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A Optimum Method for Designing Dredging System

طريقة جديدة مثلى لتصميم أنظمة الكراءة

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Abstract

The purpose of this paper is to try to reach a suitable design method for dredging systems, using a large amount of experimental data of the author and others. A theoretical model was derived and adopted, then tested against the chosen experimental data. The mostly used theories in sediment transport with special emphasis on pipe roughness have been investigated and compared with the proposed model.

Different pipe roughness, pipe diameters, sediment parameters, and velocities have been studied and tested under different flow regimes and conditions (experimentally and theoretically).

A flow regime index has been introduced by the author to allow different flow regimes to be distinguished (heterogeneous, saltation and critical flow regimes). At the end a new method of design has been introduced using the modified roughness transport parameter, which when tested against all data, a satisfactory correlation was reached. This parameter proved to be the best among all existing methods, with the best correlation, which enabled the introduction of a proper design method for dredging purposes.

ملخص

الغرض من هذا البحث هو محاولة الوصول إلى طريقة مناسبة لتصميم أنظمة الكراءة، وذلك من خلال فحص عدد كبير من النتائج المعملية الخاصة بكاتب هذه الورقة وآخرين. ولقد تم تقديم نموذج نظري، ثم فحص إمكانيات هذا النموذج من خلال تطبيقه على النتائج المعملية. الطرق الأكثر استخداماً في هذا المجال تم دراستها مع تركيز خاص على خشونة الأنبوب.

تمت دراسة وفحص قيم مختلفة لخشونة الأنابيب و أقطارها وبخواص مختلفة للرواسب وبسرعات مختلفة تحت ظروف سريان متعددة (نظرياً وتجريبياً).

كما وتم استحداث دليل رقمي لحالة السريان للتمييز بين الحالات المختلفة لتحرك المواد الصلبة في أنابيب الكراءة .

في نهاية البحث تم تقديم نموذج رياضي تجريبي لجميع النتائج المعملية كطريقة جديدة لتمثيل الجريان بطريقة صحيحة والتي أعطت دقة أكبر بكثير من الطرق الموجودة مما أتاح تقديم طريقة سليمة لتصميم أنظمة الكراءة.

Notations

a, b, n, Ac; regression parameters.
C; sediment Concentration by volume, PPM
C_D; drag coefficient
D; pipe diameter
d; particle diameter, for 50% passing
Dgr; dimensionless particle size number
Fgr; mobility number
g.; gravitational force
Ggr; transport function
i ; head loss for flow with sediment
iw; head loss for clear water
ks; pipe roughness
m'; a constant
n' ; Manning Coefficient
R ; hydraulic radius
R^2 ; Coefficient of Determination
s.; specific gravity
S; the Shear Parameter
T; the Transport Parameter:
u.; dynamic viscosity
V ; flow velocity
v.; kinematic viscosity
V*; shear velocity ($\sqrt{gRi}$)
ZI; the Author's new flow regime index
ρ ; water density
ρs; particle density

1. Introduction

Dredging is an ancient art but a relatively new science. Although work on primitive dredging can be traced back to several thousand years, it is only relatively recent that the art has been transformed into a science covering the design of dredges and dredging techniques. Dredging may be defined as raising material from the bottom of water to the surface and pumping it over some distance.

Dredging involves the transportation of a wide variety of soils (sand, silt, silty sand or gravel) in a water-pressurised flow. In most cases the water is seawater.

The above mentioned technique became widely used recently. A survey carried out by the British Hydrodynamic Research Association [1] showed that between 1971 and 1972 the conveying market in Britain grew by an order of magnitude and that during the one year period 1977 to 1978 a further 50 % increase in the sales of equipment for conveying systems was recorded.

It is well known that nearly most granular solids could be conveyed. For economical reasons the majority of the existing systems have capacities within the range of 1 to 400 tonnes per hour over distances less than 1000 m with average particle size less than 10mm.

The purpose behind performing this research is the complexity of the existing models in analysing solid conveying systems and the lack of representation of flow conditions. The proposed method has introduced a straightforward design technique with the advantage of taking into consideration all encountered hydraulic parameters.

Flow Regimes

It is extremely important for the designer of dredging systems to be able to identify the flow regime. In dredging system design; the flow regime should be heterogeneous or homogenous as the bed load transport regime is not advised and could lead to blockage of dredging pipe. Figure (1) & (2) show the different regimes expected during dredging process.

