MAJOR PROJECT

ON

PROBABILISTIC APPROACH IN PREDICTION OF NON-UNIFORM SEDIMENT BED SURFACE UNDER EQUILIBRIUM FLOW CONDITION

Submitted in partial fulfillment
of the requirement for award of the degree of

MASTER OF ENGINEERING
IN
CIVIL ENGINEERING
(**Hydraulics & Flood Control**)

Submitted By
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Under the guidance of

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DECLARATION

I here by declare that the work which is embodied in this major project entitled **'PROBABILISTIC APPROACH IN PREDICTION OF NON-UNIFORM SEDIMENT BED SURFACE UNDER EQUILIBRIUM FLOW CONDITION'** is an authentic record of my own work carried out in partial fulfillment of the requirements for the award of Master of Civil Engineering (Hydraulics & Flood Control) under the guidance of Dr. P.L. Patel, Asst. Professor Dehi College of Engineering, New Delhi. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

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This is certified that above statement made by the student is correct to the best of my knowledge.

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M.E. II

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4. ANALYSIS OF DATA

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LIST OF SYMBOLS

A Area of flow.

A_b Area corresponding to bed of flume.

A_w Area corresponding to sides of flume.

C_m Correction factor used in Roorkee's approach.

C_s Correction factor used in Roorkee's approach.

D Average depth of flow.

$d_{15.9}$ Sediment size in mixture such that, 15.9% of particle by weight are finer than this size

$d_{84.1}$ Sediment size in mixture such that, 84.1% of particle by weight are finer than this size.

d_a Arithmetic mean size of the particle.

d_{aa} Average particle size of equilibrium bed surface.

d_{ai} Average particle size of bulk mix.

d_g Geometric mean size of the particle.

d_i Geometric mean of two sieve sizes d_1 and $d_2 = (d_1 d_2)^{0.5}$

g Acceleration due to gravity.

i_b Fraction of bed sediment of given size range.

M Krammer's uniformity coefficient.

n_w Manning's coefficient for side wall.

q_{bi} Fraction transport rate.

R Hydraulic mean radius.

$\mathbf{R_b}$ Hydraulic radius corresponding to bed of flume.

$\mathbf{R_w}$ Hydraulic radius corresponding to sides of flume.

S Slope of water surface.

$\mathbf{z_0}$ Roughness length characteristic of sediment bed.

$\mathbf{\Delta\gamma_s}$ $\gamma_s - \gamma_f$

$\boldsymbol{\gamma_s}$ Unit weight of sediment.

$\boldsymbol{\gamma_f}$ Unit weight of fluid flowing.

$\boldsymbol{\sigma}$ Arithmetic standard deviation.

$\boldsymbol{\sigma_g}$ Geometric standard deviation.

$\boldsymbol{\tau_o}$ Total shear stress of flow.

$\boldsymbol{\tau_o}$' Grain shear stress.

$\boldsymbol{\tau_{oc}}$ Critical shear stress.

$\boldsymbol{\kappa}$ Von Karman's constant.

$\boldsymbol{\xi_B}$ Sheltering coefficient.

$\boldsymbol{\varphi_b}$ Dimensionless bed load parameter.

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ABSTRACT

It is well known that transport of non-uniform sediment by running water leads to development of new bed surface. If clear water is flowing then there is coarsening of bed and formed bed is known as armor layer, but when sediment laden water flows, the complete mechanism changes, there is an exchange of sediments between bed surface and flowing water until equilibrium is formed, after which there won't be any further exchange of sediments. However whenever there is change in the amount and type of sediment carried by the water a new equilibrium would be formed. In laboratory above condition is achieved by recirculating the sediment in the flume.

In present work, an attempt has been made to estimate the grain size distribution of equilibrium bed surface if bulk grain size distribution, and flow properties are known. For developing this empirical model grain size distribution of equilibrium surface were statistically analyzed and fitted to standard probability distribution. further an empirical relationship is developed to calculate the statistical parameter of that standard distribution.

Finally, estimated grain size distribution is used in calculation of bed load in Roorkee approach and results are compared with earlier results.

CHAPTER - 1

INTRODUCTION

1.1 GENERAL

It is well established that transport of mixed size sediments by running water leads to the development of a bed surface that has a grain size distribution different than that of initial sediment bed. Prediction of grain size distribution of this surface has proved to be very important in knowledge of geomorphological behavior of the river because it determines the resistance of bed to fluid motion and sediment transport. It plays a key role in estimation of aggradations or degradation of the river bed. Accurate prediction of bed load of bed load can also be done if the grain size distribution of equilibrium bed surface is known, as the transport observed at any instant is function of grain size immediately available for transport on the bed surface. In practice, it is very difficult to measure this grain size distribution. Taking transport observations at different sites or at different times at the same location require some accounting and effort, which are often complex and poorly understood.

Generally, grain size distribution of bulk sediment is only known. The sediment transport and equilibrium bed surface is related to this bulk grain distribution through surface sorting that bed undergoes as it adjust to the imposed flow and transport field.. Based on this a mathematical model can be prepared to predict the grain size distribution if bulk grain distribution and flow properties are known. the properties likely to be accounted for may be bed shear stress, depth of flow and slope and sediment properties average size of the initial bed surface, Krammer's uniformity coefficient to predict the grain size distribution of equilibrium bed surface, which is further used to calculate the bed load transport.

1.2 BRIEF REVIEW & HISTORICAL BACKGROUND

1.2.1 Armoring Concept under Clear Water

In earlier attempts Wolman (1954) detected experimentally and verified in field situation that the bed surface in gravel bed rivers is some times coarser than the underplaying material known as Armor Layer. Later Gessler conducted experiment on parallel degradation using non-uniform sediment under condition of uniform follow of clear water and gave relation using flow properties to predict the grain size distribution of armor layer. Leopold (1970); Proffit (1980); Little & Mayer (1976), Parker et al. (1982); Day and Egginton (1983) and many other worked in the same direction giving their own relationship.

1.2.2 Coarsening of Surface Layer under Sediment Laden Water

Hirrano (1971) was to first to introduce the concept of “active layer”, i.e. a surface act as a store for particle that can be entrained. Armanini and Di Silvio were first to improve it by diving transport layer into bed load layer and suspended layer. Later, improvement considered consisted of the division of bed surface layer into pavement and subpavement (Di Silvio 1991 & Marion 1992). The improved model allow for the vertical sorting of the bed and is able to simulate armoring.

Models that allow the continuous vertical changes in bed composition are under investigation. Wilcock and McAdrell (1993) performed experiments with laboratory flume data with sand-gravel sediments to study surface based fractional transport rates and determined mobilization thresholds. Fractional transport rates are referred to the size distribution of the bed surface rather than a subsurface making model more explicit and capable of predicting transient condition. Patel and Ranga Raju (1995) proposed a method to determine the bed load transport for non-uniform sediments based on bulk sediment properties and also measured the grain size distribution of the sedimented surface. Wilcock, Kenworthy and Crow (2001) studied transport of mixed sand and gravel using concept of vertical sorting. They studied the change and behavior of transport rate of gravel with different proportion of the gravel in the mix. In recent development Wilcock and Crowe (2003) further improved their work by presenting a model for mixed sand/gravel sediments. The proposed model uses the full size distribution of the bed surface, including sand and incorporates a non-linear effect of sand content on gravel transport rate.

The essence of above studies especially in recent years is that the rate and size distribution of transported sediment depends only on population of bed surface, but on the proportion of those grain sizes which can mobilized by the flow, weather clear water flow with zero sediment input leading to armoring or with steady state transport rate composed of grains entrained from the bed surface. Partial flow directly affects the rate and size of vertical sediment exchange between the bed surface and the sub surface. If the large portion of the bed is immobile, the number of sites of vertical exchange will be limited. Further, if the active grains are preliminary important ones, sediment exchange between subsurface and bed surface would be limited to smaller grains may pass through pockets vacated by entrained grains. A means of forecasting the active proportion of the bed surface is necessary for predicting any process that depends on grain sorting selective transport, including bed armoring, selective deposition, downstream fining and flushing of the fined grained sediment into subsurface of the gravel bed.

At present most of the sediment transport models completely rely on initial bulk sediment grain size distribution which may change entirely during flow in the river, particularly in case of non-uniform sediments. It has prompted author to predict the grain size distribution of sediment bed surface under antecedent flow condition for using the same in computation of sediment transport in alluvial river.

1.3 SCOPE OF WORK:

Keeping in view the existing studies enumerated in previous section, the present thesis work has been planned with following objectives in mind:

1. To collect the experimental data sets of previous studies in which tests were performed keeping concept of equilibrium bed surface in mind or in other words data sets of the experiments in which sediment were recirculated.
2. To verify the collected data sets statistically and determine whether equilibrium bed surface follows any probabilistic model, or which probability distribution is best suited for them.
3. To develop an empirical model to predict the properties of best suited distribution in terms of bulk mix parameters and flow characteristics.
4. After knowing the various parameters, computation of grain size distribution of equilibrium bed surface as obtained from model in step (2) and (3).

5. To check the performance of existing transport models which are based on characteristics of bulk sediment mixture.

CHAPTER – 2
REVIEW OF LITERATURE

2.1 GENERAL

The characteristics of sediment bed surface depends weather flow water is clear or sediment laden. The changes in the sediment bed surface due to flowing water under both conditions are described in this chapter. Also, existing probabilistic models are described in detail which would be used for verifying the grain size distribution of existing surface. Finally, the existing bed load transport models based on bulk mix characteristics are described as they would be used to check their adequacy under equilibrium sediment bed surface condition.

2.2 EXISTING STUDIES ON COARSENING/FINING OF SEDIMENT

2.2.1 Clear Water Condition:

Gessler's Approach:

Gessler (1968) conducted experiments on parallel degradation using non uniform sediment under condition of uniform flow of clear water. The run was stopped when the bed has coarsened sufficiently to result in practically no movement. The top layer of the armor coat was sampled. The ratio of the fraction of the sediment of a particular size range in the top layer of the armor coat to the fraction of the same size in the initial mixture was taken probability p_i that this size fraction would not move. This value was also interpreted as the probability that the instantaneous shear stress on the bed was smaller than the critical shear stress of that particle. The average shear stress was considered critical for that size fraction where p_i was found to be 0.5. In this manner critical shear stress similar to Shield's was obtained. However, no allowances were made for the effect of other size of the particle on critical shear stress. A curve between p_i vs τ_{0c}/τ_0 on a probability paper yielding a strait line indicating that shear fluctuation at the bottom follow a Gaussian distribution having standard deviation of 0.57.

Although the Gessler's approach is not being used in the present study as; this is an analysis for sediment laden water while Gessler's method is for clear water but the concept behind this approach is used in current work.

Garde, Sahay and Bhatnagar (2006)

Garde et al proposed a simplify method to predict the particle size distribution of the armor coat in case of parallel degradation. Using all available data they concluded that particle size distribution of the armor layer tend to follow normal distribution. They gave mathematical model to predict the median size (d_{50}) of the armor coat.

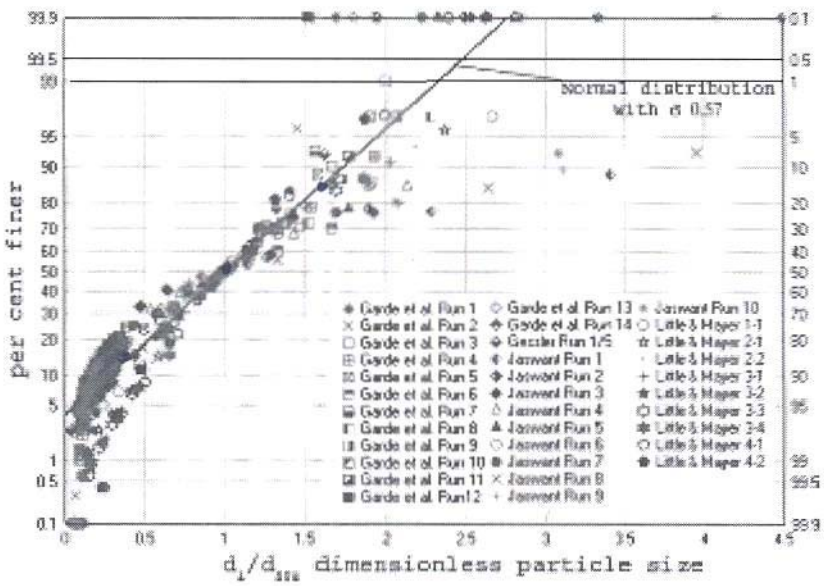

Figure 2.1, Armor Layer Following Normal Distribution (Garde et. al, 2006)

In this method, they predicted that the distribution of armor coat follows a normal distribution with standard deviation of 0.56 (Fig. 2.1). Once median size is known then particle size distribution of the armor layer can be predicted. The median size of the armor layer is a function of initial median size, standard deviation of the bulk sediment, flow properties like shear stress, depth of flow; slope of water surface etc. The curve showing this relationship is shown in Fig. 2.2. In the present study above approach is modified for equilibrium flow.

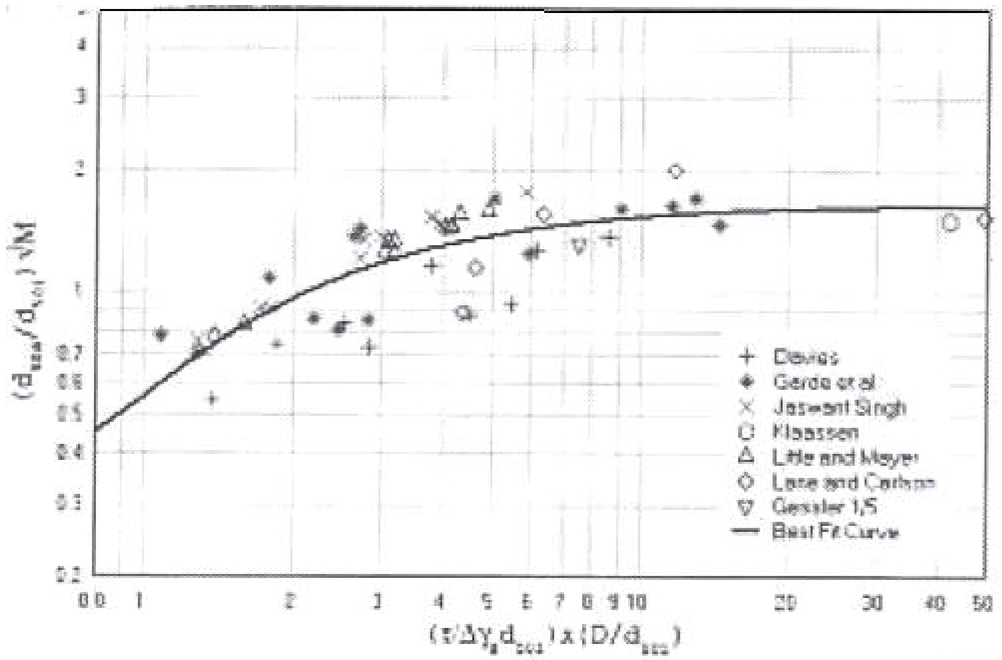

Figure 2.2, Relation between Flow Properties & Mean Size of Armor Layer (Garde et. al, 2006)

2.2.2 Sediment Laden Water Condition

Wilcock & McAdrell (1993)

Wilcock and McAdrell studied partial transport rate for non-uniform sediments. They took twenty eight coupled observation of flow, transport and bed surface grain size distribution in laboratory flume for a wide range of flow. They used fourteen different size fraction of sediment and painted each size of fraction with different color to simplify the complexity of finding grain size distribution after each run. This experiment was based on recirculation of the sediment in the flume.

They reported in their work that the fraction transport rate can be divided into two parts: one consisting of finer sizes all moving at approximately same transport rate. When scaled by their proportion on the bed surface and other consisting of coarser size substantially with smaller transport rates. They observed that decreased mobility of coarser particle fraction occurs because a portion of grains in these fractions are rarely, if ever in motion. As a result, the transport rate of these sizes depends not only on their proportion on bed surface, but also on the number of surface grain of that fraction which are essentially immobile. The transport rates of finer, equally mobile, sizes are determined only by their portion on the bed surface and total transport rate. The grain size separating these two transport regime increases consistently with flow strength.

Wilcock, Kenworthy & Crowe (2001)

Wilcock et al studied characteristic of bed load transport of sand and gravel mixture for five different proportion of sand in the mixture. The effect of sand content on transport was isolated by using the same gravel population and varying only proportion of sand from mixture to mixture. Flow depth was maintained to within a narrow range; though discharge was varied to produce a wide range of transport rate with each sediment. They conducted experiment based on equilibrium flow condition by re-circulating sediment in the flume. The bed surface composition was also measured at the end of each run, providing a set of coupled flow/transport/bed surface observation for a wide range of a wide range of transport rate. In the present study the very same data is also used for the analysis.

Based on their studies it can be concluded that total transport rate and gravel transport rate depend strongly on sand content, or in other words transport rate of coarser particle also depend on the proportion of finer particle in the mix. For same flow strength it was seen that gravel transport rate increases by the order of the magnitude sand content increases in the mixture despite of the fact that the gravel by proportion is lesser. The bed surface distribution also varies to a wide range by changing the amount of sand in the mix. In this experiment that showed that bed surface bed surface exhibit no or little sign of coarsening. In present study the above conclusion is verified.

Wilcock and Crowe (2003)

Wilcock and Crowe extended their previous work and gave a transport model for mixed size sediment. They took number of coupled observation of flow transport and bed surface grain size using five different sediments. Their model uses the full size distribution of the bed surface, including sand and incorporates the nonlinear effect sand content on gravel transport. The conclusion drawn from their studies is that the transport produced from a bed of mixed grain sizes depends on the population of grains immediately available on the bed surface. A correctly formulated and complete explicit transport model must be referenced to the bed surface; substrate models include an undefined implicit dependence on surface sorting. A surface based transport model is capable of predicting transient condition of bed armoring, scour or aggradations.

Their model incorporates a hiding function that reduces the mobility of smaller sizes and increases the mobility of coarser sizes relative to the unisize case. The hiding function gives variation of reference shear stress (surrogate to critical shear stress) as a function of fraction size relative to the median size of the bed surface. The function has two limbs corresponding to relatively finer and coarse fractions. Sediment with little sand tend to have relatively coarser median size such that majority of the fraction fall on the gentle limb for finer sizes, while sediment containing higher amount of sand has finer median size tend fall on limb of steep slope for coarser sizes.

2.3 STATISTICAL DISTRIBUTIONS

Statistics particularly probability statistic plays an important role in river sediment hydraulics. The sediment can be categorized in many ways one of the important and rational way is their shape of particle size distribution. The shape is categorized by the probability distribution it follows. There are number of probability distributions like normal distribution, lognormal distribution, gamma distribution, chi-square distribution, extreme value distribution, Wibull's distribution etc depending on characteristics of shape of their frequency distribution. Out of these few common distributions is described over here which is used in the current work.

2.3.1 Normal Distribution

Normal distribution was discovered by Moivre in about 1773. This is perhaps most common distribution also known as Gaussian frequency distribution or error curve. According to R.A. Fisher (1948) a variate is said to be normally distributed when it takes all values from "-∞ to +∞" with frequencies given by a definite mathematical law, namely that: the logarithm of the frequency at any distance'd' from the centre of the distribution is less than the logarithm of the frequency at the centre by the quantity proportional to d^2. Considering family of curves:

$$y = \frac{1}{k^{\frac{t^2}{2}}} = k^{\frac{-t^2}{2}} \qquad \text{------------------ (2.1)}$$

Where k is a constant and y and t are variables. For k>1 the above curves becomes bell shaped. It is customary to take the value of constant, taking value of constant such that area under the curve comes to unity than vaue of k = 1.0872; the form of this constant is (1/√2π)e, where e is the base of natural logarithms. So equation becomes

$$y = \frac{1}{\sqrt{2\pi}} e^{\frac{-t^2}{2}} \qquad \text{-------------------- (2.2)}$$

This is normal curve in standard measure or standard normal equation. The shape of the curve is bell shape and area under the curve is unity. Fig. 2.3 shows a standard normal curve as probability distribution function.

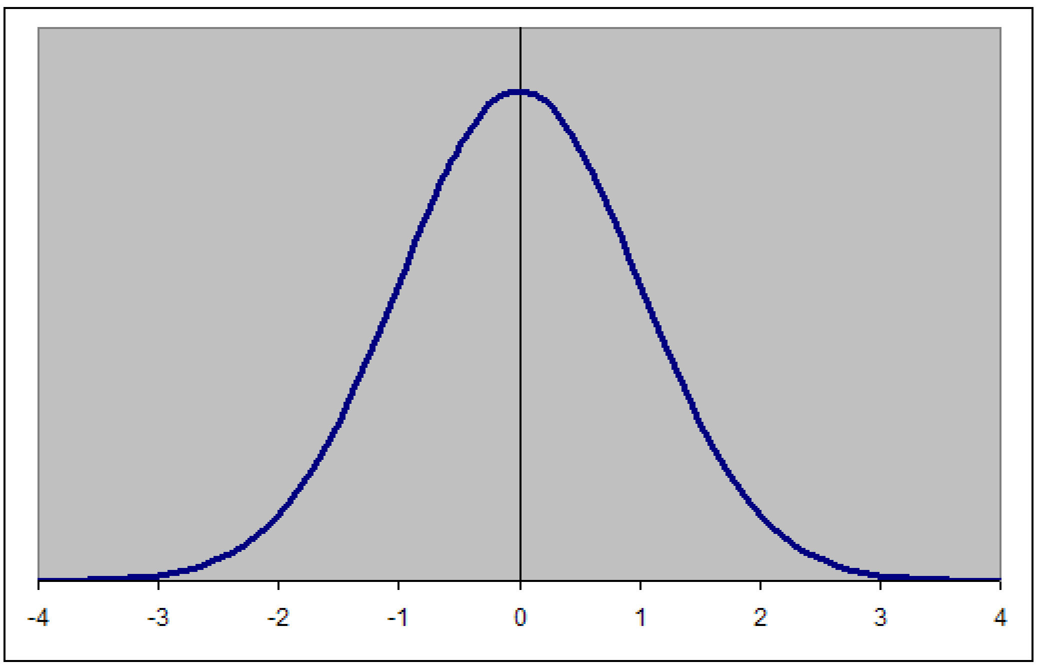

Figure 2.3 Standard Normal Curve

Substituting t = (X-μ)/σ, the frequency function becomes:

$$y = \frac{1}{\sqrt{2\pi}} e^{\frac{-(X-\mu)^2}{2\sigma^2}} \qquad \text{-------------------- (2.3)}$$

The parameters of normal distributions are mean μ and standard deviation σ. So, if σ and μ of any data is known than normal curve corresponding to that curve can be drawn. It can be seen that if value of $\mu = 0$ and value of $\sigma = 1$ above equation turns to Eq. 2.2 so, for a standard normal curve $\mu = 0$ and $\sigma = 1$. The area under this frequency curve is unity, so that each increment of the area represents a proportion. Eq. 2.3 is written for probability density function. When the equation is integrated it becomes cumulative density function where maximum value of y will be unity. Each point on that curve would correspond to the total area under the curve at that point. For a perfect normal distribution it has been seen that cumulative curve comes out to be straight line in a arithmetical probability paper, while for simple and semilog graph it comes out to symmetrical 'S' curve. Many natural occurrences like error in measurement follow normal distribution. In cumulative curve for a normal distribution it is calculated that

$$\sigma = (d_{84.1} - d_{50}) = (d_{50} - d_{15.9}) \quad \text{--------------------} \quad (2.4)$$

$$\text{or, } \sigma = (d_{84.1} - d_{15.9})$$

Here d_i corresponds to the value of X whose cumulative frequency is i% of the total cumulative frequency. For sediments d_i corresponds to that diameter of the particle for which i% of the particle is finer than that d.

