C. Paris and I. Martinez

Calculation of Sand Losses During Hopper Loading Process in Trailers

Abstract

During the actual dredging process, the instrumentation on board a trailing suction hopper dredger accurately determines when to stop the hopper loading process and when to begin the transport and dumping phase in order to achieve optimal production.
However during the study and bidding phases of a project, a method is needed for the theoretical calculations of these processes. This article establishes a procedure for calculating the theoretical trailing suction hopper dredgers production based on the application of classical sedimentation theories and on tests and actual results used in the design of sedimentation tanks of water treatment plants.

Naval architect Carlos Paris joined Dragados Y Construcciones, S.A. in 1969. He has been involved in numerous Marine Projects of all types in Spain and abroad, such as dredging, blasting, offshore operations, berth fabrication, in various capacities: Project Manager, Technical Manager and Operations Manager. At present, he is the Marine Department Manager of Dragados and Deputy Director of Dravosa.

Carlos Paris

Indalecio Martinez received a BSc in Civil Engineering in 1972 from Universidad Politécnica de Madrid. He worked between 1973 and 1978 for Compañía Internacional de Dragado (CINDRA), established in 1972 by the Spanish company Dragados Y Construcciones S.A. and Boskalis Westminster BV. He is presently Tender Manager of Marine Department of Dragados Y Construcciones, S.A.

Indalecio Martinez

Introduction

The production control instruments installed on board when dredging with trailing suction hopper dredgers accurately determine exactly when to stop the hopper loading process and when to begin the transport and dumping phase, so that optimum production is maintained for the equipment throughout the entire process (loading-transport-dumping).
However, in the study and bidding phases of a project, dredging companies need a method for making a theoretical calculation of the dredging process and especially for the hopper dredger loading.
The hopper loading process is very similar to the process that takes place in the sedimentation tanks of a water treatment plant.
The object of this article is to establish a procedure for calculating the theoretical trailing suction hopper dredgers production based on classical sedimentation theories and on the tests and actual results in sedimentation tanks.

Types of sedimentation

Sedimentation is defined as the settlement, by gravity, of particles suspended in a fluid with a lower specific weight. Particles contained in a suspension settle in different ways depending on their characteristics and on the suspension's concentration. Based on the concentration and particles' tendency to interact, there are mainly four types of sedimentation:

a) Discrete
This concerns the sedimentation of particles in a suspension with a low concentration of solids. Although the movement of each particle is affected by the other particles around it, there is no grouping and each particle settles individually.

b) Flocculant
This type of sedimentation occurs in rather dilute suspensions where the particles group together or flocculate, increasing their mass and settling at a faster rate.

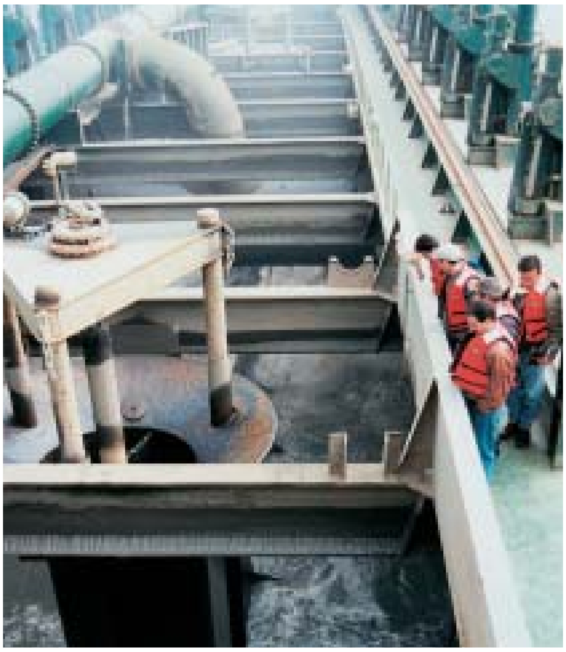

Figure 1. The hopper loading process seen here is similar to the process that takes place in sedimentation tanks of a water treatment plant.

c) Zone
This refers to suspensions with an intermediate concentration in which the interparticle forces are sufficient to hamper the settling of neighbouring particles so that they tend to stay in relatively fixed positions and the mass settles as a unit.

d) Compression
In this type of sedimentation the particles are concentrated, forming a structure. Settlement is caused by the pressure of the upper layers on the lower layers as new particles constantly join the structure.