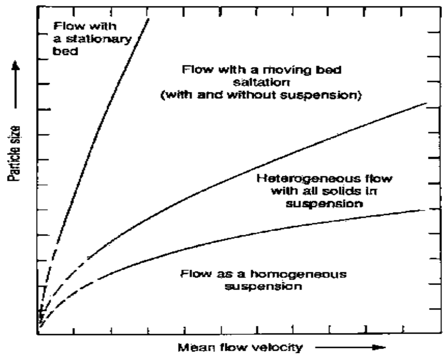

Figure 1: Different Flow regimes as function of particle size and Flow velocity [12]

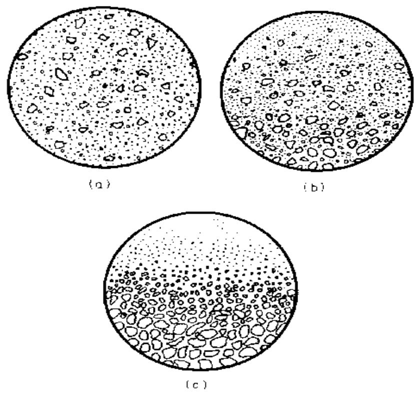

Figure 2: Flow Regimes; a. Homogeneous, b. Heterogeneous, c. Saltation [12]

Previous Studies

Different researchers use two main criteria when considering solid conveying systems transport:

A. Head loss as a criterion with heterogeneous flow conditions only

Durand and Condolios (1952) [2] Method has been used as a base for designing sediment transport systems, their formula was derived from extensive tests on sands, gravel and coal ranging in particle size from 0.2 mm to 25 mm in pipes of D = 40mm and 580mm and for C of 2 to 23 %. They came up with the well known formula relating the head loss to drag coefficient of particles:

$$\frac{i - iw}{Ciw} = a\left[\frac{V}{\sqrt{gD}}\right]^3 \left[\frac{1}{C_D}\right]^{3/2} \longrightarrow \qquad 1$$

Where; i; is the total head loss of the system containing the mixture
iw; the head loss due to water alone
C; sediment Concentration by volume, PPM
V; flow velocity
C_D; Drag Coefficient
a; a regression coefficient = 176

Newitt et.al. (1955) [3] quoted a value of a =150 for Durand's experimental data and others

Hayden and Stelson (1968) [4] introduced a modification to Durand's equation in the form of;

$$\frac{i - iw}{Ciw} = a\left[\frac{gD\ (s-1)}{V\sqrt{gd\ (s-1)}}\right]^b \longrightarrow \qquad 2$$

Where; a=100 and b= 1.3
s.; specific gravity
D; is the pipe diameter
d; particle diameter, for 50% passing

Zandi and Govates (1968) [5], collected and correlated most of available data for water- solid systems, excluding those of which a moving bed had been present, and those of concentration less than 5%, they came up with the following formula:

$$\frac{i - iw}{Ciw} = 6.3\left[\frac{V^{2}\sqrt{C_{D}}}{gD(s-1)}\right]^{-0.354} \longrightarrow \qquad 3$$

Novak & Nalluri (1975)[6], used their experimentally determined transport function for no deposition conditions;

$$\frac{CVR}{\sqrt{gd^{3}(s-1)}} = 11.6\left[\frac{(s-1)d}{iR}\right]^{-2.04} \longrightarrow \qquad 4$$

b. Flow velocity as a criterion

The critical velocity, which keeps the particles in heterogeneous conditions, has been taken as a criterion for describing flow conditions;

Charles (1970) [5] has proposed a formula for predicting the critical velocity;

$$V = \frac{4.8C^{1/3}[gD(s-1)]^{0.5}}{C_{D}^{0.25}[1 + C(s-1)]^{1/3}} \longrightarrow \qquad 5$$

May (1982) [7], reviewed precious researches and came up with a formula to predict the critical velocity conditions;

$$C = 0.0205\left[\frac{D}{A}\right]^{2}\left[\frac{d}{R}\right]^{0.6}\left[\frac{V^{2}}{gD(s-1)}\right]^{3/2}\left[1 - \frac{0.61(d/R)^{-0.27}\sqrt{gd(s-1)}}{V}\right]^{4} \longrightarrow \qquad 6$$

1. Ackers Method (1984) [8]: (originally; Ackers formula was derived for Open Channel flow. In 1984 Ackers & White combined Acker's formula with Colebrook-White equation (1939) to be applicable to designing pipes with heterogeneous flow regime.)

$$Ggr = a[\frac{Fgr - 1}{Ac}]^{b} \longrightarrow \qquad 7$$

Where; Ggr is a transport function;

$$Ggr = \frac{DC}{d}[\frac{V_*}{v}]^{n} \longrightarrow \qquad 8$$

and a, b, n & Ac are regression parameters.