2.3.2 Lognormal Distribution

If an observation X depends on the sum of the effects of a large number of small causes acting at random, and if each effect is independent of X, the distribution is likely to be normal. But, if it is not normal than it is assumed that X is not measured in the right way. Than a function of X, *f(*X) is calculated such that *f(*X) is normally distributed, and therefore the observation of X is transformed by converting them into *f(*X).When this function is log (X), than the distribution is known as lognormal distribution. Udden (1898) and Krumbein (1938) proposed lognormal distribution as appropriate distribution for a number of variants such as grain size distribution of sediments. The probability density function is given as:

$$y = \frac{1}{\sigma_g . 2\pi} . e^{\frac{-(\log d_i - \log d_a)^2}{2.\sigma_g^2}} \quad \text{--------------------} \quad (2.5)$$

Here d_g is geometric standard deviation and $\log(d_a)$ is geometric mean can also be written as μ_g. They are given as:

$$\log(d_g) = \sum_{0}^{100} \log(di).\Delta p_i \qquad \text{----------------------} \quad (2.6)$$

Here Δp_i is the fraction of sediment present in of the mix for size d_i. It has been observed that for lognormal distribution,

$$\sigma_g = \frac{d_{84.1}}{d_{50}} = \frac{d_{50}}{d_{15.9}}$$
$$\sigma_g = \sqrt{\frac{d_{84.1}}{d_{15.9}}} \qquad \text{---------------------} \ (2.7)$$

In a log probability paper a true lognormal distribution comes out to be straight line. In log-log graph it comes out to be symmetrical 'S' curve. The random variable Y = log (X) comes out to be normally distributed if X is lognormally distributed. Fig. 2.4 shows a lognormally distributed data as probability function.

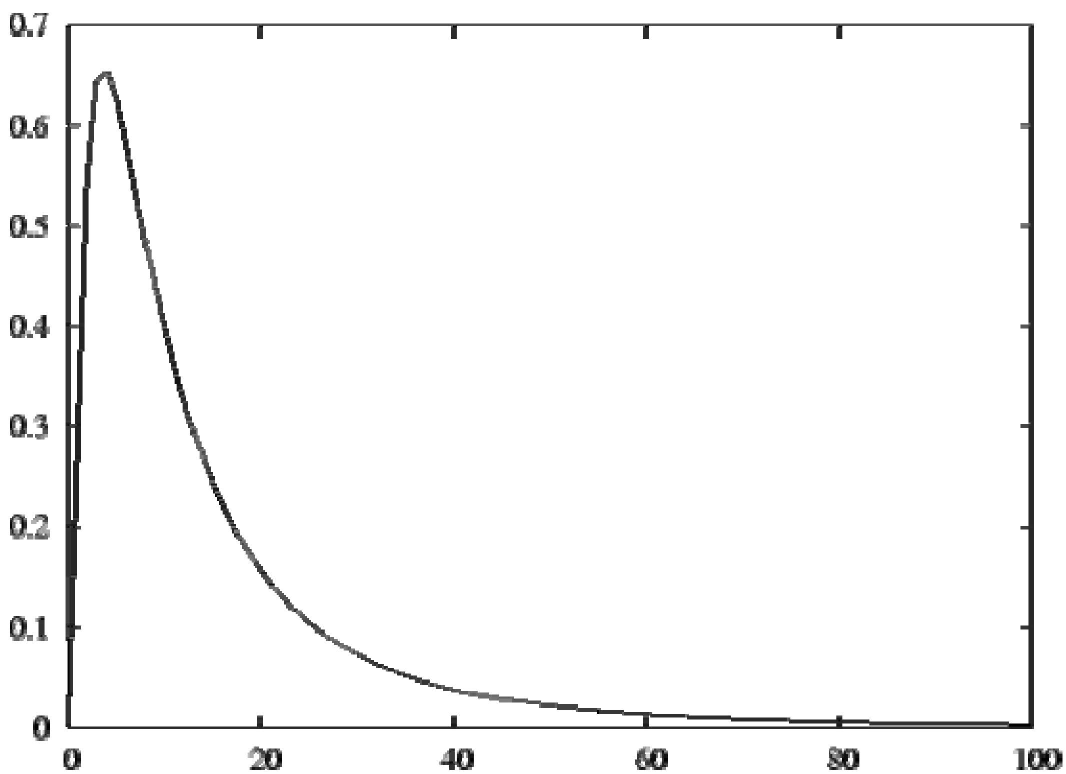

Figure 2.4 Curve showing Lognormal Distribution

2.3.3 Gamma Distribution

The gamma distribution is a family of curves based on two parameters. The chi-square and exponential distributions, which are children of the gamma distribution, are one-parameter distributions that fix one of the two gamma parameters. The gamma distribution has the following relationship with the incomplete Gamma function:

$$\Gamma\left(x,a,b\right) = gammainc\left(\frac{x}{b},a\right) \quad \text{--------------------} \quad (2.8)$$

For b = 1 the functions are identical. When a is large, the gamma distribution closely approximates a normal distribution with the advantage that the gamma distribution has density only for positive real numbers.

The gamma pdf can be defined as:

$$y = f(x) = \frac{1}{b^a\Gamma(a)} \cdot x^{a-1}.e^{x/b} \quad \text{------------------} \quad (2.9)$$

2.3.4 Method of Maximum Likelihood

There is all possibility that a particular data doesn't exactly follow a particular distribution. Then there comes a question that which defined mathematical distribution is the best representation of given data set. R.A. Fishure (1922) developed method of maximum likelihood. He reasoned that the best value of a parameter of a probability distribution should be that value which maximizes the likelihood or the joint probability of the occurrence of the observed sample. If sample space is divided into interval of length dx and that an independent and sample of independent and identically distributed observations x_1, x_2, x_3……x_n is taken. The value of probability density for X = x_i is $f(x_i)$, and the probability that the random variable will occur in the interval including x_i is $f(x_i)$. Since the observations are independent, there joint probability of occurrences given as the product of $f(x_1)dx$ $f(x_2)dx$……….. $f(x_n)dx$ = $\left[\prod_{1}^{n} f(x_i)\right](dx)^n$. Since the interval size is fixed maximizing the joint probability of the observed sample is equivalent to maximizing the likelihood function given as

$$L = \prod_{i=1}^{n} f(x_i) \quad \text{---------------} \quad (2.10)$$

Because many probability density functions are exponential, it is some time more convenient to work with the log likelihood function, given by,

$$\ln L = \sum_{i=1}^{n} \ln\left[f\left(x_i\right)\right] \quad \text{-------------------} \quad (2.11)$$

The method of maximum likelihood is theoretically the most accurate method of fitting probability function to the data in the sense that it produces the most efficient parameters with least average error. But for some of the probability distribution, there is no analytical solution for all the parameters in terms of sample statistic then log-likelihood should be maximized numerically. In the present wok fitting of various distribution to the data is done using MATLAB, which tells the value of log-likelihood parameter, out of which the distribution would give maximum value of the parameter would be the best distribution fit for given data set.

2.4 SEDIMENT TRANSPORT THEORIES

In this section various theories and formulae which is used in current analysis related to sediment transport is explained.

2.4.1 Einstein Method of Separating Side Wall Friction:

In sediment transport it is bed resistance which is responsible for the mechanism behind it. When there is same amount of resistance in the entire periphery then there is no need of applying any correction for side friction, but this is possible only for wide river. In laboratory flume where side wall is of different material or any narrow natural steam where bed friction may different because of vegetation on bank of river this correction becomes important. In these cases hydraulic radius of bed, R_b, is commonly used instead of 'R' in the resistance relation.

Einstein assumed velocity to be uniformly distributed over the whole cross sectional areas. Assuming that whole flow area can be divided into areas corresponding to the bed and the sides, it can be written:

$$A = A_w + A_b \quad \text{---------------------} \quad (2.12)$$

Here A_w is the area corresponding to sides and A_b is the area corresponding to the bed. Using Manning's equation for the sides;

$$U = (1/n_w).R_w^{2/3}.S^{1/2} \quad \text{----------------------} \quad (2.13)$$

Where, R_w is the hydraulic radius corresponding to the walls which can be easily calculated if n_w, Manning's coefficient for the side wall is known. For glass which is used in the data for current analysis, this value is equal to 0.01. S is slpoe of water surface. For rectangular channel using Eq. 2.12 can be written as:

$$(B + 2D).R = 2D.R_w + B.R_b$$

From Eq. 2.13 value of R_w is obtained and value of R_b can be calculated. Corresponding to this hydraulic radius bed shear stress would be determined.

2.4.2 Method to Obtain Grain Shear Stress

Bed shear stress consists of two components first form shear stress which occurs due to undulations present in the bed of river or flume. The other component is grain shear stress which is actually responsible for the movement of the particle. The method adopted in this work is Einstein approach who gave a formula to calculate grain shear stress. The relation is given as:

$$\frac{U}{\left(gR'S\right)^{1/2}} = \frac{1}{\kappa}\ln\left(\frac{R'}{2.718z_0}\right) \quad \text{-------------------} \quad (2.14)$$

Where, κ is Von Karman's constant; z_0 is a roughness length characteristic of sediment bed. The value of κ is taken as 0.4 and z_0 is calculated as (d_{65}/30). With help of Eq.2.14 hydraulic radius corresponding to grain shear (R') can be calculated using hit and trial. Knowing R' grain shear stress τ_0 can be obtained as:

$$\tau_0' = \gamma R'S \quad \text{----------------------} \quad (2.15)$$

2.4.3 Roorkee's Approach

This method is used to compute bed load material of non-uniform sediments. This method was developed in University of Roorkee, Roorkee (India) by Misri, Samaga, Patel and ranga Raju. They collected extensive data on partial bed load transport in a laboratory flume using sediment mixtures with size ranging from .07 mm to 40 mm and got the typical graph between $\tau_o'/(\Delta\gamma_s d_i)$ and φ_b based on their measurements (Fig. 2.5). Here, $\Delta\gamma_s = (\gamma_s - \gamma_f)$, γ_s and γ_f are unit weight of sediment and fluid respectively, d_i is diameter of sediment in concern. From that plot it can be seen that the transport of fractions coarser than the arithmetic mean size has increased while transport of fractions finer than the mean has decreased due to sheltering, if the relation for uniform sediment is used as the basis of comparison. Misri et al. introduced a parameter ξ_B defined as the factor by which $\tau_o'/(\Delta\gamma_s d_i)$ must be multiplied to get the dimensionless shear stress for use in finding $i_B q_B$. This parameter ξ_B is found to be a function of τ_o'/τ_{oc}', $\tau_o'/(\Delta\gamma_s d_i)$ and Kramer's uniformity coefficient *M*. (here, τ_{0c} is critical shear stress.)

The coefficient C_m is a function of *M* as per the equations

$C_m = 1$ for $M \geq 0.38$

$C_m = 0.7092 \log M + 1.293$ for $0.05 \leq M < 0.38$

Patel and Ranga Raju proposed a relationship between $C_m\,\xi_B$ and $C_s\,\tau_o'/(\Delta\gamma_s d_i)$.

$$C_m \xi_B = 0.0731 \left(\frac{C_s \tau_0'}{\Delta\gamma_s d_i} \right)^{-0.75144} \quad \text{------------------} \quad (2.16)$$

In which C_s is the function of τ_o'/τ_{oc} and can be expressed as:

$$\log(C_s) = -0.1957 - 0.9571\left(\log\frac{\tau_0'}{\tau_{0c}}\right) - 0.1949\left(\log\frac{\tau_0'}{\tau_{0c}}\right)^2 + 0.0644\left(\log\frac{\tau_0'}{\tau_{0c}}\right)^3 \quad \text{------} \quad (2.17)$$

…..2.2

Here τ_{oc} is the critical shear stress for the arithmetic mean size of the mixture as per Shields. Finally, Patel and Ranga Raju plot a graph between $\xi_B\,\tau_o'/(\Delta\gamma_s d_i)$ v/s φ_b for all the available data. Here,

$$\phi_B = \frac{i_B q_B}{i_b \gamma_s} \cdot \sqrt{\frac{\gamma_f}{\Delta\gamma_s g d_i^2}} \quad \text{-------------------} \quad (2.17)$$

The bed load can be computed by the above method as described below

1. Divide the bed material into convenient fractions, and determine their geometric mean sizes and availability in the bed i_b.
2. Compute τ_{oc} for size d_a using shield's curve and also find τ_o'.
3. Determine M for the mixture and C_m from above mention equation.

4. Compute C_s for the known values of τ_o'/τ_{oc} from Eq.2.17.
5. Compute ξ_B for known size d_i from Eq.2.16 and than compute $\xi_B\,\tau_o'/(\Delta\gamma_s d_i)$.
6. Read φ_B from Fig. 2.5 and determine $i_B q_B$ as

$$i_B q_B = i_b \gamma_s \phi_B \left(g d_i^3\right)^{1/2} \left(\frac{\Delta\gamma}{\gamma_f}\right)^{1/2} \quad \text{-------------------- (2.18)}$$

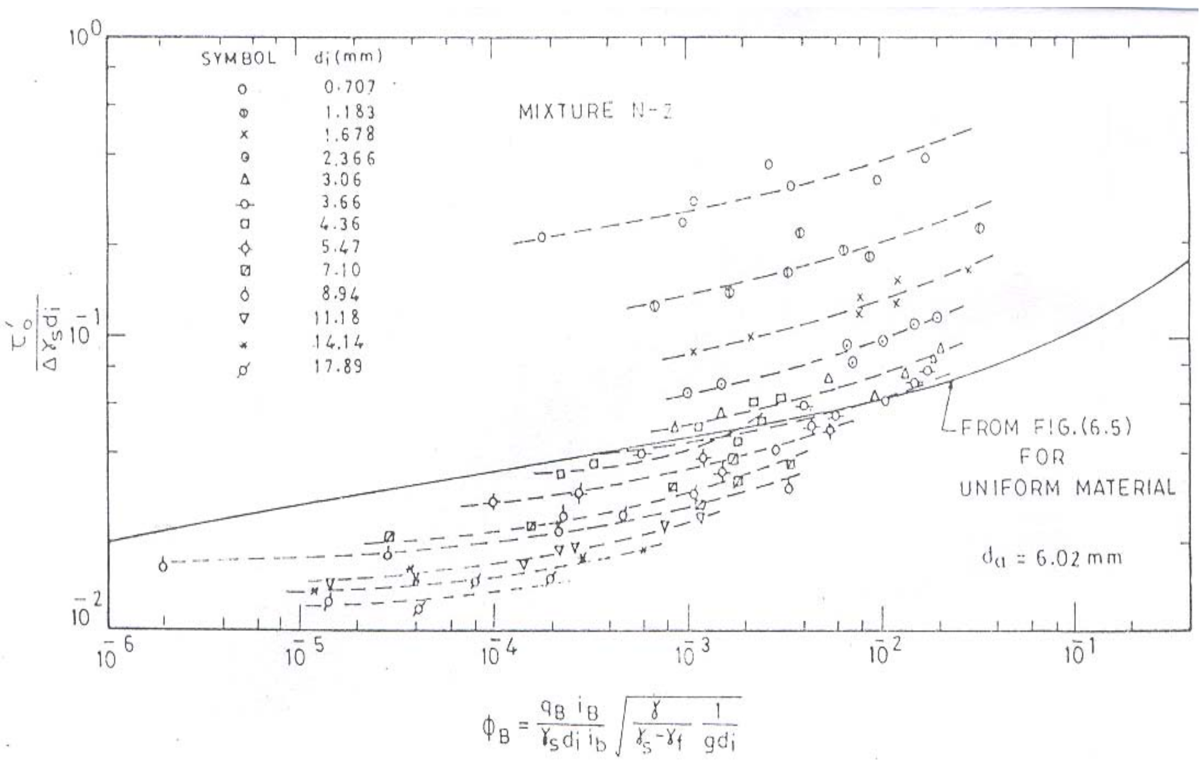

Figure 2.5 Comparison of Data on Transport of Different Fractions in a Mixture with Relationship for Uniform Material (Roorkee's Approach)

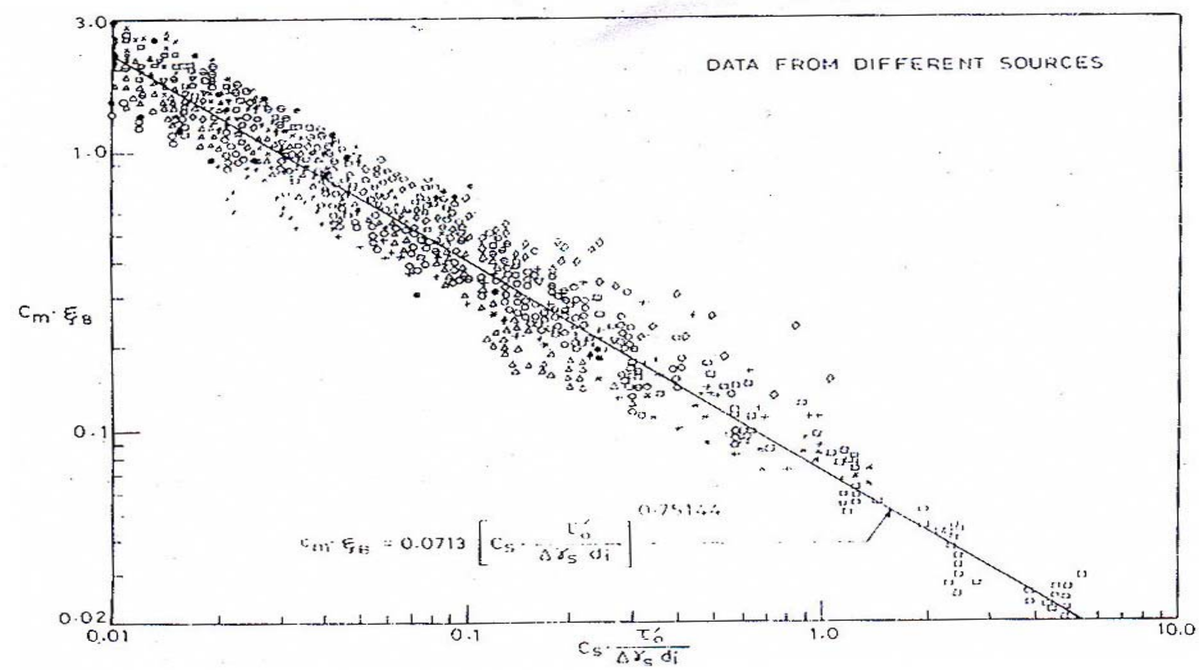

Figure 2.6 Variation of $C_m \xi_b$ with $C_s\ \tau_o'/(\Delta\gamma_s d_i)$ (Roorkee's Approach)

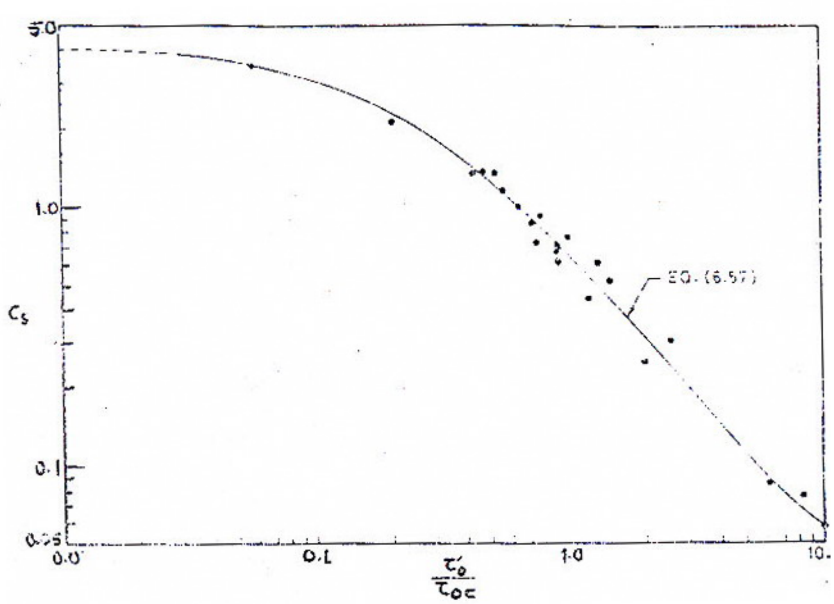

Figure 2.7 Variation of C_s with $\tau_o'/\ \tau_{oc}'$ (Roorkee's Approach)

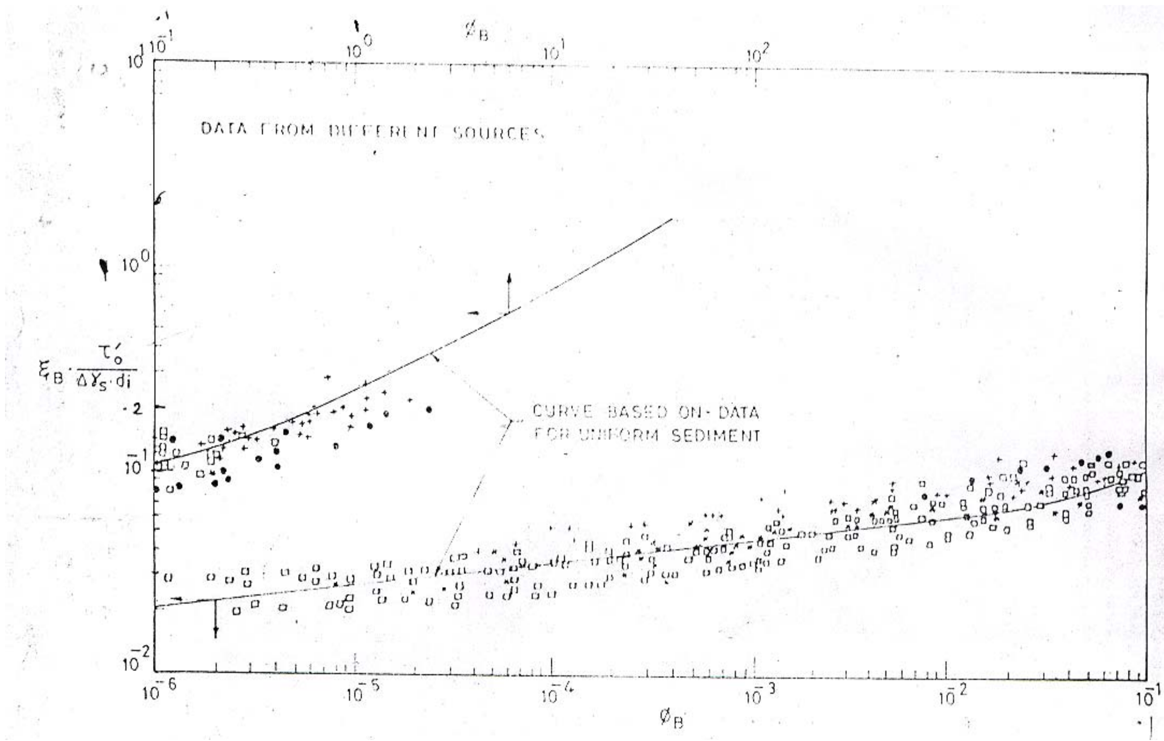

Figure 2.8 Field Data Plotted on Bed Load Transport Law for Non-uniform Sediments (Roorkee's Approach)

CHAPTER – 3
SOURCE OF DATA

3.1 GENERAL

While selection of data it was kept in mind to select the data corresponding to equilibrium flow. Initial bulk grain size distribution is measured along with the flow properties.The grain size distribution of equilibrium surface and transported material would suffice our planned analysis. The data was taken from the experiment conducted by Wilcock, Kenworthy and Crowe (2001). The data was available in the website ftp://agu.org in directory 'apend' having paper number 2001WR000683. The other experimental data has been taken from the experiments conducted by Patel et. al. (1995).

3.2 DESCRIPTION OF DATA

3.2.1 Wilcock Kenworthy and Crowe (2001)

Wilcock et al conducted experiment with sand and gravel mixture for five different set of data having different proportion of sand namely J06, J15, J21, J27 and BMC containing sand proportion as 6%, 15%, 21%, 27% and 34% respectively. They conducted 48 total run for different flow rates and obtained distribution of equilibrium surface along with transported sediments. The characteristics of sediments of these data sets are included in **Table 3.1**, while flow properties are included in **Table 3.4.**

3.2.2 Patel et al (1995)

The other data consist of five different sets namely M1, M2, M3, M4 and M5 having total 36 numbers of runs. The sediment was mix having different distribution unlike to above data where amount of sand mixed is known. Table 3.1(a) and Table 3.1(b) show the distribution of the bulk sediment used for each run in both the data. Different properties of bulk mix are indicated in Table 3.2. Various flow properties is shown of each run is shown in Table 3.3. Grain size distribution of the equilibrium sediment surface is attached in Appendix I.

