3.
FLOW OF MIXTURE IN A PIPELINE

3.1 FLOW REGIMES AND PATTERNS

3.1.1 Flow regimes

Generally, a carrying liquid may flow either in a LAMINAR or a TURBULENT regime in a pipeline. A laminar flow is composed of thin layers (lamina) that move over each other at different velocities forming a typical parabolic velocity profile in a pipeline cross section. There is no exchange of mass and momentum between neighboring layers. Thus each liquid particle has zero velocity components in directions other than is that of the flow and this is given by an axis of a conduit. A stability of a laminar flow is given by Reynolds number of the flow and its value 2300 is experimentally determined as a threshold for the maintaining of a laminar flow regime in a conduit. From this it is clear that a laminar regime can hardly occur in a dredging pipeline when the flowing carrying liquid is water. This has the value of kinematic viscosity of about 10^{-6} m^2/s and considering the diameter of a dredging pipeline of a typical value 1 meter, the velocity of a carrier should be maximally 2.3 mm/s to maintain a laminar regime of flow. However, a *laminar flow is maintained to higher velocities when viscosity of the carrier is higher* than that of water. This is the case when non-settling or very-slowly-settling solid particles are transported at high concentration with water in a pipeline. Water and very fine particles form together a carrier of high density and viscosity. As a result the laminar flow might occur in a dredging pipeline if highly dense non-settling mixtures are transported. In practice, however, the operational velocity is often higher than the threshold velocity for a laminar flow even for these high concentrated non-settling mixtures. A turbulent flow is a result of disturbances occurring at the interface between neighboring layers if the difference in their velocities becomes higher than is acceptable for maintenance of the laminar regime. *Turbulent eddies* are developed as a result of the disturbances. The turbulent eddies are responsible for an intensive random transfer of mass and momentum in all directions within a liquid stream. This is sensed as a continuous fluctuation of velocity of fluid particles in time and space within a stream. The turbulent flow regime is typical for dredging pipelines. The flow eddies due to turbulence produce energy dissipation additional to that due to friction in a laminar flow. Turbulent flows dissipate much more mechanical energy than laminar flows.

3.1.2 Flow patterns

A tendency of a solid particle to settle in a flowing carrying liquid and a tendency of a flowing carrier to suspend solid particles are the most important indicators of a pattern of a flow of solid-liquid mixture in a pipeline. The settling tendency of a solid particle to settle is given by the *particle settling velocity* and the tendency of a carrying stream to suspend the solid particles is given an *intensity of turbulence*, i.e. basically by mean velocity of a stream in a pipeline. The mixture flow is considered FULLY STRATIFIED if intensity of turbulence of a carrier flow is not sufficient to suspend any solid particle in a pipeline. Then all solid particles occupy a granular bed that is either stationary or slides over the bottom of a pipeline. The opposite extreme to the fully-stratified flow is a FULLY-SUSPENDED flow in which all solid particles are suspended within a stream of a carrying liquid. No granular bed occurs in a pipeline. The fully-suspended flow may be considered pseudo-homogeneous if a distribution of solid particles across a cross section of a stream is almost uniform. This is usually the case if solid particles of silt or clay size are transported in a pipeline. Fully-suspended flow exhibiting a certain concentration gradient across a stream is typical for fine to medium sand mixtures flowing at high velocities. An intermediate flow pattern – the PARTIALLY-STRATIFIED flow – is most usual during dredging operations. A mixture flow exhibits a considerable concentration gradient across a pipeline cross section indicating an accumulation of a portion of solids near the bottom of a pipeline and a non-uniform distribution of the rest of solids across the rest of a pipeline cross-sectional area. This pattern is also known as a heterogeneous flow.