V* is the shear velocity = √gRi

Fgr is a mobility number;

$$Fgr = \frac{V^{(1-n)}V_*}{\sqrt{gd(s-1)}[\sqrt{32}\log(\frac{12R}{d})]^{(1-n)}} \longrightarrow \qquad 9$$

This work

In this work a large amount of experimental data on sediment transport have been used including the author's to come up with a theory suitable for designing dredging system.

In order to introduce a comprehensive method, concentration was made to include all possible transport and hydraulic parameters that may be encountered in dredging system, ***keeping in mind the simple approach for design***.

Different pipe roughness, pipe diameters, sediment parameters, and velocities have been studied and tested under different flow regimes and different conditions.

The ranges of different parameters are listed in Table (1).

Table 1: Experimental Ranges.

Researcher	Laboratory	Particle diameter (d mm)	Mixture velocity (V m/s)	Particle concentration (C ppm)	Pipe diameter (D mm)	Specific Gravity (s)	Pipe Roughness mm
The Author's Full pipe flow	University of Salford, Manchester	1.3,1.8, 5.2, 8	0.52to0.33	33to1029	253, 164,	2.56, 2.61, 2.65, 2.66	0.65,0.83, 1.3, 2.7
May [8] Full pipe flow	Hydraulic Research Station, Wallingford	0.64,0.57, 5.8, 7.9	0.45to 1.2	2.5to2110	76.6,158.3	2.65	0.004, 0.05
Total No. of results		**780**					

Characteristics of the Transport regimes

Table 2 shows the different parameters that may be involved in a Transport regime;

Table 2: Transport parameters.

Sediment Properties	Water Properties	Pipe properties	Flow properties
Particle Diameter (d)	Water density (ρ)	Pipe Diameter (D)	Velocity (V)
Shape (Ω)	temperature	straightness	Solid concentration(C)
Density (ρs)	Dynamic viscosity (μ)	Roughens (Ks)	Gravity Acc. (g)

The Flow Regime Index

Newitt et. al. [3] has introduced an Index number (N) to determine the mode of transport;

$$N = \frac{V^2 \sqrt{C_d}}{C.d.g(s-1)} \longrightarrow \qquad 10$$

Because of the difficulties in calculating the drag coefficient, it was decided to simplify the Index ***by introducing a new index "ZI",*** in which the drag coefficient has been omitted and a new index has been introduced and tested against all experimental data, and compared with visual observations during experiments.

$$ZI = \frac{V^2 10^6}{C\ Dgr} \longrightarrow \qquad 11$$

Where ; *Dgr* is a dimensionless particle size;

$$Dgr = d[\frac{g(s-1)}{v^2}]^{0.333} \longrightarrow \qquad 12$$

The following regimes were observed;

For **ZI < 170**; the flow regime is saltation

For **230 > ZI < 170**; the flow regime is critical

For **ZI > 230**; the flow regime is heterogeneous

Theoretical Models and Analysis of data:

Theoretical Background:

A. The mechanism of the flow of solid-water mixture is complex and theoretical predictions of critical velocity from first principle has yet to be developed. The complexity is compounded by:

- ♦ the different definitions of flow regimes;
- ♦ different possible mechanisms depending on the variations of different hydraulic parameters encountered in the flow process.
- ♦ the uncertain effects of solid concentration in the water flow.

B. For transport of a set of particles in a dredging system in a horizontal pipe, more than one definition for the critical velocity could be introduced;

- the minimum velocity required to transport solid particles by rolling, sliding or bouncing along the bottom of the pipe.
- the minimum velocity required to pick up solid particles from rest in the bottom of the pipe and transport it in suspension
- the velocity at which the mixture flows in heterogeneous pattern (i.e. asymmetric suspension, or dunned bed) but above the velocity at which a bed is formed.

C. For dredging pipes it is usually preferable to have high speed flow of mixture to reduce time and to have a residual head at the discharging end of the pipe to allow for jetting the solids away from the dredger and the dredging area. Accordingly the homogenous and heterogeneous flow regimes are preferable for dredging purposes.

