INITIATION OF MOTION OF COARSE SOLITARY PARTICLES ON ROUGH CHANNEL BEDS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ÖMER İLKER KÜÇÜKTEPE

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

DECEMBER 2009

Approval of the thesis:

INITIATION OF MOTION OF COARSE SOLITARY PARTICLES ON ROUGH CHANNEL BEDS

submitted by **ÖMER İLKER KÜÇÜKTEPE** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ______________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Güney Özcebe ______________________
Head of Department, **Civil Engineering**

Prof. Dr. Mustafa Göğüş ______________________
Supervisor, **Civil Engineering Dept., METU**

Examining Committee Members:

Prof. Dr. Nevzat Yıldırım ______________________
Civil Engineering Dept., Gazi University

Prof. Dr. Mustafa Göğüş ______________________
Civil Engineering Dept., METU

Assoc. Prof. Dr. İsmail Aydın ______________________
Civil Engineering Dept., METU

Assoc. Prof. Dr. A. Burcu Altan Sakarya ______________________
Civil Engineering Dept., METU

Asst. Prof. Dr. Mete Köken ______________________
Civil Engineering Dept., METU

Date: 10.12.2009

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Ömer İlker Küçüktepe

Signature :

ABSTRACT

INITIATION OF MOTION OF COARSE SOLITARY PARTICLES ON ROUGH CHANNEL BEDS

Küçüktepe, Ömer İlker
M.Sc., Department of Civil Engineering
Supervisor: Prof. Dr. Mustafa Göğüş

December 2009, 124 pages

In this study the incipient motion of coarse solitary particles on channel beds having different roughness heights was experimentally investigated. The experiments were conducted in a tilting flume of a rectangular cross-section having a working length of 12 m and a rough bed composed of at least 2 layers of coarse gravel of almost constant size. The roughness material of the channel bed was changed three times. The slope of the channel bed and the discharge are two main parameters that determine the initiation of motion of a given particle. The artificial particles tested in the experiments were obtained by mixing cement and iron dust at certain ratios. Dimensionless hydraulic parameters determined from theoretical analysis were related to each other. Flow depths, velocity profiles were measured and flow conditions that represent the critical conditions of initiation of motion were expressed in terms of critical velocities and shear velocities. The results were compared with the previous studies' results.

Keywords: Incipient motion, coarse particles, sediment transport, rough channel bed.

ÖZ

İRİ KATI DANELERİN PÜRÜZLÜ AÇIK KANAL YATAKLARINDA İLK HAREKETE GEÇİŞİ

Küçüktepe, Ömer İlker
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Mustafa Göğüş

Aralık 2009, 124 sayfa

Bu çalışmada farklı pürüzlülük seviyelerine sahip kanal yatağı üzerinde iri katı danelerin akım içerisinde ilk harekete geçişleri deneysel olarak incelenmiştir. Deneyler çalışma boyu 12 m olan ve eğimi değiştirilebilen, pürüzlü zemini en az 2 katman aynı büyüklükteki iri malzeme ile oluşturulmuş dikdörtgen kesitli kanalda gerçekleştirilmiştir. Kanalın pürüzlülük malzemesi 3 sefer değiştirilmiştir. Kanal eğimi ve debi belirli danenin harekete geçmesindeki iki temel unsurdur. Deneylerde kullanılan yapay malzemeler çimento ve demir tozunun belirli oranlarda karıştırılması ile elde edilmiştir. Teorik analizden elde edilen boyutsuz hidrolik parametreler arasında ilişkiler kurulmuştur. Akım derinlikleri, hız profilleri ve harekete geçiş durumuna karşı gelen akım şartları, kritik akım hızı ve kritik kayma gerilmesi cinsinden belirtilmiştir. Elde edilen sonuçlar önceki çalışmaların sonuçları ile karşılaştırılmıştır.

Anahtar Kelimeler: İlk harekete geçiş, iri katı madde, sediment taşınımı, pürüzlü kanal yatağı.

To My Family

ACKNOWLEDGEMENTS

This research has been carried out under the supervision of Prof. Dr. Mustafa GÖĞÜŞ in the Hydromechanics Laboratory of the Department of Civil Engineering in the Middle East Technical University.

The author wishes to express his sincere appreciation to Prof. Dr. Mustafa GÖĞÜŞ for his guidance and helpful advice throughout the research.

The technical assistance of author's colleagues and the effort of laboratory staff are gratefully acknowledged.

The author offers sincere thanks to his family for their unshakable faith in him, their patience and confidence in him. They receive many indebted thanks.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS

a	: Maximum width of a grain perpendicular to flow direction and parallel to the channel bottom
a_1	: Length of the major axis of the particle used in the shape factor equation by Novak and Nalluri (1975).
b	: Height of a grain resting on channel bed
b_1	: Length of the intermediate axis of the particle used in the shape factor equation by Novak and Nalluri (1975).
B	: Cannel width
c	: Maximum length of a grain in flow direction parallel to channel bottom
c_1	: Length of the minor axis of the particle used in the shape factor equation by Novak and Nalluri (1975).
C_Q	: Discharge coefficient
d	: Grain size, usually sieve diameter
d_{50}	: Grain size for which 50% are finer
d_s	: Nominal diameter of sediment particle based on volume
f_1, f_2	: Empirical coefficients for the general form of the relationship between densimetric Froude number and relative depth
Fr_*	: Densimetric Froude number in terms of shear velocity
g	: Gravitational acceleration
h	: Depth of flow section
h_s	: Flow depth in the smooth channel
$(h^*)_r$	: Vertical distance between the theoretical bed level and the free surface
H	: Measured head above crest of weir, excluding velocity head.
k_s	: Roughness of bed.
K, K', K''	: Empirical constants for Brahms equation

L	: Characteristic length of a particle
L_l	: Effective length of crest of a weir
l_1 , l_2 ,… l_8	: Side lengths for the particles used in the experiments
n	: Manning roughness coefficient
n_b	: Manning roughness coefficient of the bed
n_{eq}	: Equivalent Manning roughness coefficient
n_w	: Manning roughness coefficient of the channel walls
p	: Height of sharp crested weir
P	: Wetted perimeter
P_b , P_w	: Wetted perimeters of the bed and the walls, respectively
q	: Unit discharge
Q	: Volumetric discharge over weir
R	: Hydraulic mean radius of conveyance
R_b	: Effective hydraulic radius corresponding to bed only
$(R_b)_s$	: Effective hydraulic radius of smooth bed corresponding to bed only
$(R^*_b)_r$	: Effective hydraulic radius of rough bed corresponding to bed only
Re_*	: Grain Reynolds number
S	: Slope of flow
S_c	: Critical slope
S_s	: Specific gravity of sediment
SF	: Shape factor for a sediment particle
t	: Height of obstructing element
u^*	: Shear velocity
$(u^*)_c$	: Critical shear velocity
V	: Velocity of flow
V_{bc}	: Critical bottom velocity
V_{cc}	: Critical mean velocity in the cross-section
$(V_{cc})_r$	: Critical velocity of single particle on rough fixed bed
$(V_{cc})_s$	: Critical velocity of single particle on smooth fixed bed
W	: Weight of a sediment grain

$\Delta\rho$	: Difference between ρ_s and ρ
γ	: Specific weight of fluid
γ_s	: Specific weight of sediment particle
ν	: Kinematic viscosity of fluid
ρ	: Density of fluid
ρ_s	: Density of sediment particle
τ_*	: Entrainment function, Shields parameter
τ_0	: Bed shear stress
τ_c	: Critical bed shear stress
$\forall$	: Volume of the grain

CHAPTER I

INTRODUCTION

I.1. Introductory Remarks

The studies on the subject of sediment transport go back to very old times. The first advancements were developed in China, Mesopotamia, Egypt about thousand of years ago. The main question in sediment transport is the beginning of the motion which is called as many ways. Initiation of motion, inception of motion, threshold of motion… all explain the same critical condition. The earliest research about this phenomenon has been made by Brahms in 1753 (Raudkivi, 1967), in which he resulted with the equation:

$$V_{bc} = K \cdot W^{1/6} \tag{1.1}$$

where W is the weight of the grain, K is an empirical constant and V_{bc} is the competent velocity of the flow at the particle level at which particle starts moving.

Although there were many researchers that have studied on the initiation of motion for more than two centuries, the effect of particle shape has not been examined explicitly until the studies of Gogus and Defne (2005) and Gülcü (2009). Defne (2002) and Gülcü (2009) aimed to clarify the effect of shape and size of particles having constant weight on the incipient motion. In their studies, the effect of shape and size of coarse solitary particles on the initiation of motion has been separately studied over smooth channel bed when the particles resting behind an obstruction of known height. Based on the earlier preliminary experiments conducted over various rough surfaces regarding the initiation of particle motion it was found that the coarse solitary particles resting over rough surfaces could be represented as if they were resting just behind an obstructing element having heights varying between 1/5 and 2/5 of the particle height. This obstruction height to particle height ratio used in Defne's study was 1/5 and Gülcü's study was 1.5/5.

The aim of this study is to investigate the effect of the channel bed roughness on the determination of the obstructing element height to be used on a smooth channel bed to determine the flow conditions required for the incipient motion of a coarse solitary particle. For this reason a series of experiments were conducted in the channel having 3 different rough bed and smooth bed with an obstructing element for artificial particles of various shapes having specific weights of $\gamma_s = 1.96$ g/cm^3.

Review of the relevant literature is given in section I-2. Theory and methodology are explained in Chapter II. The experimental investigations related to the bed roughness and the results of the experiments about the effect of bed roughness on the obstructing element height are discussed in Chapter III. Conclusion and further recommendations are given in Chapter IV.

I.2. Review of Relevant Literature

At the topic of incipient motion of particles, Albert Frank Shields is one of the most reputable researcher. What Shields did was a dimensional analysis of the question. Since there are many variables concerned with the problem after the analysis, he simplified the problem for some certain conditions and he defined the parameters affecting the initiation of motion and resulted with the relation (Yalin, 1977):

$$\frac{\tau_c}{(\gamma_s - \gamma)\cdot d} = f\left(\frac{(u_*)_c \cdot d}{\nu}\right) \tag{1.2}$$

where:

τ_c : critical bed shear stress

γ_s : specific weight of the particle

γ : specific weight of the fluid

d : grain size

$(u_*)_c$: critical shear velocity

ν : kinematic viscosity of the fluid

The word "*critical*" and the subscript "*c*" are used to define the conditions at the initiation of motion. In general, bed shear stress is denoted by τ_0 and the term $\frac{\tau_0}{(\gamma_s - \gamma)\cdot d}$ is named as *Shields parameter* or *entrainment function.* It is equivalent to the *densimetric Froude number* or *dimensionless shear stress* and it is usually denoted as τ_* or Fr_*. The term, $\frac{(u_*)_c \cdot d}{\nu}$, on the right hand side of the above relation is named as the *grain Reynolds number* or *boundary Reynolds number* and usually referred as Re_*.

Novak and Nalluri (1975) have investigated the condition of incipient motion in circular conduits and rectangular flumes with fixed smooth beds and free surface flow. They have used a tilting flume. The particle shape factor they have utilized was equal to $\frac{c_1}{\sqrt{a_1 \cdot b_1}}\cdot$, where c_1 is the minor axis and a_1 and b_1 are other two axes.

At the end of their research, Novak and Nalluri have obtained the relations for a range of $10 < Re_* < 1000$:

$$\tau_* = 0.065 \cdot (Re_*)^{-0.52} \tag{1.3}$$

$$\tau_* = 0.06 \cdot (Re_*)^{-0.61} \tag{1.4}$$

for the rectangular channel and for the channels with circular cross section, respectively.

In terms of critical cross-sectional velocity of flow, V_{cc}, the equations are represented as:

$$V_{cc} = 0.17 \cdot (S_s - 1)^{1/2} \cdot d_s^{0.24} \tag{1.5}$$

$$V_{cc} = 0.16 \cdot (S_s - 1)^{1/2} \cdot d_s^{0.16} \tag{1.6}$$

for the rectangular channel and for the channels with circular cross section, respectively. Here S_s is the specific gravity of the sediment and d_s , is the nominal diameter of the sediment particle in mm and V_{cc} is in m/s.

In terms of critical shear stress, τ_c , the equations are given as:

$$\tau_c = 0.128 \cdot (S_s - 1) \cdot d_s^{0.4} \tag{1.7}$$

for rectangular channel, and

$$\tau_c = 0.104 \cdot (S_s - 1) \cdot d_s^{0.4} \tag{1.8}$$

for circular channels. Here τ_c is in N/m^2 and d_s is in mm.

In order to decrease the effect of channel shape they proposed to analyze the results in terms of relative depth and presented the equation:

$$\frac{(V_{cc})_r}{\sqrt{g \cdot d_s \cdot (S_s - 1)}} = 0.61 \cdot (\frac{d_s}{R_b})^{-0.27} \tag{1.9}$$

where, relative depth d_s/R is the ratio of particle diameter to hydraulic mean radius of conveyance.

In their next study, Novak and Nalluri (1984) have studied on the incipient motion of single and grouped particles on smooth fixed and also rough fixed beds with roughness smaller than the particle size. Equivalent diameter sizes of particles were from 0.6 mm to 50 mm and average relative density was 2.56. In each set of the experiments, particle sizes were always larger than the roughness sizes.

They analyzed the data from the investigation of incipient motion of discrete particles on beds with various roughness elements and presented the graph shown in Figure I-1. Here, R_b is the effective hydraulic radius corresponding to bed only and $(V_{cc})_r$ is the critical cross-sectional velocity of flow for a single particle on a rough fixed bed having roughness height of k_s. An average approximate relationship for the entire data suggests the following equation:

$$\frac{(V_{cc})_r}{\sqrt{g \cdot d_s \cdot (S_s - 1)}} = 0.54 \cdot (\frac{d_s}{R_b})^{-0.38} \qquad (1.10)$$

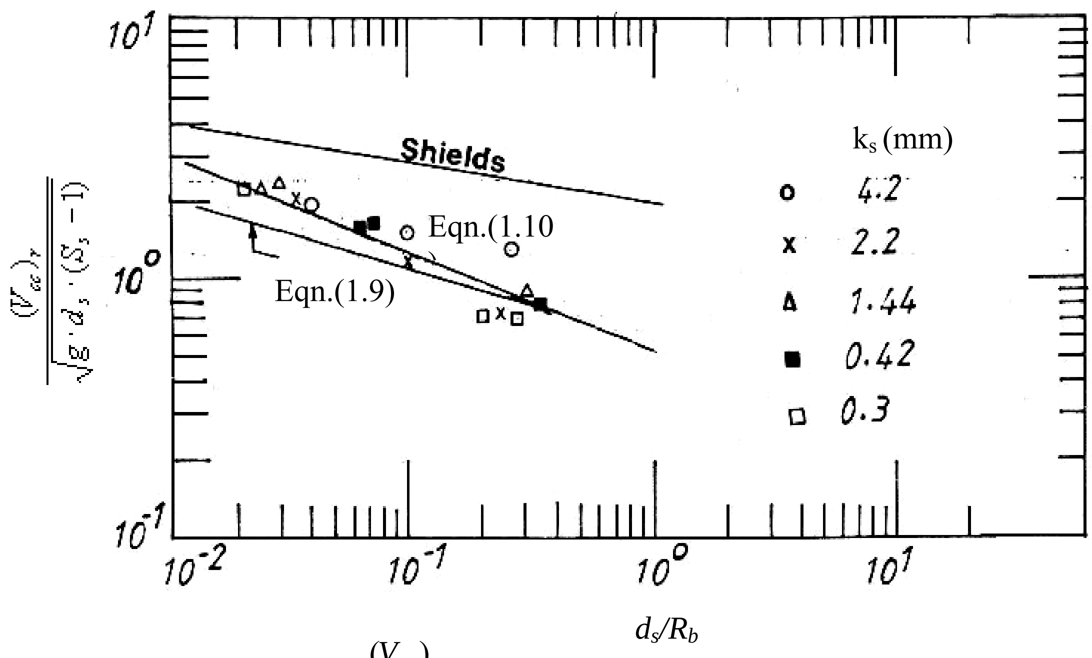


Figure I-1: $\frac{(V_{cc})_r}{\sqrt{g \cdot d_s \cdot (S_s - 1)}}$ against d_s/R_b (Novak and Nalluri, 1984)

In case of rough fixed beds and single particles, the ratio of particle diameter to roughness height, d_s/k_s, plays an important role. Novak and Nalluri obtained the graph in Figure I-2, which is quite similar to the well-known Nikuradse graph showing the friction coefficient as a function of Reynolds number. The graph indicates that the value of τ^* will be a function of d_s/k_s for Re^* well above *1000*.

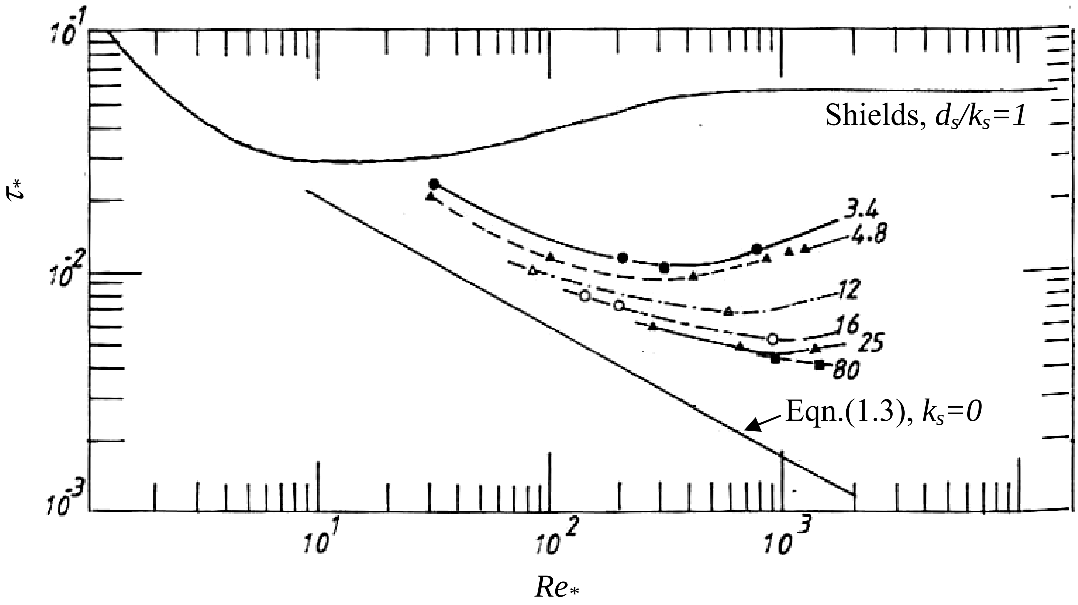


Figure I-2: τ_* against Re_* for single particles and constant d_s/k_s values (Novak and Nalluri, 1984)

The effect of d_s/k_s ratio on the critical condition is given in Figure I-2. When the critical velocities of single particles on smooth fixed beds and on rough fixed beds are compared, a representative equation in the following form is obtained within the range of $75 > d_s/k_s > 2$

$$\frac{(V_{cc})_r}{(V_{cc})_s} = 1 + 1.43\left(\frac{d_s}{k_s}\right)^{-0.4} \tag{1.11}$$

k_s : roughness of the bed

$(V_{cc})_s$: critical cross-sectional velocity of flow at which single particles on smooth beds move.

Figure I-2 shows this relation and indicates that the effect of d_s/k_s diminishes for d_s/k_s values greater than 100.

When equations (1.9) and (1.10) are compared it is seen that all the equations are of the type:

$$\frac{V_c}{\sqrt{g \cdot d_s \cdot (S_s - 1)}} = f_1 \cdot (\frac{d_s}{R})^{f_2} \tag{1.12}$$

Here, f_1 and f_2 are two empirical constants given in Table I-1.

Table I-1: f_1 and f_2 coefficients for equations of incipient motion (Novak and Nalluri, 1984).

	f_1	f_2	Eq.
Smooth bed single particles	*0.61*	*-0.27*	(1.9)
Rough bed single particles	*0.54*	*-0.38*	(1.10)
Rough and smooth bed touching particles	*0.50*	*-0.40*	-
Movable bed (d_s=k)	*1.7 ~ 1.9*	*-0.095 ~ -0.167*	-
Note: Range of experiments $0.01 < d_s/R < 0.3$, $3.5 < d_s/k_s \leq \infty$			

The ratio of flow depth to grain diameter plays an important role in critical conditions for sediment motion. Shvidchenko and Pender (2000) have studied the effect of relative depth on the incipient motion of coarse uniform sediments.

Shvidchenko and Pender deduced that the Shields parameter τ^* is dependent on the bed slope for uniform flow. They have stated that their deduction is also satisfied with the prior results obtained by Bathurst et al. in 1984 and by Graf and Suszka in 1987.

Shvidchenko and Pender suggested a family of threshold curves corresponding to different values of R_b/d_s (See Figure I-3). From this figure, they conclude that critical Shields parameter depends on grain Reynolds number Re^*, even at high values of

Re^*. However, to clarify this case further studies with coarser materials at higher Re^* and larger values of R_b/d_s are required.

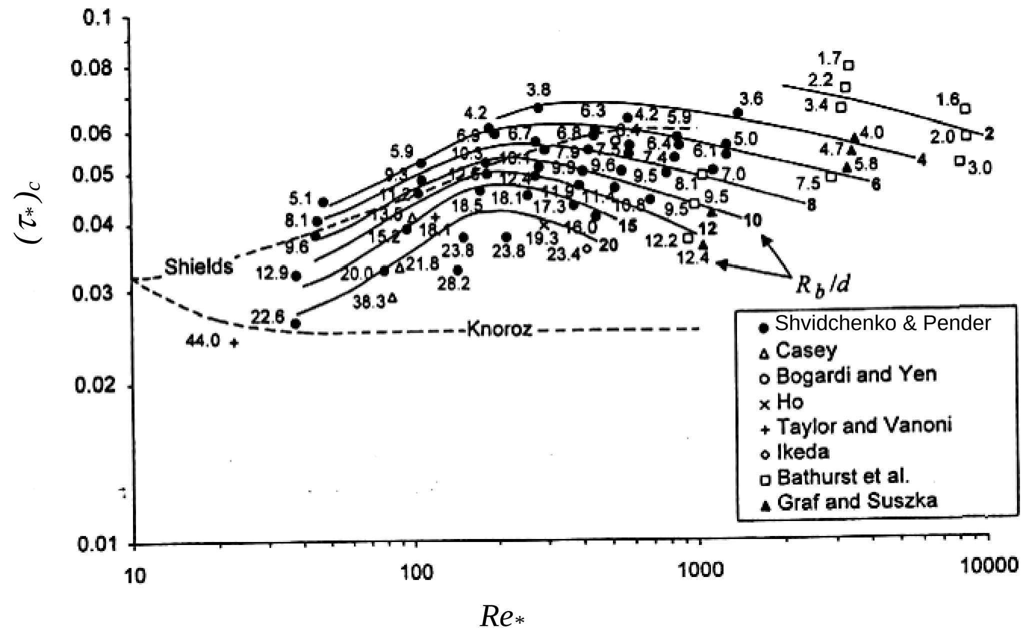


Figure I-3: Critical entrainment function vs. grain Reynolds number for different values of R_b/d_s (Shvidchenko and Pender, 2000)

Defne (2002) conducted a series of experiments in a smooth rectangular channel to determine the flow conditions under which large solitary particles have initiation of motion when they were resting behind an obstructing element. The height ratio of the obstructing element to the particle height, t/b, was kept constant as 1/5 and it was assumed that as if the particles were resting on a rough bed of which roughness height ratio to the particle height, k_s/b, was represented by 1/5 based on some preliminary experiments. Defne defined a new shape factor and showed that this shape factor is an important parameter on which the relevant parameters of the initiation of motion of particles were dependent. Figure I-4 show the relationship between R_b/d_s and Re^* obtained by Defne.

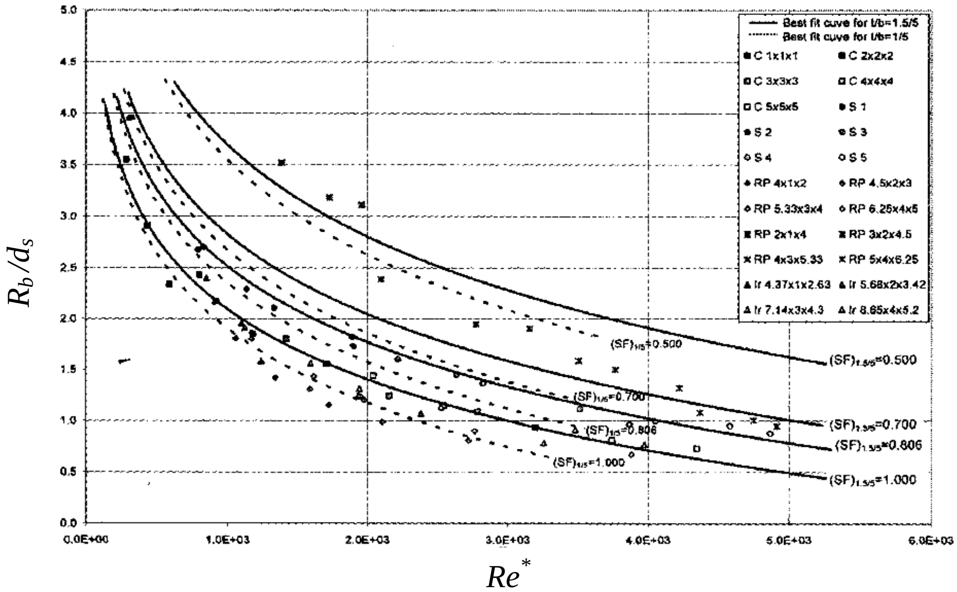


Figure I-4: R_b/d_s vs. Re* (Defne, 2002, Gülcü, 2009)

Gülcü (2009) repeated the similar experiments conducted by Defne (2002) using the same particles in the same rectangular channel but different obstructing element height ratio to particle size, t/b, as 1.5/5 just to show the effect of t/b value on the relevant parameters of the initiation of particle motion. Gülcü's were also presented in Figure I-4.

CHAPTER II

THEORY AND THE METHODOLOGY

This study involves determination of the critical flow conditions under which a coarse solitary particle will just move on the bed of a rectangular channel of which the slope and roughness properties are known. In the first part of the study, the channel bed was roughened by coarse gravels of known sizes and required flow conditions were determined for the incipient motion of the given particle. In the second part of the study, a given particle was tested under the predetermined critical flow conditions in the same channel with a smooth bed having an obstructing element just behind the particle. The required obstructing element height for the initiation of particle motion was investigated. As a consequence it can be stated that the aim of this study is to determine the obstructing element heights on a smooth bed which will represent the channel bed roughnesses.

The theoretical analysis is to be presented under two titles; the one is for rough channel bed and the other one is for smooth channel bed. Then two important parameters “theoretical bed level” and “the new shape factor” to be used in the analysis are described.

II.1. Application of Dimensional Analysis to Rough Channel Bed

The critical flow conditions required for the initiation of a coarse solitary particle of known shape in an open channel of given bed slope and roughness can be stated in the form of the flow depth, $(h^*)_r$ or discharge Q (or unit discharge q for a rectangular channel). One can write the following equations for $(h^*)_r$ which is the vertical distance between the theoretical bed level above which the logarithmic velocity distribution is valid with a constant of 8.5 and the free surface, and q as function of the relevant independent parameters (Figure II-1).

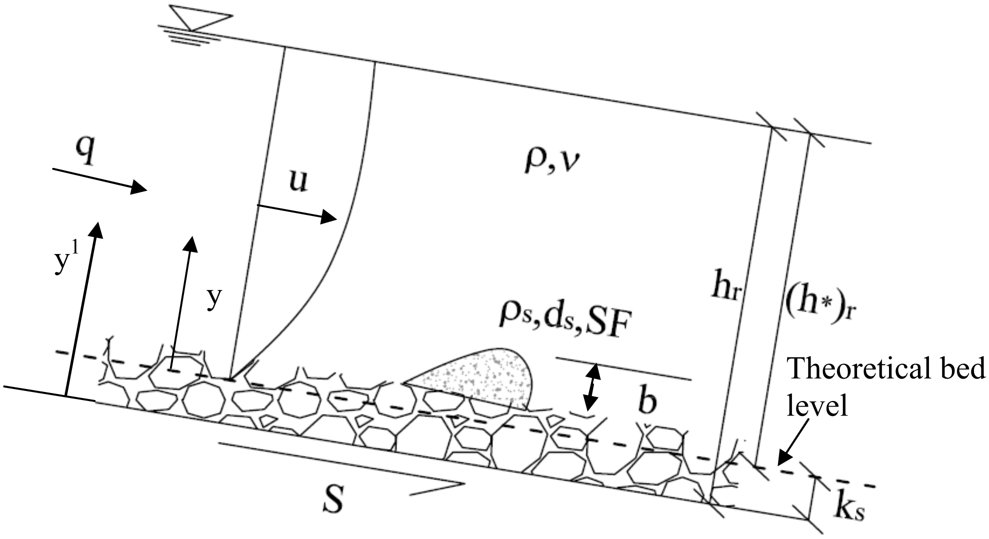


Figure II-1: Parameters related to the rough surfaces

$$(h^*)_r = f_1\left(S, k_s, g, \rho, \rho_s, d_s, SF\right) \tag{2.1}$$

and

$$q = f_2\left(S, k_s, g, \rho, \rho_s, d_s, SF\right) \tag{2.2}$$

where:

S : Bed slope of the channel,

k_s : Equivalent roughness height of the channel bed.[L],

g : Gravitational acceleration, [L/T^2],

ρ, ρ_s: Density of the fluid and particle, respectively, [M/L^3],

d_s : Nominal diameter of the particle, [L],

SF: Shape factor of the particle.

The application of dimensional analysis to Eqn. (2.1) and (2.2) yields

$$\frac{(h^*)_r}{d_s} = f_3\left(\frac{k_s}{d_s}, S, \frac{\rho_s}{\rho}, SF\right) \tag{2.3}$$

and

$$\frac{q^2}{g(d_s)^3} = f_4\left(\frac{k_s}{d_s}, S, \frac{\rho_s}{\rho}, SF\right) \tag{2.4}$$

Considering the channel side effects on the flow conditions if the flow depth $(h^*)_r$ is replaced by hydraulic radius of the channel bed $(R_b^*)_r$ and some arrangements are made into the above equations, they reduce to

$$(S)\left[\frac{(R_b^*)_r}{d_s}\right] = f_3\left(\frac{k_s}{d_s}, \frac{\rho_s}{\rho}, SF\right) \tag{2.5}$$

and

$$(S)\left[\frac{q^2}{g\,{}^{\Delta\rho}\!/\!{}_{\rho}(d_s)^3}\right] = f_4\left(\frac{k_s}{d_s}, SF\right) \tag{2.6}$$

where $\Delta\rho = \rho_s - \rho$

II.2. Application of Dimensional Analysis to Smooth Channel Bed

The obstructing element height, t, required for a given particle of known shape and size on a smooth channel bed of known slope so that the particle resting behind the obstructing element will just move at initially known unit discharge q corresponding to a channel bed of the same slope and known roughness properties is function of the following parameters (Figure II-2)

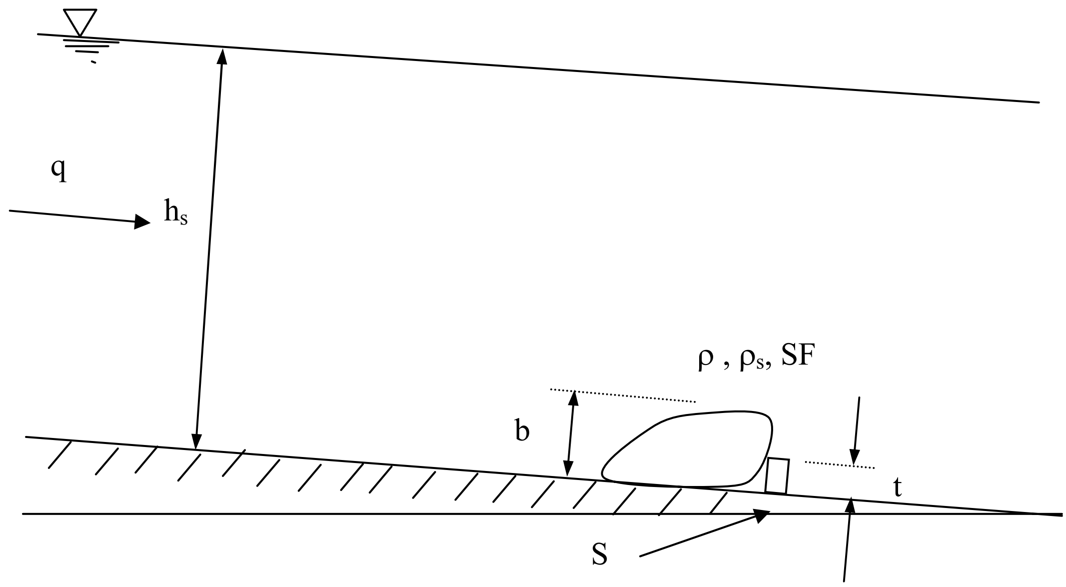


Figure II-2: Parameters related to the condition of incipient motion

$$t = f_1(S, q, g, \rho, \rho_s, d_s, SF) \tag{2.7}$$

or

$$t = f_2(S, h_s, g, \rho, \rho_s, d_s, SF) \tag{2.8}$$

where h_s is the flow depth in the smooth channel of slope S and unit discharge q.

The application of dimensional analysis to Eqns. (2.7) and (2.8) yield

$$\frac{t}{d_s} = f_3\left(\frac{q^2}{g \frac{\Delta\rho}{\rho} d_s^{\,3}}, S, SF\right) \tag{2.9}$$

and

$$\frac{t}{d_s} = f_4\left(\frac{h_s}{d_s}, S, \frac{\rho_s}{\rho}, SF\right) \tag{2.10}$$

From the same reason as discussed earlier if the flow depth h_s is replaced by hydraulic radius of the channel bed $(R_b)_s$ and some arrangements are made in the above equations, they can be written as

$$\frac{t}{d_s} = f_5\left((S)\left(\frac{q^2}{g \Delta\rho/\rho\, d_s^{\,3}}\right), SF\right) \tag{2.11}$$

and

$$\frac{t}{d_s} = f_6\left((S)\left(\frac{(R_b)_s}{d_s}\right), \frac{\rho_s}{\rho}, SF\right) \tag{2.12}$$

II.3. Determination of Theoretical Bed Level

As it was stated earlier, the channel bed roughness was changed three times in this study by using the gravels of almost the same size as roughness element in each case. In order to determine the roughness height of each rough bed to use in the analysis, the theoretical bed levels were calculated. The theoretical bed level is defined as the origin of y-axis used in the logarithmic velocity distribution which is assumed to be valid over rough surfaces with a constant of 8.5 as given below (Raudkivi, 1967) (Fig.II-1).

$$\frac{u}{u_*} = 5.75 \log \frac{y}{k_s} + 8.5 \tag{2.13}$$

First assuming the theoretical bed level, k_s, for a given bed roughness and then using measured u values and determining their y values from the assumed k_s and known flow depth, h_r, one can plot u vs. log y on a semi log paper and calculate u_* and k_s values from the straight line to be plotted on the data. If the calculated u_* value is equal to the one to be obtained from Eqn. 2.14, it can be considered that the assumed k_s value is correct. Otherwise k_s value is reassumed and above described procedure is applied until getting the same u^* value that is calculated from Eqn. 2.14.

$$u_* = \sqrt{\tau_0 / \rho} = \sqrt{g (R_b)^*{}_r S} \tag{2.14}$$

where $(R_b)_r^*$ is the hydraulic radius of the bed for rough channel.

II.4. Use of the New Shape Factor

The particle shape for each grain is expressed according to an imaginary rectangular prism including the whole volume of the grain within its body (Gülcü, 2009; Gogus and Defne, 2005; Defne, 2002). The crucial point is the determination of the defining lengths for this imaginary circumscribing rectangular prism. When determining the defining lengths, the most stable orientations of a particle on a horizontal plane are considered. Then the orientation of the particle that yields the minimum height is selected. Subsequently, the projected area of the particle perpendicular to the flow is selected as the frontal area. Note that this projected area changes according to the alignment of the particle with flow direction. In this study, two cases, most favorable and most unfavorable orientations, have been considered for rectangular prisms. The two defining lengths are the primary axes of the frontal projected area; the height of the particle, *b*, and the width of the particle, *a*. Finally the largest dimension that is parallel to the flow direction is the third defining length, which is the length of the particle and labeled as *c*. Moreover, a characteristic length is defined. The characteristic length, *L*, is the longest dimension on the projected area of the particle, perpendicular to the flow direction. For spherical particles it is merely the nominal diameter, d_s , and for other particles it is computed from the defining lengths *a* and *b* with the equation

$$L = \sqrt{a^2 + b^2} \qquad (2.15)$$

An illustrative sketch on how the defining lengths are expressed for an arbitrarily shaped grain is given in Figure II-3.

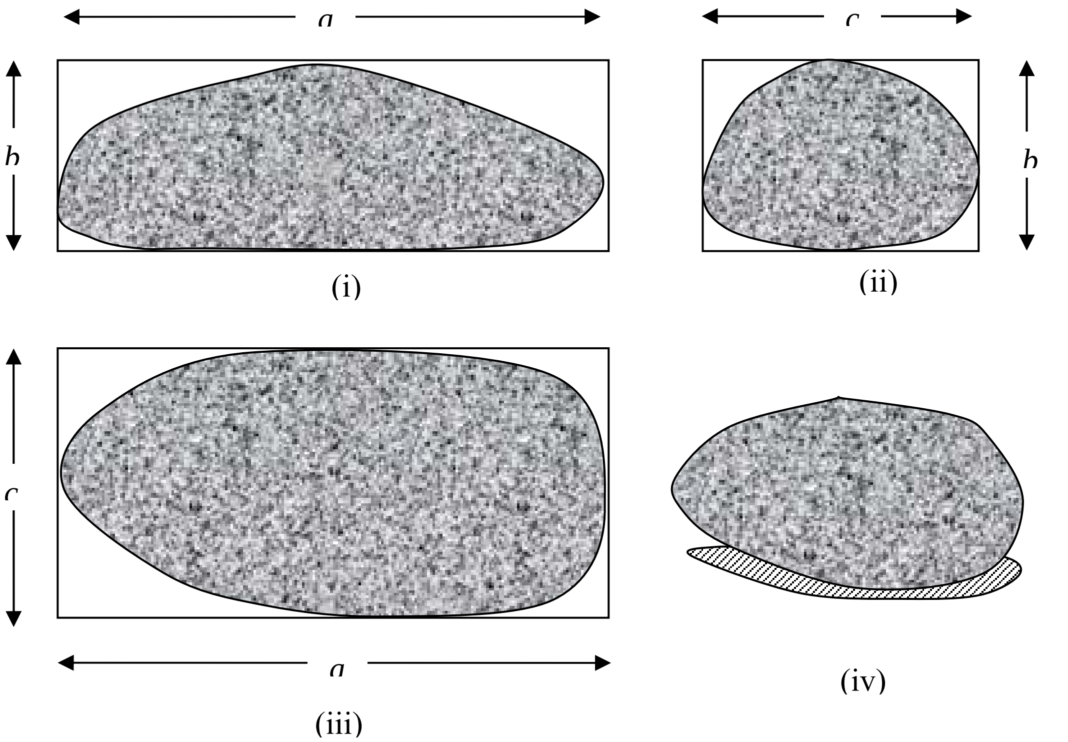


Figure II-3: Illustrative sketch for particle dimensions

(i) Frontal projected area of the particle (ii) Side view and the projected area

(iii) Top view and the projected area (iv) 3D view of the object

Defne (2002) has defined a new shape factor in the light of intuition obtained from previous studies (Gogus et al., 2001):

$$SF = \left(\frac{a+b}{2 \cdot c} \right) \cdot \left(\frac{\forall}{a.b.c} \right)^{1/3} \qquad (2.16)$$

where a, b, c are derived from the dimensions of the original particle and $\forall$ is the real volume of the particle. In this equation the first term is related to the orientation of the particle under fluid flow and in one respect is a measure of stability of the particle and the second term is the ratio of volume of enclosing imaginary rectangular prism to the volume of original particle.

CHAPTER III

THE EXPERIMENTAL INVESTIGATIONS

In this study, initiation of motion of totally 8 sediment particles of various shapes tested in a tilting flume by changing the bed roughness three times at the Hydromechanics Laboratory of Middle East Technical University.

More detailed explanation about the experimental setup and experimental procedure are explained in the following sections.

III.1. Experimental Setup

The experimental setup is a *12 m* long tilting flume having a rectangular cross section. Net working length of the channel is *8 m*. The depth of the cross section is *45 cm* and the width is *50 cm*. A detailed layout of the setup is given in Figure III-1.

The channel bottom is originally made up of concrete, and the walls are made of glass. Tilting of the channel is maintained by a motor and screw combination. In each experiment with different slopes, the uniform flow condition was always checked by monitoring the depth with the help of a mobile point gage attached to the channel.

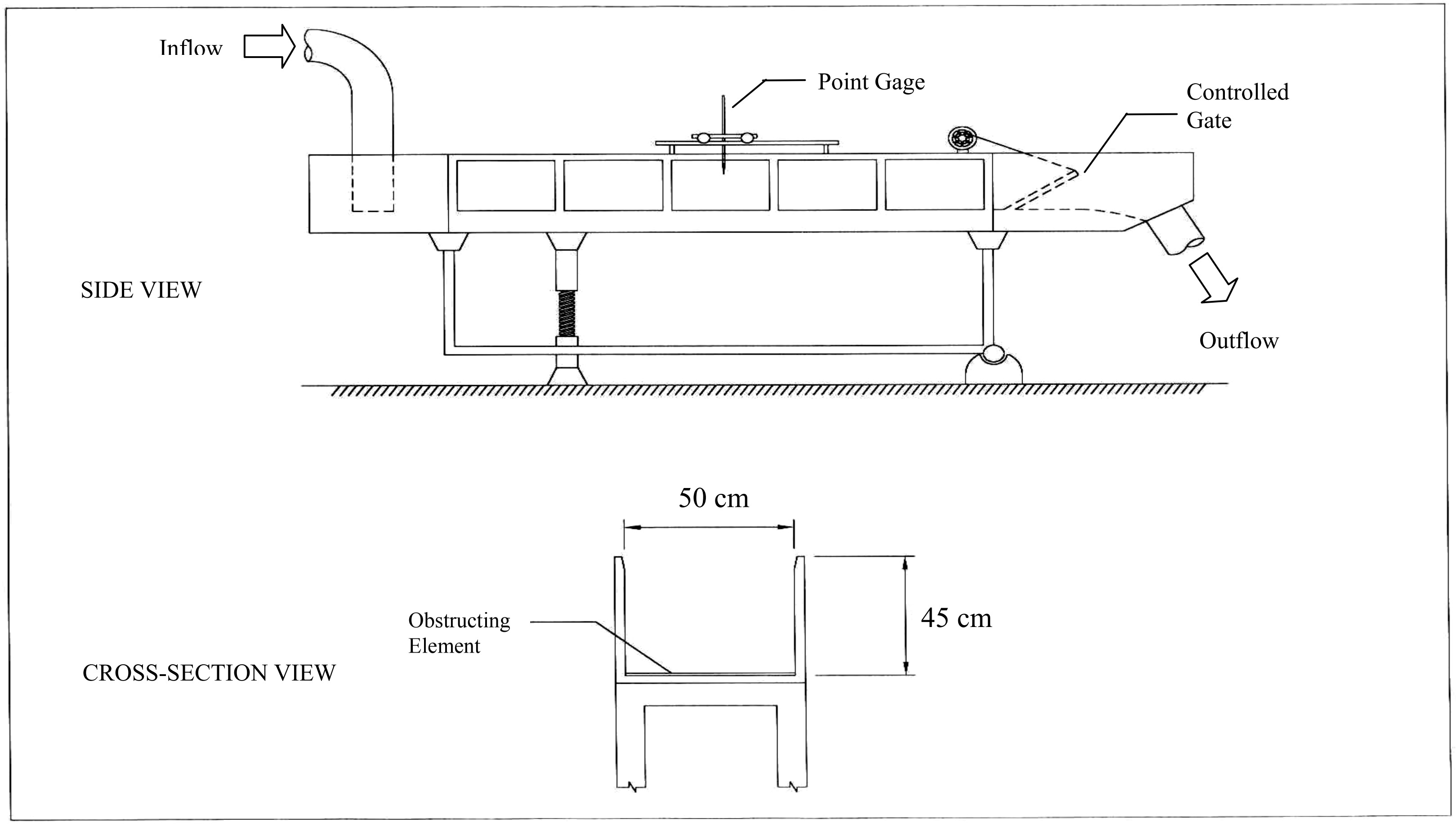


Figure III-1: Experimental setup

III.1.1. Determination of the Flow Rate

For determination of the flow rate, the Ultrasonic Flowmeter model UFP-10 was used. The ultrasonic flowmeter measures volumetric flow rate without inserting a sensor into the pipes. The methodology behind this device is based on an assumption, that is a turbulent flow has a cascade structure of eddies. Along the flow, the characteristics of those structures do not change much within a certain distance, the so-called Correlation Length. In other words, turbulence at a certain distance apart is correlated.

Based on this assumption, one can place two pairs of ultrasonic sensors along the flow direction to pick up the turbulence signature. Obviously, the upstream sensor will detect a flow signature L/V seconds earlier than the downstream one, where L is the space between the two sensors and V is the flow velocity. By comparing the signals from the two sensors, one can determine the time delay, thus, to calculate the velocity.

For calibrating ultrasonic flowmeter the traditional approach which is the sharp-crested weir is used. Water passing through the tilting flume discharges into another channel of 58 cm width and 70 cm depth. At the downstream of this channel a suppressed rectangular sharp-crested weir made of fiberglass is located to determine the flow rate. The dimensions of the weir and the channel are given in Figure III-2. The weir is aerated properly with the help of three pairs of ventilation holes. The diameter of each ventilation hole is *6 mm*. Each pair consists of two holes that are drilled symmetrically on both sides of the channel.

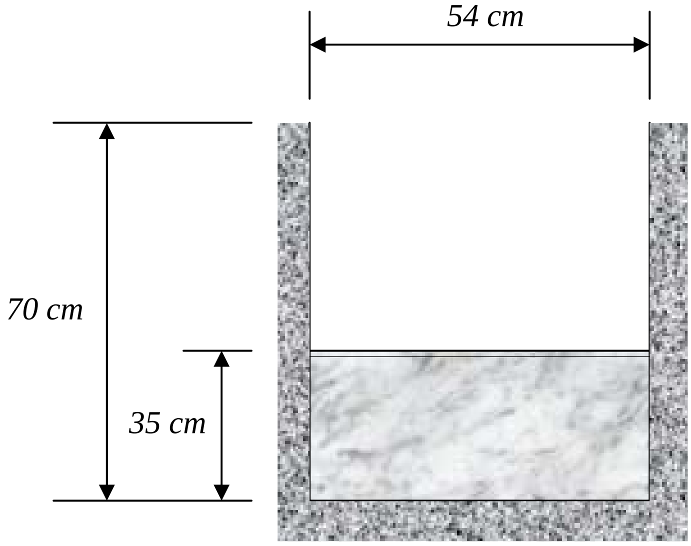


Figure III-2: Dimensions of the rectangular sharp crested weir

For a rectangular sharp crested weir, the discharge is computed from the equation (Henderson, 1966):

$$Q = C_Q \cdot \frac{2}{3} \cdot \sqrt{2g} \cdot L_l \cdot H^{3/2} \tag{3.1}$$

where Q is discharge, C_Q is the discharge coefficient, L_l is the effective length of the crest and H is the measured water head over the crest, excluding the velocity head.

The discharge coefficient, C_Q, in Eqn. (3.1) is determined by the below equation introduced by Rehbock in 1929. (Addison, 1954 and King, 1954):

$$C_Q = 0.605 + \frac{1}{1000 \cdot H} + 0.08 \cdot \frac{H}{p} \tag{3.2}$$

where p is the height of the weir. This equation is valid up to $H/p = 5$ according to measurements by Rouse. (Chow, 1959).

The difference between the measured and calculated discharges was less than 2% and therefore the measured values were accepted for all experiments.

III.1.2. Roughness Materials and the Obstructing Element

In order to represent the real life conditions the natural river bed was imitated with roughness materials. The materials were obtained from the Materials of Construction laboratory of the Middle East Technical University. Three different sizes of material were used as bed material. The mean diameter of these particles 'd_{50}' were 1.7 cm, 2.4 cm, 3.6 cm and the specific weights were all 1.6 g/cm^3 as the specific weight of the commercial aggregate in air. The main characteristics of the bed materials used are given in Table III-1

Table III-1: Characteristic diameters of the bed materials used to roughen the channel bed

Rough channel bed #	Max d (mm)	Min d (mm)	d_{50} (mm)
R1	39	9.5	17
R2	68	11	24
R3	73	19	36

In order to determine the equivalent roughness height of the natural roughness on a smooth surface under the same flow conditions, obstructing elements were placed into a thin groove available on the smooth channel bed across the width. The height of the obstruction was unknown initially for a known particle and to be determined later. Several obstructing elements were manufactured from thin aluminum sheets at various heights so that when they were placed into the groove, the height of the obstructing element over the smooth channel could vary from 0.1 cm up to 3.0 cm. (See Figure III-3).