The following flow patterns occur in dredging pipelines:

Homogeneous flow of non-Newtonian mixtures
– flow of clay and silt mixtures at high concentrations

Pseudo-homogeneous flow of Newtonian mixtures
- coarse silt or fine sand mixtures (in case of fine sand the velocities must be considerably higher than is the deposition-limit velocity)

Slightly-stratified heterogeneous flow (partially-stratified flow without a stationary deposit)
- medium or medium to coarse sand mixture in which a majority of solid particles is suspended and only a small portion of particles travels within a granular bed

Very-stratified heterogeneous flow
- medium to coarse sand, coarse sand or fine gravel mixture in which a majority of solid particles travels within a granular bed and only a small portion of particles is suspended (in case of fine gravel the velocities must be considerably higher than is the deposition-limit velocity)

Fully-stratified flow with an eroded top of the bed
- fine to medium or medium gravel mixture in which a great majority of solid particles travels within a granular bed and only a small portion of particles is either sheared or moves by jumping and rolling (the process called "saltation") over the top of the sliding granular bed

Fully-stratified flow
- medium to coarse or coarse gravel mixture or mixture containing cobbles and boulders, in this flow all solid particles travel within a granular bed

The particle settling velocity and the mean mixture velocity (indicating a measure of an intensity of turbulence in a mixture stream) are the most important parameters to determine the flow pattern in a dredging pipeline. A pipeline size is an additional parameter influencing the pattern. This might play an important role if flows are scaled from laboratory pipes (typically of a diameter between 50 mm and 150 mm) to dredging pipelines (a diameter between 500 mm and 1200 mm).

If the velocity in a dredging pipeline is too low the carrier stream might be incapable to keep all solid particles (of sand size and coarser) in motion. The bed composed of solid particles settled at the bottom of a pipeline will not slide and *the flow pattern with a stationary bed* develops. As discussed later, a pipeline operation with such flow pattern is inefficient and potentially dangerous.