More than one form of sedimentation usually occurs in the sedimentation process depending on the nature of the suspended material. It is even possible for all four types of sedimentation to take place simultaneously. Although the analysis of each type of sedimentation is fundamental when designing the equipment for a water treatment plant, only discrete sedimentation has to be considered for the process of loading suspended granular material dredged by a trailing suction hopper dredger.

Analysis of Discrete Particles Sedimentation

Discrete particles sedimentation can be analysed using the classical Laws of Newton and Stokes. Newton's Law gives the final velocity of a particle by equating its effective weight with frictional resistance or drag.

In the case of spherical particles, the sedimentation velocity is defined by the following equation:

$$V_c = \left[\frac{4}{3} \frac{g(\rho_s - \rho_w)d}{C_D \rho_w} \right]^{1/2} \qquad (1)$$

where:
V_c = Sedimentation velocity of the particle
d = Diameter of the particle
C_D = Drag coefficient
ρ_s = Density of the particle
ρ_w = Density of the fluid

The drag coefficient C_D takes on different values depending on whether the current around the particle is laminar or turbulent. In function of the Reynolds number (R_e = vd/μ), for spherical particles, the drag coefficient can be approximated by the following equation (upper limit $R_e = 10^4$).

orgineel laten! √ √ (2)

For Reynolds numbers less than 0.3, the first term of the above equation prevails and if the drag coefficient in equation (1) is substituted by the value $C_D = 24/R_e$, Stokes Law is obtained.

$$V_c = \frac{g}{18\mu} (\rho_s - \rho_w) d^2 \qquad (3)$$

where μ is the fluid's dynamic viscosity.

Stokes Law is valid for Reynolds numbers less than 0.3 that correspond to particles with a diameter of less than 80 microns.
Based on tests run by Richards, Burdryck defined the following expression for sedimentation velocity that is valid for all types of particles:

$$V_c = \frac{8{,}925}{d} \left[\sqrt{1 + 95(\rho_s - \rho_w)d^3} - 1 \right] \qquad (4)$$

B. Fitch, determined the sedimentation velocity for spherical particles suspended in a dilution as follows:

$$V_c = BY \qquad (5)$$

where:

$$B = \left[g \; \frac{\rho_s - \rho_w}{\rho_w} \left(\frac{\mu}{\rho_w} \right) \right]^{1/3} \qquad (6)$$

The value of Y can be obtained from Figure 2 in function of the reduced Reynolds number X.

$$X = \frac{dB\rho_w}{\mu} \qquad (7)$$

The different values for the sedimentation velocity of spherical particles resulting from the above equations are shown in Figure 3.

Since we know the size distribution of the particles suspended in the fluid and, as a result, its sedimentation velocities, we need to determine now the quantity of material that settles when a sedimentation tank (or dredger's hopper) with a surface area A receives a flow Q of suspended material.

Hazen and Camp have developed equations for eliminating discrete particles in an ideal sedimentation tank assuming the following:

a) That the particles and the velocity vectors are uniformly distributed across the tank.

b) That the fluid moves slowly as an ideal mass.

c) That any particle that reaches the bottom is totally settled.