Table 3.1 Grain Size Distribution of Bulk Mix, Wilcock et al (2001)

Sieve Size	% finer				
(mm)	BMC	JO6	J15	J21	J27
45.30	100.00	100.00	100.00	100.00	100.00
32.00	96.20	94.10	94.60	94.90	96.10
22.60	90.90	85.70	87.00	87.80	89.50
16.00	81.00	71.80	74.40	76.10	78.60
11.30	70.80	57.50	61.40	64.00	67.40
8.00	64.30	48.40	53.10	56.30	60.30
5.66	58.40	40.10	45.50	49.20	53.80
4.00	51.50	30.40	36.70	41.00	46.20
2.83	42.90	18.40	25.80	30.80	36.80
2.00	36.90	10.00	18.20	23.70	30.30
1.41	34.30	6.30	14.90	20.60	27.40
1.00	31.40	5.10	11.50	15.80	20.90
0.50	28.10	3.50	7.80	10.70	14.10
0.21	17.70	0.10	0.10	0.10	0.10

Table 3.2, Grain Size Distribution of Bulk Mix, Patel et al (1995)

Sieve Size	% finer				
(mm)	M1	M2	M3	M4	M5
40.00	100	100	100	100	100
31.25	100	100	100	100	97.50
25.00	100	98.97	100	98.87	95.00
20.00	100	98.06	100	96.90	93.00
16.00	99.25	93.39	99.48	93.34	89.50
12.50	97.46	90.00	98.54	90.18	85.50
10.00	94.78	86.44	97.54	87.88	82.00
8.00	91.80	81.85	95.84	84.35	78.50

6.30	82.86	68.16	90.02	75.09	74.00
4.75	72.43	63.90	86.90	72.66	68.00
4.00	57.08	54.23	78.27	65.66	63.50
3.35	51.57	49.26	70.47	62.26	58.00
2.80	39.95	38.09	55.71	53.13	50.00
2.00	15.36	17.83	32.31	30.81	28.50
1.70	11.63	14.19	26.69	25.55	22.50
1.40	10.14	8.56	15.56	18.22	16.50
1.00	4.63	5.75	4.95	13.52	9.00
0.60	0.46	0.66	0.27	1.13	0.82

Table 3.3 Properties of Bulk Sediment Mix

Run	**Properties**					
	$D_{84.1}$	**$d_{15.9}$**	**σ_g**	**M**	**d_a**	**d_g**
	(mm)	**(mm)**			**(mm)**	**(mm)**
BMC	17.650	0.173	10.101	0.061	9.613	3.258
JO6	22.074	2.570	2.931	0.190	13.919	8.753
J15	21.150	1.580	3.659	0.152	12.691	6.987
J21	20.180	1.082	4.319	0.127	11.908	6.022
J27	18.830	0.777	4.923	0.105	10.689	4.976
M1	8.839	1.854	2.183	0.380	4.160	3.383
M2	8.838	1.788	2.223	0.258	5.480	3.898
M3	4.470	1.359	1.814	0.407	3.180	2.591
M4	8.070	1.234	2.557	0.213	4.800	3.073
M5	11.451	1.360	2.902	0.180	6.080	3.524

Table 3.4 Flow Properties of Data Used in Present Study

Run	Discharge (m^3/s)	Depth (m)	Slope	Velocity (m/s)	τ_o (m^2/s)	Total Transport (N/m-s) x 10^3
M1-1	0.0250	0.0828	0.005000	0.750	3.3599	9.30
M1-2	0.0275	0.1020	0.004300	0.674	3.5937	30.70
M1-3	0.0315	0.1070	0.004300	0.737	3.6632	35.70
M1-4	0.0360	0.1200	0.004300	0.750	4.0830	54.20
M1-5	0.0335	0.1180	0.003975	0.710	3.7319	9.50
M1-6	0.0360	0.1160	0.003975	0.779	3.5411	14.10
M1-7	0.0400	0.1225	0.003975	0.816	3.6648	25.20
M1-8	0.0250	0.0750	0.007540	0.830	4.7278	63.36
M2-1	0.0310	0.1230	0.003230	0.730	3.0003	7.09
M2-2	0.0400	0.1310	0.003230	0.760	3.1360	10.83
M2-3	0.0450	0.1420	0.003230	0.790	3.3335	10.88
M2-4	0.0305	0.0986	0.004419	0.770	3.4315	31.78
M2-5	0.0360	0.1120	0.004418	0.800	3.8407	13.00
M2-6	0.0447	0.1273	0.004418	0.880	4.1883	30.23
M2-7	0.0310	0.0925	0.005930	0.840	4.4117	22.50
M2-8	0.0416	0.1125	0.005930	0.920	5.1932	88.80
M3-1	0.0140	0.0587	0.004858	0.596	2.4477	12.20
M3-2	0.0250	0.0892	0.004880	0.700	3.5930	82.50
M3-3	0.0280	0.0908	0.004858	0.770	3.5328	186.90
M3-4	0.0150	0.0598	0.005642	0.627	2.9107	8.62
M3-5	0.0185	0.0688	0.005642	0.672	3.2984	42.90
M3-6	0.0250	0.0836	0.005642	0.748	3.9001	169.20
M3-7	0.0171	0.0719	0.004408	0.594	2.6931	5.32
M3-8	0.0145	0.0661	0.004408	0.549	2.5185	0.47
M4-1	0.0125	0.0600	0.004408	0.520	2.3102	1.34
M4-2	0.0180	0.0690	0.004408	0.652	2.5246	3.03
M4-3	0.0290	0.0980	0.004408	0.740	3.4493	25.40
M4-4	0.0160	0.0640	0.004408	0.624	2.3688	4.86
M4-5	0.0340	0.1060	0.004408	0.800	3.6251	94.36
M4-6	0.0132	0.0560	0.005075	0.589	2.4566	2.36
M4-7	0.0310	0.0946	0.005075	0.820	3.7901	111.70
M5-1	0.0245	0.0850	0.004456	0.720	3.0575	5.13

M5-2	0.0280	0.0900	0.004456	0.778	3.1515	9.65
M5-3	0.0370	0.1050	0.004456	0.825	3.5928	21.10
M5-4	0.0410	0.1195	0.004458	0.860	4.0182	21.00

Table 3.3 contd….

Run	**Discharge**	**Depth**	**Slope**	**Velocity**	**τ_o**	**Total Transport**
	(m^3/s)	**(m)**		**(m/s)**	**(m^2/s)**	**(N/m-s) x 10^3**
M5-5	0.0185	0.0694	0.005400	0.670	3.1703	6.47
BMC14c	0.029	0.111	0.0006	0.26126	0.5775	0.02266
BMC7a	0.034	0.11	0.0009	0.30909	0.8641	0.32275
BMC14b	0.036	0.109	0.0009	0.33028	0.8452	0.37867
BMC7b	0.04	0.111	0.0011	0.36036	1.0548	0.93391
BMC7c	0.048	0.105	0.0017	0.45714	1.5356	4.18887
BMC1	0.067	0.12	0.0018	0.55833	1.7818	56.8980
BMC2	0.067	0.112	0.0032	0.59821	3.1129	69.6510
BMC6	0.079	0.096	0.0069	0.82292	5.8227	1226.2500
BMC4	0.081	0.094	0.0077	0.8617	6.3721	1540.1700
BMC5	0.095	0.088	0.0162	1.07955	12.8336	5611.320
J06.1	0.0780	0.104	0.0044	0.750	3.9202	0.00218
J06.2	0.0860	0.108	0.0049	0.796	4.5275	0.02482
J06.3	0.0960	0.104	0.0094	0.923	8.6511	0.90841
J06.4	0.1030	0.102	0.0133	1.010	12.1589	13.83210
J06.5	0.0910	0.103	0.0067	0.883	5.9697	0.19718
J06.6	0.1050	0.103	0.0092	1.019	8.2223	4.218
J06.7	0.1210	0.106	0.0158	1.142	14.9310	142.245
J06.8	0.0780	0.105	0.0056	0.743	5.1669	0.03257
J06.9	0.1280	0.109	0.0176	1.174	17.1674	290.376
J06.10	0.1330	0.108	0.0204	1.231	19.7894	2001.240
J14.1	0.1260	0.117	0.0165	1.077	17.4058	504.234
J14.2	0.1240	0.109	0.0173	1.138	16.9302	730.845
J14.3	0.0840	0.107	0.0061	0.785	5.7228	0.29332
J14.4	0.1010	0.104	0.0106	0.971	9.7702	17.462
J14.5	0.1100	0.106	0.0144	1.038	13.7047	122.625
J14.6	0.0790	0.102	0.0044	0.775	3.8172	0.188
J14.7	0.0960	0.106	0.0083	0.906	7.7291	15.107
J14.8	0.0910	0.106	0.0076	0.858	7.0889	5.366
J14.9	0.1330	0.117	0.0157	1.137	16.3786	1128.150

J21.1	0.1260	0.118	0.0155	1.068	16.4402	1324.350
J21.2	0.0790	0.108	0.0043	0.731	3.9900	4.7775
J21.3	0.0890	0.102	0.0071	0.873	6.3153	60.0372
J21.4	0.0990	0.105	0.0114	0.943	10.7154	117.0333
J21.5	0.0730	0.109	0.0034	0.670	3.1639	1.3047
J21.6	0.0900	0.104	0.0078	0.865	7.1443	125.5680
J21.7	0.0650	0.099	0.0032	0.657	2.6982	0.16383
J21.8	0.1120	0.102	0.0171	1.098	15.7228	1491.120
J21.9	0.1200	0.107	0.0175	1.121	16.8578	--N.A.--
J27.1	0.0650	0.102	0.0029	0.637	2.1655	4.73823
J27.2	0.0890	0.101	0.007	0.881	5.1888	359.046
J27.3	0.0500	0.110	0.001	0.455	0.7896	0.0287433
J27.4	0.0570	0.101	0.0026	0.564	1.9273	2.01105
J27.5	0.0820	0.093	0.0074	0.882	5.1536	270.756
J27.6	0.0750	0.098	0.0043	0.765	3.1160	55.1322
J27.7	0.1030	0.106	0.008	0.972	6.1470	654.5232
J27.8	0.1130	0.106	0.0098	1.066	7.5300	1030.05
J27.9	0.1250	0.106	0.0143	1.179	10.9877	3325.59
J27.10	0.1300	0.111	0.017	1.171	13.5120	7641.99

CHAPTER – 4

ANALYSIS OF DATA

4.1 GENERAL

The existing data available on equilibrium sediment bed surface were used to check their conformity with standard probabilistic models. Then, the parameters of best suited probabilistic model were derived from characteristics of bulk sediment grain size distribution and corresponding flow properties & method has been proposed to predict the equilibrium sediment bed surface on the basis of aforesaid findings. Subsequently, predicted sediment was used to check the adequacy of existing bed load transport model based on bulk mix sediment properties.

4.2 PREDICTION OF DISTRIBUTION OF EQUILIBRIUM BED SURFACE

While predicting the complete grain size distribution of the bed surface, the probabilistic models were checked for their conformity with the surface distribution. All the data were made dimensionless by dividing each size by average size of the particle of bed surface in that run. Complete analysis was carried out in distribution fitting tool of MATLAB 7.01. While entering the frequency the data was multiplied by 1000 in order to eliminate decimal, however it won't affect the results as proportion of each particle remain same. The data were fitted to different probability distribution like Normal distribution; Lognormal distribution and Gamma distribution. To check the suitability of probability distribution method of maximum likelihood was used. Log likelihood value of each distribution was determined. All three fitted distribution to the data are shown in Fig. 4.1 to Fig. 4.3. Also, the best fitting characteristic of different distributions are shown in Table 4.1. The best fitted distribution i.e. lognormal distribution is shown in log probability paper. (see Fig. 4.1 a)

Table 4.1, Properties of Distribution Fit to Data

Normal Distribution	Log likelihood	d_a	Std Err	σ	Std Err
	-115.035	1.00088	0.003292	0.953543	0.002328
Lognormal Distribution	Log likelihood	d_g	Std Err	σ_g	Std Err
	-85.206	0.629884	0.003661	2.890912	0.002588
Gamma Distribution	Log likelihood	a	Std Err	b	Std Err
	-105.067	1.22081	0.005339	0.819849	0.004407

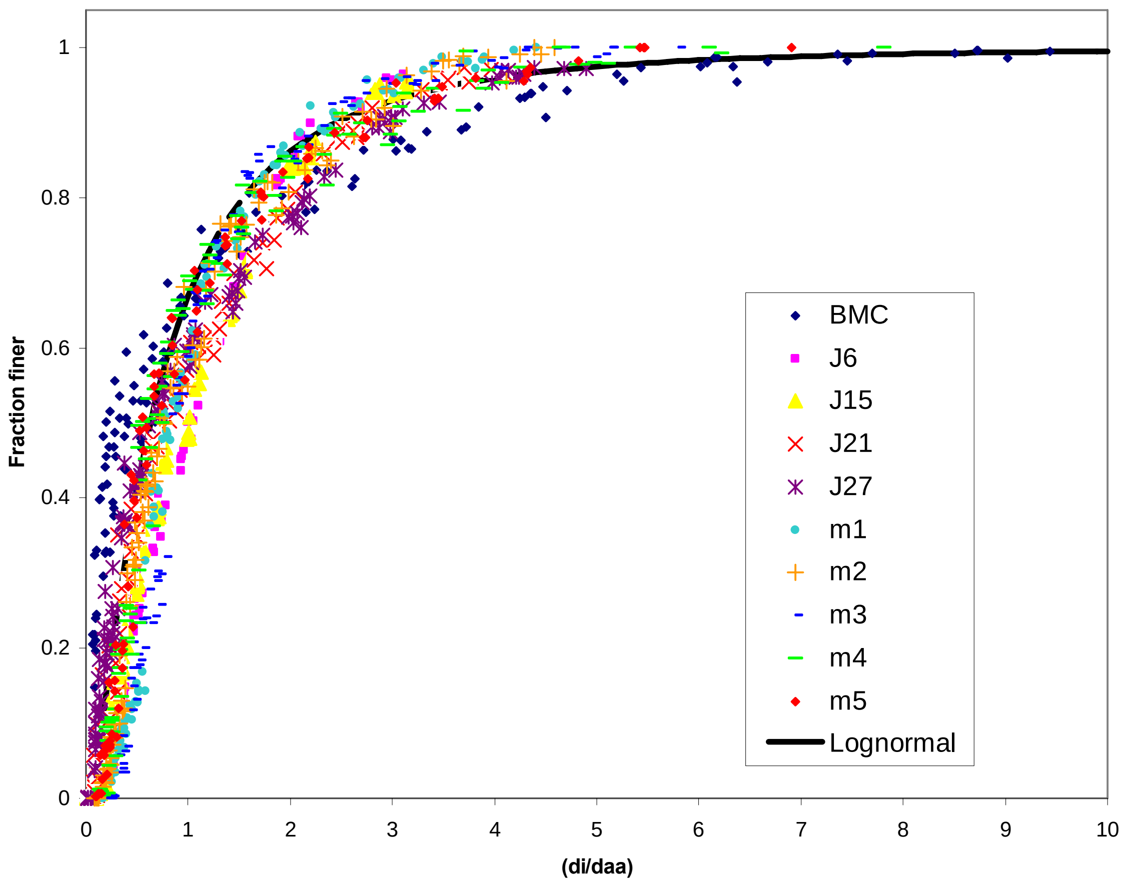

Figure 4.1 Data Showing Lognormal Distribution

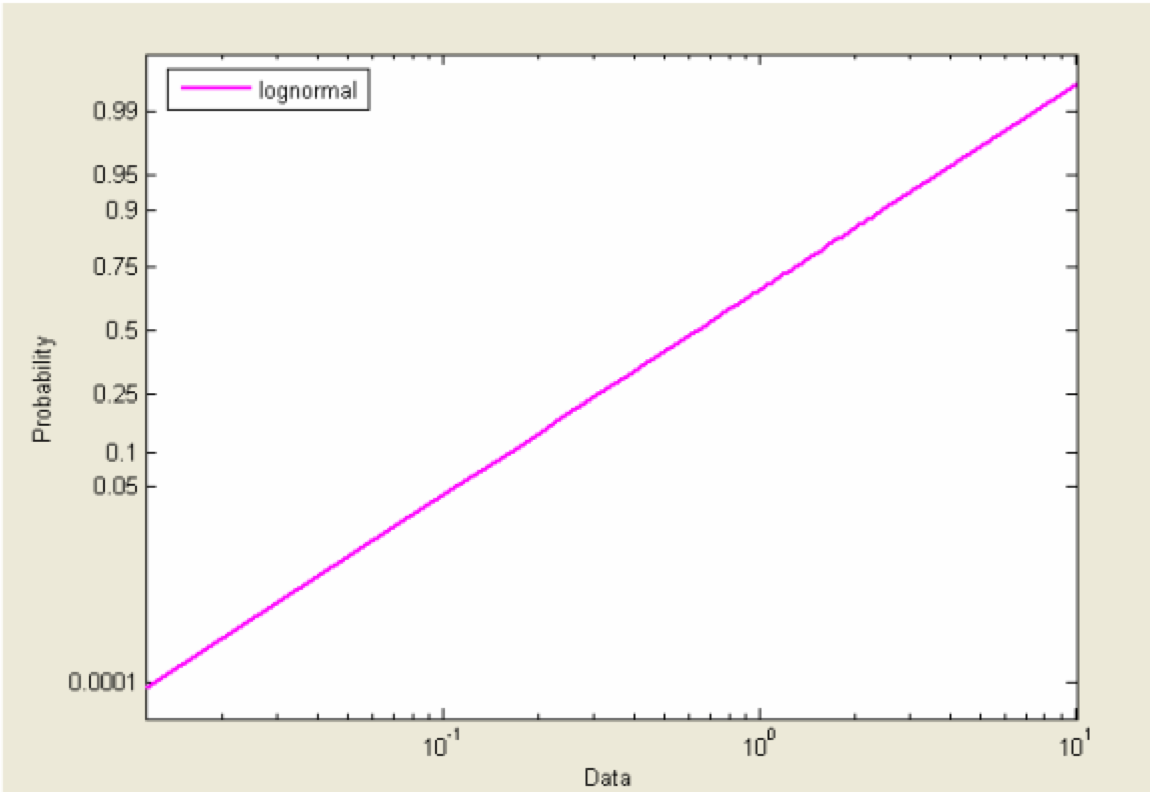

Figure 4.1 (a) Data Showing Lognormal Distribution in Log-probability Paper

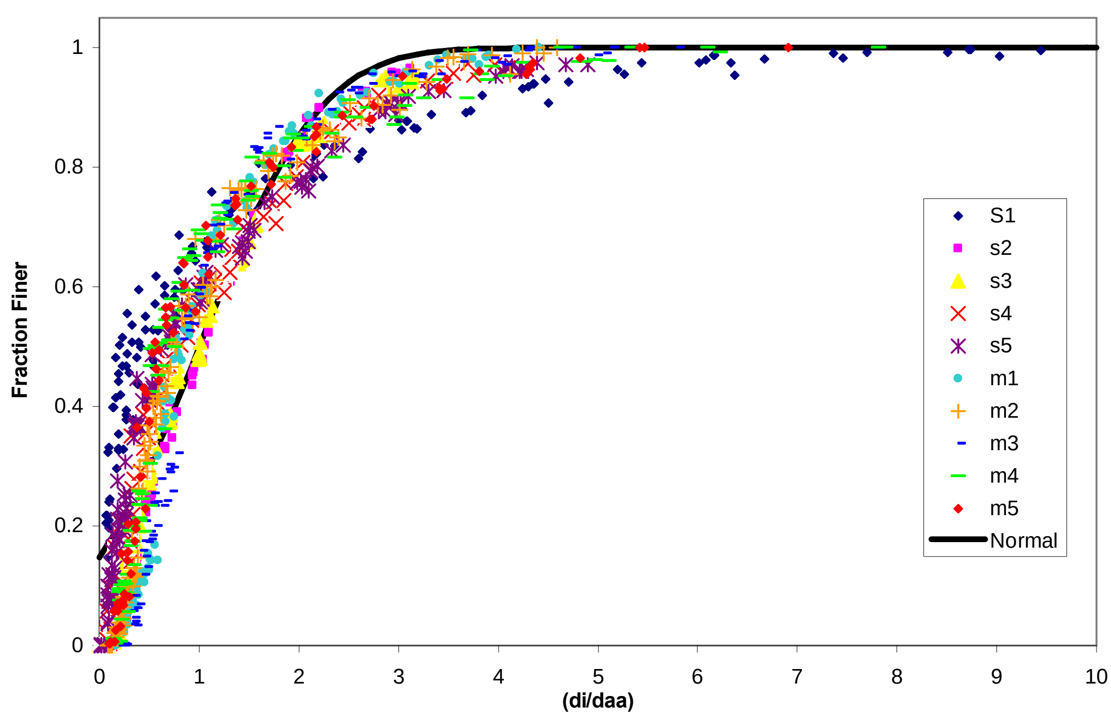

Figure 4.2 Data Showing Normal Distribution

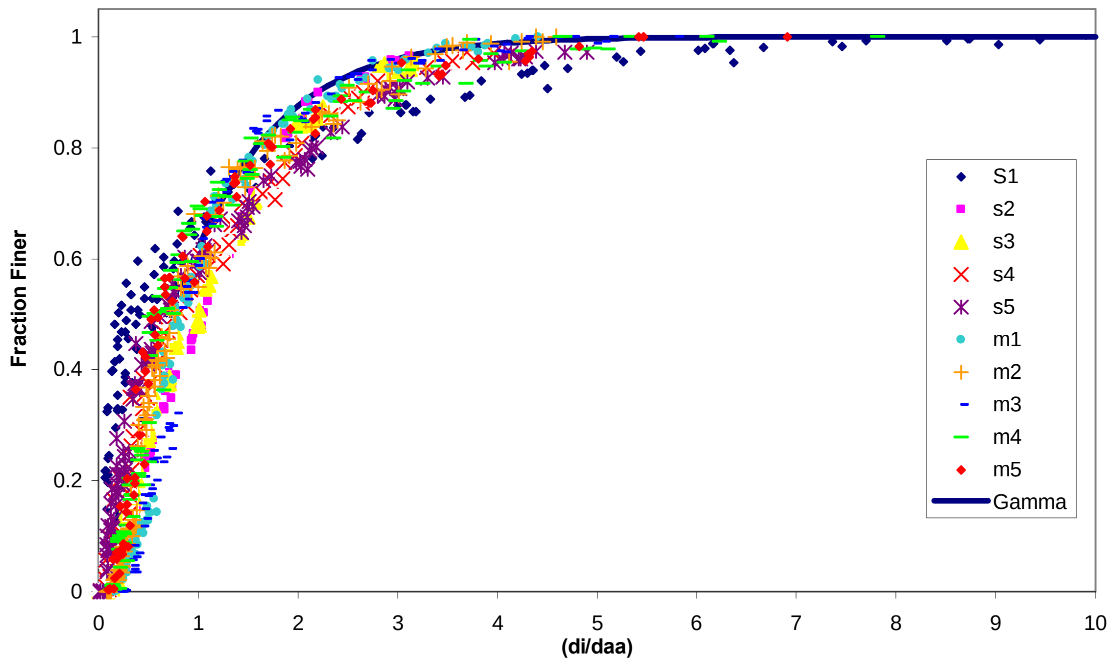

Figure 4.3 Data Showing Gamma Distribution

From Fig. 4.1 to 4.3 and Table 4.1 it is ample clear that log likelihood is maximum for lognormal distribution, therefore lognormal distribution is the best distribution for equilibrium sediment bed surface with σ_g = 2.8901.

Using the lognormal distribution with σ_g = 2.8901, the grain size distribution of equilibrium bed surface can be computed provided the model parameter like weighted average grain size distribution of sediment bed surface is known. The succeeding paragraph describes the development of model for predictor of average size of the sediment bed surface.

With the help of this curve if d_{aa} is known than for any d_i value its fraction finer can be read and whole grain size distribution can be determined.