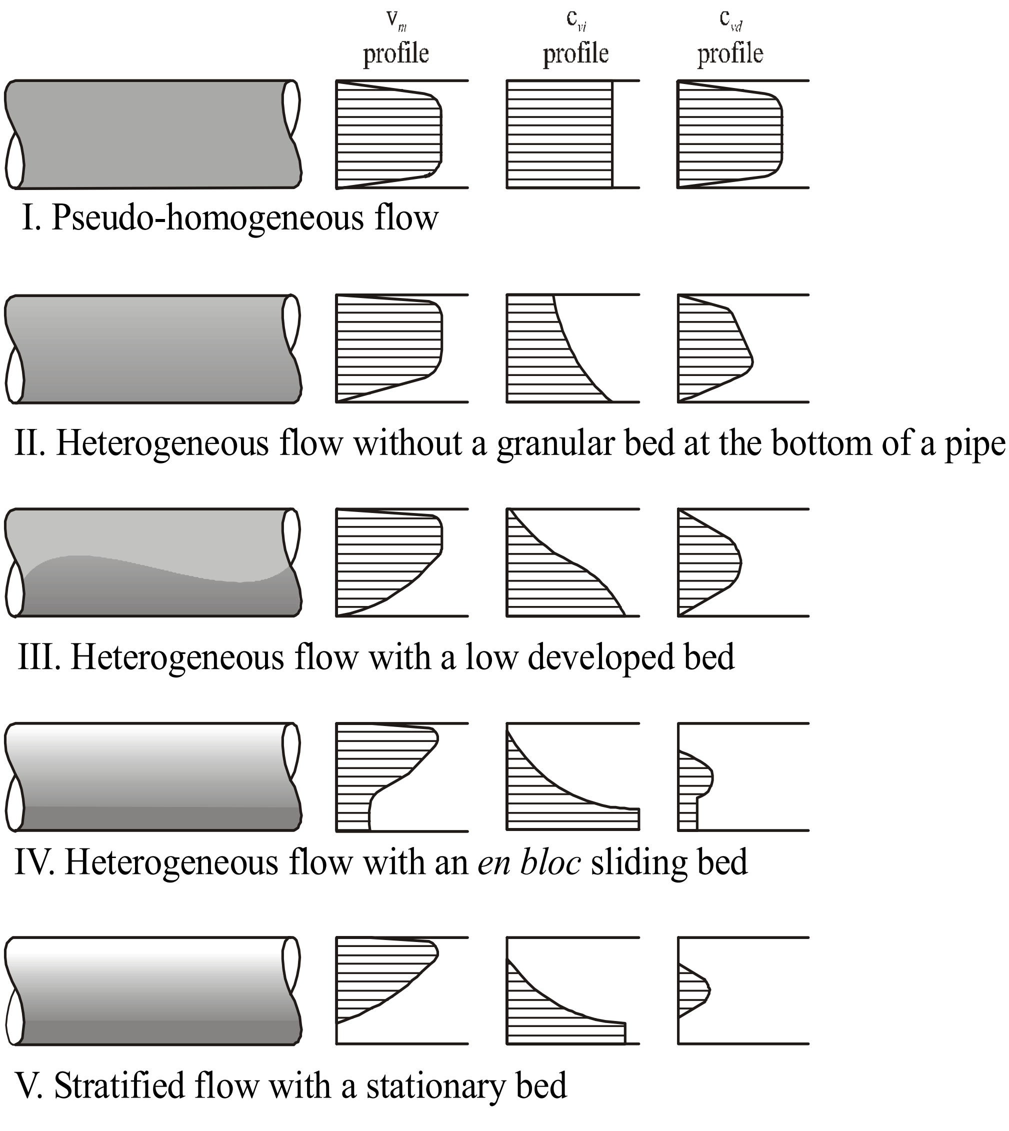

Figure 3.1. Various patterns of mixture flow with distributions of mixture velocity (v_m), spatial concentration (c_{vi}) and delivered concentration (c_{vd}).

Knowledge of a flow pattern in a dredging pipeline is important for the design and prediction of operational parameters of a dredging pipeline. Important parameters for the design and operation of a dredging pipeline are those which provide information about the safety and economy of dredging pipeline operation. These are:

- the mean mixture velocity and its important values
- the production of solids
- the frictional head loss
- the specific energy consumption.

3.2 MEAN MIXTURE VELOCITY AND ITS IMPORTANT VALUES

3.2.1 Definition

Mean velocity in a pipeline is a basic parameter characterizing pipeline flow. It is defined as the bulk velocity, V, of a matter (liquid, solids, mixture) obtained from the volumetric flow rate, Q, of a matter passing a pipeline cross section of the area, A. The equation V = Q/A is for a circular pipe of an inner diameter D written as

$$V = \frac{4Q}{\pi D^2} \quad (3.1).$$

V	bulk velocity, i.e. mean velocity of a matter in a pipe cross section	[m/s]
Q	volumetric flow rate of a matter in a pipe	[m^3/s]
D	pipe diameter	[m]

The determination of an appropriate mean mixture velocity, V_m, is crucial to safe and low-cost pipeline operation.

3.2.2 Deposition-limit velocity

Solid particles of sand/gravel size and density tend to settle in a flowing carrier. Usually, these solid particles are distributed non-uniformly in a pipeline flow. If the carrier velocity is too low for the carrier lift forces to suspend all solid particles, a portion of the particles forms a bed at a bottom of a slurry pipeline. With extremely large particles and/or extremely low mean velocities in a pipeline all particles occupy a bed. The threshold velocity at the initiation of turbulent suspension, V_{tt}, is the mean velocity of the mixture in a pipeline cross section at which the first solid particles leave the bed, being supported by the diffusive effect of carrier turbulent eddies. This velocity is used in the evaluation of a measure of a flow stratification, but for practical pipeline operation the threshold velocity at which solid particles occupying a bed at the bottom of a pipeline stop their sliding and start to form a stationary deposit, i.e. a stationary bed, is more important. Operation below this threshold velocity might be inefficient and potentially dangerous. Under certain circumstances a stationary deposit may be transformed into a solid plug which blocks the pipeline. The mean slurry velocity at the limit of stationary deposition is called the deposition-limit velocity, V_{dl}, or, less accurately, the *critical velocity*. Slurry flow at velocities above the deposition-limit value is free of a stationary deposition.