Under these conditions, ascensional velocity or surface load is defined by the following expression:

$$V_s = \frac{Q}{A} \qquad (8)$$

and it is recognised that the particles whose sedimentation velocity V_C is greater than their ascensional velocity V_S will all settle while particles whose velocity V_C is less than V_S will settle in the proportion of $\frac{V_c}{V_s}$

In this way, if X_S is the fraction of particles with a sedimentation velocity equal to or less than V_S, then the total fraction of particles that will settle is given by the equation:

$$R^0 = (1 - X_s) + \int_0^{X_s} \frac{V_c}{V_s}\, dx \qquad (9)$$

In a typical suspension with granular material, there is a wide range of particle sizes. To determine the efficiency of removal (sedimentation), it is necessary to consider the full range of sedimentation velocities in the system. This can be done by analysing the grain size and preparing a frequency distribution curve of the sedimentation velocity.
The last term of the above expression can be evaluated by graphical integration of the mentioned frequency distribution curve (see Figure 4).

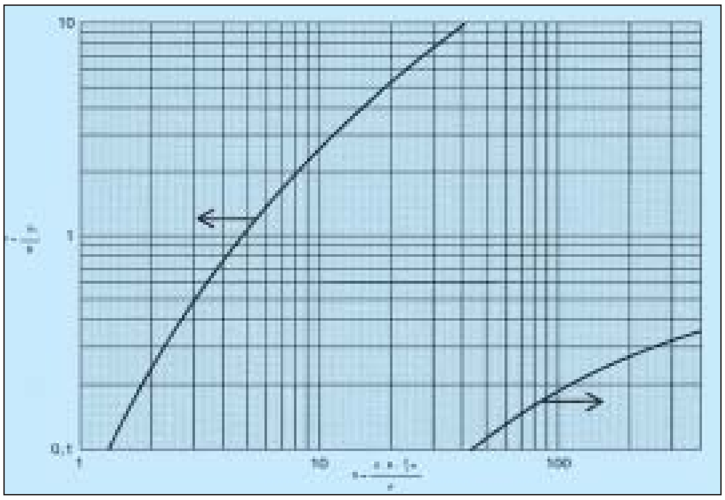

Figure 2. Dimensionless plot for calculating settling rates

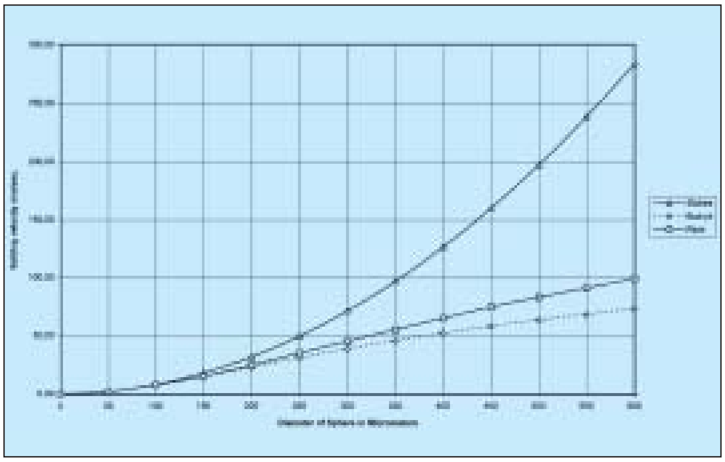

Figure 3. Settling rates of spheres in water at 20°C.

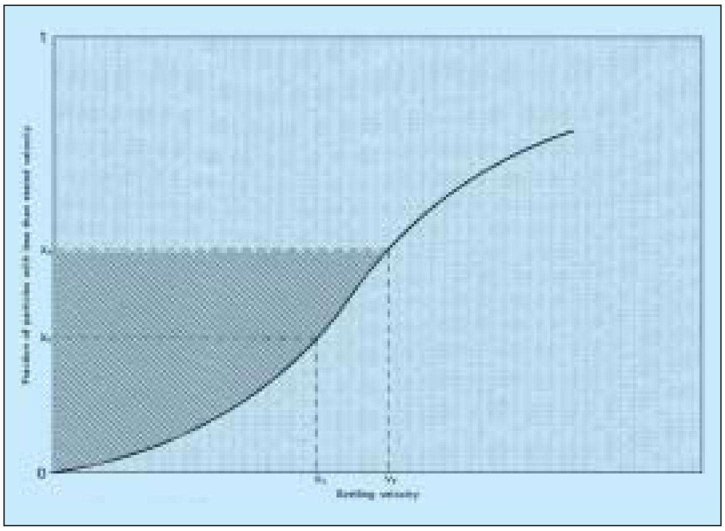

Figure 4. Definition sketch for the analysis of discrete particle settling.