4.3 PREDICTION OF AVERAGE SIZE OF EQUILIBRIUM SEDIMENT BED SURFACE

During prediction of average size of the equilibrium surface it was assumed that average size (d_{aa}) of the surface depends on the flow parameters as well the characteristics of the initial bed sediment mixture, a function relationship may be formulated as:

$$d_{aa} = f(d_{ai}, M, \tau_0, D, \Delta\gamma_s) \quad \text{-----------------------} \quad (4.1)$$

Here suffix 'a' corresponds to the property of equilibrium surface and that of 'i' corresponds to initial bulk mix and 'D' is the average depth of flow. Using dimensional analysis, Eq. 4.1 may be as:

$$\frac{d_{aa}}{d_{ai}} = f_1\left(M, \frac{\tau_0}{\Delta\gamma_s \cdot d_{ai}}, \frac{D}{d_{ai}}\right) \quad \text{----------------------} \quad (4.2)$$

D/d_{ai} was included because it describes roughness on which Manning's coefficient and Darcy-Weisbach's friction factor for hydro dynamically rough boundary depend.

A plot of $(d_{aa}/d_{ai})^a.(M)^b$ Vs $(\tau_0/\Delta\gamma_s.d_{ai})^c.(D/d_{ai})^d$ was drawn taking different values of a, b, c and d and fitting it for different curves. Regression analysis was carried out using the curve fitting tool in MATLAB 7.01. The best fitted graph was found between

$$\left(\frac{\tau_0}{\Delta\gamma_s d_{ai}}\right)\cdot\left(\frac{D}{d_{ai}}\right)^{2.8} vs \left(\frac{d_{aa}}{d_{ai}}\right)\cdot M^{1.2}$$

The resulted plot is shown in Fig. 4.4. the best fit curve passing through the datacan be expressed as:

$$\left(\frac{d_{aa}}{d_{ai}}\right)\cdot M^{1.2} = 0.4166 \times e^{-0.0001794\left(\frac{\tau_0}{\Delta\gamma_s d_{ai}}\right)\cdot\left(\frac{D}{d_{ia}}\right)^{2.8}} - 0.4369 \times e^{-0.004522\left(\frac{\tau_0}{\Delta\gamma_s d_{ai}}\right)\cdot\left(\frac{D}{d_{ia}}\right)^{2.8}} \quad \text{----} \quad (4.3)$$

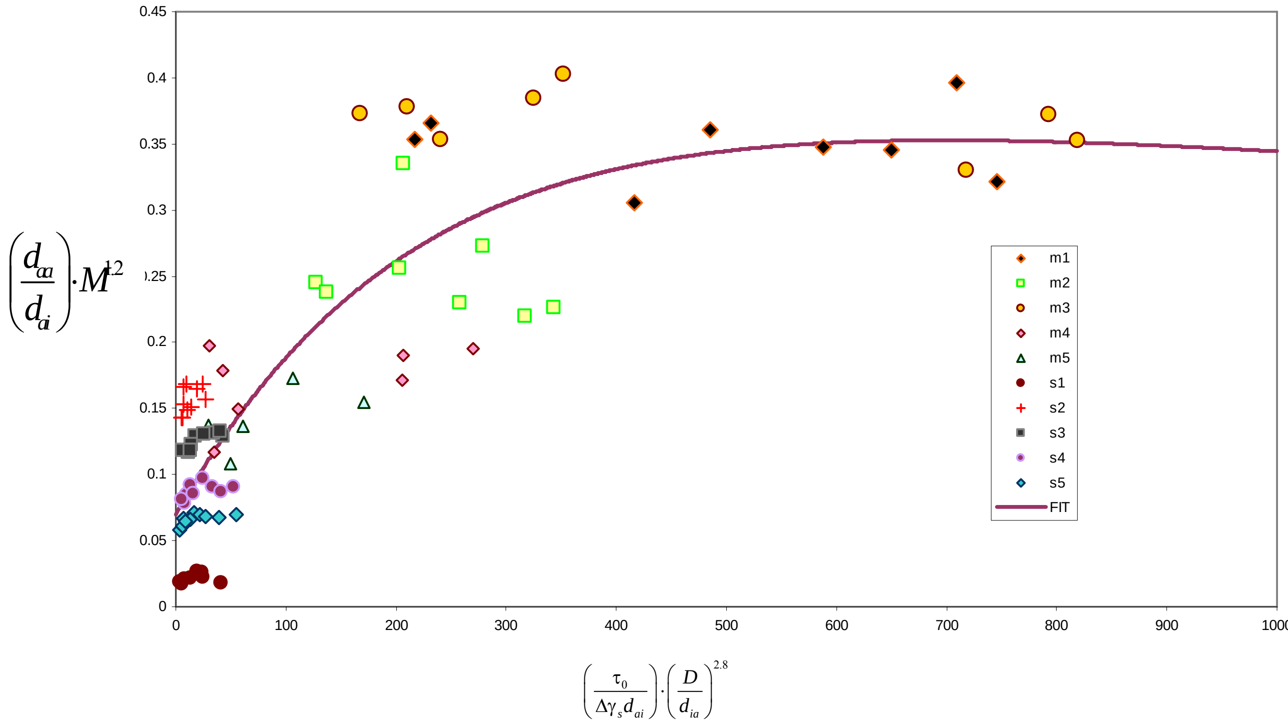

Figure 4.4 Variation of $\left(\frac{\tau_0}{\Delta\gamma_s d_{ai}}\right)\cdot\left(\frac{D}{d_{ai}}\right)^{2.8}$ **with** $\left(\frac{d_{aa}}{d_{ai}}\right)\cdot M^{1.2}$

From the above graph the average size of the particle can be computed provided grain size distribution of bulk mix and flow properties are known. In the plot it can be seen that initially the slope of curve is steep, later it becomes mild. This can be explained as with increase in shear stress, average size of the equilibrium surface increases rapidly this shows rapid increase in sediment transport, after that which with increase in x parameter change in the value in y parameter is less and later on it decreases which tells that up to certain level of shear stress there would be coarsening of the bed surface as all finer particle would move, after that further increase in the shear stress or flow would force coarser particle to move and there place would be occupied by the finer particle present in the flow, which decrease the average size of the sediment bed surface. However it is not possible to have replacement of finer particle with coarser particle. This phenomenon is also known as kinematic sorting.

Computed average size of sediment bed surface from Eq. 4.3 from known bulk sediment mix and flow properties are compared with those calculated from observed data (see Fig. 4.5)

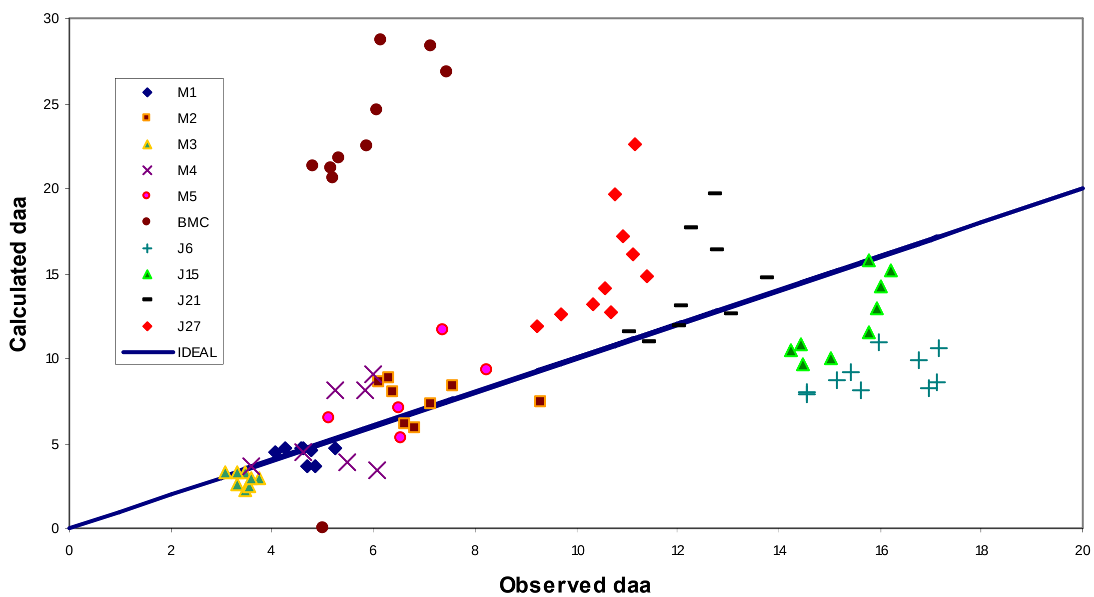

Figure 4.5 Comparison between observed d_{aa} and calculated d_{aa}.

In general, computed values match closely with observed ones except for BMC data, this disagreement with BMC data may be ascribed as extreme non-uniformity of the mix, see Table 3.3. The reason behind was sorted out, and can be explained as, BMC sediment is highly non-uniformly distributed data, having standard deviation 10.01 and Krammer's uniformity coefficient as 0.061. Most interesting feature of observed data was that after each run average size of the particle of equilibrium bed has decreased significantly for BMC mix unlikely to other sediments data where the same has increased or decrease in size (see Appendix I). This shows that there was a heavy deposition of finer particle the sediment in the bed surface due to greater non-uniformity coarser particles are transported at relatively smaller shear stress and finer particle took place of the se coarser particles. While a relatively greater shear stress is required to move finer particles when compared with corresponding uniform sediments.

4.4 PROPOSED METHOD FOR COMPUTATION OF EQUILIBRIUM SEDIMENT BED SURFACE

The following steps can be used to predict the grain size distribution of equilibrium bed surface on the basis of findings of previous sections.

Steps:

(i) Compute average size (d_{ai}), Krammer's uniformity coefficient (M) of bulk mix. Compute total bed shear stress (τ_0), average depth of flow (D) for given flowing condition.

(ii) Compute parameter x $= \left(\frac{\tau_0}{\Delta\gamma_s d_{ai}}\right)\cdot\left(\frac{D}{d_{ai}}\right)^{2.8}$

(iii) Read corresponding value of $\left(\frac{d_{aa}}{d_{ai}}\right)\cdot M^{1.2}$ for computed value of x in step (ii) from Fig. 4.4, or use Eq. 4.3 to obtain value of $\left(\frac{d_{aa}}{d_{ai}}\right)\cdot M^{1.2}$

(iv) Knowing value of $\left(\frac{d_{aa}}{d_{ai}}\right)\cdot M^{1.2}$, calculate value of average grain size of equilibrium surface (d_{aa}) as value of d_{ai} and M is known.

(v) Chose suitable value of particle size (d_i), calculate value of (d_i/d_a) and read corresponding fraction finer from Fig. 4.1 and obtain grain size distribution.

4.5 VERIFICATION OF PROPOSED METHOD

In this section estimated grain size distribution is compared with observed grain size distribution (see Fig. 4.6 to Fig. 4.25). It is seen from these figures that most of the calculated grain size distributions match observed value, except for BMC data. the reason has been explained in previous section. It was also observed that for the sediments in which estimation of d_{aa} was more accurate the estimated distribution curve was also matching better to the original distribution.

In Fig. 4.6 to Fig. 4.25; observed and calculated particle size distribution of the equilibrium surface are shown taking two runs from each sediment group. The first one shows the best estimated distribution in that group the other one shows the worst fitted distribution; rest all the values lie between these distribution.

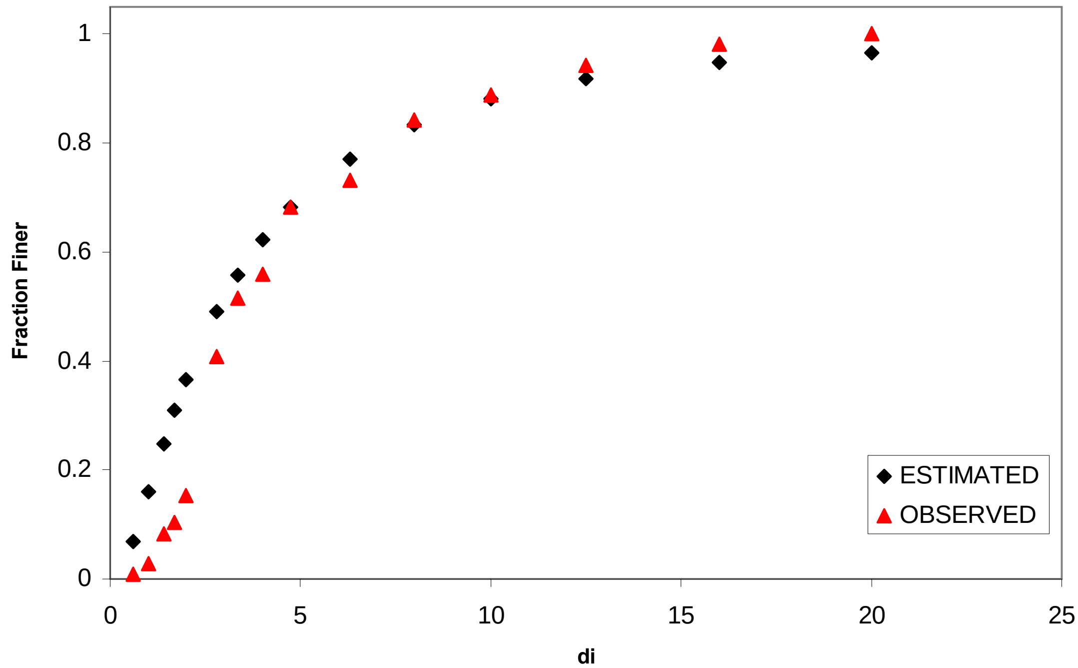

Figure 4.6 Particle Size Distribution (Data M1-3)

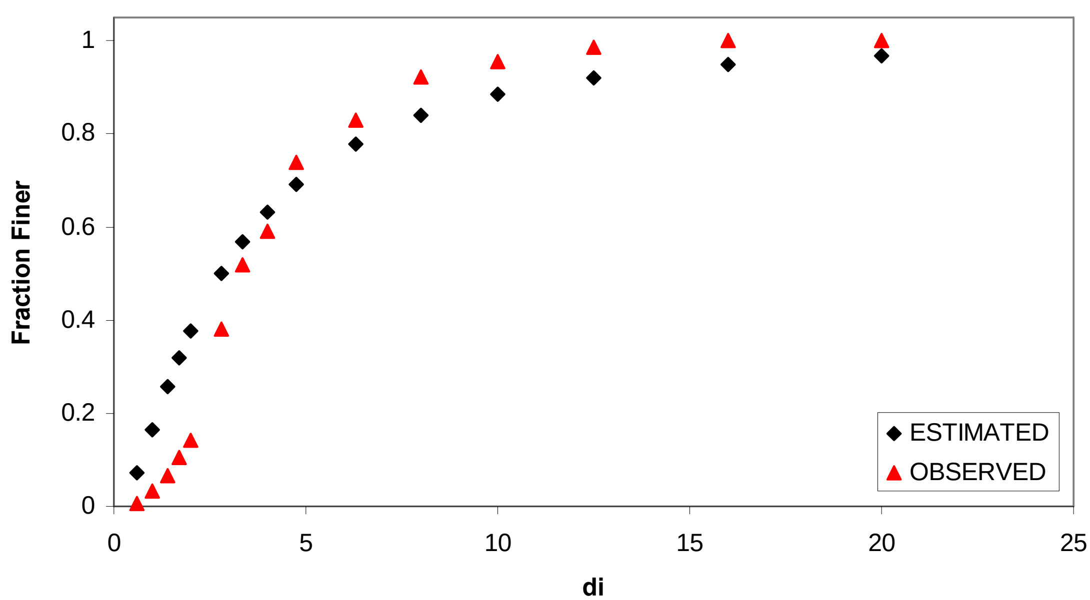

Figure 4.7 Particle Size Distribution (Data M1-2)

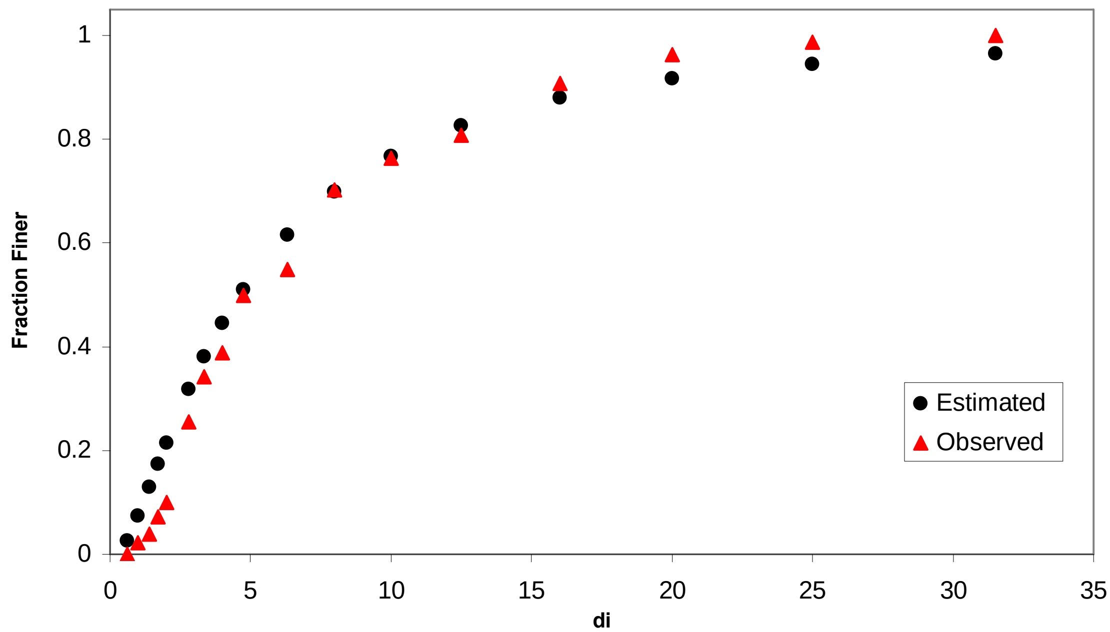

Figure 4.8 Particle Size Distribution (Data M2-5)

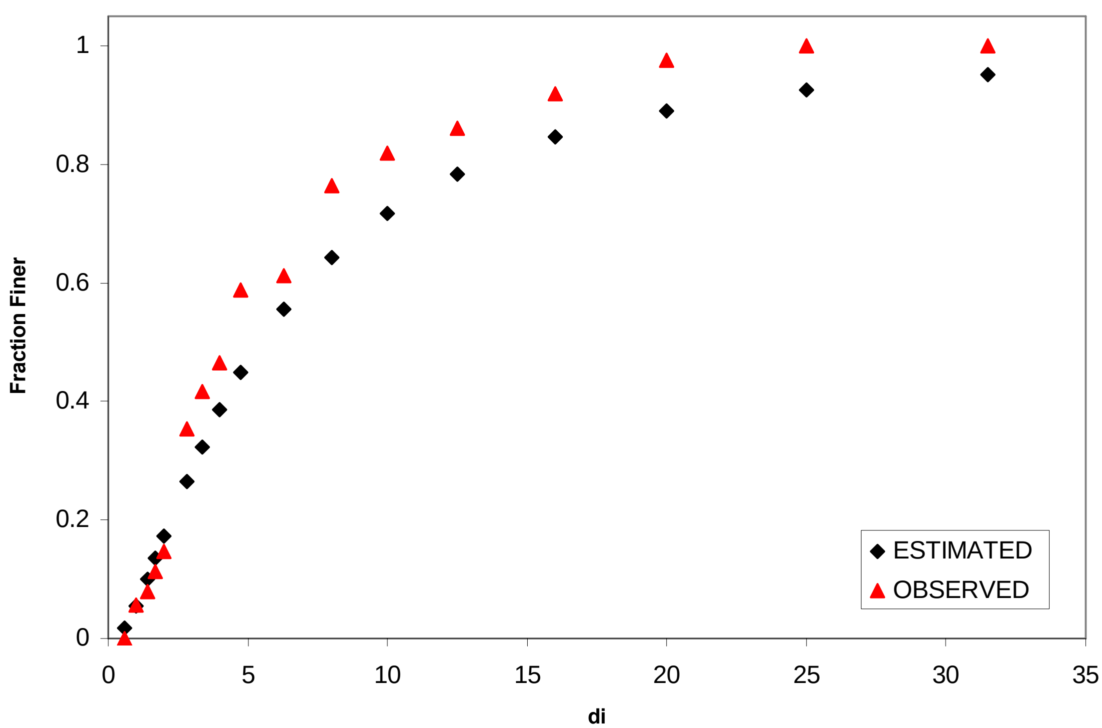

Figure 4.9 Particle Size Distribution (Data M2-6)

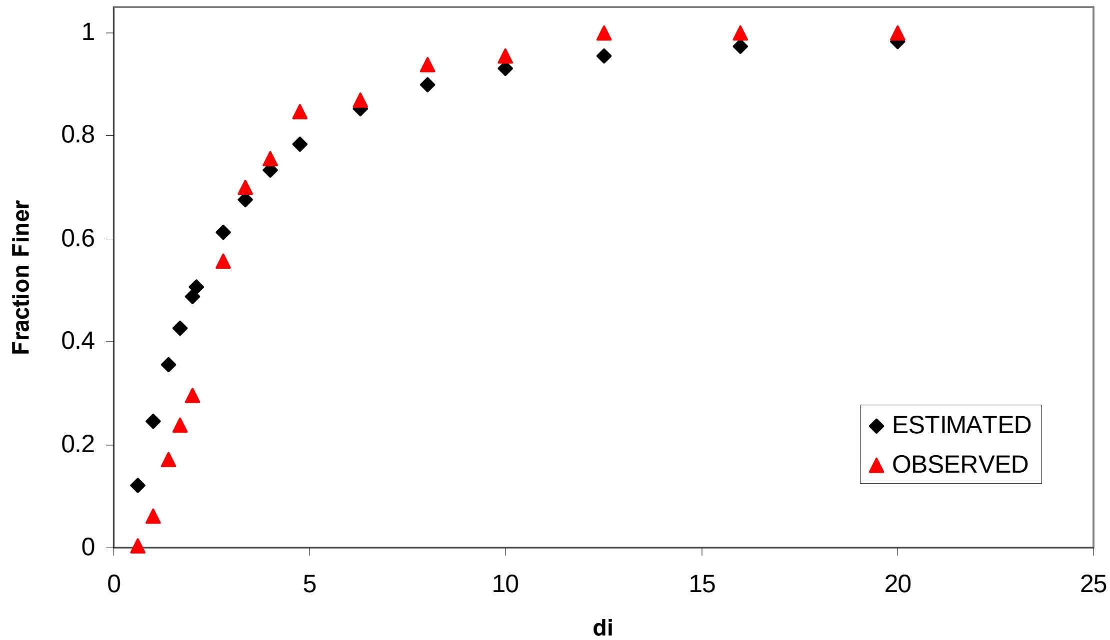

Figure 4.10 Particle Size Distribution (Data M3-1)

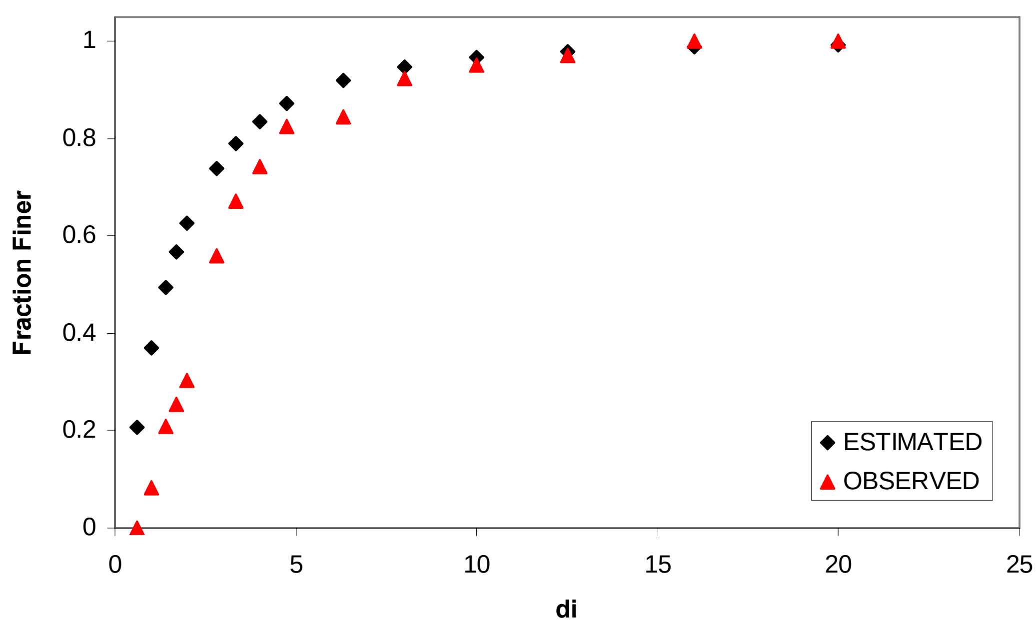

Figure 4.11 Particle Size Distribution (Data M3-3)

