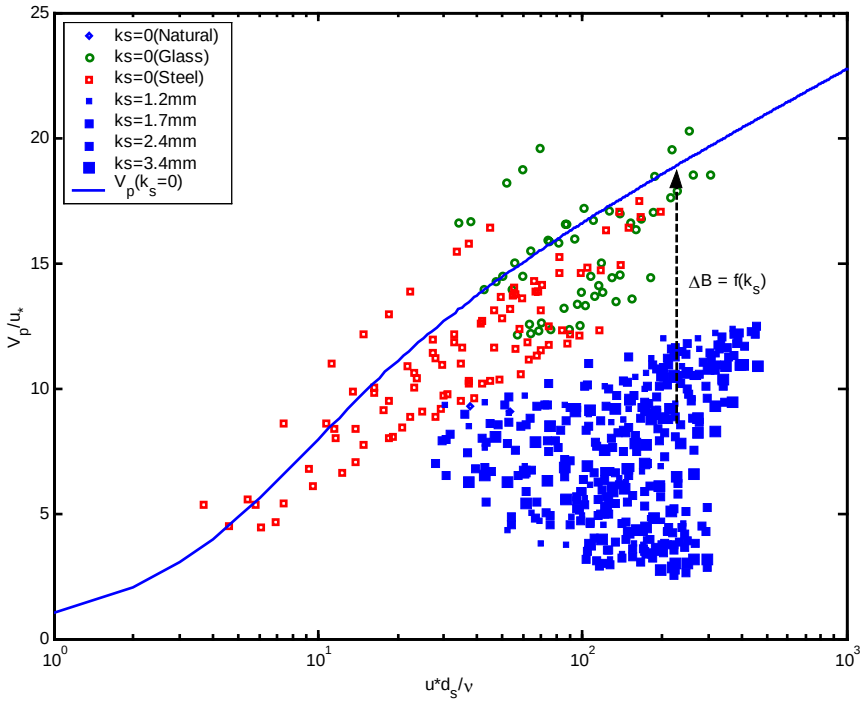

Figure 5.8: V_p/u_* vs Re_* for Smooth ($k_s = 0$) and Rough Bed ($k_s > 0$)

or

$$\Delta B = 6.47 \tan^{-1}\left(\frac{\mathrm{Re}_*}{25.88}\right) + \frac{1}{2\kappa}\ln\left[1+\left(\frac{\mathrm{Re}_*}{25.88}\right)^2\right] - \frac{V_p}{u_*} \tag{5.31}$$

Due to the effect of bed roughness k_s, particle size d_s, shear velocity u_*, and fluid kinematic viscosity ν, on bedload particle velocity V_p, we can assume that the calculated value ΔB_c can be obtained as a function of Shields parameter τ_{*ds}, dimensionless particle diameter d_*, and relative roughness (k_s/d_s) as

$$\Delta B_c = a\,\tau_{*ds}{}^{b} d_*{}^{c}\left(\frac{k_s}{d_s}\right)^{d} \tag{5.32}$$

or

$$\log \Delta B_c = \log a + b \log \tau_{*ds} + c \log d_* + d \log\left(\frac{k_s}{d_s}\right) \quad (5.33a)$$

the calibration parameters *a*, *b*, *c*, and *d* are obtained using the EXCEL multiple regression analysis toolbox. The analysis is applied to the CSU database

$$\Delta B_c = 0.884 \tau_{*ds}{}^{-0.229} d_*{}^{0.32} \left(\frac{k_s}{d_s}\right)^{0.333} \quad (5.33b)$$

Substituting (5.33b) into (5.30), and solving for V_p, one obtains

$$V_p = \left\{ 6.47 \tan^{-1}\left(\frac{\mathrm{Re}_*}{25.88}\right) + \frac{1}{2\kappa} \ln\left[1 + \left(\frac{\mathrm{Re}_*}{25.88}\right)^2\right] - 0.884 \tau_{*ds}{}^{-0.229} d_*{}^{0.32} \left(\frac{k_s}{d_s}\right)^{0.333} \right\} \times u_* \quad (5.34)$$

The agreement between ΔB and ΔB_c is shown in Fig. 5.9. There is a reasonable good fit ($R^2 = 0.9$) between calculated and observed ΔB.

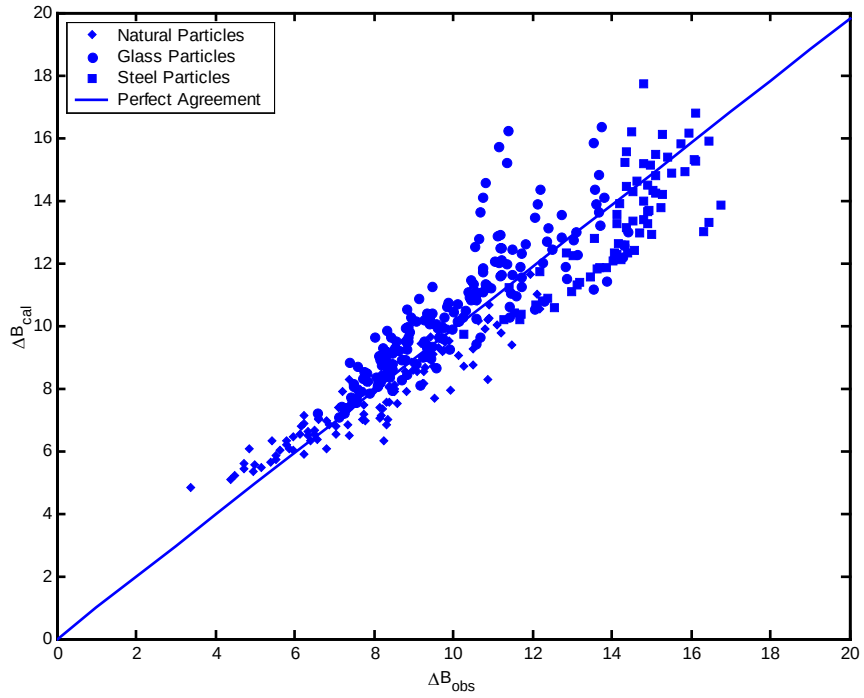

Figure 5.9: ΔB_{cal} vs ΔB_{obs} using Eq. (5.33b) for CSU data

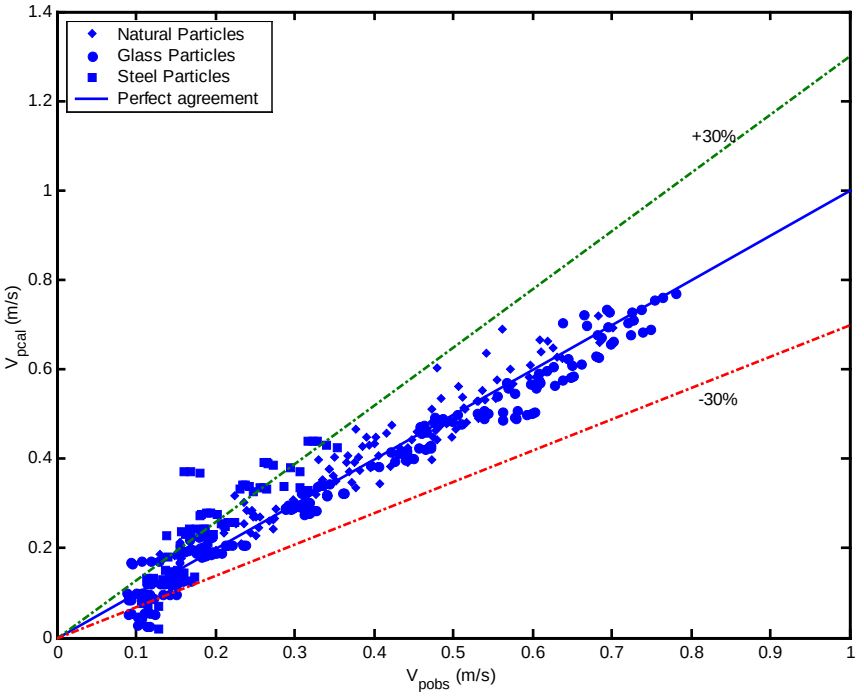

Figure 5.10: Comparison between Calculated and Observed V_p using Eq. (5.34)

