The Computer Aided Design of the Hydraulic Transport of Coarse Mineral Particles

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering

by

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ABSTRACT

There are few engineering disciplines where design procedures are less reliable than in the prediction of optimum mixture velocity and corresponding pressure drop for settling slurries, the generally proposed method of correlating pressure gradients in horizontal pipelines being of the form:

\[
\frac{J - J_w}{C - J_w} = K \left[ \frac{v^2 C_D^{0.5}}{g D (S - 1)} \right]^n
\]

Many investigators have proposed different values for the empirical constants K and n and these are particularly unsatisfactory if used for predicting pressure gradients when coarse solids are transported. A review of relevant literature shows alternative methods of correlating pressure gradients in horizontal pipes based on "credible physical processes".

A computer program presented provides a direct comparison of some equations proposed from data correlation techniques and one "credible physical process" with experimental data. This will enable the user to select the most appropriate equation when dealing with various mineral solids.

Few studies have been made using mixed size solids but designers often assume that the coarser solids are carried in a suspension of a fine fraction in water. This method is very tedious if a computer program is not available and an additional program presented enables pressure gradients to be determined when high concentrations of fines are present.
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\( V_0 \) Mixture velocity at which sliding bed is initiated. (m/s)

\( V_2 \) Mean mixture velocity at and above which the mixture flows in a heterogeneous flow regime. (m/s)

\( \theta \) Half the angle subtended at the pipe center by the surface of any sliding bed. (degrees)

\( \mu \) Dynamic viscosity. (kg/ms)

\( \nu \) Kinematic viscosity. (m\(^2\)/s)

\( \rho \) Density of fluid. (t/m\(^3\))

\( \sigma \) Density of solids. (t/m\(^3\))
1.0 INTRODUCTION

The cost of the transportation of raw materials from source to market has always been a significant element in market prices. Not unnaturally, those raw material deposits which are most accessible are the first to be exploited while other, less amenable deposits are either neglected or considered totally unworkable on economic grounds. During the past two decades we have seen the growth of hydraulic transport which has extended the economic reach of the minerals industry in a most spectacular manner.

The basic concept of transporting minerals through pipelines, usually as slurry in water is not new. The technique was employed as early as the 1850's in the California gold fields. In earlier years, slurry pipelines were developed to carry tailings distances of between three and eight kilometers to disposal areas. Since the mid-1950's an increasing number of slurry pipelines have been designed as links in the system carrying products from the mine to the consumer. Pipeline transportation of solid materials is of most significance in developing countries since the technical and economic characteristics are most favorable when an alternative means of transportation does not already exist.

The fundamental prerequisite for operating a slurry pipeline is an assured long-term supply of mineral, together with an equally assured long-term market capable of absorbing the output. In the absence of an existing means of transportation, particularly in comparison with a railway,
(usually the most common alternative to a slurry pipeline) the following factors tend to favor selection of a pipeline.

Not only can pipelines be laid to steeper grades (10-14 percent) than railways (1-2 percent) but tighter curve radii as well as far cheaper canyon crossings can be made with a pipe. A pipe is also preferable when the starting point is at a higher elevation than the terminal point, since the potential energy of the slurry at the top of the grade is converted at the bottom, largely to pressure energy. This is then available to help lift the slurry over the next hill, where as in the case of the railway or road, the energy is largely wasted in braking.

A pipeline has a further advantage when transporting minerals to flotation processes, which require the material to be reduced to fine particles. If the reduction is carried out before transportation the pipeline can be operated at a lower power level, resulting in large savings of energy.

There are, however, a number of disadvantages to be considered. Firstly, once built to certain specifications it is virtually impossible to increase the maximum operating capacity of the pipeline. Secondly, with a mine output of coarse material, conveyors and possibly aerial ropeways in rugged terrain are strong competitors.

Optimum conditions for operating a pipeline have been estimated to be a distance of 800 hundred kilometers or more and an annual capacity of 5 to 6 million tons. There are, however, numerous examples throughout the world of pipelines working on much smaller scales and each case must be
reviewed on its individual merits. Aude\textsuperscript{(1)} shows in figure 1 the transportation costs of a pipeline against a new railway. Road construction is included for completeness but as soon as the annual throughput is greater than half a million tons it is disregarded as uneconomic.
Figure 1 - Mineral ore transportation cost

Cost / ton mile

Annual throughput - million tons

Figure 1 - Mineral ore transportation cost
2.0 THEORETICAL CONSIDERATIONS

2.1 Transition Velocity.

The flow of mixtures of solids and liquids in pipes differs from the flow of homogeneous liquids in a number of ways. With liquids, the complete range of velocity is possible and the nature of the flow (i.e. laminar, transition, and turbulent) can be characterized from the knowledge of the physical properties of the fluid and the pipe system. Characterization of slurry flow is not as simple as for liquid flow for two reasons. Firstly, there are, superimposed on the properties of the liquid, the properties of the solid particles and the effect of the particles on the mixture properties. Secondly, a range of slurry behavior is possible due to the variety of operating conditions.

It is usual to divide slurry mixtures into two categories; 'non-settling' and 'settling', the usual criteria being the behavior of the mixture when at rest. 'Non-settling' slurries usually contain a high concentration of particles in the size range of 10 μm to 50 μm and, if completely non-settling, can be transported in laminar flow with great economies in power cost and pipe wear. The term 'equivalent liquid' is often used to describe these mixtures and they may be defined according to their rheological properties, permitting the use of design procedures base on continuum mechanics.

'Settling' slurries usually contain fine particles at low concentration or coarse particles at any concentration. In
addition to developing expressions for predicting pressure
gradient in pipes carrying these two phase systems, almost all
investigators have attempted to define the various flow
regimes mathematically since the proposed correlations for
pressure gradient have, in general, required the regime to be
known. The flow regimes generally classified as illustrated
in figure 2 are defined as follows:-

1. Stationary bed (often accompanied by saltation).
2. Sliding bed (often accompanied by saltation or
   suspension).
3. Heterogeneous or asymmetric suspension.
4. Homogeneous or symmetric suspension.

The first three conditions are easily recognized but the
homogenous regime is difficult to achieve with large solids.
The point at which solids begin to settle on the bottom of the
pipe can also be easily recognized, this point being referred
to as the limiting velocity by Durand and Condolios (2). They
concluded that this was approximately the velocity at which
the head loss was at a minimum and suggested how it may be
predicted.

Durand and Condolios (2) also proposed the most widely
used expression for the prediction of a transition velocity

\[ V_L = F_L \sqrt{\frac{2 g D (S-1)}{2}} \text{ m/s} \]  

(1)

the velocity \( V_L \) being normally the limiting velocity for
deposition, and \( F_L \) being a dimensionless factor dependent on
Figure 2 - Schematic curves of pressure against velocity for two concentrations in the same pipe
particle size and concentration as shown in figure 3. However, the practical work carried out by Durand and Condolios\(^{(2)}\) was only for concentrations up to 15 percent so it is not clear what \(F_L\) would be at higher concentrations particularly with particle sizes less than 1 mm. It is also not clear whether a stationary or sliding deposit is indicated, as no clear indication of the limiting velocity for deposition is given in the Durand and Condolios\(^{(2)}\) paper other than it appears to correspond fairly accurately to the minimum of the headloss curve.

Many investigators using this expression have assumed that the transition from the sliding bed to the heterogeneous regime is intended, since reference is made to the "boundary between regimes with and without deposition in the pipe bottom." This assumption is not always made however, as other investigators use \(V_L\) for the velocity at which transition from a blocked pipe to the stationary bed with the saltation flow regime occurs.

One of the conclusions of Durand and Condolios\(^{(2)}\) is that (with coarse sand and pebbles) for particle diameters exceeding 1 mm, the concentration and particle diameters have practically no further influence on the value of \(F_L\), which appears to be in the neighborhood of 1.34, thus modifying the value of \(V_L\) to:-

\[ V_L = 5.935 \left[ \frac{D}{(S-1)} \right]^{0.5} \text{ m/s} \quad \cdots \cdots \cdots \quad (2) \]

Newitt, Richardson, Abbott and Turtle\(^{(3)}\) reported \(V_L\) as the critical velocity \(V_C\) below which a stationary bed exists.
Figure 3 - Variation of the Parameter $F_L$ as a function of particle size
Since the term "stationary bed" was never mentioned in the Durand and Condolios (2) paper it is assumed that Newitt, et. al. (3) adopted this term in their analysis. They suggested that the transition velocity between flow by saltation or sliding bed and a heterogeneous suspension is given by the equation:

\[ V_2 = 17 V_s \text{ m/s} \quad \text{(3)} \]

A third important equation for the prediction of \( V_2 \) is that proposed by Zandi and Govatos (4) who used 2549 data points collected from 12 sources to compare various head loss correlations and concluded that the equation predicting the transition between saltation and heterogeneous flow is:

\[ V_2 = \left[ \frac{40 CD g (S-1)}{C_D 0.5} \right]^{0.5} \text{ m/s} \quad \text{(4)} \]

Bain and Bonnington (5) arrived at their equation for critical velocity in a pipeline, operating at a constant solids concentration by differentiating Durand's expression relating velocity and pressure drop (equation 21) with respect to velocity and obtained the equation,

\[ V_2 = 3.43 C^{0.33} \left[ \frac{g D (S-1)}{C_D 0.5} \right]^{0.5} \text{ m/s} \quad \text{(5)} \]

A great many other relationships for \( V_2 \) have been proposed and because of the serious disagreement, the safest method is to
observe the deposition velocity in an available pipe and scale it to the required pipe diameter using the following equation:

\[ V = V_{\text{experimental}} \times \left( \frac{D_{\text{required}}}{D_{\text{experimental}}} \right)^{0.5} \]

If no experimental velocity is available the deposition velocity of a similar slurry can be obtained from a data bank. Figure 4 shows, after a diagram suggested by Newitt et al.\(^{(3)}\), the variation in flow characteristics with particle size and mean velocity for a particular range of experiments.

Most equations used for the prediction of \( V_2 \) require either the terminal settling velocity or the drag coefficient of the particles being transported. Simple settling velocity tests may be unsatisfactory however, since the settling motion is often of a lateral or falling leaf nature which is not present during hydraulic transport.

Accurate correlation of the transition velocity is important as at that velocity the flow changes from sliding bed to heterogeneous flow. If the velocity drops below this figure the sliding bed increases, but then, the flow area is reduced, the velocity above the bed increases until an equilibrium is reached which keeps the solids in suspension above the bed. Until this equilibrium is reached there is the possibilities of large pressure fluctuations which produce a series of mounds or dunes along the pipe. This effect is known as 'duneing'.
Figure 4 - Variation in flow characteristics with particle size and mean velocity for sand and gravel in 25.4 mm and 152.4 mm pipes.
2.2 Particle Size.

Material transported by pipeline may consist of single size particles, or more commonly, a range of particle sizes. Figure 5 shows the 'Systeme International' sieve and grain size classification, but it is often more common to use a representative particle size.

There are many definitions of the representative size and the most commonly used are:-

(1) For graded particles the $d_{50}$ size, i.e. the size corresponding to 50 percent passed.
(2) For sieved particles the average size between two sieve sizes.
(3) The particle whose volume or mass is equal to the average volume or mass of all the particles. This is usually measured by the fluid displacement of known number of particles.
(4) The particle whose surface area to volume ratio is equal to surface area to volume ratio of all the particles (the Sauter mean diameter).
(5) The particle whose surface area is equal to the average surface area of all the particles. This is usually determined by measuring the quantity of dye required to coat the particles.

The influence of particle size on the economics of hydraulic transport can be seen by comparing the specific energy requirements when transporting particles of the same relative density, either as:-
Particle size (mm)

Figure 5 - S.I. Sieve sizes from B.S. 1377 : 1975
1. gravel (2.80 kwh/tkm)
2. sand (1.02 kwh/tkm)
3. silt (0.05 kwh/tkm)

At high velocities single particles approximately equal in size to the inside diameter of the pipe may be conveyed. The primary consideration however, is that there should be an adequate distance above the sliding or stationary bed for the largest particle to turn over without touching the upper pipe wall.

2.3 Drag Coefficient.

The drag force on a solid immersed in a moving liquid consists of two components; the viscous drag (skin friction) and the form drag. At low liquid velocities no separation of the boundary layer takes place and the whole of the drag results from a viscous drag. As the velocity increases the boundary layer separates and both viscous and form drag are present. If the velocity is continually increased, form drag becomes an increasing proportion of the total drag force.

Figure 6 shows the variation of $C_D$ with $Re$ for smooth, axial symmetric bodies, the curve for spheres may be approximated up to $Re = 10^5$ by the expression:

$$\sqrt{C_D} = 0.63 + 4.8 \sqrt{Re} \quad \text{..........................(6)}$$

A better approximation is obtained by fitting three straight lines to the curve according to the following three laws:
Figure 6 - Drag Coefficients of smooth axially-symmetric bodies

\[ Re = \frac{u_d}{\nu} \]

Stokes' law:
\[ C_D = \frac{24}{Re} \]

Circular disc

Ellipsoid 1:0.75

Sphere

Ellipsoid 1:1.8

Effect of surface roughness or main-stream turbulence
1. Stoke's law: \( C_D = \frac{24}{R_e} \), valid within 15 percent of the range \( R_e = 0 \) to 0.8.

2. Intermediate law: \( C_D = \frac{14}{R_e} \), valid within 15 percent of the range \( R_e = 6 \) to 600.

3. Newton's law: \( C_D = 0.44 \), valid within 15 percent of the range \( R_e = 1000 \) to \( 10^5 \).

In the first law, it is assumed that the viscous drag of the particles is solely responsible for the drag. In law three, it is assumed that only form drag is present. In reality both viscous and form drag are present over the whole range, but it is only in the second law that the two are of comparable magnitude.

2.4 Terminal Settling Velocity

Using the drag laws, the terminal settling velocity of a sphere may be calculated from the expression:

\[
V_s = \sqrt{\frac{4 g d (S-1)}{3 C_D}}
\]  

but the value of the drag coefficient is dependent on Reynolds number, by substituting the values of \( C_D \) obtained in Section 1.3, three equations are obtained for the three laws.

1. \( V_s = \frac{g d^2 (S-1)}{18 \sqrt{}} \) (Stokes)  

2. \( V_s = 0.2085 d \sqrt{\frac{g^2 (S-1)^2}{3 \sqrt{}}} \) (Intermediate)
3. \[ V_s = 1.7408 \sqrt{d g (S-1)} \text{ (Newtons)} \] .......(10)

To calculate the correct settling value of \( V_s \), values are calculated according to the three equations (8, 9, 10). These values are then substituted in the equation:

\[ \text{Re} = \frac{V_s d}{\sqrt{V}} \] ......................(11)

This gives three values of Reynolds number corresponding to Stoke's law, the Intermediate law and Newton's law. The value of \( \text{Re} \) which fits within the correct range is used to calculate \( C_D \) and indicates which is the appropriate settling velocity. For practical purposes when coarse particles are transported, Reynolds number is rarely less than 1000 so \( C_D \) is generally equal to 0.44.

2.5 Hindered Settling Velocity

The settling velocity of particles is reduced by the presence of others, this reduction is caused by the collision between particles and the upward flow of water. A useful method of determining the hindered settling velocity \( (V_s') \) was developed by Richardson and Zaki \(^6\) and uses the semi-empirical equation:

\[ V_s' = V_s (1-C) \alpha \] ...........................(12)

The value of \( \alpha \) being obtained from the table below.
<table>
<thead>
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<th>$Re$</th>
<th>$\alpha$</th>
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<tr>
<td>$Re &lt; 0.2$</td>
<td>4.6</td>
</tr>
<tr>
<td>$0.2 &lt; Re &lt; 1$</td>
<td>$4.4 Re^{-0.03}$</td>
</tr>
<tr>
<td>$1 &lt; Re &lt; 500$</td>
<td>$4.4 Re^{-0.1}$</td>
</tr>
<tr>
<td>$Re &gt; 500$</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Reynolds number is usually greater than 500 unless the particles are very small or the liquid medium is not water, so $\alpha$ is generally equal to 2.4.

2.6 Non-Spherical Particles

Mineral particles are generally of irregular shape and both $C_D$ and $V_s$ for spheres have to be modified. Empirical description of particle shape is provided by identifying two characteristic parameters from the following:-

(a) Volume $(V)$

(b) Surface area $(A)$

(c) Projected area $(A_p)$

(d) Projected perimeter $(P_p)$

The terminal settling velocity of a spherical particle is modified using the equation:-

$$V_s \text{ (non-spherical)} = K_A V_s \text{ (spherical)} \quad \ldots \ldots (13)$$

Figure 7 shows $K_A$ as a function of $N_D^{1/3}$ with $k$ as a parameter, where $N_D = C_D Re^2$. This was proposed by Heywood(7) and his "volumetric shape factor" is defined as:-
Figure 7 - Aid for estimating terminal settling velocity of non-spherical particles
where \( d_A \) is the diameter of a sphere with the same projected area as the particle, i.e.

\[
d_A = \sqrt[3]{\frac{4 \, A_p}{\kappa}}
\]

The volumetric shape factor \((k)\) and the value of \(N_D^{1/3}\) are calculated, this enables the value of \(K_A\) to be read off the left hand side of figure 7.

2.7 Hydraulic gradient

The last sections dealt with the characteristics of the particles being transported. After determining a suitable pipe size and mean mixture velocity, the pipeline designer is required to estimate the hydraulic gradient so that power and energy calculations may be made. For very fine slurries, fluid equations can be used with a reasonable degree of success, but as the particle size increases so the accuracy decreases.

As with the transition velocity, many researchers have proposed various equations to predict the hydraulic gradient. It was decided to include five of the better known and appropriate equations to enable a good comparison with a theory proposed by Gaskell\(^8\) to be made.

For clear water Darcy's formula is used to calculate the hydraulic gradient using the equation:-
where $h_f$ is the head lost due to the friction in meters of water.

This is converted to a hydraulic gradient by omitting the length term resulting in the equation:

$$J_w = \frac{4 f V^2}{2 g D} \quad \text{..................................(16)}$$

where $J_w$ is the hydraulic gradient in mH$_2$O/m of pipe.

The friction term ($f$) is obtained from the Moody diagram, figure 8, or by using the Colebrook-White formula:

$$\sqrt{f} = -4 log \left[ \frac{K + \frac{1.26}{3.7 D Re f}}{Re f} \right] \quad \text{..............(17)}$$

where $K$ is the pipe roughness constant.

When solids are present it is usual to relate the hydraulic gradient for the mixture to the hydraulic gradient for clear water in the same pipe. The difference between the two, $J - J_w$ is the excess hydraulic gradient but is usually considered as $(J - J_w)$ to make it dimensionless.

$$J_w$$

If homogeneous suspensions of very fine particles behave as simple Newtonian fluids, the excess hydraulic gradient is then proportional to the density of the mixture:
Figure 8 - Plot of Friction Factor against Reynolds number

Reynolds number $Re = \frac{ud}{v}$
i.e. \( J - J_w \propto C(S-1) \)

Usually these very fine particle suspensions exhibit non-Newtonian characteristics, so it is necessary to take rheological measurements which can be used to predict the behavior of the slurry. Unfortunately, results with fine particle solids of different minerals are so variable that no uniform formula exists.

Figure 2 shows schematic curves of pressure gradient against velocity for two concentrations in the same pipe and from this is can be seen that the head loss may be expressed in the form:

\[
J - J_w \propto f(C, V) \quad \text{(18)}
\]

This had led almost every investigator to propose correlations in this form.

Durand and Condolios\(^2\) considered 310 data points based on observations of both sand and gravel from a test rig and dredging operations. They considered particle sizes from 0.2 to 25mm, pipe diameters from 40 to 580mm, volumetric concentrations from 3 to 35 percent and mixture velocities up to 6 m/s. After consideration they stated all their data could be plotted on a single curve with axes of:

\[
\frac{J - J_w}{C J_w} \quad \text{against} \quad \frac{v^2 C_D^{0.5}}{g D}
\]

where \( C_D \) is the mean particle drag coefficient.
These points were plotted on log/log paper and they produced a straight line with a slope of -1.5 and an intercept on the vertical ordinate of about 180, the equation of this line being:

\[
\frac{J-J_w}{C J_w} = 180 \left[ \frac{g D}{v^2 C_D^{0.5}} \right]^{1.5}
\]  

(19)

When this equation was published the value of the intercept (180) was not stated and had to be found by extrapolation of the graph. Thirteen years later Condolios finally acknowledged that it was 180 but in the meantime other researchers had used different constants.

The equation was based on sand and gravel with a specific gravity of 2.65, Durand and Condolios suggested that the correlation should be amended to include a relative density term \((s-1)\) before applying it to other materials. This alters the intercept to 85 when replotted, giving the equation:

\[
\frac{J-J_w}{C J_w} = 85 \left[ \frac{g D (s-1)}{v^2 C_D^{0.5}} \right]^{1.5}
\]  

(20)

Tests using plastic (relative density 1.5) and corundum (3.95) confirmed that this equation is valid for other solids.

A second equation is obtained from the correlation if the drag coefficient for spheres is replaced by the one for irregular particles. This can be calculated using the equation:
where \( V_{SI} \) is the settling velocity for irregular particles. By substituting this into equation 20, the equation for irregular particles becomes:

\[
\frac{J-J_W}{C J_W} = 85 \left[ \frac{g \, V_S \, D \,(S-1)}{V_C^2 \, C_{DI}^{0.5} \, V_{SI}} \right]^{1.5}
\]

(21)

Since \( C_D = \frac{4 \, g \, d \,(S-1)}{3 \, V_S^2} \) for uniform single sized spheres an alternative form of equation 20 and 21 is possible, e.g. equation 20 becomes:

\[
\frac{J-J_W}{C J_W} = 69 \left[ \frac{g \, D \,(S-1) \, V_S}{V_C^2 \,(g \, d \,(S-1))^{0.5}} \right]^{1.5}
\]

(22)

The data produced by Durand and Condolios\(^{(2)}\) was based on material containing only very small quantities of fines. Further work using fine particles in small diameter pipes produced results which would not fit the formula proposed by Durand and Condolios\(^{(2)}\). As a result Zandi and Govatos\(^{(4)}\) separated the Durand/Condolios and other data into those relating to heterogeneous and those relating to saltation flow. From their results they proposed the following
equations:

\[
\frac{J - J_w}{C J_w} = 6.3 \left[ \frac{v^2 C_D^{0.5}}{g D (S-1)} \right]^{-0.354}
\]  

\[
\frac{J - J_w}{C J_w} = 280 \left[ \frac{v^2 C_D^{0.5}}{g D (S-1)} \right]^{-1.93}
\]

for suspensions, i.e. where the contents of the square brackets are greater than 10, and:

Durand and Condolios still adhered to the belief in their original equations and suggested that the lack of agreement with other workers was due to the variety of methods used to evaluate the drag coefficient. There is little doubt that the determination of \( C_D \) is extremely difficult. Previous tests carried out by the author produced a wide range of values for materials in a single size range due to the shape variations. A means of assessing a mean value of \( C_D \) has to be agreed before any use can be made of equations with a drag coefficient term.

Fortunately simplifying the situation, is the general assumption that for coarse particles (greater than 1mm) it is possible to ignore the drag coefficient. As a result Durand
and Condolios\(^{(2)}\) considered the data from their work with gravels larger than 1mm and plotted:

\[
\frac{J-J_w}{C J_w} \text{ against } \frac{v^2}{g D (S-1)}
\]

These points were plotted on log/log paper and produced the equation described in this work as 'Durand's Coarse'\(^{(2)}\):

\[
\frac{J-J_w}{C J_w} = 135 \left[ \frac{g D (S-1)}{v^2} \right]^{1.35}
\]  \hspace{1cm} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (25)

Worster\(^{(9)}\) analyzed experimental data from large coal particles and proposed the equation:

\[
\frac{J-J_w}{C J_w} = 120 \left[ \frac{g D (S-1)}{v^2} \right]^{1.5}
\]  \hspace{1cm} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (26)

This included no size parameter as this had been found to have no influence on the pressure gradient when coarse particles are transported.