Sources of Roughness in dredging pipes

Dredging takes place under high velocity flow and high pressure. Accordingly the continuous use of the dredging pipe causes progressive aging of the pipe material and accordingly the pipe roughness, in addition to the main pipe roughness that is a function of pipe material.

The Shear Parameter S

According to the Author's derivation [9]

$$S = \frac{V_*^2}{gd\,(s-1)} = \frac{iR}{d\,(s-1)} \longrightarrow \qquad 13$$

where;

S; is the Shear Parameter and is a function of hydraulic gradient (i), specific gravity (s), hydraulic radius and particle diameter (d); V* is the shear velocity and equals to $\sqrt{(g\,R\,i)}$

This shear parameter proved to be very representative of hydrodynamic forces. So it was decided to use the Shear Parameter as a transport criterion.

Transport Parameter T

According to the Author's derivation [9] for a transport parameter [T}

$$T = \frac{CVR}{\sqrt{gd^3(s-1)}} \longrightarrow \qquad 14$$

Multiplying " ***T***" by V/V

$$\frac{CVR}{\sqrt{gd^3(s-1)}}\frac{V}{V}$$

and introducing Manning equation

$$V = \frac{1}{n'}R^{0.667}\sqrt{i} \longrightarrow \qquad 15$$

and from Webber [10] relationship

$$n' = \frac{k_s^{0.1667}}{m'} \longrightarrow \qquad 16$$

where m' is a constant;

The Roughness Transport Parameter "***T***" becomes;

$$T = \frac{k_s^{0.1667} CV^2 R^{0.333}}{\sqrt{gd^3(s-1)i}} \longrightarrow \qquad 17$$

The relationship between transport parameter and shear parameter was used as the base for further improvement of the correlation.

Where a & b are regression factors

$$T = a[S]^b \longrightarrow \qquad 18$$

The following relationship was tested against the existing experimental data:

$$\frac{k_s^{0.1667}\ CV^2\ R^{0.333}}{\sqrt{gd^3(s-1)i}} = a\left[\frac{(s-1)d}{iR}\right]^b \longrightarrow \qquad 19$$

The derived formula has been applied to all experimental data, a computer programme was prepared for the calculation of the Transport Parameter (T) and the Shear Parameter (S) for each set of data. After applying regression analysis to the values obtained for T & S (*with The Shear Parameter “S” as an independent parameter and The Transport Parameter “T” as the dependent Parameter)*, the following was obtained:

For ZI < 170 , i.e. saltation regime;

a = 2 x 10^6 , b = -0.9842 & R^2 = 0.54

For ZI > 230 , i.e. heterogeneous regime,

a = 9 x 10 7, b = -2.6203 & R^2 = 0.78

It can be seen that the Coefficient of Determination “R^2” is ranging from 0.54 to 0.78, which is an acceptable range for the large number of parameters considered in the Flow Index “ZI”, i.e. a good correlation has been gained between the available experimental data and the theoretical model.

Figures 3, and 4: show the plot of these results and their flow regimes.

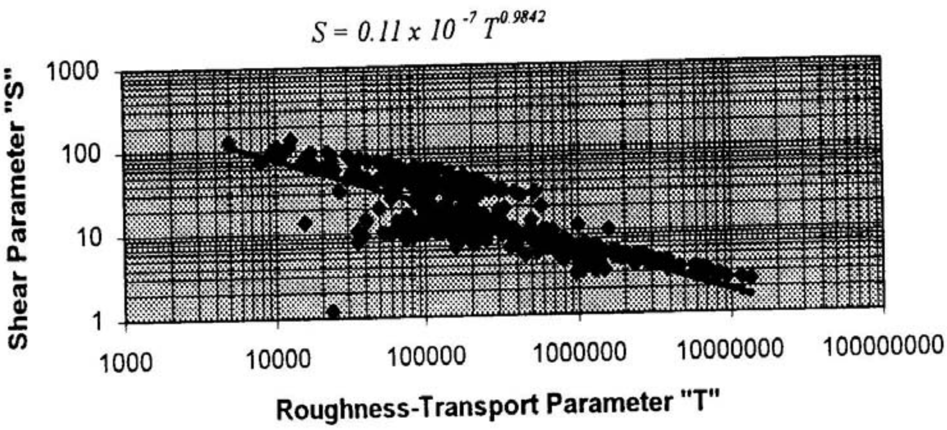

Figure 3: Saltation Flow Regime (ZI < 170).