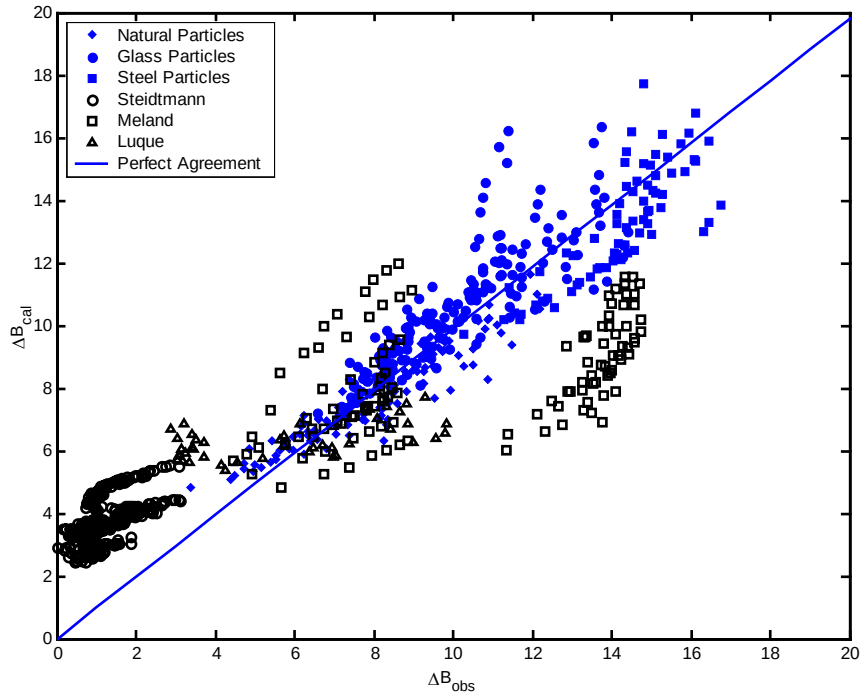

Figure 5.11: ΔB_{cal} vs ΔB_{obs} using Eq. (5.33b) for total data

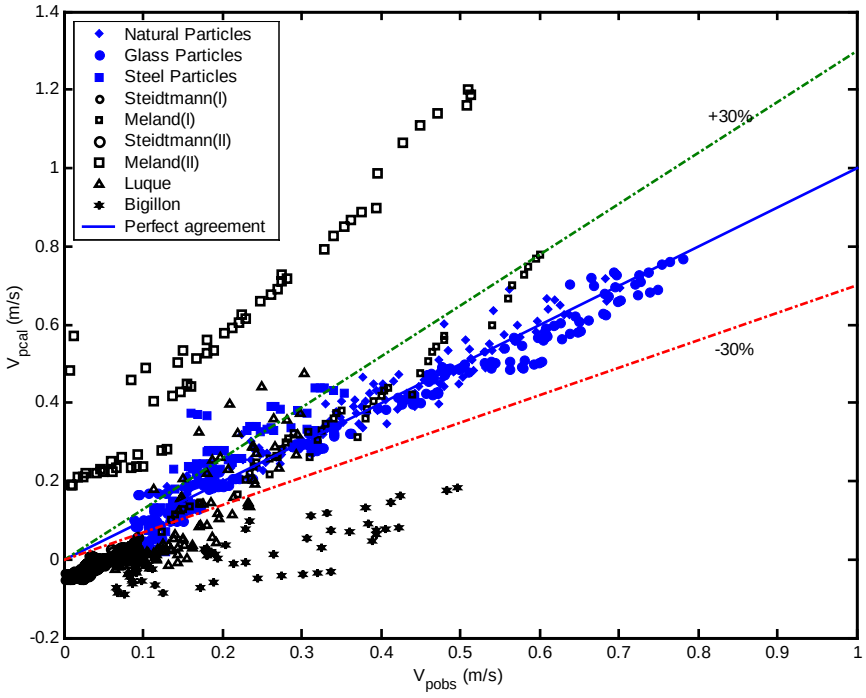

Figure 5.12: Comparison between Calculated and Observed V_p using Eq. (5.34)

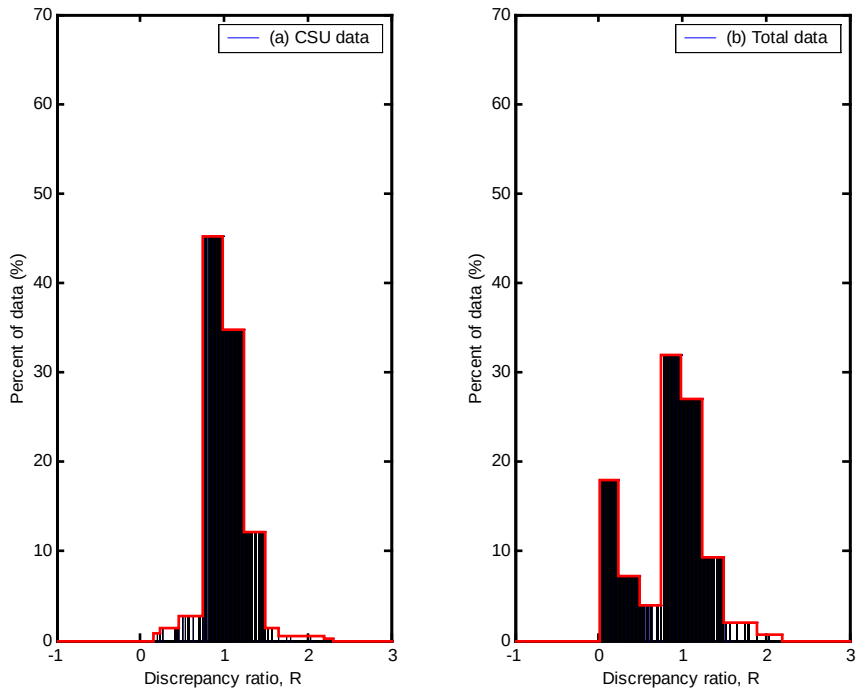

Figure 5.13: Discrepancy Ratio Distribution of V_p using Eq. (5.34)

The analysis is applied to the Total database

$$\Delta B_c = 0.096\tau_{*ds}^{-0.048} d_*^{0.93}\left(\frac{k_s}{d_s}\right)^{0.61} \tag{5.33c}$$

Substituting (5.33c) into (5.30), and solving for V_p, one obtains

$$V_p = \left\{6.47\tan^{-1}\left(\frac{\mathrm{Re}_*}{25.88}\right) + \frac{1}{2\kappa}\ln\left[1+\left(\frac{\mathrm{Re}_*}{25.88}\right)^2\right] - 0.096\tau_{*ds}^{-0.048} d_*^{0.93}\left(\frac{k_s}{d_s}\right)^{0.61}\right\}\times u_* \tag{5.35}$$

where: $\mathrm{Re}_* = u_* d_s/\nu$, shear velocity $u_* = [gR_hS]^{1/2}$ (m/s), d_s = particle size (mm), k_s = bed roughness (mm), ν = fluid kinematic viscosity (m^2/s), G = particle specific gravity, g = gravitational acceleration (m/s^2), and Shields parameter $\tau_{*ds} = u_*^2/(G\text{-}1)gd_s$, and κ = von Karman constant (0.4);