Newitt et. al.\(^{(3)}\) continued the investigation of coarse particles and proposed two equations:

\[
\frac{J-J_w}{C J_w} = \frac{66 (S-1) g d}{v^2}
\]  \hspace{1cm} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (27)
This was suggested for sliding bed and flow by saltation, and:

\[
\begin{align*}
\frac{J-J_w}{C J_w} &= \frac{1100 (S-1) g d V_s}{v^3} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (28)
\end{align*}
\]

was suggested for materials traveling as a heterogeneous suspension.

Equations 20, 21, 23, 24, 25, 26, 27 and 28 have been included in the computer program to enable a comparison of the different existing theories with the one proposed by Gaskell.

2.8 Investigating the effect of the Fine Fraction on the Relative Density of the Fluid Medium.

Many investigators have assumed that the density of the carrying medium is equal to unity and ignore the effect of the presence of fines. In cases of high concentrations of fines this is erroneous as the fines will create a heavy medium with an adjusted relative density and viscosity. The following method is based on one suggested by Gaskell(9).

From the relationships between drag coefficient, Reynolds number, settling velocity, viscosity and relative densities, the maximum size of particle in water falling in the laminar zone according to Stoke's Law is given by:-

\[
d_{L\text{max}} = 2.62 \left[ \frac{v^2}{g(S - 1)} \right]^{1/3} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (29)
\]

and the minimum particle size in water falling in the
turbulent settling zone according to Newton's Law is given by:

\[ d_{\text{Tmin}} = 69.34 \left[ \frac{v^2}{g(S - 1)} \right]^{1/3} \] ................................(30)

therefore,

\[ d_{\text{Tmin}} = 26.5 \cdot d_{\text{Lmax}} \]

It should be noted however, that the value of \( d_{\text{Tmin}} \) determined in this way is only an approximation since spherical particles are assumed.

To determine the effect of a large percentage of fines on the fluid medium the following procedure was adopted:

- Weight concentration of solids \( = C_W \)
- Volumetric concentration of solids \( = C_V \)
- \( C_W = \frac{C_W}{S - C_W(S-1)} \)
- Weight concentration of fines \( (C_{WF}) = \text{percentage of fine fraction} \times C_W \)
- Volumetric concentration of fines \( (C_{VF}) = \frac{C_{WF}}{S - C_{WF}(S-1)} \)
- Volumetric concentration of coarse fraction \( (C_{VC}) = C_V - V_{VF} \)
- Relative density of heavy medium \( (S_{\text{hm}}) = C_{VF}(S - 1) + 1 \)
- Relative density of coarse slurry fraction \( (S_{\text{CSF}}) = C_{VC}(S - S_{\text{hm}}) + S_{\text{hm}} \)
Hydraulic gradient for the heavy medium (kN/m²/m of pipe) = \frac{4 f V^2 S_{hm}}{2 D}

If an equation which contains a settling velocity or drag coefficient term is used to determine the increase in hydraulic gradient due to the presence of the solid particles then a weighted mean value must be used. The drag coefficient and settling velocity for each coarse fraction must be found and the weighted result calculated by multiplying each value by the percentage of coarse solids in each fraction.
3.0 DETERMINATION OF PRESSURE GRADIENT BASED ON "CREDIBLE PHYSICAL PROCESSES"

The generally proposed methods of correlating pressure gradients for horizontal hydraulic transport are of the form:

\[
\frac{J - J_w}{C J_w} = K \left[ \frac{V^2 cD^{0.5}}{g D (S-1)} \right]^n
\]

In the previous sections it can be seen that many investigators have proposed different values for the empirical constants \( K \) and \( n \), as a result these expressions of the above type are particularly unsatisfactory if used for predicting pressure gradients when coarse solids are transported. In expressions of this form the additional pressure gradient due to the solids, \( J - J_w \), is effectively considered to be the clear water pressure gradient \( J_w \), multiplied by \( Z \), where \( Z \) is a function of concentration, velocity, pipe diameter, particle density and drag coefficient.

While most references attribute some physical reasons for the type of expression involving \( Z \), in no case is it convincingly argued that the additional pressure gradient is dependent on \( J_w \).

Correlations which include the drag coefficient, assume that no sliding is present during the flow as the effect of the drag coefficient would not be significant in the sliding bed regime. As a result, these correlations are usually accompanied by an equation for the prediction of the transition velocity.
Data collected indicates that most empirical correlations which supposedly predict this velocity, are unrealistic if used outside the conditions of the test providing the data on which the correlation is based. Since in many cases the velocity at which the sliding bed disperses is greater than the predicted value, the effect of $C_D$ appears less than suggested.

This approach was proposed by Gaskell\(^8\) in 1977 and is based upon the assumption that the total pressure gradient is composed of two fundamental components which appears to be a more rational approach:

1. The pressure gradient due to the solids sliding friction ($J_g$).

2. The pressure due to the wall shear forces of the fluid ($J_p$).

The two components $J_g$ and $J_p$ can be found using the definitions and derivations outlined in the following sections.

3.1 The Bulking Factor

The bulking factor ($B$) is defined as the ratio of the sum of the volume of the solids and the volume of the voids in a bed of particles to the actual volume of solids in the bed.

$$B = \frac{\text{Volume of Solids + Volume of Voids}}{\text{Volume of solids}}$$
This is determined experimentally for the different material types.

3.2 Fraction Of The Solids Contributing To Solids Sliding Friction

The following equations were proposed by Gaskell\(^8\) from extensive experimental work.

The fraction of solids contributing to the solids sliding friction \((k)\) can be determined from the relationship:

\[
K = \frac{V_2 - V}{0.85 (V_2 - V_0)}
\]

where, \(V_2\) is the mean mixture velocity at and above which, mixture flows in the heterogeneous flow regime.

i.e. \(V_2 = 30 C^{0.25} v_s\),

and \(V_0\) is the velocity at which a sliding bed is initiated.

i.e. \(V_0 = 7.7161 (C^{0.2}) (D (S-1))\)

Gaskell\(^8\) deduced from practical tests that if,

\[ V \leq 0.15 V_2 + V_0 \]

then \(k\) equals one and if,

\[ V \geq V_2 \]

then \(k\) equals zero.
3.3 The Holdup Ratio

The holdup ratio (H) is defined as the ratio of the velocity of the fluids (\(V_f\)) to the velocity of the solids (\(V_p\)). The following equation was determined by Gaskell\(^{(8)}\) from experimental results to provide good correlations for the holdup ratio:

\[
H = \frac{0.04 (S-1)^{0.9} + 1}{(V-V_0)^{0.66}}
\]

3.4 Volume Fraction of Solids in Flow Section

If the holdup ratio and the delivered volumetric concentration are known the volume fraction of solids in the flow section (\(C_A\)) can be determined as follows:

By a mass balance of solids flow:

\[
A V_p \ C_A = A V \ C \quad \text{(31)}
\]

By a mass balance of fluid flow:

\[
A V_f \ (1-C_A) = A V \ (1-C) \quad \text{(32)}
\]

From (31) and (32) eliminating \(V\),

\[
V_f (1-C_A) = \frac{V_p C_A (1-C)}{C}
\]

Therefore,

\[
\frac{V_f}{V_p} \ C_A (1-C) = H
\]

\[
V_p \ C (1-C_A)
\]
or,

\[
C_A = \frac{H C}{1 - C + H C}
\]

3.5 **Derivation of the Total Pressure Gradient**

The effects of wall shear forces attributable to the impact of suspended solids on the pipe wall, and wall shear forces due to the fluid in the sliding bed were not analyzed, as they were considered to be small compared with components \(J_g\) and \(J_p\). Drag forces in the fluid were not considered in detail but this effect was taken into account to some extent.

The following definitions are used to divide the hydraulic gradient into its component parts:

- Area of bed \(= B C_A k A\)
- Area above bed \(= (1 - B C_A k) A\)
- Area of solids in bed \(= C_A k A\)
- Area of solids above the bed \(= (1 - k) C_A A\)
- Area of fluid in bed \(= B C_A k A - C_A k A\)
  \(= C_A k A (B - 1)\)
- Area of fluid above bed \(= (1 - B C_A k) A - (1 - k) C_A A\)
  \(= A 1 - C_A (B k - k + 1)\)

3.6 **Mass Balance of Solids**

\[
C V A \sigma = C_A k V_b A \sigma + C_A (1-k) A \sigma \left[ (1-k) V_f + k V_b \right] \ldots (33)
\]

The use of the term \(\left[ (1-k) V_f + k V_b \right]\) assumes that when
only low concentrations are in suspension the velocity of the suspended solids approximates to the bed velocity, whereas, when high concentrations are in suspension the velocity of the suspended solids approaches the fluid velocity.

3.7 Mass Balance of Fluid.

\[(1-C) V A \rho = A \left[ 1 - C_A (B k - k + 1) \right] V_f \rho + C_A k A (B-1) V_b \rho \]

\[\text{where } G = B + 1 - k \frac{2 - k}{2 - k} \]

there is an inconsistency in equations (33) and (34) when \( k = 0 \),
This inconsistency is due to the assumption that the velocity of the suspended solids is equal to the fluid velocity when all solids are suspended. The error produced is not considered serious however, as the velocity at which all coarse solids become suspended is well outside the practical range.

3.8 Modification of the Darcy Formula for the ratio of flow area to wetted perimeter.

In the Darcy equation the head lost in friction \( h_f \) is found from:

\[
h_f = \frac{4 f l v^2}{2 g D}
\]

where the factor \( D/4 \) is the ratio of the cross-sectional area of a circular conduit to its perimeter and is known as the hydraulic mean depth. This is modified in case of a sliding bed as follows:-
Therefore,

\[
\text{wetted perimeter/area = circular arc } \frac{\pi D^2}{4} \text{/ area of fluid and solids above bed}
\]

\[
= \frac{(\pi - \theta + \sin \theta)}{(1-B \frac{C_A k}{D^2})} \times D
\]

\[
= \frac{4}{\pi D} \left( \frac{\pi - \theta + \sin \theta}{1 - B \frac{C_A k}{D^2}} \right) \ldots (37)
\]

where \( \theta \) may be determined from the relation:

\[
B \frac{C_A k}{D} \pi = \theta - \sin \theta \cos \theta
\]

A graph of \( \theta - \sin \theta \cos \theta \) against \( \theta \) is shown in Figure 10 from which values of \( \theta \) can be determined for given values of \( B, C_A, \) and \( k. \)

Note: When \( \theta = 0, \) perimeter/area = \( \frac{A}{D} \) and when \( \theta = \pi, \) perimeter/area = 0.
Figure 10 - Plot of $\theta - \sin \theta \cos \theta$ against $\theta$
3.9 Modification of the Darcy formula to include the velocity of the fluid.

In the equation \( h_f = \frac{4 f l V^2}{2 g D} \) the true fluid velocity \( V_f \) is substituted for \( V \) and

\[ V_f = V \left( \frac{1 - G C}{1 - G C_A} \right) \]

where \( V \) is the mean mixture velocity.

The Darcy equation may now be re-written;

\[ h_f = \left( \frac{4 f l V^2}{2 g D} \right) \left( \frac{1 - C G}{1 - G C_A} \right)^2 \left[ \frac{\pi - \theta + \sin \theta}{\pi (1 - B C_A k)} \right] \]

The pressure gradient in the fluid =

\[ J_F = \left( \frac{4 f l V^2}{2 g D} \right) \left( \frac{1 - C G}{1 - G C_A} \right)^2 \left[ \frac{\pi - \theta + \sin \theta}{\pi (1 - B C_A k)} \right] \]

where \( J_F \) has the units mH2O/m of pipe for a fluid with the relative density of 1.0.

3.10 Pressure Gradient due to the Solids Sliding Friction.

- Weight of solids in pipe = \( A l C_A g S \)
- Effective weight of solids in pipe = \( A l C_A g (S-1) \)
- Effective weight of solids producing a frictional force due to the sliding bed = \( k A l C_A g (S-1) \)
- Force to move solids = \( \mu k A l C_A g (S-1) \)
Pressure to move solids

\[ \frac{\mu k A 1 C_A g (S-1)}{A} \]

Pressure gradient due to solids sliding friction \((J_S)\)

\[ \mu k A 1 C_A g (S-1) \]

\[ \frac{\mu k A 1 C_A g (S-1)}{A g 1} \]

\[ = k \mu C_A(S-1) \quad \ldots (39) \]

3.11 Total Pressure Gradient.

Total pressure gradient = \(J_S + J_F\)

Therefore, the total pressure gradient in the mixture:

\[ J = \mu k C_A (S - 1) + \]

\[ \left( \frac{4 f V^2}{2 g D} \right) \left( \frac{1 - C_G}{1 - G C_A} \right)^2 \left( \frac{\pi - \Theta + \sin \Theta}{\pi (1 - B C_A k)} \right) \quad \ldots (40) \]
4.0 INTRODUCTION TO THE COMPUTER PROGRAMS

The two programs have been written in BASIC for use on the IBM PC computer systems. Compiled (object code) versions were used to increase program speed, but source code versions are included to make any required modifications.

4.1 The Program HYP.

This program is designed to achieve two main functions: first, to enable comparison between the theory proposed by Gaskell\(^1\) and those proposed by Durand and Condolios\(^2\), Zandi and Govatos\(^4\), Worster\(^6\) and Newitt\(^3\); and second, to enable comparison between practical data and the relevant theoretical results.

The program requires the following input parameters:

**BASIC variable**

1. Mean particle size: - A7
2. Relative density: - Rd
3. Pipe diameter: - D
4. Volumetric concentration: - CV
5. A range of mixture velocities: - VEL

From the above inputs the program calculates the following outputs:

**BASIC variable**

1. Weight concentration: - CW
2. Terminal settling velocity of spherical particles: - VS
3. Drag coefficient of spherical particles: $CD$
4. Terminal settling velocity of non-spherical particles: $VSI$
5. Drag coefficient of non-spherical particles: $CDI$
6. Hindered settling velocity of spherical particles: $VSH$
7. Hindered settling velocity of non-spherical particles: $VSHI$
8. Maximum particle size falling in the laminar zone according to Stokes' Law: $DL\text{MAX}$
9. Minimum particle size falling in the turbulent zone according to Newton's Law: $DT\text{MIN}$
10. Limiting mixture velocity for deposition (Durand): $VL$
11. Transition velocity to heterogeneous flow for spherical particles (Zandi and Govatos): $VZG$
12. Transition velocity to heterogeneous flow for non-spherical particles (Zandi and Govatos): $VZGI$
13. Critical velocity for spherical particles (Bain and Bonnington): $VBB$
14. Critical velocity for non-spherical particles (Bain and Bonnington): $VBBI$
15. Transition velocity to heterogeneous flow for spherical particles (Newitt et al.): $VNA$
16. Transition velocity to heterogeneous flow for non-spherical particles (Newitt et. al.):

The program calculates the hydraulic gradient for each equation over a range of velocities and concentrations. Although only seven theories have been incorporated into the program it is possible to achieve nineteen combinations, by substituting the different values for the settling velocity for irregular particles and hindered motion.

At present the results from the hindered motion calculations are not displayed in the computer output as it is felt that the hindered motion has little effect on the hydraulic gradient. It should noted however, that the information to include all of the combinations is readily accessible within the program. The various forms of the seven theories calculated in the program are:

1. Durands Coarse (Eq. 25) only;
2. Durand Condolios (Eq. 20) - Spheres ---- UN-Hindered;
3. Durand Condolios (Eq. 21) - NON-Spheres UN-Hindered;
4. Zandi and Govatos (Eq. 23) - Spheres --- UN-Hindered;
5. Zandi and Govatos (Eq. 23) - NON-Spheres UN-Hindered;
6. Worsters Coarse (Eq. 26);
7. Newitts sliding bed (Eq. 27);
8. Newitts heterogeneous suspension (Eq. 28) Spheres;
9. Newitts heterogeneous suspension (Eq. 28) NON-Spheres;
10. Gaskell (Eq. 38) - Spheres ------------ UN-Hindered;
and

11. Gaskell (Eq. 38) - NON-Spheres --------- UN-Hindered.

Practical results can be entered to enable a direct comparison between the theoretical results and actual data. A simple graphics option is available at the end of the program to assist the user in discerning any trends and deduce the correct theory for the relevant practical conditions.

4.11 Description of the Computer Program HYD.

The following description gives a brief explanation of the general mechanics of the program and the mathematical techniques used to solve the graphical sections outlined in chapter 2. The Program is in IBM BASIC, version A3.20 and was written on an IBM Personal Computer AT.

The schematic flow chart of the program Figure 11. shows the major sections and a complete listing can be found in appendix (i). The program is structured in the following way, the first section deals with the input parameters and then proceeds to the calculation sections in the following order:-

1. ACTUAL DATA.

A subroutine is called if a comparison between actual data and the theoretical results is required.

2. SETTLING VELOCITY CALCULATIONS.

This calculates Reynolds number, the drag coefficient and the settling velocities for the various conditions, i.e. spherical or non-spherical particles. To calculate the settling velocities for irregular particles it is first
Figure 11 - Schematic Flow chart of the Programme HYD

INPUT PARAMETERS

ACTUAL DATA

 DATA SUBROUTINE

SETTLING VELOCITY CALCULATIONS
Equations 8, 9, 10, 11, 12, 13, 14, 15

TRANSITION VELOCITIES CALCULATIONS
Equations 1, 2, 3, 4, 5

HYDRAULIC GRADIENT CALCULATIONS
Equations 20, 21, 23, 24, 25, 26, 27, 28, 40

DISPLAY RESULTS GRAPHICALLY

GRAPHICS SUBROUTINE

STOP

END
necessary to find the value of $K_A$ from Figure 8. In the computer program a data map of the $k$ lines is stored in a subroutine, a listing of the data can be seen found in appendix (i). The program calculates the value of $N_D^{1/3}$ and $k$, and then iterates between the closest data points to find $K_A$. It should be noted however, that the $k$ lines are assumed to continue horizontally when $N_D^{1/3}$ is greater than 100.

3. TRANSITION VELOCITY CALCULATIONS.

This calculates the transition velocities according to the different investigators. To calculate the limiting velocity for deposition ($V_L$) according to Durand and Condolios it is first necessary to find the dimensionless parameter $F_L$. In the program a data map of the $F_L$ curves in Figure 4. has been stored in a subroutine. A listing of the data can be found in appendix (i). The program uses the particles size and volumetric concentration to iterate between the closest data points and find the correct value of $F_L$. Since coarse particles in most practical cases are greater than 2 mm in diameter $F_L$ usually equals 1.34.

4. RESULTS.

This section displays the results from the previous sections on the monitor, a screen at a time. A hard copy can be obtained either by keying CTRL Print Screen at the beginning of the program for a complete output, or by keying Print Screen at the desired point.

5. HYDRAULIC GRADIENT CALCULATIONS.

This calculates the hydraulic gradients for the different theories. The friction factor is calculated using the
Colebrook-White formula (equation 17) and the program iterates until the correct value of $f$ is found. The results are then displayed in tabular form with a menu identifying the individual theories.

6. GRAPHICS SECTION.

Due to the inherent weakness of the graphics capability of IBM BASIC, the graphics section of the program is only designed to aid the user in discerning trends by displaying the hydraulic gradient due to the water and a selected investigators result. If more than one graph needs to be plotted, a graphics package such as GRAPHER(10) can be used.

A specimen run of the program is included in appendix (i) to give the reader an idea of the format the questions take and their required responses.

4.2 The Program FINE

The program is designed to be used in solid-liquid mixture situations with high concentrations of fines to enable the user to assess the practical implications of the fine fraction.

The program requires the following input parameters.

<table>
<thead>
<tr>
<th>BASIC variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7</td>
<td>Mean particle size:</td>
</tr>
<tr>
<td>Rd</td>
<td>Relative density:</td>
</tr>
<tr>
<td>D</td>
<td>Pipe diameter:</td>
</tr>
<tr>
<td>CV</td>
<td>Volumetric concentration:</td>
</tr>
<tr>
<td>VEL</td>
<td>A range of mixture velocities:</td>
</tr>
</tbody>
</table>
6. The number of size fractions: - NS
7. The maximum size in each fraction: - FRACT(1, I)
8. The minimum size in each fraction: - FRACT(2, I)
9. The percentage weight of each fraction: - FRACT(3, I)

From the above inputs, the program calculates the following outputs.

<table>
<thead>
<tr>
<th>BASIC variable</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Weight concentration: -</td>
<td>CW</td>
</tr>
<tr>
<td>2. Terminal settling velocity of spherical particles: -</td>
<td>VS</td>
</tr>
<tr>
<td>3. Drag coefficient of spherical particles: -</td>
<td>CD</td>
</tr>
<tr>
<td>4. Terminal settling velocity of non-spherical particles: -</td>
<td>VSI</td>
</tr>
<tr>
<td>5. Drag coefficient of non-spherical particles: -</td>
<td>CDI</td>
</tr>
<tr>
<td>6. Hindered settling velocity of spherical particles: -</td>
<td>VSH</td>
</tr>
<tr>
<td>7. Hindered settling velocity of non-spherical particles: -</td>
<td>VSHI</td>
</tr>
<tr>
<td>8. Maximum particle size falling in the laminar zone according to Stoke's Law: -</td>
<td>DLMAX</td>
</tr>
<tr>
<td>9. Weight concentration of fines: -</td>
<td>CWF</td>
</tr>
<tr>
<td>10. Volumetric concentration of fines: -</td>
<td>CVF</td>
</tr>
<tr>
<td>11. Volumetric concentration of the coarse fraction: -</td>
<td>CVCF</td>
</tr>
<tr>
<td>12. Relative density of heavy medium: -</td>
<td>RDHM</td>
</tr>
</tbody>
</table>
13. Relative density of coarse slurry fraction: - RDCSF
14. Weighted drag coefficient: - CDCALC
15. Weighted settling velocity: - VSCALC
16. Weighted Reynolds number: - RECALC
17. Critical velocity for spherical particles
   (Bain and Bonnington): - VCBB
18. Critical velocity for non-spherical
   particles (Bain and Bonnington): - VCBBI
19. Critical velocity according to Makharadzye: - VCM
20. Hydraulic gradient of heavy medium: - HGHM
21. Hydraulic gradient for spherical particles
   (Durands Coarse): - HGDUR
22. Hydraulic gradient for non-spherical
   particles (Durands Coarse): - HGDURI
23. Hydraulic gradient for spherical particles
   (Zandi and Govatos): - HGZG
24. Hydraulic gradient for non-spherical
   particles (Zandi and Govatos): - HGZGI

The results from the FINE program can be compared to those
obtained from the HYD program to enable the user to assess the
impact of the fine fraction on the hydraulic gradient.

4.21 Description of the Computer Program FINE.

The following description gives a brief explanation of
the general mechanics of the program and the mathematical
techniques used to solve the graphical sections outlined in
chapter 2. The Program is in IBM BASIC, version A3.20 and was
written on an IBM Personal Computer AT.

The schematic flowchart of the program in Figure 12. show the major sections and a complete listing can be found in appendix (ii).

The program is structured in a similar manner to the HYD program, the first section deals with the input parameters and then proceeds to the calculation sections in the following order:-

1. FRACTION CALCULATIONS.

Using the maximum size of the particle falling in the laminar zone according to Stoke's Law as the cut off. The program divides the fractions into a "coarse fraction" and a "fine fraction" and weights the particle size accordingly. It then calculates the concentrations and relative densities of the two fractions.

2. SETTLING VELOCITY CALCULATIONS.

This calculates the weighted Reynolds number, the weighted settling velocity and the weighted drag coefficient of the coarse fraction. $K_A$ is determined in the same manner outlined in section 4.11.

3. CRITICAL VELOCITY CALCULATIONS.

This calculates the critical velocities according to the different investigators. The limiting velocity for deposition ($V_L$) according to Durand and Condolios is calculated in the same manner outlined in section 4.11.

4. HYDRAULIC GRADIENT.

This calculates the hydraulic gradient for the different theories. The friction factor is determined in the same
Figure 12 - Schematic Flow chart of the programme FINE
manner outlined in section 4.11.

A specimen run of the program is included in appendix (ii) to give the reader an idea of the format the questions take and their required responses. In addition the fraction data used in the example run is also included in appendix (ii) to illustrate all the information necessary to enable the effect of a large fine fraction to be assessed.