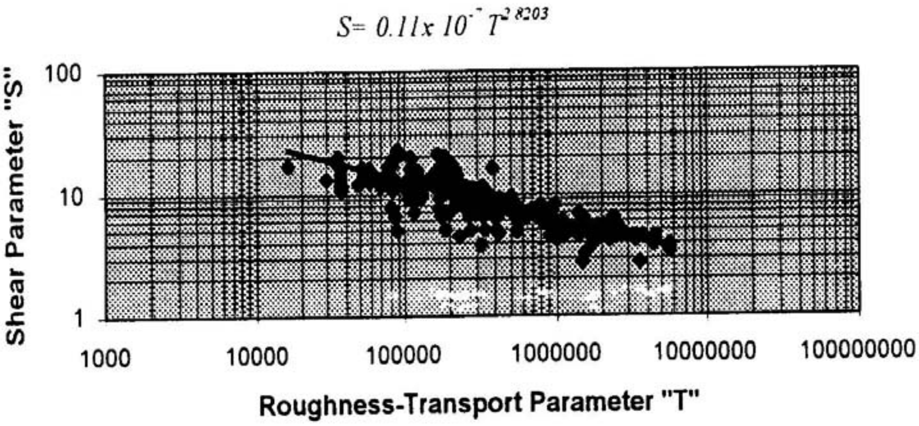

Figure 4: Heterogeneous Flow Regime (ZI > 230).

For dredging system design, it is recommended to use the heterogeneous regime equation in order to allow for speedy dredging and residual head at the discharging end.

i.e.

$$\frac{(s-1)d}{iR} = 0.111x10^{-7}[\frac{k_s^{0.1667} CV^2 R^{0.333}}{\sqrt{gd^3(s-1)i}}]^{2.8203} \qquad 19$$

Advantages of the Proposed Dredging System Design Method:

$T = 9x10^7 * S^{(-2.8203)}$

The proposed design method is recommended to be used for dredging purposes for the following reasons:

1. All flow, particle and pipe parameters are included
2. It has the roughness parameter, which is a very important element in design
3. It has been proved to represent the data obtained from experimental work

Analysis of the proposed method:

The shear parameter (S) can be used as a criterion for determining the amount of the transported materials. It was established through the derivation of the Shear parameter [9] that:

S = ¢ (Re*) -------- 20

i.e.

$$\frac{V_*^2}{gd\ (s-1)} = \Phi\ [\frac{dV_*}{v}] \longrightarrow \qquad 21$$

Figure [5] and Figure [6] were plotted for the above functional relationship in order to get a proper presentation for various modes of transport, all experimental data were used in plotting this figure.

These figures are very useful in getting a suitable value for S just by choosing the required particle diameter and the mode of transport.

It is highly recommended to use the Particle Reynolds Number Re* only when the head loss in the system is not available (which is usually the case when designing dredging system).

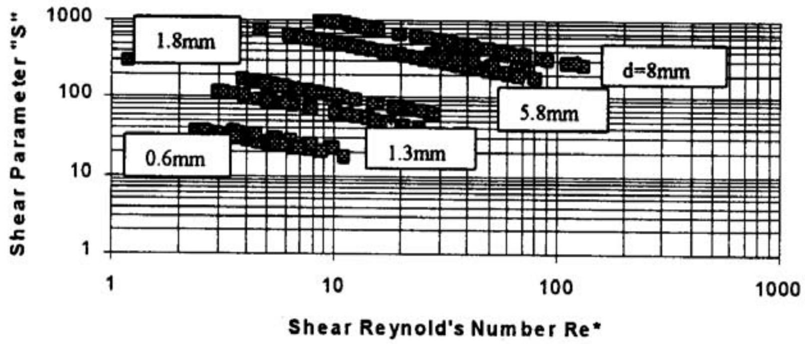

Figure 5: Shear Reynold's Number Re* Vs Shear Parameter "S" for Saltation Regime ZI < 170.