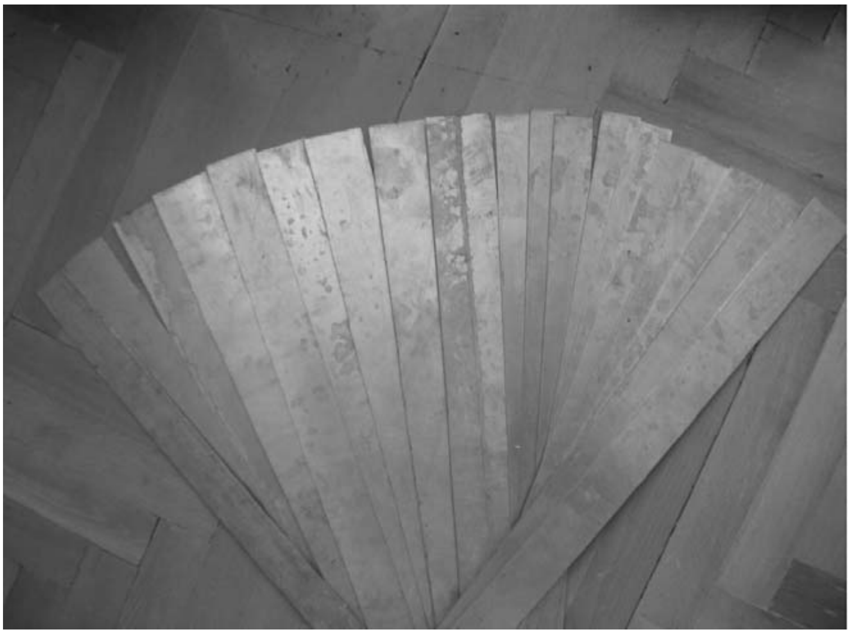


Figure III-3: Obstructing elements used in the experiments

III.1.3. Particle Shapes and Sizes

Particles of different shapes and sizes were mould from mixture of cement and iron dust to model sediment grains. Specific weights of particles have been determined by weighing the particles on a digital balance having 0.01 g accuracy and by measuring their volumes. The particles have been kept in water at least for one day before the determination of their specific weight and before the experiments, allowing them to become fully saturated. The specific weights of the particles used in the experiments were ranging between 1.90 g/cm^3 and 2.01 g/cm^3 with an average specific weight of 1.96 g/cm^3.

The solitary particles are grouped into four categories according to their shapes. These are spheres, cubes, irregular particles and rectangular prisms (See Figure III-4).

Figure III-4: Particles used in the experiments

All of the particles in each group are placed randomly and all times in a way that the shortest dimension is always the height of the grain. This is due to that a particle on the channel bed or riverbed should rest in a most stable orientation when gravitational forces are considered. The particles that are not stable may start motion very earlier than establishment of a critical condition. This type of a threshold of motion is not taken as the incipient motion of the particle, since it is probable that the particle will immediately rearrange its orientation in order to be more stable under gravitational force.

Another classification of particles is due to their sizes. The size sets are labeled as 2, 3, and 4. These are equivalent to volume of cubes with one side 2 cm, 3 cm, and 4 cm long, consequently the volumes are 8 cm^3, 27 cm^3 and 64 cm^3, respectively. The dimensions of each particle were measured with a compass having 0.1 cm accuracy.

Geometrical properties, dimensional details, shape factors and symbols of the particles are also given in Table III-2 and Table III-3.

Table III-2: Shapes and dimensions of particles used in the experiments

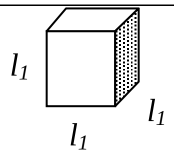
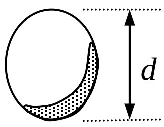
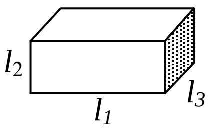
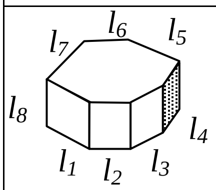
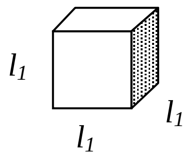
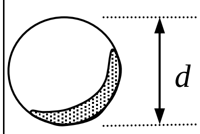
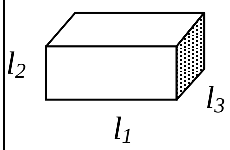
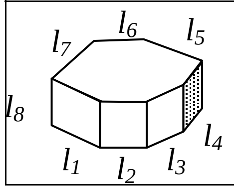
Shape of Particle	Volume of Particle (cm^3)	Dimensions of Particle (cm)								Symbol of Particle
		l_1								Cube
	8.0	2.0								C 2x2x2
	64.0	4.0								C 4x4x4
		d								Sphere
	8.0	2.48								S 2
	27.0	3.72								S 3
		l_1		l_2		l_3				Rect.Prism
	8.0	4.0		1.0		2.0				RP 4x1x2
	64.0	5.33		3.0		4.0				RP 5.33x3x4
		l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8	Irregular
	8.0	1.49	1.70	1.46	1.43	1.15	1.91	1.78	1.0	Ir 4.37x1x2.63
	64.0	2.43	2.77	2.38	2.34	1.88	3.14	2.91	3.0	Ir 7.14x3x4.3

Table III-3: Defining lengths for particles used in the experiments

Particle Shape	∀ (cm³)	a (cm)	b (cm)	c (cm)	L (cm)	SF	Particle Symbol
							
	8.0	2.0	2.0	2.0	2.82	1.000	Cube 2x2x2
	64.0	4.0	4.0	4.0	5.66	1.000	Cube 4x4x4
							
	8.0	2.48	2.48	2.48	2.48	0.806	Sphere 2
	27.0	3.76	3.76	3.76	3.76	0.806	Sphere 3
							
	8.0	4.0	1.0	2.0	4.12	1.250	Rect 4x1x2
	64.0	5.33	3.0	4.0	6.12	1.042	Rect 5.33x3x4
							
	8.0	4.37	1.0	2.63	4.48	0.905	Irreg 4.37x1x2.63
	64.0	7.14	3.0	4.3	7.74	1.044	Irreg 7.14x3x4.3

Totally three sets of experiments were conducted in this study with rough beds. In each set of experiments a different bed roughness composed of materials given in Table III-1 on the channel bed was used. During experiments of each set; first, the motion of the original bed material was observed and randomly 4 of them were selected and recorded with the flow conditions under which they had initial motion. Totally 12 original bed materials were selected and marked to test later to determine the height of the obstructing element corresponding to each particle and their bed roughness on smooth channel bed. The properties of these 12 particles are given in Table III- 4

Figure III-5: Rough channel bed # R1 particles used in the experiments

Figure III-6 Rough channel bed # R2 particles used in the experiments

Figure III-7: Rough channel bed # R3 particles used in the experiments

Table III-4: Properties of original bed materials for
Rough channel bed # R1, R2 and R3

	Q(lt/s)	a (cm)	b (cm)	c (cm)	L(cm)	SF
Rough channel bed #	25.2	1.4	1.2	2.3	1.84	0.565
	38.4	1.75	1.15	2.1	2.09	0.690
	42.5	2.1	1.7	2.5	2.7	0.760
	51.0	1.7	0.8	2.3	1.88	0.543
Rough channel bed # R2	27.9	2.3	2.0	2.5	3.05	0.860
	37.7	2.15	2.0	2.5	2.94	0.692
	43.0	2.25	1.45	3.8	2.68	0.487
	52.6	2.35	1.45	4.15	2.76	0.458
Rough channel bed #	27.8	2.05	1.7	3.6	2.66	0.521
	36.6	2.85	2.8	3.55	4.0	0.796
	42.0	3.0	2.05	3.7	3.63	0.682
	52.5	2.9	2.7	3.7	3.96	0.757

III.2. Experimental Procedure

Experiments were performed in six sets; in the first three sets the channel bed had different roughnesses i.e. R1, R2, R3 and in the remaining three sets the channel bed was smooth. In all sets the main procedure of the experiment was similar.

First, bed roughness material R1 was placed on the channel bed at least 2 layers and levelled. Then discharge was fixed and uniform flow conditions were maintained in the channel. The slope of the channel was altered slowly until a single particle of the original bed material moves. The bed slope, discharge, velocity profile and flow depth were recorded. The velocity profile and flow depth were measured in the midsection of the flume by using a total head tube and point gage accordingly. Then the moving particle was marked to follow it easily in the next tests and then dropped in to the flow to place itself randomly to simulate the natural conditions. Again the slope of the channel bed was altered slowly till the particle moves. The same recordings were taken again. The experimental procedure was applied 3 times to the same particle for each fixed discharge. After completing 3 data sets for one fixed discharge, the discharge was increased and the same procedure was followed for the same bed material. The process was repeated for four different discharges. After the experiments of the movement of the bed surface particles were finished, the same procedure was applied to 8 artificial particles. In these experiments an artificial particle was dropped in to the flow to allow it to move naturally at the channel bed and stop. Then the channel slope was altered slowly until the movement of the particle was observed. The bed slope, discharge, velocity profile and flow depth were recorded again. This procedure was applied 3 times for each particle.

After completing the experiments of artificial particles, the roughness materials of the channel bed were removed from the channel bed and the smooth surface was maintained. To represent the same flow conditions of a given particle the discharge and slope were fixed to those of rough bed experiments and both the original and artificial particles were tested to find the representative obstacle heights. For that reason with the fixed discharge and slope the height of the obstacle was raised till the critical condition of motion of the particle was observed. The flow depth, and velocity profile were recorded. So two sets of the experiments: one with rough channel bed and the other one with smooth surface were completed. Then with another bed roughness material all of the procedure described above was repeated. With all recordings the critical cross-sectional velocities, V_{cc}, the critical shear stresses, the critical dimensionless shear stresses, the grain Reynolds numbers and other important parameters were calculated and presented in Appendix B.

III.3. Analysis of Experimental Data, Comparison with Previous Study and Discussion of Results

More than 600 experiments with total duration of approximately 300 hours were performed. In order to determine the roughness heights of rough channel beds used in the experiments first, theoretical bed levels of these rough beds were determined and then the relations between relevant hydraulic parameters were investigated.

III.3.1. Determination of Theoretical Bed Level

As discussed in Section II-3 the theoretical bed levels of rough channel bed were determined using Eqn. 2.13 and referring Figure II-1. To clarify the determination of theoretical bed level an example was presented in Table III-5 for the test of Cubes of 4x4 cm on the channel bed having roughness material of R2 for discharge of Q3.

Table III.5: Experimental Data for Cube 4x4 cm on Rough Channel Bed Material R2

Depth (y^1) (cm)	$y=y^1-k_s$	u (m/s)	log (y)
11.50	8.05	1.12	0.905796
10.20	6.75	1.07	0.829304
9.20	5.75	1.03	0.759668
8.20	4.75	0.98	0.676694
7.20	3.75	0.86	0.574031
6.70	3.25	0.83	0.511883
6.20	2.75	0.79	0.439333
5.70	2.25	0.74	0.352183
5.20	1.75	0.67	0.243038
4.70	1.25	0.61	0.09691
4.20	0.75	0.54	-0.12494

In Table III-5 y^1 designates the vertical distance measured from the smooth channel bed, k_s is the distance between the theoretical bed level and the channel bottom, y is the vertical distance measured from the theoretical bed level ($y=y^1-k_s$) and u is the velocity that was measured by a total head tube.

In Table III-5, the velocity distribution of the flow, y^1 versus u values, obtained from measurements for rough channel bed material R2 is given. In order to determine the location of the theoretical bed level of the channel bed initially a value for k_s is assumed; such as k_s= 3.45 cm, and then corresponding y values of the channel bed are calculated from $y=y^1-k_s$. Following the plot of u versus $\log y$ values and determining the best fit curve of the data which is a straight line one can calculate the shear velocity, u^*, and k_s values of the flow from the semi-log equation of the velocity. If this calculated u^* is equal to the one to be obtained from the general equation of $u^* = \sqrt{g(h^*)_r S}$, the initially assumed k_s value is assumed to be correct.

For this particular example the u^* value calculated from the best fit curve is 0.1032 m/s and the one computed from the equation of u^* is 0.09691 m/s. The differences between these two values were assumed to be acceptable and the same procedure was applied to all velocity measurements made over roughened channel beds. If the u^* values stated above are not sufficiently close to each other, a new value for k_s is assumed and the same procedure is applied. The results are given in Appendix B.

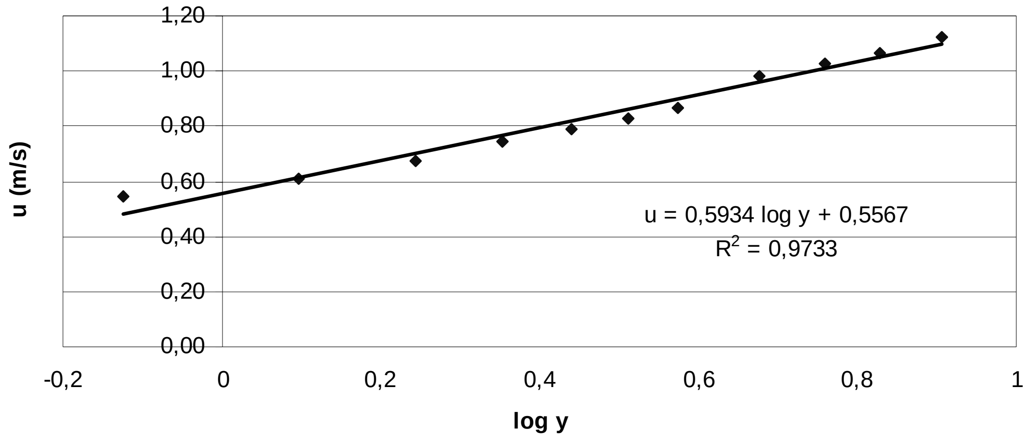


Figure III-8 Variation of *u* with *log y* over rough channel bed of material R2 (Tested particle: Cube 4x4 cm, the discharge: Q3)

III.3.2. Relationship between Relative Depth “$(R_b^*)_r/d_s$” and Dimensionless Roughness Height “k_s/d_s”

Equation 2.5 gives the relationship between $[(R_b^*)_r/d_s]$ and other relevant dimensionless terms. When the variation of $[(R_b^*)_r/d_s]$ with other terms was plotted one by one for each test conducted it was seen that, the distribution of data points, in general, was very random. Therefore, it was very difficult to say something about how these parameters were affecting each other. For this reason, many arrangements were made among the parameters given in Eqn. 2.5 and eventually it was seen that there was a certain trend between $(S^{0.5})[(R_b^*)_r/d_s]$and k_s/d_s.

Variation of $(S^{0.5})[(R_b^*)_r/d_s]$ with the dimensionless roughness height, k_s/d_s, for rough channel beds of materials R1, R2 and R3, are given in Figures III-9 through III-23. Figures III-21 through III-23 present the collective results for each rough bed tested on a log-log paper. From the analysis of these figures it can be concluded that there is a linear relationship between $(S^{0.5})[(R_b^*)_r/d_s]$ and (k_s/d_s); as d_s value decreases, k_s/d_s and $(S^{0.5})[(R_b^*)_r/d_s]$ value increase. Within the ranges of discharges tested one can estimate the critical value of $(R_b^*)_r$ required for the incipient motion of a particle of known shape and size from known values of k_s, d_s and channel slope S.

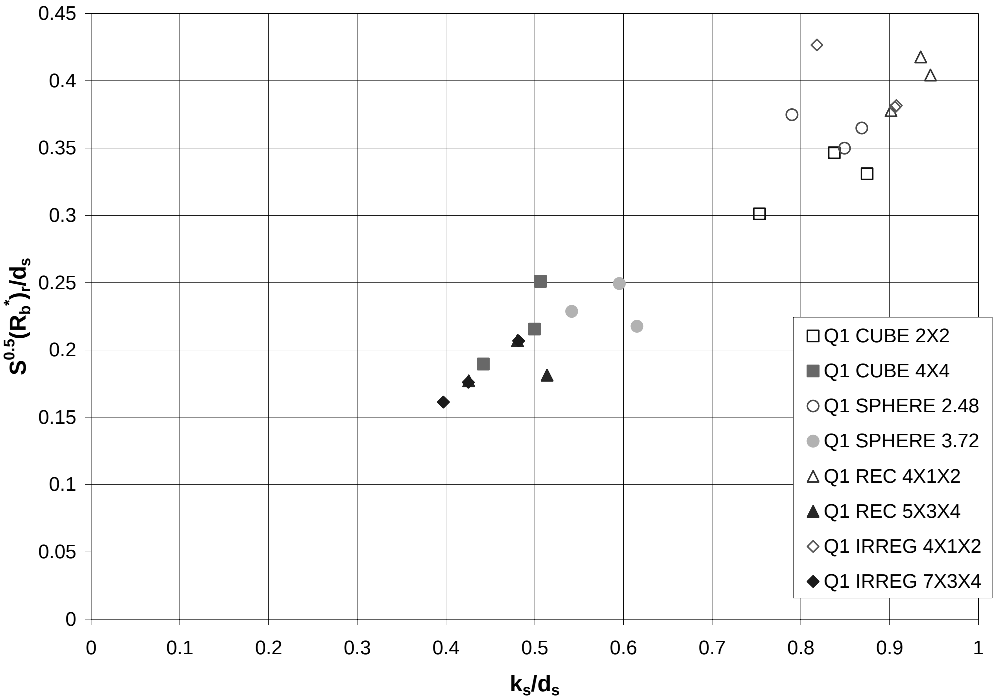


Figure III-9 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q1~0.025 m^3/s on R1

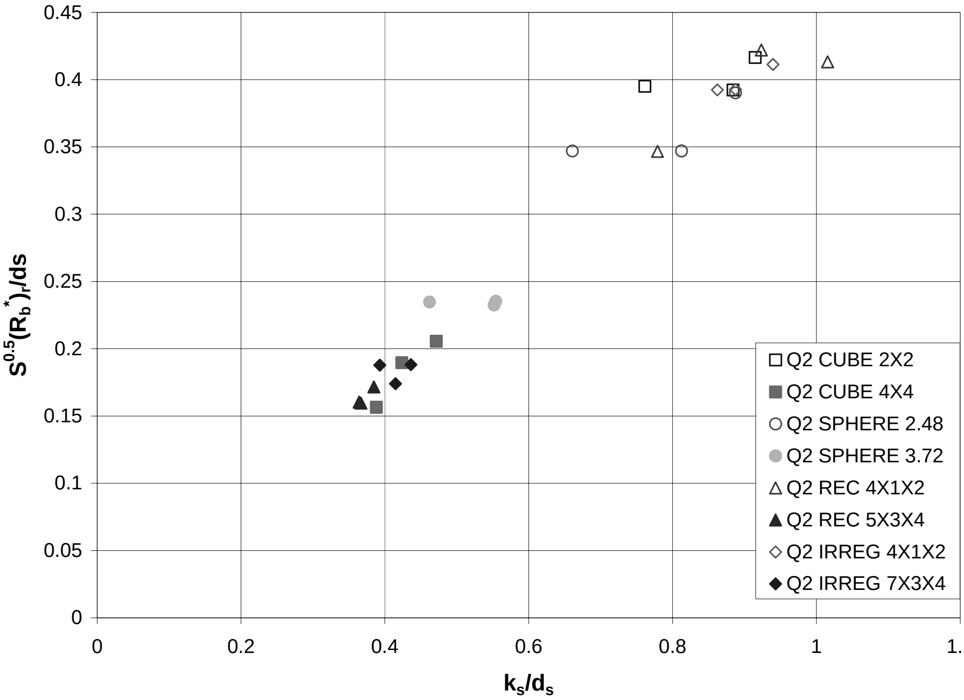


Figure III-10 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q2~0.031 m^3/s on R1

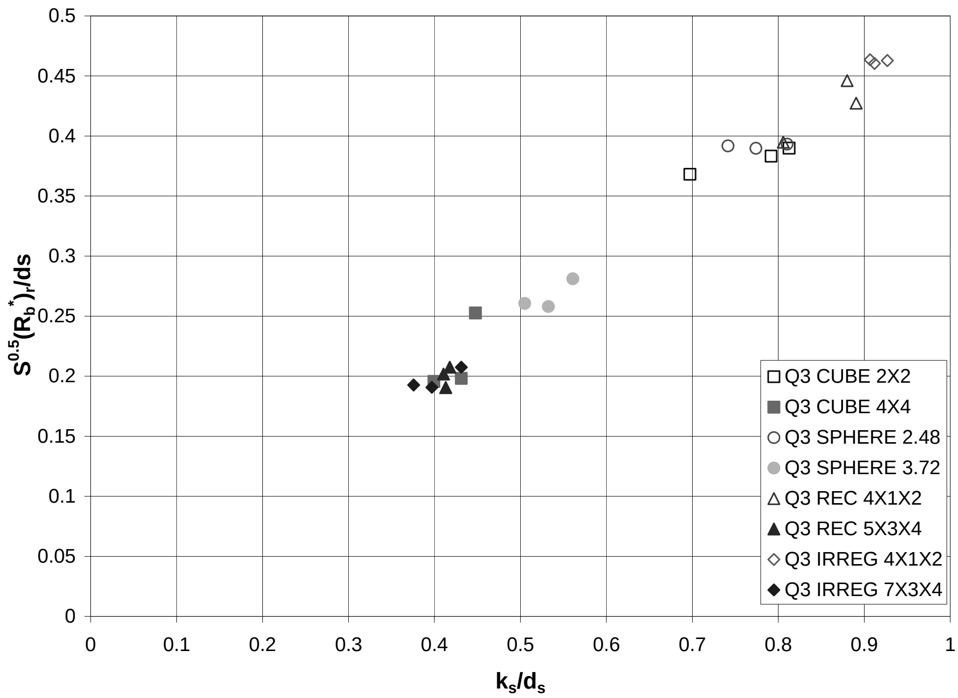


Figure III-11 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q3~0.040 m^3/s on R1

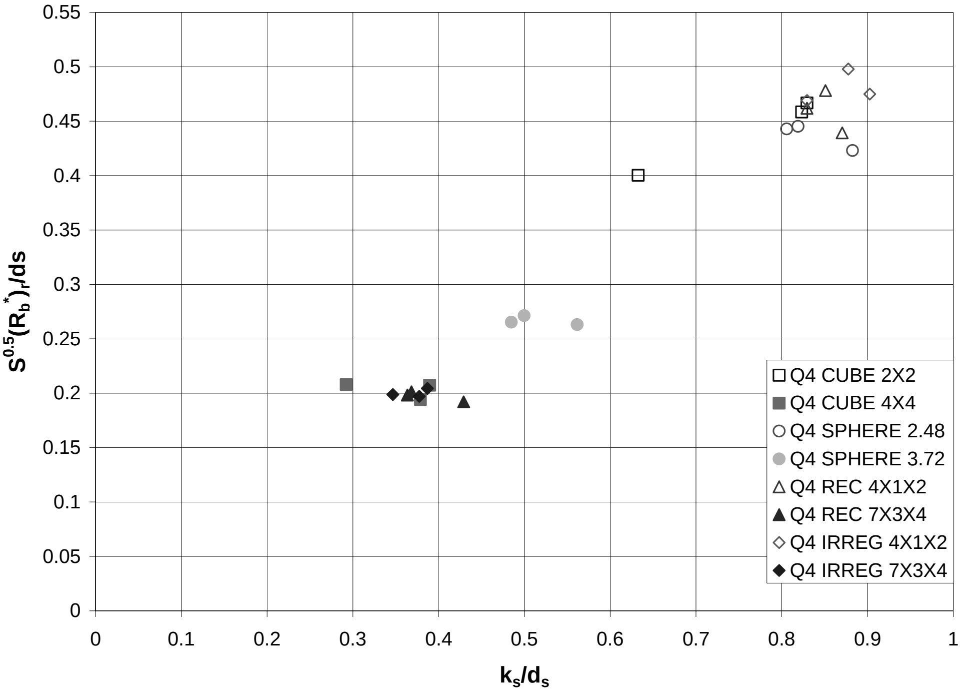


Figure III-12 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q4~0.050 m^3/s on R1

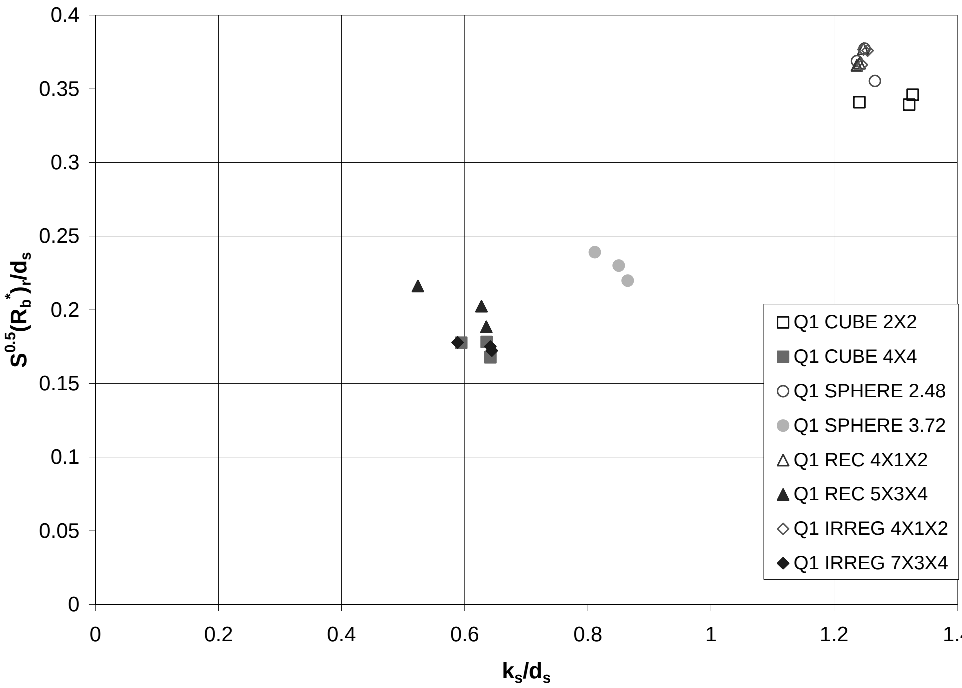


Figure III-13 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q1~0.025 m^3/s on R2

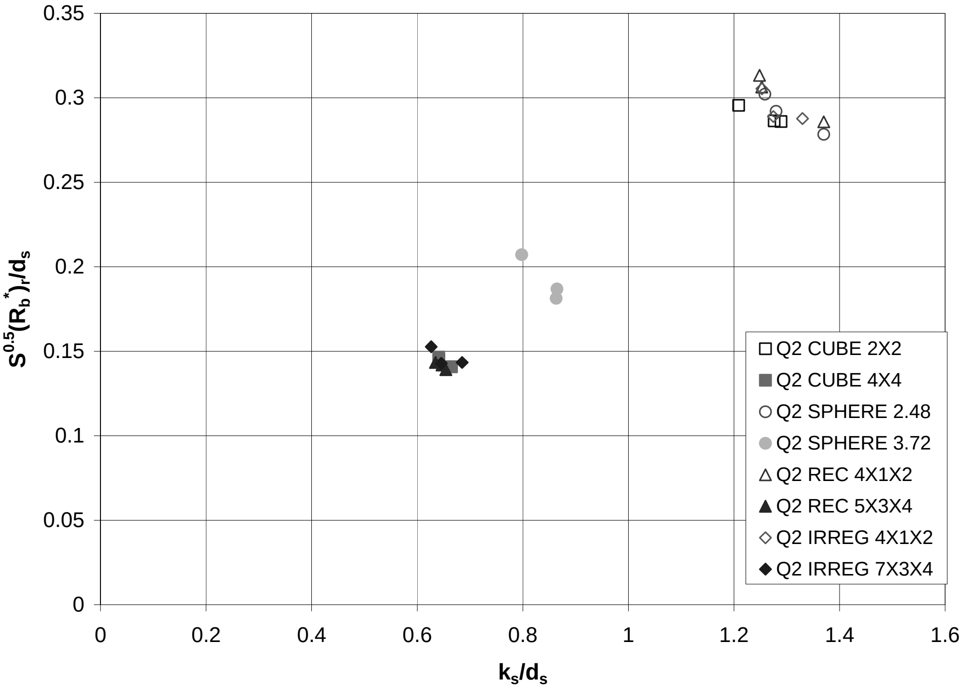


Figure III-14 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q2~0.031 m^3/s on R2

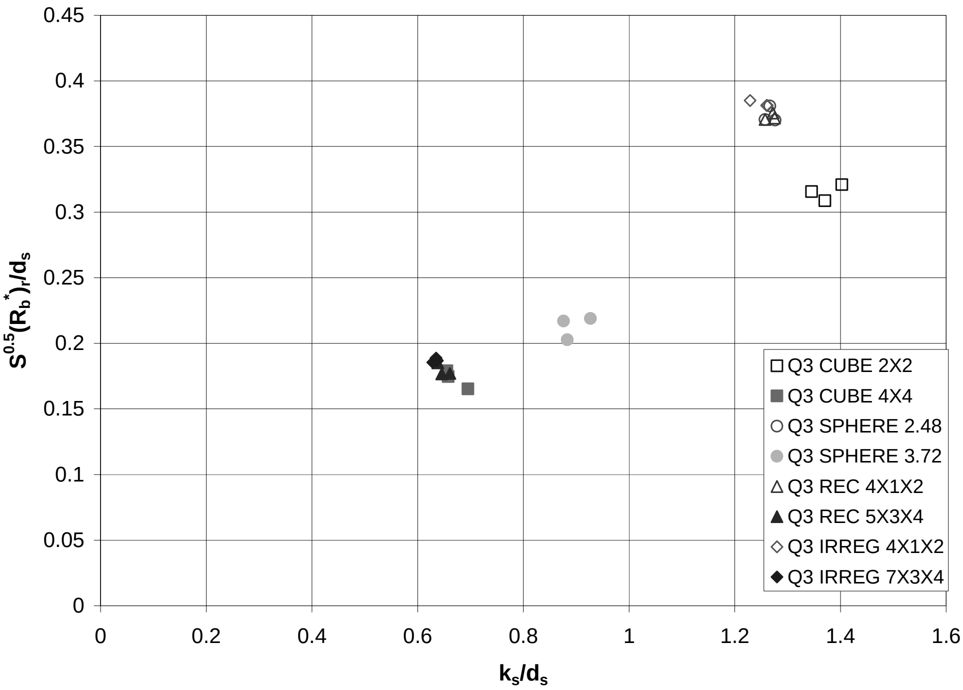


Figure III-15 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q3~0.040 m^3/s on R2

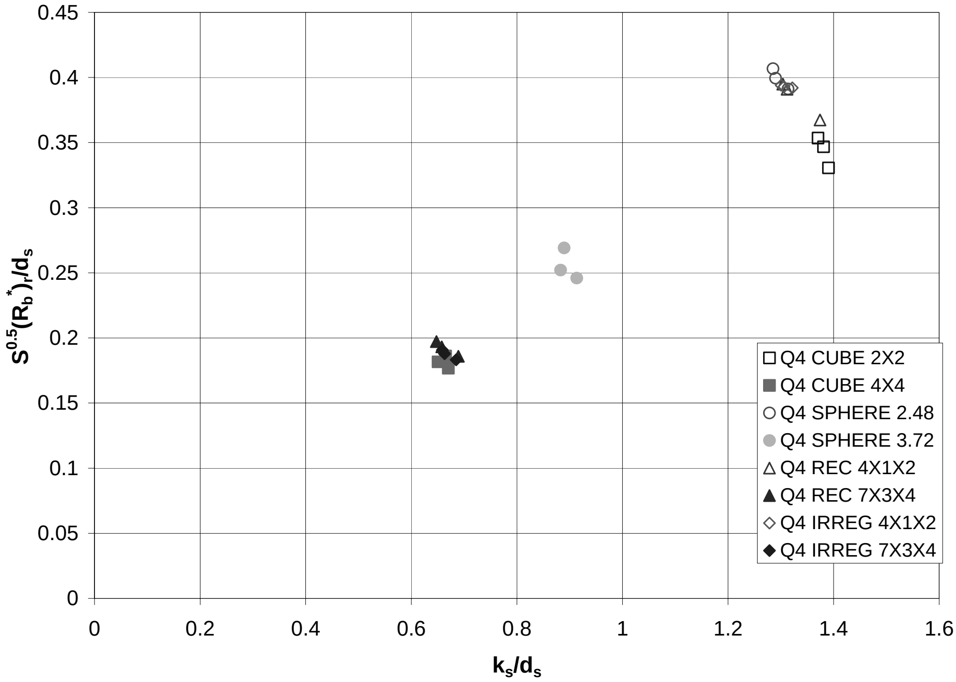


Figure III-16 $(S^{0.5})[(R_b{}^*)_r/d_s]$ vs. k_s/d_s for discharge, Q4~0.050 m^3/s on R2

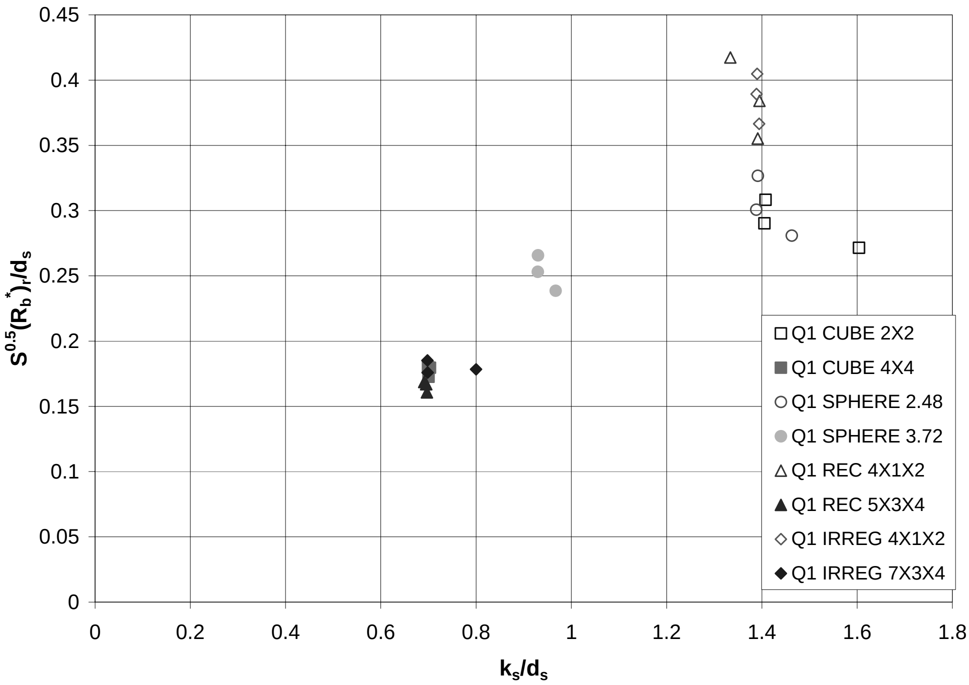


Figure III-17 $(S^{0.5})[(R_b{}^*)_r/d_s]$ vs. k_s/d_s for discharge, Q1~0.025 m^3/s on R3

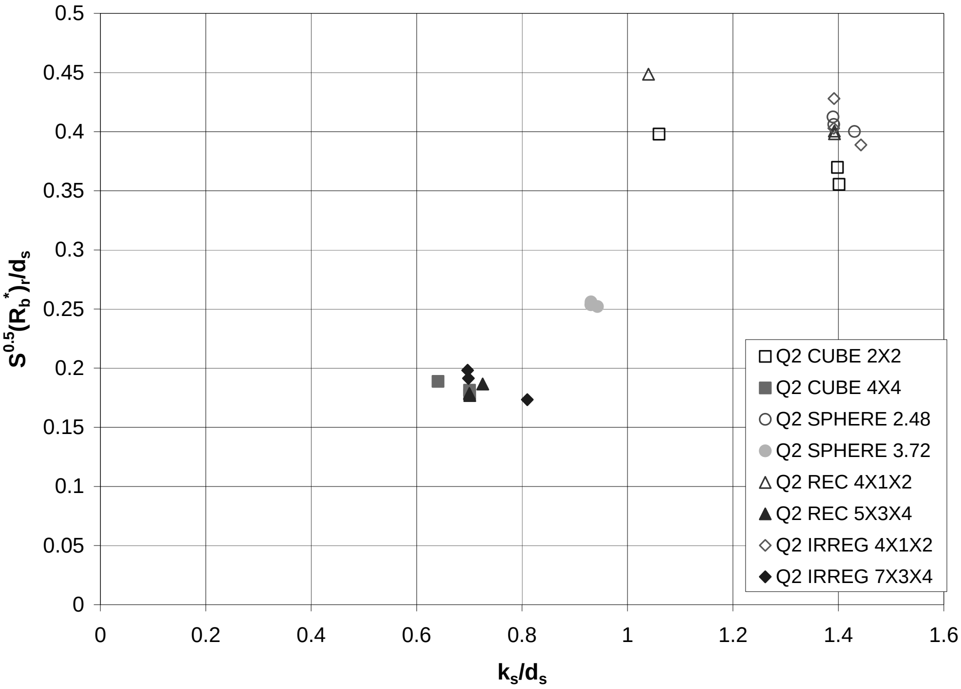


Figure III-18 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q2~0.031 m^3/s on R3

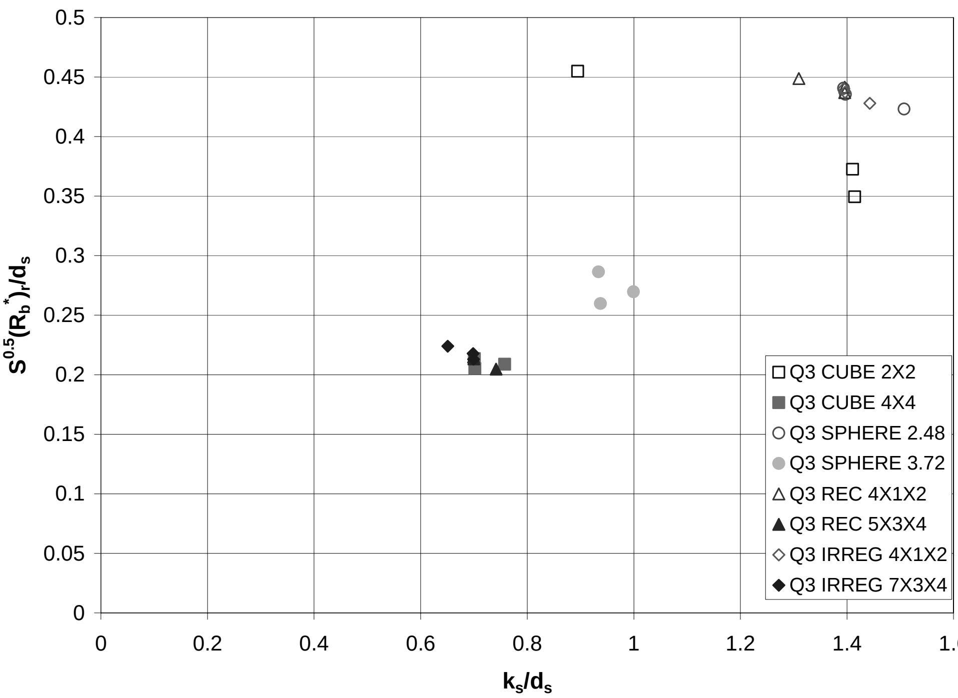


Figure III-19 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q3~0.040 m^3/s on R3

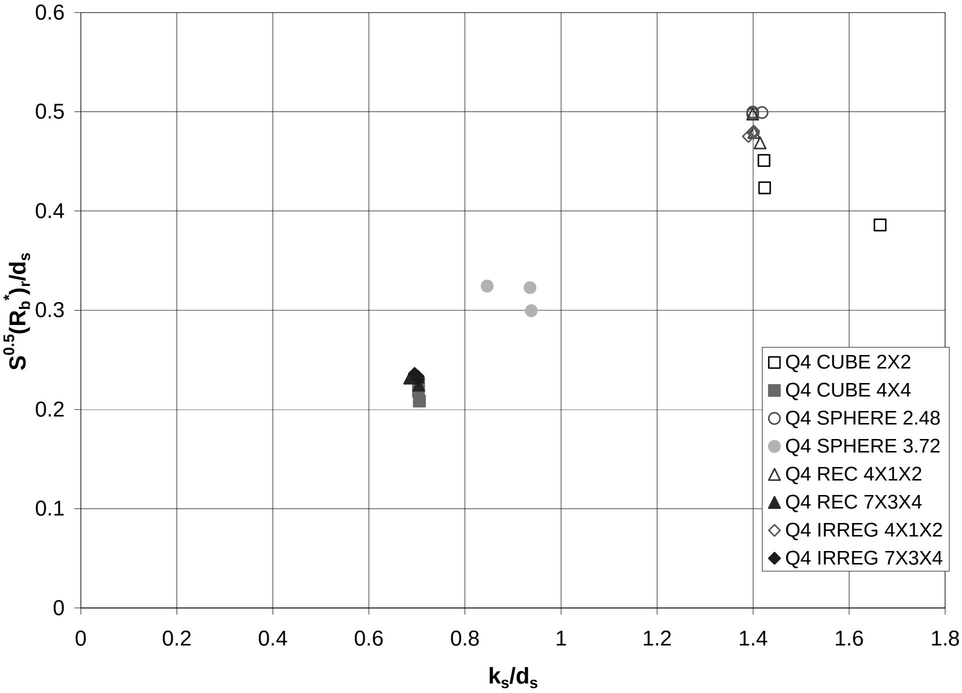


Figure III-20 $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for discharge, Q4~0.050 m^3/s on R3

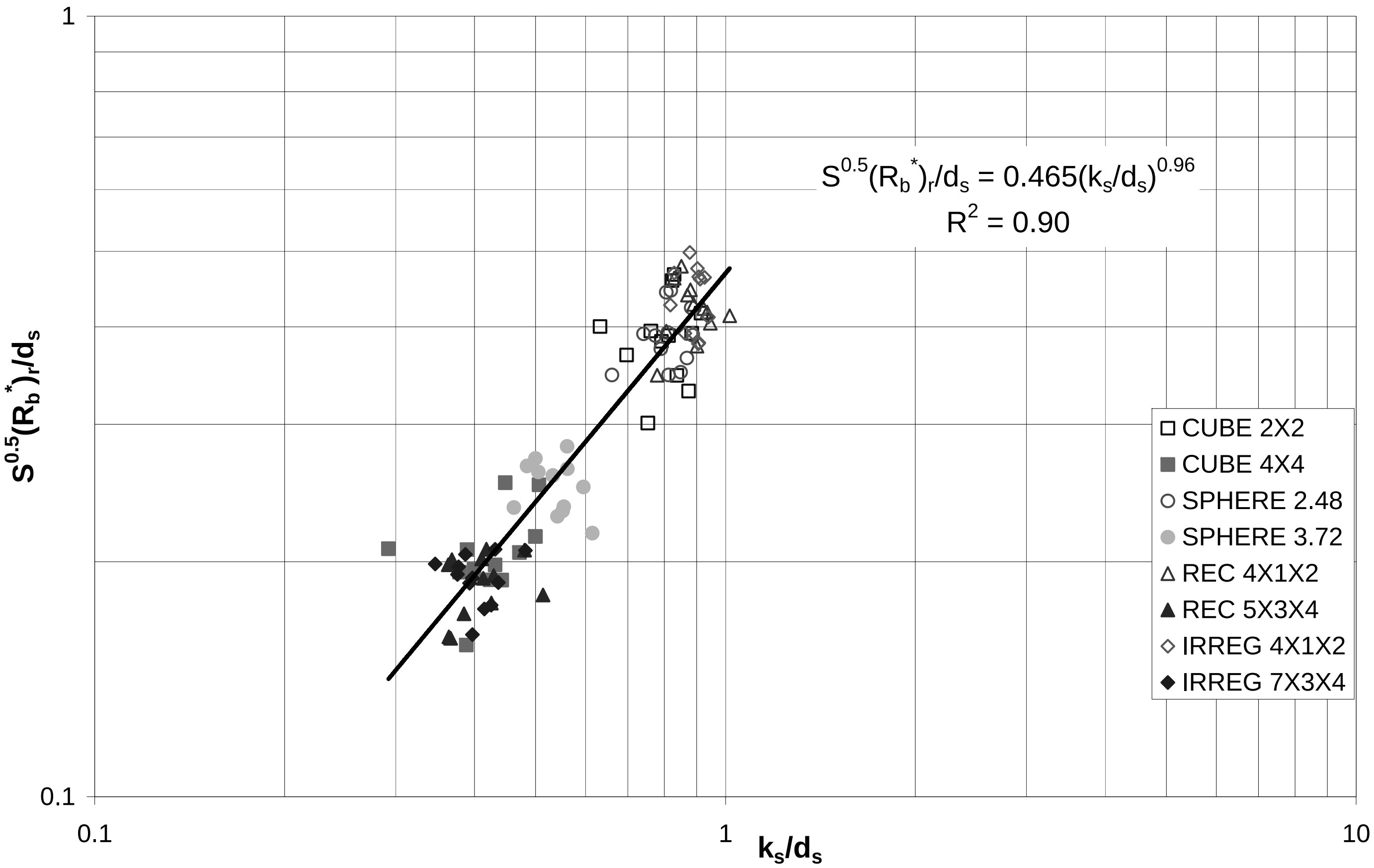


Figure III-21: $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for all 4 discharges on R1

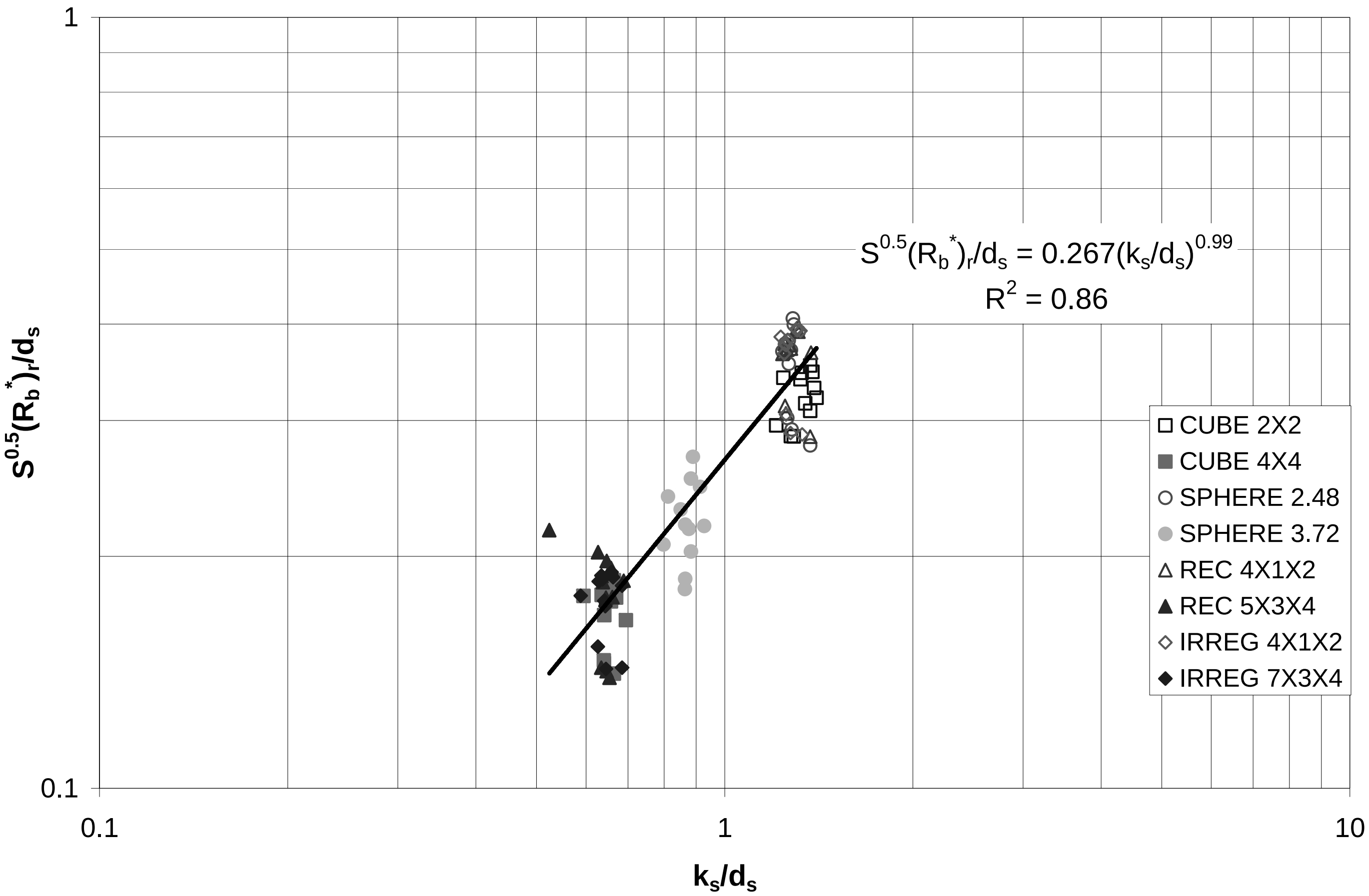


Figure III-22: $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for all 4 discharges on R2

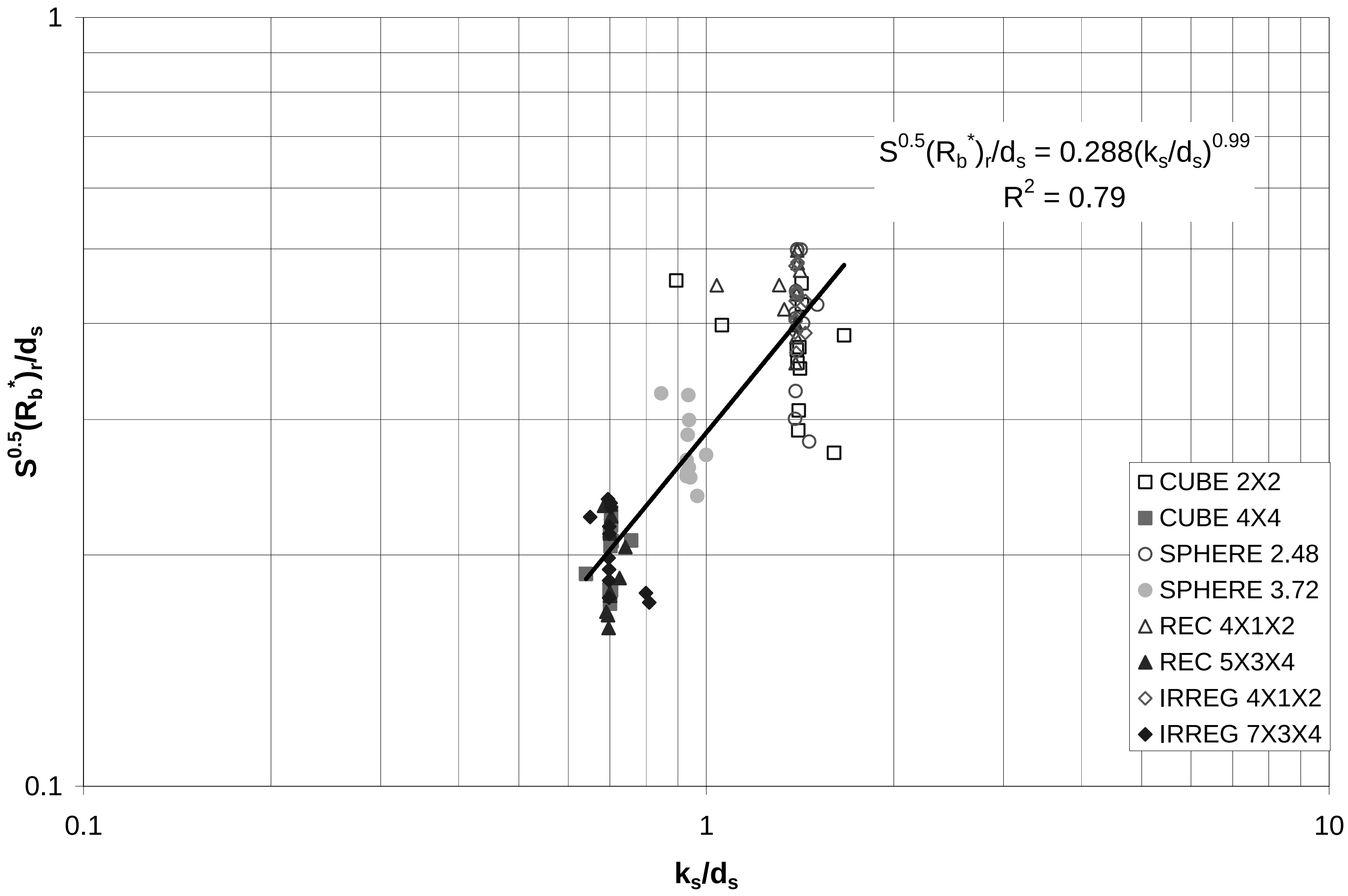


Figure III-23: $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for all 4 discharges on R3

The best fit curves of Figures III-21 through III-23 are presented in Figure III-24 to show the effect of bed roughness on the variation of $[(R_b^*)_r/d_s]$ with k_s/d_s with the ranges of n values of the rough channel bed as a third parameter. All of the curves are almost parallel to each other and those two of roughness material of R2 and R3 are very close to each other although the ranges of n values for three channel beds are similar, one may say that the channel bed of material R1 appears to be rougher than the others. For a known particle shape and size; d_s and channel slope S, as ks/ds increases, the required $(R_b^*)_r$ value required for the incipient motion of the particle increases.