If the sizes of the $F_1$ and $F_2$ curves are found to be small, then a regression analysis was attempted. From the shape of the curves, the mathematical equation was expected to be a finite series of polynomial of the form:

$$r = a x^2 + b x^3 + c x^4$$

A regression program developed by another was used, but the coefficients generated did not produce accurate results. It was theoretically possible to fit any data set using a high order polynomial and this method was considered. The accuracy of the coefficients necessary to achieve this degree of representation was on the sixth decimal place. Since the input data could only be read to three decimal places, this approach was discarded as being mathematically unwarranted.

To obtain an accurate degree of representation,
5.0 DISCUSSION.

5.1 The Computer Programs.

In attempting to write a computer program which incorporates the theories proposed by different investigators, one problem encountered was how to represent the graphical interpretations of the $F_L$ curves (figure 3), the $k$ curves (figure 7), the Moody diagram (figure 8) and the plot of $\theta - \sin \theta \cos \theta$ against $\theta$ (figure 10).

In the cases of the $F_L$ and $k$ curves no information could be found relating to the original data on which the curves were based or whether any regression analysis had been attempted.

Data was read from the $F_L$ curves (table 7) and initially a regression analysis was attempted. From the shape of the curves, the mathematical function was expected to be a third order polynomial of the form:

$$Y = A X^3 + B X^2 + C X + D$$

A regression program developed by Ross\textsuperscript{(11)} was used, but the coefficients generated did not produce accurate results. It is theoretically possible to fit any data set using a high order polynomial and this method was considered. The accuracy of the coefficients necessary to achieve this degree of representation was to the tenth decimal place. Since the input data could only be read to three decimal places, this approach was discarded as being mathematically unsound.

In order to achieve an accurate degree of representation,
the data in table 7 was used to write a program routine in which the values of the volumetric concentration and particle size are entered and the sub-routine interpolates between the closest data points to find the correct value of $F_L$. This interpolation assumes that a straight line exists between the data points which is erroneous, but the error encountered is negligible and was ignored.

Investigations of the $k$ curves failed to produce any mathematical function which accurately depicts their trends. A high order polynomial function which could have been used to fit the curves was discarded for the reasons previously mentioned. Therefore, a data map from the curves (table 6) and a program routine using the inputted values of $k$ and $N_D^{1/3}$ was developed. The routine interpolates between the closest points and calculates the value of $K_A$. This method also assumes that a straight line exists between the data points which is erroneous but this error was ignored for the reasons mentioned above. No information could be found for the values of $K_A$ when $N_D^{1/3}$ is greater than 100, so the $k$ curves are assumed to continue in a horizontal manner.

The Colebrook-White formula (equation 17) is used in place of the Moody diagram; the program iterates to find the value of $f$.

In the case of the $BC_k$ against $\Theta$ curve (figure 10), the two are equated and using the inputted values of $B$, $C_A$ and $k$ the program calculates the value of $\Theta$. 
5.2 Experimental Data

Once the program was developed, four sets of experimental data were used to assess the effects of different conditions on the various theories. The data was obtained from the following sources:

a) Experiments carried out in the hydraulic transport test loop at the Mackay School of Mines, Reno.

b) Work carried out by the Transport and Road Research Laboratory in a pipe loop belonging to English Clays Lovering Pochin and Co. Ltd., St. Austell, Cornwall, England.

c) Tests carried out by Gaskell at the Camborne School of Mines, Cornwall, England.

d) Tests carried out by Gaskell at the University of Leeds, England.

5.21 Results from the Mackay School of Mines

Test results obtained at the Mackay School of Mines were achieved using gravel particles with a relative density of 2.2 and an average particle size of 5 mm in a horizontal pipe with an internal diameter of 76.2 mm. The pressure drop was measured over a distance of 5.5 m. The results obtained are shown in table 1.

When the results were plotted on log/log paper with axis of $\frac{J-J_w}{C J_w}$ against $g D (S-1)$ an element of scatter was found. A linear regression analysis produced a straight line with a
<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Particle size (mm)</th>
<th>Delivered Concentration (%)</th>
<th>J (mH₂O/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.64</td>
<td>5.0</td>
<td>4.4</td>
<td>0.0831</td>
</tr>
<tr>
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</tr>
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<td>5.0</td>
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<td>0.1039</td>
</tr>
<tr>
<td>2.00</td>
<td>5.0</td>
<td>5.2</td>
<td>0.0987</td>
</tr>
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<td>5.0</td>
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<td>0.1074</td>
</tr>
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<td>0.1178</td>
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<td>0.1056</td>
</tr>
<tr>
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<td>5.0</td>
<td>6.7</td>
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<td>0.1160</td>
</tr>
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<td>0.1212</td>
</tr>
<tr>
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<td>5.0</td>
<td>8.8</td>
<td>0.1178</td>
</tr>
<tr>
<td>1.76</td>
<td>5.0</td>
<td>7.3</td>
<td>0.1108</td>
</tr>
<tr>
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<td>7.3</td>
<td>0.1178</td>
</tr>
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<td>0.1247</td>
</tr>
<tr>
<td>2.74</td>
<td>5.0</td>
<td>9.4</td>
<td>0.1264</td>
</tr>
<tr>
<td>2.82</td>
<td>5.0</td>
<td>11.6</td>
<td>0.1316</td>
</tr>
<tr>
<td>1.74</td>
<td>5.0</td>
<td>8.1</td>
<td>0.1212</td>
</tr>
<tr>
<td>2.09</td>
<td>5.0</td>
<td>10.7</td>
<td>0.1264</td>
</tr>
<tr>
<td>2.76</td>
<td>5.0</td>
<td>11.3</td>
<td>0.1385</td>
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<td>12.4</td>
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</tr>
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<td>2.08</td>
<td>5.0</td>
<td>13.4</td>
<td>0.1455</td>
</tr>
<tr>
<td>2.37</td>
<td>5.0</td>
<td>13.0</td>
<td>0.1524</td>
</tr>
</tbody>
</table>

Table 1 - Raw data from the Mackay School of Mines.
slope of -1.57 and an intercept on the vertical ordinate of 177, the equation of the line being:

\[
\frac{J-J_W}{C J_W} = 177 \left[ \frac{g D (S-1)}{v^2} \right]^{1.57}
\]

This equation was used to produce "corrected data" for concentrations of 5, 10, and 15 percent using a velocity range of between 3 and 5 m/s. The corrected data and results from the computer runs are included in appendix (iii).

The proposed theory matches the practical data well; with the exception of the value predicted for the theoretical deposition velocity (the velocity producing the lowest hydraulic gradient). If we consider the case with a volumetric concentration of 5 percent, the proposed theory predicts a value for the theoretical deposition velocity of approximately 2.5 m/s. The practical results and Durands equation for coarse particles seem to indicate a lower value. As the volumetric concentration increased, the proposed theory continued to predict a higher theoretical deposition velocity but accurately matched the trend of the practical data.

In pragmatic terms this difference is insignificant as the pump would not be operated at the speed suggested by the theoretical deposition velocity because a factor of safety would be incorporated (usually 10 percent). If the proposed theory was used to predict the operating velocity, there would be no need to incorporate such a large factor of safety.

In tests at the Mackay School of Mines, the settling velocity for the gravel was determined by measuring the time
for particles to fall through a 1 m column of water. One hundred tests were carried out indicating the settling velocity to be 0.32 m/s. This compares to value of 0.21 m/s predicted by the program using the drag laws and Heywood's "volumetric shape factor".

Reasons for this discrepancy might include the effect of the wall shear forces of the column in the practical tests, or the method used to calculate the drag coefficient in the program. Investigators have agreed that large discrepancies exist in the different methods used to calculate $C_D$. In the computer model $C_D$ is assumed to equal 0.44 when Reynolds number is greater than 1000 for particles up to 1mm in diameter.

5.22 Results from the Transport and Road Research Laboratory (TRRL).

The results obtained from TRRL were from tests carried out using single-size limestone aggregates of 5, 10 and 20 mm in size at volumetric concentrations of 6.5, 7.0, and 5.6 percent respectively in a pipe 100 m long and with an internal diameter of 207 mm. Test results are shown in table 2 and data from the computer runs are included in appendix (iv).

The theories included in the program predicted much lower values for the hydraulic gradient than the experimental data indicated. In the first run, for 5 mm particles at a delivered concentration of 6.5 percent, Durand's theory for coarse particles is the closest to the practical data, while the proposed theory suggests much lower values for the
<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Particle size (mm)</th>
<th>Delivered Concentration (%)</th>
<th>J (mH₂O/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>5.0</td>
<td>6.5</td>
<td>0.137</td>
</tr>
<tr>
<td>4.0</td>
<td>5.0</td>
<td>6.5</td>
<td>0.153</td>
</tr>
<tr>
<td>5.0</td>
<td>5.0</td>
<td>6.5</td>
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<td>7.0</td>
<td>0.140</td>
</tr>
<tr>
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<td>10.0</td>
<td>7.0</td>
<td>0.154</td>
</tr>
<tr>
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<td>10.0</td>
<td>7.0</td>
<td>0.180</td>
</tr>
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<td>3.0</td>
<td>20.0</td>
<td>5.6</td>
<td>0.133</td>
</tr>
<tr>
<td>4.0</td>
<td>20.0</td>
<td>5.6</td>
<td>0.141</td>
</tr>
<tr>
<td>5.0</td>
<td>20.0</td>
<td>5.6</td>
<td>0.167</td>
</tr>
</tbody>
</table>

Table 2 - Data from the Transport and Road Research Laboratory
hydraulic gradient.

The primary cause for the low values predicted by the proposed theory is due to the algorithm used to calculate the limiting velocity \( V_2 \), which suggest that the particles change from a sliding bed to a heterogeneous flow regime at a much lower velocity than actually occurs.

The limiting velocity is calculated using the equation:

\[
V_2 = 30 C^{0.25} V_s
\]

\[
= 30 \times 0.065^{0.25} \times 0.174
\]

\[
= 2.64 \text{ m/s}
\]

which compares to the value of 3.5 m/s predicted by Durand (equation 1.). At the velocity at which the sliding bed is initiated \( V_0 \), the fraction of solids in the sliding bed \( k \) equals one. As the velocity increases, the fraction of the solids decreases until at the limiting velocity all the solids are in heterogeneous suspension (i.e. \( k = 0 \)).

Gaskell\( ^{(8)} \) uses the relationship:

\[
k = \frac{V_2 - V}{0.85 (V_2 - V_0)}
\]

to determine the fraction of solids in the sliding bed. When the experimental data obtained from tests in large diameter pipes were compared to the results from the computer program, the value predicted by the proposed theory for the limiting velocity \( V_2 \) was so low that in the practical tests one would assume that all the solids are in heterogeneous
suspension. Tests observed at the Mackay School of Mines demonstrated the sliding bed to be present at surprisingly high velocities.

A second factor which indicates that the limiting velocity predicted was too low is the value predicted for the velocity at which a sliding bed is initiated \( V_0 \).

\[ V_0 = 2.65 \text{ m/s} \]

The theory suggested that the slurry would form a stationary bed at speeds lower than 2.65 m/s. The practical results show this to be incorrect as the pipeline was operated at a speed of 2.13 m/s with a sliding bed.

To assess the impact of increasing the limiting velocity, the following analysis was carried out using Durand's figure for the limiting velocity. The following conditions were used:

- Pipe diameter = 207 mm
- Particle diameter = 5.0 mm
- Mean mixture velocity = 3.0 m/s
- Delivered concentration = 6.5%
- Particle relative density = 2.7

The proposed theory predicted a value for the hydraulic gradient of 0.07 mH2O/m, solely from the pressure due to the wall shear forces of the fluid (i.e. \( J_F = 0.07 \text{ mH}_2\text{O} \) and \( J_g = 0 \)).

Using Durand's figure of 3.5 m/s for the limiting velocity the following results obtained:-
\[ k = \frac{3.5 - 3.0}{0.85(3.5 - 2.65)} = 0.69 \]

Therefore,

\[ J_s = k C_A (S - 1) = 0.3 \times 0.692 \times 0.2766 \times (2.7 - 1) = 0.10 \text{ mH}_2\text{O/m} \]

Therefore,

\[ J = J_s + J_F = 0.10 + 0.07 = 0.17 \text{ mH}_2\text{O/m} \]

which compares to the practical result of 0.15 mH\text{O/m}.

The intent of this analysis is to illustrate the effect of modifying the limiting velocity. With the limited amount of data available it is not possible to assume that the use of Durand's formula would be more accurate in all cases.

As the particle size increased, all the theories continued to predict values for the hydraulic gradient which were low compared to the actual results.

5.23 Results from the Camborne School of Mines

The data collected at the Camborne School of Mines was obtained using dolerite with a relative density of 2.7 and an average particle size of 5 mm in a horizontal pipe with an internal diameter of 50.8 mm. The pressure drop was measured
over a distance of 2 m. The results obtained are shown in table 3 and the data from the computer runs are included in appendix (v).

In the first run, with a delivered concentration of 7 percent, the proposed theory predicted a value for the hydraulic gradient higher than the practical data. Durand's theory for coarse particles also suggested a higher value which lay between the actual data and the proposed theory.

The results collected from the test loop seem suspect at the higher velocities. As the velocity increases the hydraulic gradient from the practical data is lower than the hydraulic gradient due to the water. No reasons are given for this discrepancy, so it is assumed to be the result of experimental error.

As the delivered concentration increases the proposed theory continues to predict values for the hydraulic gradient higher than the practical data. The discrepancy may be due to the high value predicted for the in-pipe concentration.

The tests were carried out at velocities exceeding the limiting velocity (predicted by both equations). With the presence of a large sliding bed the in-pipe concentration would be expected to be significantly higher than the delivered concentration. Alternatively, in conditions of homogeneous suspension, the delivered and the in-pipe concentration would be almost equal. It seems reasonable to assume therefore, that under the conditions of a heterogeneous suspension, the in-pipe concentration would be somewhere
<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Particle size (mm)</th>
<th>Delivered Concentration (%)</th>
<th>$J$ (mH$_2$O/m)</th>
</tr>
</thead>
<tbody>
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<td>0.2416</td>
</tr>
<tr>
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<td>7.0</td>
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</tr>
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</tr>
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<td>5.0</td>
<td>7.0</td>
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</tr>
<tr>
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<td>5.0</td>
<td>7.0</td>
<td>0.3413</td>
</tr>
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<td>0.2343</td>
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<tr>
<td>3.682</td>
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<td>14.0</td>
<td>0.3452</td>
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</tbody>
</table>

Table 3 - Data from the Camborne School of Mines
between the two extremes. Although no practical results could be found to accurately predict the in-pipe concentration, the proposed theory produces values higher than would be expected. The value of the in-pipe concentration is based upon the holdup ratio calculated from the equation:-

\[
H = \frac{0.04 (S-1)^{0.9} + 1}{C_V^{1.3} (V-V_0)^{0.66}}
\]

Gaskell deduced the constants from experimental work carried out at the University of Leeds and the Camborne School of Mines.

An attempt was made to calculate the in-pipe concentration using a method developed by Khan et al\(^{(12)}\). Experiments carried out using 3.5 mm gravel flowing in a 42 mm diameter horizontal pipe, indicated that the velocity of the fluid \(V_f\) and the in-pipe concentration \(C_A\) could be correlated by:-

\[
V_f - V_m = a V_m^b C_A^c \quad \ldots \quad (39)
\]

and,

\[
V_f - V_m = 0.08 V_m^{-0.64} C_A^{0.27} \quad \ldots \quad (40)
\]

using the following relationship,

\[
C = 1 - \left(1 - C_A\right) \frac{V_f}{V_m} \quad \ldots \quad (41)
\]

and equation (40) it is possible to show,
\[
\frac{(1 - C)}{(1 - C_A)} = (1 + 0.08 \ V_m^{-1.64} C^{-0.27}) \quad \ldots \ldots \ldots (42)
\]

When equation 42 was used in the case of mean mixture mixture velocity of 4.0 m/s, a particle size of 5 mm and a relative density of 2.7. As the following results indicate,

<table>
<thead>
<tr>
<th>Delivered Concentration (percent)</th>
<th>In-pipe Concentration (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00</td>
<td>5.35</td>
</tr>
<tr>
<td>10.00</td>
<td>10.40</td>
</tr>
<tr>
<td>15.00</td>
<td>15.42</td>
</tr>
<tr>
<td>20.00</td>
<td>20.45</td>
</tr>
</tbody>
</table>

the difference between the delivered and in-pipe concentration is extremely low and reflects the conditions one would expect in the homogeneous regime rather than the heterogeneous regime.

In tests at the Camborne School of Mines, the settling velocity for the dolerite was determined to be 0.30 m/s. This compares to value of 0.25 m/s that the program predicted using the drag laws and Heywoods "volumetric shape factor".

5.24 Results from the University of Leeds

Data collected from the University of Leeds was obtained using gravel with a relative density of 2.6 and an average particle size of 4 mm in a horizontal pipe with an internal diameter of 50.8 mm. The pressure drop was measured over a distance of 2 m. The results obtained are shown in table 4
<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Particle size (mm)</th>
<th>Delivered Concentration (%)</th>
<th>J (mH_2O/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.814</td>
<td>4.0</td>
<td>4.0</td>
<td>0.1330</td>
</tr>
<tr>
<td>1.888</td>
<td>4.0</td>
<td>4.0</td>
<td>0.1015</td>
</tr>
<tr>
<td>1.940</td>
<td>4.0</td>
<td>4.0</td>
<td>0.1065</td>
</tr>
<tr>
<td>1.954</td>
<td>4.0</td>
<td>4.0</td>
<td>0.1015</td>
</tr>
<tr>
<td>1.363</td>
<td>4.0</td>
<td>8.0</td>
<td>0.1880</td>
</tr>
<tr>
<td>1.494</td>
<td>4.0</td>
<td>8.0</td>
<td>0.1825</td>
</tr>
<tr>
<td>1.544</td>
<td>4.0</td>
<td>8.0</td>
<td>0.1765</td>
</tr>
<tr>
<td>2.739</td>
<td>4.0</td>
<td>15.0</td>
<td>0.2910</td>
</tr>
<tr>
<td>3.353</td>
<td>4.0</td>
<td>15.0</td>
<td>0.3000</td>
</tr>
<tr>
<td>3.522</td>
<td>4.0</td>
<td>15.0</td>
<td>0.3335</td>
</tr>
<tr>
<td>3.537</td>
<td>4.0</td>
<td>15.0</td>
<td>0.3300</td>
</tr>
<tr>
<td>3.917</td>
<td>4.0</td>
<td>15.0</td>
<td>0.3460</td>
</tr>
<tr>
<td>4.556</td>
<td>4.0</td>
<td>15.0</td>
<td>0.3996</td>
</tr>
</tbody>
</table>

Table 4 - Data from the University of Leeds.
and data from the computer runs are included in appendix (vi).

Results from the gravel particles were somewhat disappointing as there was not enough spread in the velocities to discern any trends. The one exception was the data obtained at a concentration of 15 percent. The proposed theory predicted values for the hydraulic gradient that were higher than the actual practical figures but matched the trend extremely well.

5.3 Implications of a Large Fine Fraction

The programs HYD and FINE were run using the data from the Kin Fatt Mine\(^{(12)}\), table 8, at a velocity of 3.49 m/s. The results from the computer runs are:

The HYD program,

\[
\begin{align*}
\text{Hydraulic gradient according to Durand}^{(2)} \text{ (equation 25)} & = 0.71 \text{ kN/m}^2/\text{m} \\
\text{Hydraulic gradient according to Zandi and Govatos}^{(4)} \text{ (equation 23)} & = 0.32 \text{ kN/m}^2/\text{m}
\end{align*}
\]

The FINE program,

\[
\begin{align*}
\text{Hydraulic gradient according to Durand}^{(2)} \text{ (equation 25)} & = 0.32 \text{ kN/m}^2/\text{m} \\
\text{Hydraulic gradient according to Zandi and Govatos}^{(4)} \text{ (equation 23)} & = 0.24 \text{ kN/m}^2/\text{m}
\end{align*}
\]

The results clearly show that the hydraulic gradient decreases (an indication of the reduced power requirements of the
system) when the presence of the fine fraction is taken into consideration.

\[ \frac{\partial \rho}{\partial x} = \frac{1}{\rho_0} \left( \frac{1}{\sqrt{\frac{\rho}{\rho_0}}} \right) \]

with the values expiring for the empirical constants. These values are found by the pressure conditions under which they are based. Data correlations to date have provided good predictions for the pressure gradient even when it is rearranged similar to the original conditions. When the parameters change, the predictions do not maintain their accuracy.

In these arrangements, the additional pressure gradient due to the solute, 
\( \gamma \), is effectively weighted by the column water gradient, 
\( \gamma / \gamma_{0} \), multiplied by some function of the volumetric, velocity, and diameter. Momentary and physical reasons for the type of weighting are as follows. In all circumstances, argued that the additional pressure gradient is

The method proceeds by applying\(^{10}\), while the assumptions to be the "ideal" solutions, is based on moment physical considerations. The additional methods are those which consider the additional pressure gradient due to a solution rich. The density modified by equation\(^{10}\) to ensure equal expression upon a large.
6.0 CONCLUSIONS

A review of relevant literature shows that most investigators have proposed methods of correlating pressure gradients in horizontal pipelines of the form:

\[
\frac{J - J_w}{C - J_w} = K \left( \frac{\nu^2 C_D^{0.5}}{g D (S - 1)} \right)^n
\]

with the values suggested for the empirical constants \(k\) and \(n\) varying according to the practical conditions upon which they are based. Data correlations of this form provide good predictions for the pressure gradient when used in circumstances similar to the original conditions. When the parameters change, the predictions do not maintain their accuracy.

In these expressions the additional pressure gradient due to the solids, \(J - J_w\), is effectively considered to be the clear water gradient, \(J_w\), multiplied by some function of the concentration, velocity, pipe diameter, particle density and drag coefficient. Whilst most references attribute some physical reasons for the type of function, in no case is it convincingly argued that the additional pressure gradient is dependent on \(J_w\).

The method proposed by Gaskell\(^{(8)}\), while not professing to be the "ideal" equation, is based upon tenable physical processes. Two additional methods are known which involve the frictional pressure gradient due to a sliding bed. The theory proposed by Gaessler\(^{(14)}\) whose method was based upon a large
amount of experimental data collected from test on mixtures containing coal particles and secondly, a method proposed by Wilson\textsuperscript{(15)} who, in collaboration with Streat and Bantin\textsuperscript{(16)} carried out some original work on the mechanisms involved at the point of incipient bed slip.

Gaessler\textsuperscript{(14)} and Wilson's\textsuperscript{(15)} methods were excluded from the comparison of data correlation methods with "credible physical process" techniques due to the inherent complexities of their methodologies.

The equation proposed by Durand and Condolios\textsuperscript{(2)} was expected to give accurate results due to the similarity of the practical data tested to the data upon which Durand and Condolios\textsuperscript{(2)} based their equation. The values predicted match the practical data obtained from tests using small pipe diameters, as the pipe diameter increased the equation predicted lower values than the practical results.

Durand and Condolios's\textsuperscript{(2)} theory was based on material containing only very small quantities of fines. In tests at the Mackay School of Mines, the original single size aggregate was observed to quickly degrade due to the grinding action of the particles as the slurry circulated through the test loop.

Zandi and Govatos\textsuperscript{(4)} incorporated the presence of fines in their equation, but the values predicted for the hydraulic gradient although correlated well for small diameter pipes gave lower results for large diameter pipes.

Durand's equation for coarse mineral particles is widely recognized as a very reliable predictor of the hydraulic
gradient by investigators. The computer runs show that the equation consistently provided better correlations with the practical results than the other equations included in the program. In the situation of large diameter pipes, although out-performing the other equations, Durand's equation for coarse particles suggests lower values for the hydraulic gradient than indicated by the practical results.

The results from the computer program show that the proposed theory provides accurate correlations when used in situations similar to the practical conditions upon which it was based, that is, coarse particles in small diameter pipes.

As the pipe diameter increased, the proposed theory predicted lower values for the pressure drop due to the presence of solids than the practical data indicated (approximately 25 percent of the practical results and 75 percent of the figure suggested by Durand's equation for coarse particles).

While it may seem credible to divide the hydraulic gradient into its component forces, by doing so the assumption is made that these forces act independently. Although most investigators conclude that when coarse particles are transported, a truly two-phase situation exists, it is unclear whether the component forces act in the manner on which the theory is based.