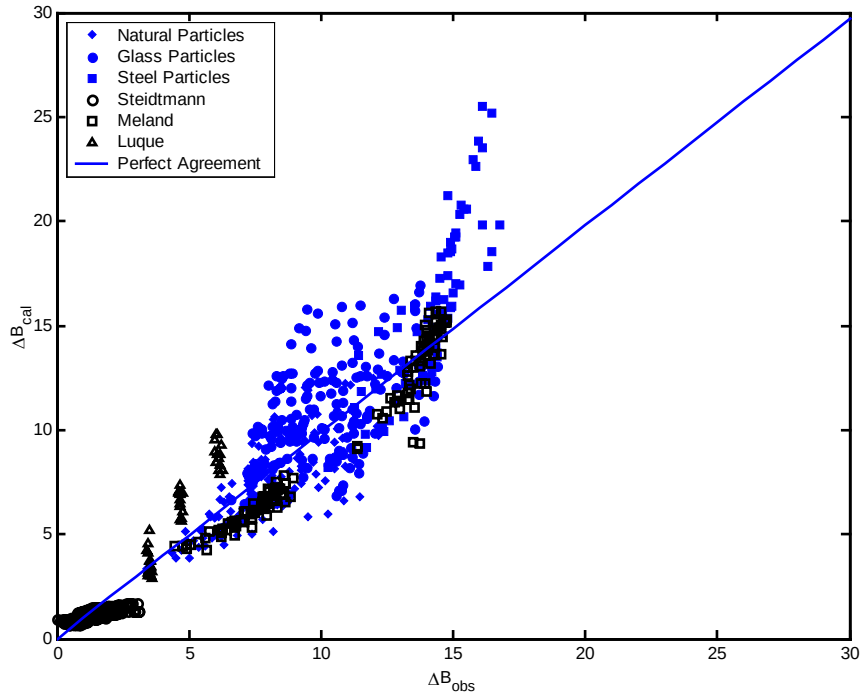

Figure 5.14: ΔB_{cal} vs ΔB_{obs} using (5.33c) for total data

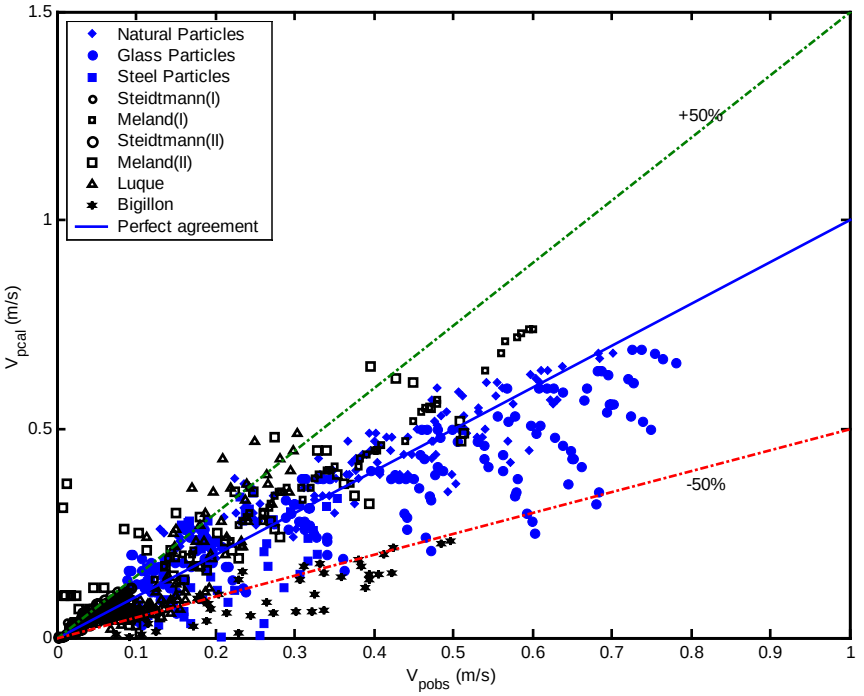

Figure 5.15: Comparison between Calculated and Observed V_p using Eq. (5.35)

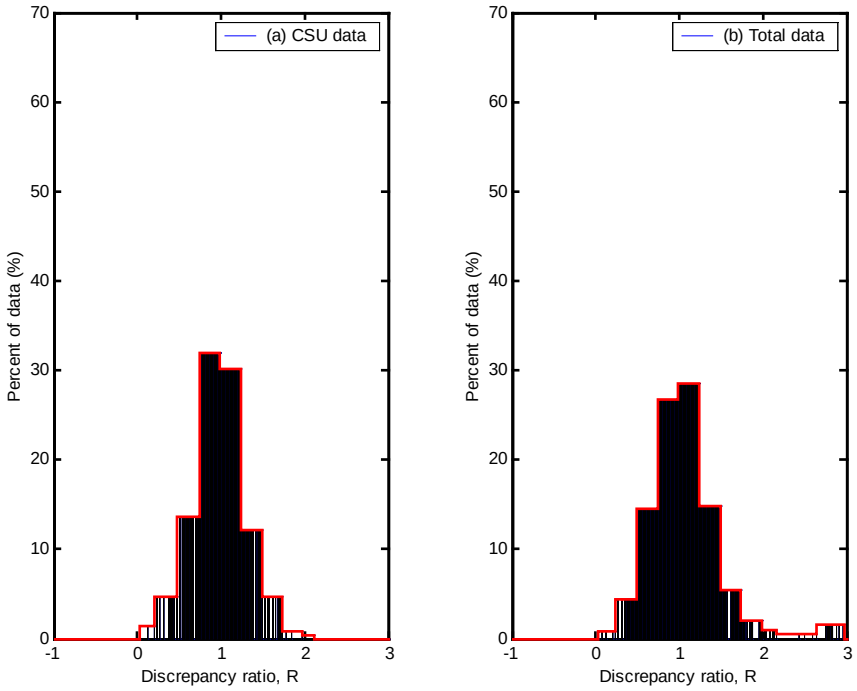

Figure 5.16: Discrepancy Ratio Distribution of V_p using Eq. (5.35)

The bedload particle velocity can be calculated by Eq. (5.34), Fig. 5.12, shows the comparison between calculated and observed rolling bedload particle velocity V_p using Eq. (5.34); and Fig. 5.13, shows the discrepancy ratio distribution for V_p using Eq. (5.34). The comparison between calculated and observed particle velocity using the proposed formula is summarized in Table 5.1. A discrepancy ratio method is used to indicate the goodness of fit between calculated and observed values. It can be seen that the percentages of data falling within the range of discrepancy ratios between 0.75 to 1.25 were at least 60% using the total database.

Table 5.1: Summary of Comparison between Calculated and Observed V_p

Equation	Data Sources	Data in Range of Discrepancy Ratio, R_i (%)				No. of Data Points	R^2
		0.75-1.25	0.5-1.5	0.25-1.75	0-2.0		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Eq. (5.34)	CSU	80	95	100	100	356	0.93
	Total[(1)]	60	75	82	100	1018	0.83
Eq. (5.35)	CSU	59.5	84	93.5	100	356	0.68
	Total	54	83	92.5	100	1018	0.82

(1) = Meland (1966) + Luque (1976) + Steidtmann (1982) + Bridge (1984) + CSU (1995) + Bigillon (2001)

5.4. ANALYSIS OF THE THRESHOLD CONDITION

The goal of this section is to find the threshold condition in term of bed roughness size required the particle to stop rolling. The first approach is with reference to the CSU data, Fig. 5.17 shows $\tau_{*ds}/0.047$ against relative roughness d_s/k_s for different values of V_p/u_*.

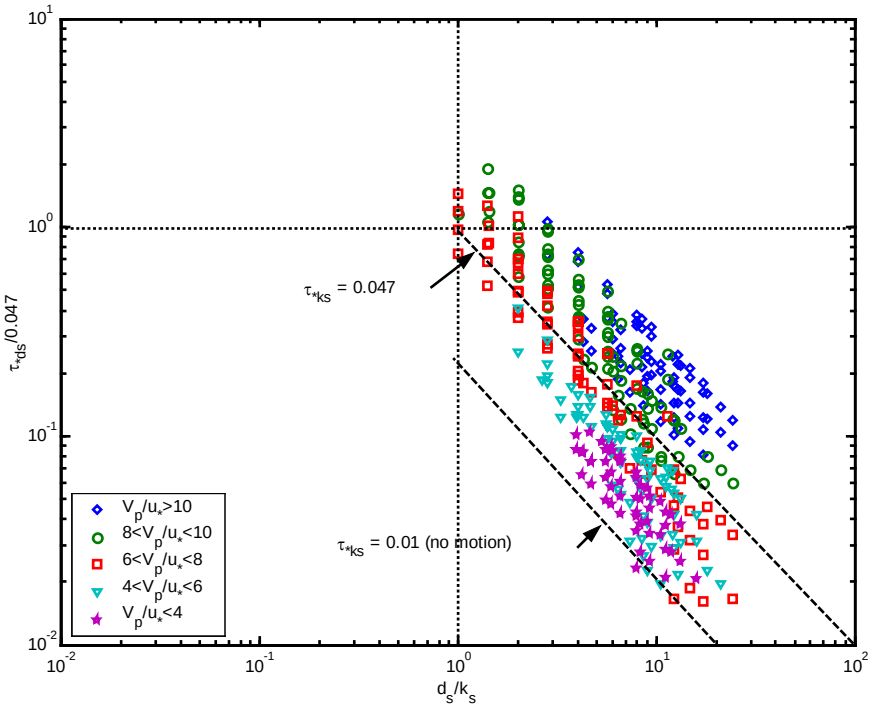

Figure 5.17: $\tau_{*ds}/0.047$ vs d_s/k_s, for different values of V_p/u_*

Very few particles are shown to move at values of shear stress below

$$\frac{\tau_{*ds}}{0.047} = 0.213\frac{k_s}{d_s} \tag{5.36}$$

this defines beginning of motion as

$$(\tau_{*ks})_c = \frac{u_*^{\,2}}{(G-1)gd_s}\left(\frac{d_s}{k_s}\right) = \left[\frac{u_*^{\,2}}{(G-1)gk_s}\right]_c = 0.213\times 0.047 = 0.01 \qquad (5.37)$$

The result describes above $(\tau_{*ks})_c \approx 0.01$. Fig. 5.17 shows there are a few data points have the values of $\tau_{*ks} < 0.01$.