III.3.3. Relationship between "$Sq^2/[g(\Delta\rho/\rho)d_s^3]$"and Dimensionless Roughness Height "k_s/d_s"

Based on Eqn. 2.6 the best relationship between $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ and the dimensionless roughness height k_s/d_s was obtained when the related data were plotted with respect to each other. In Figures III-25 through III-36 the variation of these parameters with each other are presented for each rough channel bed and the discharges tested. For k_s/d_s values up to about 0.8, $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ values slightly increases. As k_s/d_s get larger than 0.8, the rate of change of the dependent parameter increases rapidly.

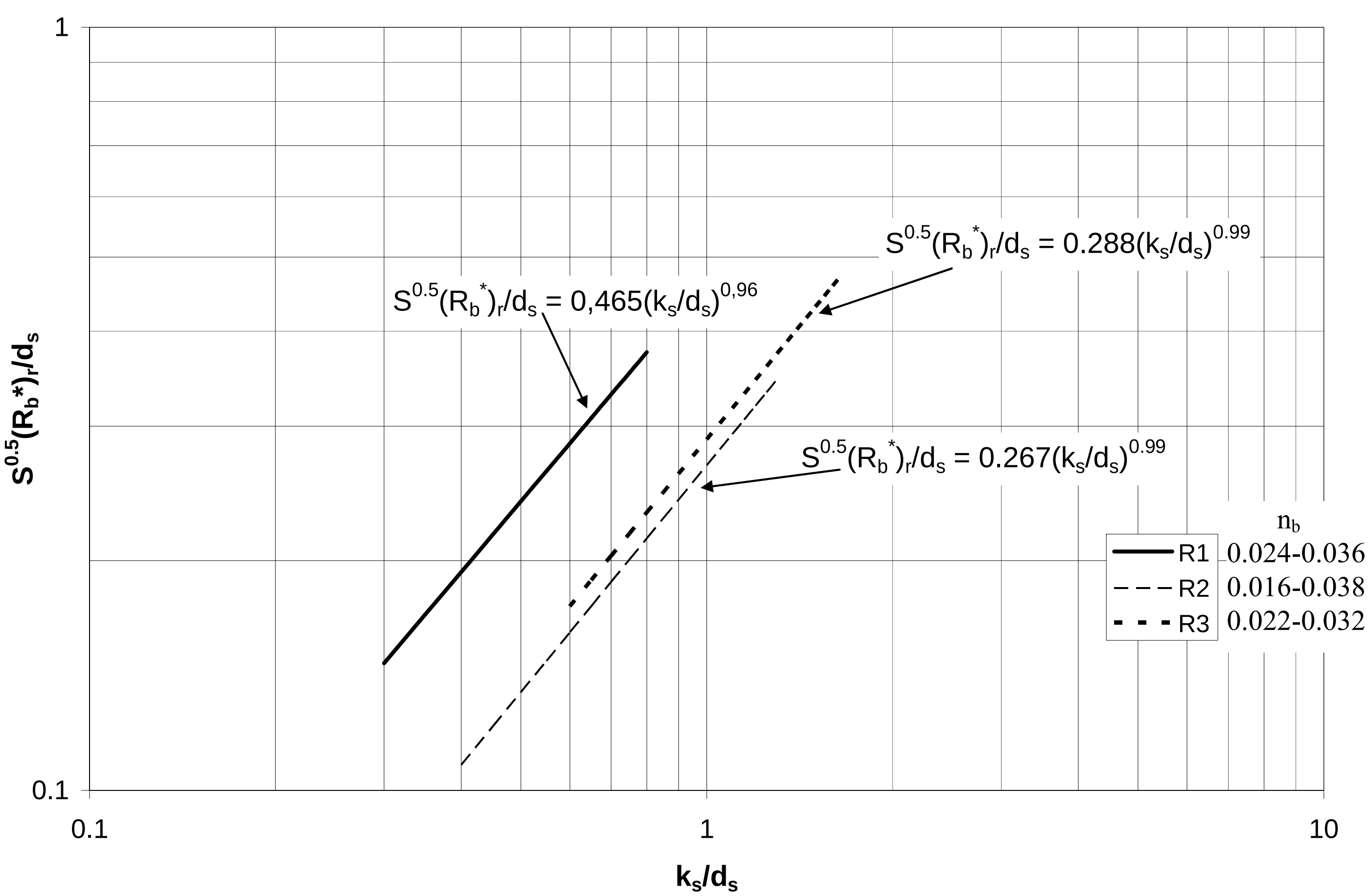


Figure III-24: Best Fit Curves of $(S^{0.5})[(R_b^*)_r/d_s]$ vs. k_s/d_s for all rough channel beds

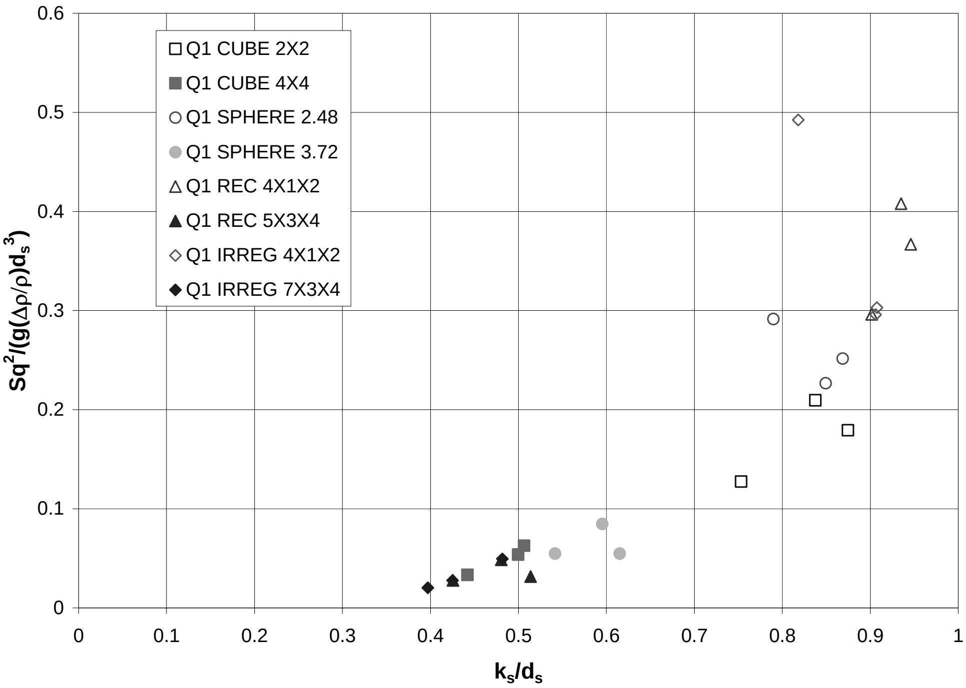


Figure III-25 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q1~0.025 m^3/s on R1.

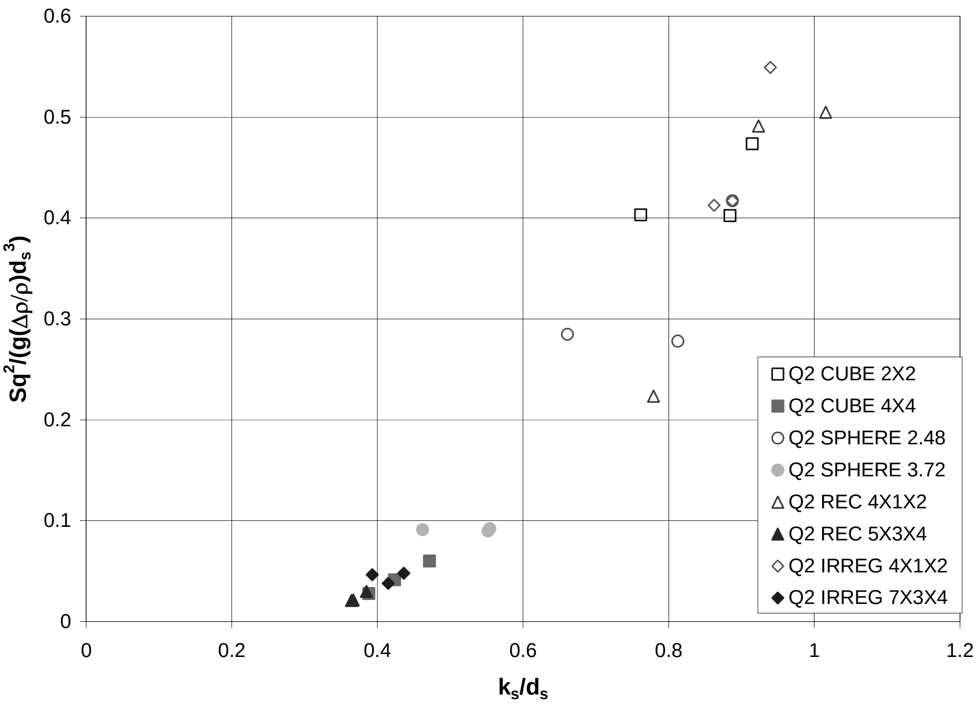


Figure III-26 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q2~0.031 m^3/s on R1

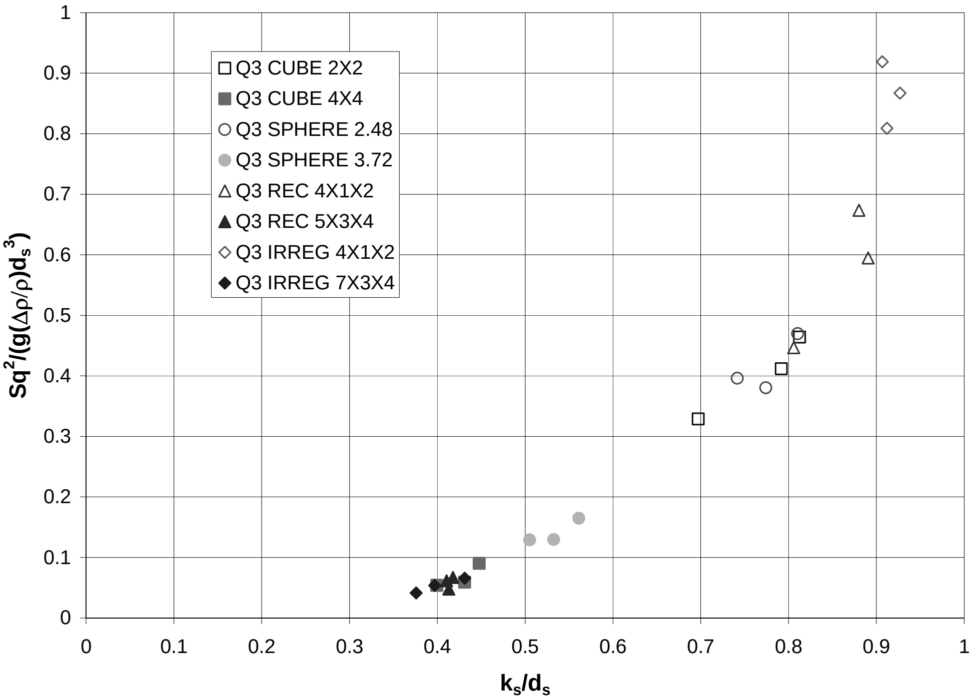


Figure III-27 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q3~0.040 m^3/s on R1

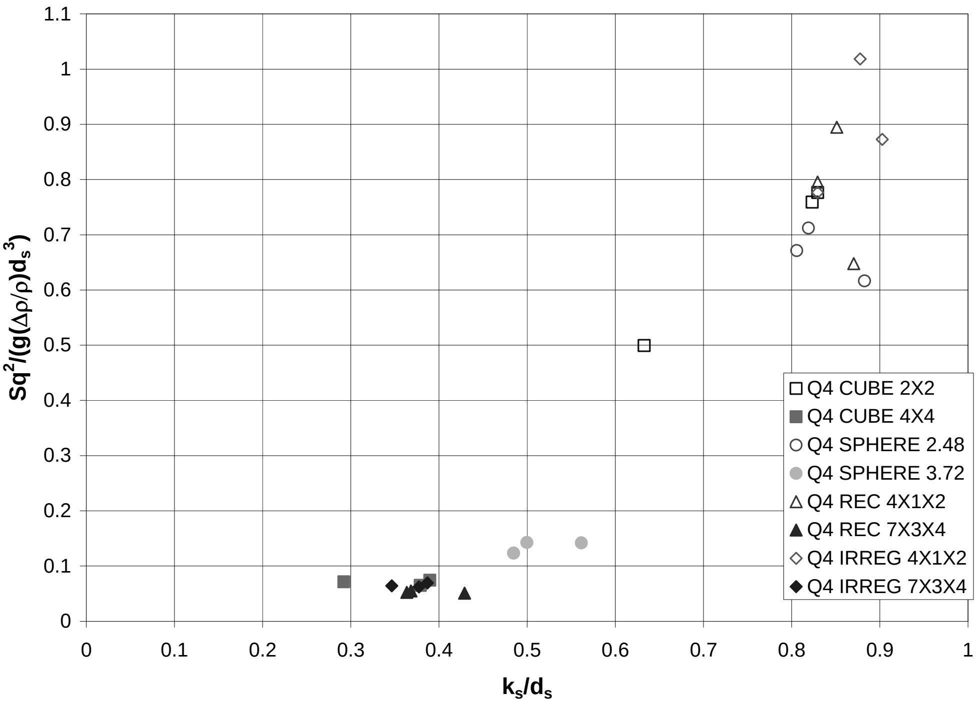


Figure III-28 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q4~0.050 m^3/s on R1

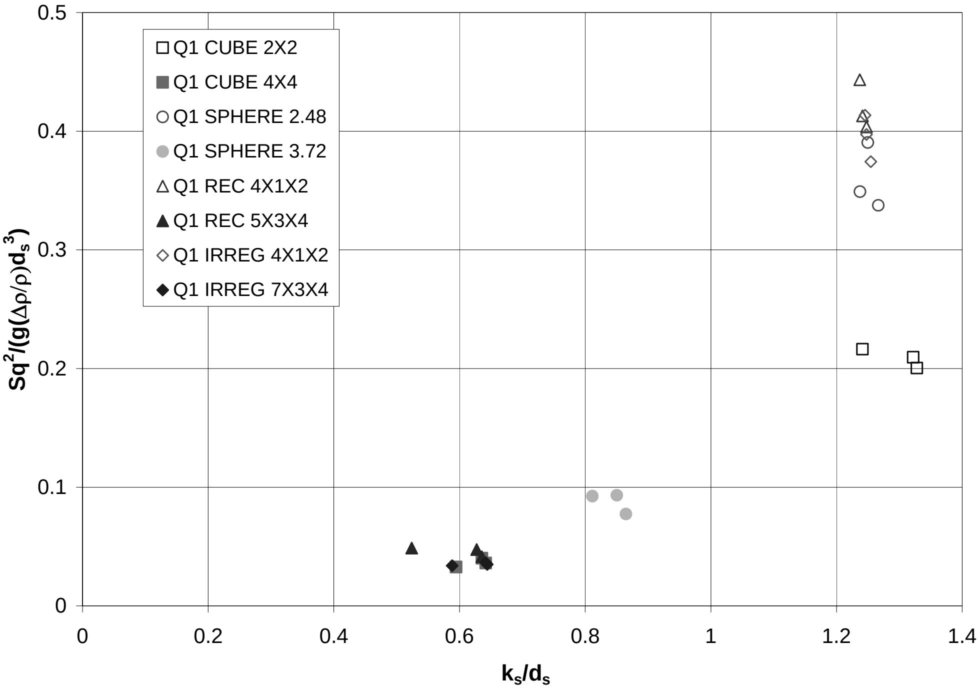


Figure III-29 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q1~0.025 m^3/s on R2

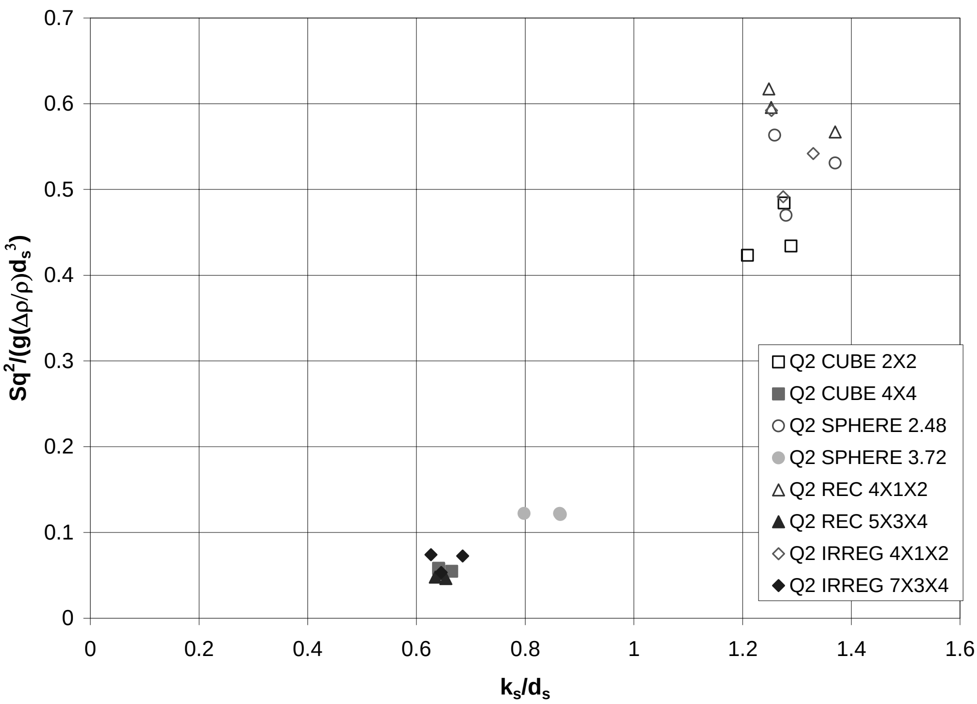


Figure III-30 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q2~0.031 m^3/s on R2

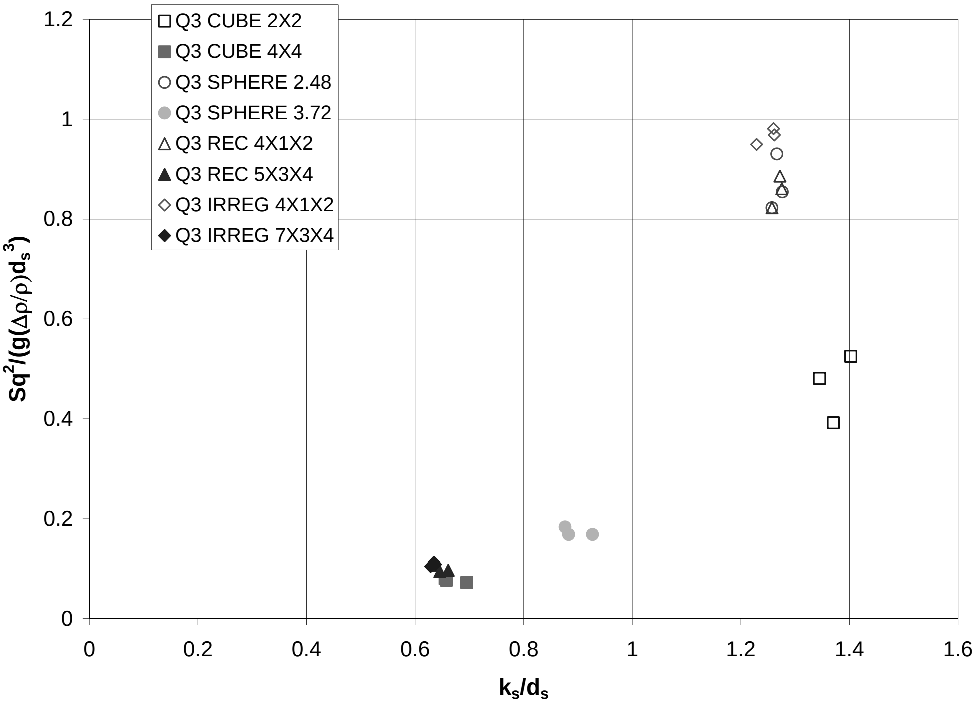


Figure III-31 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q3~0.040 m^3/s on R2

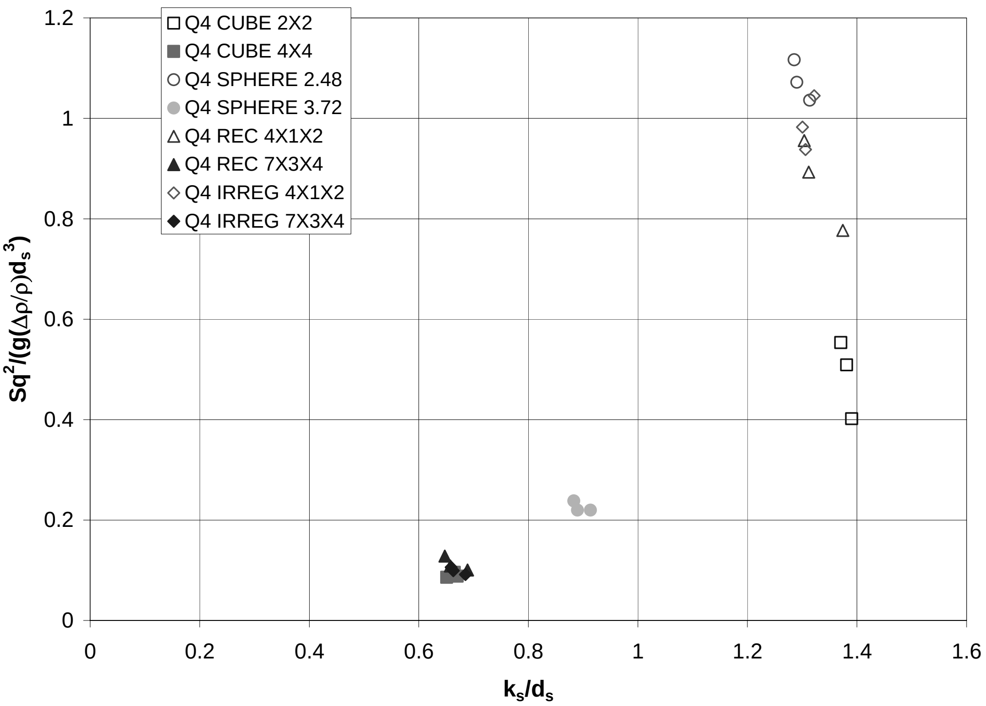


Figure III-32 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q4~0.050 m^3/s on R2

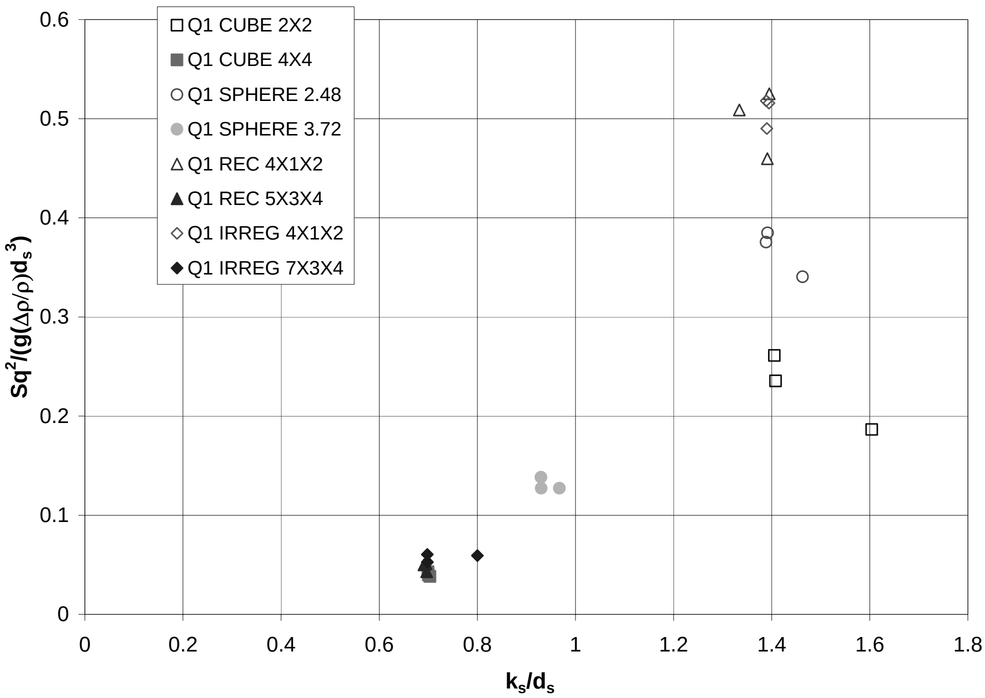


Figure III-33 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q1~0.025 m^3/s on R3

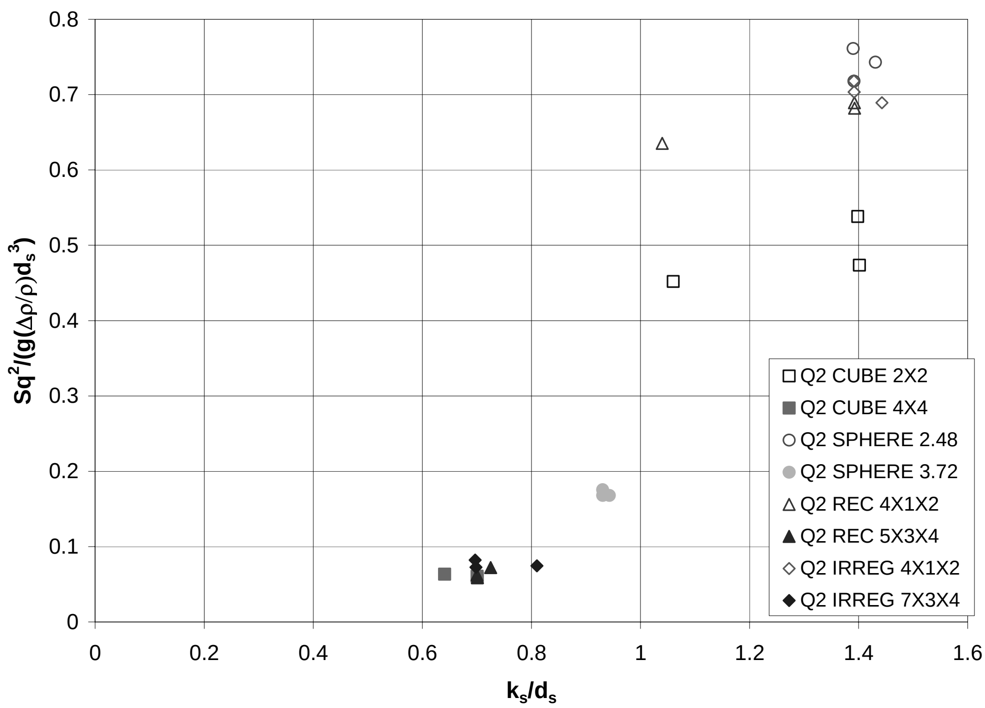


Figure III-34 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q2~0.031 m^3/s on R3

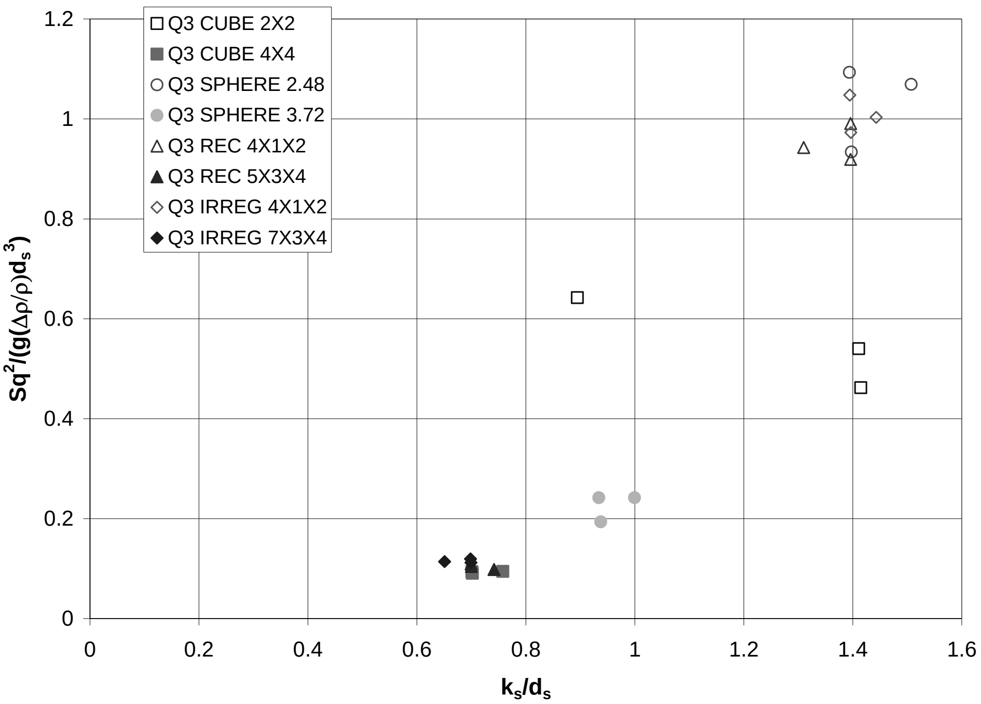


Figure III-35 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q3~0.040 m^3/s on R3

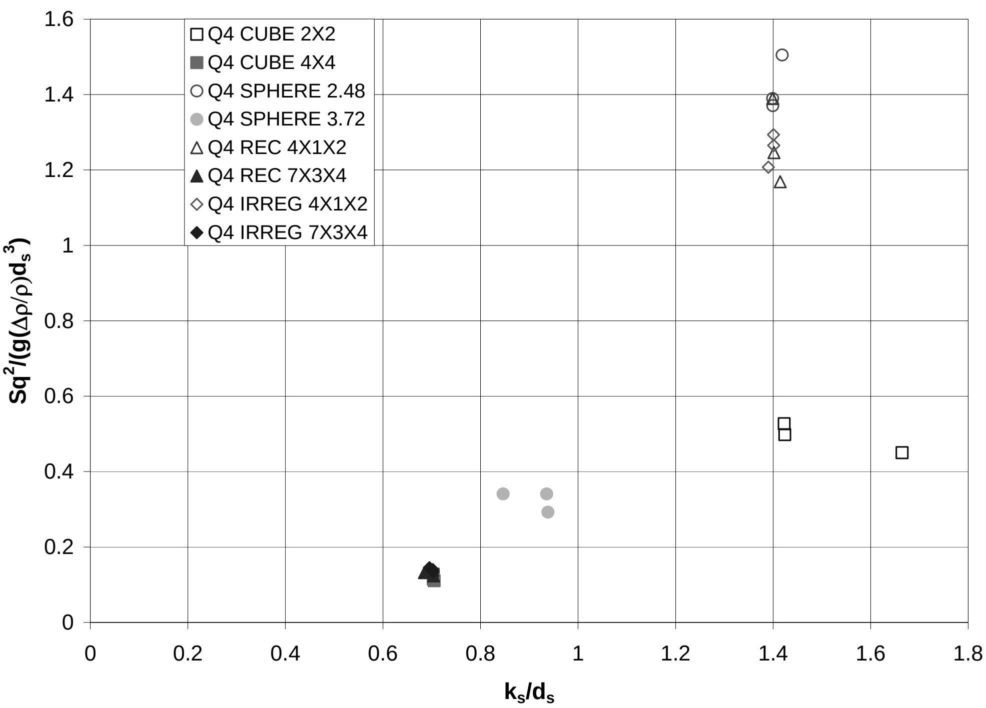


Figure III-36 $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for Q4~0.050 m^3/s on R3

Figure III-37 through III-39 show all of the relevant experimental data of rough channel beds of materials R1, R2 and R3 respectively on log-log paper with their best fit curves. These best fit curves of rough channel beds are also presented in Figure III -40 without their data just to show the effect of bed roughness on the variation of $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ with k_s/d_s. From the inspection of these figures it can be stated that there is a linear relationship between $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ and k_s/d_s, and for a given channel bed slope and particle of known d_s; as k_s value increases, the required unit discharge, q, for the initiation of particle motion increases. Although n values of each rough channel bed tested have similar ranges, the rough bed of material R1 appears to have larger n values, in general, and its best fit curve far away from the other two curves which are almost coinciding.

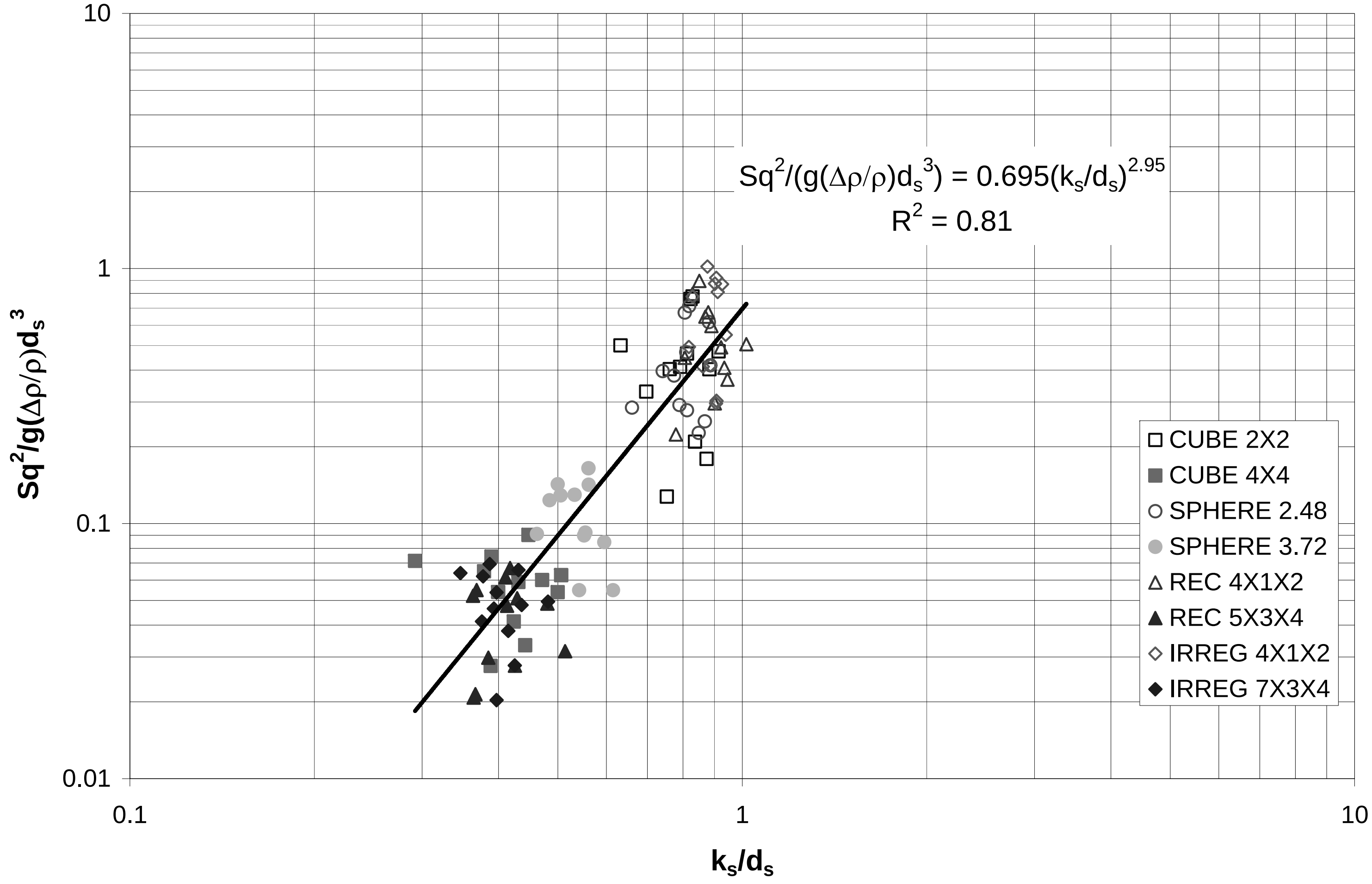


Figure III-37: $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for all 4 discharges on R1

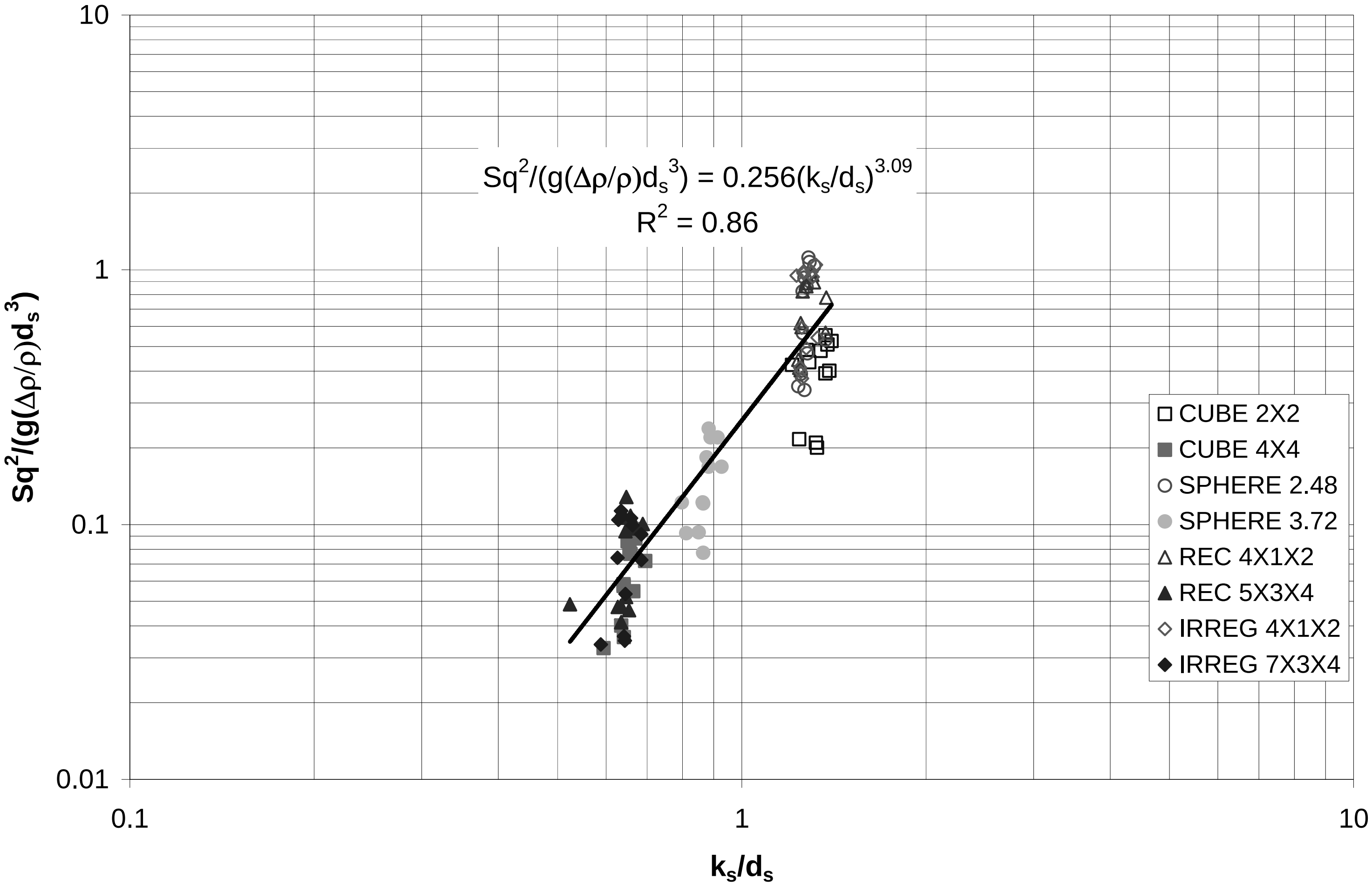


Figure III-38: $Sq^2/[g(\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for all 4 discharges on R2

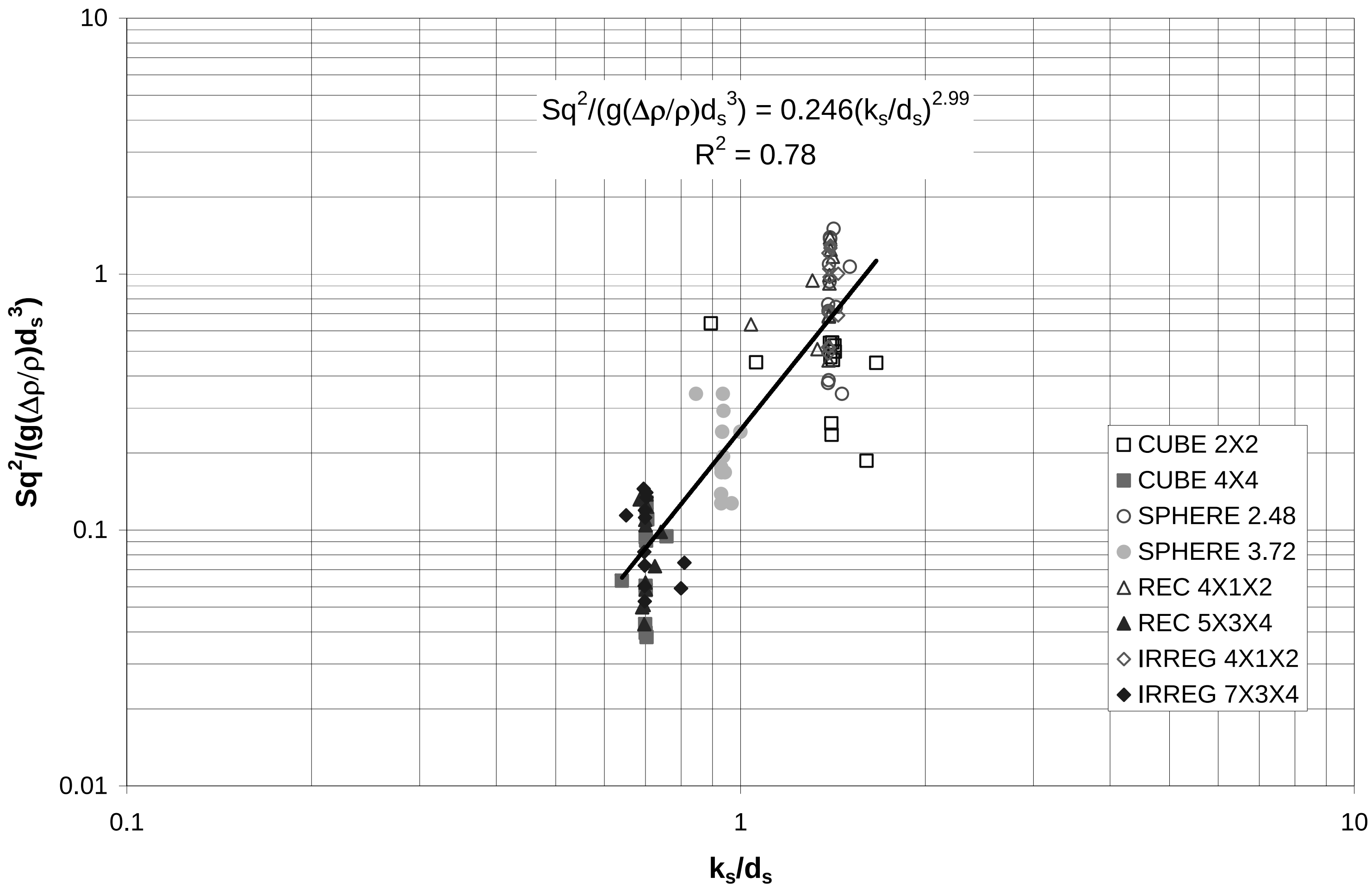


Figure III-39: $Sq^2/[g\ (\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for all 4 discharges on R3

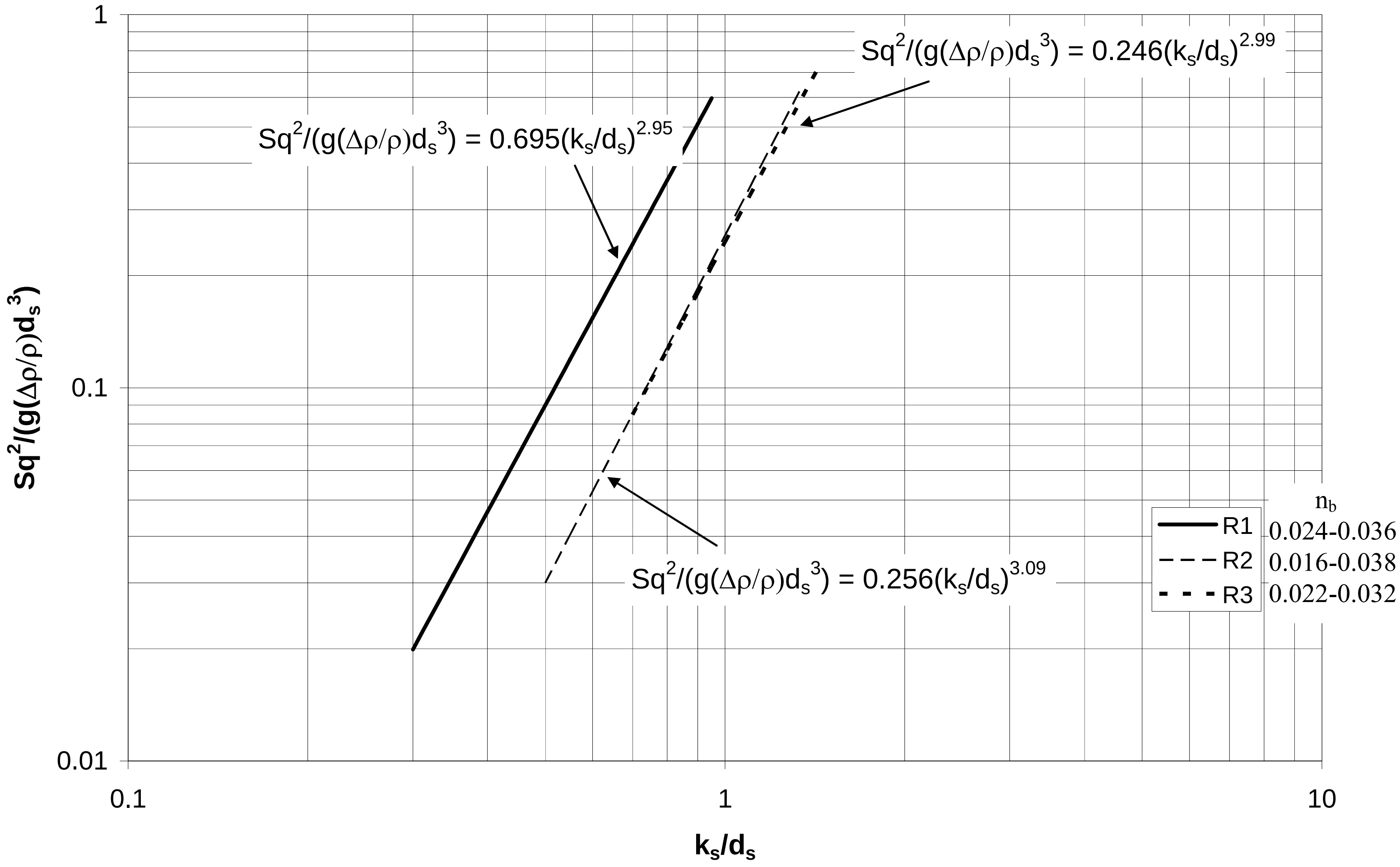


Figure III-40: Best Fit curves of $Sq^2/[g\ (\Delta\rho/\rho)d_s^3]$ vs. k_s/d_s for all rough channel beds

III.3.4. Relationship between the Dimensionless Obstructing Element Height "t/d_s" and Slope of the Channel "S"

Variation of the dimensionless obstructing element height t/d_s with slope of the rough channel bed R1 and corresponding relative depth R_b/d_s are given in Figures III-41 through III-45. Since for other rough channel beds tested the relations between above stated parameters are similar, the related figures of these channel beds were not presented here.