The results obtained are inconclusive as to whether data correlation methods or "credible physical process" techniques provide better predictions for the pressure gradient in horizontal pipes. Clearly no equation provides accurate
correlations in all conditions and no equation tested could be used with any degree of certainty in situations involving large diameter pipes.

The discrepancies in the correlation of the theories to the practical results clearly show the danger involved when a theory is proposed based upon one set of practical conditions. All of the relationships in the computer model predict reasonable results when used in situations similar to the conditions upon which they were based. When the parameters change the correlations do not maintain their accuracy.

Significant advances in accurately predicting the hydraulic gradient in horizontal pipes are unlikely until universally accepted methods for predicting the transition velocities are found. This is particularly true of the velocity at and above which, mixture flows in the heterogeneous regime. The analysis in section 5.22 clearly shows the effect on the suggested value of the pressure gradient when a different method to predict the limiting velocity is used.

To enable an investigation of the two methodologies used to predict the hydraulic gradient in horizontal pipes, the relationships incorporated in the program need to be compared to large sets of data from different practical conditions obtained over the optimum operating range. The optimum operating speed of a slurry system is usually 10 percent higher than the theoretical transition velocity from a sliding bed regime to a heterogeneous flow regime.
Most of the practical data available for comparison was obtained from systems operating at higher values than the transition velocity suggested.

It is felt however, that if an ideal equation is to be found, the approach suggested by Gaskell\(^8\), Gaessler\(^14\) and Wilson\(^15\) of splitting the hydraulic gradient into its component forces is the correct one. This will enable any change in the parameters to be reflected in the theoretical results.

The main value of this work to the user of hydraulic transport systems is the computer program which enables the direct comparison of equations used to predict the practical transport velocity and pressure gradients with practical data. Previous methods of selecting the practical transport velocity involved tedious hand calculations especially when large quantities of fines are present.

By examining the validity of the equations in practical situations, estimates can be made by the user for suitable pipe diameters and power requirements which will result in substantial savings in both capital and operating costs.
7.0 RECOMMENDATIONS FOR FURTHER WORK

The main objective of any work on the computer modeling of hydraulic transport is to produce a program which will give the optimum pumping velocity for any practical condition and to determine the pressure gradient at this velocity. The easiest way to achieve this value would be to use an "ideal" equation which works for all conditions. At present no equation exists which is able to fill these requirements.

To investigate the possibility of determining the "ideal" equation two initial objectives need to be achieved. Firstly, large sets of practical data need to be collected from different conditions over the optimum operating range. Secondly, the possibility of finding unified equations for predicting the transition velocities needs to be explored.

Once the two initial objectives have been achieved it will be possible to carry out a detailed analysis of the data correlation methods and the "credible physical process" techniques. A limited number of equations have been included in the program and the scope of the comparison needs to be increased to include a larger cross-section of equations, this will enable investigators to assess the practicalities of an "ideal" equation. Due to the large diversity of the parameters the "ideal" equation is likely to be extremely complex in nature and difficult to formulate.

A more realistic approach using the practical data, may be to determine correct data correlation expressions for the range of practical conditions. These expressions could then
be incorporated into the computer model and by entering the practical conditions to be tested, the correct equation would be chosen and produce a realistic value for the operating velocity.
REFERENCES


11. ROSS, S. M., Introduction to Probability and Statistics
12. Data Supplied from the KIN FATT MINES, by Dr. Habbi, Director, SEATRAD, Ipoh, Malaysia.
13. BROAD, B. A. and JAMES J. G., "Conveyance of Coarse Particle Solids by Hydraulic Pipelines, Trials with Limestone Aggregate in 102, 156 and 207 mm Diameter Pipes," TRRL Supplementary Report 635.
APPENDIX I

Listing of the Computer Program HYD
Do you wish to include the new theory ......(Y/N)

Enter Number of Size Fractions

For I=1 TO NS

Enter Minimum Size in Fraction

Enter Maximum Size in Fraction

Enter % Weight of Fraction

A6=(A1+A2)/2

A5=(A4*A3)/100

A6=A6+A5

Print A6

Next I

A7=A6/1000

GOTO 340

Print

Enter Weighted Mean Particle Size in mm.

A6

A7=A6/1000

Print

Enter Relative Density

RD

Print

Enter Pipe Diameter in mm.

DD

D=DD/1000

Print

Enter Volumetric Concentration.....i.e. (10%) =

CC

CV=CC/100

Print

IF Q1$="N" GOTO 460

VO=7.7161*(CV^.2)*SQR(D*(RD-1))

PRINT USING "Velocity at which sliding bed commences according to New Theory = \#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\#\##
530 INPUT A(1,I)
540 NEXT I
550 PRINT
560 PRINT "Correct any Velocities ......... (Y/N)"
570 GOSUB 4840
580 Q2$=Q$
590 IF Q2$="Y" GOTO 500
600 PRINT
610 PRINT "Actual Data ....................... (Y/N)"
620 GOSUB 4840
630 Q3$=Q$
640 IF Q3$="N" GOTO 660
650 GOSUB 4880
660 PRINT
670 PRINT "Which Group of Mineral Types in the Following Group
Most Nearly Describes the Particles being Investigated?"
680 PRINT
690 PRINT "Group 1......Sand, Gravel, Beach Flints."
700 PRINT "Group 2......Sillimanite, Bituminous Coal."
710 PRINT "Group 3......Blast Furnace Slag."
720 PRINT "Group 4......Limestone, Talc, Plumago, Granite."
730 PRINT "Group 5......Gypsum,"
740 PRINT "Group 6......Graphite."
750 PRINT "Group 7......Mica."
760 PRINT "Group 8......Calculated."
770 PRINT
780 INPUT "Enter Group Selected";G
790 IF G>8 GOTO 690
800 IF G=1 THEN K=.26
810 IF G=2 THEN K=.23
820 IF G=3 THEN K=.19
830 IF G=4 THEN K=.16
840 IF G=5 THEN K=.13
850 IF G=6 THEN K=.023
860 IF G=7 THEN K=.003
870 PRINT
880 REM PRINT K
890 PRINT
900 IF G=8 THEN INPUT "Enter Volume of Sample";VOL
910 REM
920 REM
930 REM TO CALCULATE THE SETTLING VELOCITIES
940 VSS=9.807*A7*A7*(RD-1)/(18*(10^-6))
950 VSI=.2085*A7*((9.807*9.807*(RD-1)^2)/(10^-6))^(1/3)
960 VSN=1.7408*SQR(A7*9.807*(RD-1))
970 REM
980 REM TO CALCULATE REYNOLDS NUMBER
990 REM
1000 RES=VSS*A7*10^-6
1010 REI=VSI*A7*10^-6
1020 REN=VSN*A7*10^-6
1030 IF RES>=0 AND RES<=1 THEN R%=1
1040 IF REI>1 AND REI<=800 THEN R%=2
1050 IF REN>=800 AND REN<=10^-5 THEN R%=3
1060 IF R%<0 GOTO 5630:REM ERROR
IF R% = 1 THEN CD = 24/RES: RE = RES: VS = VSS
IF R% = 2 THEN CD = 14/SQR(REI): RE = REI: VS = VSI
IF R% = 3 THEN CD = .44: RE = REN: VS = VSN
REM PRINT "VS = "; VS; " RE = "; RE; " CD = "; CD
REM TO CALCULATE HINDERED SETTLING VELOCITY FOR SPHERES
REM
IF RE < .2 THEN Q = 4.6
IF RE >= .2 AND RE < 1 THEN Q = 4.4*(RE^-.03)
IF RE >= 1 AND RE < 500 THEN Q = 4.4*(RE^-.1)
IF RE >= 500 THEN Q = 2.4
CW = (CV*RD)/((CV*(RD-1))+1)
VSH = VS*((1-CV)^Q)
REM
REM TO CALCULATE SETTLING VELOCITIES FOR IRREGULAR PARTICLES
RE
REM
ND = (CD*(RE*RE))^(1/3): REM PRINT "ND = "; ND
DA = A7*1000
IF G = 8 THEN K = VOL/(DA^3)
KK = K
REM
GOSUB 5640
VSI = KA*VS: REM PRINT "VSI = "; VSI
VSH = KA*VSH: REM PRINT "VSH = "; VSH
CDI = CD*((VS/VSI)^2): REM PRINT "CDI = "; CDI
REM
REM Maximum size of particle in water falling in laminar zone according to Stokes Law
REM
DLMAX = .1224*((1/(RD-1))^(1/3))
REM
REM Minimum size of particle in water falling in the turbulent settling zone according to Newton's Law
DTMIN = 26.5*DLMAX
REM
REM Determination of FL
GOSUB 6870
VL = FL*SQR(2*9.807*D*(RD-1))
REM Newitt et. al. ...(2)
VNA = 17*VS
VNAI = 17*VS
VZ = (40*CV*D*9.807*(RD-1))/(CD^0.5)
VZI = (40*CV*D*9.807*(RD-1))/(CDI^0.5)
REM Bain and Bonnington (20) ...(6a)
REM Zandi and Gavatos (8) ....(6)
VL = FL*SQR(2*9.807*D*(RD-1))
REM Newitt et. al. ...(2)
VNA = 17*VS
VNAI = 17*VS
REM Print Results
1590 REM VIEW (64,16)-(576,176),0
1600 GOSUB 5540
1610 PRINT USING "CALCULATED RESULTS FOR A CONCENTRATION OF ###";CV*100;
1620 PRINT "%"
1630 PRINT TAB(10);"------------- ------ --- ---- ---- --- ----"
1640 PRINT
1650 PRINT USING "Pipe Diameter..............................= ###.###";DD;
1660 PRINT "mm"
1670 PRINT
1680 PRINT USING "Shape Group..........................= ###.###";G
1690 PRINT
1700 PRINT USING "Weighted Mean Particle Diameter..................= ###.###";A7*1000;
1710 PRINT "mm"
1720 PRINT
1730 PRINT USING "Relative Density of Solids....................= ###.###";RD
1740 PRINT
1750 PRINT USING "Delivered Volume Concentration of Solids........= ###.###";CV
1760 PRINT
1770 PRINT USING "Delivered Weight Concentration of Solids.......= ###.###";CW
1780 PRINT
1790 PRINT TAB(7);"Terminal Settling Velocity of Spherical Particles"
1800 PRINT USING "of ###.###";A7*1000;
1810 PRINT USING "mm Diameter = ###.###";VS;
1820 PRINT "m/s"
1830 PRINT
1840 PRINT USING "Drag Coefficient of Spherical Particles of ###.###";A7*1000;PRINT " mm"
1850 PRINT USING "Diameter = ###.###";CD
1860 PRINT
1870 GOSUB 5540
1880 PRINT USING "Terminal Settling Velocity of NON-Spherical ###.###";A7*1000;PRINT" m/s"
1890 PRINT USING "Particles of Shape Factor ###";K;PRINT USING" = ###.###";VSI;PRINT " m/s"
1900 PRINT
1910 PRINT TAB(7);"Hindered Settling Velocity of Spherical Particles"
1920 PRINT USING "of ###.###";A7*1000;PRINT" mm Diameter and Volumetric Concentration ";
1930 PRINT USING "###.###";CV;PRINT USING" = ###.###";VSH;PRINT " m/s"
1940 PRINT
1950 PRINT USING "Hindered Settling Velocity of NON-Spherical ###.###";A7*1000;PRINT" mm"
1960 PRINT USING "Particles of Shape Factor ###";K;PRINT" and Volumetric"
86