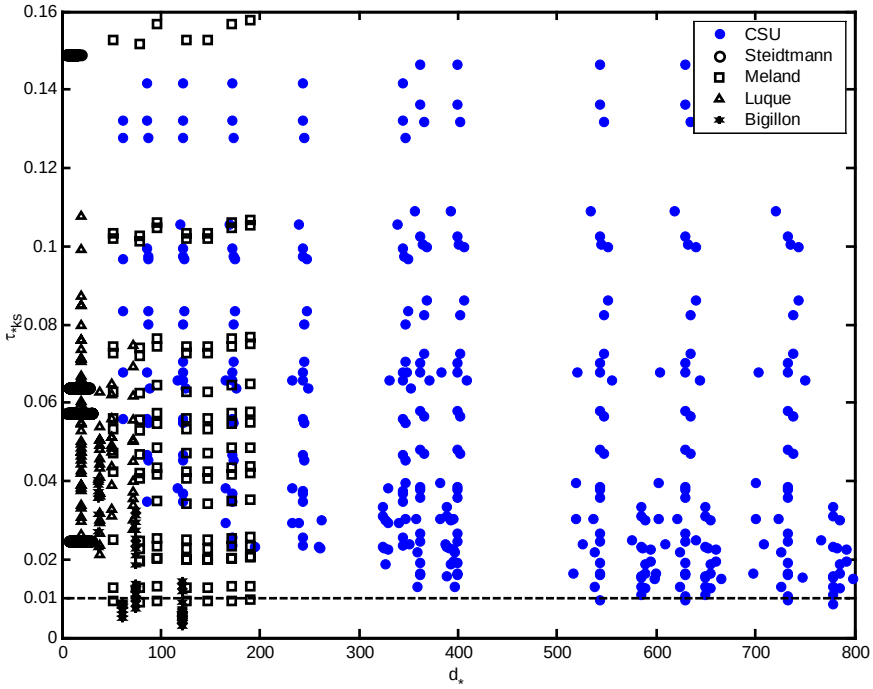

Figure 5.18: τ_{*ks} vs d_* for different databases

The second approach is to find the bed roughness size k_s that correspond to $V_p = 0$ in (5.31). Accordingly, threshold condition occurs from Eq. (5.34) when

$$k_{sc} = d_s\left\{\frac{6.47\tan^{-1}\left(\frac{\mathrm{Re}_*}{25.88}\right)+\frac{1}{2\kappa}\ln\left[1+\left(\frac{\mathrm{Re}_*}{25.88}\right)^2\right]}{0.884\tau_*^{\,-0.229}d_*^{\,0.32}}\right\}^{\frac{1}{0.333}} \qquad (5.38)$$

Threshold condition, or $V_p = 0$ (no motion), is obtained when $k_s = k_{sc}$. Particles move when $k_s < k_{sc}$, and stop when $k_s \geq k_{sc}$.

5.5. SUMMARY

Two functions of the transport velocity of a single particle on a smooth bed Eq. (5.28) and on a rough bed Eq. (5.34) are defined through theoretical and empirical analysis. The results show that the bedload particle velocity on smooth beds is approximately equal to the flow at the center of the particles. The roughness function ΔB describes the effect of bed roughness on reducing transport velocity of rolling bedload particles. This function ΔB varies with bed slope S, flow depth *y* (mm), viscosity of the fluid ν (m^2/s), particle size d_s (mm), bed roughness k_s (mm), specific gravity of the particles G, and gravitational acceleration g (m/s^2). The proposed bedload particle velocity formula, Eq. (5.34) reduces to Eq. (5.28) when $k_s \rightarrow 0$. When $k_s = d_s$, $V_p \sim (5 - 11)u_*$, and τ_{*ds} decreases when $V_p \rightarrow 0$. Particles reach incipient motion when $\tau_{*ks} \approx 0.01$, or when $k_s = k_{sc}$ defined in Eq. (5.38).

CHAPTER 6

LABORATORY AND FIELD APPLICATIONS

In this chapter, a general procedure for the calculation of bedload particle velocity is presented. This procedure is illustrated through a detailed example problem, followed with field applications.

6.1. PROPOSED METHOD

1. Input data

    - Particle diameter d_s (mm)
    - Flow depth y (mm)
    - Bed slope S_f

- Bed roughness k_s (mm)
- Flow viscosity ν (m^2/s)
- Particle specific gravity G

2. Calculation of the basic parameters
   - Shear velocity $u_* = [gR_hS_f]^{1/2}$ (m/s)
   - Shields particle parameter $\tau_{*ds} = u_*^2/(G-1)gd_s$
   - Shields roughness parameter $\tau_{*ks} = u_*^2/(G-1)gk_s$
   - Boundary relative roughness d_s/k_s, and k_s/d_s
   - Particle shear Reynolds number $Re_* = u_*d_s/\nu$
   - Dimensionless particle diameter $d_* = d_s[(G-1)g/\nu^2]^{1/3}$
3. Calculation of bed roughness critical k_{sc} from Eqs. (5.37) and (5.38) to determine the motion of the particle.
4. Calculation of $V_{psmooth}$ use Eq. (5.28); V_p use Eqs. (5.34), (5.35), and may also use Eq. (4.20).

6.2. TESTING EXISTING FORMULAS WITH ENTIRE DATABASE

Figs. 6.1, 6.3 and 6.5 illustrate the comparison between calculated and observed bedload particle velocity V_p, by applying the Meland and Norrman (1966), Fernandez Luque and van Beek (1976), and Bridge and Dominic (1984) equations to all assembled data. Figs. 6.2, 6.4 and 6.6 show a discrepancy ratio distribution for Meland and

Norrman, Fernandez Luque and van Beek, and Bridge and Dominic equations respectively. Results show that Fernandez Luque and van Beek, and Bridge and Dominic predict their own data very well, but none of Meland and Norrman, Fernandez Luque and van Beek, and Bridge and Dominic equations compare well with the entire database.

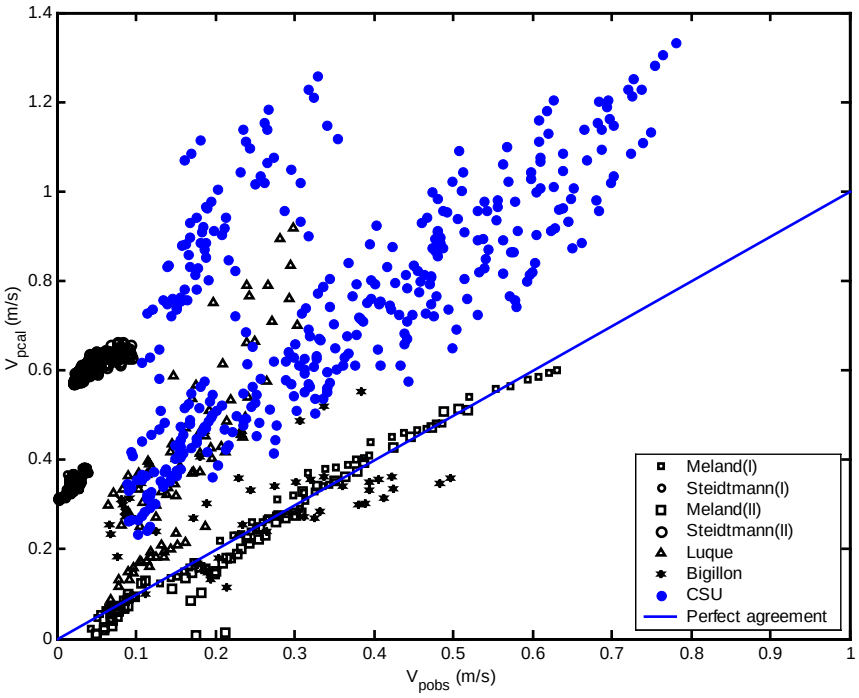

Figure 6.1: Comparison between Calculated and Observed V_p using Eq. (2.9)

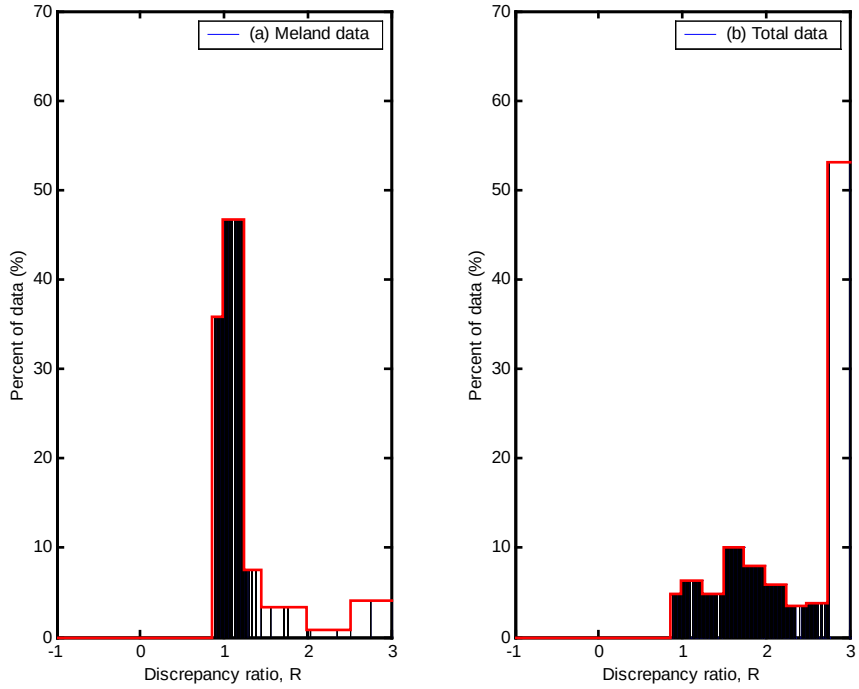

Figure 6.2: Discrepancy Ratio Distribution of V_p using Eq. (2.9)