Figures III-41 through III-45 reveal that for a given particle shape and size as t value increases, the required channel slope to give motion to the particle also increases. However, there is no a general trend between S and t/d_s values when all of the particles are considered. A random distribution of data points is seen in the related figures.

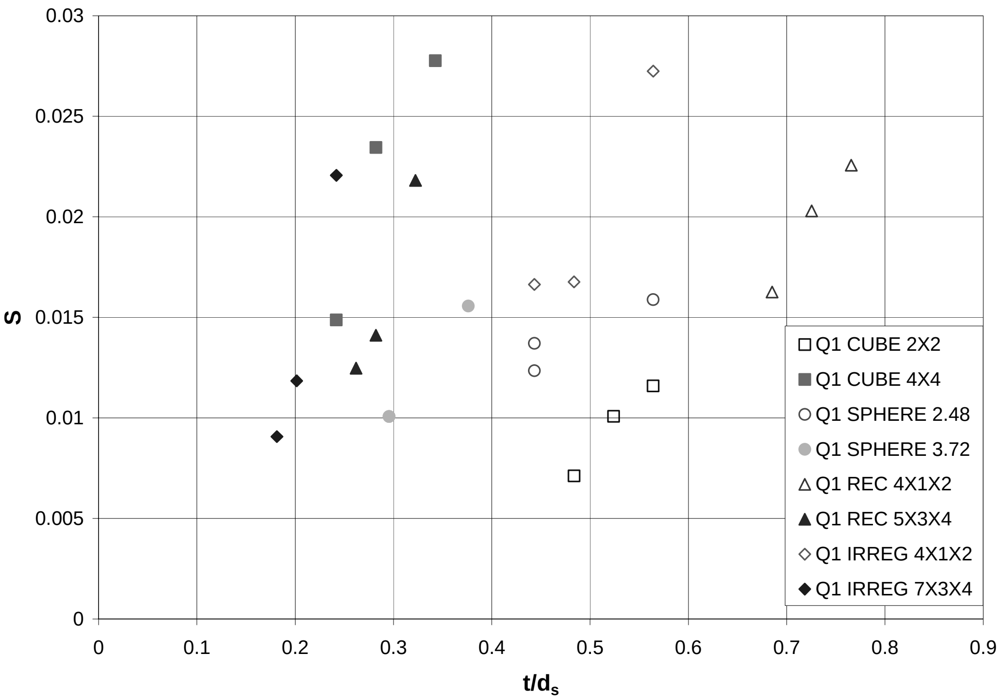


Figure III-41: t/d_s vs. S for Q1~0.025 m^3/s on 1st smooth bed

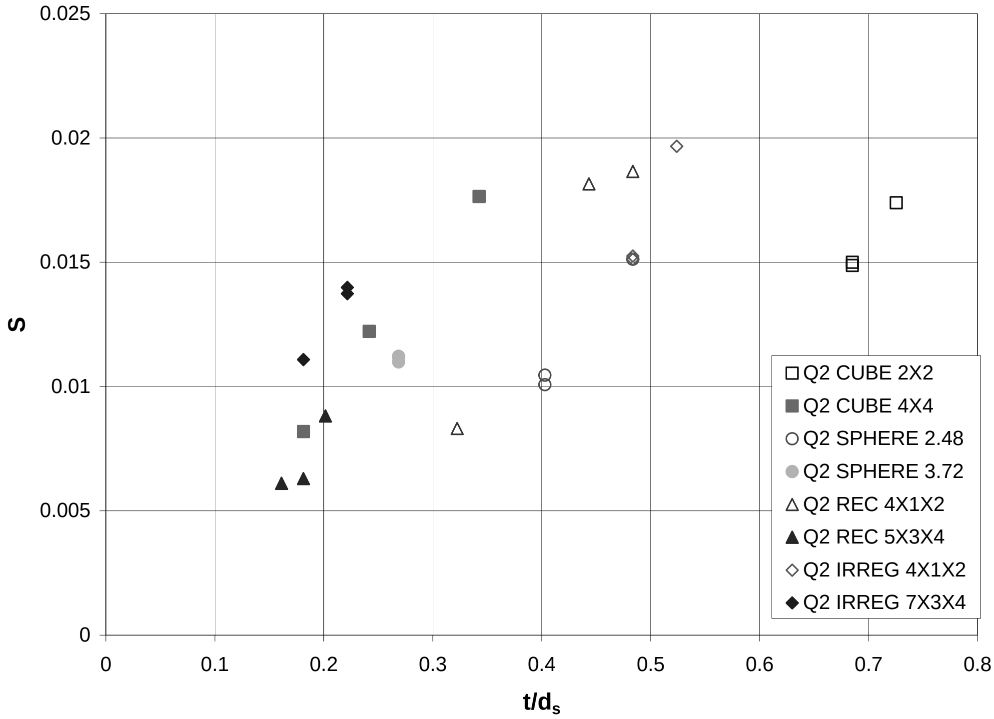


Figure III-42: t/d_s vs. S for Q2~0.031 m^3/s on 1st smooth bed

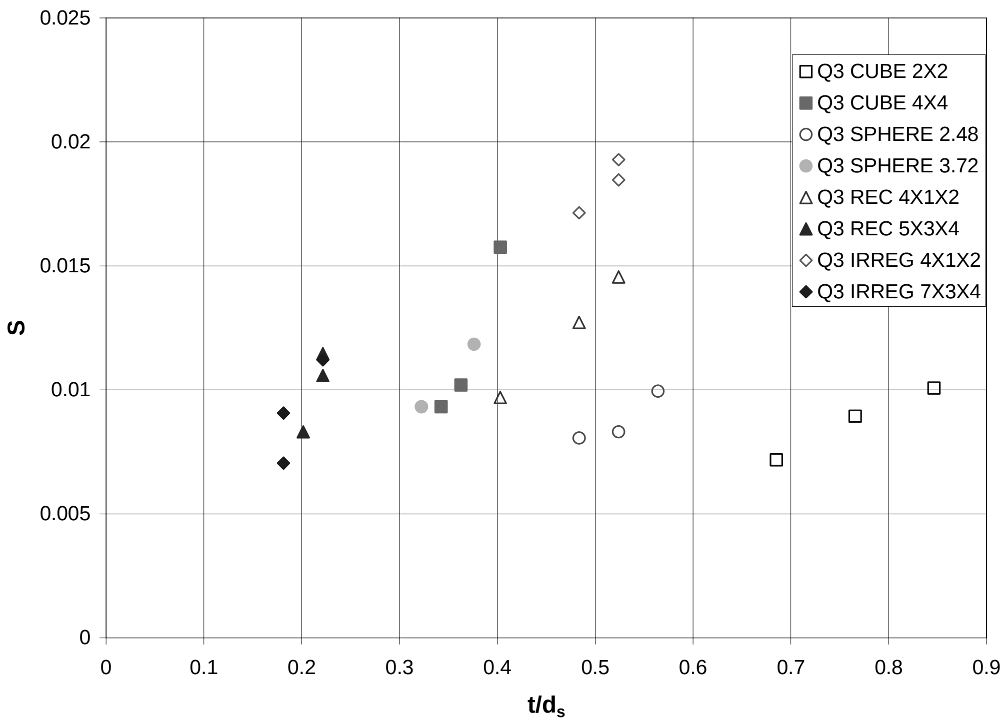


Figure III-43: t/d_s vs. S for Q3~0.040 m^3/s on 1st smooth bed

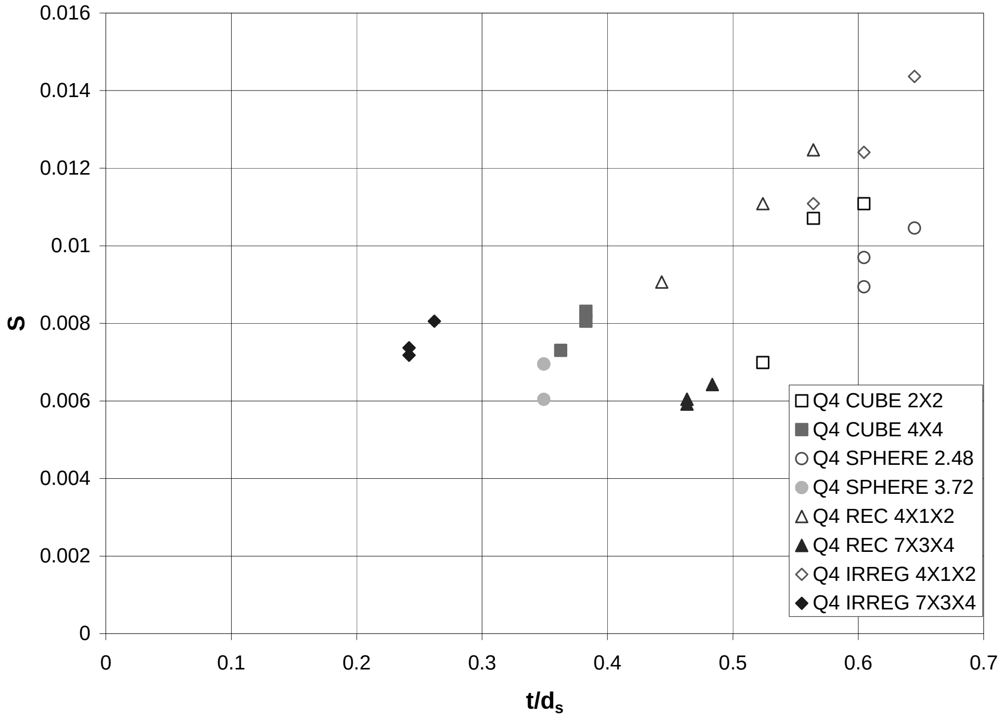


Figure III-44: t/d_s vs. S for Q4~0.050 m^3/s on 1st smooth bed

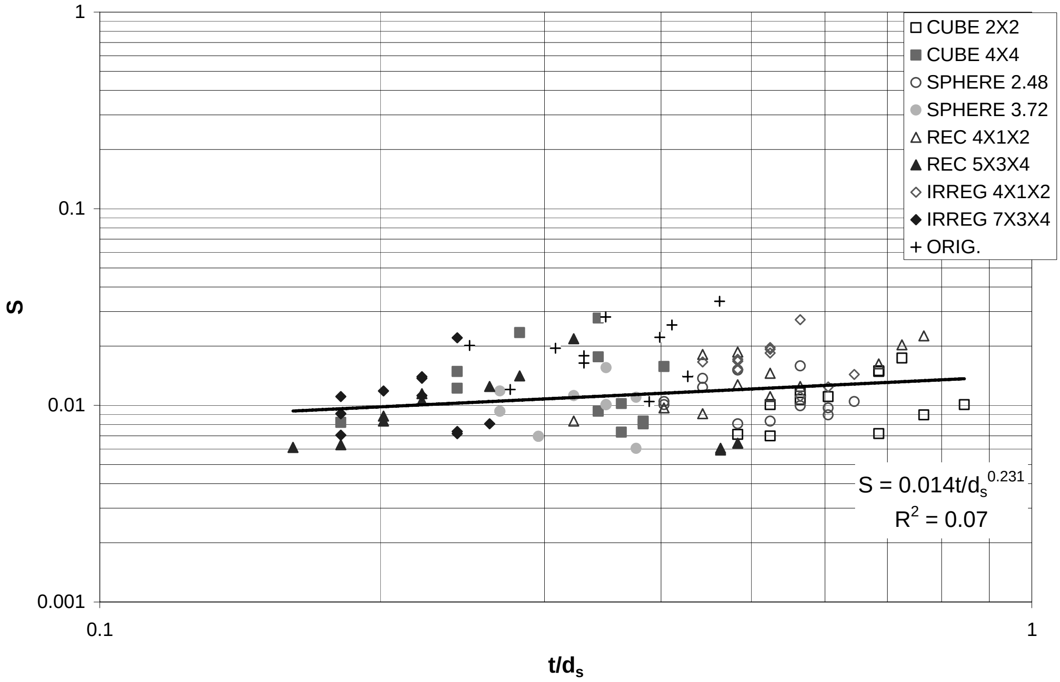


Figure III-45: t/d_s vs. S for all Discharges on 1st smooth bed

III.3.5. Relationship between the Dimensionless Obstructing Element Height "t/d_s" and Relative Depth "R_b/d_s"

Similar random distribution of data of R_b/d_s and t/d_s is observed from the Figures III-46 through III-50.

In order to get a better relationship between t/d_s and other related parameters given in Eqn. 2.10, by trial the best relationship was obtained between t/d_s and $(S^{0.5})(R_b/d_s)$ for almost all of the experiments conducted. This relationship is presented in Figures III-51 through III-62 for all rough channel beds of R1, R2 and R3. Then the collective results of these figures are given in Figures III-63 through III-65. From the inspection of these figures it can be stated that there is a linear relationship between the relevant parameters. For known values of S, R_b and d_s, one can determine the required obstructing element height, t, for the initiation of motion of particle of given d_s on a smooth channel surface. These curves can also be used to determine the R_b value required to give initial motion to a particle of d_s in a smooth channel of known slope when the particle is resting behind an obstructing element of height t. The best fit curves of Figure III-63 through III-65 are also presented in Figure III-66 all together to show the channel bed roughness effect. Since in all these experiments smooth channels were used the curves in Figure III-66 appear parallel and very close to each other.