Correction Factors

Until now, we have developed the theories on discrete particle sedimentation in an ideal sedimentation tank. In practice, design factors must be included to foresee the effects of particles influencing each another, non-spherical grains, turbulence in the tank and uneven accumulation of settled material. The following are the correction factors for sedimentation velocity V_C that take into account the effects described in the previous paragraph:

H. Hindrance factor
Correction factor that reduces the sedimentation velocity to take into account the influence that the suspended particles have on one another.

S. Shape factor
Correction factor for non-spherical particles.

J. Areal efficiency
Correction factor for turbulence in the tank.

The application of these correction factors to the theoretical sedimentation velocity V_c gives the calculation sedimentation velocity V'_c for the different suspended particles: $V'_c = H . S . J . V_c$

Hindrance Factor H
In a concentrated suspension, the movement of a particle is affected by the particles around it, usually lowering the sedimentation velocity, where:

C = Concentration of solids in the in-flow (%).
V_f = Volume of water per volume of solids (volume dilution).

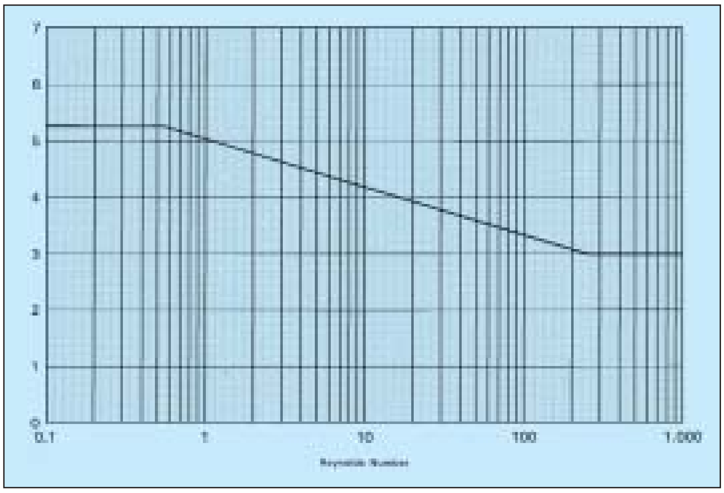

Figure 5. Hindrance Factor. Plot of exponent α vs. Reynolds number.

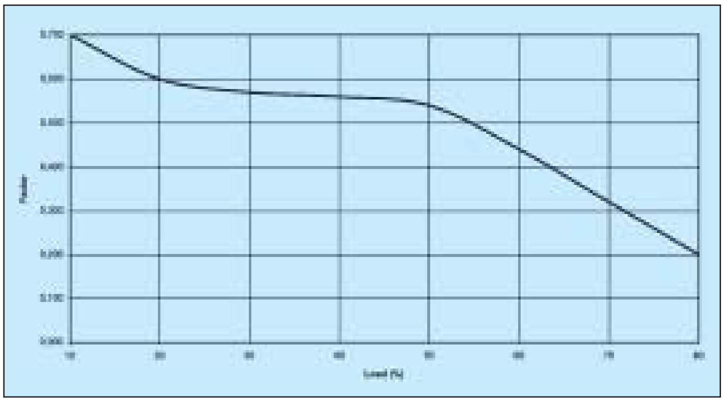

Figure 6. Areal efficiency factor vs. hopper load

$$V_f = \frac{(100 - C)}{C} \qquad (10)$$

V_s = Q/A = ascensional velocity for a given flow Q.
d_s = diameter of a particle with a sedimentation velocity equal to V_s.
M = fraction of solids finer than d_s.