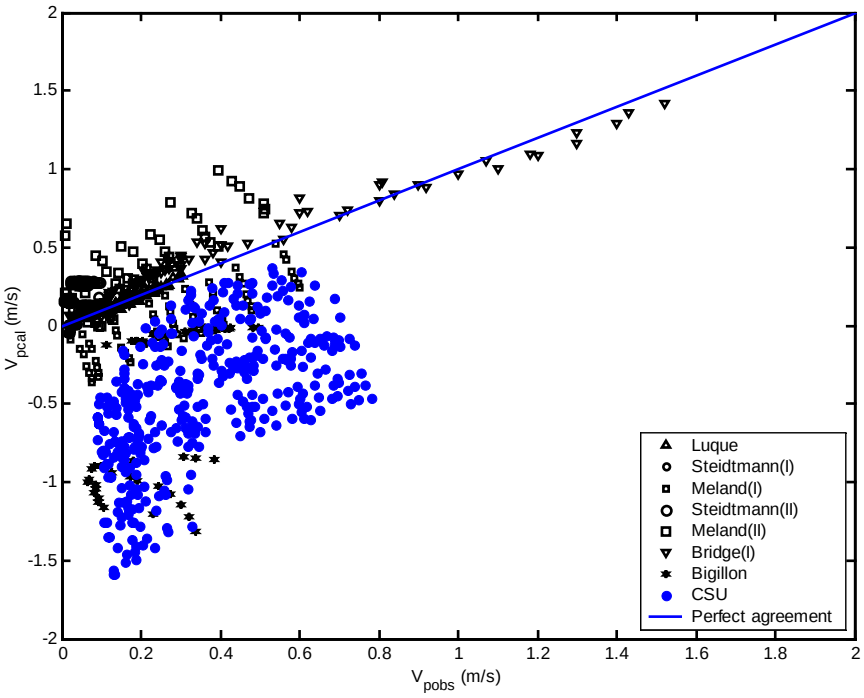

Figure 6.3: Comparison between Calculated and Observed V_p using Eq. (2.15)

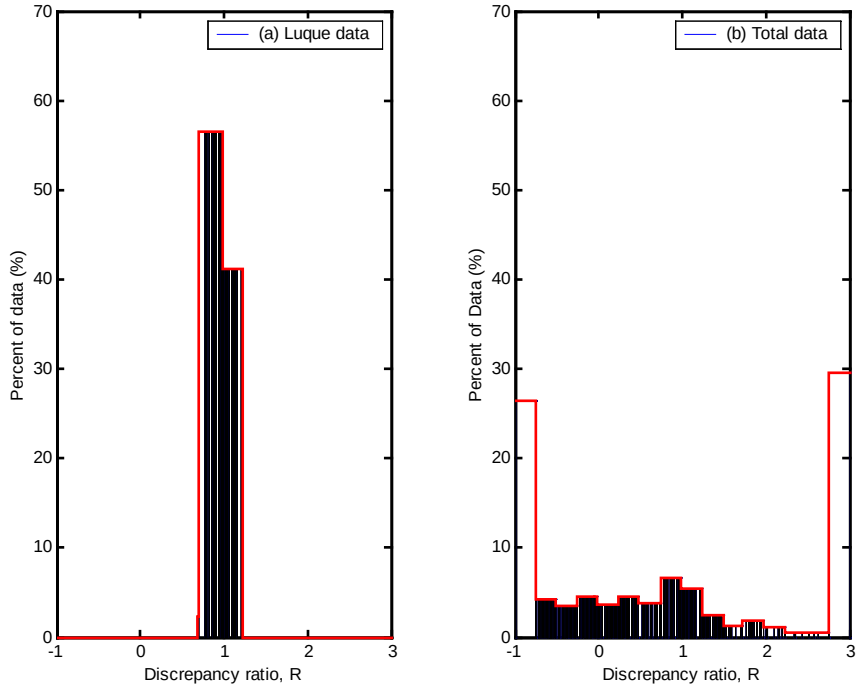

Figure 6.4: Discrepancy Ratio Distribution of V_p using Eq. (2.15)

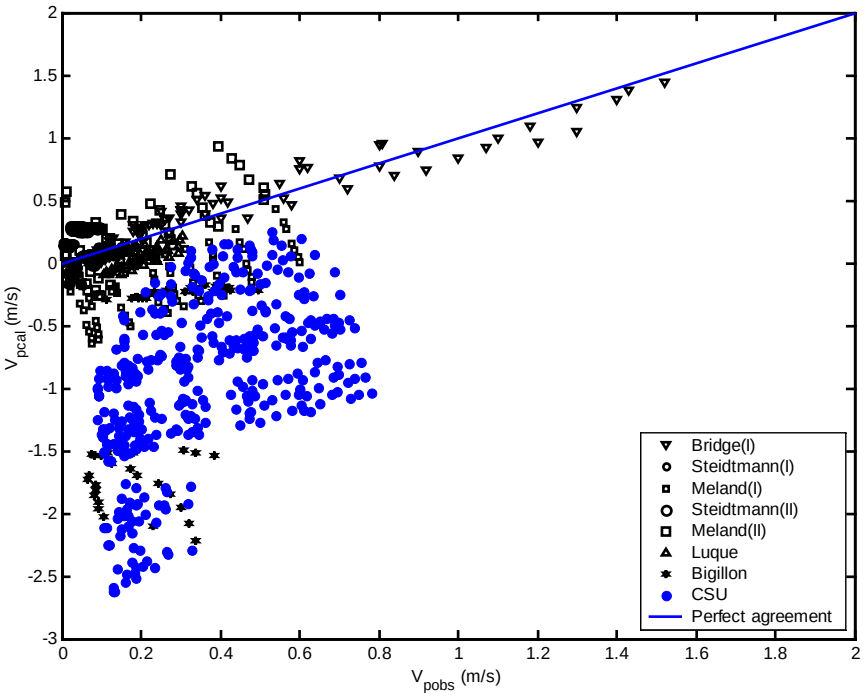

Figure 6.5: Comparison between Calculated and Observed V_p using Eq. (2.22)

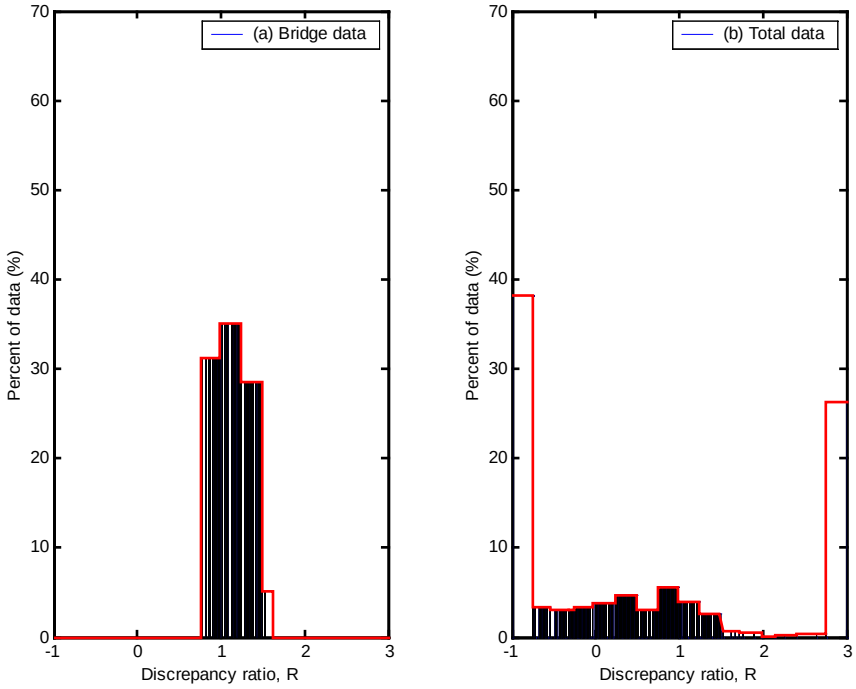

Figure 6.6: Discrepancy Ratio Distribution of V_p using Eq. (2.22)

In Table 6.1, the discrepancy ratio method indicates the goodness of fit between calculated and observed results. The percentages of data falling within the range of discrepancy ratios between 0.75 to 1.25 is 83% using Meland and Norrman's database and reduces to 12% when using the total database. Similarly, for Fernandez Luque and van Beek (1976), the percentages of data falling within the range of discrepancy ratios between 0.75 to 1.25 is 98% using Fernandez Luque and van Beek's database and reduces to 12% when using the total database. For Bridge and Dominic (1984), the percentages of data falling within the range of discrepancy ratios between 0.75 to 1.25 is 68% using Bridge and Dominic's database and reduces to 8.5% when using the total database. There is clear indication that equations of Meland and Norrman, Fernandez Luque and van Beek, and Bridge and Dominic fail to predict bedload particle velocity when applied the database from other sources.