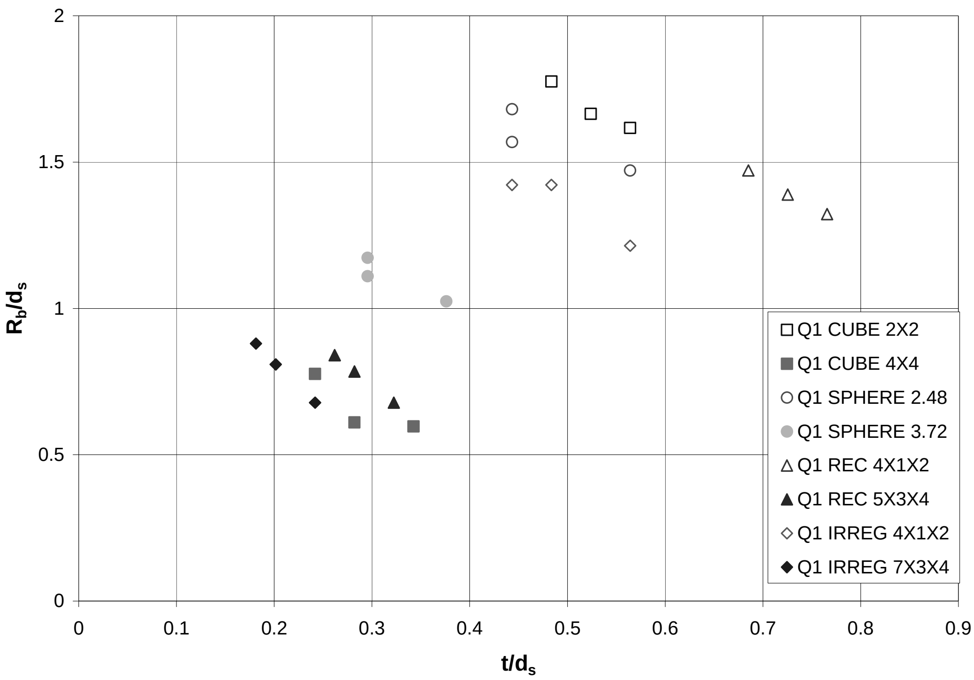


Figure III-46: t/d_s vs. R_b/d_s for Q1~0.025 m^3/s on 1st smooth bed

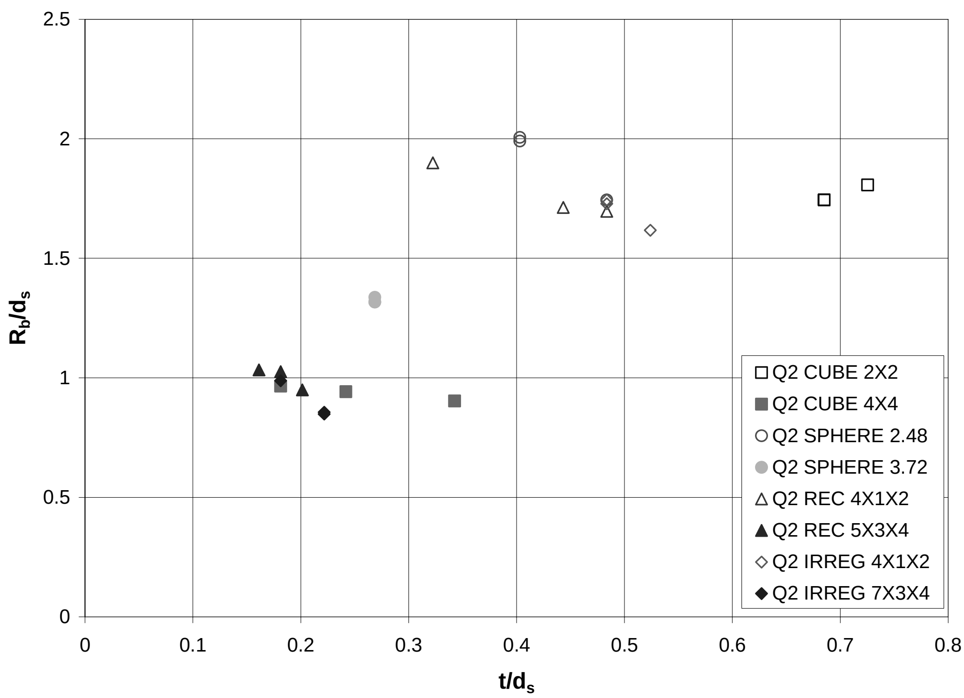


Figure III-47: t/d_s vs. R_b/d_s for Q2~0.031 m^3/s on 1st smooth bed

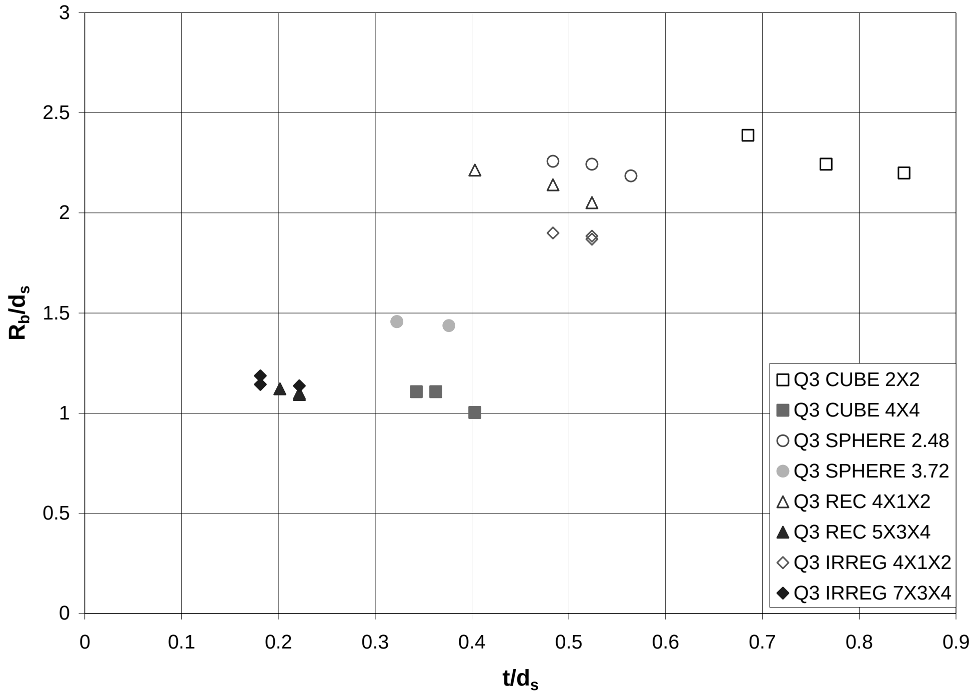


Figure III-48: t/d_s vs. R_b/d_s for Q3~0.040 m^3/s on 1st smooth bed

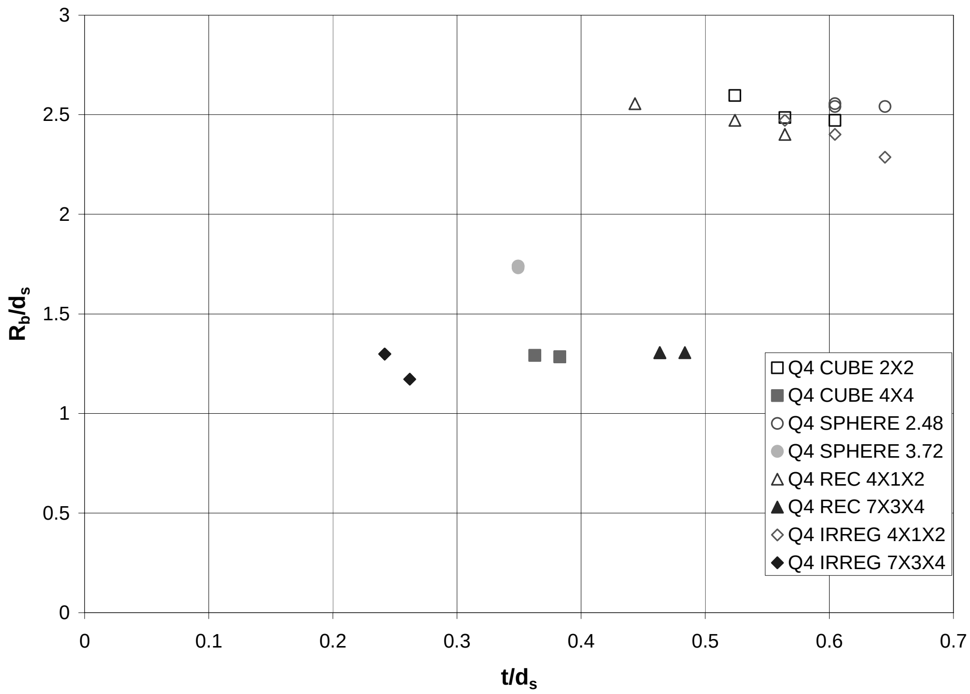


Figure III-49: t/d_s vs. R_b/d_s for Q4~0.050 m^3/s on 1st smooth bed

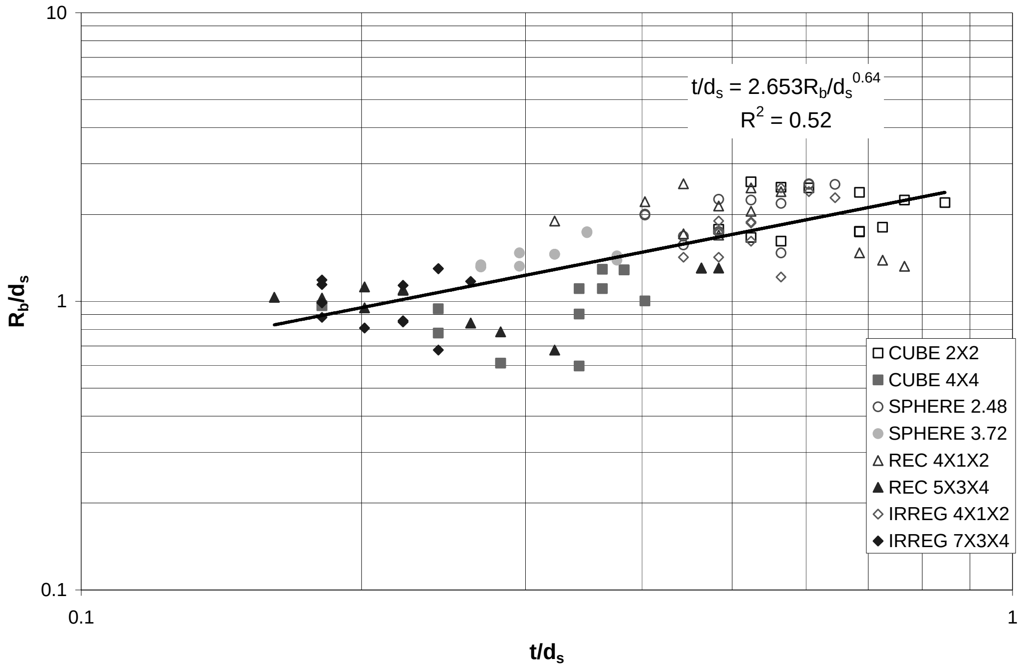


Figure III-50: t/d_s vs. R_b/d_s for all discharges on 1st smooth bed

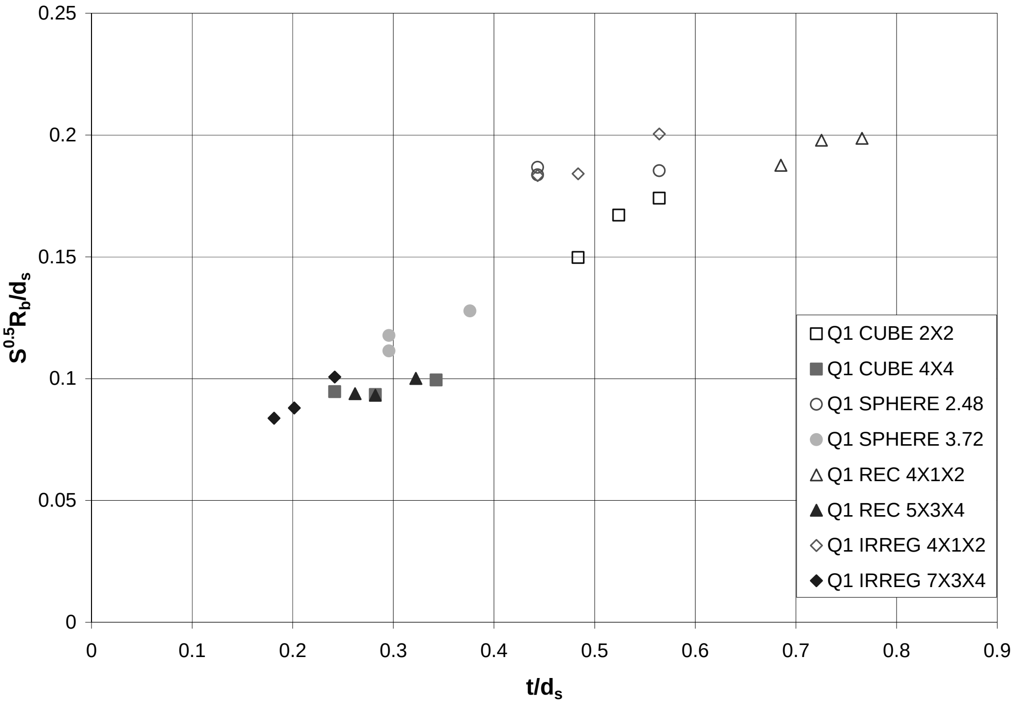


Figure III-51: t/d_s vs. $S^{0.5}R_b/d_s$ for Q1~0.025 m^3/s 1st smooth bed

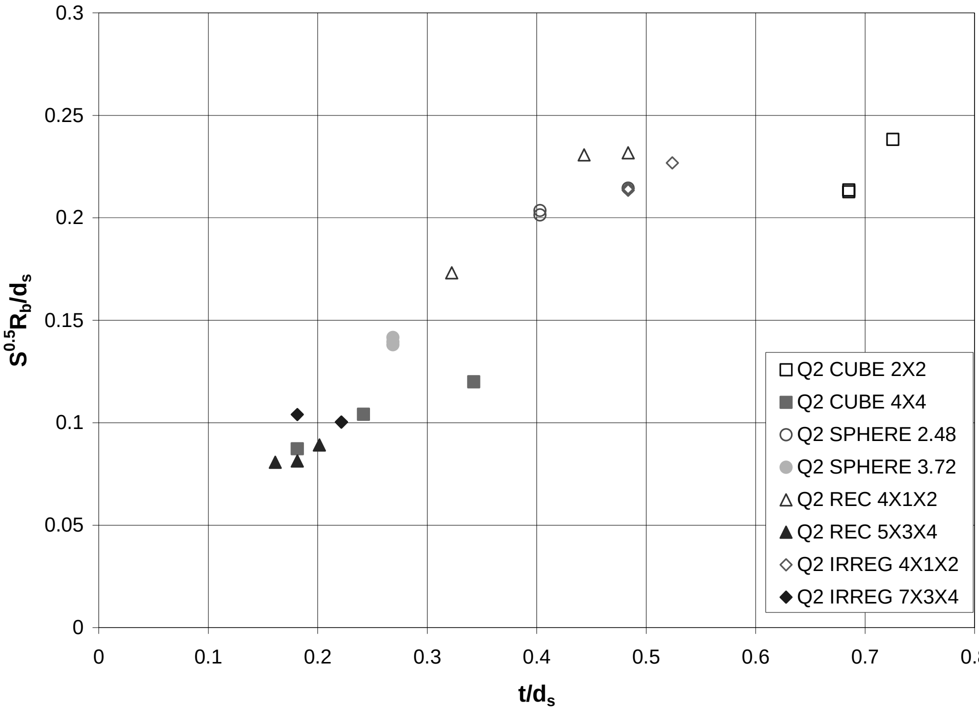


Figure III-52: t/d_s vs. $S^{0.5}R_b/d_s$ for Q2~0.031 m^3/s 1st smooth bed

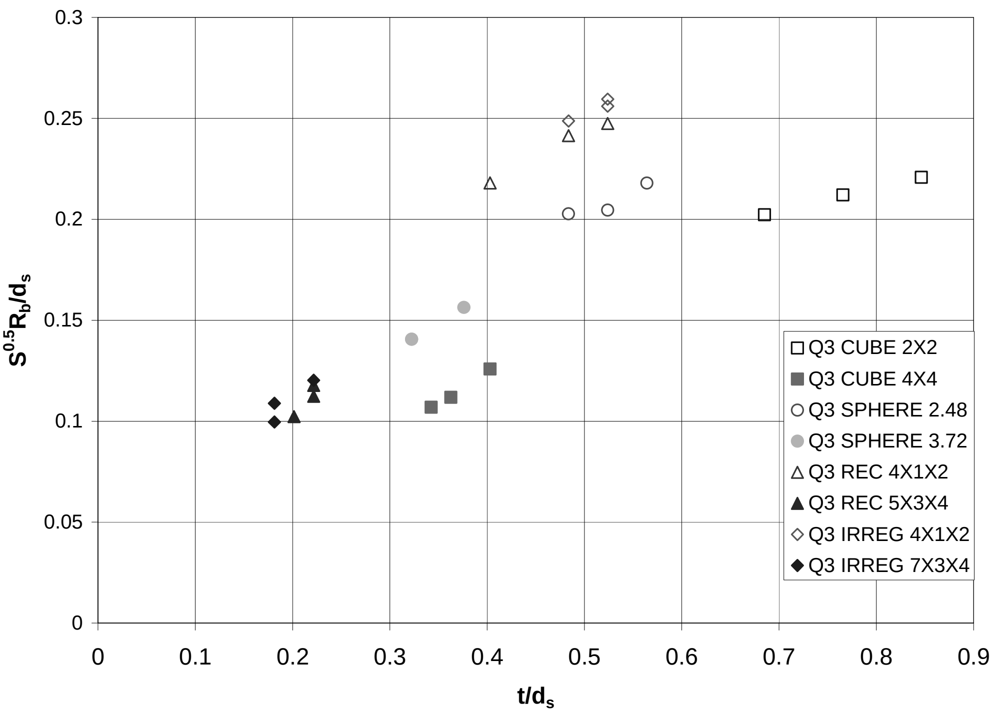


Figure III-53: t/d_s vs. $S^{0.5}R_b/d_s$ for Q3~0.040 m^3/s on 1st smooth bed

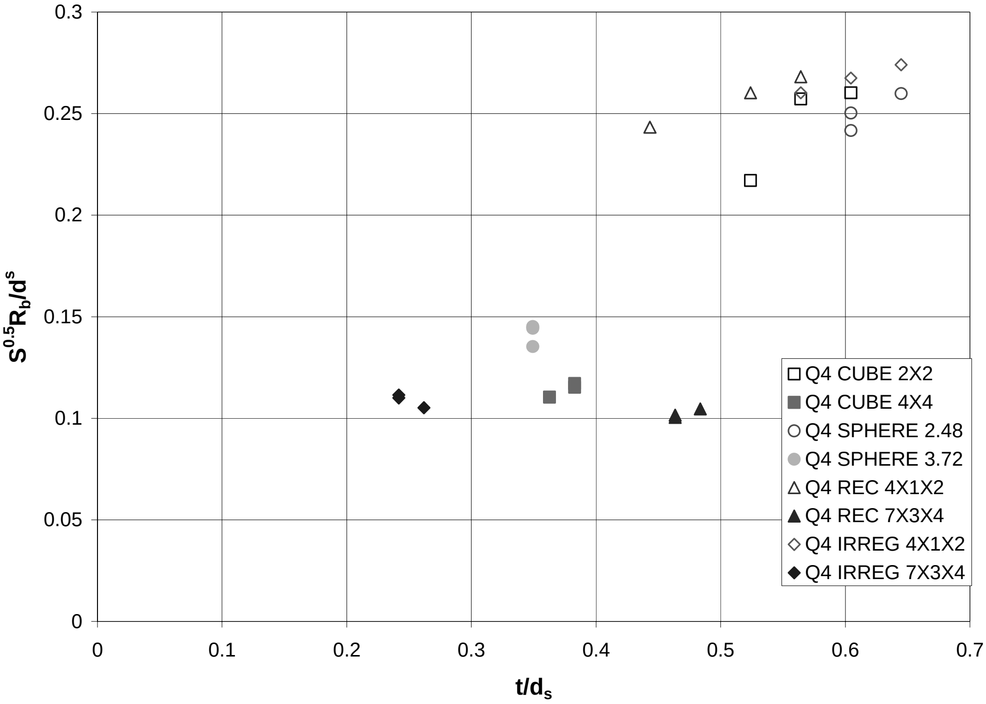


Figure III-54: t/d_s vs. $S^{0.5}R_b/d_s$ for Q4~0.050 m^3/s on 1st smooth bed

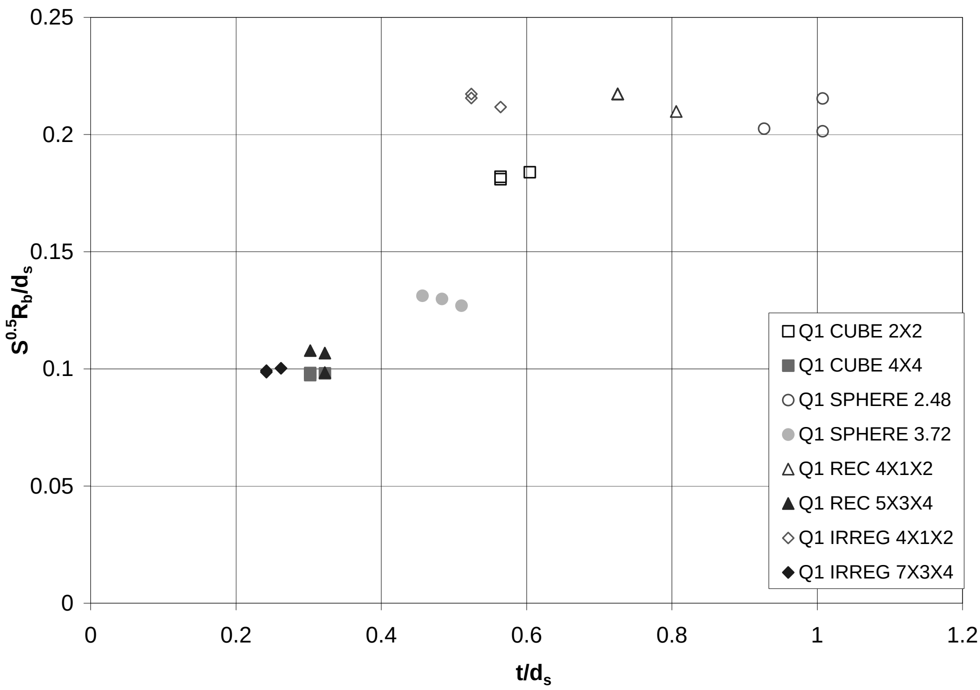


Figure III-55: t/d_s vs. $S^{0.5}R_b/d_s$ for Q1~0.025 m^3/s on 2nd smooth bed

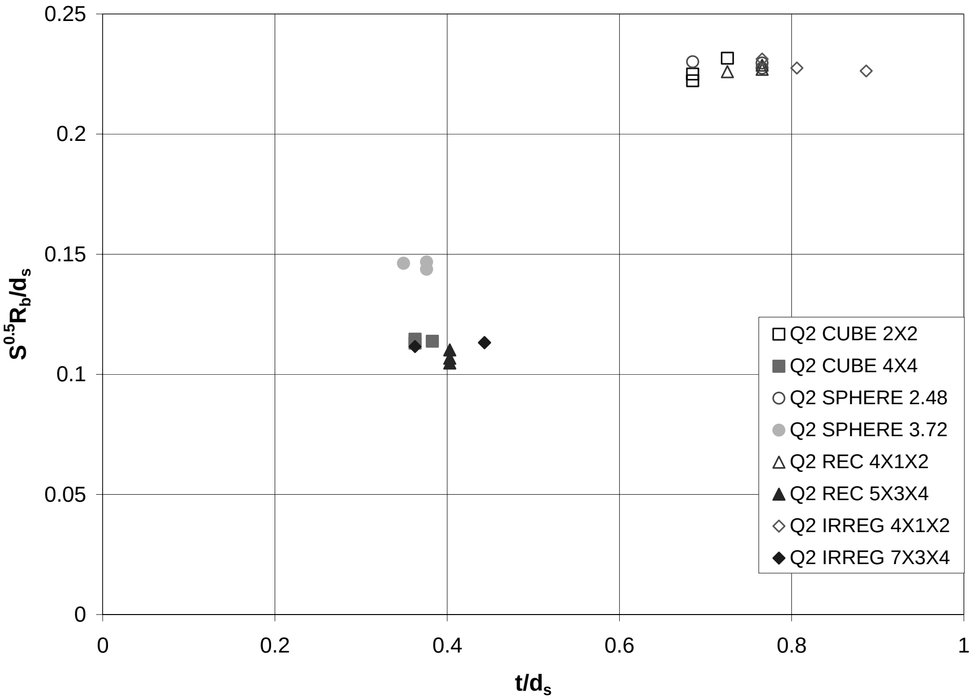


Figure III-56: t/d_s vs. $S^{0.5}R_b/d_s$ for Q2~0.031 m^3/s on 2nd smooth bed

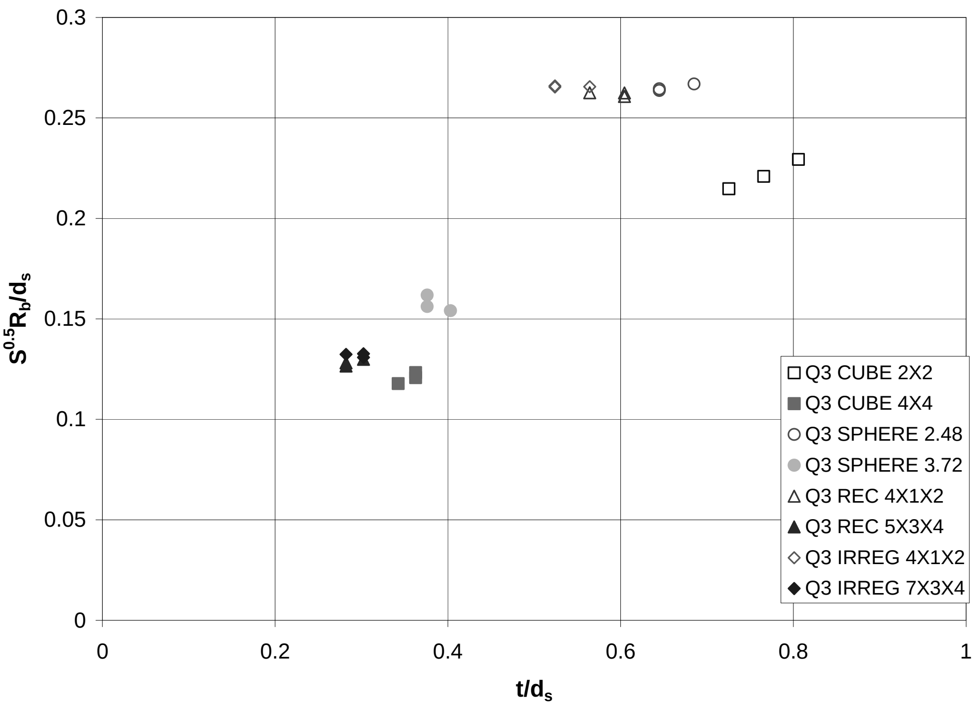


Figure III-57: t/d_s vs. $S^{0.5}R_b/d_s$ for Q3~0.040 m^3/s on 2nd smooth bed

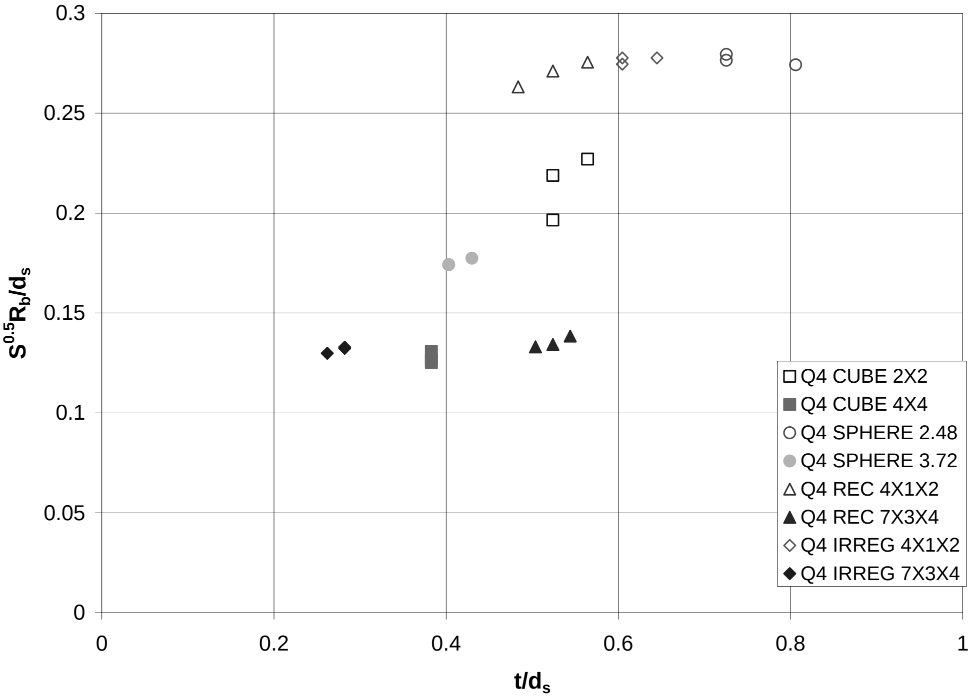


Figure III-58: t/d_s vs. $S^{0.5}R_b/d_s$ for Q4~0.050 m^3/s on 2nd smooth bed

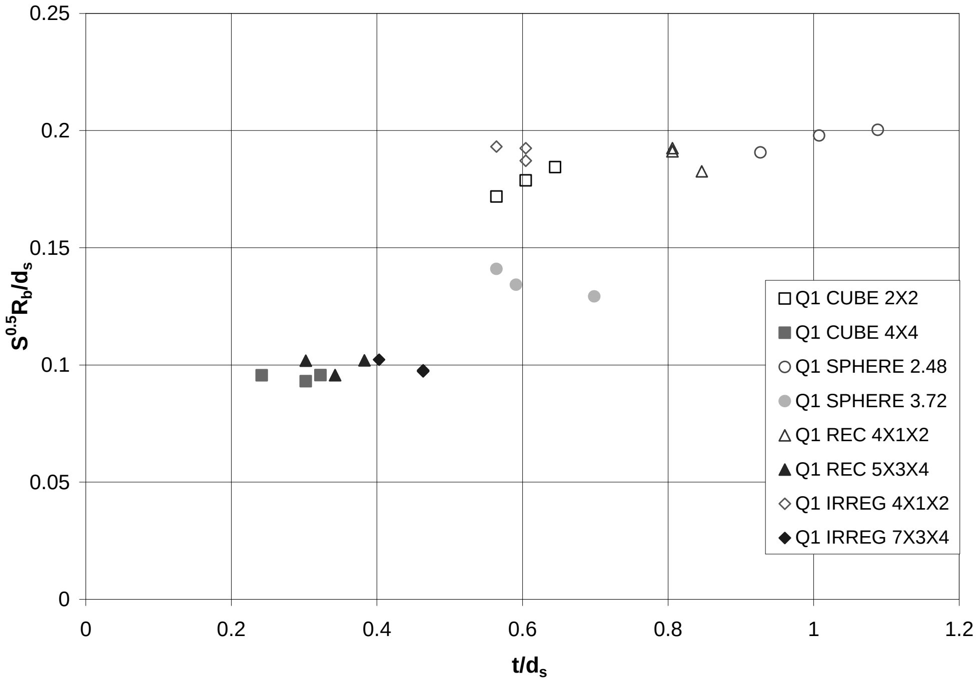


Figure III-59: t/d_s vs. $S^{0.5}R_b/d_s$ for Q1~0.025 m^3/s on 3rd smooth bed

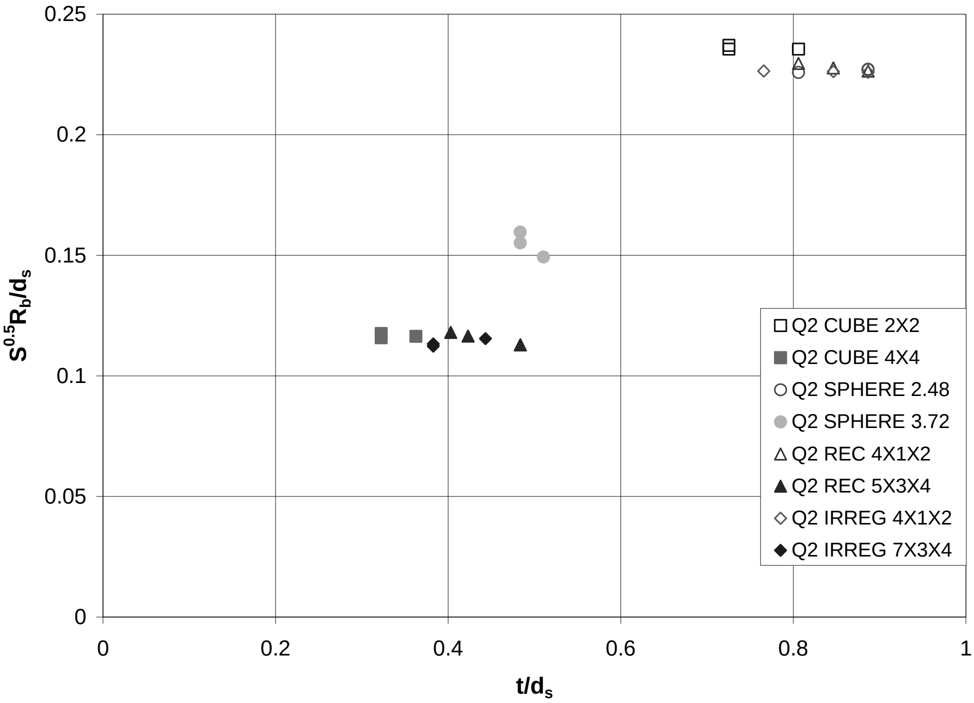


Figure III-60: t/d_s vs. $S^{0.5}R_b/d_s$ for Q2~0.031 m^3/s on 3rd smooth bed

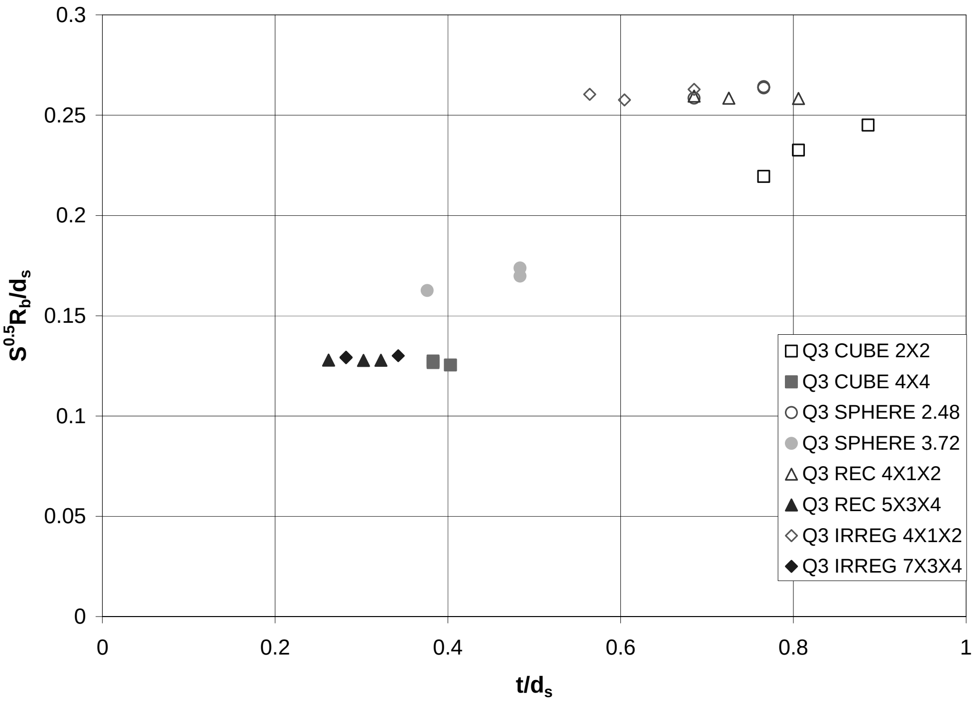


Figure III-61: t/d_s vs. $S^{0.5}R_b/d_s$ for Q3~0.040 m^3/s on 3rd smooth bed

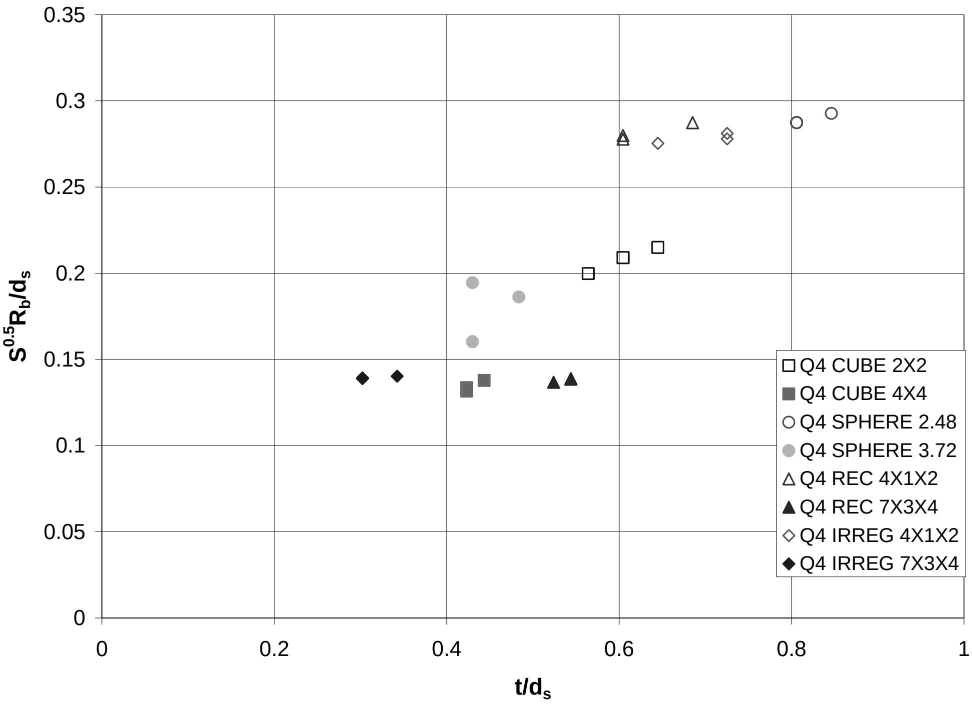


Figure III-62: t/d_s vs. $S^{0.5}R_b/d_s$ for Q4~0.050 m^3/s on 3rd smooth bed

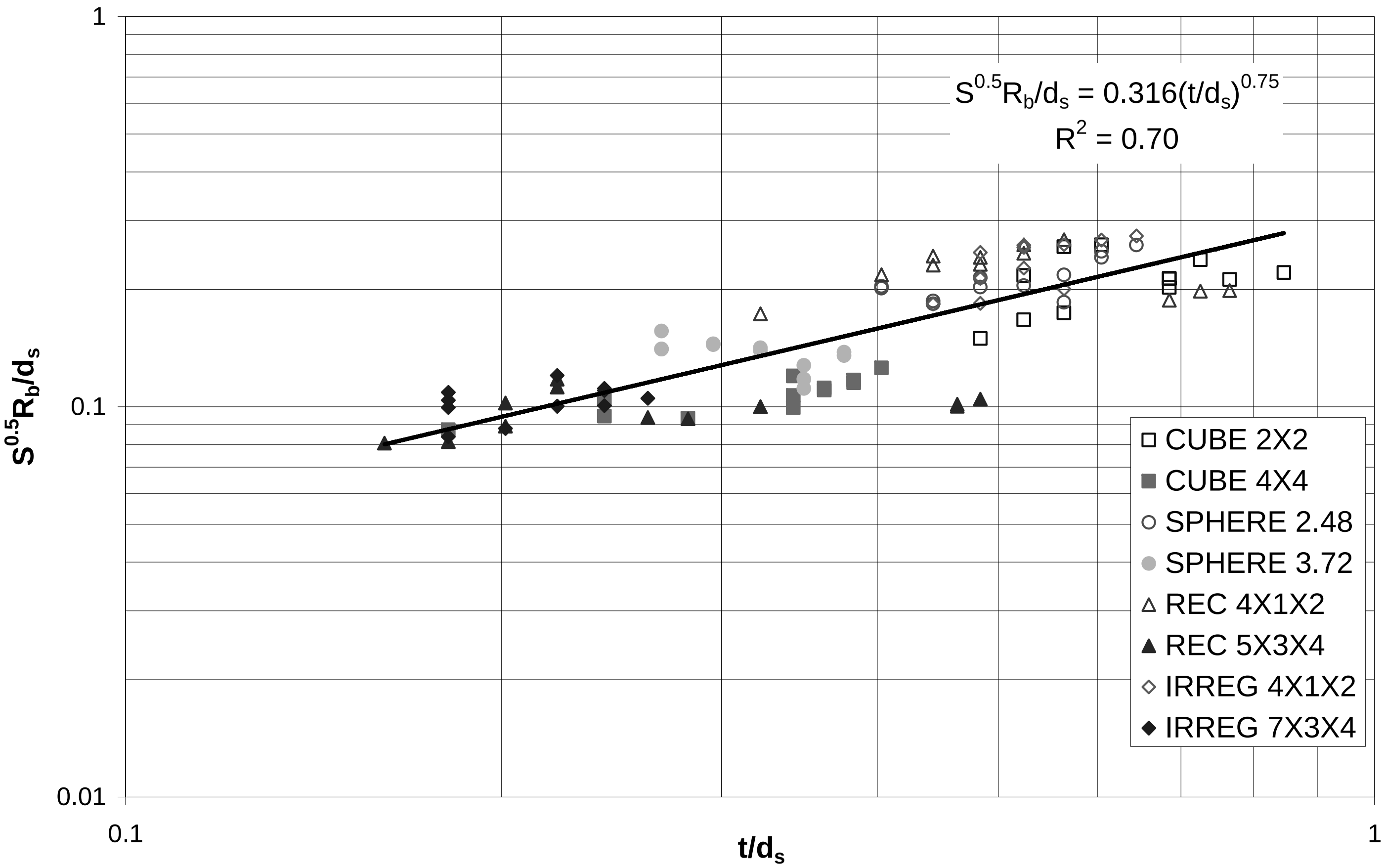


Figure III-63: t/d_s vs. $S^{0.5}R_b/d_s$ for all discharges on 1st smooth bed

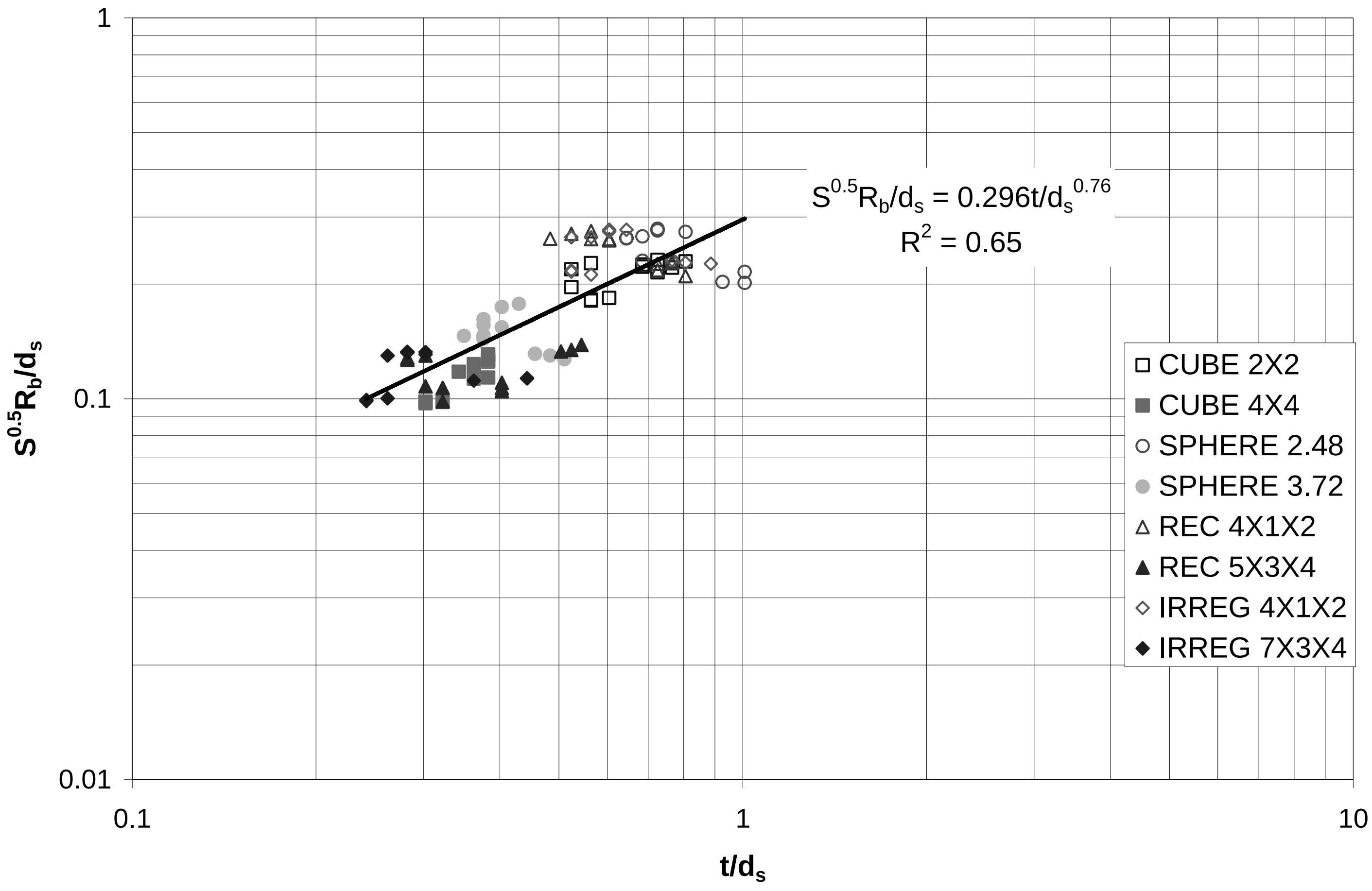


Figure III-64: t/d_s vs. $S^{0.5}R_b/d_s$ for all discharges on 2nd smooth bed

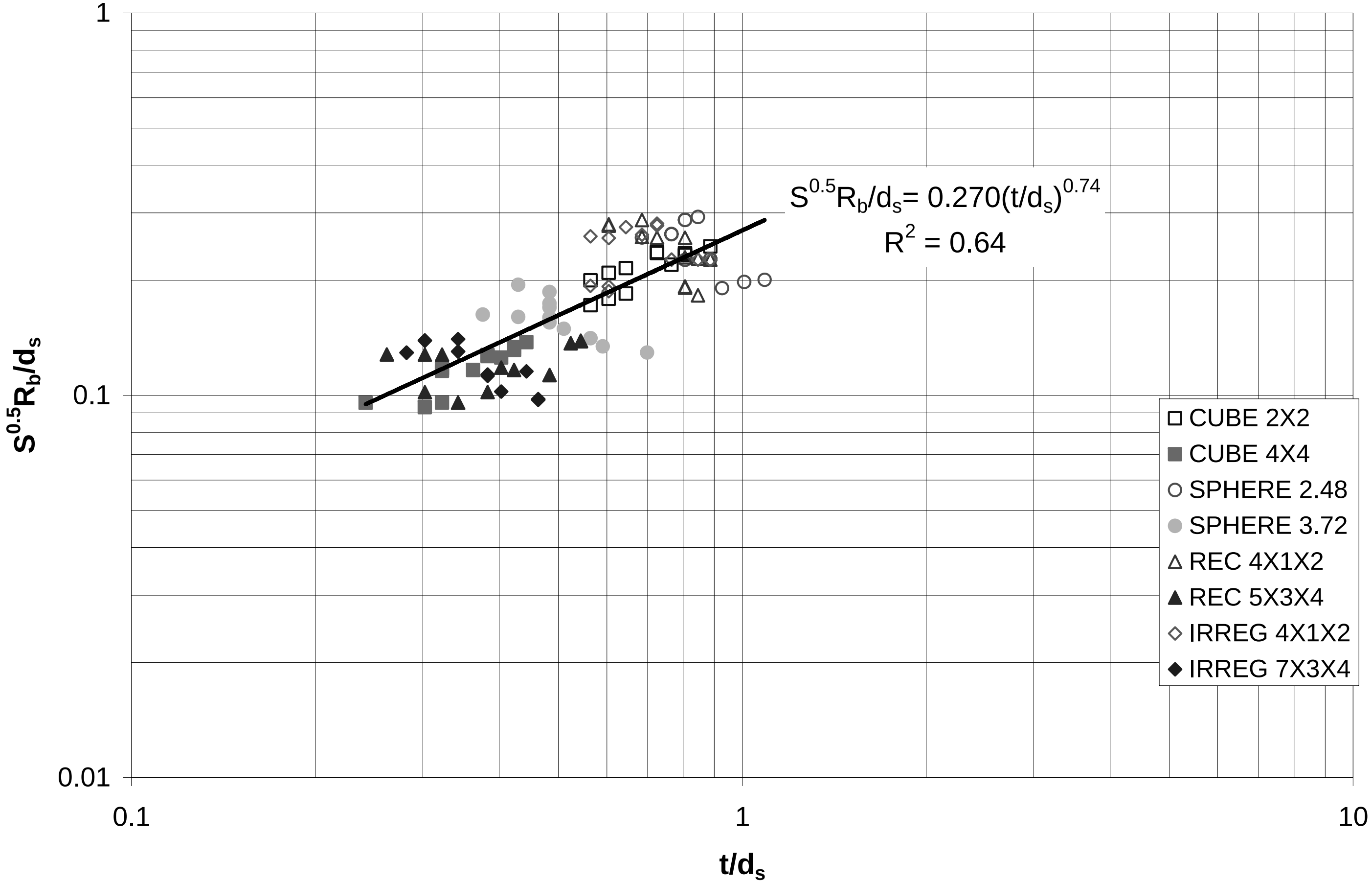


Figure III-65: t/d_s vs. $S^{0.5}R_b/d_s$ for all discharges on 3rd smooth bed

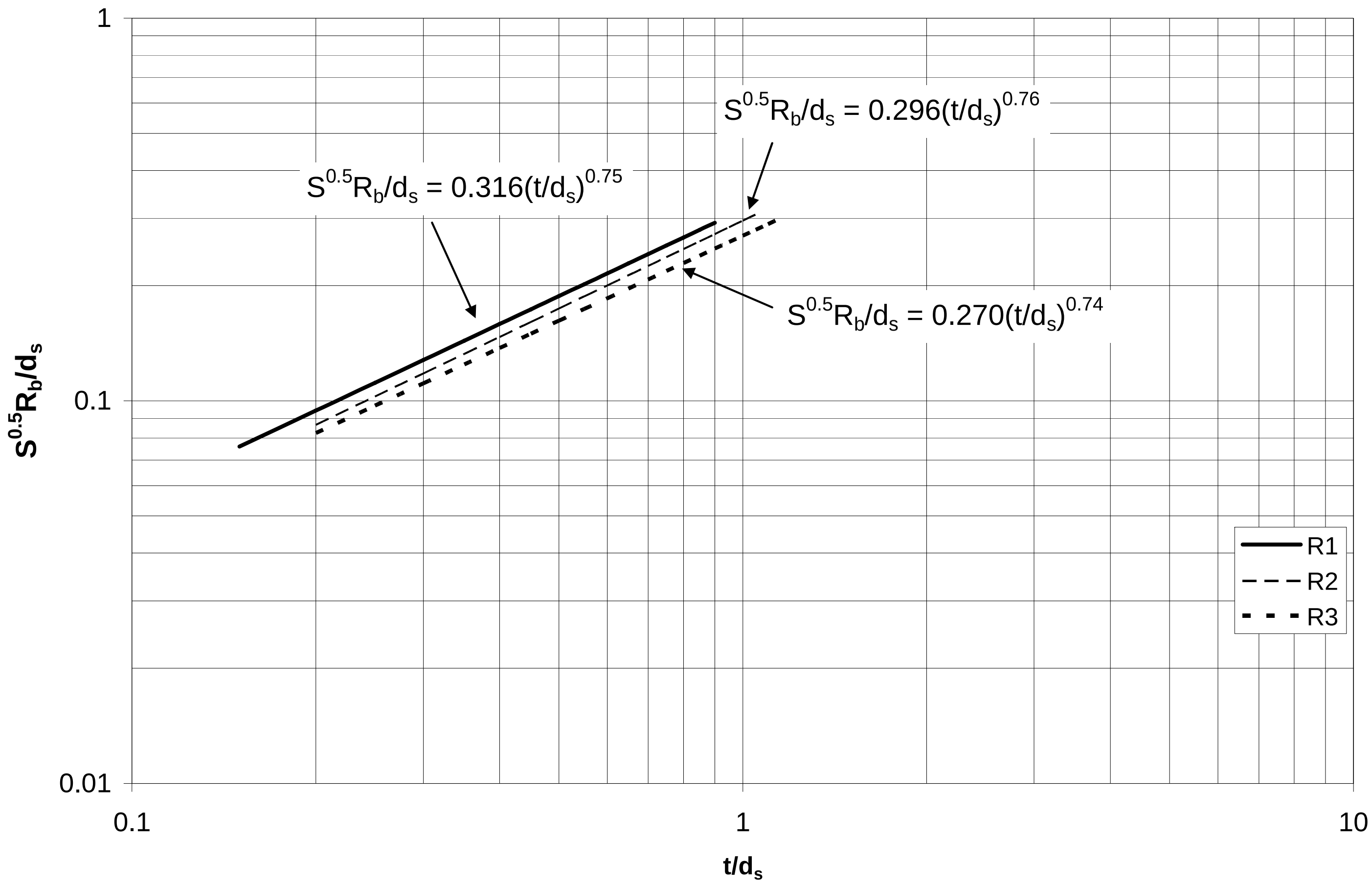


Figure III-66: Best fit curves of t/d_s vs. $S^{0.5}R_b/d_s$ for all smooth beds

III.3.6. Relationship between k_d/d_s and t/d_s

The data of relative roughness height of rough channel bed, k_s/d_s and corresponding t/d_s values on smooth bed were presented in Figures III-67 through III-69 with their best fitting curves. Since these figures are covering the experimental results obtained from the tests of particles randomly introduced into flow over channel beds having different roughness, one should not expect high correlation between data points. However a linearly varying relationship between k_s/d_s and t/d_s is observed in all three sets of data. When the best fitting curves of these data sets are given in the same figure, Figure III-70, it is seen that the curves of bed material of R2 and R3 almost coincide with each other while the curve of bed material of R1 of which n values are somewhat larger than those of the others falls a little far below them.

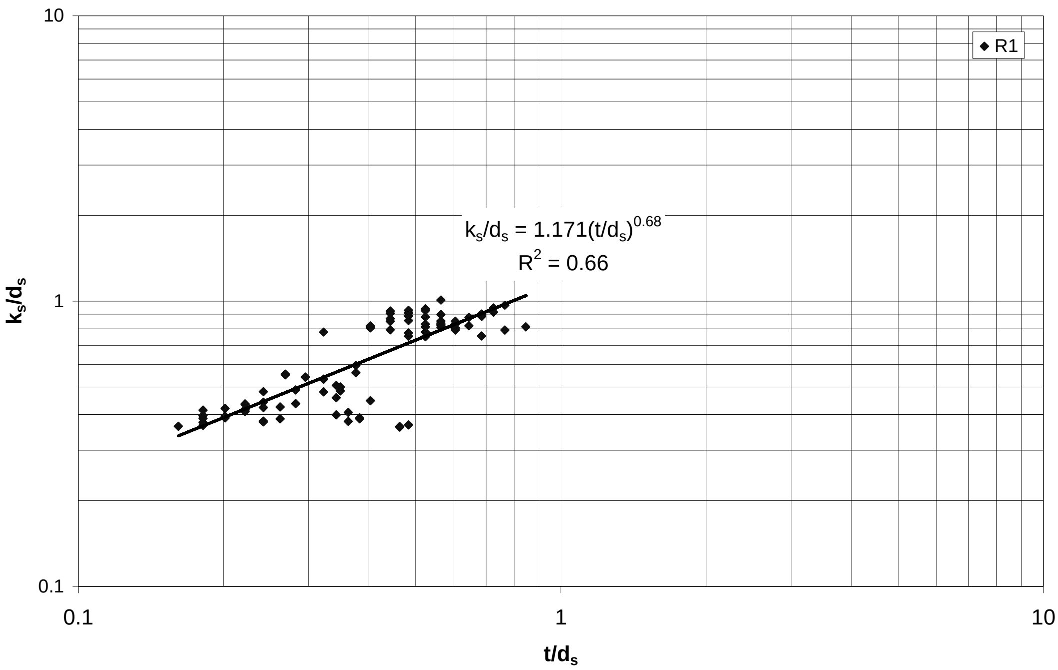


Figure III-67: Variation of k_s/d_s with t/d_s for rough channel bed of material R1

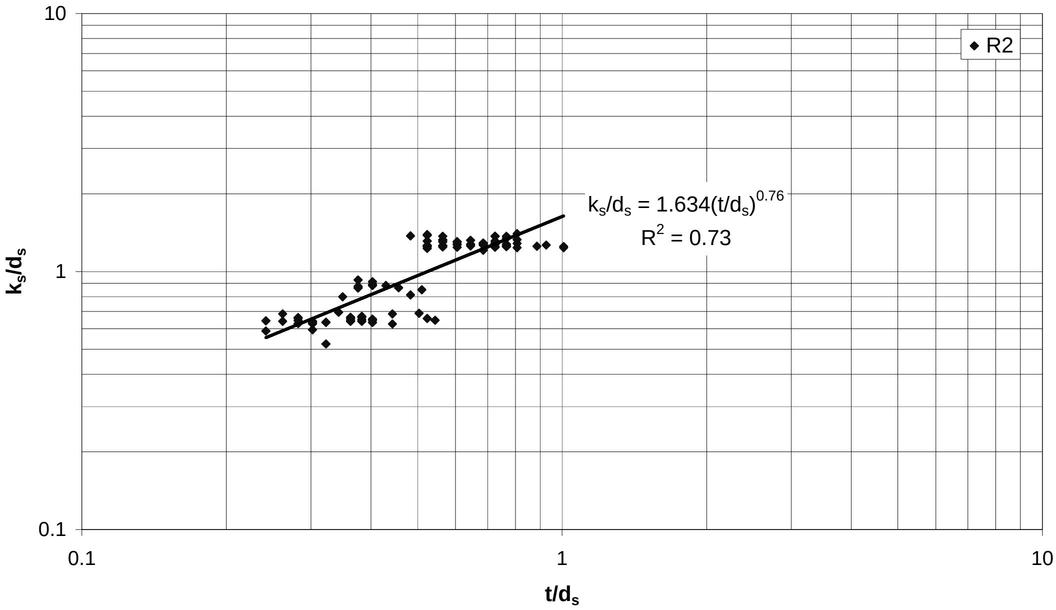


Figure III-68: Variation of k_s/d_s with t/d_s for rough channel bed of material R2

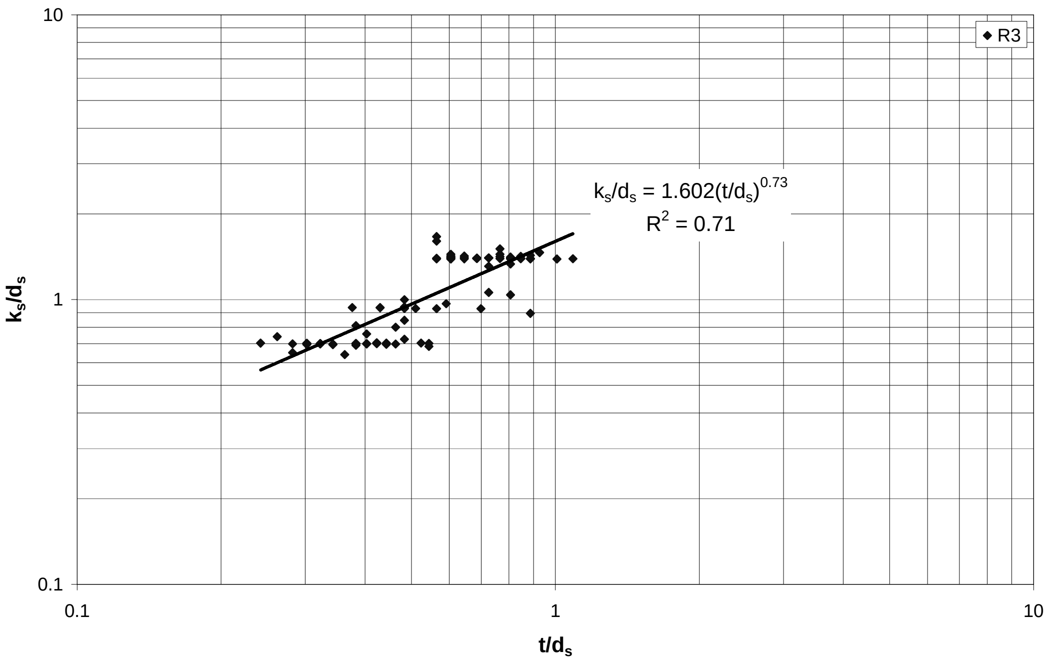


Figure III-69: Variation of k_s/d_s with t/d_s for rough channel bed of material R3

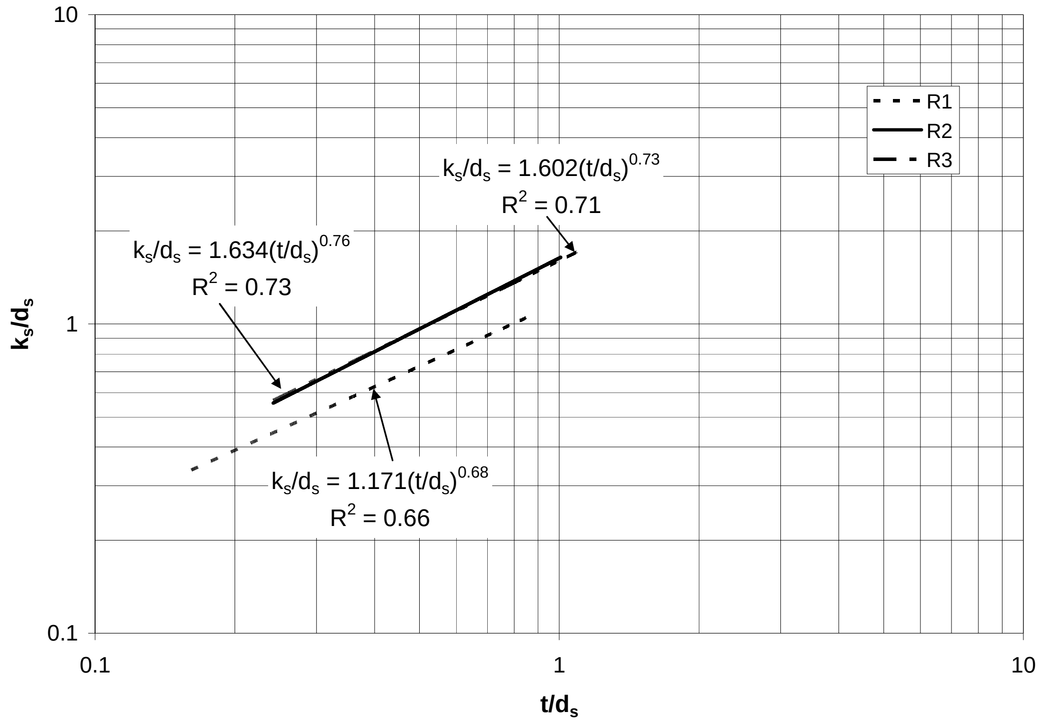


Figure III-70: Variation of k_s/d_s with t/d_s for rough channel bed of materials R1, R2 and R3

III.3.7. Relationship between Critical Cross-sectional Velocity and Relative Depth

From dimensional analysis concept a relationship between the critical cross-sectional velocity V_{cc} and the relative depth d_s/R_b can be written as follows;

$$\frac{V_{cc}}{\sqrt{g\left(\Delta\rho/\rho\right)d_s}} = C_1 \cdot S^{C_2}\left[\frac{d_s}{\left(R_b^*\right)_r}\right]^{C_3} \qquad (3.3)$$

where C_1, C_2 and C_3 are the constants to be determined from the best fitting curves of the related data. The data of the experimental studies were plotted on log-log paper in the form of Eqn. 3.3, and presented in Figures III-71 through III-73, with their best fitting curves. The each curve is valid over specified rough bed whose n values remain within the given range. Referring these curves replotted in Figure III-74 one can determine the required flow velocity for the initial motion of particle of known d_s on a known channel slope and hydraulic radius.

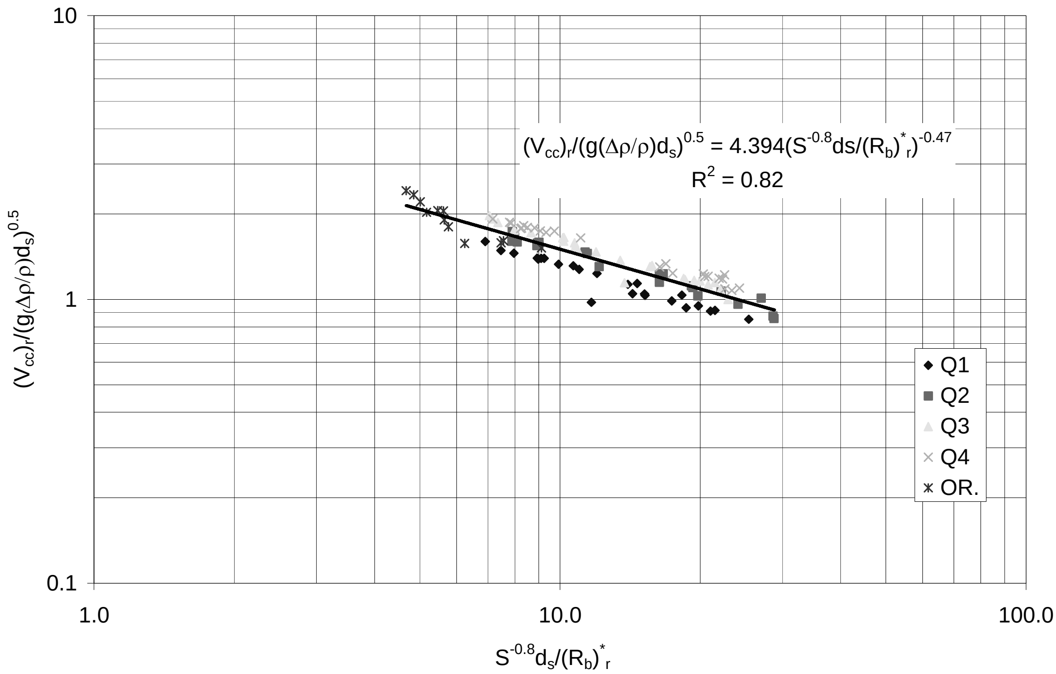


Figure III-71: $(V_{cc})_r/(g(\Delta\rho/\rho)d_s)^{0.5}$ vs. $S^{-0.8}d_s/(R_b)^*_r$ for all discharges on R1

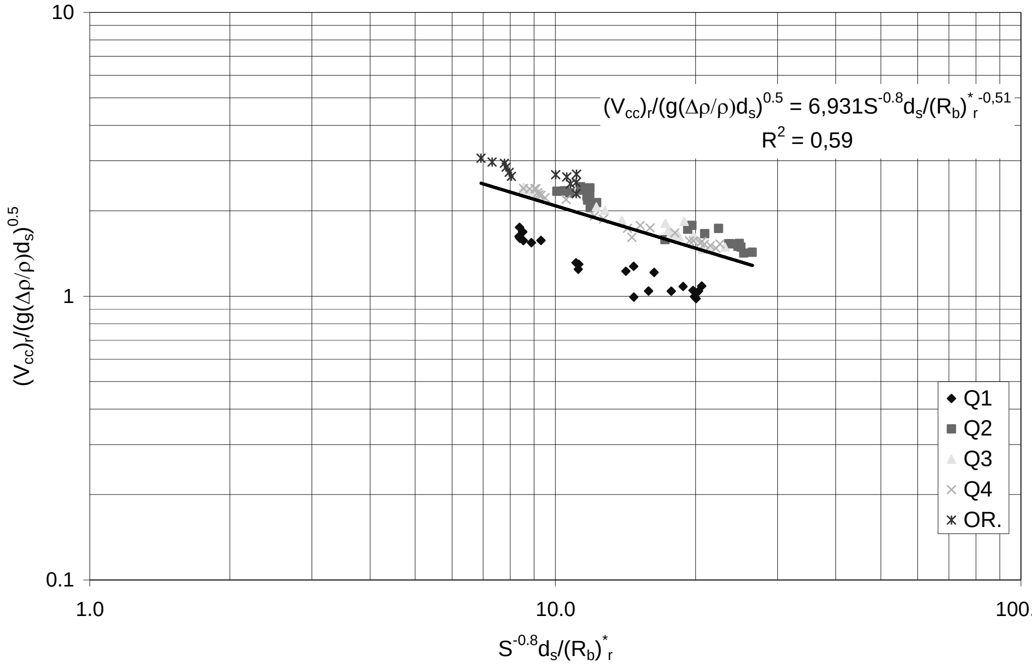


Figure III-72: $(V_{cc})_r/(g(\Delta\rho/\rho)d_s)^{0.5}$ vs. $S^{-0.8}d_s/(R_b)^*{}_r$ for all discharges on R2

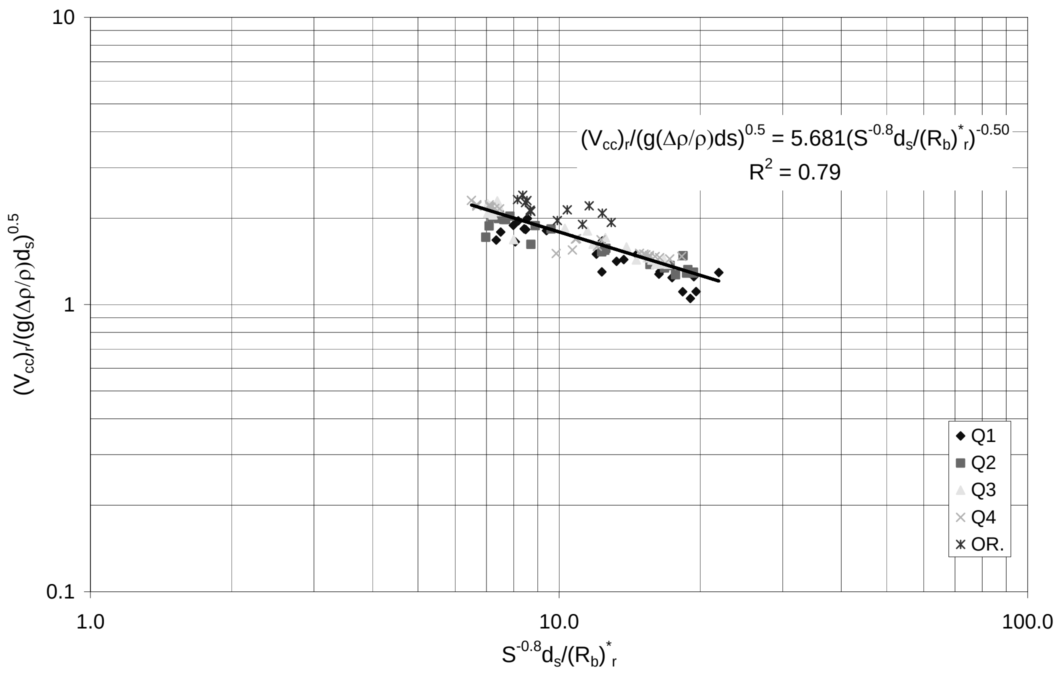


Figure III-73: $(V_{cc})_r/(g(\Delta\rho/\rho)d_s)^{0.5}$ vs. $S^{-0.8}d_s/(R_b)^*{}_r$ for all discharges on R3

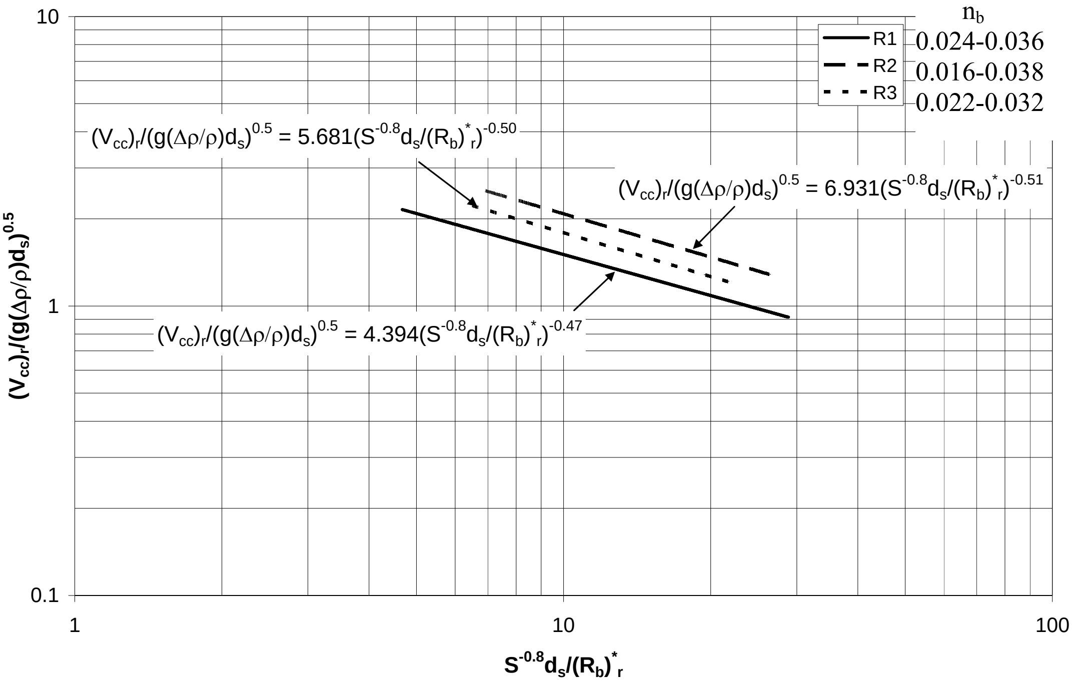


Figure III-74: Best fitting curves of $(V_{cc})_r/(g(\Delta\rho/\rho)d_s)^{0.5}$ vs. $S^{-0.8}d_s/(R_b)^*_r$ for channel beds roughness materials R1, R2 and R3

III.3.8. Comparison of Present Study with Previous Studies

In Section I.2. it had been stated that Novak and Nalluri (1984) conducted similar experiments over fixed rough beds with single particle and concluded that the ratio of particle diameter to roughness height, k_s, plays an important role on the motion of particles. They artificially roughened the channel bed by giving waterproofed sand paper to the bed having the smaller roughness sizes; 0.3 mm, 0.42 mm and the larger roughness sizes; 1.44 mm, 2.2 mm, 4.2 mm by sticking coarse gravel and sand particles to the bed. They tested single particles having the equivalent diameter sizes from 0.6 mm to 50 mm and average relative density was 2.56 g/cm^3. In each set of experiments, particle sizes were always larger than the roughness sizes. Then they tested the initiation of motion of discrete particles on beds with various roughness elements and presented the graph shown in Figure I-2.

Since Novak and Nalluri's (1984) study is similar to the present study, to compare the results of present study with those given in Figure I-2, the data of present study were marked on the aforementioned figure and presented in Figure III-75 through III-77. As it is seen from these figures the present data lie between Shield's curve (d_s/k_s=1) and the curve of d_s/k_s =3.4. The agreement between the results of both studies is quite well.

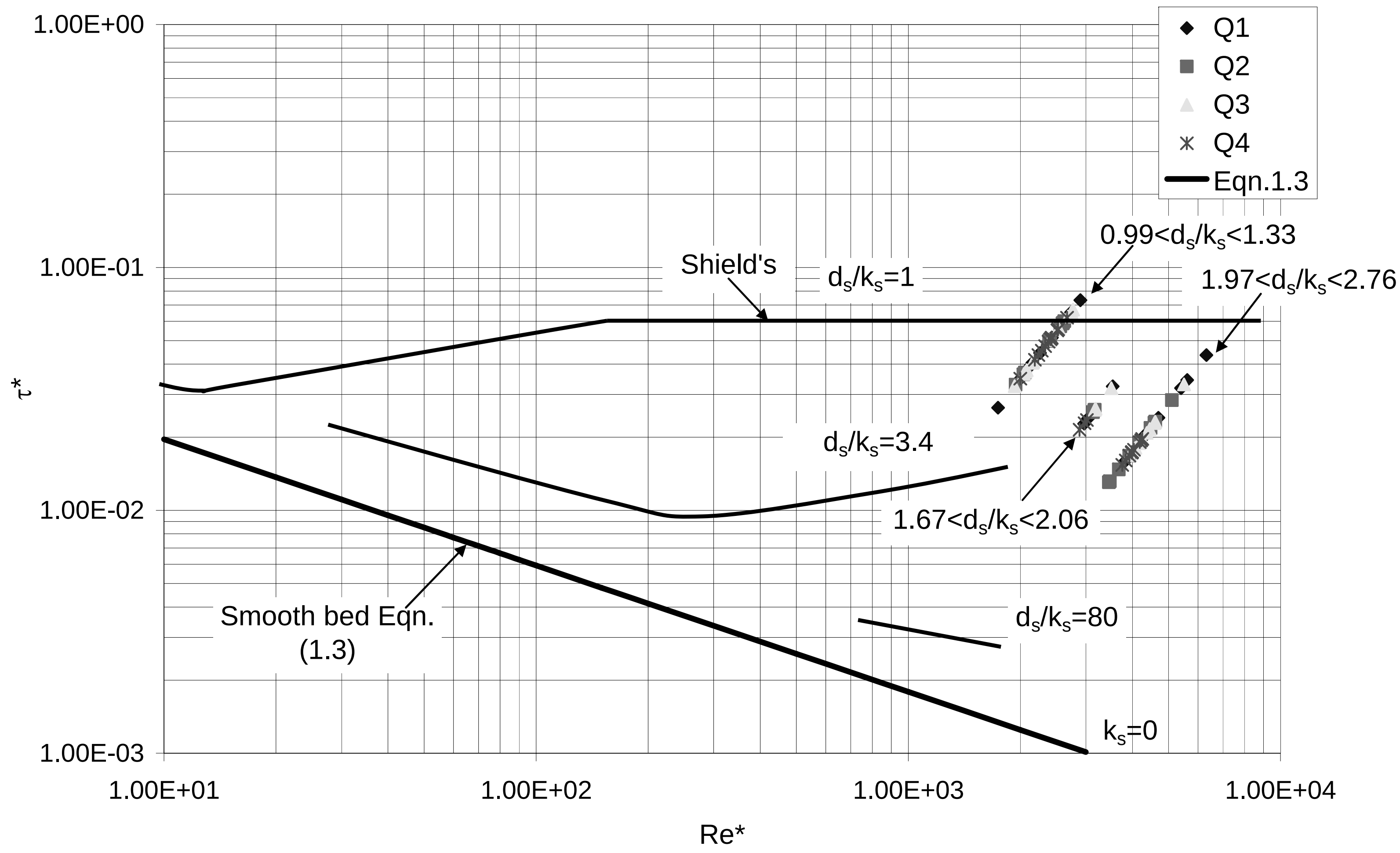


Figure III-75: Comparison of τ* vs. Re* for first case.

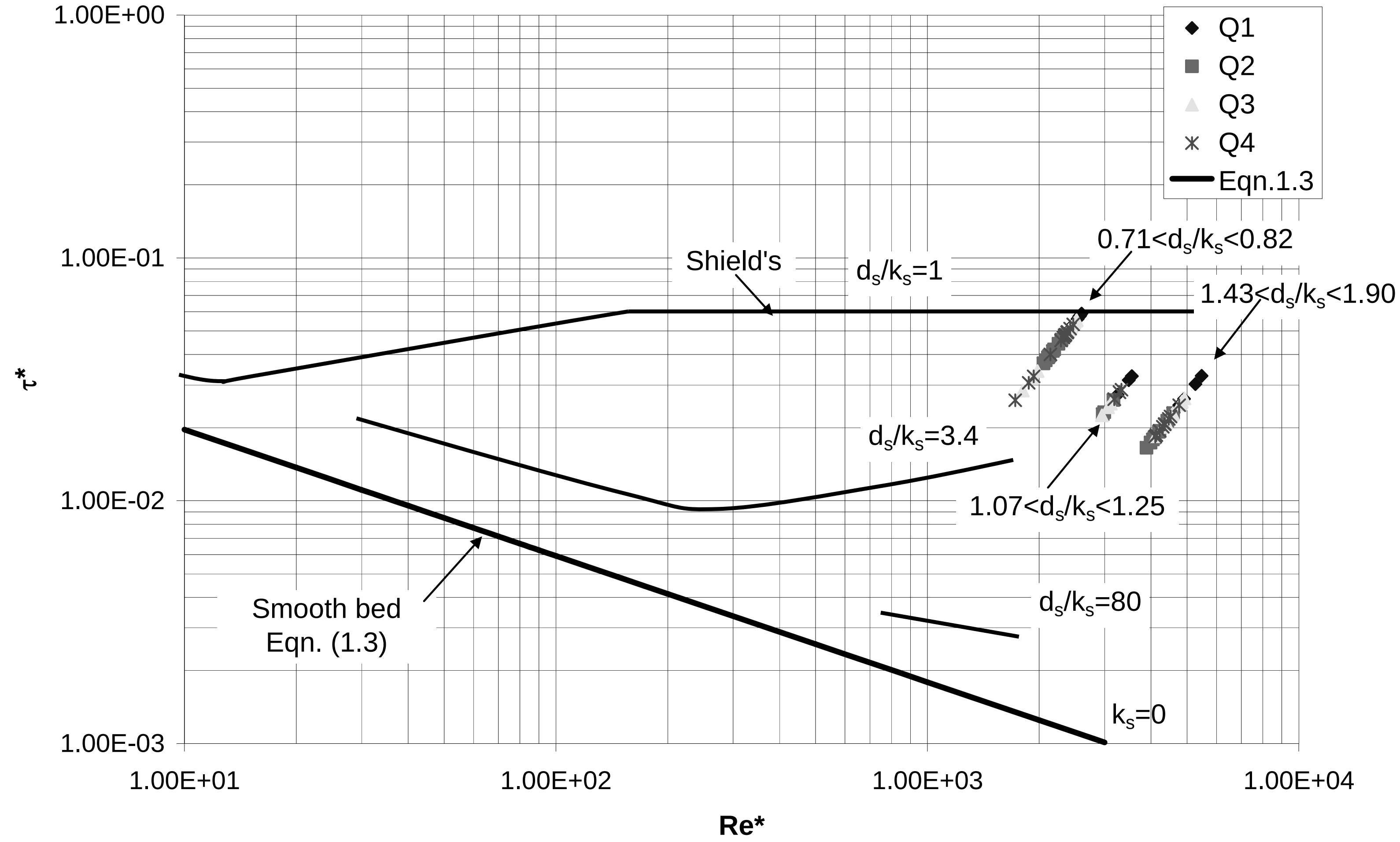


Figure III-76: Comparison of τ* vs. Re* for second case.