1970 PRINT USING "Concentration ###.###"; CV; PRINT USING "m/s"
1980 PRINT
1990 PRINT TAB(7); "Maximum Particle Size Falling in Laminar Zone according"
2000 PRINT USING "to STOKES Law = ###.###"; DLMAX; PRINT "mm"
2010 PRINT
2020 PRINT TAB(7); "Minimum Particle Falling in Turbulent Zone according"
2030 PRINT USING "to NEWTONS Law = ###.###"; DTMIN; PRINT "mm"
2040 PRINT
2050 PRINT USING "Limiting Mixture Velocity for Deposition (DURAND) = ###.###"; VL; PRINT "m/s"
2060 PRINT
2070 PRINT TAB(7); "Transition Velocity to Heterogeneous Flow"
2080 PRINT USING "(ZANDI and GOVATOS) = ###.###"; VZG; PRINT "m/s"
2090 PRINT TAB(7); "using the drag coefficient of spheres"
2100 PRINT
2110 GOSUB 5540
2120 PRINT TAB(7); "Transition Velocity to Heterogeneous Flow"
2130 PRINT USING "(ZANDI and GOVATOS) = ###.###"; VZGI; PRINT "m/s"
2140 PRINT TAB(7); "using the drag coefficient of irregular particles"
2150 PRINT
2160 PRINT USING "Critical Velocity (Bain and Bonnington) = ###.###"; VBB; PRINT "m/s"
2170 PRINT TAB(7); "using the drag coefficient of spheres"
2180 PRINT
2190 PRINT USING "Critical Velocity (Bain and Bonnington) = ###.###"; VBBI; PRINT "m/s"
2200 PRINT TAB(7); "using the drag coefficient of irregular particles"
2210 PRINT
2220 PRINT
2230 PRINT TAB(7); "Transition Velocity to Heterogeneous Flow (NEWITT et al) = 
2240 PRINT USING "###.###"; VNA; PRINT "m/s, Using the drag coefficient of spheres"
2250 PRINT
2260 PRINT TAB(7); "Transition Velocity to Heterogeneous Flow (NEWITT et al) = 
2270 PRINT USING "###.###"; VNAI; PRINT "m/s, Using the drag coefficient of irregular particles"
2280 PRINT
2290 PRINT
2300 GOSUB 5540
2310 SCREEN 0,1
2320 COLOR 3
2330 REM CALCULATION OF HYDRAULIC GRADIENTS
2340 REM
2350 MES=0
2360 IF Q1$="n" THEN NC=12 ELSE NC=10
2370 IF Q1$="N" THEN BF=0: GOTO 2400
2380 SCREEN 0,1
2390 INPUT" Enter the Bulking Factor of the Solids";BF
2400 PRINT
2410 PRINT
2420 PRINT TAB(6);"Friction Factor Adjustment (Y/N)"
2430 GOSUB 4840
2440 Q4$=Q$
2450 PRINT
2460 IF Q4$="N" GOTO 2550
2470 PRINT
2480 PRINT TAB(6);"Do you wish to input a multiplication factor...1"
2490 PRINT TAB(6);"Do you wish to input actual Friction Factors...2"
2500 PRINT
2510 INPUT"Which number";FFA
2520 IF FFA>2 OR FFA<0 GOTO 2510
2530 PRINT
2540 PRINT
2550 FOR I=1 TO NV
2560 VEL=A(1,I)
2570 IF Q4$="N" GOTO 2650
2580 IF FFA=1 GOTO 2630
2590 PRINT
2600 PRINT TAB(6);"Enter Friction Factor for Velocity ";VEL;" =";
2610 INPUT FF(I)
2620 GOTO 2770
2630 PRINT TAB(6);"Enter Friction Factor Adjustment for velocity ";VEL;" =";
2640 INPUT FA
2650 IF Q4$="N" THEN FA=1
2660 REP=VEL*D*10^-6
2670 IF REP>=4000 THEN 2700
2680 F1=16/REP
2690 GOTO 2750
2700 F1=.0001
2710 F2=(1/(-1.737177928#*LOG(((45*(10^-6))/(3.7*D))+(1.26/(REP*(SQR(F1)))))))^2
2720 IF ABS(F1-F2)<.000001 THEN 2750
2730 F1=F2
2740 GOTO 2710
2750 FF(I)=F2*FA
2760 F=FF(I)
2770 REM
2780 JW=(4*F*(VEL^2))/(2*9.807*D)
2790 IF Q4$="N" GOTO 2810
2800 IF FFA=2 GOTO 2820
2810 PRINT TAB(6);F
2820 A(2,I)=JW
2830 IF Q1$="N" GOTO 2940
2840 VSS=VS
2850 GOSUB 4990
2860 A(15,I)=JF
2870 A(14,I)=JS
2880 A(12,I)=AA
2890 VSS=VSI
2900 GOSUB 4990
2910 A(17,I)=JF
2920 A(16,I)=JS
2930 A(13,I)=AA
2940 REM
2950 REM Durand Coarse
2960 JD=CV*JW*135*((9.807*D*(RD-1))/(VEL^2)^1.35)+JW
2970 A(3,I)=JD
2980 REM
2990 REM Durand Condolis
3000 JDC=CV*JW*85*(((9.807*D*(RD-1))/(VEL^2)*(CDI^1.5))^1.5)+JW
3010 A(4,I)=JDC
3020 JDCI=CV*JW*85*(((9.807*D*(RD-1))/(VEL^2)*(CDI^1.5))^1.5)+JW
3030 A(5,I)=JDCI
3040 REM
3050 REM Zandi and Govatos
3060 B=(VEL^2*(CD^1.5))/(9.807*D*(RD-1))
3070 IF B>10 GOTO 3100
3080 JZG=CV*JW*6.3*(B^-0.354)+JW
3090 GOTO 3110
3100 JZG=CV*JW*280*(B^-1.93)+JW
3110 A(6,I)=JZG
3120 B=(VEL^2*(CDI^1.5))/(9.807*D*(RD-1))
3130 IF B>10 GOTO 3160
3140 JZGI=CV*JW*6.3*(B^-0.354)+JW
3150 GOTO 3170
3160 JZGI=CV*JW*280*(B^-1.93)+JW
3170 A(7,I)=JZGI
3180 REM
3190 REM Worster
3200 JWO=CV*JW*120*(((9.807*D*(RD-1))/(VEL^2))^1.5)+JW
3210 A(8,I)=JWO
3220 REM
3230 REM NewAlSb
3240 JNASB=((CV*JW*66*(RD-1)*9.807*D)/(VEL^2))+JW
3250 A(9,I)=JNASB
3260 REM
3270 REM NewAlHet
3280 JNAHET=((CV*JW*1100*(RD-1)*9.807*D*VS)/(VEL^3))+JW
3290 JNAHETI=((CV*JW*1100*(RD-1)*9.807*D*VSI)/(VEL^3))+JW
3300 A(10,I)=JNAHET
3310 A(11,I)=JNAHETI
3320 NEXT I
3330 CLS
3340 GOSUB 5370
3350 GOSUB 5540
3360 PRINT
3370 PRINT TAB(30);"TABLE OF RESULTS"
3380 PRINT TAB(30);"----- -- --------"
3390 PRINT
3400 IF Q1$="Y" GOTO 3510
3410 PRINT TAB(8);"V";TAB(15);"Jw";TAB(24);"1";TAB(32);"2";
TAB(40);"3";TAB(48);"4";TAB(56);"5";TAB(64);"6"; TAB(72);"7"
3420 FOR I=1 TO NV
3430 PRINT TAB(3);
3440 FOR J=1 TO 9
3450 PRINT USING "###.###";A(J,I);
3460 NEXT J
3470 PRINT
3480 NEXT I
3490 PRINT
3500 GOTO 3620
3510 PRINT TAB(4);"V";TAB(10);"Vf";TAB(16);"Cv";TAB(21);"Ca"
TAB(28);"Jw";TAB(35);"1";TAB(42);"2";TAB(49);"3";TAB(57);"4"
TAB(64);"5"
3520 FOR I=1 TO NV
3530 FOR J=1 TO 1
3540 PRINT USING "###.###";A(J,I);:PRINT".";PRINT USING
"###.###";VF(I);:PRINT".";PRINT USING "###.###";CV*100;:PRINT""
;:PRINT USING "###.###";CA(I);:PRINT""
3550 NEXT J
3560 FOR J=2 TO 7
3570 PRINT USING ".###.###";A(J,I);:PRINT"
;
3580 NEXT J
3590 PRINT
3600 NEXT I
3610 PRINT
3620 IF Q1$="Y" GOTO 3870
3630 IF Q3$="Y" GOTO 3650
3640 GOTO 3760
3650 PRINT
3660 PRINT TAB(8);"8";TAB(16);"9";TAB(21);"ACTUAL"
3670 FOR I=1 TO NV
3680 PRINT TAB(3);
3690 FOR J=10 TO 12
3700 PRINT USING "###.###";A(J,I);
3710 NEXT J
3720 PRINT
3730 NEXT I
3740 PRINT
3750 GOTO 3960
3760 PRINT
3770 PRINT TAB(8);"8";TAB(16);"9"
3780 FOR I=1 TO NV
3790 PRINT TAB(3);
3800 FOR J=10 TO 11
3810 PRINT USING "###.###";A(J,I);
3820 NEXT J
3830 PRINT
3840 NEXT I
3850 PRINT
3860 GOTO 3960
3870 IF Q3$="N" GOTO 3990
3880 PRINT
3890 PRINT TAB(5);"6";TAB(12);"7";TAB(19);"8";TAB(26);"9";
TAB(32);"10";TAB(39);"11";TAB(46);"JS";TAB(53);"JF";TAB(60);
"JSI";TAB(67);"JFI";TAB(72);"ACTUAL"
3900 FOR I=1 TO NV
3910 PRINT TAB(2);
3920 FOR J=8 TO 18
3930 PRINT USING "#.####";A(J,I);:PRINT" ";
3940 NEXT J
3950 PRINT
3960 NEXT I
3970 PRINT
3980 GOTO 4090
3990 PRINT
4000 PRINT TAB(5);"6";TAB(12);"7";TAB(19);"8";TAB(26);"9";
TAB(32);"10";TAB(39);"11";TAB(46);"JS";TAB(53);"JF";TAB(60);
"JSI";TAB(67);"JFI"
4010 FOR I=1 TO NV
4020 PRINT TAB(2);
4030 FOR J=8 TO 17
4040 PRINT USING "#.####"; A(J,I);:PRINT" ";
4050 NEXT J
4060 PRINT
4070 NEXT I
4080 PRINT
4090 FOR I=1 TO 16
4100 T=0
4110 FOR J=1 TO NV
4120 B=A(I,J)
4130 IF B>T THEN T=B
4140 NEXT J
4150 A(I,NV+1)=T
4160 NEXT I
4170 PRINT" ... Do you wish to display your results
graphically...(Y/N)?"
4180 GOSUB 4840
4190 IF Q$="N"THEN END
4200 CLS
4210 PRINT
4220 GOSUB 5370
4230 PRINT
4240 INPUT "Enter the graph you wish to plot";NN
4250 IF NN>11 OR NN<1 GOTO 4240
4260 P(2) =NN+2
4270 P(1)=2
4280 YMAX=A(P(2),NV)
4290 XMAX=A(1,NV+1)
4300 CLS
4310 SCREEN 2: KEY OFF
4320 VIEW (64,16)-(576,176),,0
4330 WINDOW (0,0)-(1.1*XMAX,1.1*YMAX)
4340 CLS
4350 L$="Graph of Hydraulic Gradient / Velocity"
4360 LOCATE 2, (80-LEN(L$))/2
4370 PRINT L$
4380 PSET (0,0)
4390 LINE -(XMAX,0),1
4400 PSET (0,0)
4410 LINE -(0,YMAX),1
4420 PSET (0,0)
4430 FOR I=1 TO NV
4440 LINE -(A(1,I),A(2,I)),1
4450 NEXT I
4460 Y=P(2)
4470 PSET (A(1,1),A(Y,1))
4480 FOR I=1 TO NV
4490 LINE -(A(1,I),A(Y,I)),1
4500 NEXT I
4510 LOCATE 3,2
4520 PRINT"J (mW/m)"
4530 LOCATE 5,2
4540 PRINT USING "#.###";YMAX
4550 LOCATE 22,2
4560 PRINT "0.000"
4570 LOCATE 14,2
4580 PRINT USING "#.###";YMAX/2
4590 NX=64/(NV+1)+8
4600 FOR I=1 TO NV
4610 XX=A(1,I)
4620 PSET(XX,0)
4630 LINE -(XX,.01)
4640 NEXT I
4650 LOCATE 24,1
4660 FOR I=1 TO NV
4670 NXN=(A(1,I)*(64/(XMAX*1.1)))+9
4680 PRINT TAB(NXN);:PRINT USING"#.#";A(1,I);
4690 NEXT I
4700 PSET(0,YMAX)
4710 LINE -(0,YMAX)
4720 PSET(0,YMAX/2)
4730 LINE -(0,YMAX/2)
4740 X$="Velocity (m/s)"
4750 LOCATE 25, (80-LEN(X$))/2
4760 PRINT X$
4770 LOCATE 24,1
4780 GOSUB 5540
4790 SCREEN 0,1
4800 PRINT "Do you wish to plot another graph "
4810 GOSUB 4840
4820 IF Q$="Y" GOTO 4200
4830 END
4840 Q$=" ";Q$=INKEYS
4850 IF Q$="Y" OR Q$="N" GOTO 4870 ELSE 4840
4860 PRINT
4870 RETURN
4880 IF Q1$="N" THEN QC=12 ELSE QC=18
4890 FOR J=1 TO NV
4900 PRINT
4910 PRINT"For Velocity ";A(1,J); "=
4920 INPUT A(QC,J)
4930 NEXT J
4940 PRINT  
4950 PRINT"Correct any Data.......(Y/N)"
4960 GOSUB 4840
4970 IF QS="Y" GOTO 4890
4980 RETURN
4990 REM SUBROUTINE ***** NEW THEORY *******
5000 X2=0
5010 XX=0
5020 X3=0
5030 REM Coefficient of friction of solids on the pipe wall
(u) = 0.3
5040 U=.3
5050 V0=7.7161*(CV^.2)*SQR(D*(RD-1))
5060 V2=30*(CV^.25)*VSS
5070 IF V0=VEL GOTO 5110
5080 IF F66=1 GOTO 5340
5090 PRINT"DATA INPUT ERROR VELOCITY ";I;" IS TOO SMALL":JF=0:JS=0:F66=1:GOTO 5350
5100 PRINT
5110 IF VEL<=((.15*V2)+(.85*V0)) THEN K=1 ELSE 5130
5120 GOTO 5160
5130 IF VEL>=V2 THEN K=0 ELSE 5150
5140 GOTO 5160
5150 K=((V2-VEL)/(.85*(V2-V0)))
5160 H=((.04*{(RD-1)^.9})/((CV^1.3)*((VEL-V0)^.66)))+1
5170 CA=(H*CV)/(1-CV+H*CV)
5180 CA(I)=CA*100
5190 G=(BF+1-K)/(2-K)
5200 TH1=.0001
5210 TH2=BF*CA*K*3.14159+(SIN(TH2)*COS(TH1))
5220 X1=ABS(TH2-TH1)
5230 IF X1<.001 GOTO 5310
5240 XX=XX+1
5250 IF XX=1 GOTO 5290
5260 X3=X1-X2
5270 IF X3>X1 THEN PRINT "ERROR 1"
5280 X2=X1
5290 TH1=TH2
5300 GOTO 5210
5310 JF=((4*F*VEL*VEL)/(2*9.807*D))*/(1-(CV*G))/(1-(CA*G))
5320 VF(I)=VEL*(((1-(CV*G))/(1-(CA*G))))
5330 JS=U*K*CA*(RD-1)
5340 F66=0:REM PRINT"TH2 = ";TH2
5350 AA=JF+JS
5360 RETURN
5370 PRINT
5380 PRINT TAB(20);"MENU"
5390 PRINT
5400 PRINT
5410 PRINT TAB(6);"1. Durand Coarse only"
5420 PRINT TAB(6);"2. Durand Condolios - Spheres ------- UN-Hindered"
5430 PRINT TAB(6);"3. Durand Condolios - NON-Spheres -- UN-Hindered"
5440 PRINT TAB(6);"4. Zandi and Govatos - Spheres ------ UN-
Hindered"
5450 PRINT TAB(6);"5. Zandi and Govatos - NON-Spheres -- UN-
Hindered"
5460 PRINT TAB(6);"6. Worsters Coarse"
5470 PRINT TAB(6);"7. Newitts sliding bed"
5480 PRINT TAB(6);"8. Newitts heterogeneous suspension -
Spheres"
5490 PRINT TAB(6);"9. Newitts heterogeneous suspension - NON-
Spheres"
5500 PRINT TAB(6);"10. New Theory - Spheres ------ UN-
Hindered"
5510 PRINT TAB(6);"11. New Theory - NON-Spheres -- UN-
Hindered"
5520 PRINT
5530 RETURN
5540 Q$=" " : Q$=INKEY$  
5550 IF Q$=" " GOTO 5560 ELSE 5540
5560 RETURN
5570 REM COLOR 23
5580 XX$="Press SPACE BAR to Scroll"
5590 LOCATE 25,(70-LEN(XX$))/2 
5600 PRINT XX$  
5610 REM COLOR 1
5620 RETURN
5630 STOP
5640 REM SUBROUTINE ***** KA FIT **********
5650 DIM KW(21,2):DIM KX(21,2):DIM KY(21,2):DIM KZ(21,2)
5660 KW(1,1)=.1
5670 KW(2,1)=1:KW(2,2)=.259
5680 KW(3,1)=2:KW(3,2)=.27 
5690 KW(4,1)=3:KW(4,2)=.281 
5700 KW(5,1)=4:KW(5,2)=.291 
5710 KW(6,1)=5:KW(6,2)=.31  
5720 KW(7,1)=6:KW(7,2)=.327 
5730 KW(8,1)=7:KW(8,2)=.335 
5740 KW(9,1)=8:KW(9,2)=.346 
5750 KW(10,1)=9:KW(10,2)=.354 
5760 KW(11,1)=10:KW(11,2)=.362 
5770 KW(12,1)=15:KW(12,2)=.365 
5780 KW(13,1)=20:KW(13,2)=.354 
5790 KW(14,1)=30:KW(14,2)=.32 
5800 KW(15,1)=40:KW(15,2)=.3  
5810 KW(16,1)=50:KW(16,2)=.283 
5820 KW(17,1)=60:KW(17,2)=.272 
5830 KW(18,1)=70:KW(18,2)=.267 
5840 KW(19,1)=80:KW(19,2)=.261 
5850 KW(20,1)=90:KW(20,2)=.256 
5860 KW(21,1)=100:KW(21,2)=.253 
5870 REM
5880 KX(1,1)=.2
5890 KX(2,1)=1:KX(2,2)=.414
5900 KX(3,1)=2:KX(3,2)=.424
5910 KX(4,1)=3:KX(4,2)=.432
5920 KX(5,1)=4:KX(5,2)=.443
5930 KX(6,1)=5:KX(6,2)=.457
5940 KX(7,1)=6:KX(7,2)=.471
5950 KX(8,1)=7:KX(8,2)=.476
5960 KX(9,1)=8:KX(9,2)=.486
5970 KX(10,1)=9:KX(10,2)=.495
5980 KX(11,1)=10:KX(11,2)=.5
5990 KX(12,1)=15:KX(12,2)=.5
6000 KX(13,1)=20:KX(13,2)=.486
6010 KX(14,1)=30:KX(14,2)=.462
6020 KX(15,1)=40:KX(15,2)=.443
6030 KX(16,1)=50:KX(16,2)=.433
6040 KX(17,1)=60:KX(17,2)=.429
6050 KX(18,1)=70:KX(18,2)=.419
6060 KX(19,1)=80:KX(19,2)=.414
6070 KX(20,1)=90:KX(20,2)=.412
6080 KX(21,1)=100:KX(21,2)=.407
6090 REM
6100 KY(1,1)=.3
6110 KY(2,1)=1:KY(2,2)=.567
6120 KY(3,1)=2:KY(3,2)=.576
6130 KY(4,1)=3:KY(4,2)=.582
6140 KY(5,1)=4:KY(5,2)=.588
6150 KY(6,1)=5:KY(6,2)=.6
6160 KY(7,1)=6:KY(7,2)=.607
6170 KY(8,1)=7:KY(8,2)=.62
6180 KY(9,1)=8:KY(9,2)=.629
6190 KY(10,1)=9:KY(10,2)=.633
6200 KY(11,1)=10:KY(11,2)=.64
6210 KY(12,1)=15:KY(12,2)=.64
6220 KY(13,1)=20:KY(13,2)=.627
6230 KY(14,1)=30:KY(14,2)=.6
6240 KY(15,1)=40:KY(15,2)=.582
6250 KY(16,1)=50:KY(16,2)=.577
6260 KY(17,1)=60:KY(17,2)=.568
6270 KY(18,1)=70:KY(18,2)=.564
6280 KY(19,1)=80:KY(19,2)=.564
6290 KY(20,1)=90:KY(20,2)=.555
6300 KY(21,1)=100:KY(21,2)=.555
6310 REM
6320 KZ(1,1)=.4
6330 KZ(2,1)=1:KZ(2,2)=.725
6340 KZ(3,1)=2:KZ(3,2)=.725
6350 KZ(4,1)=3:KZ(4,2)=.725
6360 KZ(5,1)=4:KZ(5,2)=.731
6370 KZ(6,1)=5:KZ(6,2)=.738
6380 KZ(8,1)=7:KZ(8,2)=.75
6390 KZ(9,1)=8:KZ(9,2)=.759
6400 KZ(10,1)=9:KZ(10,2)=.763
6410 KZ(11,1)=10:KZ(11,2)=.769
6420 KZ(12,1)=15:KZ(12,2)=.769
6430 KZ(13,1)=20:KZ(13,2)=.753
6440 KZ(14,1)=30:KZ(14,2)=.729
6450 KZ(15,1)=40:KZ(15,2)=.713
6460 KZ(16,1)=50:KZ(16,2)=.695
6470 KZ(17,1)=60:KZ(17,2)=.689
6400 KZ(10,1)=70;KZ(18,2) = .689
6490 KZ(19,1)=80;KZ(19, 2) = .683
6500 KZ(20,1)=90;KZ(20,2) = .678
6510 KZ(21,1)=100;KZ(21,2) = .678
6520 REM
6530 IF K => .5 THEN KA=1: GOTO 6850
6540 IF ND<=10 THEN I = INT(ND)+1
6550 IF ND>10 AND ND<=15 THEN I = 12
6560 IF ND>15 AND ND<=20 THEN I = 13
6570 IF ND>21 AND ND<=30 THEN I = 14
6580 IF ND>31 AND ND<=40 THEN I = 15
6590 IF ND>41 AND ND<=50 THEN I = 16
6600 IF ND>51 AND ND<=60 THEN I = 17
6610 IF ND>61 AND ND<=70 THEN I = 18
6620 IF ND>71 AND ND<=80 THEN I = 19
6630 IF ND>81 AND ND<=90 THEN I = 20
6640 IF ND>91 THEN I = 21
6650 IF ND>100 THEN ND = 100
6660 IF ND<0 THEN PRINT "ERROR ND"
6670 IF K <= KW(1,1) GOTO 6710
6680 IF K <= KX(1,1) GOTO 6740
6690 IF K <= KY(1,1) GOTO 6780
6700 IF K <= KZ(1,1) GOTO 6820
6710 KA1 = ((ND - KW(I-1,1))/(KW(I,1)-KW(I-1,1))*(KW(I,2)-KW(I-1,2)))+KW(I-1,2)
6720 KA = (K/I)* (KA1- .2)+ .2
6730 GOTO 6850
6740 KA2= ((ND-KX(I-1,1))/(KX(I,1)-KX(I-1,1))*(KX(I,2)-KX(I-1,2)))+KX(I-1,2)
6750 KA1 = ((ND - KW(I-1,1))/(KW(I,1)-KW(I-1,1))*(KW(I,2)-KW(I-1,2)))+KW(I-1,2)
6760 KA= ((K-KW(1,1))/(KX(1,1)-KW(1,1))*(KA2-KA1))+KA1
6770 GOTO 6850
6780 KA2= ((ND-KY(I-1,1))/(KY(I,1)-KY(I-1,1))*(KY(I,2)-KY(I-1,2)))+KY(I-1,2)
6790 KA1= ((ND - KX(I-1,1))/(KX(I,1)-KX(I-1,1))*(KX(I,2)-KX(I-1,2)))+KX(I-1,2)
6800 KA= ((K-KY(1,1))/(KX(1,1)-KX(1,1))*(KA2-KA1))+KA1
6810 GOTO 6850
6820 KA2= ((ND-KZ(I-1,1))/(KZ(I,1)-KZ(I-1,1))*(KZ(I,2)-KZ(I-1,2)))+KZ(I-1,2)
6830 KA1= ((ND - KX(I-1,1))/(KX(I,1)-KX(I-1,1))*(KX(I,2)-KX(I-1,2)))+KX(I-1,2)
6840 KA= ((K-KX(1,1))/(KZ(1,1)-KX(1,1))*(KA2-KA1))+KA1
6850 REM PRINT "KA = ";KA
6860 RETURN
6870 REM SUBROUTINE ***** FL FIT **********
6880 DIM W(22,2): DIM X(22,2): DIM Y(22,2): DIM Z(22,2)
6890 W(1,1) = .02
6900 W(2,1) = 0: W(2,2) = 0
6910 W(3,1) = .1: W(3,2) = .8
6920 W(4,1) = .2: W(4,2) = .948
6930 W(5,1) = .3: W(5,2) = 1.021
6940 W(6,1) = .4: W(6,2) = 1.082
6950 W(7,1) = .5: W(7,2) = 1.123
<table>
<thead>
<tr>
<th></th>
<th>W(8,1) = .6: W(8,2) = 1.157</th>
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<tbody>
<tr>
<td>6970</td>
<td>W(9,1) = .7: W(9,2) = 1.183</td>
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<td>6980</td>
<td>W(10,1) = .8: W(10,2) = 1.21</td>
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<td>6990</td>
<td>W(11,1) = .9: W(11,2) = 1.227</td>
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<tr>
<td>7000</td>
<td>W(12,1) = 11: W(12,2) = 1.243</td>
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<tr>
<td>7010</td>
<td>W(13,1) = 1.1: W(13,2) = 1.257</td>
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<td>7020</td>
<td>W(14,1) = 1.2: W(14,2) = 1.27</td>
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<td>7030</td>
<td>W(15,1) = 1.3: W(15,2) = 1.28</td>
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<td>7040</td>
<td>W(16,1) = 1.4: W(16,2) = 1.287</td>
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<td>7050</td>
<td>W(17,1) = 1.5: W(17,2) = 1.293</td>
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<td>7060</td>
<td>W(18,1) = 1.6: W(18,2) = 1.3</td>
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<td>7070</td>
<td>W(19,1) = 1.7: W(19,2) = 1.303</td>
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<tr>
<td>7080</td>
<td>W(20,1) = 1.8: W(20,2) = 1.307</td>
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<tr>
<td>7090</td>
<td>W(21,1) = 1.9: W(21,2) = 1.313</td>
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<td>7100</td>
<td>W(22,1) = 21: W(22,2) = 1.317</td>
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<td>7110</td>
<td>X(1,1) = .05</td>
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<tr>
<td>7120</td>
<td>X(2,1) = 0: X(2,2) = 0</td>
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<td>7130</td>
<td>X(3,1) = 0.1: X(3,2) = .907</td>
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<td>7140</td>
<td>X(4,1) = .2: X(4,2) = 1.073</td>
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<td>7150</td>
<td>X(5,1) = .3: X(5,2) = 1.173</td>
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<td>7160</td>
<td>X(6,1) = .4: X(6,2) = 1.253</td>
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<td>7170</td>
<td>X(7,1) = .5: X(7,2) = 1.307</td>
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<td>7180</td>
<td>X(8,1) = .6: X(8,2) = 1.343</td>
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<td>7190</td>
<td>X(9,1) = .7: X(9,2) = 1.367</td>
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<td>7200</td>
<td>X(10,1) = .8: X(10,2) = 1.38</td>
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<td>7210</td>
<td>X(11,1) = .9: X(11,2) = 1.39</td>
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<td>7220</td>
<td>X(12,1) = 1: X(12,2) = 1.393</td>
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<td>7230</td>
<td>X(13,1) = 1.1: X(13,2) = 1.397</td>
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<td>7240</td>
<td>X(14,1) = 1.2: X(14,2) = 1.39</td>
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<td>7250</td>
<td>X(15,1) = 1.3: X(15,2) = 1.386</td>
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<td>7260</td>
<td>X(16,1) = 1.4: X(16,2) = 1.377</td>
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<tr>
<td>7270</td>
<td>X(17,1) = 1.5: X(17,2) = 1.367</td>
</tr>
<tr>
<td>7280</td>
<td>X(18,1) = 1.6: X(18,2) = 1.36</td>
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<td>X(19,1) = 1.7: X(19,2) = 1.353</td>
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<td>X(20,1) = 1.8: X(20,2) = 1.347</td>
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<tr>
<td>7310</td>
<td>X(21,1) = 1.9: X(21,2) = 1.343</td>
</tr>
<tr>
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<td>X(22,1) = 21: X(22,2) = 1.337</td>
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<tr>
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<td>Y(3,1) = 1: Y(3,2) = .907</td>
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<td>7470</td>
<td>Y(15,1) = 1.3: Y(15,2) = 1.39</td>
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<td>7490</td>
<td>Y(17,1) = 1.5: Y(17,2) = 1.367</td>
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<td>Y(18,1) = 1.6: Y(18,2) = 1.36</td>
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7510  Y(19,1)=1.7:Y(19,2)=1.353
7520  Y(20,1)=1.8:Y(20,2)=1.347
7530  Y(21,1)=1.9:Y(21,2)=1.343
7540  Y(22,1)=2.1:Y(22,2)=1.337
7550  Z(1,1)=.15
7560  Z(2,1)=0.1:Z(2,2)=0.1
7570  Z(3,1)=.2:Z(3,2)=.1
7580  Z(4,1)=.2:Z(4,2)=.128
7590  Z(5,1)=.2:Z(5,2)=.139
7600  Z(6,1)=.4:Z(6,2)=.1452
7610  Z(7,1)=.5:Z(7,2)=.1483
7620  Z(8,1)=.6:Z(8,2)=.15
7630  Z(9,1)=.7:Z(9,2)=.1507
7640  Z(10,1)=.8:Z(10,2)=.15
7650  Z(11,1)=.9:Z(11,2)=.1483
7660  Z(12,1)=1:Z(12,2)=.1455
7670  Z(13,1)=1.1:Z(13,2)=.1428
7680  Z(14,1)=1.2:Z(14,2)=.1407
7690  Z(15,1)=1.3:Z(15,2)=.139
7700  Z(16,1)=1.4:Z(16,2)=.1337
7710  Z(17,1)=1.5:Z(17,2)=.1367
7720  Z(18,1)=1.6:Z(18,2)=.136
7730  Z(19,1)=1.7:Z(19,2)=.1353
7740  Z(20,1)=1.8:Z(20,2)=.1347
7750  Z(21,1)=1.9:Z(21,2)=.1343
7760  Z(22,1)=2:Z(22,2)=.1337
7770  IF A7>.002 THEN FL=1.34:GOTO 8130
7780  IF CV=W(1,1) GOTO 7870
7790  IF CV=W(1,1) GOTO 7870
7800  IF CV=X(1,1) GOTO 7900
7810  IF CV=X(1,1) GOTO 7950
7820  IF CV=Y(1,1) GOTO 7980
7830  IF CV=Y(1,1) GOTO 8030
7840  IF CV=Z(1,1) GOTO 8060
7850  IF CV=Z(1,1) GOTO 8110
7860  IF CV=Z(1,1) THEN PRINT "ERROR FL":GOTO 8130
7870  I=INT(A7*10000)+2
7880  FL=(((A7*10000)-(I-3))*(W(I,2)-W(I-1,2)))+W(I-1,2)
7890  GOTO 8130
7900  I=INT(A7*10000)+2
7910  FL1=(((A7*10000)-(I-3))*(W(I,2)-W(I-1,2)))+W(I-1,2)
7920  FL2=(((A7*10000)-(I-3))*(X(I,2)-X(I-1,2)))+X(I-1,2)
7930  FL=(((CV-W(1,1))/(X(1,1)-W(1,1)))*(FL2-FL1))+FL1
7940  GOTO 8130
7950  I=INT(A7*10000)+2
7960  FL=(((A7*10000)-(I-3))*(X(I,2)-X(I-1,2)))+X(I-1,2)
7970  GOTO 8130
7980  I=INT(A7*10000)+2
7990  FL1=(((A7*10000)-(I-3))*(X(I,2)-X(I-1,2)))+X(I-1,2)
8000  FL2=(((A7*10000)-(I-3))*(Y(I,2)-Y(I-1,2)))+Y(I-1,2)
8010  FL=(((CV-X(1,1))/(Y(1,1)-X(1,1)))*(FL2-FL1))+FL1
8020  GOTO 8130
8030  I=INT(A7*10000)+2
8040  FL=(((A7*10000)-(I-3))*(Y(I,2)-Y(I-1,2)))+Y(I-1,2)
8050  GOTO 8130
8060 \( I = \text{INT}(A7 \times 10000) + 2 \)
8070 \( FL1 = (((A7 \times 10000) - (I - 3)) \times (Y(I, 2) - Y(I - 1, 2))) + Y(I - 1, 2) \)
8080 \( FL2 = (((A7 \times 10000) - (I - 3)) \times (Z(I, 2) - Z(I - 1, 2))) + Z(I - 1, 2) \)
8090 \( FL = (((CV - Y(1, 1)) / (Y(1, 1) - X(1, 1))) \times (FL2 - FL1)) + FL1 \)
8100 GOTO 8130
8110 \( I = \text{INT}(A7 \times 10000) + 2 \)
8120 \( FL = (((A7 \times 10000) - (I - 3)) \times (Z(I, 2) - Z(I - 1, 2))) + Z(I - 1, 2) \)
8130 REM PRINT "FL = " ; FL
8140 REM GOSUB 4840
8150 RETURN

<table>
<thead>
<tr>
<th>Concentration of 10 percent</th>
<th>Velocity [m/s]</th>
<th>( a_1 ) [mg/cm^2]</th>
<th>( a_2 ) [mg/cm^2]</th>
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<th>( a_2 ) [mg/cm^2]</th>
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Table 9: Corrected Data from The Rookhi School at Mines
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Table 5 - Corrected Data from The Mackay School of Mines
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Table 6 - Data from the k curves
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Table 7 – Data from the F_L curves
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 4
Enter Relative Density? 2.6
Enter Pipe Diameter in mm.? 50.8
Enter Volumetric Concentration......i.e. (10%) =? 4
Velocity at which sliding bed commences according to New Theory = 1.1556 m/s
Enter Number of Velocities ? 4

Velocity 1 =? 1.814
Velocity 2 =? 1.888
Velocity 3 =? 1.940
Velocity 4 =? 1.954
Correct any Velocities............(Y/N)

Actual Data.....................(Y/N)
For Velocity 1.814 =? .1330
For Velocity 1.888 =? .1070
For Velocity 1.94 =? .1065
For Velocity 1.954 =? .1015
Correct any Data ...... (Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1.....Sand, Gravel, Beach Flints.
Group 2.....Sillimanite, Bituminous Coal.
Group 3.....Blast Furnace Slag.
Group 4.....Limestone, Talc, Plumago, Granite.
Group 5.....Gypsum,
Group 6.....Graphite.
Group 7.....Mica.
Group 8.....Calculated.