Table 6.1: Summary of Comparison between Calculated and Observed V_p

Equations	Data Sources	Data in Range of Discrepancy Ratio, R_i (%)				No. of Data Points	R^2
		0.75-1.25	0.5-1.5	0.25-1.75	0-2.0		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Meland and Norrman (1966)	Meland Total[(1)]	83 12	95 17	100 28	100 100	120 1018	0.95 -0.4
Fernandez Luque and van Beek (1976)	Luque Total[(1)]	98 12	100 20	100 28	100 100	85 1018	0.93 -0.096
Bridge and Dominic (1984)	Bridge Total[(1)]	68 8.5	96.5 16	100 22.5	100 100	77 1018	0.93 -0.27

Where: (1) = Meland (1966) + Luque (1976) + Steidtmann (1982) + Bridge (1984) + CSU (1995) + Bigillon (2001)

6.3. HALFMOON CREEK, COLORADO

Dixon and Ryan (2000) conducted the data collection on 6/9/2000 at the Halfmoon Creek near Leadville, Colorado to observe the bed-load with the underwater video camera. The original movie was obtained from Dr. Bunte at the Engineering Research Center, Colorado State University. At Halfmoon Creek, they observed slurries of sand and pea gravel moving along the bed of the stream. Saltating particles in the coarse sand to fine gravel size class were typically moving too quickly to distinguish them when observing the video frame by frame. These smaller particles, however, were easily seen

while the video was moving at a normal or slow motion speed. Larger particles in the medium to coarse gravel size class were moving slower and were easily view frame by frame. Occasionally sweeps were observed that would briefly entrain small to medium sized gravel.

In some other cases a larger particle would turn over and come to rest. For example, at Halfmoon Creek they observed a relatively large particle (b-axis = 46 mm) move into the frame and come to rest behind a similar sized stationary particle (Fig. 6.7). This particle adjusted its orientation slightly during the next 17 seconds. The particle then rolled over and came to rest downstream against a partially buried large cobble (Fig. 6.8). The particle adjusted its position slightly during next 7 minutes and 19 seconds as smaller particles filled in and subsequently scoured away both on top and beneath. Just before the particle moved out of the view frame, there was a sweep of sediment followed by the particle being struck by another particle (b-axis = 26 mm) that initiated its movement out of the view frame (Fig. 6.9).

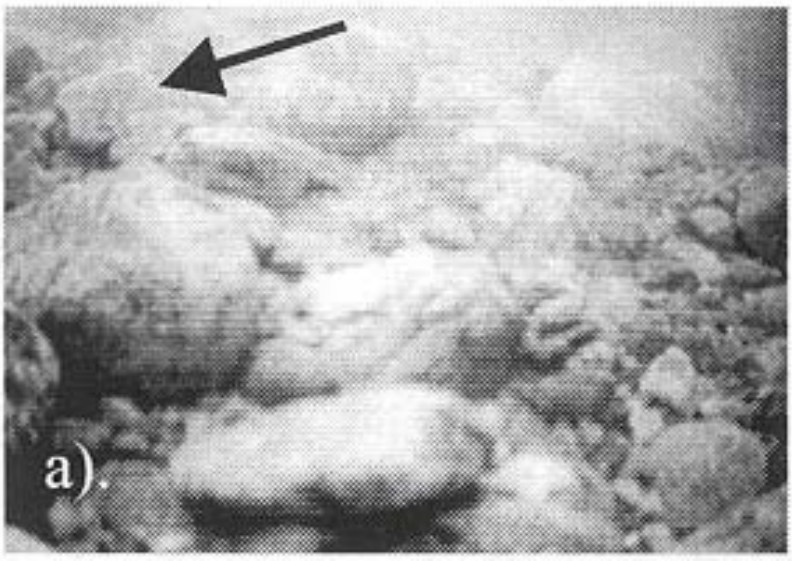

Figure 6.7: Track of a single particle at Halfmoon Creek (Dixon and Ryan, 2000); a) the particle move into view and comes to rest.

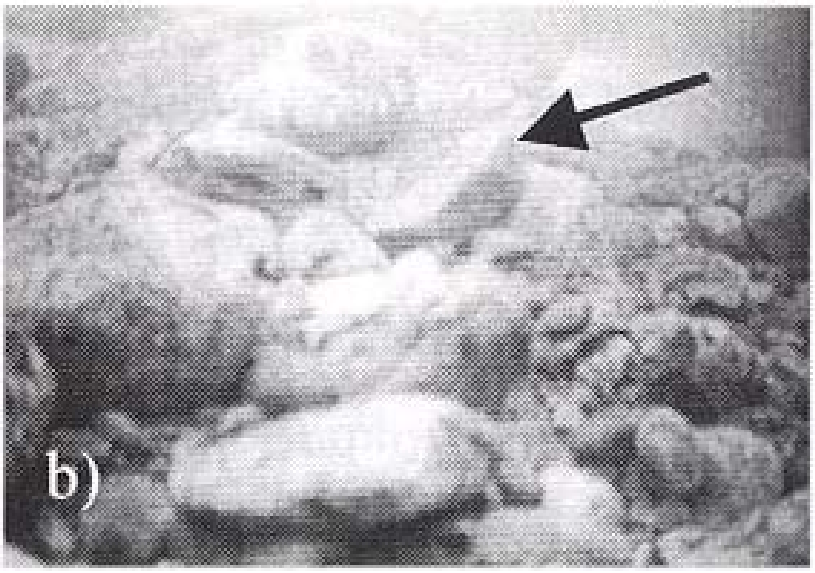

Figure 6.8: Track of a single particle at Halfmoon Creek (Dixon and Ryan, 2000); b) after 17 seconds the particle moves 23 mm and comes to rest again.

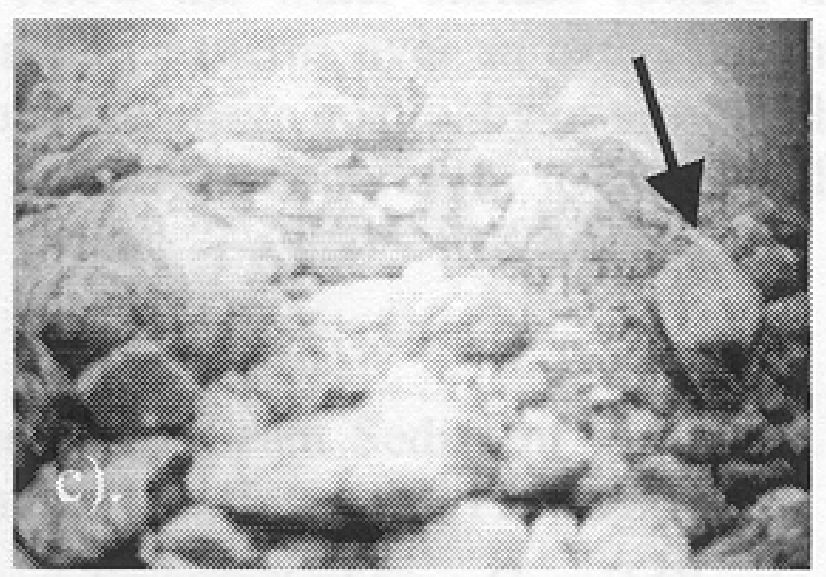

Figure 6.9: Track of a single particle at Halfmoon Creek (Dixon and Ryan, 2000); c) after being stationary for over 7 minutes, the particle moves out of the view.

Due to the lack of measured data, assumptions have been made to estimate bedload particle velocity conducted by Dixon and Ryan (2000). The estimated flow and sediment properties include:

1. Input data: Particle size d_s = 40 mm, bed slope S_f = 0.005, flow rate Q = 5.2 m^3/s, mean flow velocity u_f = 1.27 m/s, bed roughness k_s = 50 mm, mean flow depth y = 480 mm;

2. Calculation of basic parameters

   - Shear velocity $u_* = [gR_hS_f]^{1/2} = [9.81\times0.48\times0.005]^{1/2} = 0.153$ m/s

   - Shields particle parameter $\tau_{*ds} = u_*^2/(G-1)gd_s = (0.153)^2/(2.65-1)\times9.81\times0.04 = 0.036$

   - Shields roughness parameter $\tau_{*ks} = u_*^2/(G-1)gk_s = (0.153)^2/(2.65-1)\times9.81\times0.05 = 0.029$

- Boundary relative roughness $d_s/k_s = 40/50 = 0.8$, and $k_s/d_s = 1.25$
- Particle shear Reynolds number $Re_* = u_* d_s/\nu = 0.153 \times 0.04/1.004 \times 10^{-6} = 6096$
- Dimensionless particle diameter $d_* = d_s[(G-1)g/\nu^2]^{1/3} = 1009$

3. Calculation of bed roughness critical k_{sc} from Eqs. (5.37) and (5.38) to determine the motion of the particle; From Eq. (5.37), one obtains $k_{sc1} = (0.153)^2/(2.65-1) \times 9.81 \times 0.01 = 140$ mm which is comparable to $k_{sc2} = 110$ mm, obtained from Eq. (5.38).