The expression used to determine the hindrance factor is:

$$H = a^{\alpha} \qquad (11)$$

where

$$a = \frac{1}{1 + M / V_f} \qquad (12)$$

and α can be obtained from Figure 5 in function of the Reynolds number.

Shape Factor S
Sand grains are generally triaxial ellipsoids with a maximum diameter of d_a, an intermediate diameter of d_b and a short diameter of d_c. The diameter of the sphere that has the same volume and weight as the grain is called the nominal diameter d_n.

For ellipsoid particles,

$$d_n = (d_a d_b d_c)^{1/3} \qquad (13)$$

Using three axial diameters, the shape of the grains can be expressed in terms of the Corey Shape Factor.

$$S = \frac{d_c}{\sqrt{d_a d_b}} \qquad (14)$$

When faced with the difficulty of measuring the diameters of the particles, the Krumbein and Sloss chart gives the following Shape Factors for each type of sand:

Angular - subangular	0.70
Subrounded - rounded	0.80
Well rounded	0.90
Spheres	1.00

Areal Efficiency J
As the level of solids that have settled in the tank increases, turbulence also increases. This affects the sedimentation velocity of the particles and a correction factor must be included for it. The areal or detention efficiency factors vary depending on the design and dimensions of the sedimentation tank.

Based on the experience obtained in mechanical classifiers, the following values have been established for the different types of sedimentation tanks:

Table I. Grain size distribution

Sand Type A.				Sand Type B.			
d (microns)	% Passing	d (microns)	Range Gradation %	d (microns)	% Passing	d (microns)	Range Gradation %
400	100			1.200	100		
		335	10			970	10
270	90			740	90		
		235	10			625	10
200	80			510	80		
		180	10			460	10
160	70			410	70		
		145	10			380	10
130	60			350	60		
		120	10			330	10
110	50			310	50		
		100	10			285	10
90	40			260	40		
		80	10			235	10
70	30			210	30		
		62	10			185	10
53	20			160	20		
		44	10			128	10
35	10			95	10		
		28	10			68	10
20	0			40	0		
D-50 = 110 microns				D-50 = 310 microns			
D.M.F. = 124 microns				D.M.F. = 338 microns			

Rake classifiers	0.2 - 0.6
Bowl classifiers	0.4 - 0.6
Hydroseparators	0.3 - 0.7

In the case of the trailing hopper suction dredgers, it is more difficult to determine this factor because other conditions intervene such as the device used to dump the material, the overflow devices, the hopper's shape, and so on.

Nevertheless, since for a given material and a constant flow, the S and H factors are also constant, then the J factor can be expected to develop in a way similar to the overflow loss gradient in the real loading process of a trailing suction hopper dredger.

For a dredger and a determined kind of sand material, it would be possible to start with the experimental loading curve, theoretically obtain the values of S and H and deduce from them the value of J.
For this article, we have started with the variation range of 0.2 - 0.7 for this factor and distributed it according to the typical variations of the loading curves for trailing suction hopper dredgers (Figure 6).

Application of the Theoretical Calculations to the Loading Process of a TSHD

After developing the theoretical sedimentation process, it is convenient to apply the theories presented to a practical case of dredging, for a trailing suction hopper dredger Eurotrailer type with a 2,500 m^3 hopper capacity.

Characteristics of the dredged material
The level of losses produced during the loading process basically depends on the grain size distribution of the dredged material. Figure 7 shows the grain size distribution of two types of dredged sand and Table I shows the frequency distribution curves based on the different sizes of particles.

Loading curves
Tables IIa and IIb summarise the amount of material lost by overflow for different loading levels of the dredger's hopper. Figures 8 and 9 show the dredger loading curves assuming constant flows and density of the dredged mixture to simplify calculations.