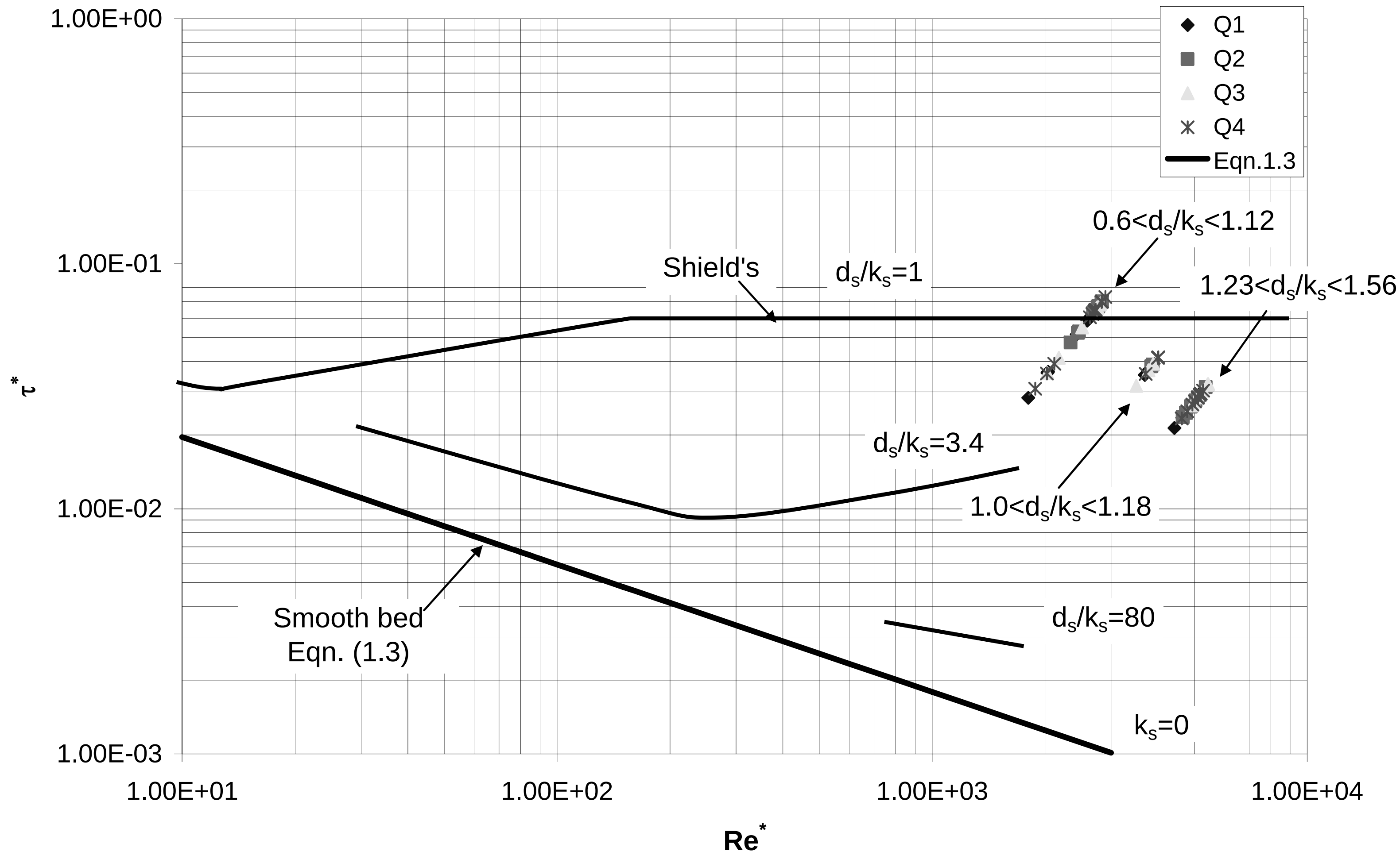


Figure III-77: Comparison of τ* vs. Re* for third case.

Defne (2002) and Gülcü (2009) used the same experimental setup and particles in their studies, and conducted their experiments in the smooth channel with an obstructing element of height ratio t/b=1/5 and 1.5/5, respectively. They presented their experimental data in the form of (R_b/d_s) versus Re^* with particle shape factor, SF, as a third parameter (Figure I-4). This figure clearly shows that R_b/d_s values rapidly decrease as Re_* increase up to $4x10^3$, and then slightly decrease with increasing Re_*. In order to see the agreement between the data given in Figure I-4 and those of present study, the relevant data were given in Figures III-78 through III-80 with their best fitting curves and then only the best fitting curves were shown in Figure III-81. There is no good correlation between data points since they have a very large t/b ranges; between 0.2 and 2.2. However, when the best fitting curves given in Figure III-81 are replotted in Figure III-82 along with Defne (2002) and Gülcü's (2009) curves it can be stated that the agreement between the data of present study and those of previous studies is quite good considering the t/b and SF values. As a consequence it can be concluded that, the zone between the upper and lower envelope curves given in Figure III-82 can be used to estimate critical hydraulic parameters of a particle of known size and shape; R_b or u^*, for a channel of slope S for the t/b values within the ranges used in this study(0.2-2.2).

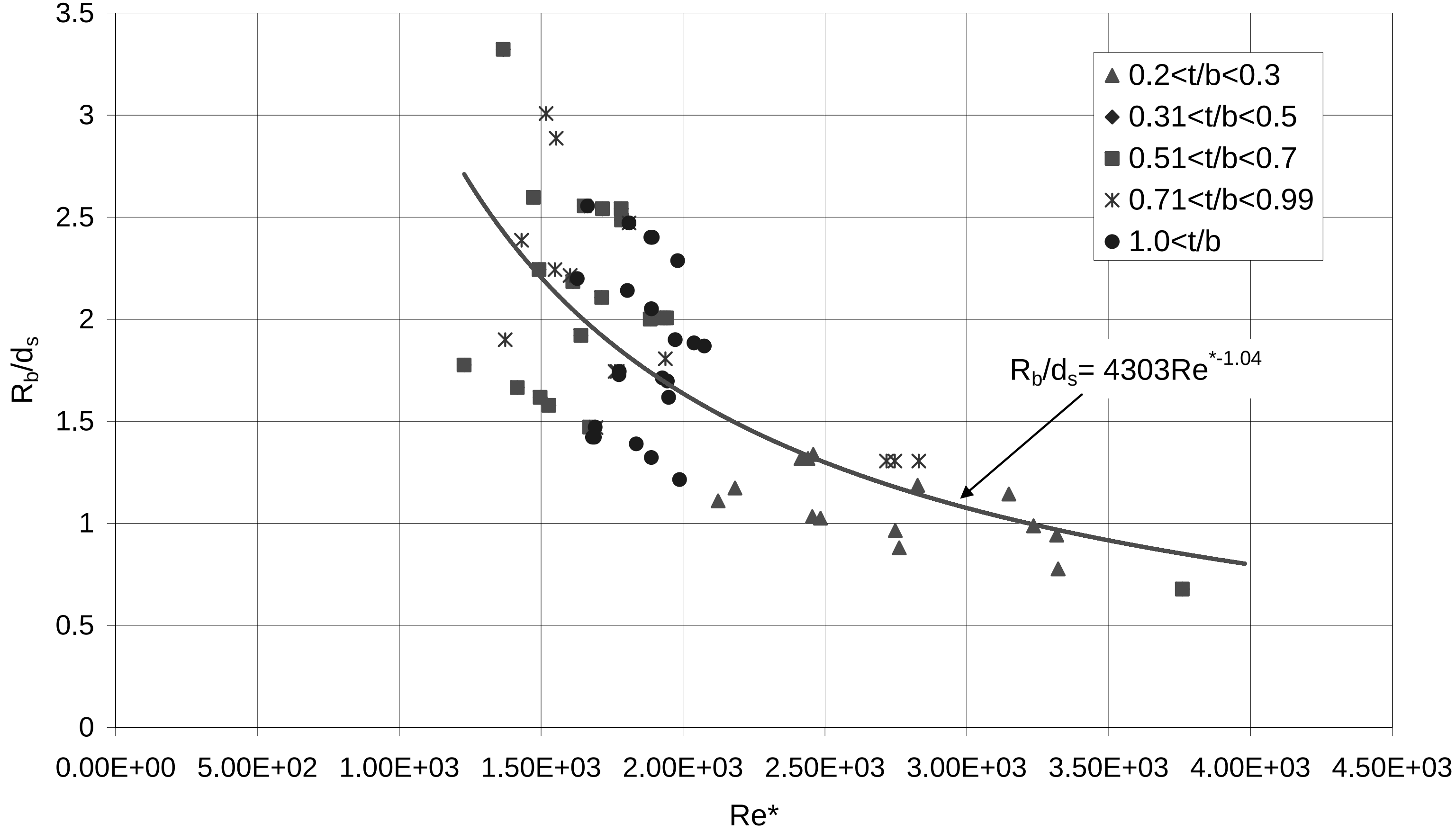


Figure III-78: Relative depth “R_b/d_s” vs. Grain Reynolds Number “Re*” for the 1st smooth bed

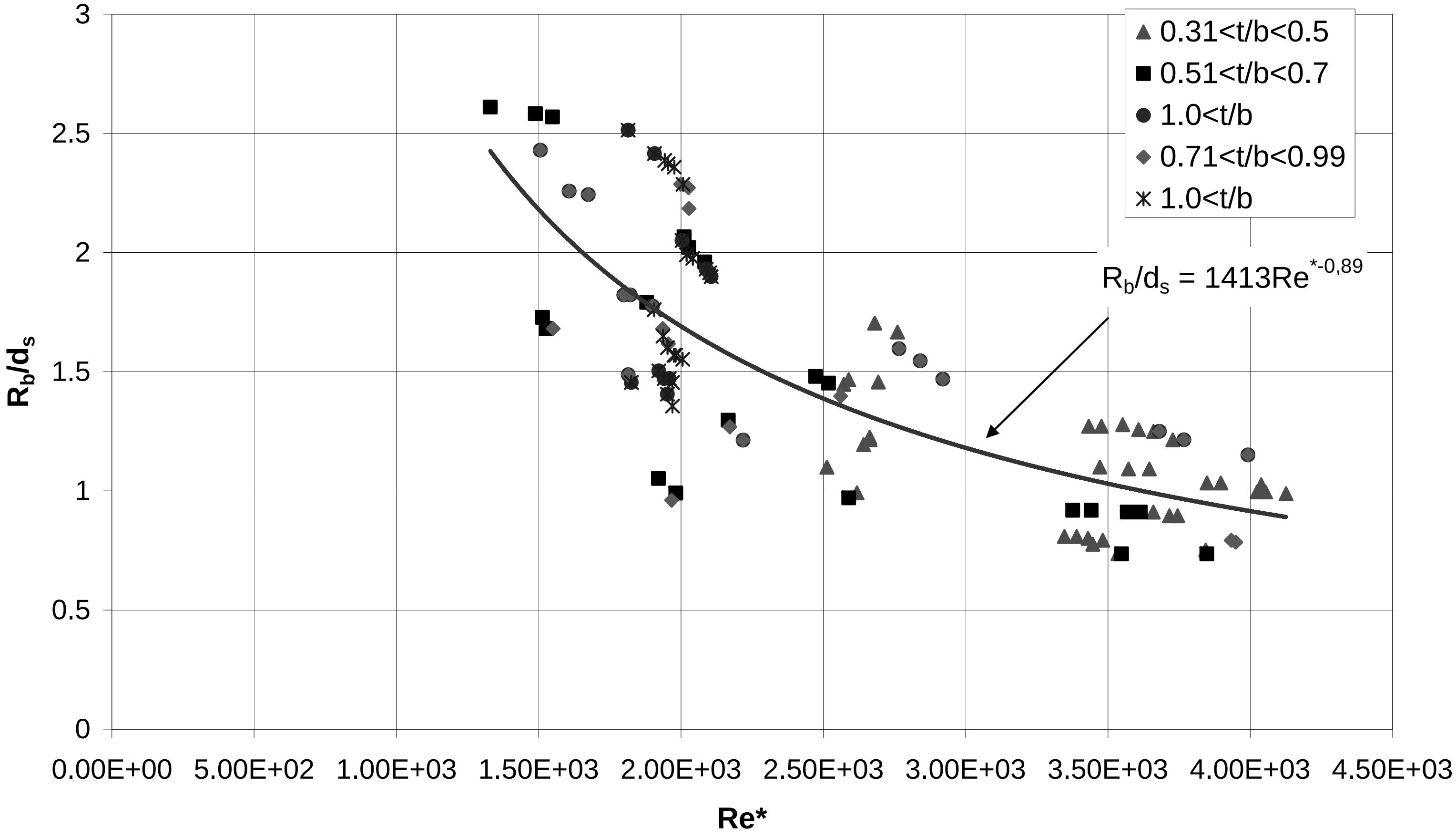


Figure III-79: Relative depth “R_b/d_s” vs. Grain Reynolds Number “Re*” for the 2nd smooth bed.

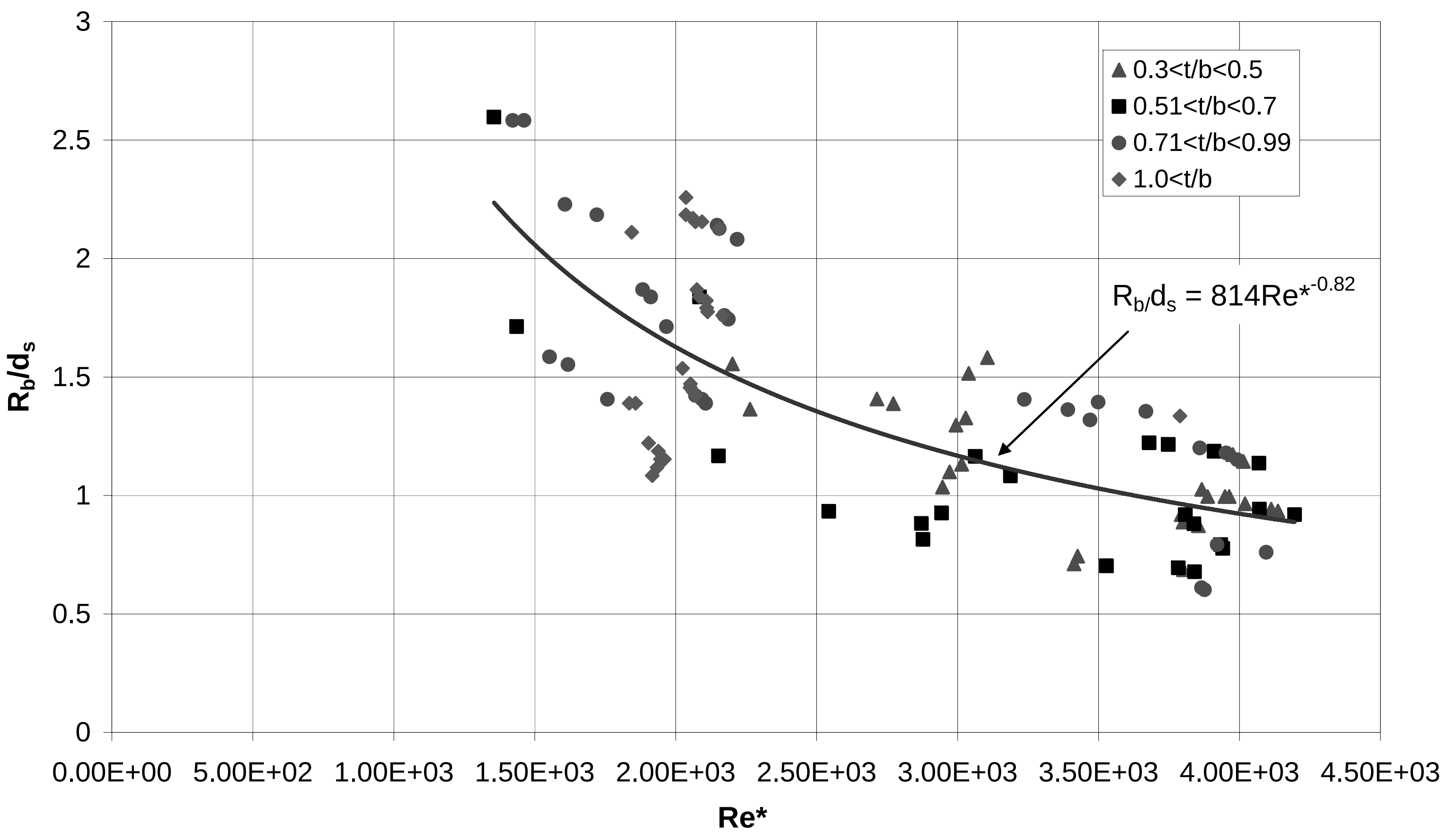


Figure III-80: Relative depth “R_b/d_s” vs. Grain Reynolds Number “Re*” for the 3rd smooth bed.

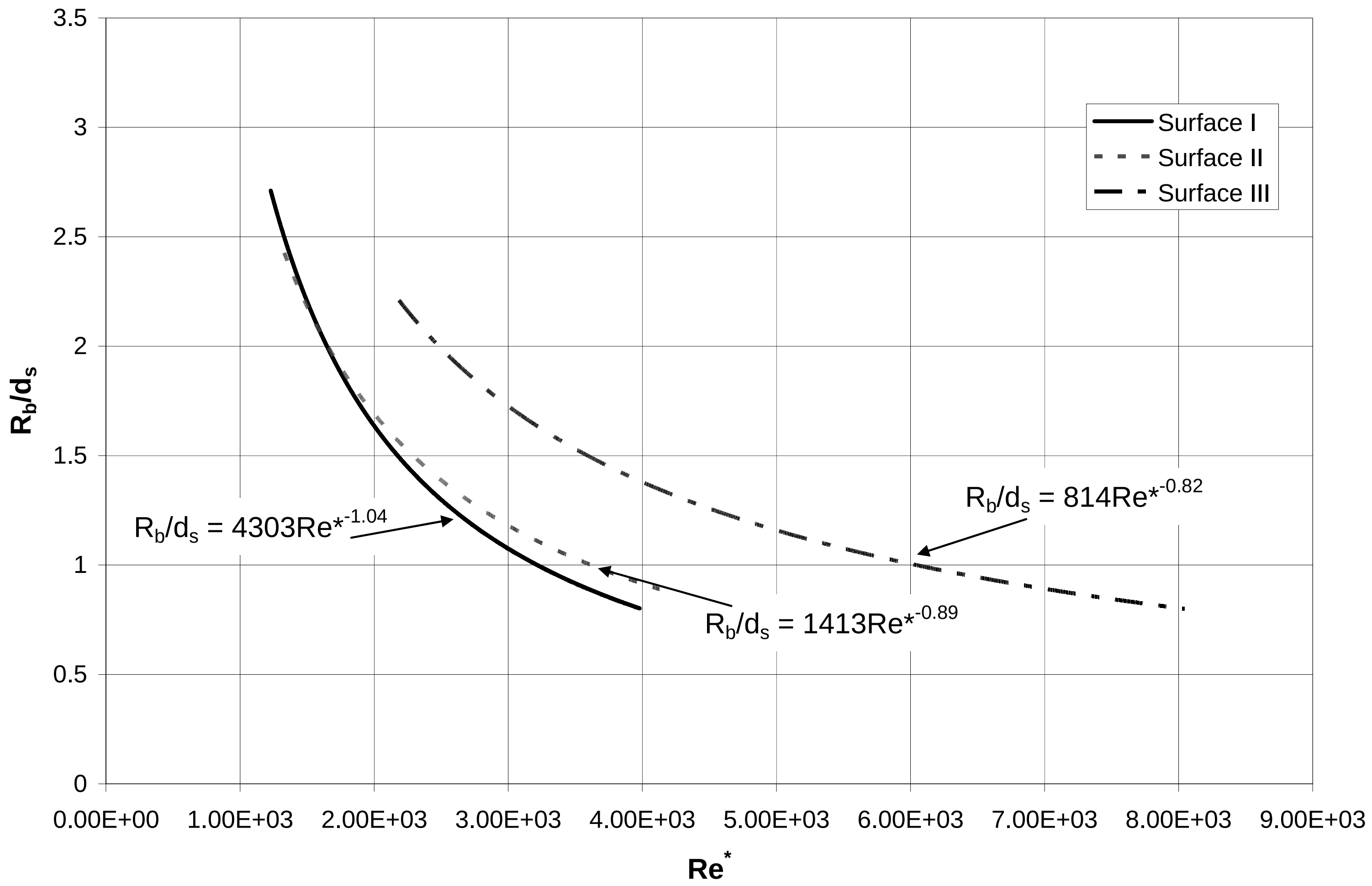


Figure III-81 Comparison of Relative depth “R_b/d_s” vs. Grain Reynolds Number “Re*” for all smooth beds.

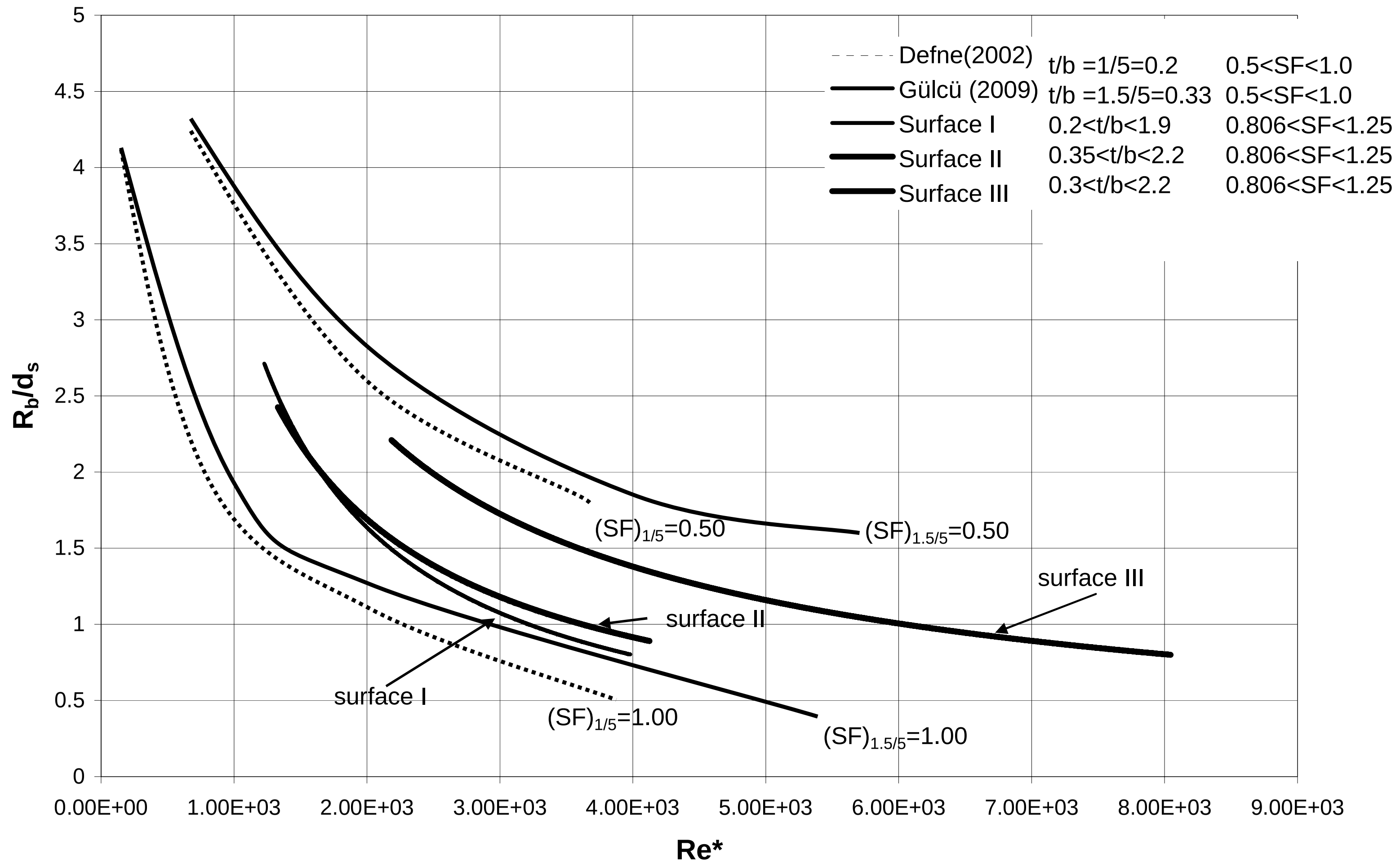


Figure III-82: Relative depth “R_b/d_s” vs. Grain Reynolds Number “Re*” for all smooth beds tested in this study and those of previous studies

CHAPTER IV

CONCLUSIONS AND THE FURTHER RECOMMENDATIONS

In this study, the effect of channel bottom roughness and corresponding obstacle height on incipient motion of coarse solitary particles was investigated. The hydraulic parameters are given in Appendix B in a tabular form.

From the analysis of the experimental results the following conclusions can be drawn:

The hydraulic parameters; flow depth $(R_b^*)_r$ or discharge q at which a particle of known shape and size has incipient motion on a rough channel bottom of given slope is function of k_s/d_s, S, ρ_s/ρ and SF.

For channels of known slope and roughness characteristics; k_s and n, the critical flow parameters $(R_b^*)_r$ or q at which the particle of known shape and size will have its initial motion can be estimated (Figure III-24 and III-40).

Since the particles were introduced into the flow slowly from upstream section and then their natural motion was observed over the rough channel bottom, during each experiment the same particle could have different orientations in the flow and has its initial motion under different flow conditions. Therefore, high correlation between the relevant parameters regarding the incipient particle motion could not be obtained from this study.

The location of the theoretical bed level changes for the same rough channel bed as a function of discharge and channel slope.

For channel of known slope and roughness characteristics; ks and n values, one can estimate the critical cross-sectional velocity at which particles of known shape and size will have incipient motion (Figure III-74).

The agreement between the results of present study and those of Novak and Nalluri (1984) is quite good (Figures III-75 through III-77).

The R_b/d_s versus Re^* values of the present study, having a wide range of t/d_s values, fit very well to those of Defne (2002) and Gülcü's (2009) results (Figure III-82)

Recommendations for future studies are as follows:

Experiments similar to those conducted in this study should be repeated using coarse solitary particles of different shapes and specific weights in rough channel beds having smaller roughness materials in size.

REFERENCES

Addison, H. (1954). “A Treatise on Applied Hydraulics”, New York, John Willey & Sons Inc.

Bathurst, J. C., Cao, H. H., and Graf, W. H. (1984). “Hydraulics and Sediment Transport in a Steep Flume: Data from the EPFL Study Report”, Inst. of Hydrol., Wallingford, Oxon, England.

Chow, V. T. (1959). “Open-Channel Hydraulics”, McGraw-Hill, New York.

Defne, Zafer. (2002). “Effect Of Particle Shape And Size On Incipient Motion Of Solid Particles”, Thesis Submitted In Partial Fulfillment Of The Requirements For The Degree Of Master Of Science In The Department Of Civil Engineering”, The Middle East Technical University , Ankara, Turkey.

Gogus, M., and Defne, Z. (2005). “Effect of Shape on Incipient Motion of Large Solitary Particles”, J. Hydr. Eng., ASCE, 131(1), 38-45.

Gogus, M., Ipekci, O. N., and Kokpinar, M. A. (2001). “Effect of Particle Shape on Fall Velocity of Angular Particles”, J. Hydr. Eng., ASCE, 127, 860-869.

Gülcü, B., (2009). “Incipient Motion Of Coarse Solitary Particles”, Thesis Submitted In Partial Fulfillment Of The Requirements For The Degree Of Master Of Science In The Department Of Civil Engineering”, The Middle East Technical University, Ankara, Turkey.

Graf, W. H., and Suszka, L. (1987). "Sediment Transport in Steep Channels", J. Hydrosci. Hydraul. Eng. Jpn. Soc. Civ. Eng., 5(1), 11-26.

Henderson, F. M. (1966). "Open Channel Flow", New York, Macmillan Publishing Co. Inc.

King, H. W. (1954). "Handbook of Hydraulics", New York, McGraw Hill Book Co. Inc.

Novak, P., and Nalluri C. (1975). "Sediment Transport In Smooth Fixed Bed Channels", J. Hydr. Res., 101, No. HY9, 1139-1154.

Novak, P., and Nalluri C. (1984). "Incipient Motion Of Sediment Particles Over Fixed Beds", J. Hydr. Res., 22(3), 181-197.

Raudkivi, A. J. (1967). "Loose Boundary Hydraulics", Pergamon Press Ltd.

Shvidchenko, Andrey B. and Pender, Gareth (2000). "Flume Study Of The Effect Of Relative Depth On The Incipient Motion Of Coarse Uniform Sediments", Water Resources Research, AGU, Vol. 36, No.2, 619-628.

Yalin, M. Selim (1977). "Mechanics Of Sediment Transport", Oxford; New York: Pergamon Press.

APPENDIX A

SIDE-WALL CORRECTION PROCEDURE

Side-wall correction procedure used in the present study is based on the procedure proposed by Shvidchenko and Pender (2000).

This method is based on the Manning roughness coefficient of the bed, n_b , and Manning roughness coefficient of the walls, n_w . The principal assumption is that cross-sectional water area can be divided into bed area and wall area having the same energy gradient, which is equal to the bed slope, and having mean flow velocity V of the total section. Applying the Manning formula $V = \frac{1}{n} \cdot R^{2/3} \cdot \sqrt{S}$ to each part of the water area one can obtain $n_{eq} = \frac{(P_b \cdot n_b^{3/2} + P_w \cdot n_w^{3/2})^{2/3}}{P^{2/3}}$. Then the calculation of the bed hydraulic radius is straightforward using the relationship $R_b = R\left(\frac{n_b}{n}\right)^{3/2}$. In these equations R is the hydraulic radius of the total area, n_{eq} is the equivalent Manning roughness coefficient, P is the wetted perimeter of the complete section, P_b and P_w are the wetted perimeters associated with the bed and walls, respectively. This method was shown to give comparable results with the commonly used Vanoni and Brooks method (Shvidchenko and Pender, 2000).

In the present study Manning roughness for the finished concrete bed and the glass walls were taken as 0.013 and 0.010, respectively.

APPENDIX B

EXPERIMENTAL RESULTS

Table B-1: Experimental data of R1

Q1	q $m^3/s/m$	S	vol (cm3)	d_s (cm)	γ_s (g/cm^3)	$ks_{cal.}$ (cm)	n_{eq}	n_b	h_r (m)	$(h^*)_r$ (m)	$(Vcc)_r$ (m/s)	$(u^*)_r$ (m/s)	$(Rb)^*_r$ (m)	Re_r^*	τ^* (N/m^2)
CUBE 2X2	0.0506	0.0101	8.00	2.48	1.96	2.17	0.027	0.032	0.1050	0.0833	0.5964	0.0899	0.0818	1.99E+03	3.46E-02
	0.0508	0.0071	8.00	2.48	1.96	1.87	0.025	0.030	0.1110	0.0923	0.5503	0.0786	0.0886	1.74E+03	2.65E-02
	0.0510	0.0116	8.00	2.48	1.96	2.08	0.027	0.032	0.1035	0.0827	0.6166	0.0953	0.0799	2.11E+03	3.89E-02
CUBE 4X4	0.0514	0.0235	64.00	4.96	1.96	2.48	0.031	0.036	0.0960	0.0712	0.7161	0.1268	0.0698	5.62E+03	3.44E-02
	0.0508	0.0149	64.00	4.96	1.96	2.19	0.029	0.035	0.1015	0.0796	0.6385	0.1061	0.0771	4.70E+03	2.41E-02
	0.0510	0.0278	64.00	4.96	1.96	2.51	0.038	0.044	0.1015	0.0764	0.6678	0.1427	0.0747	6.32E+03	4.36E-02
SPHERE 2.48	0.0514	0.0159	8.00	2.48	1.96	1.96	0.028	0.033	0.0985	0.0789	0.6742	0.1072	0.0738	2.38E+03	4.92E-02
	0.0514	0.0123	8.00	2.48	1.96	2.11	0.027	0.032	0.1020	0.0809	0.6351	0.0973	0.0781	2.16E+03	4.05E-02
	0.0514	0.0137	8.00	2.48	1.96	2.16	0.028	0.033	0.1015	0.0799	0.6429	0.1020	0.0773	2.26E+03	4.45E-02
SPHERE 3.72	0.0514	0.0101	27.00	3.72	1.96	2.29	0.026	0.031	0.1040	0.0811	0.6131	0.0893	0.0807	2.97E+03	2.28E-02
	0.0514	0.0101	27.00	3.72	1.96	2.02	0.028	0.033	0.1080	0.0878	0.5852	0.0915	0.0848	3.04E+03	2.39E-02
	0.0514	0.0156	27.00	3.72	1.96	2.22	0.028	0.033	0.0990	0.0768	0.6689	0.1066	0.0744	3.54E+03	3.24E-02
REC. 4X1X2	0.0510	0.0226	8.00	2.48	1.96	2.32	0.030	0.035	0.0950	0.0718	0.7186	0.1236	0.0690	2.74E+03	6.54E-02
	0.0512	0.0163	8.00	2.48	1.96	2.24	0.028	0.033	0.0983	0.0759	0.6743	0.1083	0.0735	2.40E+03	5.02E-02
	0.0510	0.0203	8.00	2.48	1.96	2.35	0.030	0.035	0.0960	0.0725	0.7032	0.1184	0.0704	2.62E+03	6.00E-02
REC. 5X3X4	0.0508	0.0141	64.00	4.96	1.96	2.55	0.028	0.033	0.1000	0.0745	0.6487	0.1024	0.0758	4.54E+03	2.24E-02
	0.0506	0.0125	64.00	4.96	1.96	2.11	0.028	0.033	0.1025	0.0814	0.6218	0.0981	0.0787	4.35E+03	2.06E-02
	0.0506	0.0218	64.00	4.96	1.96	2.38	0.030	0.035	0.0954	0.0716	0.7072	0.1220	0.0696	5.41E+03	3.18E-02
IRREG. 4X1X2	0.0510	0.0272	8.00	2.48	1.96	2.03	0.030	0.034	0.0910	0.0707	0.7731	0.1309	0.0641	2.90E+03	7.33E-02
	0.0510	0.0168	8.00	2.48	1.96	2.25	0.029	0.034	0.0980	0.0755	0.6757	0.1097	0.0731	2.43E+03	5.15E-02
	0.0506	0.0166	8.00	2.48	1.96	2.25	0.029	0.034	0.0980	0.0755	0.6700	0.1093	0.0732	2.42E+03	5.11E-02
IRREG. 7X3X4	0.0520	0.0118	64.00	4.96	1.96	2.11	0.027	0.032	0.1040	0.0829	0.6256	0.0966	0.0803	4.28E+03	1.99E-02
	0.0508	0.0091	64.00	4.96	1.96	1.97	0.026	0.031	0.1070	0.0873	0.5819	0.0865	0.0841	3.83E+03	1.60E-02
	0.0508	0.0221	64.00	4.96	1.96	2.39	0.030	0.035	0.0950	0.0711	0.7146	0.1223	0.0691	5.42E+03	3.20E-02

Table B-1: (Continued)

Q2	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.0622	0.0150	8.00	2.48	1.96	1.89	0.026	0.030	0.1052	0.0863	0.7474	0.1085	0.0800	2.40E+03	5.04E-02
	0.0624	0.0149	8.00	2.48	1.96	2.19	0.026	0.030	0.1050	0.0831	0.7513	0.1079	0.0798	2.39E+03	4.98E-02
	0.0626	0.0174	8.00	2.48	1.96	2.27	0.027	0.031	0.1040	0.0813	0.7700	0.1156	0.0784	2.56E+03	5.72E-02
CUBE 4X4	0.0626	0.0176	64.00	4.96	1.96	2.34	0.026	0.031	0.1025	0.0791	0.7852	0.1153	0.0768	5.11E+03	2.84E-02
	0.0624	0.0082	64.00	4.96	1.96	1.93	0.022	0.026	0.1097	0.0904	0.6900	0.0830	0.0858	3.68E+03	1.47E-02
	0.0624	0.0122	64.00	4.96	1.96	2.10	0.026	0.030	0.1097	0.0887	0.7037	0.1010	0.0852	4.48E+03	2.18E-02
SPHERE 2.48	0.0626	0.0105	8.00	2.48	1.96	1.64	0.023	0.028	0.1085	0.0921	0.7099	0.0929	0.0842	2.06E+03	3.70E-02
	0.0630	0.0101	8.00	2.48	1.96	2.02	0.023	0.028	0.1100	0.0898	0.7013	0.0921	0.0858	2.04E+03	3.63E-02
	0.0630	0.0151	8.00	2.48	1.96	2.20	0.025	0.029	0.1040	0.0820	0.7685	0.1081	0.0787	2.39E+03	5.00E-02
SPHERE 3.72	0.0628	0.0112	27.00	3.72	1.96	1.72	0.023	0.028	0.1070	0.0898	0.7271	0.0953	0.0825	3.17E+03	2.59E-02
	0.0628	0.0112	27.00	3.72	1.96	2.06	0.023	0.028	0.1072	0.0866	0.7255	0.0954	0.0827	3.17E+03	2.60E-02
	0.0630	0.0110	27.00	3.72	1.96	2.05	0.023	0.027	0.1070	0.0865	0.7287	0.0943	0.0825	3.13E+03	2.54E-02
REC. 4X1X2	0.0624	0.0187	8.00	2.48	1.96	2.52	0.026	0.030	0.1010	0.0758	0.8005	0.1172	0.0751	2.60E+03	5.88E-02
	0.0622	0.0083	8.00	2.48	1.96	1.93	0.025	0.030	0.1180	0.0987	0.6304	0.0877	0.0944	1.94E+03	3.29E-02
	0.0624	0.0182	8.00	2.48	1.96	2.29	0.027	0.032	0.1035	0.0806	0.7743	0.1176	0.0777	2.61E+03	5.92E-02
REC. 5X3X4	0.0624	0.0088	64.00	4.96	1.96	1.91	0.024	0.029	0.1145	0.0954	0.6574	0.0886	0.0907	3.92E+03	1.68E-02
	0.0626	0.0063	64.00	4.96	1.96	1.82	0.023	0.029	0.1231	0.1049	0.5968	0.0785	0.0998	3.48E+03	1.32E-02
	0.0626	0.0061	64.00	4.96	1.96	1.81	0.024	0.029	0.1250	0.1069	0.5855	0.0781	0.1018	3.46E+03	1.30E-02
IRREG. 4X1X2	0.0624	0.0152	8.00	2.48	1.96	2.14	0.025	0.030	0.1041	0.0827	0.7606	0.1086	0.0789	2.41E+03	5.05E-02
	0.0630	0.0151	8.00	2.48	1.96	2.20	0.025	0.030	0.1045	0.0825	0.7638	0.1084	0.0792	2.40E+03	5.03E-02
	0.0634	0.0197	8.00	2.48	1.96	2.33	0.025	0.029	0.0990	0.0757	0.8377	0.1185	0.0728	2.63E+03	6.01E-02
IRREG. 7X3X4	0.0624	0.0137	64.00	4.96	1.96	1.95	0.024	0.029	0.1045	0.0850	0.7524	0.1035	0.0795	4.59E+03	2.29E-02
	0.0628	0.0140	64.00	4.96	1.96	2.17	0.024	0.029	0.1040	0.0823	0.7626	0.1041	0.0789	4.61E+03	2.32E-02
	0.0628	0.0111	64.00	4.96	1.96	2.06	0.023	0.027	0.1065	0.0859	0.7309	0.0944	0.0820	4.18E+03	1.91E-02

Table B-1: (Continued)

Q3	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.0812	0.0072	8.00	2.48	1.96	1.73	0.022	0.027	0.1330	0.1157	0.7106	0.0871	0.1078	1.93E+03	3.25E-02
	0.0814	0.0089	8.00	2.48	1.96	1.96	0.022	0.027	0.1260	0.1064	0.7654	0.0939	0.1006	2.08E+03	3.77E-02
	0.0814	0.0101	8.00	2.48	1.96	2.02	0.022	0.026	0.1220	0.1018	0.7993	0.0976	0.0964	2.16E+03	4.08E-02
CUBE 4X4	0.0816	0.0102	64.00	4.96	1.96	2.14	0.022	0.027	0.1230	0.1016	0.7939	0.0987	0.0974	4.37E+03	2.08E-02
	0.0816	0.0093	64.00	4.96	1.96	1.98	0.022	0.027	0.1260	0.1062	0.7685	0.0959	0.1005	4.25E+03	1.97E-02
	0.0812	0.0158	64.00	4.96	1.96	2.22	0.028	0.035	0.1260	0.1038	0.7824	0.1242	0.0999	5.50E+03	3.30E-02
SPHERE 2.48	0.0828	0.0083	8.00	2.48	1.96	1.84	0.023	0.028	0.1320	0.1136	0.7349	0.0932	0.1066	2.07E+03	3.72E-02
	0.0824	0.0081	8.00	2.48	1.96	1.92	0.023	0.028	0.1330	0.1138	0.7241	0.0923	0.1077	2.04E+03	3.64E-02
	0.0824	0.0100	8.00	2.48	1.96	2.01	0.022	0.027	0.1235	0.1034	0.7970	0.0977	0.0978	2.17E+03	4.09E-02
SPHERE 3.72	0.0820	0.0093	27.00	3.72	1.96	1.88	0.022	0.027	0.1260	0.1072	0.7723	0.0959	0.1005	3.19E+03	2.62E-02
	0.0820	0.0093	27.00	3.72	1.96	1.98	0.022	0.027	0.1250	0.1052	0.7796	0.0954	0.0994	3.17E+03	2.59E-02
	0.0822	0.0118	27.00	3.72	1.96	2.09	0.023	0.028	0.1220	0.1011	0.8129	0.1057	0.0961	3.51E+03	3.19E-02
REC. 4X1X2	0.0820	0.0127	8.00	2.48	1.96	2.21	0.023	0.028	0.1200	0.0979	0.8300	0.1083	0.0940	2.40E+03	5.02E-02
	0.0814	0.0097	8.00	2.48	1.96	2.00	0.022	0.027	0.1250	0.1050	0.7752	0.0973	0.0995	2.16E+03	4.05E-02
	0.0816	0.0146	8.00	2.48	1.96	2.18	0.024	0.029	0.1180	0.0962	0.8486	0.1145	0.0918	2.54E+03	5.61E-02
REC. 5X3X4	0.0812	0.0083	64.00	4.96	1.96	2.05	0.022	0.027	0.1290	0.1085	0.7404	0.0920	0.1037	4.07E+03	1.81E-02
	0.0820	0.0115	64.00	4.96	1.96	2.07	0.023	0.028	0.1220	0.1013	0.8098	0.1040	0.0962	4.61E+03	2.31E-02
	0.0818	0.0106	64.00	4.96	1.96	2.04	0.022	0.027	0.1230	0.1026	0.7971	0.1005	0.0973	4.45E+03	2.16E-02
IRREG. 4X1X2	0.0828	0.0193	8.00	2.48	1.96	2.25	0.023	0.028	0.1100	0.0875	0.9541	0.1252	0.0828	2.77E+03	6.70E-02
	0.0824	0.0171	8.00	2.48	1.96	2.26	0.024	0.029	0.1140	0.0914	0.9018	0.1211	0.0872	2.68E+03	6.28E-02
	0.0822	0.0185	8.00	2.48	1.96	2.30	0.024	0.028	0.1115	0.0885	0.9288	0.1237	0.0845	2.74E+03	6.55E-02
IRREG. 7X3X4	0.0822	0.0112	64.00	4.96	1.96	2.14	0.023	0.028	0.1230	0.1016	0.8030	0.1034	0.0972	4.58E+03	2.29E-02
	0.0826	0.0091	64.00	4.96	1.96	1.97	0.021	0.026	0.1250	0.1053	0.7845	0.0940	0.0994	4.17E+03	1.89E-02
	0.0822	0.0070	64.00	4.96	1.96	1.87	0.023	0.029	0.1390	0.1203	0.6830	0.0887	0.1139	3.93E+03	1.68E-02

Table B-1: (Continued)

Q4	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.1014	0.0070	8.00	2.48	1.96	1.57	0.020	0.025	0.1460	0.1303	0.7960	0.0903	0.1188	2.00E+03	3.49E-02
	0.1010	0.0107	8.00	2.48	1.96	2.04	0.022	0.027	0.1370	0.1166	0.8664	0.1075	0.1099	2.38E+03	4.94E-02
	0.1004	0.0111	8.00	2.48	1.96	2.06	0.023	0.028	0.1370	0.1164	0.8624	0.1094	0.1100	2.42E+03	5.12E-02
CUBE 4X4	0.1010	0.0081	64.00	4.96	1.96	1.45	0.021	0.026	0.1420	0.1275	0.8225	0.0953	0.1149	4.22E+03	1.94E-02
	0.1014	0.0083	64.00	4.96	1.96	1.93	0.020	0.025	0.1400	0.1207	0.8403	0.0959	0.1128	4.25E+03	1.97E-02
	0.1012	0.0073	64.00	4.96	1.96	1.88	0.019	0.024	0.1400	0.1212	0.8350	0.0898	0.1127	3.98E+03	1.73E-02
SPHERE 2.48	0.0996	0.0089	8.00	2.48	1.96	2.19	0.021	0.026	0.1380	0.1161	0.8415	0.0987	0.1110	2.19E+03	4.17E-02
	0.0990	0.0105	8.00	2.48	1.96	2.03	0.022	0.027	0.1350	0.1147	0.8633	0.1053	0.1081	2.33E+03	4.74E-02
	0.0998	0.0097	8.00	2.48	1.96	2.00	0.022	0.027	0.1385	0.1185	0.8422	0.1030	0.1116	2.28E+03	4.54E-02
SPHERE 3.72	0.0996	0.0070	27.00	3.72	1.96	2.09	0.020	0.025	0.1445	0.1236	0.7911	0.0895	0.1175	2.97E+03	2.28E-02
	0.0996	0.0070	27.00	3.72	1.96	1.86	0.021	0.027	0.1480	0.1294	0.7697	0.0909	0.1211	3.02E+03	2.36E-02
	0.0996	0.0060	27.00	3.72	1.96	1.80	0.021	0.027	0.1540	0.1360	0.7326	0.0868	0.1270	2.88E+03	2.15E-02
REC. 4X1X2	0.1014	0.0091	8.00	2.48	1.96	2.16	0.022	0.027	0.1415	0.1199	0.8325	0.1009	0.1145	2.24E+03	4.36E-02
	0.1016	0.0111	8.00	2.48	1.96	2.06	0.022	0.027	0.1360	0.1154	0.8803	0.1088	0.1088	2.41E+03	5.07E-02
	0.1016	0.0125	8.00	2.48	1.96	2.11	0.022	0.028	0.1335	0.1124	0.9041	0.1140	0.1062	2.53E+03	5.56E-02
REC. 5X3X4	0.0996	0.0059	64.00	4.96	1.96	2.13	0.020	0.026	0.1510	0.1297	0.7486	0.0848	0.1239	3.76E+03	1.54E-02
	0.0992	0.0064	64.00	4.96	1.96	1.83	0.021	0.027	0.1515	0.1332	0.7446	0.0886	0.1246	3.93E+03	1.68E-02
	0.0996	0.0060	64.00	4.96	1.96	1.80	0.021	0.027	0.1535	0.1355	0.7353	0.0866	0.1265	3.84E+03	1.61E-02
IRREG. 4X1X2	0.1006	0.0124	8.00	2.48	1.96	2.24	0.022	0.028	0.1330	0.1106	0.8990	0.1135	0.1058	2.51E+03	5.51E-02
	0.1004	0.0111	8.00	2.48	1.96	2.06	0.023	0.028	0.1375	0.1169	0.8587	0.1096	0.1105	2.43E+03	5.14E-02
	0.1010	0.0144	8.00	2.48	1.96	2.18	0.023	0.028	0.1305	0.1087	0.9290	0.1205	0.1031	2.67E+03	6.22E-02
IRREG. 7X3X4	0.1000	0.0074	64.00	4.96	1.96	1.72	0.020	0.025	0.1420	0.1248	0.8119	0.0911	0.1149	4.04E+03	1.78E-02
	0.0998	0.0072	64.00	4.96	1.96	1.87	0.020	0.025	0.1425	0.1238	0.8063	0.0902	0.1154	3.99E+03	1.74E-02
	0.0996	0.0081	64.00	4.96	1.96	1.92	0.020	0.025	0.1400	0.1208	0.8245	0.0945	0.1130	4.19E+03	1.91E-02