Enter Group Selected? 1

Figure 12 - Specimen run of the computer programme HYD
CALCULATED RESULTS FOR A CONCENTRATION OF 4.0 %

Pipe Diameter............................... = 50.80 mm
Shape Group.................................. = 1.000
Weighted Mean Particle Diameter.......... = 4.000 mm
Relative Density of Solids................. = 2.600
Delivered Volume Concentration of Solids.. = 0.040
Delivered Weight Concentration of Solids.. = 0.098

Terminal Settling Velocity of Spherical Particles of 4.000 mm Diameter = 0.436 m/s
Drag Coefficient of Spherical Particles of 4.000 mm Diameter = 0.440

Terminal Settling Velocity of NON-Spherical 4.000 m/s Particles of Shape Factor 0.26 = 0.216 m/s

Hindered Settling Velocity of Spherical Particles of 4.000 mm Diameter and Volumetric Concentration 0.040 = 0.395 m/s

Hindered Settling Velocity of NON-Spherical 4.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.040 = 0.196 m/s

Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.773 mm

Limiting Mixture Velocity for Deposition (DURAND) = 1.692 m/s

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.387 m/s using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 0.976 m/s using the drag coefficient of irregular particles

Critical Velocity (Bain and Bonnington) = 1.300 m/s using the drag coefficient of spheres

Critical Velocity (Bain and Bonnington) = 0.915 m/s using the drag coefficient of irregular particles

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 7.414 m/s, Using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 3.676 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.8

Friction Factor Adjustment (Y/N)
5.494281E-03
5.471272E-03
5.455984E-03
5.451985E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts hetrogeneous suspension - Spheres
9. Newitts hetrogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

TABLE OF RESULTS

<table>
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Do you wish to display your results graphically...(Y/N)?
APPENDIX II

Listing of the Computer Program FINE
10 DIM CD(50), RE(50), VS(50)
20 Z$ = " 
30 Z$ = INKEY$: IF Z$ = "Z" GOTO 40 ELSE 20
40 CLS
50 KEY OFF
60 PRINT TAB(10); "Enter the Pipe Diameter in meters"; D
70 PRINT
80 PRINT TAB(10); "Enter the Relative Density of the Material"; RD
90 PRINT
100 PRINT TAB(10); "Enter Volumetric Concentration...
......(20%)"; CC: CV = CC / 100
110 PRINT
120 DLMAX = 0.1224 * ((1 / (RD - 1)) ^ (1/3))
130 REM
140 PRINT TAB(10); "Maximum particle size falling"
150 PRINT TAB(10); "in the laminar zone (Stokes Law) = "; DLMAX
160 PRINT
170 PRINT TAB(10); "Enter Data"; Y$
180 PRINT
190 IF Y$ = "Y" GOTO 220
200 GOSUB 2070
210 GOTO 410
220 PRINT TAB(10); "Enter Number of Size Fractions"; NS
230 DIM FRACT(4, NS)
240 K = 0
250 FOR I = 1 TO NS
260 PRINT
270 PRINT TAB(10); "Enter Maximum Size in Fraction "; I; " in mm";
280 INPUT FRACT(1, I)
290 PRINT
300 PRINT TAB(10); "Enter Minimum Size in Fraction "; I; " in mm";
310 INPUT FRACT(2, I)
320 PRINT
330 PRINT TAB(10); "Enter % Weight of Fraction "; I;
340 INPUT FRACT(3, I)
350 PRINT
360 DUM = 0
370 Z$ = INKEY$: IF Z$ = " " GOTO 380 ELSE 360
380 IF K = 1 GOTO 400
390 IF DLMAX > (FRACT(1, I)) THEN FRAC = I - 1: K = 1
400 NEXT I
410 FOR I = 1 TO NS
420 AV = (FRACT(1, I) + FRACT(2, I)) / 2
430 GM = AV * FRACT(3, I) / 100
440 TOT = GM + TOT
450 IF I > FRAC GOTO 470
460 CTOT = CTOT + FRACT(3, I)
470 NEXT I
480 FOR I = 1 TO FRAC
490 FRACT(4, I) = FRACT(3, I) / CTOT * 100
500 NEXT I
510 FOR I = 1 TO FRAC
520  \textit{AV1}=(\textit{FRACT}(1,I)+\textit{FRACT}(2,I))/2 \\
530  \textit{GM1}=\textit{AV1} \times \textit{FRACT}(4,I)/100 \\
540  \textit{TOT1}=\textit{GM1}+\textit{TOT1} \\
550  \textbf{NEXT} I \\
560  \textit{A7}=\textit{TOT1}/1000: \textit{C7}=\textit{TOT1}/1000 \\
570  \textbf{PRINT TAB}(10);"\textit{A7}";\textit{A7};"\textit{C7}";\textit{C7};\textbf{PRINT} \\
580  \textit{CW}=((\textit{CV}\times\textit{RD})/(1+\textit{CV}\times(\textit{RD}-1))) \\
590  \textbf{FOR} I=\textit{FRAC}+1 \textbf{TO} \textit{NS} \\
600  \textit{FTOT}=\textit{FRACT}(3,I)+\textit{FTOT} \\
610  \textbf{NEXT} I \\
620  \textit{CF}=\textit{FTOT}\times\textit{CW}/100 \\
630  \textit{CVF}=\textit{CF}/(\textit{RD}-\textit{CF}(\textit{RD}-1)) \\
640  \textit{CVCF}=\textit{CVF}-\textit{CF} \\
650  \textit{RDHM}=\textit{CVF}\times(\textit{RD}-1)+1 \\
660  \textit{RDCSF}=\textit{CVCF}\times(\textit{RD}-\textit{RDHM})+\textit{RDHM} \\
670  \textbf{REM} \textbf{TO} \textbf{CALCULATE} \textbf{THE} \textit{SETTLING} \textbf{VELOCITIES} \\
680  \textbf{FOR} I=1 \textbf{TO} \textit{FRAC} \\
690  \textit{AV}=((\textit{FRACT}(1,I)+\textit{FRACT}(2,I))/2)/1000 \\
700  \textit{VSS}=9.807\times\textit{AV}\times\textit{AV}\times(\textit{RD}-1)/(18\times(10^-6)) \\
710  \textit{VSI}=2.085\times\textit{AV}\times((9.807\times9.807*((\textit{RD}-1)^2)/(10^-6))^{(1/3)}) \\
720  \textit{VSN}=1.7408\times\textit{SQR}(\textit{AV}\times9.807\times(\textit{RD}-1)) \\
730  \textbf{REM} \\
740  \textbf{REM} \textbf{TO} \textbf{CALCULATE} \textit{REYNOLDS} \textit{NUMBER} \\
750  \textbf{REM} \\
760  \textit{RES}=\textit{VSS}\times\textit{AV}\times10^-6 \\
770  \textit{REI}=\textit{VSI}\times\textit{AV}\times10^-6 \\
780  \textit{REN}=\textit{VSN}\times\textit{AV}\times10^-6 \\
790  \textbf{IF} \textit{RES}>0 \textbf{AND} \textit{RES}<1 \textbf{THEN} \textit{R}\%=1 \\
800  \textbf{IF} \textit{REI}>1 \textbf{AND} \textit{REI}<800 \textbf{THEN} \textit{R}\%=2 \\
810  \textbf{IF} \textit{REN}>800 \textbf{AND} \textit{REN}<10^-5 \textbf{THEN} \textit{R}\%=3 \\
820  \textbf{IF} \textit{R}\%=0 \textbf{GOTO} 2190:\textbf{REM} \textit{ERROR} \\
830  \textbf{IF} \textit{R}\%=1 \textbf{THEN} \textit{CD}(I)=24/\textit{RES}:\textit{RE}(I)=\textit{RES}:\textit{VS}(I)=\textit{VSS} \\
840  \textbf{IF} \textit{R}\%=2 \textbf{THEN} \textit{CD}(I)=14/\textit{SQR(ReI)}:\textit{RE}(I)=\textit{REI}:\textit{VS}(I)=\textit{VSI} \\
850  \textbf{IF} \textit{R}\%=3 \textbf{THEN} \textit{CD}(I)=.44:\textit{RE}(I)=\textit{REI}:\textit{VS}(I)=\textit{VSN} \\
860  \textit{CDCALC}=(\textit{CD}(I))+(\textit{FRACT}(4,I))\times\textit{CDCALC} \\
870  \textit{VSCALC}=(\textit{VS}(I))+(\textit{FRACT}(4,I))\times\textit{VSCALC} \\
880  \textit{RECALC}=(\textit{RE}(I))+(\textit{FRACT}(4,I))\times\textit{RECALC} \\
890  \textbf{NEXT} I \\
900  \textit{CD}=\textit{CDCALC}/100 \\
910  \textit{VS}=\textit{VSCALC}/100 \\
920  \textbf{PRINT TAB}(10);"CD = ";\textit{CD},"VS = ";\textit{VS} \\
930  \textbf{REM} \\
940  \textit{ZS}=$\textbf{INKEY}$;\textbf{IF} \textit{ZS}="Z" \textbf{THEN} \textbf{GOTO} 950 \textbf{ELSE} 930 \\
950  \textbf{PRINT} \\
960  \textbf{PRINT TAB}(10);"Which Group of Mineral Types in the \textbf{Following} \textit{Group}" \\
970  \textbf{PRINT TAB}(10);"Most \textit{Nearly} \textbf{Describes} the \textit{Particles} \textbf{being} \textbf{Investigated} ?" \\
980  \textbf{PRINT} \\
990  \textbf{PRINT TAB}(10);"Group 1......Sand, Gravel, Beach Flints." \\
1000 \textbf{PRINT TAB}(10);"Group 2......Sillimanite, Bituminous Coal." \\
1010 \textbf{PRINT TAB}(10);"Group 3......Blast Furnace Slag." \\
1020 \textbf{PRINT TAB}(10);"Group 4......Limestone, Talc, Plumago, Granite."
1030 PRINT TAB(10);"Group 5.....Gypsum,"
1040 PRINT TAB(10);"Group 6.....Graphite."
1050 PRINT TAB(10);"Group 7.....Mica."
1060 PRINT TAB(10);"Group 8.....Calculated."
1070 PRINT
1080 PRINT TAB(10);:INPUT"Enter Group Selected";G
1090 IF G>8 GOTO 990
1100 IF G=1 THEN K=.26
1110 IF G=2 THEN K=.23
1120 IF G=3 THEN K=.19
1130 IF G=4 THEN K=.16
1140 IF G=5 THEN K=.13
1150 IF G=6 THEN K=.023
1160 IF G=7 THEN K=.003
1170 PRINT
1180 PRINT TAB(10);K
1190 PRINT
1200 IF G=8 THEN INPUT"Enter Volume of Sample";VOL
1210 REM
1220 ND=(CD*((RECALC/100)^2))^(1/3)
1230 IF G=8 THEN K=VOL/((C7*1000)^3)
1240 GOSUB 2200
1250 VS=K*VS:PRINT TAB(10);"VSI = ";VSI
1260 VSH=K*VSH
1270 CDI=CD*((VS/VSI)^2):PRINT TAB(10);"CDI = ";CDI
1280 REM Determination of FL
1290 IF C7<=.0002 THEN FL=5391*(C7*1000)+.45 ELSE 1310
1300 GOTO 1320
1310 GOSUB 3430
1320 CLS
1330 FOR I=1 TO 10
1340 PRINT
1350 NEXT I
1360 PRINT
1370 PRINT TAB(20);"Critical Velocity Calculations"
1380 PRINT
1390 PRINT TAB(15);"1. Bain and Bonnington"
1400 PRINT TAB(15);"2. Durand"
1410 PRINT TAB(15);"3. Makharadzye"
1420 PRINT
1430 PRINT TAB(10);:INPUT"Enter Selection";NN:PRINT
1440 IF NN>3 OR NN<1 GOTO 1440
1450 IF NN=2 GOTO 1570
1460 IF NN=3 GOTO 1620
1470 VCBB=3.43*(CV^(.33))*(9.807*D*(RD-1)/(CD^3)^.5)
1480 VCBB=3.43*(CV^(.33))*(9.807*D*(RD-1)/(CDI^3)^.5)
1490 PRINT TAB(10);"Critical Velocity according to Bain and Bonnington"
1500 PRINT TAB(10);"for Spheres = ";VCBB;" m/s"
1510 PRINT
1520 PRINT TAB(10);"Critical Velocity according to Bain and Bonnington"
1530 PRINT TAB(10);"for Irregular Particles ";VCBB;" m/s"
1540 PRINT
1550 VEL=VCBB
1560 GOTO 1660
1570 VCD=PL*(2*9.807*D*(RD-RDHM)/RDHM)^.5
1580 PRINT TAB(10);"Critical Velocity according to Durand = ";VCD;" m/s"
1590 PRINT
1600 VEL=VCD
1610 GOTO 1660
1620 VCM=(C7*1000)^.25*((2*9.807*D*(RD-RDHM)/RDHM)*(RDCSF/RDHM))^.5
1630 PRINT TAB(10);"Critical Velocity according to Makharadzye = ";VCM;" m/s"
1640 PRINT
1650 VEL=VCM
1660 REM
1670 REP=VEL*D*10^-6
1680 IF REP>=4000 THEN 1710
1690 F2=16/REP
1700 GOTO 1760
1710 F1=.0001
1720 F2=(1/(-1.737177928#*LOG(((45*(10^-6))/(3.7*D)+1.26/(REP*(SQR(F1)))))))^2
1730 IF ABS(F1-F2)<.000001 THEN 1760
1740 F1=F2
1750 GOTO 1720
1760 F=F2
1770 HGHM=(4*F*(VEL^2)*RDHM)/(2*D)
1780 REM PRESSURE GRADIENT ACCORDING TO DURAND
1790 HGDUR=CV*HGHM*85*(((9.807*D*(RD-1))/((VEL^2)*(CD^2))^.5)+HGHM
1800 HGDURI=CV*HGHM*85*(((9.807*D*(RD-1))/((VEL^2)*(CD1^2))^.5)+HGHM
1810 PRINT TAB(10);"Hydraulic Gradient according to Durand and Condolios"
1820 PRINT TAB(10);"for Spheres = ";HGDUR;" kN/m2/m"
1830 PRINT
1840 PRINT TAB(10);"Hydraulic Gradient according to Durand and Condolios"
1850 PRINT TAB(10);"for Irregular Particles = ";HGDURI;" kN/m2/m"
1860 PRINT
1870 B=(VEL^2*(CD^2))/(9.807*D*(RD-1))
1880 IF B>10 GOTO 1910
1890 HGZG=CV*HGHM*6.3*(B^(-.354))+HGHM
1900 GOTO 1920
1910 HGZG=CV*HGHM*280*(B^-1.93)+HGHM
1920 B=(VEL^2*(CD1^2))/((9.807*D*(RD-1))
1930 IF B>10 GOTO 1960
1940 HGZGI=CV*HGHM*6.3*(B^--.354)+HGHM
1950 GOTO 1970
1960 HGZGI=CV*HGHM*280*(B^-1.93)+HGHM
1970 PRINT TAB(10);"Hydraulic Gradient according to Zandi and Gavatos"
1980 PRINT TAB(10);"for Spheres = ";HGZG;" kN/m2/m"
1990 PRINT
2000 PRINT TAB(10);"Hydraulic Gradient according to Zandi and
GAVATOS
2010 PRINT TAB(10):"for Irregular Particles = ";HGZGI;
2020 PRINT
2030 YS=" 
2040 PRINT TAB(10);:INPUT"Another Velocity";Y$:Z$=INKEY$
2050 IF Y$="Y" GOTO 1360 ELSE STOP
2060 STOP
2070 DIM FRACT(4,9)
2080 FRACT(1,1)=12.7:FRACT(2,1)=4.76:FRACT(3,1)=1
2090 FRACT(1,2)=4.76:FRACT(2,2)=21:FRACT(3,2)=2.03
2100 FRACT(1,3)=21:FRACT(2,3)=.841:FRACT(3,3)=4.75
2110 FRACT(1,4)=.841:FRACT(2,4)=.42:FRACT(3,4)=5.92
2120 FRACT(1,5)=.42:FRACT(2,5)=.3:FRACT(3,5)=8.28
2130 FRACT(1,6)=.3:FRACT(2,6)=.25:FRACT(3,6)=1.08
2140 FRACT(1,7)=.25:FRACT(2,7)=.149:FRACT(3,7)=5.24
2150 FRACT(1,8)=.149:FRACT(2,8)=.074:FRACT(3,8)=3.21
2160 FRACT(1,9)=.074:FRACT(2,9)=.074:FRACT(3,9)=68.49
2170 FRACT=8:NS=9
2180 RETURN
2190 STOP
2200 REM SUBROUTINE ***** KA FIT ********
2210 DIM KW(21,2):DIM KX(21,2):DIM KY(21,2):DIM KZ(21,2)
2220 KW(1,1)=.1
2230 KW(2,1)=1:KW(2,2)=.259
2240 KW(3,1)=2:KW(3,2)=.27
2250 KW(4,1)=3:KW(4,2)=.281
2260 KW(5,1)=4:KW(5,2)=.291
2270 KW(6,1)=5:KW(6,2)=.31
2280 KW(7,1)=6:KW(7,2)=.327
2290 KW(8,1)=7:KW(8,2)=.335
2300 KW(9,1)=8:KW(9,2)=.346
2310 KW(10,1)=9:KW(10,2)=.354
2320 KW(11,1)=10:KW(11,2)=.362
2330 KW(12,1)=15:KW(12,2)=.365
2340 KW(13,1)=20:KW(13,2)=.354
2350 KW(14,1)=30:KW(14,2)=.32
2360 KW(15,1)=40:KW(15,2)=.3
2370 KW(16,1)=50:KW(16,2)=.283
2380 KW(17,1)=60:KW(17,2)=.272
2390 KW(18,1)=70:KW(18,2)=.267
2400 KW(19,1)=80:KW(19,2)=.261
2410 KW(20,1)=90:KW(20,2)=.256
2420 KW(21,1)=100:KW(21,2)=.253
2430 REM
2440 KX(1,1)=.2
2450 KX(2,1)=1:KX(2,2)=.414
2460 KX(3,1)=2:KX(3,2)=.424
2470 KX(4,1)=3:KX(4,2)=.432
2480 KX(5,1)=4:KX(5,2)=.443
2490 KX(6,1)=5:KX(6,2)=.457
2500 KX(7,1)=6:KX(7,2)=.471
2510 KX(8,1)=7:KX(8,2)=.476
2520 KX(9,1)=8:KX(9,2)=.486
2530 KX(10,1)=9:KX(10,2)=.495
2540  KX(11,1) = 10: KX(11,2) = .5
2550  KX(12,1) = 15: KX(12,2) = .5
2560  KX(13,1) = 20: KX(13,2) = .486
2570  KX(14,1) = 30: KX(14,2) = .462
2580  KX(15,1) = 40: KX(15,2) = .443
2590  KX(16,1) = 50: KX(16,2) = .433
2600  KX(17,1) = 60: KX(17,2) = .429
2610  KX(18,1) = 70: KX(18,2) = .419
2620  KX(19,1) = 80: KX(19,2) = .414
2630  KX(20,1) = 90: KX(20,2) = .412
2640  KX(21,1) = 100: KX(21,2) = .407
2650  REM
2660  KY(1,1) = .3
2670  KY(2,1) = 1: KY(2,2) = .567
2680  KY(3,1) = 2: KY(3,2) = .576
2690  KY(4,1) = 3: KY(4,2) = .582
2700  KY(5,1) = 4: KY(5,2) = .588
2710  KY(6,1) = 5: KY(6,2) = .6
2720  KY(7,1) = 6: KY(7,2) = .607
2730  KY(8,1) = 7: KY(8,2) = .62
2740  KY(9,1) = 8: KY(9,2) = .629
2750  KY(10,1) = 9: KY(10,2) = .633
2760  KY(11,1) = 10: KY(11,2) = .64
2770  KY(12,1) = 15: KY(12,2) = .64
2780  KY(13,1) = 20: KY(13,2) = .627
2790  KY(14,1) = 30: KY(14,2) = .6
2800  KY(15,1) = 40: KY(15,2) = .582
2810  KY(16,1) = 50: KY(16,2) = .577
2820  KY(17,1) = 60: KY(17,2) = .568
2830  KY(18,1) = 70: KY(18,2) = .564
2840  KY(19,1) = 80: KY(19,2) = .564
2850  KY(20,1) = 90: KY(20,2) = .555
2860  KY(21,1) = 100: KY(21,2) = .555
2870  REM
2880  KZ(1,1) = .4
2890  KZ(2,1) = 1: KZ(2,2) = .725
2900  KZ(3,1) = 2: KZ(3,2) = .725
2910  KZ(4,1) = 3: KZ(4,2) = .725
2920  KZ(5,1) = 4: KZ(5,2) = .731
2930  KZ(6,1) = 5: KZ(6,2) = .738
2940  KZ(8,1) = 7: KZ(8,2) = .75
2950  KZ(9,1) = 8: KZ(9,2) = .759
2960  KZ(10,1) = 9: KZ(10,2) = .763
2970  KZ(11,1) = 10: KZ(11,2) = .769
2980  KZ(12,1) = 15: KZ(12,2) = .769
2990  KZ(13,1) = 20: KZ(13,2) = .753
3000  KZ(14,1) = 30: KZ(14,2) = .729
3010  KZ(15,1) = 40: KZ(15,2) = .713
3020  KZ(16,1) = 50: KZ(16,2) = .695
3030  KZ(17,1) = 60: KZ(17,2) = .689
3040  KZ(18,1) = 70: KZ(18,2) = .689
3050  KZ(19,1) = 80: KZ(19,2) = .683
3060  KZ(20,1) = 90: KZ(20,2) = .678
3070  KZ(21,1) = 100: KZ(21,2) = .678
3080  REM
3090 IF K => .5 THEN KA=1:GOTO 3410
3100 IF ND<=10 THEN I=INT(ND)+1
3110 IF ND>10 AND ND<=15 THEN I=12
3120 IF ND>15 AND ND<=20 THEN I=13
3130 IF ND>21 AND ND<=30 THEN I=14
3140 IF ND>31 AND ND<=40 THEN I=15
3150 IF ND>41 AND ND<=50 THEN I=16
3160 IF ND>51 AND ND<=60 THEN I=17
3170 IF ND>61 AND ND<=70 THEN I=18
3180 IF ND>71 AND ND<=80 THEN I=19
3190 IF ND>81 AND ND<=90 THEN I=20
3200 IF ND>91 THEN I=21
3210 IF ND>100 THEN ND=100
3220 IF ND<0 THEN PRINT"ERROR ND"
3230 IF K<=KW(1,1) GOTO 3270
3240 IF K<=KX(1,1) GOTO 3300
3250 IF K<=KY(1,1) GOTO 3340
3260 IF K<=KZ(1,1) GOTO 3380
3270 KA1=((ND-KW(I-1,1))/(KW(I,1)-KW(I-1,1))*(KW(I,2)-KW(I-1,2)))+KW(I-1,2)
3280 KA2=(K/.1)*(KA1-.2)+.2
3290 GOTO 3410
3300 KA2=((ND-KX(I-1,1))/(KX(I,1)-KX(I-1,1))*(KX(I,2)-KX(I-1,2)))+KX(I-1,2)
3310 KA1=((ND-KW(I-1,1))/(KW(I,1)-KW(I-1,1))*(KW(I,2)-KW(I-1,2)))+KW(I-1,2)
3320 KA=((K-KW(I-1,1))/(KX(I,1)-KW(I-1,1))*(KA2-KA1))+KA1
3330 GOTO 3410
3340 KA2=((ND-KY(I-1,1))/(KY(I,1)-KY(I-1,1))*(KY(I,2)-KY(I-1,2)))+KY(I-1,2)
3350 KA1=((ND-KX(I-1,1))/(KX(I,1)-KX(I-1,1))*(KX(I,2)-KX(I-1,2)))+KX(I-1,2)
3360 KA=((K-KX(I-1,1))/(KY(I,1)-KX(I-1,1))*(KA2-KA1))+KA1
3370 GOTO 3410
3380 KA2=((ND-KZ(I-1,1))/(KZ(I,1)-KZ(I-1,1))*(KZ(I,2)-KZ(I-1,2)))+KZ(I-1,2)
3390 KA1=((ND-KY(I-1,1))/(KY(I,1)-KY(I-1,1))*(KY(I,2)-KY(I-1,2)))+KY(I-1,2)
3400 KA=((K-KY(I-1,1))/(KZ(I,1)-KY(I-1,1))*(KA2-KA1))+KA1
3410 PRINT TAB(10);"KA = ";KA
3420 RETURN
3430 REM SUBROUTINE ***** FL FIT ********
3440 DIM W(22,2):DIM X(22,2):DIM Y(22,2):DIM Z(22,2)
3570 \( W(13,1) = 1.1 : W(13,2) = 1.257 \)
3580 \( W(14,1) = 1.2 : W(14,2) = 1.27 \)
3590 \( W(15,1) = 1.3 : W(15,2) = 1.28 \)
3600 \( W(16,1) = 1.4 : W(16,2) = 1.287 \)
3610 \( W(17,1) = 1.5 : W(17,2) = 1.293 \)
3620 \( W(18,1) = 1.6 : W(18,2) = 1.3 \)
3630 \( W(19,1) = 1.7 : W(19,2) = 1.303 \)
3640 \( W(20,1) = 1.8 : W(20,2) = 1.307 \)
3650 \( W(21,1) = 1.9 : W(21,2) = 1.313 \)
3660 \( W(22,1) = 2 : W(22,2) = 1.317 \)
3670 \( X(1,1) = .05 \)
3680 \( X(2,1) = 0 : X(2,2) = 0 \)
3690 \( X(3,1) = 0.1 : X(3,2) = .907 \)
3700 \( X(4,1) = .2 : X(4,2) = 1.073 \)
3710 \( X(5,1) = .3 : X(5,2) = 1.173 \)
3720 \( X(6,1) = .4 : X(6,2) = 1.253 \)
3730 \( X(7,1) = .5 : X(7,2) = 1.307 \)
3740 \( X(8,1) = .6 : X(8,2) = 1.343 \)
3750 \( X(9,1) = .7 : X(9,2) = 1.367 \)
3760 \( X(10,1) = .8 : X(10,2) = 1.38 \)
3770 \( X(11,1) = .9 : X(11,2) = 1.39 \)
3780 \( X(12,1) = 1 : X(12,2) = 1.393 \)
3790 \( X(13,1) = 1.1 : X(13,2) = 1.397 \)
3800 \( X(14,1) = 1.2 : X(14,2) = 1.39 \)
3810 \( X(15,1) = 1.3 : X(15,2) = 1.386 \)
3820 \( X(16,1) = 1.4 : X(16,2) = 1.377 \)
3830 \( X(17,1) = 1.5 : X(17,2) = 1.367 \)
3840 \( X(18,1) = 1.6 : X(18,2) = 1.36 \)
3850 \( X(19,1) = 1.7 : X(19,2) = 1.353 \)
3860 \( X(20,1) = 1.8 : X(20,2) = 1.347 \)
3870 \( X(21,1) = 1.9 : X(21,2) = 1.343 \)
3880 \( X(22,1) = 2 : X(22,2) = 1.337 \)
3890 \( Y(1,1) = .1 \)
3900 \( Y(2,1) = 0 : Y(2,2) = 0 \)
3910 \( Y(3,1) = .1 : Y(3,2) = .907 \)
3920 \( Y(4,1) = .2 : Y(4,2) = 1.203 \)
3930 \( Y(5,1) = .3 : Y(5,2) = 1.32 \)
3940 \( Y(6,1) = .4 : Y(6,2) = 1.39 \)
3950 \( Y(7,1) = .5 : Y(7,2) = 1.427 \)
3960 \( Y(8,1) = .6 : Y(8,2) = 1.448 \)
3970 \( Y(9,1) = .7 : Y(9,2) = 1.459 \)
3980 \( Y(10,1) = .8 : Y(10,2) = 1.462 \)
3990 \( Y(11,1) = .9 : Y(11,2) = 1.455 \)
4000 \( Y(12,1) = 1 : Y(12,2) = 1.444 \)
4010 \( Y(13,1) = 1.1 : Y(13,2) = 1.428 \)
4020 \( Y(14,1) = 1.2 : Y(14,2) = 1.407 \)
4030 \( Y(15,1) = 1.3 : Y(15,2) = 1.39 \)
4040 \( Y(16,1) = 1.4 : Y(16,2) = 1.377 \)
4050 \( Y(17,1) = 1.5 : Y(17,2) = 1.367 \)
4060 \( Y(18,1) = 1.6 : Y(18,2) = 1.36 \)
4070 \( Y(19,1) = 1.7 : Y(19,2) = 1.353 \)
4080 \( Y(20,1) = 1.8 : Y(20,2) = 1.347 \)
4090 \( Y(21,1) = 1.9 : Y(21,2) = 1.343 \)
4100 \( Y(22,1) = 2 : Y(22,2) = 1.337 \)
4110 \( Z(1,1) = .15 \)
1120 Z(2,1)=0! Z(2,2)=0!
1130 Z(3,1)=.1; Z(3,2)=1!
1140 Z(4,1)=.2; Z(4,2)=1.28
1150 Z(5,1)=.3; Z(5,2)=1.39
1160 Z(6,1)=.4; Z(6,2)=1.452
1170 Z(7,1)=.5; Z(7,2)=1.483
1180 Z(8,1)=.6; Z(8,2)=1.5
1190 Z(9,1)=.7; Z(9,2)=1.507
1200 Z(10,1)=.8; Z(10,2)=1.5
1210 Z(11,1)=.9; Z(11,2)=1.483
1220 Z(12,1)=1; Z(12,2)=1.455
1230 Z(13,1)=1.1; Z(13,2)=1.428
1240 Z(14,1)=1.2; Z(14,2)=1.407
1250 Z(15,1)=1.3; Z(15,2)=1.39
1260 Z(16,1)=1.4; Z(16,2)=1.377
1270 Z(17,1)=1.5; Z(17,2)=1.367
1280 Z(18,1)=1.6; Z(18,2)=1.36
1290 Z(19,1)=1.7; Z(19,2)=1.353
1300 Z(20,1)=1.8; Z(20,2)=1.347
1310 Z(21,1)=1.9; Z(21,2)=1.343
1320 Z(22,1)=2; Z(22,2)=1.337
1330 IF A7>.002 THEN FL=1.34: GOTO 4690
1340 IF CV< W(1,1) GOTO 4430
1350 IF CV=W(1,1) GOTO 4430
1360 IF CV< X(1,1) GOTO 4460
1370 IF CV=X(1,1) GOTO 4510
1380 IF CV< Y(1,1) GOTO 4540
1390 IF CV=Y(1,1) GOTO 4590
1400 IF CV< Z(1,1) GOTO 4620
1410 IF CV=Z(1,1) GOTO 4670
1420 IF CV> Z(1,1) THEN PRINT"ERROR FL": GOTO 4690
1430 I=INT(A7*10000)+2
1440 FL=((A7*10000)-(I-3))*(W(I,2)-W(I-1,2))+W(I-1,2)
1450 GOTO 4690
1460 I=INT(A7*10000)+2
1470 FL1=((A7*10000)-(I-3))*(W(I,2)-W(I-1,2))+W(I-1,2)
1480 FL2=((A7*10000)-(I-3))*(X(I,2)-X(I-1,2))+X(I-1,2)
1490 FL=(((CV-W(1,1))/(X(1,1)-W(1,1)))*(FL2-FL1))+FL1
1500 GOTO 4690
1510 I=INT(A7*10000)+2
1520 FL=((A7*10000)-(I-3))*(X(I,2)-X(I-1,2))+X(I-1,2)
1530 GOTO 4690
1540 I=INT(A7*10000)+2
1550 FL1=((A7*10000)-(I-3))*(X(I,2)-X(I-1,2))+X(I-1,2)
1560 FL2=((A7*10000)-(I-3))*(Y(I,2)-Y(I-1,2))+Y(I-1,2)
1570 FL=(((CV-X(1,1))/(Y(1,1)-X(1,1)))*(FL2-FL1))+FL1
1580 GOTO 4690
1590 I=INT(A7*10000)+2
1600 FL=((A7*10000)-(I-3))*(Y(I,2)-Y(I-1,2))+Y(I-1,2)
1610 GOTO 4690
1620 I=INT(A7*10000)+2
1630 FL1=((A7*10000)-(I-3))*(Y(I,2)-Y(I-1,2))+Y(I-1,2)
1640 FL2=((A7*10000)-(I-3))*(Z(I,2)-Z(I-1,2))+Z(I-1,2)
1650 FL=(((CV-Y(1,1))/(Y(1,1)-X(1,1)))*(FL2-FL1))+FL1
1660 GOTO 4690
I = INT(A7*10000) + 2
FL = (((A7*10000) - (I-3)) * (Z(I,2) - Z(I-1,2))) + Z(I-1,2)
PRINT TAB(10); "FL = "; FL
RETURN