4. Calculation of $V_{psmooth} = 3.64$ m/s by using Eq. (5.28); $V_p = 1.4$ m/s, and 0.79 m/s by using Eqs. (4.20), and (5.34) respectively. Similarly, applied the above procedures for different d_s, k_s, and the results is shown in Fig. 6.10.

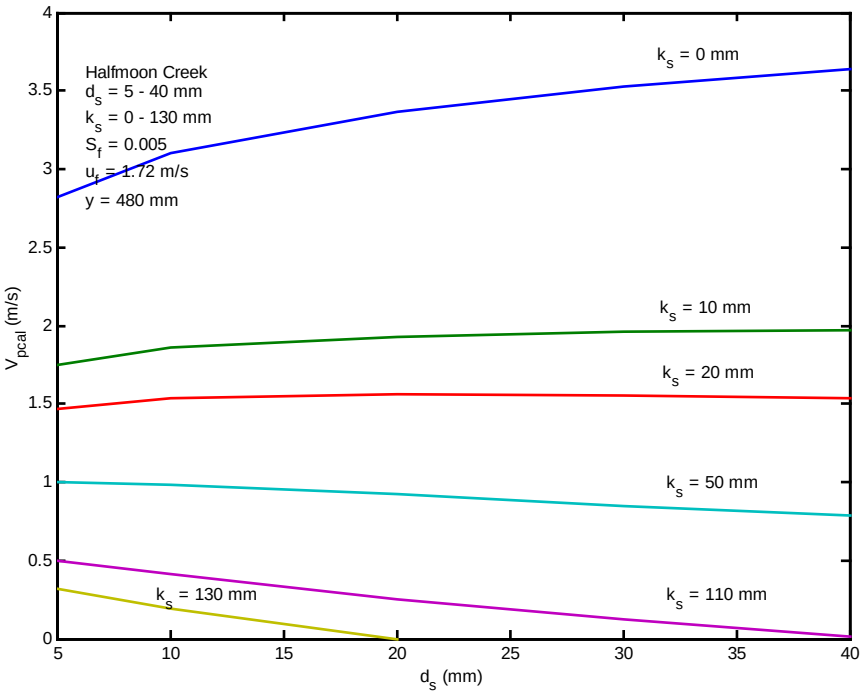

Figure 6.10: Predicted V_p using Eq. (5.34) for different values of d_s and k_s

6.4. AVILA MOUNTAIN, VENEZUELA

Mountain Avila, located on the north of Venezuela, witnessed on December 16th, 1999, a severe debris flows occurring over an area of about 500 km^2. As a faulted-block mountain, the Avila region has abundant neotectonic uplift. Altitude steeply ascends from sea level to 2000 m within only 6-9 km from the ridge to the beach. Average sediment deposition in the river canyon was about 2-3 m and essentially buried most of the standing houses to the rafters. Water level marks as high as 7 m were observed in some of the buildings. The debris surges destroyed approximately 60% of the structures in the town of Tanaguarena and resulted in approximately 100 casualties. The mining operation (Cantera Cerro Grande) reports damages in excess of 3 million dollars in lost structures

and equipment. Structures in the canyon sustained impact damage from debris and boulders in surges. Some structures were completely destroyed by impact, scour and exposure to high velocity flows. Foundations were undermined by scour and collapsed. High velocity surges with boulders and debris were experienced across the entire canyon bottom as the channel conveyance velocity was lost. The structures that remain standing were buried in a coarse-grained mixture of boulders, cobbles, sand and debris (Bello et al., 2000). Fig. 6.11 shows an aerial view of Caraballeda looking Southwest with newly opened channels in the foreground and center right of photograph; Figs. 6.12, and 6.14 shows road damaged in Los Corales; Fig. 6.13 shows an aerial view of Caraballeda looking North with a massive deposition of coarse sediment delivered by debris flows and flash floods in Los Corales section; Fig. 6.15 shows a view of Los Corales with deposited boulder on the road; Fig. 6.16 shows Big boulders transported by debris flow on a fairly smooth bed; Fig. 6.17 Big boulder transported by debris flow in December 1999 in Caraballeda; Fig. 6.18 shows an aerial view of Los Corales sector of Caraballeda with damage to apartment building; Fig. 6.19 shows a view of Los Corales with damage to an apartment building; Fig. 6.20 shows a control canal for debris and mudflow at the Saint Julian Ravine.

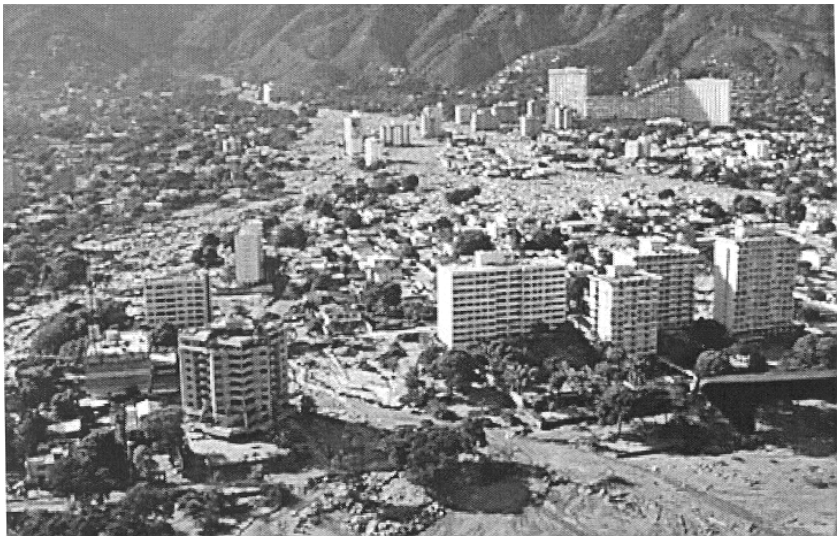

Figure 6.11: Aerial view of Caraballeda looking Southwest (Larsen et al., 2000)

Figure 6.12: View of road damaged in Los Corales, Leon and Rojas, 2000 (personal communication)

Figure 6.13: Aerial view of Caraballeda looking North (Larsen et al., 2000)

Figure 6.14: View of road damaged in Los Corales, Leon and Rojas, 2000 (personal communication)

Figure 6.15: View of deposited boulders on the road in Los Corales, Leon and Rojas, 2000 (personal communication)

Figure 6.16: Big boulder transported by debris flow, Leon and Rojas, 2000 (personal communication)

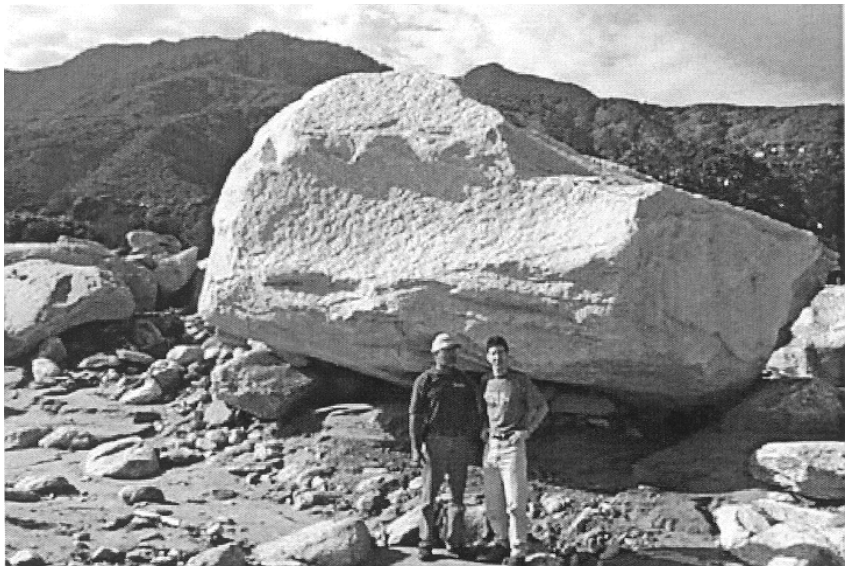

Figure 6.17: Boulder transported by debris flow in December 1999 (Larsen et al., 2000)

Figure 6.18: Aerial view of Los Corales sector of Caraballeda (Larsen et al., 2000)

Figure 6.19: View of damaged to apartment building in Los Corales, Leon and Rojas, 2000 (personal communication)

Figure 6.20: Control canal for debris flow at the Saint Julian Ravine, Leon and Rojas, 2000 (personal communication)

This particular example problem is derived from the measurement of field data, due to the insufficient of the nature of the database, some assumptions have been made. Given a uniform flow with T_{water} = 20°C, $\nu_{water} = 1.004\times10^{-6}$ m^2/s, particle diameter d_s = 0.1-3 m, G = 2.65, k_s = 0-250 mm, bed slope S_f = 0.01 (Leon and Rojas, 2000, personal communication), flow depth y = 3 m (Bello et al., 2000), determine the rolling bedload particle velocity, V_{pcal} = ?