Table B-2: Experimental Data 1st Smooth surface

Q1	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0506	0.0101	8.00	2.48	1.96	1.30	1.0882	0.0639	0.0465	0.0392	0.0413	1.42E+03	1.75E-02
	0.0508	0.0071	8.00	2.48	1.96	1.20	1.0160	0.0554	0.0500	0.0417	0.0441	1.23E+03	1.32E-02
	0.0510	0.0116	8.00	2.48	1.96	1.40	1.1333	0.0675	0.0450	0.0381	0.0401	1.50E+03	1.95E-02
CUBE 4X4	0.0514	0.0235	64.00	4.96	1.96	1.40	1.5576	0.0835	0.0330	0.0292	0.0303	3.70E+03	1.49E-02
	0.0508	0.0149	64.00	4.96	1.96	1.20	1.1814	0.0750	0.0430	0.0367	0.0385	3.32E+03	1.20E-02
	0.0510	0.0278	64.00	4.96	1.96	1.70	1.5839	0.0898	0.0430	0.0285	0.0296	3.98E+03	1.73E-02
SPHERE 2.48	0.0514	0.0159	8.00	2.48	1.96	1.40	1.2691	0.0754	0.0405	0.0349	0.0365	1.67E+03	2.43E-02
	0.0514	0.0123	8.00	2.48	1.96	1.10	1.0936	0.0711	0.0470	0.0396	0.0417	1.57E+03	2.16E-02
	0.0514	0.0137	8.00	2.48	1.96	1.10	1.1816	0.0723	0.0435	0.0371	0.0389	1.60E+03	2.24E-02
SPHERE 3.72	0.0514	0.0101	27.00	3.72	1.96	1.10	1.1054	0.0639	0.0465	0.0392	0.0413	2.12E+03	1.16E-02
	0.0514	0.0101	27.00	3.72	1.96	1.10	1.0384	0.0657	0.0495	0.0413	0.0437	2.18E+03	1.23E-02
	0.0514	0.0156	27.00	3.72	1.96	1.40	1.2094	0.0763	0.0425	0.0363	0.0381	2.54E+03	1.66E-02
REC. 4X1X2	0.0510	0.0226	8.00	2.48	1.96	1.90	1.4167	0.0852	0.0360	0.0315	0.0328	1.89E+03	3.11E-02
	0.0512	0.0163	8.00	2.48	1.96	1.70	1.2642	0.0763	0.0405	0.0349	0.0365	1.69E+03	2.49E-02
	0.0510	0.0203	8.00	2.48	1.96	1.80	1.3421	0.0828	0.0380	0.0330	0.0345	1.84E+03	2.94E-02
REC. 5X3X4	0.0508	0.0141	64.00	4.96	1.96	1.40	1.1678	0.0734	0.0435	0.0371	0.0389	3.25E+03	1.15E-02
	0.0506	0.0125	64.00	4.96	1.96	1.30	1.0766	0.0714	0.0470	0.0396	0.0417	3.17E+03	1.09E-02
	0.0506	0.0218	64.00	4.96	1.96	1.60	1.3676	0.0848	0.0370	0.0322	0.0336	3.76E+03	1.54E-02
IRREG. 4X1X2	0.0510	0.0272	8.00	2.48	1.96	1.40	1.5549	0.0897	0.0328	0.0290	0.0301	1.99E+03	3.45E-02
	0.0510	0.0168	8.00	2.48	1.96	1.20	1.3077	0.0762	0.0390	0.0337	0.0353	1.69E+03	2.48E-02
	0.0506	0.0166	8.00	2.48	1.96	1.10	1.2974	0.0759	0.0390	0.0337	0.0353	1.68E+03	2.46E-02
IRREG. 7X3X4	0.0520	0.0118	64.00	4.96	1.96	1.00	1.1556	0.0683	0.0450	0.0381	0.0401	3.03E+03	9.97E-03
	0.0508	0.0091	64.00	4.96	1.96	0.90	1.0263	0.0623	0.0495	0.0413	0.0437	2.76E+03	8.31E-03
	0.0508	0.0221	64.00	4.96	1.96	1.20	1.3730	0.0853	0.0370	0.0322	0.0336	3.78E+03	1.56E-02

Table B 2: (Continued)

Q2	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0622	0.0150	8.00	2.48	1.96	1.70	1.2694	0.0798	0.0490	0.0410	0.0433	1.77E+03	2.72E-02
	0.0624	0.0149	8.00	2.48	1.96	1.70	1.2735	0.0795	0.0490	0.0410	0.0433	1.76E+03	2.70E-02
	0.0626	0.0174	8.00	2.48	1.96	1.80	1.2275	0.0875	0.0510	0.0424	0.0448	1.94E+03	3.27E-02
CUBE 4X4	0.0626	0.0176	64.00	4.96	1.96	1.70	1.2275	0.0881	0.0510	0.0424	0.0448	3.90E+03	1.66E-02
	0.0624	0.0082	64.00	4.96	1.96	0.90	1.1345	0.0620	0.0550	0.0451	0.0479	2.75E+03	8.23E-03
	0.0624	0.0122	64.00	4.96	1.96	1.20	1.1664	0.0749	0.0550	0.0441	0.0468	3.32E+03	1.20E-02
SPHERE 2.48	0.0626	0.0105	8.00	2.48	1.96	1.00	1.0982	0.0712	0.0570	0.0464	0.0494	1.58E+03	2.17E-02
	0.0630	0.0101	8.00	2.48	1.96	1.00	1.0957	0.0701	0.0575	0.0467	0.0498	1.55E+03	2.11E-02
	0.0630	0.0151	8.00	2.48	1.96	1.20	1.2857	0.0801	0.0490	0.0410	0.0433	1.78E+03	2.75E-02
SPHERE 3.72	0.0628	0.0112	27.00	3.72	1.96	1.00	1.0922	0.0740	0.0575	0.0467	0.0498	2.46E+03	1.56E-02
	0.0632	0.0112	27.00	3.72	1.96	1.00	1.1186	0.0734	0.0565	0.0461	0.0490	2.44E+03	1.54E-02
	0.0630	0.0110	27.00	3.72	1.96	1.00	1.1150	0.0727	0.0565	0.0461	0.0490	2.42E+03	1.51E-02
REC. 4X1X2	0.0624	0.0187	8.00	2.48	1.96	1.20	1.3137	0.0878	0.0475	0.0399	0.0421	1.94E+03	3.30E-02
	0.0622	0.0083	8.00	2.48	1.96	0.80	1.1519	0.0620	0.0540	0.0444	0.0471	1.37E+03	1.64E-02
	0.0624	0.0182	8.00	2.48	1.96	1.10	1.3000	0.0870	0.0480	0.0403	0.0425	1.93E+03	3.24E-02
REC. 5X3X4	0.0624	0.0088	64.00	4.96	1.96	1.00	1.1556	0.0638	0.0540	0.0444	0.0471	2.83E+03	8.72E-03
	0.0626	0.0063	64.00	4.96	1.96	0.90	1.0610	0.0561	0.0590	0.0477	0.0509	2.48E+03	6.73E-03
	0.0626	0.0061	64.00	4.96	1.96	0.80	1.0521	0.0554	0.0595	0.0481	0.0513	2.46E+03	6.57E-03
IRREG. 4X1X2	0.0624	0.0152	8.00	2.48	1.96	1.20	1.2866	0.0801	0.0485	0.0406	0.0429	1.77E+03	2.74E-02
	0.0630	0.0151	8.00	2.48	1.96	1.20	1.2857	0.0801	0.0490	0.0410	0.0433	1.78E+03	2.75E-02
	0.0634	0.0197	8.00	2.48	1.96	1.30	1.4089	0.0880	0.0450	0.0381	0.0401	1.95E+03	3.31E-02
IRREG. 7X3X4	0.0624	0.0137	64.00	4.96	1.96	1.10	1.3000	0.0757	0.0480	0.0403	0.0425	3.35E+03	1.23E-02
	0.0628	0.0140	64.00	4.96	1.96	1.10	1.3221	0.0760	0.0475	0.0399	0.0421	3.37E+03	1.24E-02
	0.0628	0.0111	64.00	4.96	1.96	0.90	1.1115	0.0730	0.0565	0.0461	0.0490	3.24E+03	1.14E-02

Table B-2: (Continued)

Q3	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0812	0.0072	8.00	2.48	1.96	1.70	1.1518	0.0646	0.0705	0.0550	0.0592	1.43E+03	1.78E-02
	0.0814	0.0089	8.00	2.48	1.96	1.90	1.2427	0.0699	0.0655	0.0519	0.0557	1.55E+03	2.09E-02
	0.0814	0.0101	8.00	2.48	1.96	2.10	1.2719	0.0735	0.0640	0.0510	0.0546	1.63E+03	2.31E-02
CUBE 4X4	0.0816	0.0102	64.00	4.96	1.96	1.80	1.2651	0.0741	0.0645	0.0513	0.0549	3.29E+03	1.18E-02
	0.0816	0.0093	64.00	4.96	1.96	1.70	1.2651	0.0709	0.0645	0.0513	0.0549	3.14E+03	1.07E-02
	0.0812	0.0158	64.00	4.96	1.96	2.00	1.4122	0.0877	0.0645	0.0467	0.0498	3.89E+03	1.65E-02
SPHERE 2.48	0.0828	0.0083	8.00	2.48	1.96	1.30	1.2641	0.0674	0.0655	0.0519	0.0557	1.49E+03	1.94E-02
	0.0824	0.0081	8.00	2.48	1.96	1.20	1.2485	0.0666	0.0660	0.0522	0.0560	1.47E+03	1.90E-02
	0.0824	0.0100	8.00	2.48	1.96	1.40	1.2976	0.0727	0.0635	0.0506	0.0542	1.61E+03	2.26E-02
SPHERE 3.72	0.0820	0.0093	27.00	3.72	1.96	1.20	1.2913	0.0704	0.0635	0.0506	0.0542	2.34E+03	1.41E-02
	0.0822	0.0093	27.00	3.72	1.96	1.20	1.2945	0.0704	0.0635	0.0506	0.0542	2.34E+03	1.41E-02
	0.0822	0.0118	27.00	3.72	1.96	1.40	1.3152	0.0788	0.0625	0.0500	0.0535	2.62E+03	1.77E-02
REC. 4X1X2	0.0820	0.0127	8.00	2.48	1.96	1.20	1.3226	0.0814	0.0620	0.0497	0.0531	1.80E+03	2.84E-02
	0.0814	0.0097	8.00	2.48	1.96	1.00	1.2620	0.0723	0.0645	0.0513	0.0549	1.60E+03	2.24E-02
	0.0816	0.0146	8.00	2.48	1.96	1.30	1.3831	0.0852	0.0590	0.0477	0.0509	1.89E+03	3.11E-02
REC. 5X3X4	0.0812	0.0083	64.00	4.96	1.96	1.00	1.2397	0.0674	0.0655	0.0519	0.0557	2.99E+03	9.71E-03
	0.0820	0.0115	64.00	4.96	1.96	1.10	1.2813	0.0783	0.0640	0.0510	0.0546	3.47E+03	1.31E-02
	0.0818	0.0106	64.00	4.96	1.96	1.10	1.2882	0.0750	0.0635	0.0506	0.0542	3.32E+03	1.20E-02
IRREG. 4X1X2	0.0828	0.0193	8.00	2.48	1.96	1.30	1.5623	0.0937	0.0530	0.0437	0.0464	2.08E+03	3.75E-02
	0.0824	0.0171	8.00	2.48	1.96	1.20	1.5259	0.0890	0.0540	0.0444	0.0471	1.97E+03	3.39E-02
	0.0822	0.0185	8.00	2.48	1.96	1.30	1.5364	0.0920	0.0535	0.0441	0.0468	2.04E+03	3.62E-02
IRREG. 7X3X4	0.0822	0.0112	64.00	4.96	1.96	1.10	1.2361	0.0788	0.0665	0.0525	0.0564	3.49E+03	1.33E-02
	0.0826	0.0091	64.00	4.96	1.96	0.90	1.2328	0.0710	0.0670	0.0528	0.0567	3.15E+03	1.08E-02
	0.0822	0.0070	64.00	4.96	1.96	0.90	1.1743	0.0638	0.0700	0.0547	0.0589	2.83E+03	8.71E-03

Table B-2: (Continued)

Q4	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.1014	0.0070	8.00	2.48	1.96	1.30	1.3000	0.0665	0.0780	0.0595	0.0644	1.47E+03	1.89E-02
	0.1010	0.0107	8.00	2.48	1.96	1.40	1.3649	0.0805	0.0740	0.0571	0.0617	1.78E+03	2.77E-02
	0.1004	0.0111	8.00	2.48	1.96	1.50	1.3660	0.0817	0.0735	0.0568	0.0613	1.81E+03	2.85E-02
CUBE 4X4	0.1010	0.0081	64.00	4.96	1.96	1.90	1.3117	0.0710	0.0770	0.0589	0.0638	3.15E+03	1.08E-02
	0.1014	0.0083	64.00	4.96	1.96	1.90	1.3169	0.0721	0.0770	0.0589	0.0638	3.19E+03	1.11E-02
	0.1012	0.0073	64.00	4.96	1.96	1.80	1.3058	0.0678	0.0770	0.0592	0.0641	3.00E+03	9.83E-03
SPHERE 2.48	0.0996	0.0089	8.00	2.48	1.96	1.50	1.3020	0.0746	0.0765	0.0586	0.0634	1.65E+03	2.38E-02
	0.0990	0.0105	8.00	2.48	1.96	1.60	1.3026	0.0804	0.0760	0.0583	0.0631	1.78E+03	2.77E-02
	0.0998	0.0097	8.00	2.48	1.96	1.50	1.3132	0.0775	0.0760	0.0583	0.0631	1.72E+03	2.57E-02
SPHERE 3.72	0.0996	0.0070	27.00	3.72	1.96	1.30	1.2769	0.0663	0.0780	0.0595	0.0644	2.20E+03	1.25E-02
	0.0998	0.0070	27.00	3.72	1.96	1.30	1.2713	0.0665	0.0785	0.0597	0.0648	2.21E+03	1.26E-02
	0.0996	0.0060	27.00	3.72	1.96	1.30	1.2688	0.0620	0.0785	0.0597	0.0648	2.06E+03	1.10E-02
REC. 4X1X2	0.1014	0.0091	8.00	2.48	1.96	1.10	1.3255	0.0751	0.0765	0.0586	0.0634	1.66E+03	2.41E-02
	0.1016	0.0111	8.00	2.48	1.96	1.30	1.3823	0.0817	0.0735	0.0568	0.0613	1.81E+03	2.85E-02
	0.1016	0.0125	8.00	2.48	1.96	1.40	1.4310	0.0854	0.0710	0.0553	0.0596	1.89E+03	3.12E-02
REC. 5X3X4	0.0996	0.0059	64.00	4.96	1.96	2.30	1.2688	0.0613	0.0785	0.0597	0.0648	2.72E+03	8.05E-03
	0.0992	0.0064	64.00	4.96	1.96	2.40	1.2637	0.0639	0.0785	0.0597	0.0648	2.83E+03	8.73E-03
	0.0996	0.0060	64.00	4.96	1.96	2.30	1.2688	0.0620	0.0785	0.0597	0.0648	2.75E+03	8.22E-03
IRREG. 4X1X2	0.1006	0.0124	8.00	2.48	1.96	1.50	1.4169	0.0852	0.0710	0.0553	0.0596	1.89E+03	3.10E-02
	0.1004	0.0111	8.00	2.48	1.96	1.40	1.3660	0.0817	0.0735	0.0568	0.0613	1.81E+03	2.85E-02
	0.1010	0.0144	8.00	2.48	1.96	1.60	1.5075	0.0894	0.0670	0.0528	0.0567	1.98E+03	3.42E-02
IRREG. 7X3X4	0.1000	0.0074	64.00	4.96	1.96	1.20	1.2821	0.0682	0.0780	0.0595	0.0644	3.02E+03	9.96E-03
	0.0998	0.0072	64.00	4.96	1.96	1.20	1.2795	0.0674	0.0780	0.0595	0.0644	2.98E+03	9.71E-03
	0.0996	0.0081	64.00	4.96	1.96	1.30	1.4435	0.0678	0.0690	0.0541	0.0582	3.00E+03	9.84E-03

Table B-3: Experimental Data of Bed Materials of R1

	Q (m^3/s)	**q** $m^3/s/m$	**S**	**vol** (cm3)	d_s (cm)	γ_s (g/cm^3)	$ks_{cal.}$ (cm)	n_{eq}	n_b	h_r (m)	$(h^*)_r$ (m)	$(Vcc)_r$ (m/s)	$(u^*)_r$ (m/s)	$(Rb)^*_r$ (m)	Re_r^*	τ^* (N/m^2)
ORIGINAL BED PARTICLES ON R1	0.0252	0.0504	0.0256	3.86	1.95	1.60	2.72	0.029	0.033	0.0900	0.063	0.7717	0.1262	0.0634	2.19E+03	8.68E-02
	0.0252	0.0504	0.0195	3.86	1.95	1.60	2.33	0.031	0.036	0.0980	0.075	0.6745	0.1180	0.0726	2.05E+03	7.59E-02
	0.0253	0.0506	0.0338	3.86	1.95	1.60	2.62	0.028	0.031	0.0845	0.058	0.8684	0.1369	0.0565	2.38E+03	1.02E-01
	0.0348	0.0696	0.0222	4.23	2.01	1.60	2.57	0.025	0.030	0.1020	0.076	0.8916	0.1278	0.0751	2.29E+03	8.65E-02
	0.0347	0.0694	0.0281	4.23	2.01	1.60	2.52	0.026	0.030	0.0975	0.072	0.9599	0.1386	0.0696	2.48E+03	1.02E-01
	0.0347	0.0694	0.0202	4.23	2.01	1.60	2.34	0.027	0.032	0.1072	0.084	0.8286	0.1264	0.0807	2.26E+03	8.46E-02
	0.0425	0.0850	0.0141	8.93	2.57	1.60	2.53	0.027	0.033	0.1290	0.104	0.7921	0.1193	0.1029	2.74E+03	5.88E-02
	0.0426	0.0852	0.0140	8.93	2.57	1.60	2.16	0.027	0.034	0.1310	0.109	0.7791	0.1199	0.1049	2.76E+03	5.93E-02
	0.0425	0.0850	0.0105	8.93	2.57	1.60	2.03	0.025	0.031	0.1340	0.114	0.7477	0.1054	0.1084	2.42E+03	4.59E-02
	0.051	0.1020	0.0120	3.13	1.81	1.60	2.71	0.024	0.030	0.1410	0.114	0.8497	0.1160	0.1140	1.88E+03	7.87E-02
	0.051	0.1020	0.0164	3.13	1.81	1.60	2.24	0.023	0.029	0.1280	0.106	0.9660	0.1270	0.1003	2.06E+03	9.43E-02
	0.051	0.1020	0.0179	3.13	1.81	1.60	2.28	0.023	0.028	0.1250	0.102	0.9984	0.1305	0.0971	2.11E+03	9.96E-02

Table B-3: (Continued)

	Q (m^3/s)	q m^3/s/m	S	vol (cm3)	d_s (cm)	γ_s (g/cm^3)	t (cm)	$(Vcc)_s$ (m/s)	$(u^*)_s$ (m/s)	h_s (m)	R_s (m)	$(Rb)_s$ (m)	Re_s*	τ* (N/m^2)
ORIGINAL BED PARTICLES ON 1ST SMOOTH SURFACE	0.0252	0.0504	0.0256	3.86	1.95	1.60	0.80	1.5045	0.0878	0.0335	0.0295	0.0307	1.53E+03	4.21E-02
	0.0252	0.0504	0.0195	3.86	1.95	1.60	0.60	1.3091	0.0818	0.0385	0.0334	0.0349	1.42E+03	3.65E-02
	0.0253	0.0506	0.0338	3.86	1.95	1.60	0.90	1.6323	0.0974	0.0310	0.0276	0.0286	1.69E+03	5.18E-02
	0.0348	0.0696	0.0222	4.23	2.01	1.60	0.80	1.6186	0.0916	0.0430	0.0367	0.0385	1.64E+03	4.44E-02
	0.0348	0.0696	0.0281	4.23	2.01	1.60	0.70	1.5422	0.1052	0.0450	0.0367	0.0401	1.88E+03	5.86E-02
	0.0348	0.0696	0.0202	4.23	2.01	1.60	0.50	1.4925	0.0904	0.0465	0.0367	0.0413	1.62E+03	4.33E-02
	0.0425	0.0850	0.0141	8.93	2.57	1.60	1.10	1.4167	0.0845	0.0600	0.0484	0.0516	1.94E+03	2.95E-02
	0.0426	0.0852	0.0140	8.93	2.57	1.60	1.10	1.4200	0.0841	0.0600	0.0484	0.0516	1.93E+03	2.92E-02
	0.0425	0.0850	0.0105	8.93	2.57	1.60	1.00	1.3386	0.0746	6.3500	0.0506	0.0542	1.71E+03	2.29E-02
	0.051	0.1020	0.0120	3.13	1.81	1.60	0.50	1.4167	0.0844	0.0720	0.0559	0.0603	1.37E+03	4.16E-02
	0.051	0.1020	0.0164	3.13	1.81	1.60	0.60	1.5938	0.0937	0.0640	0.0510	0.0546	1.52E+03	5.13E-02
	0.051	0.1020	0.0179	3.13	1.81	1.60	0.60	1.6721	0.0959	0.0610	0.0490	0.0524	1.55E+03	5.38E-02

Table B-4: Experimental data of R2

Q1	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.0506	0.0120	8.00	2.48	1.96	3.08	0.027	0.031	0.1032	0.0724	0.7044	0.0953	0.0773	2.11E+03	3.88E-02
	0.0508	0.0110	8.00	2.48	1.96	3.29	0.028	0.033	0.1097	0.0768	0.6645	0.0940	0.0815	2.08E+03	3.78E-02
	0.0510	0.0116	8.00	2.48	1.96	3.28	0.027	0.031	0.1062	0.0734	0.6948	0.0943	0.0782	2.09E+03	3.80E-02
CUBE 4X4	0.0514	0.0145	64.00	4.96	1.96	2.95	0.027	0.031	0.0975	0.0680	0.7500	0.1020	0.0732	4.52E+03	2.23E-02
	0.0508	0.0178	64.00	4.96	1.96	3.15	0.026	0.030	0.0925	0.0610	0.8367	0.1075	0.0663	4.76E+03	2.47E-02
	0.0510	0.0160	64.00	4.96	1.96	3.18	0.024	0.028	0.0925	0.0607	0.8409	0.1016	0.0658	4.50E+03	2.21E-02
SPHERE 2.48	0.0514	0.0192	8.00	2.48	1.96	3.07	0.026	0.030	0.0913	0.0606	0.8449	0.1115	0.0661	2.47E+03	5.32E-02
	0.0514	0.0214	8.00	2.48	1.96	3.10	0.027	0.030	0.0893	0.0583	0.8784	0.1159	0.0639	2.57E+03	5.75E-02
	0.0514	0.0185	8.00	2.48	1.96	3.14	0.025	0.029	0.0908	0.0594	0.8623	0.1085	0.0648	2.40E+03	5.04E-02
SPHERE 3.72	0.0514	0.0171	27.00	3.72	1.96	3.02	0.026	0.030	0.0928	0.0626	0.8179	0.1069	0.0680	3.55E+03	3.26E-02
	0.0514	0.0171	27.00	3.72	1.96	3.16	0.025	0.028	0.0918	0.0602	0.8545	0.1049	0.0654	3.48E+03	3.14E-02
	0.0514	0.0142	27.00	3.72	1.96	3.22	0.024	0.028	0.0958	0.0636	0.8081	0.0979	0.0685	3.25E+03	2.73E-02
REC. 4X1X2	0.0510	0.0223	8.00	2.48	1.96	3.08	0.025	0.028	0.0862	0.0554	0.9314	0.1156	0.0610	2.56E+03	5.72E-02
	0.0512	0.0240	8.00	2.48	1.96	3.07	0.025	0.028	0.0837	0.0530	0.9735	0.1174	0.0587	2.60E+03	5.90E-02
	0.0510	0.0218	8.00	2.48	1.96	3.10	0.026	0.030	0.0887	0.0577	0.8937	0.1164	0.0634	2.58E+03	5.80E-02
REC. 5X3X4	0.0508	0.0211	64.00	4.96	1.96	2.60	0.032	0.038	0.0940	0.0680	0.7588	0.1236	0.0739	5.48E+03	3.27E-02
	0.0506	0.0205	64.00	4.96	1.96	3.11	0.029	0.034	0.0955	0.0644	0.8016	0.1188	0.0701	5.27E+03	3.02E-02
	0.0506	0.0179	64.00	4.96	1.96	3.15	0.028	0.032	0.0960	0.0645	0.8003	0.1108	0.0699	4.91E+03	2.63E-02
IRREG. 4X1X2	0.0510	0.0227	8.00	2.48	1.96	3.09	0.025	0.028	0.0856	0.0547	0.9360	0.1159	0.0603	2.57E+03	5.75E-02
	0.0510	0.0205	8.00	2.48	1.96	3.11	0.027	0.031	0.0906	0.0595	0.8609	0.1145	0.0651	2.54E+03	5.61E-02
	0.0506	0.0218	8.00	2.48	1.96	3.10	0.026	0.030	0.0886	0.0576	0.8883	0.1163	0.0633	2.58E+03	5.79E-02
IRREG. 7X3X4	0.0520	0.0149	64.00	4.96	1.96	2.92	0.027	0.031	0.0963	0.0671	0.7630	0.1027	0.0723	4.55E+03	2.26E-02
	0.0508	0.0160	64.00	4.96	1.96	3.18	0.026	0.030	0.0953	0.0635	0.8069	0.1038	0.0687	4.60E+03	2.31E-02
	0.0508	0.0154	64.00	4.96	1.96	3.20	0.025	0.029	0.0958	0.0638	0.8021	0.1020	0.0690	4.52E+03	2.23E-02

Table B-4: (Continued)

Q2	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.0622	0.0150	8.00	2.48	1.96	3.00	0.017	0.019	0.0945	0.0645	0.9922	0.0941	0.0601	2.08E+03	3.79E-02
	0.0624	0.0170	8.00	2.48	1.96	3.17	0.016	0.017	0.0905	0.0588	1.0879	0.0954	0.0545	2.11E+03	3.89E-02
	0.0626	0.0152	8.00	2.48	1.96	3.20	0.016	0.018	0.0940	0.0620	1.0321	0.0927	0.0575	2.05E+03	3.68E-02
CUBE 4X4	0.0626	0.0154	64.00	4.96	1.96	3.30	0.016	0.017	0.0940	0.0610	1.0492	0.0922	0.0564	4.09E+03	1.82E-02
	0.0624	0.0163	64.00	4.96	1.96	3.18	0.016	0.018	0.0930	0.0612	1.0458	0.0952	0.0568	4.22E+03	1.94E-02
	0.0624	0.0161	64.00	4.96	1.96	3.18	0.016	0.018	0.0930	0.0612	1.0462	0.0948	0.0568	4.20E+03	1.92E-02
SPHERE 2.48	0.0626	0.0187	8.00	2.48	1.96	3.40	0.015	0.016	0.0890	0.0550	1.1636	0.0962	0.0506	2.13E+03	3.96E-02
	0.0630	0.0165	8.00	2.48	1.96	3.18	0.016	0.018	0.0925	0.0607	1.0536	0.0956	0.0564	2.12E+03	3.91E-02
	0.0630	0.0198	8.00	2.48	1.96	3.12	0.016	0.018	0.0885	0.0573	1.1176	0.1017	0.0533	2.25E+03	4.43E-02
SPHERE 3.72	0.0628	0.0145	27.00	3.72	1.96	2.97	0.018	0.021	0.0980	0.0683	0.9370	0.0954	0.0640	3.17E+03	2.60E-02
	0.0628	0.0145	27.00	3.72	1.96	3.21	0.015	0.017	0.0930	0.0609	1.0516	0.0893	0.0561	2.97E+03	2.27E-02
	0.0630	0.0142	27.00	3.72	1.96	3.22	0.016	0.018	0.0950	0.0628	1.0190	0.0901	0.0581	2.99E+03	2.31E-02
REC. 4X1X2	0.0624	0.0199	8.00	2.48	1.96	3.40	0.015	0.016	0.0885	0.0545	1.1743	0.0991	0.0503	2.20E+03	4.20E-02
	0.0622	0.0209	8.00	2.48	1.96	3.11	0.016	0.018	0.0875	0.0564	1.1345	0.1037	0.0526	2.30E+03	4.60E-02
	0.0624	0.0217	8.00	2.48	1.96	3.10	0.017	0.018	0.0875	0.0565	1.1323	0.1060	0.0528	2.35E+03	4.81E-02
REC. 5X3X4	0.0624	0.0135	64.00	4.96	1.96	3.15	0.017	0.019	0.0975	0.0660	0.9697	0.0900	0.0613	3.99E+03	1.73E-02
	0.0626	0.0130	64.00	4.96	1.96	3.25	0.016	0.018	0.0980	0.0655	0.9766	0.0878	0.0606	3.89E+03	1.65E-02
	0.0626	0.0146	64.00	4.96	1.96	3.21	0.016	0.018	0.0950	0.0629	1.0177	0.0914	0.0582	4.05E+03	1.79E-02
IRREG. 4X1X2	0.0624	0.0190	8.00	2.48	1.96	3.30	0.015	0.017	0.0890	0.0560	1.1429	0.0983	0.0518	2.18E+03	4.14E-02
	0.0630	0.0173	8.00	2.48	1.96	3.16	0.016	0.017	0.0905	0.0589	1.0871	0.0961	0.0546	2.13E+03	3.95E-02
	0.0634	0.0208	8.00	2.48	1.96	3.11	0.016	0.018	0.0875	0.0564	1.1346	0.1035	0.0525	2.29E+03	4.59E-02
IRREG. 7X3X4	0.0624	0.0204	64.00	4.96	1.96	3.40	0.015	0.016	0.0880	0.0540	1.1852	0.0999	0.0498	4.43E+03	2.13E-02
	0.0628	0.0208	64.00	4.96	1.96	3.11	0.016	0.018	0.0875	0.0564	1.1346	0.1035	0.0525	4.59E+03	2.29E-02
	0.0628	0.0150	64.00	4.96	1.96	3.20	0.016	0.018	0.0945	0.0625	1.0246	0.0923	0.0579	4.09E+03	1.82E-02

Table B-4: (Continued)

Q3	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.0812	0.0105	8.00	2.48	1.96	3.48	0.016	0.019	0.1200	0.0852	0.9977	0.0894	0.0779	1.98E+03	3.42E-02
	0.0814	0.0096	8.00	2.48	1.96	3.34	0.016	0.019	0.1210	0.0876	0.9701	0.0867	0.0801	1.92E+03	3.22E-02
	0.0814	0.0078	8.00	2.48	1.96	3.40	0.017	0.019	0.1290	0.0950	0.8948	0.0815	0.0867	1.81E+03	2.84E-02
CUBE 4X4	0.0816	0.0115	64.00	4.96	1.96	3.45	0.017	0.019	0.1180	0.0835	1.0180	0.0928	0.0766	4.11E+03	1.84E-02
	0.0816	0.0122	64.00	4.96	1.96	3.26	0.018	0.020	0.1175	0.0849	1.0017	0.0969	0.0784	4.30E+03	2.01E-02
	0.0812	0.0127	64.00	4.96	1.96	3.25	0.018	0.021	0.1175	0.0850	1.0003	0.0992	0.0788	4.39E+03	2.10E-02
SPHERE 2.48	0.0828	0.0164	8.00	2.48	1.96	3.12	0.018	0.020	0.1085	0.0773	1.0996	0.1074	0.0718	2.38E+03	4.94E-02
	0.0824	0.0170	8.00	2.48	1.96	3.17	0.017	0.020	0.1075	0.0758	1.1209	0.1084	0.0704	2.40E+03	5.03E-02
	0.0824	0.0185	8.00	2.48	1.96	3.14	0.018	0.020	0.1060	0.0746	1.1398	0.1123	0.0694	2.49E+03	5.40E-02
SPHERE 3.72	0.0820	0.0113	27.00	3.72	1.96	3.45	0.016	0.019	0.1180	0.0835	1.0180	0.0923	0.0765	3.07E+03	2.43E-02
	0.0820	0.0113	27.00	3.72	1.96	3.29	0.015	0.017	0.1110	0.0781	1.0879	0.0888	0.0709	2.95E+03	2.25E-02
	0.0822	0.0123	27.00	3.72	1.96	3.26	0.016	0.018	0.1120	0.0794	1.0707	0.0938	0.0727	3.12E+03	2.51E-02
REC. 4X1X2	0.0820	0.0164	8.00	2.48	1.96	3.12	0.018	0.020	0.1085	0.0773	1.0996	0.1074	0.0718	2.38E+03	4.94E-02
	0.0814	0.0171	8.00	2.48	1.96	3.16	0.018	0.020	0.1075	0.0759	1.1206	0.1089	0.0705	2.41E+03	5.07E-02
	0.0816	0.0176	8.00	2.48	1.96	3.16	0.018	0.020	0.1070	0.0754	1.1268	0.1102	0.0701	2.44E+03	5.20E-02
REC. 5X3X4	0.0812	0.0154	64.00	4.96	1.96	3.28	0.017	0.019	0.1095	0.0767	1.1082	0.1034	0.0708	4.58E+03	2.29E-02
	0.0820	0.0170	64.00	4.96	1.96	3.17	0.017	0.020	0.1075	0.0758	1.1209	0.1084	0.0704	4.80E+03	2.51E-02
	0.0818	0.0150	64.00	4.96	1.96	3.20	0.017	0.019	0.1095	0.0775	1.0973	0.1026	0.0716	4.55E+03	2.25E-02
IRREG. 4X1X2	0.0828	0.0189	8.00	2.48	1.96	3.05	0.018	0.020	0.1050	0.0745	1.1409	0.1135	0.0695	2.52E+03	5.51E-02
	0.0824	0.0195	8.00	2.48	1.96	3.13	0.018	0.020	0.1040	0.0727	1.1688	0.1139	0.0677	2.52E+03	5.55E-02
	0.0822	0.0193	8.00	2.48	1.96	3.13	0.018	0.020	0.1045	0.0732	1.1614	0.1135	0.0681	2.52E+03	5.52E-02
IRREG. 7X3X4	0.0822	0.0166	64.00	4.96	1.96	3.12	0.018	0.020	0.1080	0.0768	1.1068	0.1079	0.0714	4.78E+03	2.49E-02
	0.0826	0.0173	64.00	4.96	1.96	3.16	0.018	0.020	0.1075	0.0759	1.1203	0.1093	0.0705	4.84E+03	2.56E-02
	0.0822	0.0180	64.00	4.96	1.96	3.15	0.018	0.020	0.1065	0.0750	1.1334	0.1111	0.0698	4.92E+03	2.64E-02

Table B-4: (Continued)

Q4	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.1014	0.0057	8.00	2.48	1.96	3.45	0.017	0.020	0.1550	0.1205	0.8382	0.0778	0.1090	1.72E+03	2.59E-02
	0.1010	0.0072	8.00	2.48	1.96	3.43	0.017	0.020	0.1460	0.1117	0.9040	0.0846	0.1016	1.87E+03	3.06E-02
	0.1004	0.0078	8.00	2.48	1.96	3.40	0.017	0.020	0.1430	0.1090	0.9267	0.0872	0.0993	1.93E+03	3.25E-02
CUBE 4X4	0.1010	0.0097	64.00	4.96	1.96	3.23	0.017	0.020	0.1325	0.1002	1.0080	0.0933	0.0915	4.14E+03	1.86E-02
	0.1014	0.0108	64.00	4.96	1.96	3.30	0.017	0.020	0.1300	0.0970	1.0413	0.0971	0.0888	4.30E+03	2.02E-02
	0.1012	0.0100	64.00	4.96	1.96	3.33	0.016	0.019	0.1300	0.0967	1.0441	0.0927	0.0879	4.11E+03	1.84E-02
SPHERE 2.48	0.0996	0.0146	8.00	2.48	1.96	3.26	0.017	0.019	0.1200	0.0874	1.1556	0.1073	0.0803	2.38E+03	4.93E-02
	0.0990	0.0151	8.00	2.48	1.96	3.20	0.017	0.020	0.1195	0.0875	1.1545	0.1094	0.0806	2.42E+03	5.12E-02
	0.0998	0.0158	8.00	2.48	1.96	3.19	0.017	0.020	0.1190	0.0871	1.1595	0.1115	0.0804	2.47E+03	5.32E-02
SPHERE 3.72	0.0996	0.0105	27.00	3.72	1.96	3.40	0.017	0.020	0.1320	0.0980	1.0306	0.0958	0.0896	3.19E+03	2.62E-02
	0.0996	0.0105	27.00	3.72	1.96	3.31	0.019	0.023	0.1390	0.1059	0.9538	0.1002	0.0980	3.33E+03	2.87E-02
	0.0996	0.0113	27.00	3.72	1.96	3.29	0.017	0.020	0.1290	0.0961	1.0506	0.0990	0.0881	3.29E+03	2.80E-02
REC. 4X1X2	0.1014	0.0110	8.00	2.48	1.96	3.41	0.017	0.019	0.1295	0.0954	1.0587	0.0968	0.0871	2.14E+03	4.01E-02
	0.1016	0.0135	8.00	2.48	1.96	3.24	0.017	0.020	0.1240	0.0916	1.1020	0.1057	0.0844	2.34E+03	4.78E-02
	0.1016	0.0126	8.00	2.48	1.96	3.26	0.017	0.020	0.1265	0.0939	1.0751	0.1034	0.0864	2.29E+03	4.57E-02
REC. 5X3X4	0.0996	0.0113	64.00	4.96	1.96	3.42	0.017	0.020	0.1290	0.0948	1.0654	0.0982	0.0866	4.35E+03	2.06E-02
	0.0992	0.0145	64.00	4.96	1.96	3.21	0.017	0.020	0.1205	0.0884	1.1430	0.1075	0.0813	4.76E+03	2.47E-02
	0.0996	0.0122	64.00	4.96	1.96	3.26	0.017	0.020	0.1270	0.0944	1.0704	0.1020	0.0867	4.52E+03	2.22E-02
IRREG. 4X1X2	0.1006	0.0147	8.00	2.48	1.96	3.28	0.017	0.019	0.1200	0.0872	1.1583	0.1077	0.0801	2.39E+03	4.96E-02
	0.1004	0.0139	8.00	2.48	1.96	3.23	0.017	0.020	0.1225	0.0902	1.1194	0.1063	0.0830	2.35E+03	4.83E-02
	0.1010	0.0132	8.00	2.48	1.96	3.24	0.017	0.020	0.1245	0.0921	1.0967	0.1049	0.0848	2.32E+03	4.71E-02
IRREG. 7X3X4	0.1000	0.0103	64.00	4.96	1.96	3.40	0.017	0.020	0.1320	0.0980	1.0306	0.0952	0.0895	4.22E+03	1.94E-02
	0.0998	0.0120	64.00	4.96	1.96	3.27	0.017	0.020	0.1270	0.0943	1.0711	0.1008	0.0865	4.47E+03	2.17E-02
	0.0996	0.0112	64.00	4.96	1.96	3.29	0.017	0.020	0.1290	0.0961	1.0510	0.0984	0.0880	4.36E+03	2.07E-02

Table B-5**:** Experimental Data 2nd Smooth surface

Q1	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0506	0.0120	8.00	2.48	1.96	1.30	1.0882	0.0639	0.0465	0.0396	0.0417	1.55E+03	2.10E-02
	0.0508	0.0111	8.00	2.48	1.96	1.20	1.0160	0.0554	0.0500	0.0406	0.0429	1.51E+03	2.00E-02
	0.0510	0.0116	8.00	2.48	1.96	1.40	1.1333	0.0675	0.0450	0.0396	0.0417	1.53E+03	2.03E-02
CUBE 4X4	0.0514	0.0145	64.00	4.96	1.96	1.40	1.5576	0.0835	0.0330	0.0381	0.0401	3.35E+03	1.22E-02
	0.0508	0.0178	64.00	4.96	1.96	1.20	1.1814	0.0750	0.0430	0.0349	0.0365	3.54E+03	1.36E-02
	0.0510	0.0160	64.00	4.96	1.96	1.70	1.5839	0.0898	0.0430	0.0367	0.0385	3.45E+03	1.29E-02
SPHERE 2.48	0.0514	0.0192	8.00	2.48	1.96	1.40	1.2691	0.0754	0.0405	0.0345	0.0361	1.83E+03	2.90E-02
	0.0514	0.0214	8.00	2.48	1.96	1.10	1.0936	0.0711	0.0470	0.0349	0.0365	1.94E+03	3.28E-02
	0.0514	0.0185	8.00	2.48	1.96	1.10	1.1816	0.0723	0.0435	0.0352	0.0369	1.81E+03	2.87E-02
SPHERE 3.72	0.0514	0.0171	27.00	3.72	1.96	1.10	1.1054	0.0639	0.0465	0.0352	0.0369	2.62E+03	1.77E-02
	0.0514	0.0171	27.00	3.72	1.96	1.10	1.0384	0.0657	0.0495	0.0345	0.0361	2.59E+03	1.73E-02
	0.0514	0.0142	27.00	3.72	1.96	1.40	1.2094	0.0763	0.0425	0.0389	0.0409	2.51E+03	1.63E-02
REC. 4X1X2	0.0510	0.0223	8.00	2.48	1.96	1.90	1.4167	0.0852	0.0360	0.0345	0.0361	1.97E+03	3.38E-02
	0.0512	0.0240	8.00	2.48	1.96	1.70	1.2642	0.0763	0.0405	0.0322	0.0336	1.97E+03	3.38E-02
	0.0510	0.0218	8.00	2.48	1.96	1.80	1.3421	0.0828	0.0380	0.0349	0.0365	1.96E+03	3.34E-02
REC. 5X3X4	0.0508	0.0211	64.00	4.96	1.96	1.40	1.1678	0.0734	0.0435	0.0349	0.0365	3.85E+03	1.61E-02
	0.0506	0.0205	64.00	4.96	1.96	1.30	1.0766	0.0714	0.0470	0.0356	0.0373	3.84E+03	1.61E-02
	0.0506	0.0179	64.00	4.96	1.96	1.60	1.3676	0.0848	0.0370	0.0349	0.0365	3.55E+03	1.37E-02
IRREG. 4X1X2	0.0510	0.0227	8.00	2.48	1.96	1.40	1.5549	0.0897	0.0328	0.0334	0.0349	1.95E+03	3.32E-02
	0.0510	0.0205	8.00	2.48	1.96	1.20	1.3077	0.0762	0.0390	0.0356	0.0373	1.92E+03	3.22E-02
	0.0506	0.0218	8.00	2.48	1.96	1.10	1.2974	0.0759	0.0390	0.0349	0.0365	1.96E+03	3.34E-02
IRREG. 7X3X4	0.0520	0.0149	64.00	4.96	1.96	1.00	1.1556	0.0683	0.0450	0.0381	0.0401	3.39E+03	1.25E-02
	0.0508	0.0160	64.00	4.96	1.96	0.90	1.0263	0.0623	0.0495	0.0374	0.0393	3.48E+03	1.32E-02
	0.0508	0.0154	64.00	4.96	1.96	1.20	1.3730	0.0853	0.0370	0.0378	0.0397	3.43E+03	1.28E-02

Table B-5: (Continued)

Q2	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0622	0.0149	8.00	2.48	1.96	1.70	1.2694	0.0798	0.0490	0.0427	0.0452	1.80E+03	2.82E-02
	0.0624	0.0170	8.00	2.48	1.96	1.70	1.2735	0.0795	0.0490	0.0417	0.0441	1.90E+03	3.15E-02
	0.0626	0.0152	8.00	2.48	1.96	1.80	1.2275	0.0875	0.0510	0.0427	0.0452	1.82E+03	2.89E-02
CUBE 4X4	0.0626	0.0154	64.00	4.96	1.96	1.70	1.2275	0.0881	0.0510	0.0427	0.0452	3.66E+03	1.46E-02
	0.0624	0.0164	64.00	4.96	1.96	0.90	1.1345	0.0620	0.0550	0.0420	0.0444	3.74E+03	1.53E-02
	0.0624	0.0161	64.00	4.96	1.96	1.20	1.1664	0.0749	0.0550	0.0420	0.0444	3.72E+03	1.50E-02
SPHERE 2.48	0.0626	0.0187	8.00	2.48	1.96	1.00	1.0982	0.0712	0.0570	0.0396	0.0417	1.94E+03	3.27E-02
	0.0630	0.0165	8.00	2.48	1.96	1.00	1.0957	0.0701	0.0575	0.0420	0.0444	1.88E+03	3.08E-02
	0.0630	0.0198	8.00	2.48	1.96	1.20	1.2857	0.0801	0.0490	0.0381	0.0401	1.96E+03	3.33E-02
SPHERE 3.72	0.0628	0.0145	27.00	3.72	1.96	1.00	1.0922	0.0740	0.0575	0.0427	0.0452	2.66E+03	1.83E-02
	0.0632	0.0145	27.00	3.72	1.96	1.00	1.1186	0.0734	0.0565	0.0420	0.0444	2.64E+03	1.80E-02
	0.0630	0.0144	27.00	3.72	1.96	1.00	1.1150	0.0727	0.0565	0.0430	0.0456	2.66E+03	1.83E-02
REC. 4X1X2	0.0624	0.0199	8.00	2.48	1.96	1.20	1.3137	0.0878	0.0475	0.0378	0.0397	1.95E+03	3.32E-02
	0.0622	0.0209	8.00	2.48	1.96	0.80	1.1519	0.0620	0.0540	0.0371	0.0389	1.98E+03	3.42E-02
	0.0624	0.0217	8.00	2.48	1.96	1.10	1.3000	0.0870	0.0480	0.0367	0.0385	2.01E+03	3.51E-02
REC. 5X3X4	0.0624	0.0135	64.00	4.96	1.96	1.00	1.1556	0.0638	0.0540	0.0430	0.0456	3.44E+03	1.29E-02
	0.0626	0.0130	64.00	4.96	1.96	0.90	1.0610	0.0561	0.0590	0.0430	0.0456	3.38E+03	1.24E-02
	0.0626	0.0146	64.00	4.96	1.96	0.80	1.0521	0.0554	0.0595	0.0427	0.0452	3.57E+03	1.39E-02
IRREG. 4X1X2	0.0624	0.0190	8.00	2.48	1.96	1.20	1.2866	0.0801	0.0485	0.0389	0.0409	1.94E+03	3.27E-02
	0.0630	0.0173	8.00	2.48	1.96	1.20	1.2857	0.0801	0.0490	0.0413	0.0437	1.91E+03	3.16E-02
	0.0634	0.0208	8.00	2.48	1.96	1.30	1.4089	0.0880	0.0450	0.0371	0.0389	1.97E+03	3.40E-02
IRREG. 7X3X4	0.0624	0.0204	64.00	4.96	1.96	1.10	1.3000	0.0757	0.0480	0.0374	0.0393	3.93E+03	1.69E-02
	0.0628	0.0208	64.00	4.96	1.96	1.10	1.3221	0.0760	0.0475	0.0371	0.0389	3.95E+03	1.70E-02
	0.0628	0.0150	64.00	4.96	1.96	0.90	1.1115	0.0730	0.0565	0.0427	0.0452	3.61E+03	1.42E-02

Table B-5: (Continued)

Q3	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0812	0.0105	8.00	2.48	1.96	1.70	1.1518	0.0646	0.0705	0.0519	0.0557	1.67E+03	2.44E-02
	0.0814	0.0096	8.00	2.48	1.96	1.90	1.2427	0.0699	0.0655	0.0522	0.0560	1.61E+03	2.25E-02
	0.0814	0.0078	8.00	2.48	1.96	2.10	1.2719	0.0735	0.0640	0.0559	0.0603	1.51E+03	1.98E-02
CUBE 4X4	0.0816	0.0115	64.00	4.96	1.96	1.80	1.2651	0.0741	0.0645	0.0510	0.0546	3.47E+03	1.31E-02
	0.0816	0.0122	64.00	4.96	1.96	1.70	1.2651	0.0709	0.0645	0.0506	0.0542	3.57E+03	1.39E-02
	0.0812	0.0127	64.00	4.96	1.96	2.00	1.4122	0.0877	0.0645	0.0506	0.0542	3.65E+03	1.45E-02
SPHERE 2.48	0.0828	0.0164	8.00	2.48	1.96	1.30	1.2641	0.0674	0.0655	0.0481	0.0513	2.01E+03	3.53E-02
	0.0824	0.0170	8.00	2.48	1.96	1.20	1.2485	0.0666	0.0660	0.0471	0.0502	2.03E+03	3.58E-02
	0.0824	0.0185	8.00	2.48	1.96	1.40	1.2976	0.0727	0.0635	0.0458	0.0486	2.08E+03	3.78E-02
SPHERE 3.72	0.0820	0.0113	27.00	3.72	1.96	1.20	1.2913	0.0704	0.0635	0.0510	0.0546	2.59E+03	1.73E-02
	0.0822	0.0113	27.00	3.72	1.96	1.20	1.2945	0.0704	0.0635	0.0503	0.0538	2.57E+03	1.71E-02
	0.0822	0.0123	27.00	3.72	1.96	1.40	1.3152	0.0788	0.0625	0.0506	0.0542	2.69E+03	1.87E-02
REC. 4X1X2	0.0820	0.0164	8.00	2.48	1.96	1.20	1.3226	0.0814	0.0620	0.0477	0.0509	2.00E+03	3.50E-02
	0.0814	0.0171	8.00	2.48	1.96	1.00	1.2620	0.0723	0.0645	0.0464	0.0494	2.02E+03	3.55E-02
	0.0816	0.0176	8.00	2.48	1.96	1.30	1.3831	0.0852	0.0590	0.0461	0.0490	2.04E+03	3.63E-02
REC. 5X3X4	0.0812	0.0154	64.00	4.96	1.96	1.00	1.2397	0.0674	0.0655	0.0481	0.0513	3.90E+03	1.65E-02
	0.0820	0.0170	64.00	4.96	1.96	1.10	1.2813	0.0783	0.0640	0.0464	0.0494	4.02E+03	1.76E-02
	0.0818	0.0150	64.00	4.96	1.96	1.10	1.2882	0.0750	0.0635	0.0481	0.0513	3.85E+03	1.61E-02
IRREG. 4X1X2	0.0828	0.0189	8.00	2.48	1.96	1.30	1.5623	0.0937	0.0530	0.0451	0.0479	2.09E+03	3.80E-02
	0.0824	0.0195	8.00	2.48	1.96	1.20	1.5259	0.0890	0.0540	0.0444	0.0471	2.11E+03	3.87E-02
	0.0822	0.0193	8.00	2.48	1.96	1.30	1.5364	0.0920	0.0535	0.0447	0.0475	2.10E+03	3.85E-02
IRREG. 7X3X4	0.0822	0.0166	64.00	4.96	1.96	1.10	1.2361	0.0788	0.0665	0.0477	0.0509	4.04E+03	1.78E-02
	0.0826	0.0173	64.00	4.96	1.96	0.90	1.2328	0.0710	0.0670	0.0464	0.0494	4.05E+03	1.79E-02
	0.0822	0.0180	64.00	4.96	1.96	0.90	1.1743	0.0638	0.0700	0.0461	0.0490	4.13E+03	1.85E-02

Table B-5**:** (Continued)