<table>
<thead>
<tr>
<th>Particle size (µm)</th>
<th>Weight (%)</th>
<th>Charge yields (%)</th>
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<tbody>
<tr>
<td>0.075</td>
<td>2.96</td>
<td>3.07</td>
</tr>
<tr>
<td>0.120</td>
<td>2.96</td>
<td>3.14</td>
</tr>
<tr>
<td>0.180</td>
<td>2.93</td>
<td>3.13</td>
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<tr>
<td>0.250</td>
<td>2.95</td>
<td>3.14</td>
</tr>
<tr>
<td>0.500</td>
<td>2.94</td>
<td>3.14</td>
</tr>
<tr>
<td>0.750</td>
<td>2.95</td>
<td>3.14</td>
</tr>
<tr>
<td>1.000</td>
<td>2.96</td>
<td>3.14</td>
</tr>
<tr>
<td>1.250</td>
<td>2.94</td>
<td>3.14</td>
</tr>
<tr>
<td>1.500</td>
<td>2.95</td>
<td>3.14</td>
</tr>
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</table>

Table 3 - Data from 29% spin 1.0% KCl
<table>
<thead>
<tr>
<th>Particle size (mm)</th>
<th>Weight (%)</th>
<th>Coarse solids (%)</th>
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<tbody>
<tr>
<td>- 12.700 + 4.760</td>
<td>1.00</td>
<td>3.17</td>
</tr>
<tr>
<td>- 4.760 + 2.000</td>
<td>2.03</td>
<td>5.44</td>
</tr>
<tr>
<td>- 2.000 + 0.841</td>
<td>4.75</td>
<td>15.07</td>
</tr>
<tr>
<td>- 0.841 + 0.420</td>
<td>5.92</td>
<td>18.79</td>
</tr>
<tr>
<td>- 0.420 + 0.300</td>
<td>8.28</td>
<td>26.28</td>
</tr>
<tr>
<td>- 0.300 + 0.250</td>
<td>1.08</td>
<td>3.43</td>
</tr>
<tr>
<td>- 0.250 + 0.149</td>
<td>5.24</td>
<td>16.63</td>
</tr>
<tr>
<td>- 0.149 + 0.074</td>
<td>3.21</td>
<td>10.19</td>
</tr>
<tr>
<td>- 0.074</td>
<td>68.49</td>
<td></td>
</tr>
</tbody>
</table>

Table 8 - Data from the Kin Fatt Mine
Enter the Pipe Diameter in meters? 0.305
Enter the Relative Density of the Material? 2.55
Enter Volumetric Concentration........(20%)? 4.2
Maximum particle size falling in the laminar zone (Stokes Law) = 1057639
Enter Data? Y
Enter Number of Size Fractions? 9
Enter Maximum Size in Fraction 1 in mm? 12.7
Enter Minimum Size in Fraction 1 in mm? 4.75
Enter % Weight of Fraction 1 ? 1.00
Enter Maximum Size in Fraction 2 in mm? 4.76
Enter Minimum Size in Fraction 2 in mm? 2.00
Enter % Weight of Fraction 2 ? 2.03
Enter Maximum Size in Fraction 3 in mm? 2.00
Enter Minimum Size in Fraction 3 in mm? 0.841
Enter % Weight of Fraction 3 ? 4.74
Enter Maximum Size in Fraction 4 in mm? 0.841
Enter Minimum Size in Fraction 4 in mm? 0.420
Enter % Weight of Fraction 4 ? 5.92
Enter Maximum Size in Fraction 5 in mm? 0.420
Enter Minimum Size in Fraction 5 in mm? 0.300
Enter % Weight of Fraction 5 ? 8.28

Figure 14 - Specimen of the computer programme FINE
Enter Maximum Size in Fraction 6 in mm? 0.300
Enter Minimum Size in Fraction 6 in mm? 0.250
Enter % Weight of Fraction 6 ? 1.08

Enter Maximum Size in Fraction 7 in mm? 0.250
Enter Minimum Size in Fraction 7 in mm? 0.149
Enter % Weight of Fraction 7 ? 5.24

Enter Maximum Size in Fraction 8 in mm? 0.149
Enter Minimum Size in Fraction 8 in mm? 0.074
Enter % Weight of Fraction 8 ? 3.21

Enter Maximum Size in Fraction 9 in mm? 0.074
Enter Minimum Size in Fraction 9 in mm? 0.074
Enter % Weight of Fraction 9 ? 68.49

A7 3.580648E-04  C7 9.758167E-04
CD = 3.763644  VS = .1070823

Which Group of Mineral Types in the Following Group
Most Nearly Describes the Particles being Investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plumago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.

Enter Group Selected? 1

.26

KA = .5055729
VSI = 5.413791E-02
CDI = 14.72451
FL = 1.186351
Critical Velocity Calculations

1. Bain and Bonnington
2. Durand
3. Makharadzye

Enter Selection? 1

Critical Velocity according to Bain and Bonnington for Spheres = 1.862722 m/s

Critical Velocity according to Bain and Bonnington for Irregular Particles = 1.324464 m/s

Hydraulic Gradient according to Durand and Condolios for Spheres = 0.2657906 kN/m²/m

Hydraulic Gradient according to Durand and Condolios for Irregular Particles = 0.1515359 kN/m²/m

Hydraulic Gradient according to Zandi and Gavatos for Spheres = 0.1076816 kN/m²/m

Hydraulic Gradient according to Zandi and Gavatos for Irregular Particles = 0.1033336 kN/m²/m

Another Velocity? N
APPENDIX III

Results from the Mackay School of Mines Data
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 5
Enter Relative Density? 2.2
Enter Pipe Diameter in mm.? 76.2
Enter Volumetric Concentration......i.e. (10%) =? 5

Velocity at which sliding bed commences according to New Theory = 1.2816 m/s

Enter Number of Velocities ? 5

Velocity 1 =? 3
Velocity 2 =? 3.5
Velocity 3 =? 4
Velocity 4 =? 4.5
Velocity 5 =? 5

Correct any Velocities............(Y/N)

Actual Data.......................(Y/N)

For Velocity 3 =? .1420
For Velocity 3.5 =? .1771
For Velocity 4 =? .2193
For Velocity 4.5 =? .2681
For Velocity 5 =? .3233

Correct any Data............(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plumago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.
Group 8......Calculated.

Enter Group Selected? 1
CALCULATED RESULTS FOR A CONCENTRATION OF 5.0 %

Pipe Diameter.......................... = 76.20 mm
Shape Group.......................... = 1.000
Weighted Mean Particle Diameter...... = 5.000 mm
Relative Density of Solids............... = 2.200
Delivered Volume Concentration of Solids = 0.050
Delivered Weight Concentration of Solids = 0.104
Terminal Settling Velocity of Spherical Particles of 5.000 mm Diameter = 0.422 m/s
Drag Coefficient of Spherical Particles of 5.000 mm Diameter = 0.440
Terminal Settling Velocity of NON-Spherical 5.000 m/s Particles of Shape Factor 0.26 = 0.209 m/s
Hindered Settling Velocity of Spherical Particles of 5.000 mm Diameter and Volumetric Concentration 0.050 = 0.373 m/s
Hindered Settling Velocity of NON-Spherical 5.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.050 = 0.185 m/s
Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.12 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 3.052 mm
Limiting Mixture Velocity for Deposition (DURAND) = 1.795 m/s
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.644 m/s
using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.158 m/s
using the drag coefficient of irregular particles
Critical Velocity (Bain and Bonnington) = 1.484 m/s
using the drag coefficient of spheres
Critical Velocity (Bain and Bonnington) = 1.045 m/s
using the drag coefficient of irregular particles
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 7.179 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 3.559 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.7

Friction Factor Adjustment (Y/N)
4.767265E-03
4.713845E-03
4.672325E-03
4.639067E-03
4.611861E-03

MENU
1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------- UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------- UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

TABLE OF RESULTS

\[
\begin{array}{cccccccc}
V & V_f & C_v & C_a & J_w & 1 & 2 & 3 & 4 & 5 & 6 \\
3.00 & 3.34 & 5.00 & 12.12 & 0.1148 & 0.1493 & 0.1432 & 0.1247 & 0.1333 & 0.1255 & 0.1365 \\
3.50 & 3.84 & 5.00 & 11.08 & 0.1545 & 0.1851 & 0.1786 & 0.1629 & 0.1769 & 0.1625 & 0.1729 \\
4.00 & 4.34 & 5.00 & 10.36 & 0.2001 & 0.2277 & 0.2210 & 0.2074 & 0.2238 & 0.2062 & 0.2160 \\
4.50 & 4.84 & 5.00 & 9.83 & 0.2514 & 0.2767 & 0.2698 & 0.2579 & 0.2704 & 0.2563 & 0.2655 \\
5.00 & 5.34 & 5.00 & 9.41 & 0.3086 & 0.3319 & 0.3251 & 0.3143 & 0.3241 & 0.3126 & 0.3211 \\
\end{array}
\]

7 8 9 10 11 JS JF JSI JFI ACTUAL
0.1526 0.2034 0.1587 0.2002 0.1427 0.0326 0.1676 0.0000 0.1427 0.1420
0.1919 0.2296 0.1918 0.2335 0.1858 0.0248 0.2087 0.0000 0.1858 0.1771
0.2371 0.2652 0.2324 0.2741 0.2352 0.0186 0.2556 0.0000 0.2352 0.2193
0.2882 0.3089 0.2799 0.3208 0.2906 0.0132 0.3077 0.0000 0.2906 0.2681
0.3451 0.3600 0.3341 0.3731 0.3521 0.0084 0.3647 0.0000 0.3521 0.3233

Do you wish to display your results graphically...(Y/N)?
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 5
Enter Relative Density? 2.2
Enter Pipe Diameter in mm.? 76.2
Enter Volumetric Concentration.....i.e. (10%) =? 10
Velocity at which sliding bed commences according to New Theory = 1.4722 m/s
Enter Number of Velocities ? 5

Velocity 1 =? 3
Velocity 2 =? 3.5
Velocity 3 =? 4
Velocity 4 =? 4.5
Velocity 5 =? 5
Correct any Velocities............(Y/N)

Actual Data......................(Y/N)
For Velocity 3 =? .1692
For Velocity 3.5 =? .1996
For Velocity 4 =? .2385
For Velocity 4.5 =? .2847
For Velocity 5 =? .3380
Correct any Data............(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plumago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.
Group 8......Calculated.

Enter Group Selected? 1
CALCULATED RESULTS FOR A CONCENTRATION OF 10.0 %

Pipe Diameter.................................= 76.20 mm
Shape Group....................................= 1.000
Weighted Mean Particle Diameter..........= 5.000 mm
Relative Density of Solids..................= 2.200
Delivered Volume Concentration of Solids.= 0.100
Delivered Weight Concentration of Solids..= 0.196
Terminal Settling Velocity of Spherical Particles of 5.000 mm Diameter = 0.422 m/s
Drag Coefficient of Spherical Particles of 5.000 mm Diameter = 0.440
Terminal Settling Velocity of NON-Spherical 5.000 m/s Particles of Shape Factor 0.26 = 0.209 m/s
Hindered Settling Velocity of Spherical Particles of 5.000 mm Diameter and Volumetric Concentration 0.100 = 0.328 m/s
Hindered Settling Velocity of NON-Spherical 5.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.100 = 0.163 m/s
Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.12 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 3.052 mm
Limiting Mixture Velocity for Deposition (DURAND) = 1.795 m/s
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 2.325 m/s using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.637 m/s using the drag coefficient of irregular particles
Critical Velocity (Bain and Bonnington) = 1.865 m/s using the drag coefficient of spheres
Critical Velocity (Bain and Bonnington) = 1.313 m/s using the drag coefficient of irregular particles
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 7.179 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 3.559 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.7

Friction Factor Adjustment (Y/N)
4.767265E-03
4.713845E-03
4.672325E-03
4.639067E-03
4.611861E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

TABLE OF RESULTS

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<tr>
<th>V</th>
<th>Vf</th>
<th>Cv</th>
<th>Ca</th>
<th>Jw</th>
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<th>3</th>
<th>4</th>
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<td>3.33</td>
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Do you wish to display your results graphically...(Y/N)?
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 5
Enter Relative Density? 2.2
Enter Pipe Diameter in mm.? 76.2
Enter Volumetric Concentration.....i.e. (10%) =? 15
Velocity at which sliding bed commences according to New Theory = 1.5966 m/s
Enter Number of Velocities ? 5

Velocity 1 =? 3
Velocity 2 =? 3.5
Velocity 3 =? 4
Velocity 4 =? 4.5
Velocity 5 =? 5

Correct any Velocities...........(Y/N)
Actual Data.....................(Y/N)
For Velocity 3 =? .1964
For Velocity 3.5 =? .2222
For Velocity 4 =? .2577
For Velocity 4.5 =? .3014
For Velocity 5 =? .3527
Correct any Data...........(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plamago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.
Group 8......Calculated.

Enter Group Selected? 1
CALCULATED RESULTS FOR A CONCENTRATION OF 15.0 %

Pipe Diameter..............................= 76.20 mm
Shape Group.................................= 1.000
Weighted Mean Particle Diameter.............= 5.000 mm
Relative Density of Solids...................= 2.200
Delivered Volume Concentration of Solids.....= 0.150
Delivered Weight Concentration of Solids.....= 0.280

Terminal Settling Velocity of Spherical Particles
of 5.000 mm Diameter = 0.422 m/s

Drag Coefficient of Spherical Particles of 5.000 mm
Diameter = 0.440

Terminal Settling Velocity of NON-Spherical 5.000 m/s
Particles of Shape Factor 0.26 = 0.209 m/s

Hindered Settling Velocity of Spherical Particles
of 5.000 mm Diameter and Volumetric Concentration 0.150
= 0.286 m/s

Hindered Settling Velocity of NON-Spherical 5.000 mm
Particles of Shape Factor 0.26 and Volumetric
Concentration 0.150 = 0.142 m/s

Maximum Particle Size Falling in Laminar Zone according
to STOKES Law = 0.12 mm

Minimum Particle Falling in Turbulent Zone according
to NEWTONS Law = 3.052 mm

Limiting Mixture Velocity for Deposition (DURAND) = 1.795 m/s

Transition Velocity to Heterogeneous Flow
(ZANDI and GOVATOS) = 2.848 m/s
using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow
(ZANDI and GOVATOS) = 2.005 m/s
using the drag coefficient of irregular particles

Critical Velocity (Bain and Bonnington) = 2.132m/s
using the drag coefficient of spheres

Critical Velocity (Bain and Bonnington) = 1.502m/s
using the drag coefficient of irregular particles

Transition Velocity to Heterogeneous Flow (NEWITT et al) =
7.179 m/s, Using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow (NEWITT et al) =
3.559 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.7

Friction Factor Adjustment (Y/N)
4.767265E-03
4.713845E-03
4.672325E-03
4.639067E-03
4.611861E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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Do you wish to display your results graphically...(Y/N)?
Hydraulic Gradient (mH₂O/m)

Velocity (m/s)

1.
APPENDIX IV

Results from the TRRL Data
Enter Number of Size Fractions? 1

Enter Weighted Mean Particle Size in mm.? 5

Enter Relative Density? 2.7

Enter Pipe Diameter in mm.? 207

Enter Volumetric Concentration......i.e. (10%) =? 6.5

Velocity at which sliding bed commences according to New Theory = 2.6497 m/s

Enter Number of Velocities ? 3

Velocity 1 =? 2.13

Velocity 2 =? 4.0

Velocity 3 =? 5.0

Correct any Velocities...........(Y/N)

Actual Data.....................(Y/N)

For Velocity 2.13 =? .137

For Velocity 4 =? .153

For Velocity 5 =? .180

Correct any Data..............(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plumago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.
Group 8......Calculated.