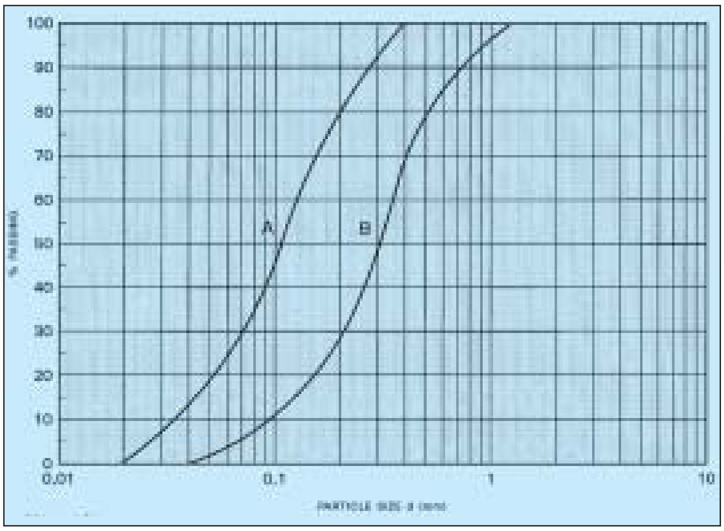

Figure 7. Particle size distribution curve.

Conclusion

The above theorical calculations, even considering a constant in-flow and mixture density, are similar to the practical results obtained on tests with very similar sand in the Laboratory for Research and Development of the Dredging Division of IHC Holland (S.E.M. de Bree) and tests in dredging works in Spain with a trailer suction hopper dredger type Eurotrailer.

Once calculated the overflow losses rates during the loading operations, it is possible to calculate the optimum loading level to obtain the maximum production in the dredging cycle, taking into account the dredger velocity and sailing distance.

References

Metcalf and Eddy. Wastewater Engineering. *Treatment disposal and reuse.* McGraw-Hill. New York 1991.

B. Fitch and E.J. Roberts.
Classification Theory. *SME, mineral processing handbook.*

S.E.M. de Bree.
Load process in traling suction hopper dredgers.
IHC publications.

Keith R. Dyer.
Coastal and Estuarine Sediment Dynamics.
John Wiley & Sons. U.K. 1986

Table IIa. Overflow losses during hopper load process. Sand Type A.

Sand Type A:						Hindrance Factor	
D-50 =	110	mic.				**dc**	84,0
DMF =	124	mic.	Flow	8.000	m^3/hr	**C**	13,79
			Hopper area	460	m^2	**Vf.**	6,25
			Q/A	4,8309	mm/sec	**a**	0,9441
Flow density =	**1,25**	T/m^3				**Re.**	0,3565
Solids density	2,65	T/m^3				∝	5,30
Solids concentration	13,79	%				**Hindrance. Fact.**	0,7373
						Shape Factor.	0,8000

Areal Efficiency Factor.							
Hopper load (%)							
10	20	30	40	50	60	70	80
0,70	0,60	0,57	0,56	0,54	0,44	0,32	0,20

d (microns)	Gradation %	Vs. Fitch. mm/sec	**Hopper load (%).** **10** **Vs'** mm/sec	Losses %	**20** **Vs'** mm/sec	Losses %	**30** **Vs'** mm/sec	Losses %	**40** **Vs'** mm/sec	Losses %	**50** **Vs'** mm/sec	Losses %	**60** **Vs'** mm/sec	Losses %	**70** **Vs'** mm/sec	Losses %	**80** **Vs'** mm/sec	Losses %
28	10	0,4	0,2	9,7	0,1	9,7	0,1	9,7	0,1	9,7	0,1	9,7	0,1	9,8	0,1	9,8	0,0	9,9
44	10	1,2	0,5	9,0	0,4	9,1	0,4	9,2	0,4	9,2	0,4	9,2	0,3	9,4	0,2	9,5	0,1	9,7
62	10	3,6	1,5	6,9	1,3	7,4	1,2	7,5	1,2	7,5	1,1	7,6	0,9	8,1	0,7	8,6	0,4	9,1
80	10	5,2	2,1	5,6	1,8	6,2	1,7	6,4	1,7	6,4	1,7	6,6	1,3	7,2	1,0	8,0	0,6	8,7
100	10	8,0	3,3	3,2	2,8	4,1	2,7	4,4	2,6	4,5	2,5	4,7	2,1	5,7	1,5	6,9	0,9	8,0
120	10	10,6	4,4	0,9	3,8	2,2	3,6	2,6	3,5	2,8	3,4	3,0	2,8	4,3	2,0	5,9	1,3	7,4
145	10	13,7	5,7	0,0	4,8	0,0	4,6	0,5	4,5	0,6	4,4	1,0	3,6	2,6	2,6	4,6	1,6	6,7
180	10	20,4	8,4	0,0	7,2	0,0	6,9	0,0	6,7	0,0	6,5	0,0	5,3	0,0	3,9	2,0	2,4	5,0
235	10	30,5	12,6	0,0	10,8	0,0	10,3	0,0	10,1	0,0	9,7	0,0	7,9	0,0	5,8	0,0	3,6	2,6
335	10	52,5	21,7	0,0	16,6	0 0	17,6	0,0	17 3	0,0	16,7	0,0	13,6	0,0	9,9	0,0	6,2	0,0
	100			35,2		38,8		40,3		40,8		41,8		47,1		55,3		67,1