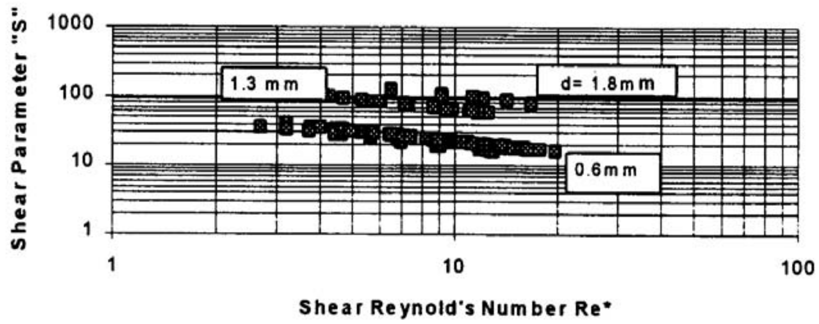

Figure 6: Shear Reynold's Number Re* Vs Shear Parameter "S" for Hetrogeous Regime ZI > 230.

Characteristics of the proposed method:

1. Different values for particle diameters were chosen with different solid concentrations and were substituted in the proposed equations. It was concluded that when the particle diameter increases, the friction increases inside the pipe and accordingly the head loss, which means that the particle diameter is directly proportional to the total head loss in the system;

   i.e. $\boldsymbol{i \; \alpha \; d}$

2. When the solid concentration (C) increases more solid enters the system and more loss in the available head will take place, this mainly due to the increase in the friction.

   i.e. $\boldsymbol{i \; \alpha \; C \; \alpha \; d}$

3. Different values for the velocity of the mixture inside the system were chosen and different solid concentration ratios were used. It was concluded that, when the velocity increases, the friction increases inside the pipe and so the head loss increases which means that the velocity is directly proportional to the total head loss in the system

   i.e. $\boldsymbol{i \; \alpha \; V}$

4. When the solid concentration ratio (C) increases more solid enters the system and more loss in the available head will take place, this mainly due to the increase in the friction.

   i.e. $\boldsymbol{i \; \alpha \; C \; \alpha \; V}$

5. For fixed solid concentration; when d increases the needed velocity increases, which means that the velocity is directly proportional to the particle diameter and inversely proportional to the solid concentration;

   i.e. $\boldsymbol{V \; \alpha \; d \; \alpha \; 1/C}$

Comparisons between most available methods and the proposed method:

The Coefficient of determination was considered as the base for judging the applicability of the method to the range of the experimental data. Table (3) summarises the results of the regression analysis applied by using the available experimental data for every method:

Table 3: Comparison between most available methods and its accuracy

Method	Coefficient of determination (R^2) for saltation flow	Coefficient of determination (R^2) for heterogeneous flow
Ackers	0.0469	0.3101
Durand	0.0013	0.44
Hayden	0.153	0.432
Newitt	0.066	0.52
The proposed method	***0.54***	***0.78***

It can be seen that the Coefficient of determination for saltation is very low, which means that mentioned methods are not applicable, this is due to the fact that the saltation flow is slower and in most cases the amount of sediment inside the pipe moves as dunes which increases the resistance to the flow, i.e. the overall roughness and accordingly the shear.

It can be seen that the proposed method gives the best correlation, especially for heterogeneous regime, this is simply due to the actual representation of all encountered hydraulic parameters.

Design procedures for dredging purposes:

1. Get the particle diameter, the specific gravity of the particles,
2. Assume the diameter of the dredging pipe, D and the needed rate of dredging materials C from dredging site data,

3. Assume Q of a given dredging pump and accordingly the expected velocity inside the dredging pipe.
4. Calculate the head loss using the heterogeneous equation for a given C
5. Draw the system curve for the dredging pipe, taking into consideration the maximum and minimum elevation of the discharging end of the pipe (i.e. minimum and maximum static head)
6. Calculate the “ZI” to know the flow regime (i.e. if ZI < 170, the flow is saltation and if ZI > 230 the flow is heterogeneous). To avoid blockage of the pipe the ZI should be more than 230 and preferably more than 400, to give a satisfactory factor of safety against blockage, or sudden stoppage of the system.
7. From the above the system curve of the pipe could be modified and if it is combined with the dredging pump curve, the optimum operation point could be obtained.

Conclusions:

Theoretical model was introduced and a comprehensive method was derived; all of its characteristics were proved to be reasonable.

Comprehensive design procedures were introduced on how to use the proposed method.

It was found through the literature survey that the effect of the roughness of the pipe has not been studied in a detailed way.

A roughness transport parameter has been introduced to take care of most of the sediment and flow parameters, it has proved to give satisfactory results.

A flow regime index has been also introduced, ZI, which enables the designer to figure out the flow regime.

Comprehensive study of different sediment transport theories has been carried out making use of a large number of experimental data.

Comparisons lead to a serious error in the coefficient of determination when regression analyses applied to the experimental data.

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