Solution:

1) Particle size d_s = 2 m, bed slope S_f = 0.01, bed roughness k_s = 150 mm, mean flow depth y = 3 m;

2) Calculation of basic parameters

- Shear velocity $u_* = [gR_hS_f]^{1/2} = [9.81\times3\times0.01]^{1/2} = 0.54$ m/s
- Shields particle parameter $\tau_{*ds} = u_*^2/(G-1)gd_s = (0.54)^2/(2.65-1)\times9.81\times2 = 0.009$
- Shields roughness parameter $\tau_{*ks} = u_*^2/(G-1)gk_s = (0.54)^2/(2.65-1)\times9.81\times0.15 = 0.12$
- Boundary relative roughness $d_s/k_s = 13.33$, and $k_s/d_s = 0.075$
- Particle shear Reynolds number $Re_* = u_*d_s/\nu = 0.54\times2/1.004\times10^{-6} = 1075697$
- Dimensionless particle diameter $d_* = d_s[(G-1)g/\nu^2]^{1/3} = 50457$

3) Calculation of bed roughness critical k_{sc} from Eqs. (5.37) and (5.38) to determine the motion of the particle; From Eq. (5.37), one obtains $k_{sc1} = (0.54)^2/(2.65-1)\times 9.81\times 0.01 =$ 1.8 m which is about ten times $k_{sc2} = 170$ mm, obtained from Eq. (5.38).

4) Calculation of $V_{psmooth} = 19.85$ m/s by using Eq. (5.28); $V_p = 0.9$ m/s by using Eq. (5.34). Similarly, applied the above procedures for different d_s, and k_s, and the results is shown in Fig. 6.21, where, proposed formula Eq. (5.34) gives realistic estimates of particle velocity values, and therefore it could help define particle velocities during devastating floods.

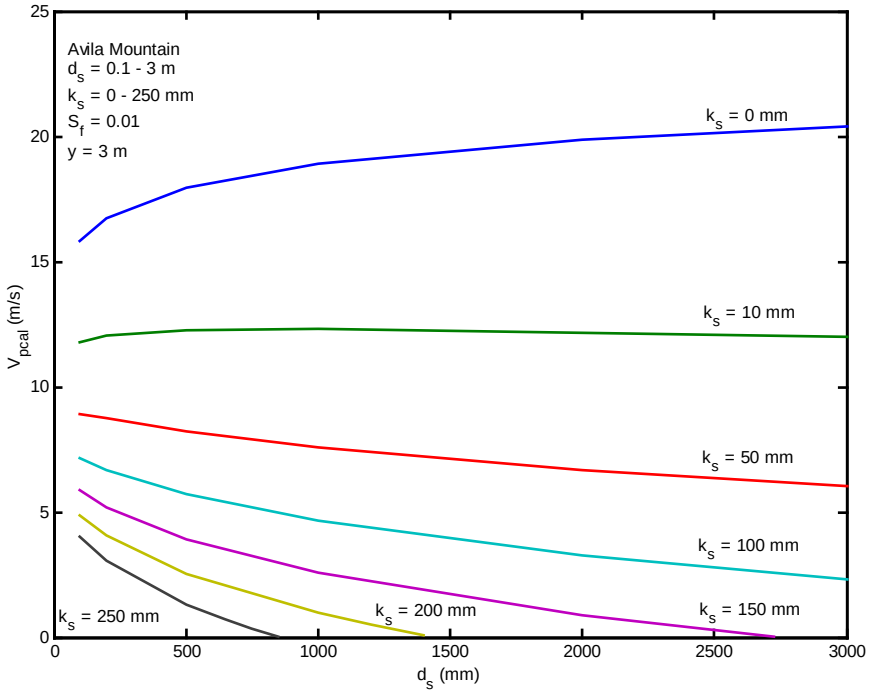

Figure 6.21: Predicted V_p using Eq. (5.34) for different values of d_s and k_s

CHAPTER 7

SUMMMARY AND CONCLUSIONS

This study aims at defining the bedload particle velocity in smooth and rough open channels as a function of the following variables: bed slope S_f, flow depth y, viscosity of the fluid ν, particle size d_s, bed roughness k_s, particle specific gravity G, and gravitational acceleration *g*.

Sources of data used in this analysis include 6 laboratory data sets for a total of 1018 points collected from different sources. In previous studies documented in the literature, 120 points could be obtained from Meland and Norrman (1966), 85 points from Fernandez Luque and van Beek (1976), 330 points from Steidtmann (1982), and 77 points from Bridge and Dominic (1984). Additionally, 356 points were collected at CSU on plates with bed roughness set at 1.2 mm, 1.7 mm, 2.4 mm, and 3.4mm, and 50 points from Bigillon (2001), with bed roughness set at 1.5 mm and 3 mm. Each set of data contains a complete record for flow and bedload particles information. These data are limited to the particle sizes with median diameters in the range of 0.21 to 29.3 mm, bed

roughness in the range of 0.19 to 7.76 mm, average flow velocity in the range of 0.22 to 1.00 m/s, shear velocity in the range of 0.0097 to 0.1108 m/s, flow depth in the range of 2.13 to 180 mm, and slope in the range of 0.00073 to 0.05.

The existing formulas such as Meland and Norrman (1966), Fernandez Luque and van Beek (1976), and Bridge and Dominic (1984) are verified with the laboratory measurements. Results show that all of the existing formulas fail to predict V_p when applied to the data sources other than their own database.

The analysis of the data leads to the following conclusions:

(1) For a smooth bed ($k_s = 0$), the rolling bedload particle velocity V_p increases with particle sizes d_s;

(2) For a rough bed ($k_s > 0$), particle velocity decreases with particle density G, thus lighter particles move faster than heavier ones; and on a very rough boundary V_p decreases with particle sizes;

(3) Bedload particles move at values of the Shields parameter τ_{*ds} below the critical value of $\tau_{*dsc} = 0.047$;

(4) Very few of the observed particles moved at values of Shields roughness parameter τ_{*ks} less than 0.01;

(5) Particles are observed to move at values of the Shields roughness parameter $0.01 < \tau_{*ks} < 0.15$;

(6) The ratio of particle velocity V_p to mean flow velocity u_f lies in the range of 0.2 to 0.9, while Kalinske (1942) suggested 0.9 to 1.0;

(7) The ratio of particle velocity V_p to shear velocity u_* lies in the range of 2.5 to 12.5, compared to the values cited in the literature $6.0 < V_p/u_* < 14.3$;

New methods for predicting transport velocities of bedload particles in rough and smooth open channels are examined. Two approaches for transport velocities of bedload particles were considered. The first approach combines dimensional analysis and regression analysis to define bedload particle velocity as a power function of the Shields parameter τ_*, boundary relative roughness k_s/d_s, dimensionless particle diameter d_*, and excess specific gravity (G-1). The second approach considers the transport velocity of a single particle on a smooth bed. The reduction in particle velocity due to bed roughness is then examined through a theoretical and empirical analysis. Results show that the bedload particle velocity on smooth beds is approximately equal to the flow velocity at the center of the particle. Bed roughness decreases the transport velocity of rolling bedload particles.

Comparatively, The first approach gives satisfactory results, except when k_s equals 0, then V_p goes to ∞, and when k_s is large, V_p does not stop (unbounded); for the second approach V_{pmax} when k_s equals 0, and when V_p equals 0, then values of k_s follow the criteria a and b described in Chapter 5 (section 5.4) and there is an insufficient evidence to suggest that one criteria is better than other.

The analysis shows that the proposed formula, Eq. (5.34) provides much better predictions than the existing formulas. Plots showing the comparison between calculated and observed bedload particle velocity and the discrepancy ratio distribution are shown in Figs. 5.12, and 5.13 respectively; the discrepancy ratio for the predictions of bedload particle velocity using the newly proposed formula, Eq. (5.34) are normally distributed

and have higher density (close to perfect agreement) than all other formulas. Predictions with extreme discrepancy ratios ($R_i < -1.0$ and $R_i > 3.0$) are very limited in utility; and less than 2.5 % of data with discrepancy ratio $R_i < 0.75$ and $R_i > 1.25$. The statistical results of calculated V_p are shown in Table 5.1, which indicate that the newly proposed formula Eq. (5.34) gives the best prediction amongst all formulas. In addition, the proposed formula, Eq. (5.34) is also verified with the most current laboratory data from Bigillon (2001). Field application to Halfmoon Creek (Dixon and Ryan, 2000), and the devastating flood of the Avila Mountain in Venezuela in December 1999 (Leon and Rojas, 2000, personal communication), the results give realistic estimates of particle velocities.

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