Enter Group Selected? 4
Pipe Diameter.................................= 207.00 mm
Shape Group...................................= 4.000
Weighted Mean Particle Diameter...........= 5.000 mm
Relative Density of Solids..................= 2.700
Delivered Volume Concentration of Solids...= 0.065
Delivered Weight Concentration of Solids...= 0.158

Terminal Settling Velocity of Spherical Particles of 5.000 mm Diameter = 0.503 m/s
Drag Coefficient of Spherical Particles of 5.000 mm Diameter = 0.440

Terminal Settling Velocity of NON-Spherical 5.000 m/s Particles of Shape Factor 0.16 = 0.174 m/s

Hindered Settling Velocity of Spherical Particles of 5.000 mm Diameter and Volumetric Concentration 0.065 = 0.428 m/s
Hindered Settling Velocity of NON-Spherical 5.000 mm Particles of Shape Factor 0.16 and Volumetric Concentration 0.065 = 0.148 m/s

Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.718 mm

Limiting Mixture Velocity for Deposition (DURAND) = 3.520 m/s

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 3.678 m/s using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 2.162 m/s using the drag coefficient of irregular particles

Critical Velocity (Bain and Bonnington) = 3.174 m/s using the drag coefficient of spheres

Critical Velocity (Bain and Bonnington) = 1.866 m/s using the drag coefficient of irregular particles

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 8.544 m/s, Using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 2.951 m/s, Using the drag coefficient of irregular particles
Friction Factor Adjustment (Y/N)
3.83225E-03
3.75838E-03
3.711104E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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Do you wish to display your results graphically...(Y/N)?
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 10
Enter Relative Density? 2.7
Enter Pipe Diameter in mm.? 207
Enter Volumetric Concentration......i.e. (10%) =? 7.0
Velocity at which sliding bed commences according to New Theory = 2.6892 m/s
Enter Number of Velocities ? 3

Velocity 1 =? 3
Velocity 2 =? 4
Velocity 3 =? 5
Correct any Velocities.........(Y/N)

Actual Data....................(Y/N)

For Velocity 3 =? .140
For Velocity 4 =? .154
For Velocity 5 =? .180
Correct any Data.......(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1.......Sand, Gravel, Beach Flints.
Group 2.......Sillimanite, Bituminous Coal.
Group 3.......Blast Furnace Slag.
Group 4.......Limestone, Talc, Plumago, Granite.
Group 5.......Gypsum,
Group 6.......Graphite.
Group 7.......Mica.
Group 8.......Calculated.

Enter Group Selected? 4
CALCULATED RESULTS FOR A CONCENTRATION OF 7.0 %

Pipe Diameter.................................= 207.00 mm
Shape Group....................................= 4.000
Weighted Mean Particle Diameter................= 10.000 mm
Relative Density of Solids.....................= 2.700
Delivered Volume Concentration of Solids......= 0.070
Delivered Weight Concentration of Solids.......= 0.169
Terminal Settling Velocity of Spherical Particles of 10.000 mm Diameter = 0.711 m/s
Drag Coefficient of Spherical Particles of 10.000 mm Diameter = 0.440
Terminal Settling Velocity of NON-Spherical 10.000 m/s Particles of Shape Factor 0.16 = 0.246 m/s
Hindered Settling Velocity of Spherical Particles of 10.000 mm Diameter and Volumetric Concentration 0.070 = 0.597 m/s
Hindered Settling Velocity of NON-Spherical 10.000 mm Particles of Shape Factor 0.16 and Volumetric Concentration 0.070 = 0.206 m/s
Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.718 mm
Limiting Mixture Velocity for Deposition (DURAND) = 3.520 m/s
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 3.817 m/s using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 2.243 m/s using the drag coefficient of irregular particles
Critical Velocity (Bain and Bonnington) = 3.253 m/s using the drag coefficient of spheres
Critical Velocity (Bain and Bonnington) = 1.912 m/s using the drag coefficient of irregular particles
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 12.083 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 4.174 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.7

Friction Factor Adjustment (Y/N)
3.8322E-03
3.7583E-03
3.7111E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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Do you wish to display your results graphically...(Y/N)?
Hydraulic Gradient (mH2O/m)

Velocity (m/s)

Actual Data.

1.

11.

Jw.
Enter the Bulking Factor of the Solids? 1.7

Friction Factor Adjustment (Y/N)
3.83225E-03
3.75838E-03
3.71104E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
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10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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Do you wish to display your results graphically...(Y/N)?
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 20
Enter Relative Density? 2.7
Enter Pipe Diameter in mm.? 207
Enter Volumetric Concentration......i.e. (10%) =? 5.6
Velocity at which sliding bed commences according to New Theory = 2.5718 m/s
Enter Number of Velocities ? 3

Velocity 1 =? 3
Velocity 2 =? 4
Velocity 3 =? 5
Correct any Velocities..........(Y/N)

Actual Data..................(Y/N)
For Velocity 3 =? .133
For Velocity 4 =? .141
For Velocity 5 =? .167
Correct any Data.......(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plumago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.
Group 8......Calculated.

Enter Group Selected? 4
Pipe Diameter .................. = 207.00 mm
Shape Group .................. = 4.000
Weighted Mean Particle Diameter ........ = 20.000 mm
Relative Density of Solids ............ = 2.700
Delivered Volume Concentration of Solids .... = 0.056
Delivered Weight Concentration of Solids .... = 0.138
Terminal Settling Velocity of Spherical Particles of 20.000 mm Diameter = 1.005 m/s
Drag Coefficient of Spherical Particles of 20.000 mm Diameter = 0.440
Terminal Settling Velocity of NON-Spherical 20.000 m/s Particles of Shape Factor 0.16 = 0.347 m/s
Hindered Settling Velocity of Spherical Particles of 20.000 mm Diameter and Volumetric Concentration 0.056 = 0.875 m/s
Hindered Settling Velocity of NON-Spherical 20.000 mm Particles of Shape Factor 0.16 and Volumetric Concentration 0.056 = 0.302 m/s
Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.718 mm
Limiting Mixture Velocity for Deposition (DURAND) = 3.520 m/s
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 3.414 m/s using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 2.006 m/s using the drag coefficient of irregular particles
Critical Velocity (Bain and Bonnington) = 3.022 m/s using the drag coefficient of spheres
Critical Velocity (Bain and Bonnington) = 1.776 m/s using the drag coefficient of irregular particles
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 17.089 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 5.902 m/s, Using the drag coefficient of irregular particles
APPENDIX V

Results from the Camborne School of Mines Data
Enter Number of Size Fractions? 1

Enter Weighted Mean Particle Size in mm.? 5

Enter Relative Density? 2.7

Enter Pipe Diameter in mm.? 50.8

Enter Volumetric Concentration.....i.e. (10%) =? 7

Velocity at which sliding bed commences according to New Theory = 1.3322 m/s

Enter Number of Velocities ? 6

Velocity 1 =? 2.877
Velocity 2 =? 3.268
Velocity 3 =? 3.826
Velocity 4 =? 3.946
Velocity 5 =? 4.210
Velocity 6 =? 4.184

Correct any Velocities............(Y/N)

Actual Data....................(Y/N)

For Velocity 2.877 =? .2416
For Velocity 3.268 =? .2642
For Velocity 3.826 =? .3018
For Velocity 3.946 =? .3178
For Velocity 4.21 =? .3413
For Velocity 4.184 =? .3244

Correct any Data............(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1.....Sand, Gravel, Beach Flints.
Group 2.....Sillimanite, Bituminous Coal.
Group 3.....Blast Furnace Slag.
Group 4.....Limestone, Talc, Plumago, Granite.
Group 5.....Gypsum,
Group 6.....Graphite.
Group 7.....Mica.
Group 8.....Calculated.

Enter Group Selected? 1
CALCULATED RESULTS FOR A CONCENTRATION OF 7.0 %

Pipe Diameter......................................= 50.80 mm
Shape Group........................................= 1.000
Weighted Mean Particle Diameter..................= 5.000 mm
Relative Density of Solids........................= 2.700
Delivered Volume Concentration of Solids........= 0.070
Delivered Weight Concentration of Solids........= 0.169

Terminal Settling Velocity of Spherical Particles of 5.000 mm Diameter = 0.503 m/s

Drag Coefficient of Spherical Particles of 5.000 mm Diameter = 0.440

Terminal Settling Velocity of NON-Spherical 5.000 m/s Particles of Shape Factor 0.26 = 0.249 m/s

Hindered Settling Velocity of Spherical Particles of 5.000 mm Diameter and Volumetric Concentration 0.070 = 0.422 m/s

Hindered Settling Velocity of NON-Spherical 5.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.070 = 0.209 m/s

Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm

Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.718 mm

Limiting Mixture Velocity for Deposition (DURAND) = 1.744 m/s

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.891 m/s
using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.331 m/s
using the drag coefficient of irregular particles

Critical Velocity (Bain and Bonnington) = 1.612 m/s
using the drag coefficient of spheres

Critical Velocity (Bain and Bonnington) = 1.135 m/s
using the drag coefficient of irregular particles

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 8.544 m/s, Using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 4.236 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.5

Friction Factor Adjustment (Y/N)
5.263736E-03
5.212364E-03
5.155288E-03
5.14896E-03
5.123903E-03
5.125865E-03

MENU
1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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Do you wish to display your results graphically... (Y/N)?
Hydraulic Gradient (mH2O/m)

Velocity (m/s)

Actual Data
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 5
Enter Relative Density? 2.7
Enter Pipe Diameter in mm.? 50.8
Enter Volumetric Concentration......i.e. (10%) =? 10
Velocity at which sliding bed commences according to New Theory = 1.4307 m/s
Enter Number of Velocities ? 7

Velocity 1 =? 2.083
Velocity 2 =? 2.466
Velocity 3 =? 2.733
Velocity 4 =? 2.989
Velocity 5 =? 3.206
Velocity 6 =? 3.774
Velocity 7 =? 3.984
Correct any Velocities.........(Y/N)

Actual Data....................(Y/N)
For Velocity 2.083 =? .2343
For Velocity 2.466 =? .2267
For Velocity 2.733 =? .3199
For Velocity 2.989 =? .2686
For Velocity 3.206 =? .2462
For Velocity 3.774 =? .2776
For Velocity 3.984 =? .2958
Correct any Data............(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plumago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.
Group 8......Calculated.
CALCULATED RESULTS FOR A CONCENTRATION OF 10.0 %

Pipe Diameter .......................................... = 50.80 mm
Shape Group ............................................. = 1.000
Weighted Mean Particle Diameter ................. = 5.000 mm
Relative Density of Solids ......................... = 2.700
Delivered Volume Concentration of Solids ....... = 0.100
Delivered Weight Concentration of Solids ........ = 0.231

Terminal Settling Velocity of Spherical Particles of 5.000 mm Diameter = 0.503 m/s
Drag Coefficient of Spherical Particles of 5.000 mm Diameter = 0.440

Terminal Settling Velocity of NON-Spherical 5.000 m/s Particles of Shape Factor 0.26 = 0.249 m/s
Hindered Settling Velocity of Spherical Particles of 5.000 mm Diameter and Volumetric Concentration 0.100 = 0.390 m/s
Hindered Settling Velocity of NON-Spherical 5.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.100 = 0.194 m/s

Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.718 mm
Limiting Mixture Velocity for Deposition (DURAND) = 1.744 m/s

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 2.260 m/s using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.591 m/s using the drag coefficient of irregular particles
Critical Velocity (Bain and Bonnington) = 1.813 m/s using the drag coefficient of spheres
Critical Velocity (Bain and Bonnington) = 1.276 m/s using the drag coefficient of irregular particles

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 8.544 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 4.236 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.5

Friction Factor Adjustment (Y/N)
5.41727E-03
5.332646E-03
5.285841E-03
5.247826E-03
5.219778E-03
5.159972E-03
5.141722E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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Do you wish to display your results graphically...{(Y/N)?
Hydraulic Gradient (mll20/m)

Velocity (m/s)
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 5
Enter Relative Density? 2.7
Enter Pipe Diameter in mm.? 50.8
Enter Volumetric Concentration......i.e. (10%) =? 14
Velocity at which sliding bed commences according to New Theory = 1.5303 m/s
Enter Number of Velocities ? 5

Velocity 1 =? 2.488
Velocity 2 =? 2.783
Velocity 3 =? 2.889
Velocity 4 =? 3.266
Velocity 5 =? 3.682
Correct any Velocities............(Y/N)

Actual Data..........................(Y/N)
For Velocity 2.488 =? .2777
For Velocity 2.783 =? .2835
For Velocity 2.889 =? .2900
For Velocity 3.266 =? .3081
For Velocity 3.682 =? .3452
Correct any Data............(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plumago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.
Group 8......Calculated.

Enter Group Selected? 1
CALCULATED RESULTS FOR A CONCENTRATION OF 14.0 %

Pipe Diameter......................................= 50.80 mm
Shape Group........................................= 1.000
Weighted Mean Particle Diameter...................= 5.000 mm
Relative Density of Solids........................= 2.700
Delivered Volume Concentration of Solids........= 0.140
Delivered Weight Concentration of Solids........= 0.305

Terminal Settling Velocity of Spherical Particles of 5.000 mm Diameter = 0.503 m/s
Drag Coefficient of Spherical Particles of 5.000 mm Diameter = 0.440

Terminal Settling Velocity of NON-Spherical 5.000 m/s Particles of Shape Factor 0.26 = 0.249 m/s

Hindered Settling Velocity of Spherical Particles of 5.000 mm Diameter and Volumetric Concentration 0.140 = 0.350 m/s
Hindered Settling Velocity of NON-Spherical 5.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.140 = 0.174 m/s

Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.718 mm
Limiting Mixture Velocity for Deposition (DURAND) = 1.744 m/s

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 2.674 m/s using the drag coefficient of spheres

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.883 m/s using the drag coefficient of irregular particles

Critical Velocity (Rain and Bonnington) = 2.026 m/s using the drag coefficient of spheres
Critical Velocity (Rain and Bonnington) = 1.426 m/s using the drag coefficient of irregular particles

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 8.544 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 4.236 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.5

Friction Factor Adjustment (Y/N)
5.328465E-03
5.277942E-03
5.26198E-03
5.212599E-03
5.168549E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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Do you wish to display your results graphically... (Y/N)?
Hydraulic Gradient (mll20/m)

Velocity (m/s)
APPENDIX VI

Results from the University of Leeds Data
Enter Number of Size Fractions? 1

Enter Weighted Mean Particle Size in mm.? 4

Enter Relative Density? 2.6

Enter Pipe Diameter in mm.? 50.8

Enter Volumetric Concentration.......i.e. (10%) =? 8

Velocity at which sliding bed commences according to New Theory = 1.3274 m/s

Enter Number of Velocities ? 2

Velocity 1 =? 1.494

Velocity 2 =? 1.544

Correct any Velocities............(Y/N)

Actual Data......................(Y/N)

For Velocity 1.494 =? .1825

For Velocity 1.544 =? .1765

Correct any Data ......(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1 ......Sand, Gravel, Beach Flints.
Group 2 ......Sillimanite, Bituminous Coal.
Group 3 ......Blast Furnace Slag.
Group 4 ......Limestone, Talc, Plumago, Granite.
Group 5 ......Gypsum,
Group 6 ......Graphite.
Group 7 ......Mica.
Group 8 ......Calculated.

Enter Group Selected? 1
CALCULATED RESULTS FOR A CONCENTRATION OF 8.0 %

Pipe Diameter......................................= 50.80 mm
Shape Group.....................................= 1.000
Weighted Mean Particle Diameter...............= 4.000 mm
Relative Density of Solids.......................= 2.600
Delivered Volume Concentration of Solids......= 0.080
Delivered Weight Concentration of Solids......= 0.184
Terminal Settling Velocity of Spherical Particles of 4.000 mm Diameter = 0.436 m/s
Drag Coefficient of Spherical Particles of 4.000 mm Diameter = 0.440
Terminal Settling Velocity of NON-Spherical 4.000 m/s Particles of Shape Factor 0.26 = 0.216 m/s
Hindered Settling Velocity of Spherical Particles of 4.000 mm Diameter and Volumetric Concentration 0.080 = 0.357 m/s
Hindered Settling Velocity of NON-Spherical 4.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.080 = 0.177 m/s
Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.773 mm
Limiting Mixture Velocity for Deposition (DURAND) = 1.692 m/s

Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.961 m/s using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.381 m/s using the drag coefficient of irregular particles
Critical Velocity (Bain and Bonnington) = 1.634 m/s using the drag coefficient of spheres
Critical Velocity (Bain and Bonnington) = 1.150 m/s using the drag coefficient of irregular particles
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 7.414 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 3.676 m/s, Using the drag coefficient of irregular particles
Friction Factor Adjustment (Y/N)
5.61494E-03
5.593396E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------ UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------ UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------ UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

TABLE OF RESULTS
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7 8 9 10 11 JS JF JSI JFI ACTUAL
0.1452 0.5119 0.2792 0.7459 0.7459 0.1701 0.5758 0.1701 0.5758 0.1825
0.1480 0.4984 0.2741 0.5656 0.5656 0.1547 0.4109 0.1547 0.4109 0.1765

Do you wish to display your results graphically...(Y/N)?
Hydraulic Gradient (mH2O/m) vs. Velocity (m/s)

Actual Data.
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 4
Enter Relative Density? 2.6
Enter Pipe Diameter in mm.? 50.8
Enter Volumetric Concentration......i.e. (10%) =? 4
Velocity at which sliding bed commences according to New Theory = 1.1556 m/s
Enter Number of Velocities ? 4

Velocity 1 =? 1.814
Velocity 2 =? 1.888
Velocity 3 =? 1.940
Velocity 4 =? 1.954
Correct any Velocities...........(Y/N)

Actual Data..................(Y/N)
For Velocity 1.814 =? .1330
For Velocity 1.888 =? .1070
For Velocity 1.94 =? .1065
For Velocity 1.954 =? .1015
Correct any Data.......(Y/N)

Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1......Sand, Gravel, Beach Flints.
Group 2......Sillimanite, Bituminous Coal.
Group 3......Blast Furnace Slag.
Group 4......Limestone, Talc, Plumago, Granite.
Group 5......Gypsum,
Group 6......Graphite.
Group 7......Mica.
Group 8......Calculated.

Enter Group Selected? 1
CALCULATED RESULTS FOR A CONCENTRATION OF 4.0 %

Pipe Diameter.......................... = 50.80 mm
Shape Group.......................... = 1.000
Weighted Mean Particle Diameter.............. = 4.000 mm
Relative Density of Solids.................. = 2.600
Delivered Volume Concentration of Solids...... = 0.040
Delivered Weight Concentration of Solids...... = 0.098

Terminal Settling Velocity of Spherical Particles of 4.000 mm Diameter = 0.436 m/s

Terminal Settling Velocity of NON-Spherical 4.000 mm Particles of Shape Factor 0.26 = 0.216 m/s
Hindered Settling Velocity of Spherical Particles of 4.000 mm Diameter and Volumetric Concentration 0.040 = 0.395 m/s
Hindered Settling Velocity of NON-Spherical 4.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.040 = 0.196 m/s

Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.773 mm

Limiting Mixture Velocity for Deposition (DURAND) = 1.692 m/s
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.387 m/s using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 0.976 m/s using the drag coefficient of irregular particles
Critical Velocity (Bain and Bonnington) = 1.300 m/s using the drag coefficient of spheres
Critical Velocity (Bain and Bonnington) = 0.915 m/s using the drag coefficient of irregular particles
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 7.414 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 3.676 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.8

Friction Factor Adjustment (Y/N)
5.494281E-03
5.471272E-03
5.45984E-03
5.451985E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------- UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------- UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------- UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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| 7   | 8   | 9   | 10  | 11  | JS  | JF  | JSI | JFI  | ACTUAL |
| 0.1190 | 0.2586 | 0.1648 | 0.3222 | 0.2555 | 0.0996 | 0.2226 | 0.0730 | 0.1825 | 0.1330 |
| 0.1245 | 0.2562 | 0.1665 | 0.3164 | 0.2453 | 0.0944 | 0.2220 | 0.0649 | 0.1804 | 0.1070 |
| 0.1285 | 0.2551 | 0.1681 | 0.3119 | 0.2399 | 0.0904 | 0.2215 | 0.0597 | 0.1802 | 0.1065 |
| 0.1296 | 0.2549 | 0.1685 | 0.3109 | 0.2387 | 0.0893 | 0.2216 | 0.0584 | 0.1803 | 0.1015 |

Do you wish to display your results graphically...(Y/N)?
Enter Number of Size Fractions? 1
Enter Weighted Mean Particle Size in mm.? 4
Enter Relative Density? 2.6
Enter Pipe Diameter in mm.? 50.8
Enter Volumetric Concentration......i.e. (10%) =? 15
Velocity at which sliding bed commences according to New Theory = 1.5052 m/s
Enter Number of Velocities ? 5
Velocity  1 =? 2.739
Velocity  2 =? 3.353
Velocity  3 =? 3.522
Velocity  4 =? 3.917
Velocity  5 =? 4.556
Correct any Velocities..........(Y/N)
Actual Data.....................(Y/N)
For Velocity  2.739 =? .2910
For Velocity  3.353 =? .3000
For Velocity  3.522 =? .3335
For Velocity  3.917 =? .3460
For Velocity  4.556 =? .3966
Correct any Data.......(Y/N)
Which group of mineral types in the following group most nearly describes the particles being investigated?

Group 1.....Sand, Gravel, Beach Flints.
Group 2.....Sillimanite, Bituminous Coal.
Group 3.....Blast Furnace Slag.
Group 4.....Limestone, Talc, Plumago, Granite.
Group 5.....Gypsum,
Group 6.....Graphite.
Group 7.....Mica.
Group 8.....Calculated.
Enter Group Selected? 1
CALCULATED RESULTS FOR A CONCENTRATION OF 15.0 %

Pipe Diameter.......................... = 50.80 mm
Shape Group............................ = 1.000
Weighted Mean Particle Diameter......... = 4.000 mm
Relative Density of Solids............... = 2.600
Delivered Volume Concentration of Solids= 0.150
Delivered Weight Concentration of Solids= 0.315

Terminal Settling Velocity of Spherical Particles of 4.000 mm Diameter = 0.436 m/s
Drag Coefficient of Spherical Particles of 4.000 mm Diameter = 0.440

Terminal Settling Velocity of NON-Spherical 4.000 m/s
Particles of Shape Factor 0.26 = 0.216 m/s

Hindered Settling Velocity of Spherical Particles of 4.000 mm Diameter and Volumetric Concentration 0.150 = 0.295 m/s
Hindered Settling Velocity of NON-Spherical 4.000 mm Particles of Shape Factor 0.26 and Volumetric Concentration 0.150 = 0.146 m/s

Maximum Particle Size Falling in Laminar Zone according to STOKES Law = 0.10 mm
Minimum Particle Falling in Turbulent Zone according to NEWTONS Law = 2.773 mm

Limiting Mixture Velocity for Deposition (DURAND) = 1.692 m/s
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 2.685 m/s
using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (ZANDI and GOVATOS) = 1.891 m/s
using the drag coefficient of irregular particles
Critical Velocity (Bain and Bonnington) = 2.010 m/s
using the drag coefficient of spheres
Critical Velocity (Bain and Bonnington) = 1.416 m/s
using the drag coefficient of irregular particles

Transition Velocity to Heterogeneous Flow (NEWITT et al) = 7.414 m/s, Using the drag coefficient of spheres
Transition Velocity to Heterogeneous Flow (NEWITT et al) = 3.676 m/s, Using the drag coefficient of irregular particles
Enter the Bulking Factor of the Solids? 1.8

Friction Factor Adjustment (Y/N)
5.28488E-03
5.202593E-03
5.184405E-03
5.147355E-03
5.099715E-03

MENU

1. Durand Coarse only
2. Durand Condolios - Spheres ------- UN-Hindered
3. Durand Condolios - NON-Spheres -- UN-Hindered
4. Zandi and Govatos - Spheres ------- UN-Hindered
5. Zandi and Govatos - NON-Spheres -- UN-Hindered
6. Worsters Coarse
7. Newitts sliding bed
8. Newitts heterogeneous suspension - Spheres
9. Newitts heterogeneous suspension - NON-Spheres
10. New Theory - Spheres ------- UN-Hindered
11. New Theory - NON-Spheres -- UN-Hindered

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7
8
9
10
11
JS   | JF   | JSI  | JFI  | ACTUAL|
0.3266| 0.6035| 0.3795| 0.4339| 0.3339| 0.1025| 0.3314| 0.0646| 0.2694| 0.2910|
0.3996| 0.5921| 0.4120| 0.4919| 0.3553| 0.0844| 0.4076| 0.0316| 0.3237| 0.3000|
0.4224| 0.5971| 0.4262| 0.5128| 0.3649| 0.0802| 0.4326| 0.0234| 0.3414| 0.3335|
0.4801| 0.6196| 0.4671| 0.5670| 0.3911| 0.0713| 0.4957| 0.0053| 0.3858| 0.3460|
0.5865| 0.6827| 0.5527| 0.6686| 0.4956| 0.0585| 0.6101| 0.0000| 0.4956| 0.3966|

Do you wish to display your results graphically...(Y/N)?
Hydraulic Gradient (mH2O/m)

- Velocity (m/s)
  - 0.00
  - 1.00
  - 2.00
  - 3.00
  - 4.00
  - 5.00

- Actual Data
  - Jr.
  - 1
  - 11

- 0.20
- 0.40