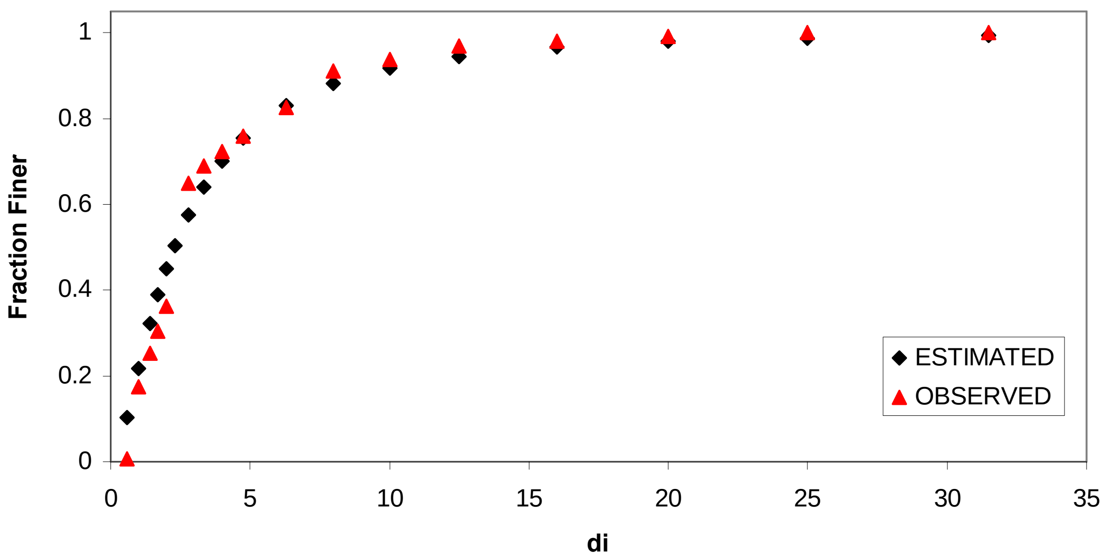

Figure 4.12 Particle Size Distribution (Data M4-5)

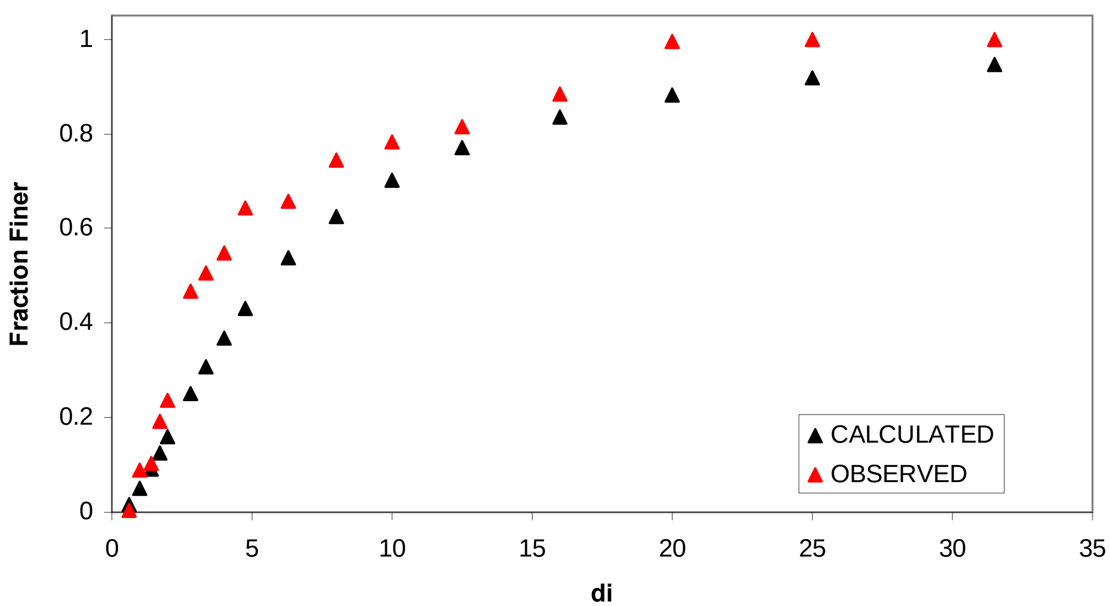

Figure 4.13 Particle Size Distribution (Data M4-5)

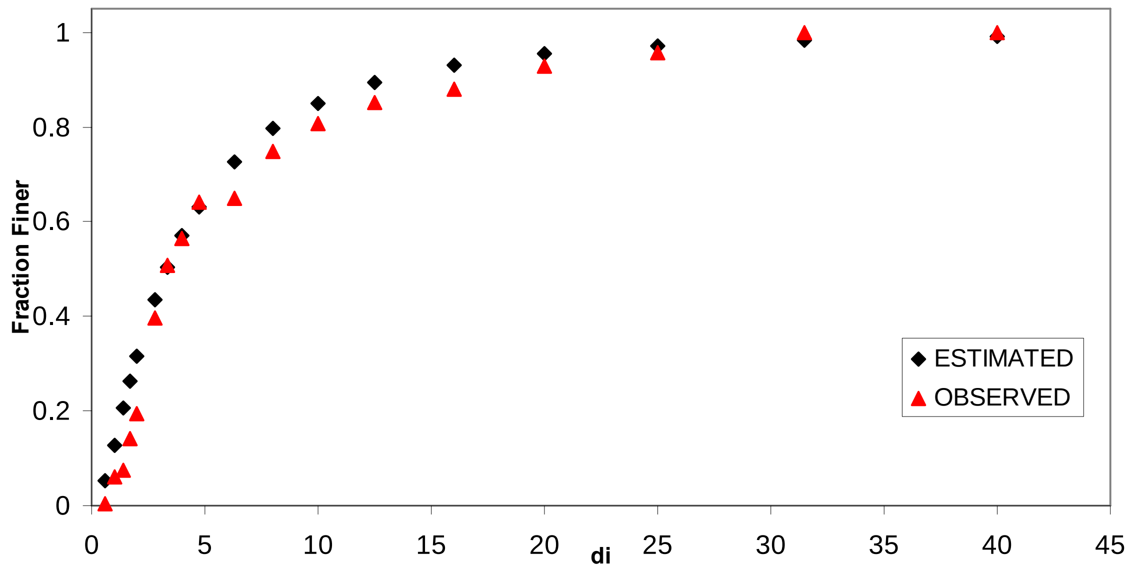

Figure 4.14 Particle Size Distribution (Data M5-5)

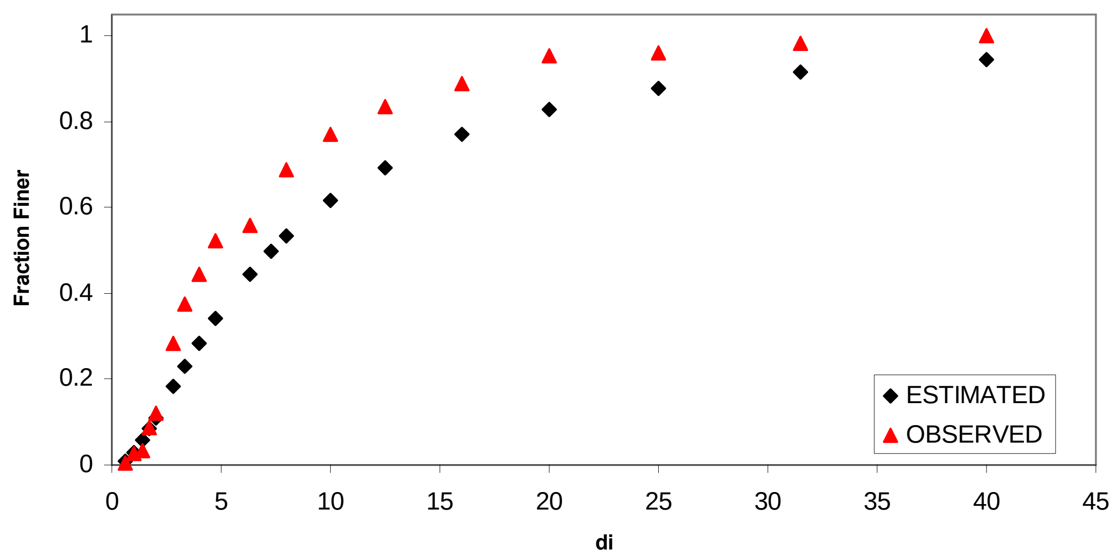

Figure 4.15 Particle Size Distribution (Data M5-4)

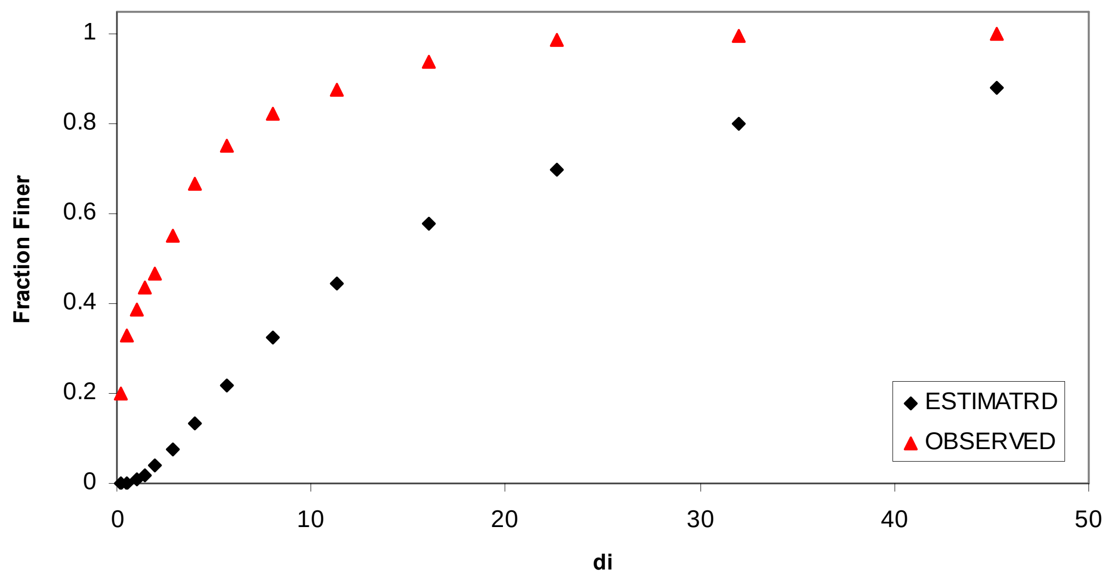

Figure 4.16 Particle Size Distribution (Data BMC-1)

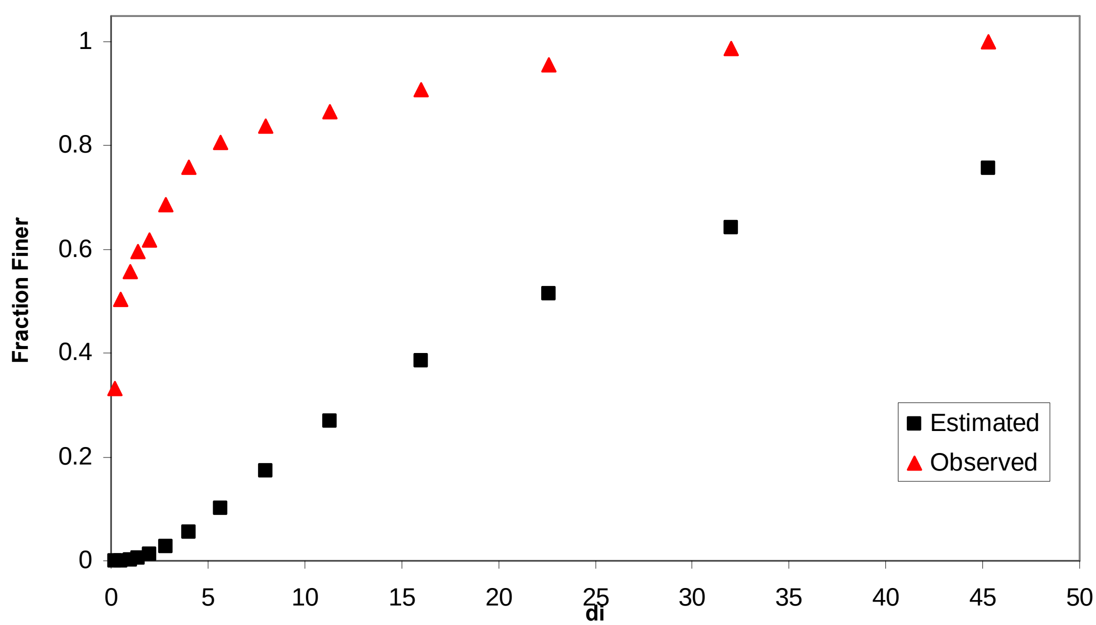

Figure 4.17 Particle Size Distribution (Data BMC-9)

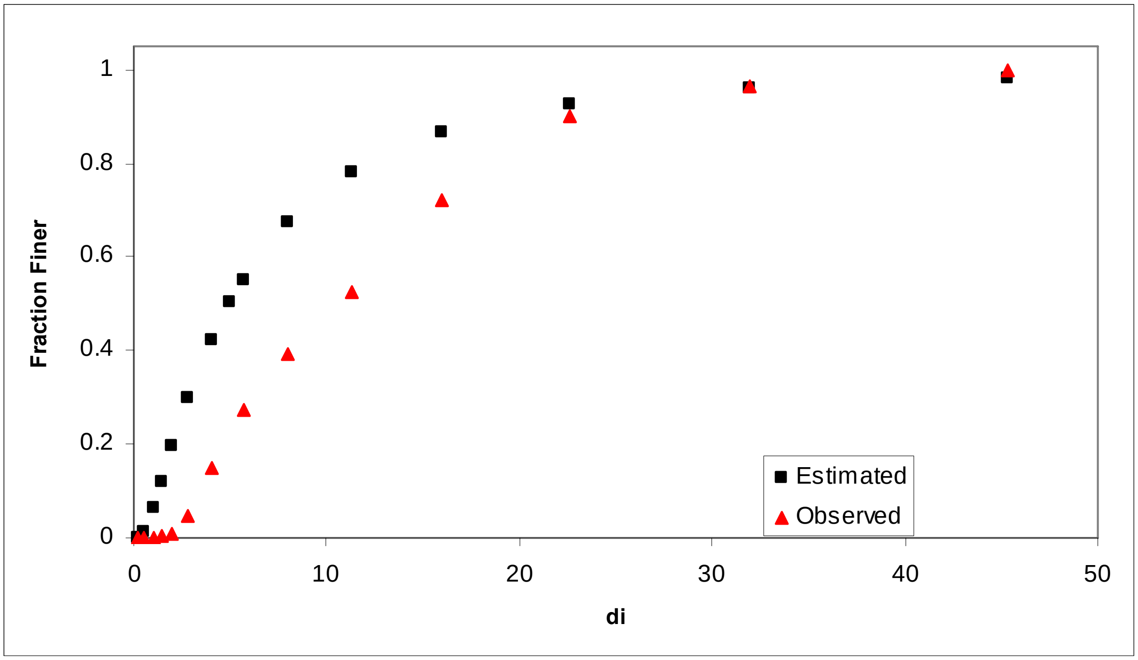

Figure 4.18 Particle Size Distribution (Data J6-1)

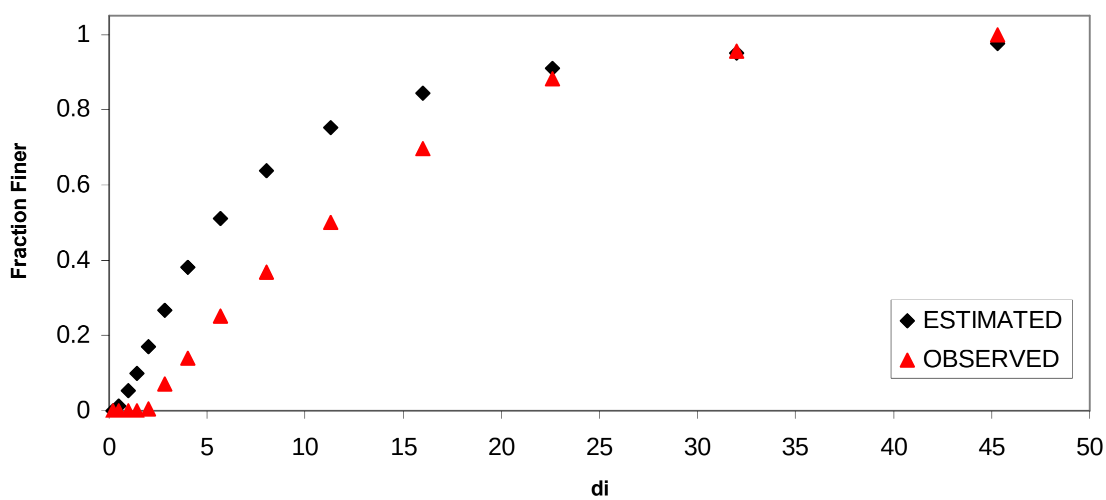

Figure 4.19 Particle Size Distribution (Data J6-3)

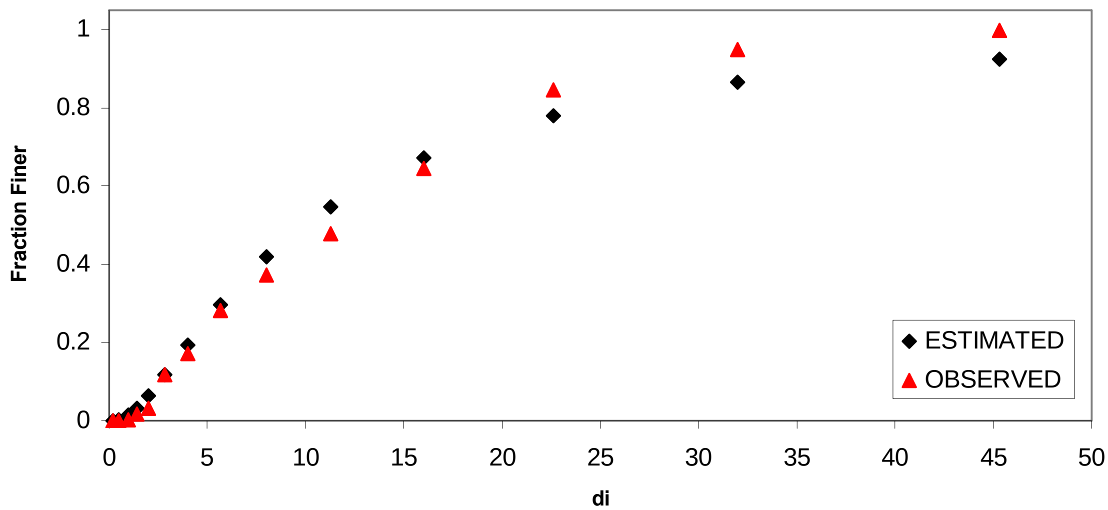

Figure 4.20 Particle Size Distribution (Data J15-1)

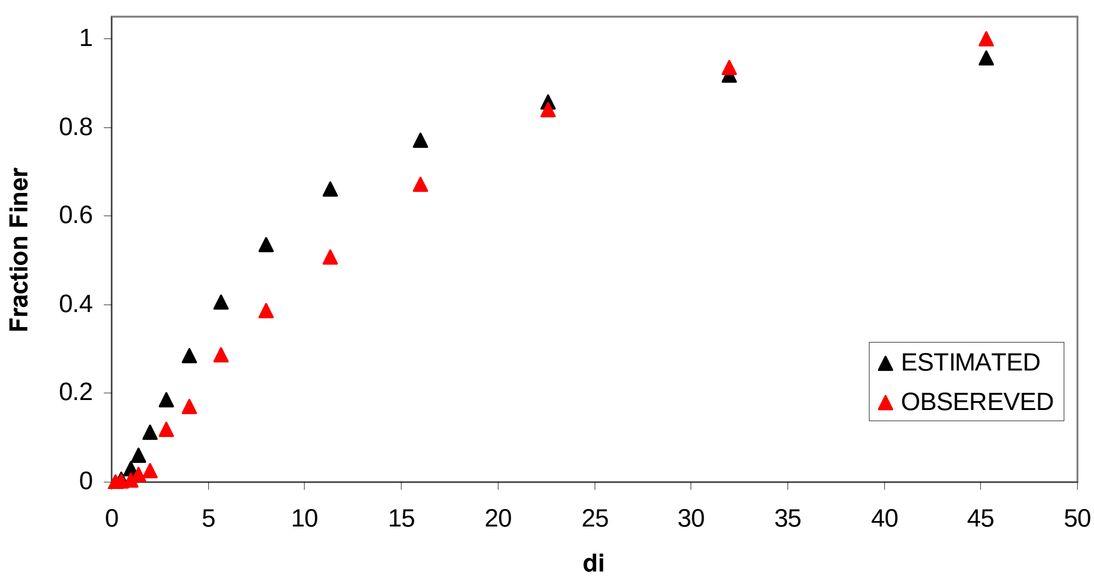

Figure 4.21 Particle Size Distribution (Data J15-4)

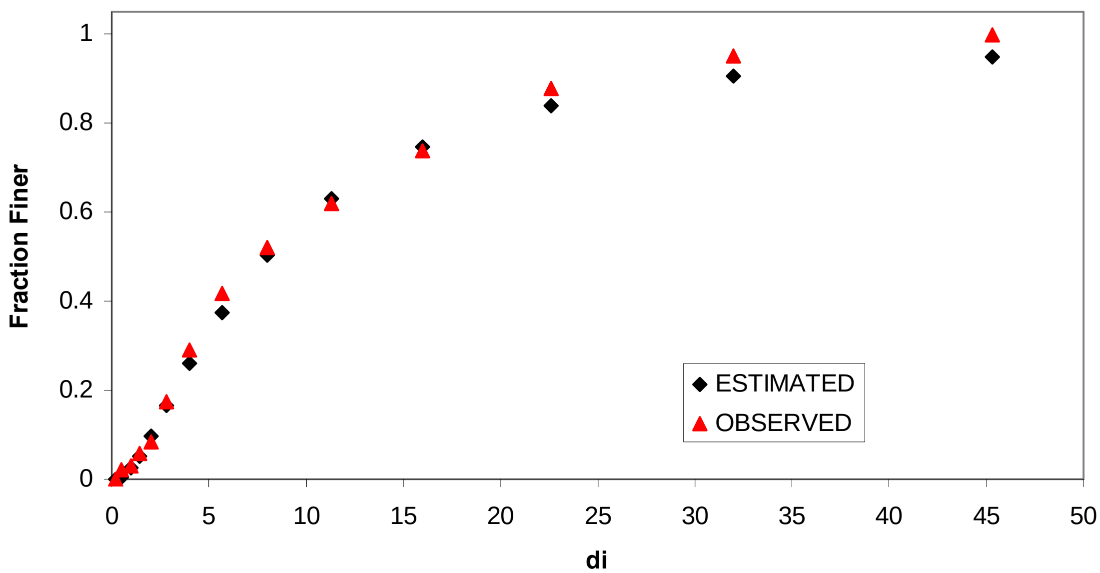

Figure 4.22 Particle Size Distribution (Data J21-3)