Adjusted settling velocity **Vs'** = settling velocity **Vs** x Shape factor x Hindrance factor x Areal efficiency.

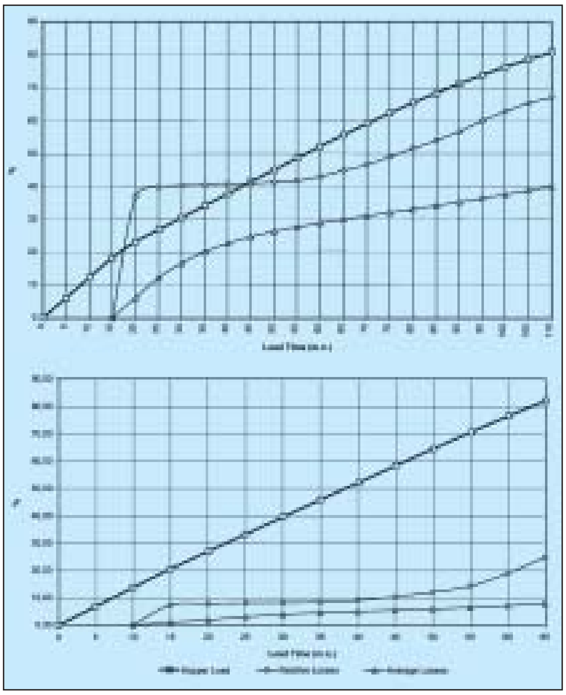

Figure 8a. Overflow losses during hopper load sequence. Soil Type A (top) and Figure 8b. Overflow losses during hopper load sequence. Soil Type B (under).