Q4	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.1014	0.0057	8.00	2.48	1.96	1.30	1.3000	0.0665	0.0780	0.0597	0.0648	1.33E+03	1.54E-02
	0.1010	0.0072	8.00	2.48	1.96	1.40	1.3649	0.0805	0.0740	0.0592	0.0641	1.49E+03	1.93E-02
	0.1004	0.0078	8.00	2.48	1.96	1.50	1.3660	0.0817	0.0735	0.0589	0.0638	1.55E+03	2.09E-02
CUBE 4X4	0.1010	0.0097	64.00	4.96	1.96	1.90	1.3117	0.0710	0.0770	0.0583	0.0631	3.43E+03	1.28E-02
	0.1014	0.0108	64.00	4.96	1.96	1.90	1.3169	0.0721	0.0770	0.0577	0.0624	3.61E+03	1.42E-02
	0.1012	0.0100	64.00	4.96	1.96	1.80	1.3058	0.0678	0.0770	0.0583	0.0631	3.48E+03	1.32E-02
SPHERE 2.48	0.0996	0.0146	8.00	2.48	1.96	1.50	1.3020	0.0746	0.0765	0.0528	0.0567	2.00E+03	3.48E-02
	0.0990	0.0151	8.00	2.48	1.96	1.60	1.3026	0.0804	0.0760	0.0525	0.0564	2.03E+03	3.58E-02
	0.0998	0.0158	8.00	2.48	1.96	1.50	1.3132	0.0775	0.0760	0.0506	0.0542	2.03E+03	3.58E-02
SPHERE 3.72	0.0996	0.0105	27.00	3.72	1.96	1.30	1.2769	0.0663	0.0780	0.0586	0.0634	2.68E+03	1.86E-02
	0.0998	0.0105	27.00	3.72	1.96	1.30	1.2713	0.0665	0.0785	0.0586	0.0634	2.68E+03	1.86E-02
	0.0996	0.0113	27.00	3.72	1.96	1.30	1.2688	0.0620	0.0785	0.0574	0.0620	2.76E+03	1.97E-02
REC. 4X1X2	0.1014	0.0110	8.00	2.48	1.96	1.10	1.3255	0.0751	0.0765	0.0577	0.0624	1.81E+03	2.87E-02
	0.1016	0.0135	8.00	2.48	1.96	1.30	1.3823	0.0817	0.0735	0.0547	0.0589	1.96E+03	3.33E-02
	0.1016	0.0126	8.00	2.48	1.96	1.40	1.4310	0.0854	0.0710	0.0556	0.0599	1.91E+03	3.17E-02
REC. 5X3X4	0.0996	0.0113	64.00	4.96	1.96	2.30	1.2688	0.0613	0.0785	0.0574	0.0620	3.68E+03	1.48E-02
	0.0992	0.0145	64.00	4.96	1.96	2.40	1.2637	0.0639	0.0785	0.0531	0.0571	3.99E+03	1.74E-02
	0.0996	0.0122	64.00	4.96	1.96	2.30	1.2688	0.0620	0.0785	0.0559	0.0603	3.77E+03	1.55E-02
IRREG. 4X1X2	0.1006	0.0147	8.00	2.48	1.96	1.50	1.4169	0.0852	0.0710	0.0528	0.0567	2.01E+03	3.51E-02
	0.1004	0.0139	8.00	2.48	1.96	1.40	1.3660	0.0817	0.0735	0.0544	0.0585	1.98E+03	3.41E-02
	0.1010	0.0132	8.00	2.48	1.96	1.60	1.5075	0.0894	0.0670	0.0550	0.0592	1.94E+03	3.29E-02
IRREG. 7X3X4	0.1000	0.0103	64.00	4.96	1.96	1.20	1.2821	0.0682	0.0780	0.0586	0.0634	3.55E+03	1.37E-02
	0.0998	0.0120	64.00	4.96	1.96	1.20	1.2795	0.0674	0.0780	0.0559	0.0603	3.73E+03	1.51E-02
	0.0996	0.0112	64.00	4.96	1.96	1.30	1.4435	0.0678	0.0690	0.0574	0.0620	3.66E+03	1.46E-02

Table B-6: Experimental Data of Bed Materials of R2

	Q (m^3/s)	q $m^3/s/m$	S	vol (cm3)	d_s (cm)	γ_s (g/cm^3)	$ks_{cal.}$ (cm)	n_{eq}	n_b	h_r (m)	$(h^*)_r$ (m)	$(Vcc)_r$ (m/s)	$(u^*)_r$ (m/s)	$(Rb)^*_r$ (m)	Re_r^*	τ^* (N/m^2)
ORIGINAL BED PARTICLES R2	0.0279	0.0558	0.0231	11.50	2.80	1.60	3.29	0.019	0.021	0.0875	0.0546	1.0220	0.1080	0.0515	2.70E+03	4.42E-02
	0.0279	0.0558	0.0204	11.50	2.80	1.60	3.11	0.020	0.023	0.0910	0.0599	0.9323	0.1067	0.0568	2.67E+03	4.32E-02
	0.0279	0.0558	0.0235	11.50	2.80	1.60	3.08	0.019	0.021	0.0860	0.0552	1.0100	0.1097	0.0523	2.74E+03	4.56E-02
	0.0377	0.0754	0.0188	12.90	2.91	1.60	3.33	0.017	0.019	0.1010	0.0677	1.1137	0.1078	0.0630	2.80E+03	4.24E-02
	0.0377	0.0754	0.0211	12.90	2.91	1.60	3.11	0.019	0.021	0.0990	0.0679	1.1098	0.1147	0.0638	2.98E+03	4.80E-02
	0.0377	0.0754	0.0193	12.90	2.91	1.60	3.13	0.018	0.021	0.1005	0.0692	1.0898	0.1107	0.0648	2.88E+03	4.47E-02
	0.043	0.0860	0.0236	12.40	2.87	1.60	3.14	0.021	0.024	0.1080	0.0766	1.1227	0.1293	0.0723	3.32E+03	6.19E-02
	0.043	0.0860	0.0253	12.40	2.87	1.60	3.05	0.020	0.023	0.1040	0.0735	1.1707	0.1313	0.0693	3.37E+03	6.37E-02
	0.043	0.0860	0.0223	12.40	2.87	1.60	3.09	0.021	0.024	0.1100	0.0791	1.0872	0.1280	0.0748	3.28E+03	6.05E-02
	0.0526	0.1052	0.0247	14.14	3.00	1.60	2.97	0.020	0.023	0.1140	0.0843	1.2479	0.1386	0.0792	3.71E+03	6.80E-02
	0.0526	0.1052	0.0275	14.14	3.00	1.60	3.03	0.020	0.023	0.1120	0.0817	1.2878	0.1440	0.0768	3.86E+03	7.34E-02
	0.0526	0.1052	0.0227	14.14	3.00	1.60	3.08	0.019	0.023	0.1160	0.0852	1.2354	0.1333	0.0797	3.57E+03	6.29E-02

Table B-6: (Continued)

	Q (m^3/s)	q ($m^3/s/m$)	S	vol (cm3)	d_s (cm)	γ_s (g/cm^3)	t (cm)	$(Vcc)_s$ (m/s)	$(u^*)_s$ (m/s)	h_s (m)	R_s (m)	$(Rb)_s$ (m)	Re_s*	τ* (N/m^2)
ORIGINAL BED PARTICLES ON 2^{nd} SMOOTH SURFACE	0.0279	0.0504	0.0231	3.86	1.95	1.60	0.80	1.5045	0.0878	0.0335	0.0268	0.0278	1.38E+03	3.43E-02
	0.0279	0.0504	0.0204	3.86	1.95	1.60	0.60	1.3091	0.0818	0.0385	0.0284	0.0295	1.34E+03	3.22E-02
	0.0279	0.0506	0.0235	3.86	1.95	1.60	0.90	1.6323	0.0974	0.0310	0.0260	0.0269	1.37E+03	3.37E-02
	0.0377	0.0696	0.0188	4.23	2.01	1.60	0.80	1.6186	0.0916	0.0430	0.0360	0.0377	1.49E+03	3.68E-02
	0.0377	0.0696	0.0211	4.23	2.01	1.60	0.70	1.5422	0.1052	0.0450	0.0360	0.0353	1.53E+03	3.86E-02
	0.0377	0.0696	0.0193	4.23	2.01	1.60	0.50	1.4925	0.0904	0.0465	0.0360	0.0369	1.50E+03	3.70E-02
	0.0430	0.0850	0.0236	8.93	2.57	1.60	1.10	1.4167	0.0845	0.0600	0.0396	0.0417	2.26E+03	3.98E-02
	0.0430	0.0852	0.0253	8.93	2.57	1.60	1.10	1.4200	0.0841	0.0600	0.0381	0.0401	2.30E+03	4.12E-02
	0.0430	0.0850	0.0223	8.93	2.57	1.60	1.00	1.3386	0.0746	6.3500	0.0403	0.0425	2.22E+03	3.84E-02
	0.0526	0.1020	0.0247	3.13	1.81	1.60	0.50	1.4167	0.0844	0.0720	0.0437	0.0464	1.72E+03	6.58E-02
	0.0526	0.1020	0.0275	3.13	1.81	1.60	0.60	1.5938	0.0937	0.0640	0.0417	0.0441	1.77E+03	6.95E-02
	0.0526	0.1020	0.0227	3.13	1.81	1.60	0.60	1.6721	0.0959	0.0610	0.0451	0.0479	1.67E+03	6.24E-02

Table B-7: Experimental data of R3

Q1	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.0516	0.0101	8.00	2.48	1.96	3.98	0.020	0.023	0.1112	0.0714	0.7227	0.0814	0.0671	1.80E+03	2.84E-02
	0.0516	0.0127	8.00	2.48	1.96	3.49	0.023	0.026	0.1062	0.0713	0.7241	0.0920	0.0678	2.04E+03	3.62E-02
	0.0516	0.0141	8.00	2.48	1.96	3.49	0.020	0.023	0.0990	0.0641	0.8046	0.0916	0.0606	2.03E+03	3.59E-02
CUBE 4X4	0.0518	0.0165	64.00	4.96	1.96	3.49	0.026	0.030	0.1071	0.0722	0.7175	0.1060	0.0694	4.70E+03	2.40E-02
	0.0518	0.0185	64.00	4.96	1.96	3.47	0.026	0.029	0.1031	0.0684	0.7574	0.1093	0.0657	4.84E+03	2.55E-02
	0.0518	0.0171	64.00	4.96	1.96	3.48	0.025	0.028	0.1031	0.0683	0.7579	0.1049	0.0655	4.65E+03	2.36E-02
SPHERE 2.48	0.0520	0.0275	8.00	2.48	1.96	3.63	0.022	0.024	0.0902	0.0539	0.9647	0.1177	0.0514	2.61E+03	5.93E-02
	0.0518	0.0284	8.00	2.48	1.96	3.45	0.022	0.025	0.0892	0.0547	0.9462	0.1207	0.0524	2.68E+03	6.24E-02
	0.0518	0.0248	8.00	2.48	1.96	3.45	0.023	0.026	0.0932	0.0587	0.8829	0.1170	0.0562	2.59E+03	5.86E-02
SPHERE 3.72	0.0518	0.0216	27.00	3.72	1.96	3.60	0.023	0.026	0.0970	0.0610	0.8492	0.1110	0.0583	3.69E+03	3.52E-02
	0.0518	0.0216	27.00	3.72	1.96	3.46	0.027	0.031	0.1020	0.0674	0.7687	0.1172	0.0649	3.89E+03	3.92E-02
	0.0518	0.0221	27.00	3.72	1.96	3.46	0.024	0.027	0.0965	0.0619	0.8369	0.1133	0.0593	3.77E+03	3.66E-02
REC. 4X1X2	0.0518	0.0232	8.00	2.48	1.96	3.31	0.026	0.030	0.0979	0.0648	0.7994	0.1192	0.0624	2.64E+03	6.08E-02
	0.0518	0.0217	8.00	2.48	1.96	3.46	0.022	0.025	0.0939	0.0593	0.8737	0.1097	0.0566	2.43E+03	5.15E-02
	0.0518	0.0252	8.00	2.48	1.96	3.45	0.023	0.026	0.0929	0.0584	0.8873	0.1176	0.0559	2.61E+03	5.92E-02
REC. 5X3X4	0.0518	0.0256	64.00	4.96	1.96	3.43	0.024	0.027	0.0937	0.0594	0.8721	0.1197	0.0570	5.30E+03	3.06E-02
	0.0518	0.0228	64.00	4.96	1.96	3.46	0.024	0.027	0.0957	0.0611	0.8476	0.1145	0.0586	5.07E+03	2.81E-02
	0.0518	0.0261	64.00	4.96	1.96	3.45	0.024	0.027	0.0927	0.0582	0.8901	0.1195	0.0558	5.30E+03	3.06E-02
IRREG. 4X1X2	0.0518	0.0279	8.00	2.48	1.96	3.46	0.024	0.026	0.0914	0.0568	0.9120	0.1220	0.0545	2.70E+03	6.37E-02
	0.0518	0.0265	8.00	2.48	1.96	3.45	0.028	0.031	0.0984	0.0639	0.8106	0.1266	0.0617	2.81E+03	6.86E-02
	0.0518	0.0280	8.00	2.48	1.96	3.45	0.026	0.029	0.0944	0.0599	0.8642	0.1259	0.0577	2.79E+03	6.78E-02
IRREG. 7X3X4	0.0518	0.0184	64.00	4.96	1.96	3.97	0.020	0.022	0.0983	0.0586	0.8840	0.0999	0.0553	4.43E+03	2.14E-02
	0.0518	0.0203	64.00	4.96	1.96	3.47	0.022	0.025	0.0953	0.0606	0.8541	0.1073	0.0578	4.76E+03	2.46E-02
	0.0518	0.0208	64.00	4.96	1.96	3.46	0.022	0.025	0.0943	0.0597	0.8682	0.1077	0.0569	4.77E+03	2.48E-02

Table B-7: (Continued)

Q2	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.0640	0.0159	8.00	2.48	1.96	2.63	0.025	0.029	0.1080	0.0817	0.7834	0.1105	0.0784	2.45E+03	5.22E-02
	0.0640	0.0189	8.00	2.48	1.96	3.47	0.022	0.025	0.1050	0.0703	0.9103	0.1112	0.0667	2.46E+03	5.30E-02
	0.0640	0.0166	8.00	2.48	1.96	3.48	0.021	0.024	0.1070	0.0722	0.8861	0.1056	0.0684	2.34E+03	4.77E-02
CUBE 4X4	0.0640	0.0178	64.00	4.96	1.96	3.18	0.023	0.026	0.1055	0.0737	0.8684	0.1108	0.0702	4.91E+03	2.63E-02
	0.0640	0.0164	64.00	4.96	1.96	3.48	0.021	0.024	0.1075	0.0727	0.8801	0.1052	0.0688	4.66E+03	2.37E-02
	0.0640	0.0170	64.00	4.96	1.96	3.48	0.022	0.025	0.1075	0.0727	0.8798	0.1073	0.0690	4.75E+03	2.46E-02
SPHERE 2.48	0.0640	0.0261	8.00	2.48	1.96	3.55	0.022	0.025	0.1000	0.0645	0.9922	0.1254	0.0615	2.78E+03	6.73E-02
	0.0640	0.0252	8.00	2.48	1.96	3.45	0.023	0.026	0.1010	0.0665	0.9627	0.1253	0.0635	2.78E+03	6.72E-02
	0.0640	0.0267	8.00	2.48	1.96	3.45	0.023	0.026	0.1000	0.0655	0.9769	0.1281	0.0626	2.84E+03	7.03E-02
SPHERE 3.72	0.0640	0.0205	27.00	3.72	1.96	3.51	0.023	0.026	0.1050	0.0699	0.9156	0.1158	0.0665	3.85E+03	3.82E-02
	0.0640	0.0205	27.00	3.72	1.96	3.46	0.023	0.026	0.1055	0.0709	0.9033	0.1167	0.0675	3.88E+03	3.88E-02
	0.0640	0.0208	27.00	3.72	1.96	3.46	0.022	0.025	0.1035	0.0689	0.9294	0.1156	0.0655	3.84E+03	3.81E-02
REC. 4X1X2	0.0640	0.0223	8.00	2.48	1.96	2.58	0.027	0.032	0.1030	0.0772	0.8290	0.1277	0.0745	2.83E+03	6.98E-02
	0.0640	0.0240	8.00	2.48	1.96	3.46	0.023	0.026	0.1015	0.0669	0.9560	0.1225	0.0638	2.71E+03	6.42E-02
	0.0640	0.0242	8.00	2.48	1.96	3.45	0.023	0.026	0.1015	0.0670	0.9559	0.1232	0.0639	2.73E+03	6.49E-02
REC. 5X3X4	0.0640	0.0203	64.00	4.96	1.96	3.60	0.022	0.025	0.1045	0.0685	0.9343	0.1137	0.0650	5.04E+03	2.77E-02
	0.0640	0.0165	64.00	4.96	1.96	3.48	0.021	0.024	0.1070	0.0722	0.8861	0.1052	0.0683	4.66E+03	2.37E-02
	0.0640	0.0175	64.00	4.96	1.96	3.47	0.021	0.024	0.1055	0.0708	0.9045	0.1073	0.0670	4.75E+03	2.46E-02
IRREG. 4X1X2	0.0640	0.0242	8.00	2.48	1.96	3.58	0.022	0.025	0.1010	0.0652	0.9816	0.1213	0.0620	2.69E+03	6.30E-02
	0.0640	0.0247	8.00	2.48	1.96	3.45	0.025	0.029	0.1050	0.0705	0.9083	0.1280	0.0675	2.84E+03	7.01E-02
	0.0640	0.0252	8.00	2.48	1.96	3.45	0.023	0.026	0.1005	0.0660	0.9700	0.1248	0.0629	2.76E+03	6.66E-02
IRREG. 7X3X4	0.0640	0.0209	64.00	4.96	1.96	4.02	0.020	0.022	0.1035	0.0633	1.0111	0.1105	0.0595	4.90E+03	2.61E-02
	0.0640	0.0204	64.00	4.96	1.96	3.46	0.022	0.026	0.1045	0.0699	0.9162	0.1154	0.0665	5.11E+03	2.85E-02
	0.0640	0.0231	64.00	4.96	1.96	3.46	0.023	0.026	0.1025	0.0679	0.9422	0.1211	0.0648	5.36E+03	3.14E-02

Table B-7: (Continued)

Q3	q	S	vol	d_s	γ_s	$ks_{cal.}$	n_{eq}	n_b	h_r	$(h^*)_r$	$(Vcc)_r$	$(u^*)_r$	$(Rb)^*_r$	Re_r^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)			(m)	(m)	(m/s)	(m/s)	(m)		(N/m^2)
CUBE 2X2	0.0828	0.0135	8.00	2.48	1.96	2.22	0.025	0.030	0.1240	0.1018	0.8134	0.1134	0.0972	2.51E+03	5.50E-02
	0.0828	0.0113	8.00	2.48	1.96	3.50	0.020	0.023	0.1280	0.0930	0.8904	0.0983	0.0868	2.18E+03	4.13E-02
	0.0828	0.0097	8.00	2.48	1.96	3.51	0.019	0.022	0.1300	0.0949	0.8725	0.0915	0.0880	2.03E+03	3.58E-02
CUBE 4X4	0.0828	0.0159	64.00	4.96	1.96	3.76	0.021	0.025	0.1250	0.0874	0.9474	0.1132	0.0822	5.02E+03	2.74E-02
	0.0828	0.0152	64.00	4.96	1.96	3.48	0.021	0.025	0.1225	0.0877	0.9444	0.1111	0.0825	4.92E+03	2.64E-02
	0.0828	0.0164	64.00	4.96	1.96	3.48	0.022	0.026	0.1225	0.0877	0.9439	0.1154	0.0828	5.11E+03	2.85E-02
SPHERE 2.48	0.0828	0.0224	8.00	2.48	1.96	3.74	0.020	0.023	0.1120	0.0746	1.1099	0.1242	0.0701	2.75E+03	6.60E-02
	0.0828	0.0229	8.00	2.48	1.96	3.46	0.021	0.024	0.1110	0.0764	1.0835	0.1275	0.0722	2.82E+03	6.95E-02
	0.0828	0.0198	8.00	2.48	1.96	3.47	0.021	0.025	0.1160	0.0813	1.0181	0.1221	0.0768	2.71E+03	6.38E-02
SPHERE 3.72	0.0828	0.0171	27.00	3.72	1.96	3.72	0.020	0.023	0.1190	0.0818	1.0122	0.1136	0.0767	3.77E+03	3.68E-02
	0.0828	0.0171	27.00	3.72	1.96	3.48	0.022	0.026	0.1210	0.0862	0.9601	0.1170	0.0814	3.89E+03	3.91E-02
	0.0828	0.0137	27.00	3.72	1.96	3.49	0.020	0.024	0.1230	0.0881	0.9397	0.1054	0.0825	3.50E+03	3.17E-02
REC. 4X1X2	0.0828	0.0198	8.00	2.48	1.96	3.25	0.022	0.026	0.1160	0.0835	0.9916	0.1240	0.0792	2.75E+03	6.58E-02
	0.0828	0.0208	8.00	2.48	1.96	3.46	0.022	0.025	0.1150	0.0804	1.0303	0.1245	0.0760	2.76E+03	6.63E-02
	0.0828	0.0208	8.00	2.48	1.96	3.46	0.022	0.026	0.1170	0.0824	1.0053	0.1262	0.0781	2.80E+03	6.82E-02
REC. 5X3X4	0.0828	0.0165	64.00	4.96	1.96	3.68	0.021	0.024	0.1210	0.0842	0.9834	0.1132	0.0791	5.01E+03	2.74E-02
	0.0828	0.0184	64.00	4.96	1.96	3.47	0.021	0.025	0.1180	0.0833	0.9941	0.1191	0.0786	5.28E+03	3.04E-02
	0.0828	0.0175	64.00	4.96	1.96	3.47	0.022	0.025	0.1195	0.0848	0.9769	0.1172	0.0800	5.19E+03	2.94E-02
IRREG. 4X1X2	0.0828	0.0211	8.00	2.48	1.96	3.58	0.021	0.024	0.1135	0.0777	1.0656	0.1229	0.0732	2.72E+03	6.47E-02
	0.0828	0.0204	8.00	2.48	1.96	3.46	0.021	0.025	0.1150	0.0804	1.0305	0.1233	0.0759	2.73E+03	6.51E-02
	0.0828	0.0223	8.00	2.48	1.96	3.46	0.021	0.024	0.1120	0.0774	1.0697	0.1265	0.0731	2.80E+03	6.85E-02
IRREG. 7X3X4	0.0828	0.0192	64.00	4.96	1.96	3.23	0.022	0.026	0.1170	0.0847	0.9776	0.1229	0.0803	5.44E+03	3.23E-02
	0.0828	0.0200	64.00	4.96	1.96	3.47	0.021	0.025	0.1155	0.0808	1.0243	0.1225	0.0763	5.43E+03	3.21E-02
	0.0828	0.0188	64.00	4.96	1.96	3.47	0.021	0.025	0.1165	0.0818	1.0122	0.1192	0.0771	5.28E+03	3.04E-02

Table B-7: (Continued)

Q4	q ($m^3/s/m$)	S	vol (cm3)	d_s (cm)	γ_s (g/cm^3)	$ks_{cal.}$ (cm)	n_{eq}	n_b	h_r (m)	$(h^*)_r$ (m)	$(Vcc)_r$ (m/s)	$(u^*)_r$ (m/s)	$(Rb)^*_r$ (m)	Re_r^*	τ^* (N/m^2)
CUBE 2X2	0.1046	0.0059	8.00	2.48	1.96	4.13	0.020	0.025	0.1770	0.1357	0.7708	0.0850	0.1245	1.88E+03	3.09E-02
	0.1046	0.0069	8.00	2.48	1.96	3.53	0.023	0.030	0.1790	0.1437	0.7279	0.0956	0.1344	2.12E+03	3.91E-02
	0.1046	0.0065	8.00	2.48	1.96	3.53	0.022	0.028	0.1750	0.1397	0.7490	0.0913	0.1298	2.02E+03	3.57E-02
CUBE 4X4	0.1046	0.0121	64.00	4.96	1.96	3.49	0.020	0.024	0.1410	0.1061	0.9859	0.1081	0.0985	4.79E+03	2.50E-02
	0.1046	0.0135	64.00	4.96	1.96	3.49	0.020	0.024	0.1390	0.1041	1.0048	0.1133	0.0970	5.02E+03	2.75E-02
	0.1046	0.0116	64.00	4.96	1.96	3.50	0.019	0.022	0.1390	0.1040	1.0057	0.1045	0.0961	4.63E+03	2.34E-02
SPHERE 2.48	0.1046	0.0198	8.00	2.48	1.96	3.52	0.021	0.025	0.1290	0.0938	1.1151	0.1307	0.0880	2.90E+03	7.31E-02
	0.1046	0.0180	8.00	2.48	1.96	3.47	0.022	0.026	0.1330	0.0983	1.0644	0.1278	0.0923	2.83E+03	6.99E-02
	0.1046	0.0183	8.00	2.48	1.96	3.47	0.021	0.026	0.1320	0.0973	1.0752	0.1280	0.0914	2.84E+03	7.01E-02
SPHERE 3.72	0.1046	0.0151	27.00	3.72	1.96	3.15	0.022	0.026	0.1360	0.1045	1.0010	0.1207	0.0982	4.01E+03	4.15E-02
	0.1046	0.0151	27.00	3.72	1.96	3.48	0.021	0.026	0.1390	0.1042	1.0041	0.1204	0.0977	4.00E+03	4.13E-02
	0.1046	0.0130	27.00	3.72	1.96	3.49	0.020	0.024	0.1400	0.1051	0.9955	0.1116	0.0978	3.71E+03	3.55E-02
REC. 4X1X2	0.1046	0.0154	8.00	2.48	1.96	3.51	0.021	0.025	0.1355	0.1004	1.0418	0.1189	0.0938	2.64E+03	6.05E-02
	0.1046	0.0164	8.00	2.48	1.96	3.48	0.021	0.025	0.1340	0.0992	1.0542	0.1222	0.0929	2.71E+03	6.39E-02
	0.1046	0.0183	8.00	2.48	1.96	3.47	0.021	0.026	0.1320	0.0973	1.0752	0.1280	0.0914	2.84E+03	7.01E-02
REC. 5X3X4	0.1046	0.0139	64.00	4.96	1.96	3.40	0.021	0.025	0.1385	0.1045	1.0010	0.1152	0.0976	5.11E+03	2.84E-02
	0.1046	0.0130	64.00	4.96	1.96	3.49	0.020	0.024	0.1400	0.1051	0.9955	0.1116	0.0978	4.95E+03	2.67E-02
	0.1046	0.0145	64.00	4.96	1.96	3.49	0.021	0.025	0.1375	0.1026	1.0191	0.1167	0.0959	5.17E+03	2.92E-02
IRREG. 4X1X2	0.1046	0.0159	8.00	2.48	1.96	3.45	0.021	0.025	0.1345	0.1000	1.0460	0.1207	0.0936	2.67E+03	6.24E-02
	0.1046	0.0170	8.00	2.48	1.96	3.48	0.021	0.025	0.1320	0.0972	1.0757	0.1232	0.0910	2.73E+03	6.50E-02
	0.1046	0.0166	8.00	2.48	1.96	3.48	0.021	0.025	0.1335	0.0987	1.0595	0.1228	0.0924	2.72E+03	6.46E-02
IRREG. 7X3X4	0.1046	0.0152	64.00	4.96	1.96	3.45	0.021	0.025	0.1360	0.1015	1.0305	0.1192	0.0949	5.28E+03	3.04E-02
	0.1046	0.0147	64.00	4.96	1.96	3.48	0.021	0.025	0.1370	0.1022	1.0239	0.1175	0.0954	5.21E+03	2.95E-02
	0.1046	0.0141	64.00	4.96	1.96	3.49	0.020	0.025	0.1380	0.1031	1.0143	0.1154	0.0962	5.11E+03	2.85E-02

Table B-8**:** Experimental Data 3rd Smooth surface

Q1	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0516	0.0101	8.00	2.48	1.96	1.40	1.0750	0.0648	0.0480	0.0403	0.0425	1.44E+03	1.80E-02
	0.0516	0.0127	8.00	2.48	1.96	1.50	1.1727	0.0701	0.0440	0.0374	0.0393	1.55E+03	2.10E-02
	0.0516	0.0141	8.00	2.48	1.96	1.60	1.2000	0.0730	0.0430	0.0367	0.0385	1.62E+03	2.28E-02
CUBE 4X4	0.0516	0.0165	64.00	4.96	1.96	1.20	1.2585	0.0773	0.0410	0.0352	0.0369	3.43E+03	1.28E-02
	0.0516	0.0185	64.00	4.96	1.96	1.60	1.3403	0.0796	0.0385	0.0334	0.0349	3.53E+03	1.36E-02
	0.0516	0.0171	64.00	4.96	1.96	1.50	1.3403	0.0770	0.0385	0.0337	0.0353	3.41E+03	1.27E-02
SPHERE 2.48	0.0516	0.0184	8.00	2.48	1.96	2.30	1.3403	0.0793	0.0385	0.0334	0.0349	1.76E+03	2.69E-02
	0.0516	0.0203	8.00	2.48	1.96	2.50	1.3579	0.0828	0.0380	0.0330	0.0345	1.84E+03	2.94E-02
	0.0516	0.0208	8.00	2.48	1.96	2.70	1.3579	0.0839	0.0380	0.0330	0.0345	1.86E+03	3.01E-02
SPHERE 3.72	0.0516	0.0232	27.00	3.72	1.96	2.20	1.4333	0.0864	0.0360	0.0315	0.0328	2.87E+03	2.13E-02
	0.0516	0.0232	27.00	3.72	1.96	2.10	1.3579	0.0886	0.0380	0.0330	0.0345	2.94E+03	2.24E-02
	0.0516	0.0252	27.00	3.72	1.96	2.60	1.5636	0.0866	0.0330	0.0292	0.0303	2.88E+03	2.14E-02
REC. 4X1X2	0.0516	0.0275	8.00	2.48	1.96	2.00	1.6645	0.0878	0.0310	0.0276	0.0286	1.95E+03	3.30E-02
	0.0516	0.0284	8.00	2.48	1.96	2.10	1.7793	0.0865	0.0290	0.0260	0.0269	1.92E+03	3.20E-02
	0.0516	0.0248	8.00	2.48	1.96	2.00	1.5636	0.0859	0.0330	0.0292	0.0303	1.90E+03	3.16E-02
REC. 5X3X4	0.0516	0.0216	64.00	4.96	1.96	1.90	1.3579	0.0854	0.0380	0.0330	0.0345	3.78E+03	1.56E-02
	0.0516	0.0185	64.00	4.96	1.96	1.70	1.3403	0.0796	0.0385	0.0334	0.0349	3.53E+03	1.36E-02
	0.0516	0.0220	64.00	4.96	1.96	1.50	1.3760	0.0858	0.0375	0.0326	0.0341	3.80E+03	1.57E-02
IRREG. 4X1X2	0.0516	0.0279	8.00	2.48	1.96	1.50	1.6645	0.0884	0.0310	0.0276	0.0286	1.96E+03	3.35E-02
	0.0516	0.0265	8.00	2.48	1.96	1.40	1.6125	0.0875	0.0320	0.0284	0.0295	1.94E+03	3.27E-02
	0.0516	0.0280	8.00	2.48	1.96	1.50	1.7200	0.0873	0.0300	0.0268	0.0278	1.93E+03	3.26E-02
IRREG. 7X3X4	0.0516	0.0256	64.00	4.96	1.96	2.30	1.5636	0.0872	0.0330	0.0292	0.0303	3.87E+03	1.63E-02
	0.0516	0.0228	64.00	4.96	1.96	2.00	1.3946	0.0867	0.0370	0.0322	0.0336	3.84E+03	1.61E-02
	0.0516	0.0261	64.00	4.96	1.96	2.30	1.5877	0.0875	0.0325	0.0288	0.0299	3.88E+03	1.64E-02

Table B-8**:** (Continued)

Q2	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0640	0.0159	8.00	2.48	1.96	1.80	1.2075	0.0850	0.0530	0.0437	0.0464	1.88E+03	3.09E-02
	0.0640	0.0189	8.00	2.48	1.96	2.00	1.3333	0.0888	0.0480	0.0403	0.0425	1.97E+03	3.37E-02
	0.0640	0.0166	8.00	2.48	1.96	1.80	1.2308	0.0863	0.0520	0.0430	0.0456	1.91E+03	3.18E-02
CUBE 4X4	0.0640	0.0178	64.00	4.96	1.96	1.80	1.3061	0.0870	0.0490	0.0410	0.0433	3.85E+03	1.62E-02
	0.0640	0.0164	64.00	4.96	1.96	1.60	1.2308	0.0856	0.0520	0.0430	0.0456	3.79E+03	1.57E-02
	0.0640	0.0170	64.00	4.96	1.96	1.60	1.2308	0.0858	0.0520	0.0417	0.0441	3.80E+03	1.57E-02
SPHERE 2.48	0.0640	0.0261	8.00	2.48	1.96	2.20	1.6623	0.0945	0.0385	0.0334	0.0349	2.09E+03	3.82E-02
	0.0640	0.0252	8.00	2.48	1.96	2.00	1.6410	0.0934	0.0390	0.0337	0.0353	2.07E+03	3.74E-02
	0.0640	0.0267	8.00	2.48	1.96	2.20	1.6842	0.0951	0.0380	0.0330	0.0345	2.11E+03	3.87E-02
SPHERE 3.72	0.0640	0.0199	27.00	3.72	1.96	1.80	1.3913	0.0894	0.0460	0.0389	0.0409	2.97E+03	2.28E-02
	0.0640	0.0199	27.00	3.72	1.96	1.80	1.3474	0.0907	0.0475	0.0399	0.0421	3.01E+03	2.35E-02
	0.0640	0.0208	27.00	3.72	1.96	1.90	1.4884	0.0887	0.0430	0.0367	0.0385	2.95E+03	2.24E-02
REC. 4X1X2	0.0640	0.0223	8.00	2.48	1.96	2.00	1.5059	0.0914	0.0425	0.0363	0.0381	2.02E+03	3.57E-02
	0.0640	0.0240	8.00	2.48	1.96	2.10	1.5802	0.0926	0.0405	0.0349	0.0365	2.05E+03	3.67E-02
	0.0640	0.0242	8.00	2.48	1.96	2.20	1.6000	0.0926	0.0400	0.0345	0.0361	2.05E+03	3.67E-02
REC. 5X3X4	0.0640	0.0203	64.00	4.96	1.96	2.40	1.4545	0.0885	0.0440	0.0374	0.0393	3.92E+03	1.68E-02
	0.0640	0.0165	64.00	4.96	1.96	2.00	1.2308	0.0859	0.0520	0.0430	0.0456	3.81E+03	1.58E-02
	0.0640	0.0175	64.00	4.96	1.96	2.10	1.2929	0.0866	0.0495	0.0413	0.0437	3.84E+03	1.61E-02
IRREG. 4X1X2	0.0640	0.0242	8.00	2.48	1.96	1.90	1.6000	0.0926	0.0400	0.0345	0.0361	2.05E+03	3.67E-02
	0.0640	0.0247	8.00	2.48	1.96	2.10	1.6203	0.0930	0.0395	0.0341	0.0357	2.06E+03	3.70E-02
	0.0640	0.0252	8.00	2.48	1.96	2.20	1.6410	0.0934	0.0390	0.0337	0.0353	2.07E+03	3.74E-02
IRREG. 7X3X4	0.0640	0.0209	64.00	4.96	1.96	1.90	1.4884	0.0889	0.0430	0.0367	0.0385	3.94E+03	1.69E-02
	0.0640	0.0204	64.00	4.96	1.96	1.90	1.4545	0.0888	0.0440	0.0374	0.0393	3.93E+03	1.69E-02
	0.0640	0.0231	64.00	4.96	1.96	2.20	1.5238	0.0924	0.0420	0.0360	0.0377	4.09E+03	1.83E-02

Table B-8: (Continued)

Q3	q	S	vol	d_s	γ_s	t	$(Vcc)_s$	$(u^*)_s$	h_s	R_s	$(Rb)_s$	Re_s^*	τ^*
	$m^3/s/m$		(cm3)	(cm)	(g/cm^3)	(cm)	(m/s)	(m/s)	(m)	(m)	(m)		(N/m^2)
CUBE 2X2	0.0828	0.0135	8.00	2.48	1.96	2.20	1.3574	0.0832	0.0610	0.0490	0.0524	1.84E+03	2.96E-02
	0.0828	0.0113	8.00	2.48	1.96	2.00	1.3039	0.0777	0.0635	0.0506	0.0542	1.72E+03	2.58E-02
	0.0828	0.0097	8.00	2.48	1.96	1.90	1.2738	0.0725	0.0650	0.0516	0.0553	1.61E+03	2.25E-02
CUBE 4X4	0.0828	0.0159	64.00	4.96	1.96	2.00	1.4526	0.0877	0.0570	0.0464	0.0494	3.89E+03	1.65E-02
	0.0828	0.0152	64.00	4.96	1.96	1.90	1.4034	0.0873	0.0590	0.0477	0.0509	3.87E+03	1.63E-02
	0.0812	0.0164	64.00	4.96	1.96	1.90	1.3763	0.0891	0.0590	0.0464	0.0494	3.95E+03	1.70E-02
SPHERE 2.48	0.0828	0.0224	8.00	2.48	1.96	1.90	1.6727	0.0980	0.0495	0.0413	0.0437	2.17E+03	4.11E-02
	0.0828	0.0229	8.00	2.48	1.96	1.90	1.6898	0.0987	0.0490	0.0410	0.0433	2.19E+03	4.17E-02
	0.0824	0.0198	8.00	2.48	1.96	1.70	1.5846	0.0941	0.0520	0.0430	0.0456	2.08E+03	3.79E-02
SPHERE 3.72	0.0828	0.0171	27.00	3.72	1.96	1.80	1.4919	0.0901	0.0555	0.0454	0.0483	2.99E+03	2.32E-02
	0.0828	0.0171	27.00	3.72	1.96	1.80	1.4526	0.0911	0.0570	0.0464	0.0494	3.03E+03	2.37E-02
	0.0828	0.0137	27.00	3.72	1.96	1.40	1.3800	0.0834	0.0600	0.0484	0.0516	2.77E+03	1.98E-02
REC. 4X1X2	0.0828	0.0198	8.00	2.48	1.96	1.80	1.5923	0.0941	0.0520	0.0430	0.0456	2.08E+03	3.79E-02
	0.0828	0.0208	8.00	2.48	1.96	2.00	1.6396	0.0952	0.0505	0.0420	0.0444	2.11E+03	3.88E-02
	0.0828	0.0193	8.00	2.48	1.96	1.70	1.5623	0.0937	0.0530	0.0437	0.0464	2.08E+03	3.75E-02
REC. 5X3X4	0.0828	0.0165	64.00	4.96	1.96	1.30	1.4526	0.0894	0.0570	0.0464	0.0494	3.96E+03	1.71E-02
	0.0828	0.0184	64.00	4.96	1.96	1.60	1.5477	0.0919	0.0535	0.0441	0.0468	4.07E+03	1.81E-02
	0.0828	0.0175	64.00	4.96	1.96	1.50	1.5055	0.0907	0.0550	0.0451	0.0479	4.02E+03	1.76E-02
IRREG. 4X1X2	0.0828	0.0211	8.00	2.48	1.96	1.50	1.6560	0.0954	0.0500	0.0417	0.0441	2.11E+03	3.89E-02
	0.0828	0.0204	8.00	2.48	1.96	1.40	1.6078	0.0952	0.0515	0.0427	0.0452	2.11E+03	3.88E-02
	0.0822	0.0223	8.00	2.48	1.96	1.70	1.6606	0.0978	0.0495	0.0413	0.0437	2.17E+03	4.09E-02
IRREG. 7X3X4	0.0828	0.0192	64.00	4.96	1.96	1.40	1.5623	0.0934	0.0530	0.0437	0.0464	4.14E+03	1.86E-02
	0.0828	0.0200	64.00	4.96	1.96	1.70	1.5923	0.0947	0.0520	0.0430	0.0456	4.20E+03	1.92E-02
	0.0828	0.0188	64.00	4.96	1.96	1.40	1.5477	0.0928	0.0535	0.0441	0.0468	4.11E+03	1.84E-02

Table B-8**:** (Continued)

Q4	**q**	**S**	**vol**	**d_s**	**γ_s**	**t**	**$(Vcc)_s$**	**$(u^*)_s$**	**h_s**	**R_s**	**$(Rb)_s$**	**Re_s^***	**τ^***
	$m^3/s/m$		**(cm3)**	**(cm)**	**(g/cm^3)**	**(cm)**	**(m/s)**	**(m/s)**	**(m)**	**(m)**	**(m)**		**(N/m^2)**
CUBE 2X2	0.1046	0.0059	8.00	2.48	1.96	1.40	1.3410	0.0612	0.0780	0.0595	0.0644	1.36E+03	1.60E-02
	0.1046	0.0069	8.00	2.48	1.96	1.60	1.3497	0.0660	0.0775	0.0592	0.0641	1.46E+03	1.86E-02
	0.1046	0.0065	8.00	2.48	1.96	1.50	1.3497	0.0642	0.0775	0.0592	0.0641	1.42E+03	1.76E-02
CUBE 4X4	0.1046	0.0121	64.00	4.96	1.96	2.10	1.4528	0.0846	0.0720	0.0559	0.0603	3.75E+03	1.53E-02
	0.1046	0.0135	64.00	4.96	1.96	2.20	1.4943	0.0882	0.0700	0.0547	0.0589	3.91E+03	1.67E-02
	0.1046	0.0116	64.00	4.96	1.96	2.10	1.4943	0.0830	0.0700	0.0562	0.0606	3.68E+03	1.48E-02
SPHERE 2.48	0.1046	0.0198	8.00	2.48	1.96	2.10	1.7433	0.1001	0.0600	0.0484	0.0516	2.22E+03	4.29E-02
	0.1046	0.0180	8.00	2.48	1.96	2.00	1.6871	0.0969	0.0620	0.0497	0.0531	2.15E+03	4.02E-02
	0.1046	0.0183	8.00	2.48	1.96	2.00	1.7008	0.0972	0.0615	0.0494	0.0527	2.15E+03	4.05E-02
SPHERE 3.72	0.1046	0.0151	27.00	3.72	1.96	1.80	1.5729	0.0915	0.0665	0.0525	0.0564	3.04E+03	2.39E-02
	0.1046	0.0151	27.00	3.72	1.96	1.60	1.4943	0.0935	0.0700	0.0547	0.0589	3.11E+03	2.49E-02
	0.1046	0.0130	27.00	3.72	1.96	1.60	1.7148	0.0817	0.0610	0.0490	0.0524	2.71E+03	1.90E-02
REC. 4X1X2	0.1046	0.0154	8.00	2.48	1.96	1.50	1.5848	0.0919	0.0660	0.0522	0.0560	2.04E+03	3.62E-02
	0.1046	0.0164	8.00	2.48	1.96	1.50	1.6603	0.0930	0.0630	0.0503	0.0538	2.06E+03	3.70E-02
	0.1046	0.0183	8.00	2.48	1.96	1.70	1.7008	0.0972	0.0615	0.0494	0.0527	2.15E+03	4.05E-02
REC. 5X3X4	0.1046	0.0139	64.00	4.96	1.96	2.70	1.5050	0.0892	0.0695	0.0544	0.0585	3.95E+03	1.70E-02
	0.1046	0.0130	64.00	4.96	1.96	2.60	1.4732	0.0871	0.0710	0.0553	0.0596	3.86E+03	1.62E-02
	0.1046	0.0145	64.00	4.96	1.96	2.70	1.5496	0.0901	0.0675	0.0531	0.0571	3.99E+03	1.74E-02
IRREG. 4X1X2	0.1046	0.0159	8.00	2.48	1.96	1.60	1.6472	0.0919	0.0635	0.0506	0.0542	2.04E+03	3.61E-02
	0.1046	0.0170	8.00	2.48	1.96	1.80	1.6736	0.0945	0.0625	0.0500	0.0535	2.09E+03	3.82E-02
	0.1046	0.0166	8.00	2.48	1.96	1.80	1.6736	0.0934	0.0625	0.0500	0.0535	2.07E+03	3.73E-02
IRREG. 7X3X4	0.1046	0.0152	64.00	4.96	1.96	1.70	1.5729	0.0918	0.0665	0.0525	0.0564	4.07E+03	1.80E-02
	0.1046	0.0147	64.00	4.96	1.96	1.50	1.5612	0.0906	0.0670	0.0528	0.0567	4.01E+03	1.76E-02
	0.1046	0.0141	64.00	4.96	1.96	1.50	1.5159	0.0897	0.0690	0.0541	0.0582	3.98E+03	1.72E-02

Table B-9: Experimental Data of Bed Materials of R3

	Q (m^3/s)	q $m^3/s/m$	S	vol (cm3)	d_s (cm)	γ_s (g/cm^3)	$ks_{cal.}$ (cm)	n_{eq}	n_b	h_r (m)	$(h^*)_r$ (m)	$(Vcc)_r$ (m/s)	$(u^*)_r$ (m/s)	$(Rb)^*_r$ (m)	Re_r^*	τ^* (N/m^2)
ORIGINAL BED PARTICLES ON R3	0.0278	0.0558	0.0200	11.50	2.88	1.60	3.29	0.025	0.029	0.1020	0.069	0.8075	0.1142	0.0663	2.94E+03	4.80E-02
	0.0278	0.0558	0.0212	11.50	2.88	1.60	3.46	0.023	0.026	0.0980	0.063	0.8805	0.1121	0.0605	2.89E+03	4.63E-02
	0.0278	0.0558	0.0166	11.50	2.88	1.60	3.48	0.024	0.028	0.1060	0.071	0.7834	0.1054	0.0681	2.71E+03	4.09E-02
	0.0366	0.0754	0.0164	12.90	3.78	1.60	3.33	0.023	0.027	0.1160	0.083	0.9117	0.1123	0.0785	3.79E+03	3.54E-02
	0.0366	0.0754	0.0190	12.90	3.78	1.60	3.47	0.022	0.025	0.1115	0.077	0.9817	0.1166	0.0728	3.94E+03	3.81E-02
	0.0366	0.0754	0.0222	12.90	3.78	1.60	3.46	0.022	0.025	0.1070	0.072	1.0414	0.1222	0.0686	4.13E+03	4.19E-02
	0.042	0.0860	0.0219	12.40	3.52	1.60	3.14	0.026	0.031	0.1210	0.090	0.9598	0.1358	0.0857	4.26E+03	5.57E-02
	0.042	0.0860	0.0248	12.40	3.52	1.60	3.45	0.025	0.029	0.1180	0.083	1.0303	0.1393	0.0797	4.37E+03	5.86E-02
	0.042	0.0860	0.0269	12.40	3.52	1.60	3.45	0.025	0.029	0.1160	0.082	1.0550	0.1432	0.0779	4.50E+03	6.20E-02
	0.0525	0.1052	0.0203	14.14	3.81	1.60	2.97	0.025	0.030	0.1340	0.104	1.0086	0.1406	0.0993	4.78E+03	5.51E-02
	0.0525	0.1052	0.0248	14.14	3.81	1.60	3.45	0.023	0.027	0.1270	0.092	1.1377	0.1461	0.0876	4.97E+03	5.95E-02
	0.0525	0.1052	0.0229	14.14	3.81	1.60	3.46	0.024	0.028	0.1310	0.096	1.0911	0.1434	0.0914	4.88E+03	5.73E-02

Table B-9: (Continued)

	Q (m^3/s)	**q** $m^3/s/m$	**S**	**vol** **(cm3)**	d_s **(cm)**	γ_s (g/cm^3)	**t** **(cm)**	$(Vcc)_s$ **(m/s)**	$(u^*)_s$ **(m/s)**	h_s **(m)**	R_s **(m)**	$(Rb)_s$ **(m)**	Re_s^*	τ^* (N/m^2)
ORIGINAL BED PARTICLES ON 3rd SMOOTH SURFACE	0.0278	0.0556	0.0200	3.86	1.95	1.60	0.90	1.8600	0.0879	0.0440	0.0374	0.0393	2.26E+03	4.22E-02
	0.0278	0.0556	0.0212	3.86	1.95	1.60	1.30	1.7438	0.0836	0.0370	0.0322	0.0336	2.15E+03	3.81E-02
	0.0278	0.0556	0.0166	3.86	1.95	1.60	0.60	1.7448	0.0855	0.0510	0.0424	0.0448	2.20E+03	3.99E-02
	0.0366	0.0732	0.0164	4.23	2.01	1.60	1.30	1.7952	0.0753	0.0390	0.0337	0.0353	2.54E+03	3.00E-02
	0.0366	0.0732	0.0190	4.23	2.01	1.60	1.10	1.9333	0.0907	0.0500	0.0337	0.0441	3.06E+03	4.35E-02
	0.0366	0.0732	0.0222	4.23	2.01	1.60	1.10	1.8390	0.0944	0.0460	0.0337	0.0409	3.19E+03	4.72E-02
	0.042	0.0840	0.0219	8.93	2.57	1.60	1.20	1.8298	0.1031	0.0570	0.0464	0.0494	3.24E+03	4.39E-02
	0.042	0.0840	0.0248	8.93	2.57	1.60	1.30	1.9111	0.1080	0.0550	0.0451	0.0479	3.39E+03	4.82E-02
	0.042	0.0840	0.0269	8.93	2.57	1.60	1.30	1.7917	0.1105	0.0530	0.0437	0.0464	3.47E+03	5.04E-02
	0.0525	0.1050	0.0203	3.13	1.81	1.60	1.20	1.9849	0.1028	0.0620	0.0497	0.0531	3.50E+03	6.19E-02
	0.0525	0.1050	0.0248	3.13	1.81	1.60	1.50	2.1040	0.1114	0.0590	0.0477	0.0509	3.79E+03	7.26E-02
	0.0525	0.1050	0.0229	3.13	1.81	1.60	1.40	1.9127	0.1078	0.0600	0.0484	0.0516	3.67E+03	6.80E-02