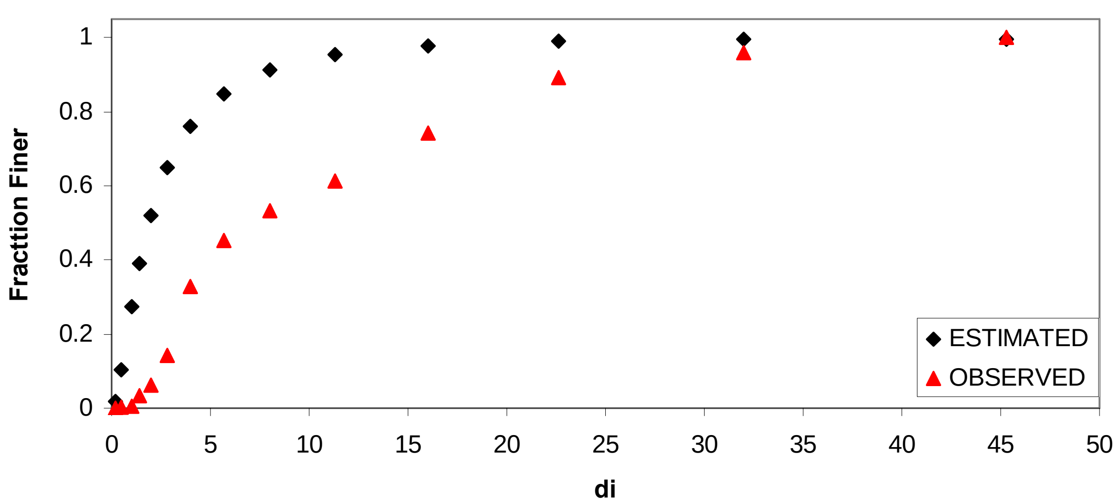

Figure 4.23 Particle Size Distribution (Data J21-1)

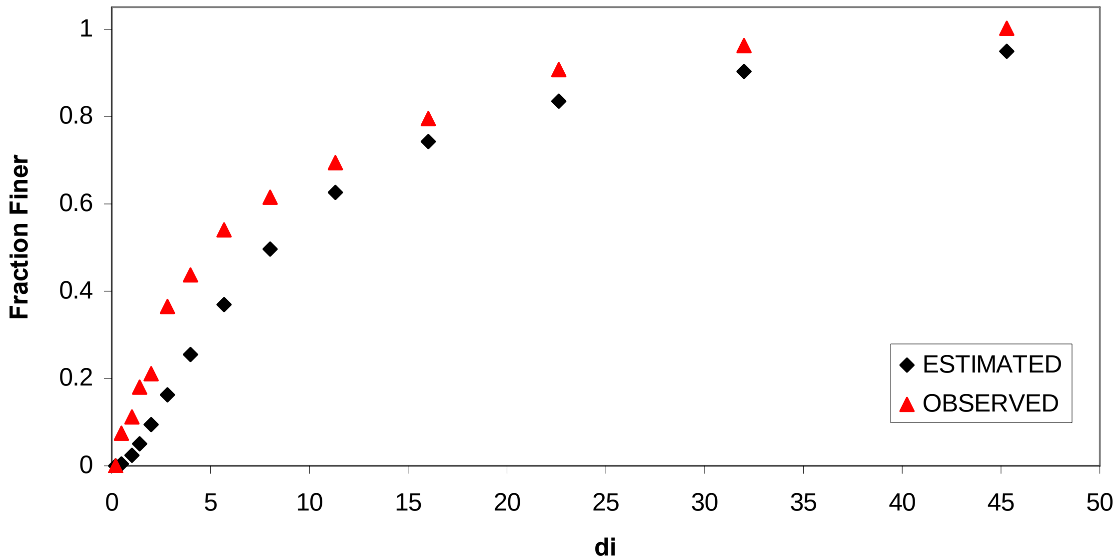

Figure 4.24 Particle Size Distribution (Data J27-1)

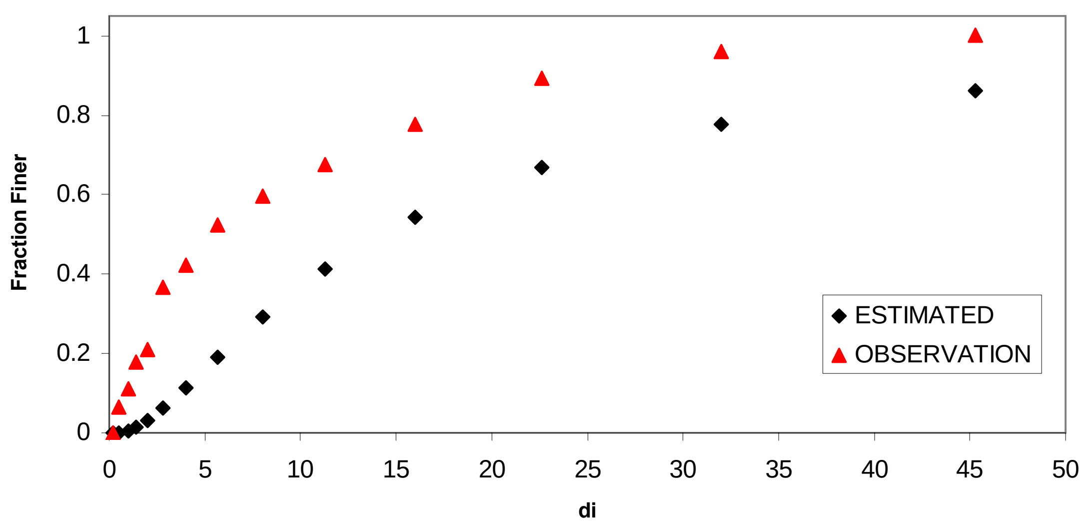

Figure 4.25 Particle Size Distribution (Data J27-1)

4.6 VERIFICATION OF BED LOAD TRANSPORT MODELS

In Roorkee's approach, for the calculation of bed load in non-uniform sediments properties of bulk mix is used, It is felt worthwhile to check the model taking equilibrium bed surface. In current work 'i_b' of equilibrium surface is used in place of bulk mix and the results are compared, with measured sediment transport. (see Fig.4.26 & Fig. 4.27) Here grain size distribution of bed surface has been obtained using method explained in previous sections. Table 4.2 shows the calculation for determining total bed load transport. The analysis is done using spreadsheet. The complete grain size distribution of transported material in each run is given in Appendix III. In this section of analysis BMC data is not analyzed as there is a huge variation in estimation of grain size distribution of the equilibrium bed surface.

Table 4.2 Calculation of Total Bed Load Transport

Run	d_{ai}	M	τ_{0c}	C_m	C_s	d_{aa}	τ_0'	T.T. (1)*	T.T. (2)*	T.T. (3)*
	(mm)		(N/m)			(mm)	(N/m)	(N-s/m)x10^{-3}	((N-s/m)x10^{-3}	(N-s/m)x10^{-3}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
M1-1	4.160	0.380	3.666	1	0.638	3.603	3.66	9.300	37.912	39.233
M1-2	4.160	0.380	3.666	1	0.765	4.431	3.02	30.700	8.344	9.778
M1-3	4.160	0.380	3.666	1	0.637	4.556	3.67	35.700	38.734	39.706
M1-4	4.160	0.380	3.666	1	0.624	4.680	3.75	54.200	45.926	47.050
M1-5	4.160	0.380	3.666	1	0.725	4.678	3.2	9.500	13.090	14.768
M1-6	4.160	0.380	3.666	1	0.640	4.654	3.65	14.100	37.381	38.804
M1-7	4.160	0.380	3.666	1	0.598	4.683	3.92	25.200	63.894	61.918
M1-8	4.160	0.380	3.666	1	0.495	3.688	4.75	63.360	257.359	217.358
M2-1	5.480	0.258	5.042	0.876	0.959	7.373	3.23	7.085	7.608	6.140
M2-2	5.480	0.258	5.042	0.876	0.964	8.051	3.21	10.830	7.255	6.872
M2-3	5.480	0.258	5.042	0.876	0.909	8.848	3.43	10.880	11.876	11.299
M2-4	5.480	0.258	5.042	0.876	0.862	5.929	3.64	31.780	18.854	17.219
M2-5	5.480	0.258	5.042	0.876	0.790	7.324	4.01	13.000	38.580	34.434
M2-6	5.480	0.258	5.042	0.876	0.691	8.620	4.63	30.230	104.920	95.820
M2-7	5.480	0.258	5.042	0.876	0.692	6.150	4.62	22.500	103.752	93.525
M2-8	5.480	0.258	5.042	0.876	0.601	8.310	5.36	88.800	272.093	241.961
M3-1	3.180	0.407	2.631	1	0.695	2.257	2.4	12.200	12.445	11.306
M3-2	3.180	0.407	2.631	1	0.552	3.287	3.05	82.500	76.281	63.285
M3-3	3.180	0.407	2.631	1	0.480	3.281	3.51	186.900	191.769	152.570
M3-4	3.180	0.407	2.631	1	0.626	2.490	2.68	8.620	29.605	25.747

M3-5	3.180	0.407	2.631	1	0.567	2.995	2.97	42.900	63.015	52.641
M3-6	3.180	0.407	2.631	1	0.483	3.297	3.49	169.200	185.274	145.819
M3-7	3.180	0.407	2.631	1	0.718	2.927	2.32	5.320	9.534	8.641
M3-8	3.180	0.407	2.631	1	0.801	2.635	2.06	0.469	3.720	3.438
M4-1	4.800	0.213	4.337	0.817	1.263	3.620	2	1.337	1.039	0.992
M4-2	4.800	0.213	4.337	0.817	0.949	4.420	2.81	3.030	12.402	11.332
M4-3	4.800	0.213	4.337	0.817	0.800	8.140	3.4	25.400	48.603	42.036
M4-4	4.800	0.213	4.337	0.817	0.996	3.920	2.66	4.860	8.330	7.201
M4-5	4.800	0.213	4.337	0.817	0.719	9.050	3.82	94.360	103.865	92.022
M4-6	4.800	0.213	4.337	0.817	1.050	3.450	2.5	2.361	5.318	4.414
M4-7	4.800	0.213	4.337	0.817	0.672	8.120	4.1	111.700	159.824	146.321
M5-1	6.080	0.180	5.660	0.765	1.027	6.480	3.35	5.130	18.019	16.490
M5-2	6.080	0.180	5.660	0.765	0.926	7.060	3.77	9.650	41.461	35.625
M5-3	6.080	0.180	5.660	0.765	0.856	9.240	4.12	21.100	73.997	60.547
M5-4	6.080	0.180	5.660	0.765	0.810	11.600	4.38	21.000	109.788	94.925
M5-5	6.080	0.180	5.660	0.765	1.088	5.270	3.13	6.470	11.204	9.461
J06.1	13.919	0.190	0.782	13.493	1.605	7.835	4.56	0.002	1.104	1.518
J06.2	13.919	0.190	0.782	13.493	1.472	8.039	5.12	0.025	2.443	3.239
J06.3	13.919	0.190	0.782	13.493	1.060	8.697	7.69	0.908	39.603	49.290
J06.4	13.919	0.190	0.782	13.493	0.864	9.200	9.72	13.832	194.533	221.611
J06.5	13.919	0.190	0.782	13.493	1.218	8.180	6.51	0.197	12.431	16.333
J06.6	13.919	0.190	0.782	13.493	0.948	8.578	8.75	4.218	97.328	115.611
J06.7	13.919	0.190	0.782	13.493	0.705	9.940	12.13	142.245	794.160	804.436
J06.8	13.919	0.190	0.782	13.493	1.532	8.090	4.85	0.033	1.717	2.248
J06.9	13.919	0.190	0.782	13.493	0.658	10.590	13.06	290.376	1232.522	1195.215
J06.10	13.919	0.190	0.782	13.493	0.590	10.995	14.61	2001.240	2328.305	2081.626
J14.1	12.691	0.152	0.712	12.281	0.703	15.776	11.07	504.234	1913.835	1976.000
J14.2	12.691	0.152	0.712	12.281	0.646	14.241	12.11	730.845	11.116	10.998
J14.3	12.691	0.152	0.712	12.281	1.345	10.455	5.24	0.293	216.008	238.261
J14.4	12.691	0.152	0.712	12.281	0.911	11.528	8.34	17.462	678.196	727.448
J14.5	12.691	0.152	0.712	12.281	0.768	12.888	10.07	122.625	5.193	5.149
J14.6	12.691	0.152	0.712	12.281	1.476	9.659	4.64	0.188	72.051	80.926
J14.7	12.691	0.152	0.712	12.281	1.058	10.046	7.02	15.107	37.619	39.323
J14.8	12.691	0.152	0.712	12.281	1.152	10.843	6.34	5.366	1617.733	1662.597
J14.9	12.691	0.152	0.712	12.281	0.666	15.175	11.72	1128.150	1170.329	1219.800
J21.1	11.908	0.127	0.658	11.507	0.697	19.620	10.47	1324.350	1679.400	1827.945
J21.2	11.908	0.127	0.658	11.507	1.525	11.883	4.16	4.777	6.997	5.624
J21.3	11.908	0.127	0.658	11.507	1.111	12.573	6.20	60.037	79.695	79.631
J21.4	11.908	0.127	0.658	11.507	0.891	14.744	8.01	117.033	369.823	397.234

J21.5	11.908	0.127	0.658	11.507	1.755	11.509	3.43	1.305	2.047	1.591
J21.6	11.908	0.127	0.658	11.507	1.095	13.087	6.32	125.568	89.364	88.842
J21.7	11.908	0.127	0.658	11.507	1.812	10.934	3.27	0.164	1.500	1.231
J21.8	11.908	0.127	0.658	11.507	0.652	16.343	11.23	1491.120	2391.469	2603.822
J21.9	11.908	0.127	0.658	11.507	0.630	17.675	11.64	"--NA--"	2889.824	3106.125
J27.1	10.689	0.105	0.599	10.299	1.815	12.763	2.92	4.738	2.939	1.946
J27.2	10.689	0.105	0.599	10.299	1.041	14.840	6.00	359.046	197.058	203.453
J27.3	10.689	0.105	0.599	10.299	2.859	11.876	1.33	0.029	0.027	0.013
J27.4	10.689	0.105	0.599	10.299	2.074	12.548	2.39	2.011	0.815	0.541
J27.5	10.689	0.105	0.599	10.299	1.025	14.084	6.11	270.756	217.789	231.503
J27.6	10.689	0.105	0.599	10.299	1.379	13.219	4.25	55.132	27.601	22.192
J27.7	10.689	0.105	0.599	10.299	0.892	16.100	7.16	654.523	535.377	605.241
J27.8	10.689	0.105	0.599	10.299	0.750	17.148	8.66	1030.050	1500.791	1746.634
J27.9	10.689	0.105	0.599	10.299	0.588	19.662	11.19	3325.590	5071.220	5913.166
J27.10	10.689	0.105	0.599	10.299	0.563	22.640	11.70	7641.990	6091.666	7147.174

*Col (9): Total bed load transport rate measured in the laboratory.

*Col (10): Total bed load transport rate calculated taking "i_b" for bulk sediment.

*Col (11): Total bed load transport rate calculated taking "i_b" for equilibrium bed surface.

To analyze the situation a curve is plotted between observed value of bed sediment transport and two method used for the calculation. Two different curves are drawn here as the range of the sediment particle is from 10^{-5} to 10**.** Fig. 4.25 curve is corresponding to 'M' data only in natural axes as the range of the data is not much. The other curve (Fig. 4.26) is plotted in a log-log paper which corresponds to 'J' series of data. The fraction wise transport rate values is given in Appendix II.

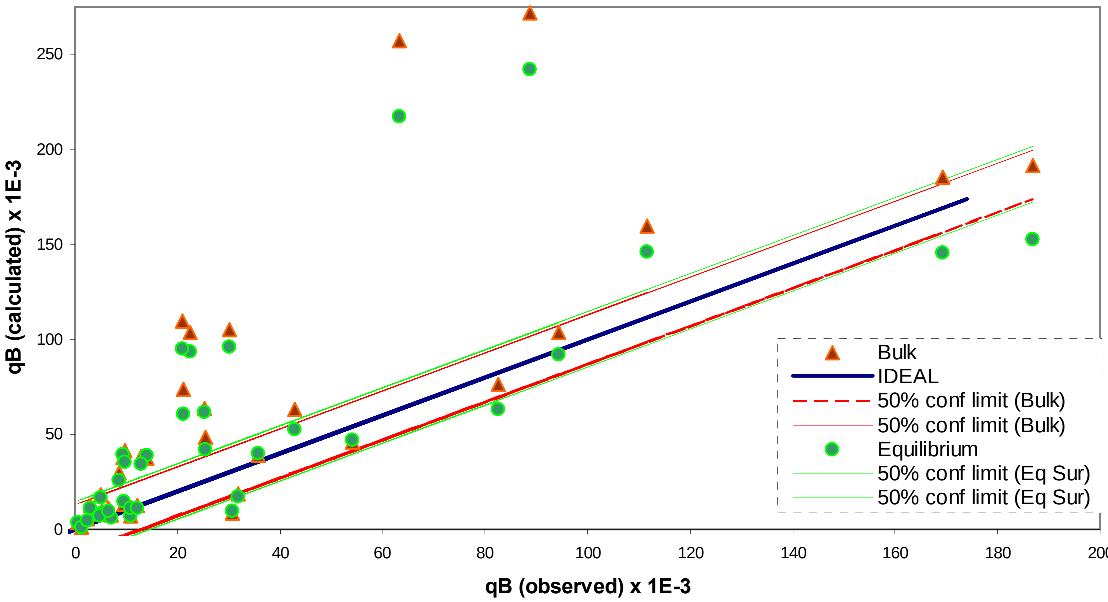

Figure 4.26 Comparison of observed & calculated value of q_b for M data

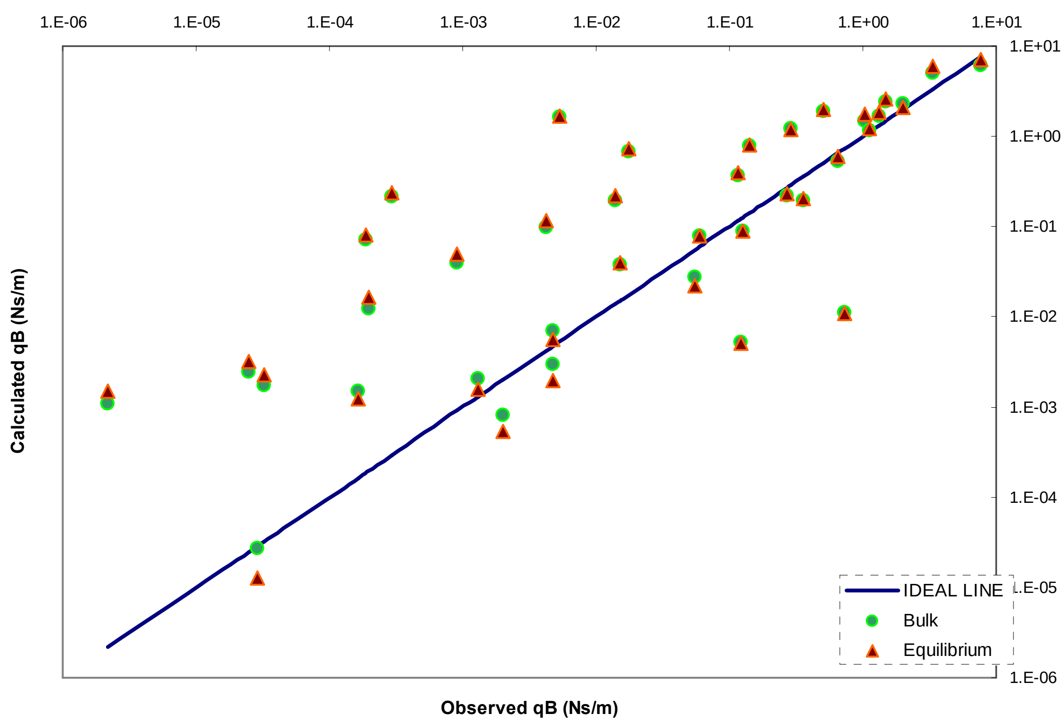

Figure 4.27 Comparison of observed & calculated value of q_b for J data

4.7 DISCUSSION OF RESULTS

From curves it cab be easily observed that there is not a noticeable difference in value of total bed load when calculated using bulk mix properties and that of equilibrium bed surface specially in ‘M’ data where 50% confidence line almost overlap each other. But, strictly speaking results are better when bulk mix property is used. The reason behind it was there was not a much difference in grain size distribution of bulk mix and the bed surface. Moreover, Roorkee’s Approach is designed taking property of bulk mix, therefore it gives the better result.

Similar trend is observed in J series also where most of the points are overlapping. However in ‘J’ series of data unlike M series grain size distribution is not same to that extent but the total transport is coming out to be of same order. Same reasons can be quoted for this behavior.

The whole analysis suggests that in Roorkee approach of finding bed load transport of non-uniform sediment the total bed sediment transport comes out to be almost same weather calculated taking fraction of bed sediment (i_b) for bulk mix or equilibrium surface. However in the data itself there was not much difference in the distribution both the surface.

Apart from these if Table 4.02 is observed carefully, one interesting point comes out. When shear stress is small and grain size distribution of bulk mix is on finer side or in other words average diameter of the sediment is smaller than the average grain size of the bed surface formed would be coarser than that of bulk, and if for the same condition shear stress is high than the amount of coarsening would be larger than that of previous case but the increase in average size of the particle would not be proportional to increase in the shear stress. Taking reverse case when bulk mix has coarser distribution or average size of the grain is higher than for lower shear stress there would be coarsening in the bed surface but when shear stress is high or there is greater amount of flow, than there is fining in the bed surface or average size of the particle decreases than that of bulk mix.

The reason behind this phenomenon is quite interesting, when bulk mix has finer distribution at low stress only larger fraction of the particle would be moving resulting in a coarser bed distribution. Further increase in the shear stress would mobilize more particles but after a certain points all the particle would be in moving stage and further increase in the flow wont effect the grain size distribution of the bed surface. In reverse condition when bulk mix is having coarser distribution, at smaller shear stress only finer particles would be moving as shear stress is not enough to move the coarser particle, resulting in decrease in the portion of finer particle in the mix or coarser bed surface is obtained. When shear stress is high enough to move coarser particle than because of recirculation of the sediment their space would be occupied by the finer particles resulting in a finer distribution of grain in the bed surface.

This phenomenon has got a simple mechanism and a tough analysis, as definition of the limit of coarse grain and fine grain and high shear stress and low shear stress is not easy to determine; because all the parameters depend on each other and form a complex mesh of interdependency. So this work can be further carried in the same direction to know more rational behavior of sediment laden water.

CHAPTER – 5

CONCLUSIONS

5.1 GENERAL

In the present laboratory sediment bed surface data were collected for equilibrium flow condition. The data was checked for its suitability for a standard probability distribution. Subsequently, an empirical model was developed to obtain parameters of that probability distribution if grain size distribution of bulk mix and flow properties are known with help of these parameters grain size distribution of sediment bed surface under equilibrium flow was obtained. Finally, obtained particle size distribution was used in the estimation of bed load in Roorkee's approach.

5.2 FINDING OF CURRENT INVESTIGATION

While undergoing the project work, performing various analyses and reviewing various research works and literatures following points are concluded:-

1. Sediment particle of the equilibrium bed surface possess lognormal distribution having geometric standard deviation (σ_g) value as 2.891.

2. Combining flow properties and initial bulk mix properties a relationship has been developed to obtain average size of the particle of equilibrium surface.
   (see Eq. 4.3)

3. The proposed model has been used to predict the grain size distribution of equilibrium sediment bed surface and results are compared with observed data. (see Fig. 4.6 to Fig.4.25) .

4. For set of data used in the current analysis not much difference is observed in the value of total bed load when calculated taking bed load fraction of bulk mix against taking the same of equilibrium surface in Roorkee's approach.

5. There is coarsening in the bed surface with increase in shear stress for lower value of shear stress. For higher value of shear stress there is fining of the bed surface because of kinematic sorting of bed surface.

5.3 SCOPE OF FURTHER STUDY

The proposed method is applicable only for steady flow. In case of transient condition which is very much possible in the field this method can't be applied. This model can further be extended for unsteady and transient flow conditions. However lack of data in this field is a huge problem, experimental study should be the solution in this regard.

In this study bed load was calculated using Roorkee's approach, taking value of 'i_b' of equilibrium surface obtained using proposed model. This could be extended for other methods of estimation of bed load transport and results can be compared.