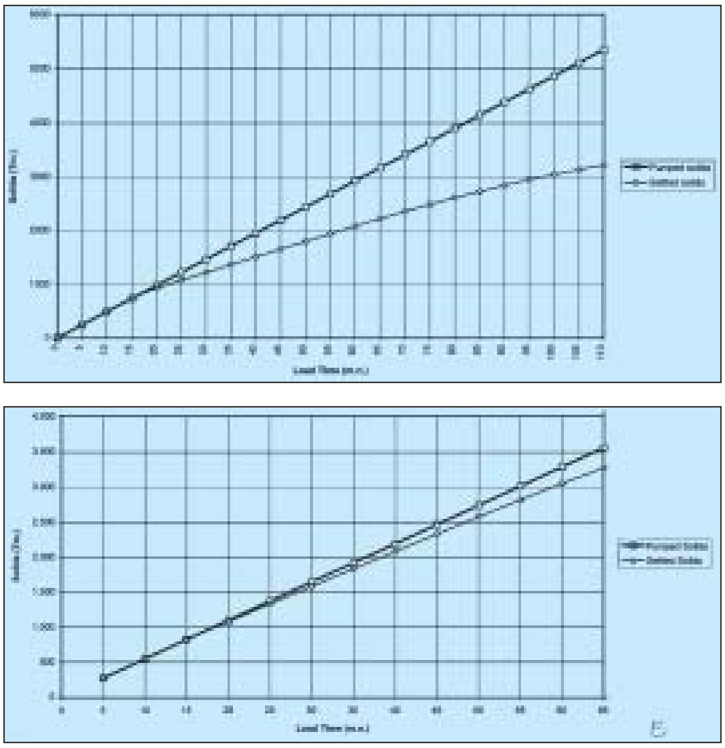

Figure 9a. Load Sequence. Soil Type A (top) and Figure 9b. Load Sequence. Soil Type B (under).

Table IIb. Overflow losses during hopper load process. Sand Type B.

						Hindrance Factor	
Sand Type B:						**dc**	89,3
D-50 =	310	mic.				**M**	9,5
DMF =	338	mic.	Flow	9.000	m^3/hr	**C**	13,79
			Hopper area	460	m^2	**Vf.**	6,25
			Q/A	5,4348	mm/sec	**a**	0,9850
Flow density =	**1,25**	T/m^3				**Re.**	0,4263
Solids density	2,65	T/m^3				∝	5,30
Solids concentration	13,79	%				**Hindrance. Fact.**	0,9232
						Shape Factor.	0,8000

Areal Efficiency Factor.							
Hopper load (%)							
10	20	30	40	50	60	70	80
0,70	0,60	0,57	0,56	0,54	0,44	0,32	0,20

d	Grada-tion	Vs. Fitch.	Hopper load (%). 10		20		30		40		50		60		70		80	
(microns)	%	mm/sec	**Vs'** mm/sec	Losses %	**Vs'** mm/sec	Losses %	**Vs'** mm/sec	Losses %	**Vs'** mm/sec	Losses %	**Vs'** mm/sec	Losses %	**Vs'** mm/sec	Losses %	**Vs'** mm/sec	Losses %	**Vs'** mm/sec	Losses %
68	10	3,8	2,0	6,4	1,7	6,9	1,6	7,1	1,6	7,1	1,5	7,2	1,2	7,7	0,9	8,3	0,6	9,0
128	10	11,7	6,0	0,0	5,2	0,5	4,9	0,9	4,8	1,1	4,7	1,4	3,8	3,0	2,8	4,9	1,7	6,8
185	10	21,8	11,3	0,0	9,7	0,0	9,2	0,0	9,0	0,0	8,7	0,0	7,1	0,0	5,2	0,5	3,2	4,1
235	10	30,5	15,8	0,0	13,5	0,0	12,8	0,0	12,6	0,0	12,2	0,0	9,9	0,0	7,2	0,0	4,5	1,7
285	10	40,6	21,0	0,0	18,0	0,0	17,1	0,0	16,8	0,0	16.2	0,0	13.2	0,0	9,6	0,0	6,0	0,0
330	10	51,8	26,8	0,0	23,0	0,0	21,8	0,0	21,4	0,0	20,7	0,0	16,8	0,0	12,2	0,0	7,7	0,0
380	10	60,3	31,2	0,0	26,7	0,0	25,4	0,0	24,9	0,0	24,0	0,0	19,6	0,0	14,3	0,0	8,9	0,0
460	10	76,2	39,4	0,0	33,8	0,0	32,1	0,0	31,5	0,0	30,4	0,0	24,8	0,0	18,0	0,0	11,3	0,0
625	10	101,6	52,5	0,0	45,0	0,0	42,8	0,0	42,0	0,0	40,5	0,0	33,0	0,0	24,0	0,0	15,0	0,0
970	10	162,5	84,0	0,0	72,0	0,0	68,4	0,0	67,2	0,0	64,8	0,0	52,8	0,0	38,4	0,0	24,0	0,0
	100			6,4		7,4		8,0		8,2		8,6		10,7		13,8		21,6

Adjusted settling velocity **Vs'** = settling velocity **Vs** x Shape factor x Hindrance factor x Areal efficiency.