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APPENDIX I

OBSERVED GRAIN SIZE DISTRIBUTION OF EQUILIBRIUM BED SURFACE

1. BMC

Run	14c	7a	14b	7b	7c	1	2	6	4	5	BULK
45.30	0.003	0.005	0.003	0.007	0.007	0.018	0.02	0.025	0.009	0.014	0.038
32.00	0.01	0.014	0.01	0.018	0.019	0.027	0.046	0.027	0.027	0.032	0.053
22.60	0.048	0.038	0.048	0.043	0.053	0.061	0.071	0.082	0.073	0.047	0.099
16.00	0.062	0.055	0.062	0.054	0.057	0.068	0.082	0.081	0.076	0.042	0.102
11.30	0.055	0.052	0.055	0.063	0.061	0.047	0.057	0.056	0.047	0.028	0.065
8.00	0.069	0.055	0.069	0.059	0.069	0.051	0.058	0.046	0.048	0.031	0.059
5.66	0.088	0.077	0.088	0.08	0.091	0.061	0.071	0.056	0.064	0.048	0.069
4.00	0.114	0.11	0.114	0.094	0.141	0.065	0.066	0.056	0.07	0.072	0.086
2.83	0.085	0.067	0.076	0.102	0.089	0.052	0.047	0.064	0.057	0.068	0.06
2.00	0.029	0.028	0.035	0.041	0.036	0.014	0.014	0.019	0.022	0.023	0.026
1.41	0.051	0.043	0.063	0.045	0.049	0.02	0.026	0.033	0.039	0.039	0.029
1.00	0.059	0.037	0.048	0.04	0.032	0.034	0.044	0.056	0.053	0.054	0.033
0.50	0.13	0.174	0.119	0.114	0.148	0.158	0.18	0.194	0.197	0.171	0.104
0.21	0.198	0.246	0.21	0.242	0.15	0.325	0.216	0.205	0.217	0.332	0.177
da	5.196	4.799	5.186	5.324	5.886	6.075	7.446	7.149	6.152	5.019	9.613

2. J6

Run	1	2	3	4	5	6	7	8	9	10	BULK
45.30	0.035	0.035	0.043	0.041	0.073	0.075	0.080	0.057	0.073	0.067	0.060
32.00	0.065	0.065	0.074	0.077	0.104	0.109	0.094	0.090	0.102	0.101	0.084
22.60	0.178	0.178	0.186	0.192	0.174	0.187	0.183	0.172	0.217	0.183	0.139
16.00	0.199	0.199	0.194	0.211	0.193	0.177	0.179	0.175	0.172	0.148	0.143
11.30	0.132	0.132	0.133	0.131	0.128	0.120	0.103	0.118	0.103	0.095	0.091
8.00	0.118	0.118	0.117	0.104	0.106	0.102	0.095	0.108	0.089	0.101	0.083
5.66	0.125	0.125	0.111	0.111	0.104	0.098	0.117	0.133	0.094	0.117	0.097
4.00	0.103	0.103	0.069	0.052	0.075	0.088	0.103	0.105	0.101	0.128	0.120
2.83	0.038	0.038	0.068	0.077	0.038	0.038	0.040	0.037	0.041	0.055	0.084
2.00	0.004	0.004	0.003	0.004	0.003	0.004	0.006	0.005	0.008	0.005	0.037
1.41	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.000	0.002	0.001	0.012
1.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.016
0.50	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.034
0.21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
da	14.546	14.546	15.17	15.412	16.953	17.139	16.757	15.634	17.174	15.994	13.919

3. J14

Run	1	2	3	4	5	6	7	8	9	Bulk
45.30	0.049	0.056	0.049	0.066	0.072	0.058	0.063	0.046	0.063	0.054
32.00	0.102	0.105	0.077	0.095	0.088	0.089	0.096	0.085	0.098	0.076
22.60	0.203	0.196	0.154	0.169	0.175	0.151	0.165	0.165	0.201	0.126
16.00	0.166	0.163	0.152	0.163	0.178	0.132	0.131	0.152	0.160	0.130
11.30	0.105	0.096	0.118	0.122	0.102	0.103	0.098	0.111	0.105	0.083
8.00	0.091	0.112	0.117	0.098	0.089	0.108	0.107	0.111	0.091	0.076
5.66	0.110	0.105	0.129	0.118	0.108	0.134	0.114	0.130	0.126	0.088
4.00	0.054	0.067	0.068	0.051	0.054	0.070	0.066	0.062	0.054	0.109
2.83	0.085	0.076	0.118	0.092	0.113	0.123	0.120	0.110	0.086	0.076
2.00	0.016	0.012	0.012	0.010	0.013	0.015	0.021	0.015	0.006	0.033
1.41	0.015	0.007	0.006	0.013	0.007	0.011	0.012	0.011	0.009	0.034
1.00	0.001	0.003	0.000	0.002	0.001	0.003	0.004	0.001	0.001	0.037
0.50	0.001	0.001	0.000	0.002	0.001	0.002	0.002	0.001	0.000	0.077
0.21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
da	15.776	16.03	14.2	15.79	15.93	14.464	15.027	14.45	16.205	12.691

4. J21

Run	1	2	3	4	5	6	7	8	9	Bulk
45.30	0.04	0.041	0.05	0.056	0.034	0.046	0.029	0.043	0.027	0.051
32.00	0.068	0.06	0.08	0.085	0.061	0.074	0.051	0.083	0.084	0.071
22.60	0.149	0.127	0.14	0.142	0.097	0.107	0.135	0.168	0.146	0.117
16.00	0.129	0.123	0.12	0.122	0.109	0.111	0.125	0.115	0.119	0.121
11.30	0.082	0.088	0.1	0.092	0.092	0.085	0.09	0.075	0.081	0.077
8.00	0.079	0.097	0.1	0.097	0.094	0.099	0.102	0.063	0.077	0.071
5.66	0.124	0.115	0.13	0.114	0.14	0.132	0.12	0.068	0.111	0.082
4.00	0.188	0.13	0.12	0.113	0.114	0.091	0.069	0.034	0.093	0.102
2.83	0.08	0.116	0.09	0.12	0.155	0.154	0.176	0.148	0.157	0.071
2.00	0.027	0.031	0.03	0.026	0.031	0.028	0.03	0.038	0.041	0.031
1.41	0.03	0.046	0.03	0.026	0.044	0.04	0.045	0.067	0.038	0.048
1.00	0.001	0.004	0.01	0.003	0.012	0.016	0.015	0.041	0.018	0.051
0.50	0.003	0.021	0.02	0.005	0.018	0.016	0.015	0.057	0.009	0.106
0.21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
da	12.757	12.03	13	13.76	11.05	12.082	11.429	12.77	12.249	11.908

5. J27

Run	1	2	3	4	5	6	7	8	9	10	Bulk
45.30	0.039	0.047	0.028	0.028	0.036	0.026	0.031	0.030	0.039	0.040	0.038
32.00	0.054	0.059	0.044	0.046	0.057	0.055	0.063	0.062	0.073	0.067	0.066
22.60	0.113	0.120	0.091	0.098	0.108	0.117	0.139	0.129	0.127	0.117	0.109
16.00	0.101	0.106	0.087	0.087	0.097	0.108	0.119	0.119	0.085	0.102	0.112
11.30	0.079	0.072	0.079	0.080	0.079	0.080	0.074	0.080	0.059	0.078	0.071
8.00	0.074	0.079	0.068	0.091	0.083	0.076	0.067	0.070	0.062	0.074	0.065
5.66	0.103	0.107	0.107	0.128	0.111	0.110	0.091	0.084	0.068	0.100	0.076
4.00	0.073	0.063	0.087	0.078	0.063	0.058	0.051	0.051	0.040	0.055	0.094
2.83	0.155	0.153	0.158	0.160	0.148	0.141	0.113	0.133	0.140	0.157	0.065
2.00	0.029	0.038	0.041	0.028	0.039	0.035	0.026	0.031	0.032	0.032	0.029
1.41	0.069	0.080	0.082	0.062	0.098	0.076	0.068	0.077	0.092	0.069	0.065
1.00	0.038	0.039	0.051	0.035	0.041	0.040	0.059	0.050	0.066	0.045	0.068
0.50	0.074	0.036	0.078	0.079	0.041	0.078	0.100	0.085	0.119	0.065	0.140
0.21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
da	10.693	11.41	9.25	9.686	10.58	10.332	11.134	10.95	10.756	11.175	10.6891

6. M1

Sieve Size	Percentage Finer							
	M1-1	**M1-2**	**M1-3**	**M1-4**	**M1-5**	**M1-6**	**M1-7**	**M1-8**
(mm)								
20.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
16.00	97.22	100.00	98.07	99.67	98.76	98.40	97.91	98.21
12.50	93.94	98.67	94.34	97.02	95.88	95.88	92.50	94.30
10.00	89.39	95.63	88.74	92.16	90.65	91.36	86.95	89.25
8.00	86.11	92.21	84.24	88.74	85.58	86.85	82.16	84.36
6.30	78.28	82.91	73.15	80.43	77.50	76.21	70.63	74.24
4.75	71.21	73.99	68.17	73.53	71.16	69.35	62.23	68.55
4.00	56.82	58.99	55.95	58.63	55.89	55.28	47.78	53.55
3.35	51.01	51.78	51.45	52.83	48.50	48.91	41.34	47.84
2.80	43.30	38.12	40.80	41.07	38.83	37.51	31.77	36.43
2.00	12.83	14.21	15.28	16.92	14.27	14.41	11.97	12.95
1.70	8.59	10.41	10.30	12.53	10.78	10.66	9.03	9.36
1.40	7.78	6.62	8.21	9.71	7.77	6.63	5.44	6.43
1.00	2.22	3.38	2.90	4.57	3.97	3.43	2.94	3.25
0.60	0.00	0.72	0.93	0.15	0.48	0.46	0.33	0.07
d_a	4.69	4.06	4.78	4.27	4.58	4.61	5.26	4.85

7. M2

Sieve Size	Percentage Finer							
	M2-1	M2-2	M2-3	M2-4	M2-5	M2-6	M2-7	M2-8
(mm)								
31.50	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
25.00	89.60	100.00	99.11	95.50	98.80	100.00	99.12	98.88
20.00	84.98	98.34	98.40	94.32	96.29	97.57	96.82	94.60
16.00	78.63	90.49	90.55	88.21	90.78	91.93	91.52	84.28
12.50	74.70	85.97	86.63	84.89	80.78	86.18	83.72	77.65
10.00	71.29	82.05	82.26	81.14	76.40	81.98	79.41	72.75
8.00	68.11	76.22	76.32	76.53	70.22	76.45	74.28	67.85
6.30	50.20	58.39	60.15	60.46	54.94	61.19	58.37	53.85
4.75	41.82	54.59	56.94	56.92	49.99	58.81	54.66	50.69
4.00	31.13	42.23	45.65	45.99	38.86	46.59	43.35	40.99
3.35	26.22	37.00	40.89	40.42	34.14	41.61	38.05	36.81
2.80	19.00	29.15	31.89	33.46	25.60	35.31	30.89	29.98
2.00	3.41	11.98	12.11	13.10	9.98	14.69	11.62	11.42
1.70	1.97	8.65	8.72	9.89	7.17	11.32	8.17	8.26
1.40	1.51	5.44	4.62	6.46	3.91	7.89	4.63	3.87
1.00	0.41	2.23	2.84	3.14	2.22	5.68	2.60	2.14
0.60	0.00	0.16	0.16	0.03	0.08	0.04	0.09	0.00
d_a	9.33	6.40	6.30	6.81	7.12	6.12	6.61	7.59

8. M3

Sieve Size	Percentage Finer							
	M3-1	M3-2	M3-3	M3-4	M3-5	M3-6	M3-7	M3-8
(mm)								
20.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
16.00	100.00	100.00	100.00	99.10	100.00	100.00	98.72	100.00
12.50	97.20	98.59	100.00	97.42	99.47	99.90	98.21	99.64
10.00	95.10	95.59	95.57	95.19	95.19	97.60	96.08	97.89
8.00	92.30	93.30	93.91	93.31	92.52	95.80	92.73	95.73
6.30	84.60	86.07	86.98	85.07	81.29	89.60	85.40	88.27
4.75	82.54	83.25	84.76	82.84	75.41	86.70	83.27	85.87
4.00	74.20	71.97	75.62	73.92	66.85	77.70	72.17	74.95
3.35	67.20	65.62	70.08	67.20	58.90	70.40	63.34	66.37
2.80	56.00	52.57	55.68	53.85	51.34	59.90	54.89	53.97

2.00	30.30	28.95	29.65	29.49	23.54	32.10	24.14	25.97
1.70	25.40	23.31	23.83	23.83	19.20	27.80	18.38	20.22
1.40	20.80	14.85	17.18	17.48	16.05	17.70	11.76	13.47
1.00	8.30	3.92	6.10	4.72	5.86	6.90	3.42	3.67
0.60	0.00	0.00	0.28	0.00	0.00	0.20	0.00	0.00
$\mathbf{d_a}$	3.49	3.48	3.30	3.53	3.76	3.08	3.59	3.31

9. M4

Sieve Size	**Percentage Finer**						
	M4-1	**M4-2**	**M4-3**	**M4-4**	**M4-5**	**M4-6**	**M4-7**
(mm)							
31.50	100.00	100.00	100.00	100.00	100.00	100.00	100.00
25.00	100.00	100.00	97.65	97.82	100.00	100.00	100.00
20.00	99.20	97.75	95.57	95.32	99.50	91.61	97.37
16.00	98.00	94.65	90.19	91.57	88.40	87.00	94.56
12.50	96.90	92.16	88.25	88.44	81.61	85.72	89.82
10.00	93.90	89.29	84.89	84.85	78.20	80.25	86.67
8.00	91.20	85.63	81.61	80.63	74.54	77.62	82.10
6.30	82.70	75.21	71.45	71.25	65.84	67.59	69.47
4.75	76.00	73.80	59.46	69.53	64.33	66.27	67.54
4.00	72.30	65.35	50.03	59.22	54.87	57.88	55.96
3.35	68.90	60.84	46.73	54.53	50.58	53.21	50.87
2.80	64.90	56.33	42.40	50.15	46.80	49.66	45.08
2.00	36.20	23.43	20.77	24.52	23.67	25.81	18.94
1.70	30.40	21.39	16.60	19.83	19.30	20.55	13.33
1.40	25.30	17.42	8.78	11.93	10.37	10.85	5.44
1.00	17.40	10.38	7.58	10.14	8.95	9.70	4.21
0.60	0.64	0.52	1.07	1.23	0.50	0.65	0.70
$\mathbf{d_a}$	3.59	4.60	5.84	5.49	6.01	6.06	5.26

10. M5

Sieve Size	Percentage Finer				
	M5-1	M5-2	M5-3	M5-4	M5-5
(mm)					
40.00	100.00	100.00	100.00	100.00	100.00
31.50	100.00	100.00	96.84	98.31	100.00
25.00	100.00	96.36	93.30	96.06	95.62
20.00	97.36	93.17	88.03	95.41	92.90
16.00	94.72	90.29	82.66	88.86	87.98
12.50	90.20	86.80	77.20	83.56	85.16
10.00	85.30	80.27	73.66	77.03	80.73
8.00	80.03	73.74	67.72	68.81	74.77
6.30	71.17	62.05	56.52	55.87	64.95
4.75	70.24	60.36	54.89	52.36	64.04
4.00	63.84	53.56	48.95	44.50	56.40
3.35	56.68	46.28	43.10	37.53	50.69
2.80	49.36	42.33	36.46	28.30	39.56
2.00	22.84	20.63	20.36	12.10	19.48
1.70	17.38	15.74	15.39	8.71	14.17
1.40	8.15	6.79	6.96	3.36	7.43
1.00	7.18	5.88	5.81	2.66	6.08
0.60	0.57	0.72	0.35	0.48	0.36
d_a	5.14	6.49	8.23	7.36	6.55

APPENDIX II

FRACTION OF TRANSPORTED SEDIMENT ESTIMATED USING ROORKEE'S APPROACH TRANSPORTED RATE (N-S/m

[A] Taking i_b of bulk mix

1. M1

di (mm)	1	2	3	4	5	6	7	8
17.88854	0.000291	5.82E-05	0.000296	0.000345	9.85E-05	0.0003	0.000493	0.002419
14.14214	0.000471	0.000108	0.000471	0.000613	0.000174	0.0005	0.000896	0.004054
11.18034	0.000626	0.00014	0.000663	0.000774	0.000217	0.0006	0.001105	0.005527
8.944272	0.002136	0.000475	0.002215	0.00261	0.000712	0.0021	0.003717	0.018192
7.099296	0.002806	0.0006	0.002871	0.003458	0.000979	0.0027	0.004829	0.024144
5.470375	0.004677	0.001039	0.004807	0.005716	0.001689	0.0046	0.008444	0.040273
4.358899	0.00199	0.000431	0.00199	0.002488	0.00068	0.0020	0.003483	0.016253
3.660601	0.004845	0.000996	0.004845	0.005922	0.001561	0.0046	0.008075	0.034992
3.062679	0.010898	0.00231	0.011334	0.013513	0.003575	0.010898	0.018744	0.074106
2.366432	0.001931	0.0004	0.001931	0.00229	0.000674	0.001886	0.003234	0.010778
1.843909	0.000851	0.000197	0.000876	0.001036	0.000308	0.000839	0.001357	0.003949
1.542725	0.003457	0.000803	0.003492	0.003841	0.001222	0.003387	0.005238	0.01327
1.183216	0.002663	0.000692	0.002663	0.003018	0.001065	0.002663	0.003905	0.008698
0.774597	0.00027	9.33E-05	0.00028	0.000301	0.000135	0.00027	0.000373	0.000705
qb	0.037912	0.008344	0.038734	0.045926	0.01309	0.037381	0.063894	0.257359

2. M2

di (mm)	1	2	3	4	5	6	7	8
27.95085	2.22E-05	2.16E-05	3.32E-05	5.54E-05	0.000126	0.0004	0.000373	0.001259
22.36068	2.13E-05	2.04E-05	3.5E-05	5.73E-05	0.00013	0.0004	0.000382	0.001241
17.88854	0.000129	0.000117	0.000222	0.000351	0.000736	0.0023	0.00222	0.007129
14.14214	0.000113	0.000107	0.000185	0.000298	0.00059	0.0018	0.001849	0.005963
11.18034	0.000141	0.000136	0.000224	0.000335	0.000748	0.0022	0.002201	0.007483
8.944272	0.000207	0.000199	0.000309	0.000487	0.001056	0.0032	0.003127	0.010964
7.099296	0.000668	0.000642	0.001028	0.001713	0.003597	0.0111	0.011134	0.036829
5.470375	0.000252	0.000234	0.000397	0.000613	0.001262	0.004146	0.004146	0.012799
4.358899	0.00064	0.000611	0.00099	0.001572	0.003202	0.010478	0.010187	0.032017
3.660601	0.000357	0.000345	0.000564	0.000863	0.001957	0.005871	0.005756	0.016118

3.062679	0.000891	0.000851	0.001386	0.002178	0.00495	0.014257	0.014059	0.037623
2.366432	0.00183	0.001756	0.002927	0.004879	0.010001	0.026833	0.026833	0.063423
1.843909	0.000392	0.000362	0.000633	0.000995	0.00202	0.005124	0.005124	0.010249
1.542725	0.000678	0.000642	0.00107	0.001677	0.003425	0.00785	0.007493	0.014629
1.183216	0.000395	0.000371	0.00061	0.000945	0.001794	0.003589	0.003589	0.00622
0.774597	0.000872	0.000838	0.001262	0.001836	0.002984	0.005279	0.005279	0.008149
qb	0.007608	0.007255	0.011876	0.018854	0.03858	0.10492	0.103752	0.272093

3. M3

di								
(mm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
17.88854	1.95E-05	0.00013	0.000455	5.2E-05	0.000111	0.000429	0.0000	5.86E-06
14.14214	4.3E-05	0.000298	0.000926	0.000104	0.000231	0.000893	3.31E-05	1.14E-05
11.18034	5.44E-05	0.000359	0.001113	0.000122	0.000284	0.001051	4.08E-05	1.48E-05
8.944272	9.93E-05	0.000692	0.002256	0.000241	0.000556	0.002106	7.82E-05	3.01E-05
7.099296	0.000364	0.002622	0.008739	0.000947	0.002112	0.008375	0.000288	0.00012
5.470375	0.000251	0.001716	0.005413	0.000581	0.00132	0.005149	0.000185	7.39E-05
4.358899	0.000753	0.005455	0.016624	0.001792	0.004416	0.015845	0.000597	0.000221
3.660601	0.000759	0.00542	0.016442	0.001807	0.004336	0.015719	0.000578	0.000217
3.062679	0.00157	0.01099	0.031399	0.003925	0.008896	0.031399	0.001204	0.000471
2.366432	0.002817	0.019722	0.050713	0.007325	0.016059	0.047896	0.002141	0.000873
1.843909	0.000838	0.00512	0.011635	0.001955	0.004375	0.01117	0.000605	0.000242
1.542725	0.001834	0.010581	0.021867	0.004232	0.008464	0.021161	0.001411	0.000515
1.183216	0.001987	0.009485	0.018066	0.004517	0.008581	0.018066	0.001536	0.000587
0.774597	0.001055	0.003693	0.00612	0.002005	0.003271	0.006015	0.000823	0.000338
qb	0.012445	0.076281	0.191769	0.029605	0.063015	0.185274	0.009534	0.00372

4. M4

Di							
(mm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
27.95085	0	3.37E-05	0.000166	2.32E-05	0.000392	1.71E-05	0.000663
22.36068	6.89E-06	6.68E-05	0.000331	4.34E-05	0.000758	2.89E-05	0.001378
17.88854	1.6E-05	0.000151	0.000641	8.91E-05	0.001604	5.61E-05	0.002851
14.14214	1.45E-05	0.000156	0.000667	0.0001	0.001612	5.56E-05	0.002835
11.18034	1.05E-05	0.000134	0.00054	8.53E-05	0.001365	5.4E-05	0.002303
8.944272	1.69E-05	0.000219	0.000937	0.000153	0.002311	9.37E-05	0.00406
7.099296	4.87E-05	0.000637	0.002839	0.000429	0.006952	0.000284	0.012745
5.470375	1.65E-05	0.000206	0.000833	0.000134	0.002262	8.12E-05	0.003805
4.358899	5.48E-05	0.000653	0.00295	0.000442	0.007164	0.000274	0.01222

3.660601	3.07E-05	0.000354	0.001575	0.000236	0.00378	0.00015	0.006537
3.062679	8.9E-05	0.00102	0.004694	0.000696	0.011006	0.000437	0.017804
2.366432	0.000239	0.002956	0.012899	0.001908	0.029561	0.001236	0.045685
1.843909	6.53E-05	0.000828	0.003398	0.000523	0.00697	0.000327	0.010019
1.542725	0.000102	0.001254	0.00511	0.000836	0.009755	0.000511	0.013472
1.183216	7.6E-05	0.00094	0.003201	0.00062	0.005802	0.0004	0.007803
0.774597	0.000251	0.002794	0.007822	0.002011	0.012572	0.001313	0.015645
qb	0.001039	0.012402	0.048603	0.00833	0.103865	0.005318	0.159824

5. M5

di					
(mm)	**1**	**2**	**3**	**4**	**5**
7.608246	9.91E-05	0.000261	0.000539	0.000869	6.61E-05
5.943942	0.000112	0.000305	0.000623	0.000929	6.84E-05
4.755154	0.000112	0.000287	0.000532	0.000839	6.16E-05
3.804123	0.000228	0.000552	0.001051	0.001752	0.000131
3.043299	0.000303	0.000697	0.001407	0.002252	0.000183
2.377577	0.00029	0.000736	0.001385	0.00225	0.000186
1.902062	0.00031	0.000805	0.001579	0.002477	0.000201
1.521649	0.000507	0.001182	0.002252	0.00366	0.000282
1.198299	0.000762	0.001777	0.003555	0.00584	0.000457
0.903479	0.000637	0.00149	0.003115	0.005012	0.000393
0.760825	0.000841	0.002166	0.004204	0.006625	0.000522
0.637191	0.001376	0.003545	0.006665	0.010495	0.000837
0.532577	0.004401	0.010613	0.020191	0.031064	0.002589
0.380412	0.001441	0.003329	0.005963	0.008447	0.000894
0.32335	0.001559	0.00365	0.006084	0.008366	0.000951
0.266289	0.002203	0.004789	0.007343	0.009578	0.001373
0.190206	0.002841	0.005276	0.007508	0.009335	0.002009
qb	0.018019	0.041461	0.073997	0.109788	0.011204

6. J6

di	1	2	3	4	5	6	7	8	9	10
(mm)										
45.30	0	0	0.0008	0.0049	0.00025	0.00236	0.02844	0	0.04901	0.13311
32.00	0	0.0001	0.0015	0.0085	0.00039	0.00377	0.04727	7E-05	0.09052	0.21625
22.60	9.38E-05	0.00017	0.003	0.0173	0.00089	0.0079	0.09879	0.00013	0.17782	0.42478
16.00	9.99E-05	0.00018	0.0036	0.0209	0.00115	0.00969	0.12411	0.00013	0.21491	0.45404
11.30	6.63E-05	0.00015	0.0029	0.0171	0.00083	0.00732	0.09261	9.9E-05	0.14863	0.27439
8.00	7.45E-05	0.00018	0.0032	0.0193	0.00093	0.0087	0.08696	0.00012	0.13666	0.22362
5.66	0.000117	0.00025	0.0043	0.0264	0.00134	0.0121	0.09936	0.00018	0.13824	0.216
4.00	0.000178	0.00038	0.007	0.0349	0.00197	0.01778	0.11113	0.00026	0.14606	0.20638
2.83	0.000145	0.00032	0.0058	0.0251	0.00172	0.01455	0.06481	0.00022	0.08068	0.10978
2.00	7.96E-05	0.00017	0.003	0.0104	0.00093	0.00623	0.02215	0.00012	0.027	0.03807
1.41	3.12E-05	6.6E-05	0.0011	0.0029	0.00037	0.00186	0.00545	4.7E-05	0.00678	0.00964
1.00	4.97E-05	0.00012	0.0013	0.003	0.00053	0.00217	0.00566	7.9E-05	0.00714	0.0099
0.50	0.000163	0.00034	0.002	0.0038	0.00111	0.00286	0.00732	0.00024	0.00895	0.01217
0.21	6.05E-06	9.5E-06	3E-05	6E-05	2E-05	4.5E-05	0.00011	7.6E-06	0.00013	0.00017
qb	0.001104	0.00244	0.0396	0.1945	0.01243	0.09733	0.79416	0.00172	1.23252	2.32831

7. J15

di	1	2	3	4	5	6	7	8	9
(mm)									
45.30	0.098018	0.00018	0.005	0.0223	9.3E-05	0.00142	0.0006	0.07624	0.0452
32.00	0.163807	0.00027	0.0091	0.0369	0.00014	0.0025	0.00118	0.12741	0.0819
22.60	0.322372	0.00058	0.0179	0.0806	0.00024	0.00448	0.00242	0.25521	0.1657
16.00	0.357732	0.00077	0.0217	0.0991	0.0003	0.00633	0.00275	0.3027	0.2009
11.30	0.229409	0.00059	0.0177	0.074	0.00026	0.0048	0.00229	0.1877	0.1356
8.00	0.187696	0.00063	0.0199	0.0739	0.0003	0.00518	0.00256	0.16494	0.1251
5.66	0.180284	0.00094	0.027	0.0823	0.00039	0.00784	0.00349	0.16069	0.1293
4.00	0.175929	0.00138	0.0375	0.0923	0.00061	0.01154	0.00548	0.16151	0.1327
2.83	0.093342	0.00115	0.0251	0.055	0.00051	0.00945	0.00467	0.08616	0.0730
2.00	0.031797	0.00065	0.0099	0.0188	0.00026	0.00432	0.00238	0.0284	0.02439
1.41	0.025606	0.00079	0.0087	0.0147	0.00036	0.00433	0.00264	0.02316	0.01939
1.00	0.02166	0.001	0.0073	0.0124	0.00045	0.00416	0.00281	0.0197	0.01664
0.50	0.026022	0.00216	0.009	0.0158	0.00126	0.00567	0.00432	0.02377	0.02044
0.21	0.000162	1.8E-05	6E-05	0.0001	1.3E-05	3.9E-05	2.9E-05	0.00015	0.00013
qb	1.913835	0.01112	0.216	0.6782	0.00519	0.07205	0.03762	1.61773	1.17033

8. J21

di (mm)	1	2	3	4	5	6	7	8	9
45.30	0.082287	0.00011	0.0015	0.0098	0	0.0017	0	0.144	0.19029
32.00	0.136027	0.00015	0.0025	0.0166	5.1E-05	0.00285	0	0.2338	0.31031
22.60	0.266085	0.00027	0.005	0.0324	1E-04	0.00582	7.9E-05	0.41576	0.54048
16.00	0.307353	0.00036	0.0064	0.0435	0.0001	0.00717	8.5E-05	0.46103	0.56348
11.30	0.193477	0.0003	0.0048	0.0329	7.4E-05	0.00542	5.5E-05	0.27087	0.31924
8.00	0.16472	0.00033	0.0053	0.0361	9E-05	0.00638	6.4E-05	0.21786	0.24442
5.66	0.160688	0.00047	0.008	0.0475	0.00014	0.00913	9.9E-05	0.20086	0.22277
4.00	0.159233	0.0007	0.0116	0.0567	0.00019	0.01322	0.00015	0.19162	0.21321
2.83	0.083848	0.00059	0.0096	0.0358	0.00017	0.01096	0.00012	0.10174	0.11515
2.00	0.02813	0.00032	0.0044	0.0131	8.7E-05	0.00493	6.7E-05	0.03538	0.03944
1.41	0.034555	0.00061	0.0064	0.0159	0.00016	0.00691	0.00012	0.04253	0.04705
1.00	0.028507	0.00078	0.0061	0.013	0.00022	0.00641	0.00016	0.03458	0.03829
0.50	0.034335	0.00198	0.0081	0.0165	0.00066	0.00843	0.0005	0.04128	0.04549
0.21	0.000157	1.4E-05	4E-05	8E-05	7E-06	4.3E-05	5.7E-06	0.00018	0.0002
qb	1.6794	0.007	0.0797	0.3698	0.00205	0.08936	0.0015	2.39147	2.88982

9. J27

di (mm)	1	2	3	4	5	6	7	8	9	10
45.30	0	0.00326	0	0	0.00376	0.00026	0.01265	0.05748	0.3832	0.53648
32.00	6.32E-05	0.00711	0	0	0.0083	0.00059	0.02608	0.11854	0.71127	0.90884
22.60	0.000112	0.01433	0	0	0.01627	0.00124	0.05423	0.2324	1.08452	1.31692
16.00	0.000116	0.01731	0	5E-05	0.01968	0.00152	0.06875	0.26078	0.97202	1.13797
11.30	8.92E-05	0.01427	0	3E-05	0.01606	0.00116	0.05174	0.16948	0.4906	0.56196
8.00	0.000107	0.01557	0	3E-05	0.018	0.00131	0.05351	0.14594	0.34538	0.38916
5.66	0.000159	0.02166	0	4E-05	0.02437	0.00183	0.06431	0.14555	0.30801	0.35879
4.00	0.000224	0.02985	3E-06	7E-05	0.03233	0.00274	0.07213	0.14177	0.30344	0.34821
2.83	0.000194	0.02047	3E-06	6E-05	0.02252	0.00246	0.04299	0.07574	0.16274	0.18525
2.00	0.000106	0.00841	1E-06	3E-05	0.00895	0.00128	0.01519	0.02577	0.05561	0.06294
1.41	0.000281	0.01584	3E-06	8E-05	0.01692	0.00338	0.02628	0.04571	0.0943	0.10654
1.00	0.000382	0.01304	4E-06	0.0001	0.01372	0.0036	0.02092	0.03711	0.07489	0.08434
0.50	0.001097	0.01588	1E-05	0.0003	0.01686	0.00622	0.02652	0.04437	0.08497	0.09397
0.21	8.28E-06	6.1E-05	1E-07	4E-06	6.4E-05	2.4E-05	9.6E-05	0.00015	0.00027	0.0003
qb	0.002939	0.19706	3E-05	0.0008	0.21779	0.0276	0.53538	1.50079	5.07122	6.09167

[B] Taking i_b of equilibrium bed surface

1. M1

di (mm)	1	2	3	4	5	6	7	8
17.88854	0.000324	5.1E-05	0.00034	0.000329	0.000106	0.000311	0.0007	0.002842
14.14214	0.000551	0.000103	0.000566	0.000626	0.000197	0.000539	0.0012	0.004962
11.18034	0.000804	0.00015	0.000872	0.000886	0.000272	0.000789	0.0016	0.007396
8.944272	0.001165	0.000222	0.001229	0.00129	0.000379	0.001143	0.0023	0.010242
7.099296	0.001716	0.000326	0.001789	0.001965	0.000589	0.001659	0.0032	0.01516
5.470375	0.002736	0.000557	0.00284	0.00316	0.000973	0.00267	0.0052	0.024001
4.358899	0.002186	0.000444	0.002187	0.002621	0.000742	0.002163	0.0040	0.017973
3.660601	0.002714	0.000539	0.002736	0.003274	0.000869	0.002566	0.0046	0.019803
3.062679	0.002979	0.000627	0.003108	0.003686	0.000978	0.003006	0.005146	0.020258
2.366432	0.006405	0.001348	0.006354	0.007678	0.002244	0.00625	0.010393	0.035424
1.843909	0.003166	0.000774	0.003242	0.003976	0.001149	0.003139	0.004776	0.014498
1.542725	0.003799	0.000952	0.003809	0.004483	0.001371	0.003754	0.005347	0.014322
1.183216	0.005545	0.001603	0.005434	0.006728	0.00226	0.005658	0.007389	0.01758
0.774597	0.005141	0.002081	0.005199	0.006347	0.00264	0.005158	0.006139	0.012898
qb	0.039233	0.009778	0.039706	0.04705	0.014768	0.038804	0.061918	0.217358

2. M2

di (mm)	1	2	3	4	5	6	7	8
27.95085	6.15E-05	3.35E-05	5E-05	9.51E-05	0.000233	0.00054	0.0006	0.002572
22.36068	8.9E-05	5.12E-05	8.59E-05	0.000158	0.000384	0.000894	0.0010	0.003985
17.88854	0.000133	7.85E-05	0.000146	0.000256	0.000567	0.001478	0.0016	0.005918
14.14214	0.00022	0.000146	0.000247	0.000434	0.000901	0.002393	0.0026	0.009687
11.18034	0.000276	0.000203	0.000329	0.000525	0.00122	0.003202	0.0034	0.012828
8.944272	0.000351	0.000275	0.000422	0.000702	0.001565	0.00423	0.0044	0.016803
7.099296	0.000431	0.000365	0.000578	0.001006	0.002144	0.006195	0.0065	0.022525
5.470375	0.000626	0.000559	0.000943	0.001483	0.003094	0.009764	0.009971	0.031728
4.358899	0.000414	0.00041	0.000664	0.001049	0.002134	0.006983	0.006775	0.02114
3.660601	0.000429	0.000459	0.000754	0.001153	0.002571	0.007855	0.007721	0.021034
3.062679	0.000446	0.000498	0.00081	0.001239	0.002793	0.00842	0.008123	0.02096
2.366432	0.000792	0.000965	0.00162	0.00261	0.005229	0.015077	0.014509	0.031627
1.843909	0.00036	0.000464	0.000825	0.001215	0.00238	0.006756	0.006352	0.011634
1.542725	0.000395	0.000554	0.000921	0.001365	0.002669	0.00701	0.006354	0.010599
1.183216	0.000571	0.00085	0.001445	0.002046	0.003662	0.008647	0.007934	0.011855
0.774597	0.000543	0.000961	0.001458	0.001884	0.002889	0.006375	0.005775	0.007065
qb	0.00614	0.006872	0.011299	0.017219	0.034434	0.09582	0.093525	0.241961

3. M3

di (mm)	1	2	3	4	5	6	7	8
17.88854	4.48E-05	0.000298	0.000941	0.000122	0.000292	0.00078	0.0000	1.22E-05
14.14214	9.13E-05	0.00063	0.00179	0.000226	0.000557	0.001539	7.38E-05	2.22E-05
11.18034	0.000141	0.000929	0.002658	0.000324	0.000822	0.002272	0.000111	3.56E-05
8.944272	0.000204	0.001422	0.004328	0.000504	0.001257	0.003697	0.000167	5.79E-05
7.099296	0.000305	0.002192	0.006904	0.000804	0.001914	0.006141	0.000249	9.54E-05
5.470375	0.00059	0.004037	0.01214	0.001382	0.003298	0.010912	0.000445	0.000166
4.358899	0.000458	0.003307	0.009776	0.001097	0.002804	0.008883	0.000371	0.00013
3.660601	0.000576	0.004131	0.01218	0.001384	0.003419	0.011274	0.000447	0.000161
3.062679	0.000684	0.004779	0.01343	0.001718	0.003949	0.013076	0.000529	0.000201
2.366432	0.001519	0.010615	0.027181	0.003935	0.008639	0.025358	0.001151	0.000468
1.843909	0.000899	0.005484	0.012581	0.002094	0.004644	0.0121	0.00065	0.000259
1.542725	0.001138	0.006553	0.013796	0.002617	0.005136	0.013661	0.000862	0.000325
1.183216	0.002001	0.009537	0.018628	0.004492	0.008225	0.019169	0.001512	0.000606
0.774597	0.002655	0.009371	0.016237	0.005048	0.007684	0.016956	0.002039	0.000896
qb	0.011306	0.063285	0.15257	0.025747	0.052641	0.145819	0.008641	0.003438

4. M4

di (mm)	1	2	3	4	5	6	7
27.95085	#N/A	2.57E-05	0.000199	2.49E-05	0.000494	2.2E-05	0.000655
22.36068	2.87E-06	4.48E-05	0.000333	3.95E-05	0.000797	3.08E-05	0.001165
17.88854	5.68E-06	8.23E-05	0.000498	6.35E-05	0.001296	4.59E-05	0.001904
14.14214	9.59E-06	0.00015	0.000879	0.000122	0.002192	7.64E-05	0.003275
11.18034	1.24E-05	0.000218	0.001141	0.000169	0.002956	0.000118	0.004355
8.944272	1.74E-05	0.000296	0.001568	0.000244	0.003954	0.000161	0.00624
7.099296	2.64E-05	0.000434	0.002273	0.000331	0.005652	0.000232	0.009541
5.470375	5.08E-05	0.000749	0.003386	0.000532	0.009329	0.000335	0.014862
4.358899	4.18E-05	0.00056	0.002702	0.000398	0.006511	0.000249	0.010944
3.660601	5.44E-05	0.000682	0.003083	0.000466	0.007464	0.000295	0.012703
3.062679	6.31E-05	0.000749	0.00341	0.00051	0.007922	0.000313	0.013164
2.366432	0.000135	0.001643	0.006691	0.001007	0.015129	0.000631	0.024539
1.843909	7.41E-05	0.000876	0.00317	0.000513	0.006441	0.000303	0.009986
1.542725	9.59E-05	0.001043	0.003683	0.000628	0.006798	0.00035	0.010338
1.183216	0.000169	0.001771	0.00483	0.00099	0.008623	0.000586	0.013099
0.774597	0.000233	0.002008	0.004189	0.001165	0.006464	0.000664	0.00955
qb	0.000992	0.011332	0.042036	0.007201	0.092022	0.004414	0.146321

5. M5

di					
(mm)	**1**	**2**	**3**	**4**	**5**
7.608246	2.92E-05	0.000123	0.000391	0.000518	3.18E-05
5.943942	4.8E-05	0.000199	0.000593	0.000744	4.53E-05
4.755154	8.97E-05	0.000335	0.000865	0.001175	7.28E-05
3.804123	0.00015	0.000504	0.001275	0.001872	0.000121
3.043299	0.000268	0.000817	0.002091	0.003004	0.000217
2.377577	0.000352	0.001126	0.002555	0.003826	0.000287
1.902062	0.000469	0.001471	0.003315	0.004904	0.000369
1.521649	0.000769	0.002062	0.004309	0.006734	0.000493
1.198299	0.001193	0.003029	0.006262	0.010211	0.00078
0.903479	0.00088	0.002126	0.004406	0.007193	0.000561
0.760825	0.001008	0.002608	0.004829	0.007808	0.000634
0.637191	0.001157	0.002888	0.004979	0.008224	0.000678
0.532577	0.002476	0.005444	0.009005	0.01497	0.001324
0.380412	0.001289	0.002602	0.003834	0.005786	0.000686
0.32335	0.001477	0.002898	0.003805	0.005977	0.000756
0.266289	0.002373	0.004042	0.004745	0.007147	0.001157
0.190206	0.002462	0.00335	0.003288	0.004831	0.001248
qb	0.01649	0.035625	0.060547	0.094925	0.009461

6. J6

di	1	2	3	4	5	6	7	8	9	10
(mm)										
38.074	0	2.4E-05	0.0004	0.0025	9.6E-05	0.00104	0.01565	0	0.03191	0.08445
26.892	2.2E-05	4.8E-05	0.0009	0.0053	0.0002	0.00193	0.03303	3.6E-05	0.0638	0.16038
19.016	3.98E-05	7.4E-05	0.0015	0.0095	0.00044	0.00406	0.05979	5.6E-05	0.11181	0.24904
13.446	5.74E-05	0.00012	0.0027	0.0156	0.00076	0.00678	0.09376	8.6E-05	0.1709	0.33321
9.5079	8.41E-05	0.00021	0.004	0.0248	0.00107	0.01004	0.12797	0.00014	0.20216	0.36033
6.729	0.000137	0.0003	0.0052	0.0318	0.0016	0.01468	0.14175	0.00021	0.20222	0.3223
4.7582	0.000179	0.00036	0.0067	0.0379	0.00196	0.0177	0.12529	0.00026	0.16594	0.2394
3.3645	0.000188	0.00042	0.0074	0.0348	0.00218	0.01903	0.09179	0.0003	0.1136	0.15505
2.3791	0.0002	0.00043	0.0072	0.0266	0.00229	0.0163	0.05812	0.00029	0.06867	0.0912
1.6793	0.000188	0.00038	0.006	0.0172	0.00211	0.0119	0.03193	0.00027	0.03535	0.04872
1.1874	0.000145	0.00033	0.004	0.0092	0.00163	0.00682	0.015	0.00022	0.01757	0.02341
0.7071	0.000199	0.00041	0.003	0.0055	0.00166	0.00465	0.00917	0.00028	0.01004	0.01265
0.324	7.96E-05	0.00014	0.0005	0.0008	0.00034	0.00068	0.00118	0.0001	0.00124	0.00148
qb	0.001518	0.00324	0.0493	0.2216	0.01633	0.11561	0.80444	0.00225	1.19522	2.08163

7. J15

di (mm)	1	2	3	4	5	6	7	8	9
38.074	0.11885	0.00011	0.0042	0.0205	5.5E-05	0.00095	0.0005	0.08732	0.05239
26.892	0.202145	0.00021	0.0079	0.0383	9.1E-05	0.00179	0.001	0.15003	0.09752
19.016	0.294693	0.00041	0.0135	0.0645	0.00015	0.00333	0.00166	0.23064	0.14992
13.446	0.347174	0.0007	0.0216	0.0951	0.00027	0.0053	0.0026	0.2831	0.20221
9.5079	0.338255	0.00092	0.0305	0.1242	0.00041	0.00746	0.00372	0.2881	0.21294
6.729	0.274309	0.00127	0.0366	0.1249	0.00053	0.01047	0.00473	0.24957	0.19252
4.7582	0.189468	0.00141	0.0405	0.1064	0.00065	0.01205	0.00548	0.17237	0.14005
3.3645	0.108559	0.00145	0.0345	0.0735	0.00069	0.01249	0.00574	0.10291	0.08821
2.3791	0.057369	0.00139	0.0237	0.0428	0.00063	0.0113	0.00528	0.0547	0.04727
1.6793	0.027434	0.00121	0.0142	0.0218	0.0006	0.00784	0.00392	0.02653	0.02207
1.1874	0.011609	0.00087	0.0069	0.0095	0.00044	0.0045	0.00258	0.01128	0.00952
0.7071	0.005631	0.00088	0.0037	0.0052	0.00051	0.00306	0.00187	0.00554	0.00473
0.324	0.000504	0.00016	0.0005	0.0005	0.00012	0.00039	0.00026	0.00051	0.00044
qb	1.976	0.011	0.2383	0.7274	0.00515	0.08093	0.03932	1.6626	1.2198

8. J21

di (mm)	1	2	3	4	5	6	7	8	9
38.074	0.133391	8.8E-05	0.0014	0.0118	0	0.00173	0	0.18561	0.27035
26.892	0.212047	0.00014	0.0025	0.0205	5.1E-05	0.00302	3.5E-05	0.31297	0.42712
19.016	0.29752	0.00023	0.0043	0.0311	7.3E-05	0.00522	5.6E-05	0.42025	0.53152
13.446	0.339929	0.00038	0.0066	0.0481	9.7E-05	0.00765	7.3E-05	0.47443	0.56518
9.5079	0.304278	0.00055	0.0086	0.0616	0.00013	0.00982	9.6E-05	0.42585	0.48504
6.729	0.234865	0.00064	0.0111	0.0695	0.00019	0.01251	0.00013	0.3314	0.36045
4.7582	0.153049	0.00074	0.0123	0.062	0.00021	0.0137	0.00016	0.21724	0.22737
3.3645	0.083061	0.00074	0.0117	0.044	0.0002	0.01275	0.00016	0.12089	0.1248
2.3791	0.041065	0.00066	0.0092	0.0263	0.00019	0.01047	0.00015	0.06514	0.0657
1.6793	0.018182	0.00057	0.0062	0.0134	0.00016	0.00645	0.00013	0.0308	0.03079
1.1874	0.007208	0.0004	0.0034	0.0058	0.00011	0.00331	9E-05	0.01265	0.01193
0.7071	0.003095	0.00042	0.002	0.0029	0.00013	0.00198	0.00011	0.00606	0.00543
0.324	0.000255	8.5E-05	0.0002	0.0003	3.9E-05	0.00021	3.4E-05	0.00053	0.00047
qb	1.827945	0.00562	0.0796	0.3972	0.00159	0.08884	0.00123	2.60382	3.10613

9. J27

di (mm)	1	2	3	4	5	6	7	8	9	10
38.074	3.49E-05	0.00509	0	0	0.00556	0.00035	0.02201	0.10556	0.81282	1.19093
26.892	6.97E-05	0.00957	0	0	0.01015	0.00072	0.03799	0.17953	1.0613	1.40954
19.016	9.48E-05	0.01476	0	3E-05	0.01619	0.00124	0.06269	0.26156	1.11479	1.40626
13.446	0.000129	0.02007	0	5E-05	0.02366	0.00171	0.08425	0.31338	1.01783	1.16411
9.5079	0.000186	0.02882	0	5E-05	0.03252	0.00236	0.10284	0.2986	0.768	0.83
6.729	0.000243	0.03218	0	6E-05	0.03784	0.00279	0.10408	0.24329	0.50846	0.5291
4.7582	0.000257	0.03291	0	7E-05	0.03736	0.00297	0.08315	0.16625	0.31153	0.32298
3.3645	0.000247	0.02676	4E-06	7E-05	0.03004	0.00311	0.05436	0.09403	0.17513	0.1653
2.3791	0.000221	0.01727	3E-06	6E-05	0.01952	0.00261	0.03023	0.04826	0.08527	0.07925
1.6793	0.000175	0.00931	2E-06	5E-05	0.01085	0.00202	0.01459	0.02216	0.03733	0.03261
1.1874	0.00012	0.00434	1E-06	4E-05	0.00497	0.00123	0.0058	0.0093	0.01427	0.01192
0.7071	0.000134	0.00215	2E-06	4E-05	0.00257	0.00095	0.00295	0.00433	0.00599	0.00485
0.324	3.48E-05	0.00021	6E-07	1E-05	0.00027	0.00012	0.00029	0.00039	0.00045	0.00033
qb	0.001946	0.20345	1E-05	0.0005	0.2315	0.02219	0.60524	1.74663	5.91317	7.14717

All values of transport rates are in N-s/m