3.2.3 Minimum velocity

The mean slurry velocity at which the least energy is dissipated in slurry flow is called the minimum velocity, V_{min}. The minimum slurry velocity determines the velocity at which the slurry flow is most economical of energy. This is the optimal transport velocity for slurry of a given slurry density. It is well known, however, that the minimum velocity is not a viable operation velocity in a conveying system. In practice the operation velocity, a result of an interaction between a pipeline and a pump, is taken as $V_m > V_{min}$. This avoids an unstable transport regime in a conveying system experiencing a variation in V_m.

At the minimum velocity the hydraulic gradient (see below) is minimal (Fig. 3.3). Therefore the derivative of the hydraulic-gradient correlation I_m = fn(V_m, etc.) (see Chapter 4) determines a relationship between the minimum velocity and additional parameters of mixture flow: $dI_m/dV_m = 0$ at $V_m = V_{min}$.

3.2.4 Relation between deposition-limit velocity and minimum velocity

Sometimes the deposition-limit velocity is considered equal to the minimum velocity (Fig. 3.2). In majority of slurry pipeline conditions, however, the deposition-limit velocity and the minimum velocity differ. To estimate V_{dl} as equal to V_{min} might be acceptable for low-concentration flows but fails for high concentrated flows. Actually, the trends seem to be opposite in a development of V_{dl} and V_{min} when solids concentration grows in a pipeline. The deposition-limit velocity tends to drop while the minimum velocity tends to grow (see a 0.20-0.50 mm sand in Fig. 3.5).

Some authors have tried to relate the minimum and the critical velocity by using coefficient of proportionality ξ as

$$V_{min} = \xi V_{dl} \qquad (3.2)$$

(e.g. $\xi = 0.64/\sqrt[6]{D}$ according to Jufin & Lopatin, 1966).

3.3 PRODUCTION

3.3.1 Definition

The *flow rate of solids* transported through a dredging pipeline is termed production in the dredging practice. This is an important parameter from the economic point of view. It gives the amount of dry solids (in volume or mass) delivered at the pipeline outlet over a certain time period. It is defined as the flow rate (either volumetric, Q_s, in m^3/s or mass in kg/s) of solids at the outlet of a slurry pipeline.

3.3.2 Production of solids (on the dry-weight basis)

In the dredging practice the volumetric flow rate is handled rather than the mass flow rate and the production $Q_s = Q_m C_{vd}$ is calculated as

$$Q_s = \frac{\pi}{4} D^2 V_m C_{vd} 3600 \quad \left[\frac{m^3}{hour}\right] \qquad (3.3).$$

Q_s	volumetric flow rate of solids, i.e. production of solids	$[m^3/s]$
D	pipe diameter	[m]
V_m	mean mixture velocity	[m/s]
C_{vd}	volumetric delivered concentration of solids	[-].

During a dredging operation the parameters V_m and C_{vd} are usually measured in a pipeline of known D so that the production of solids given by a solids flow rate can be determined.

3.3.3 Production of in-situ soil

For the payment of a dredging work, however, the production based on in-situ volume of transported soil is decisive. As discussed in Chapter 2 the in-situ volume of soil is composed of the volume of solid particles and of the volume of pores in an in-situ soil body. The delivered concentration of the in situ soil $C_{vdsi} = \frac{C_{vd}}{1-n}$ so that the production of in-situ soil can be calculated as

$$Q_{si} = \frac{\pi}{4} D^2 V_m C_{vdsi} 3600 = \frac{Q_s}{1-n} \quad \left[\frac{m^3}{hour}\right] \qquad (3.4).$$

Q_{si}	production of in-situ soil	$[m^3/s]$
Q_s	production of solids	$[m^3/s]$
n	porosity for in-situ soil	[-]
D	pipe diameter	[m]
V_m	mean mixture velocity	[m/s]
C_{vdsi}	volumetric delivered concentration of in-situ soil	[-].

Since the porosity gives a value lower than one (typically n=0.4 for a loose-poured sand), the production of in situ soil is higher than the production of the solid particles.

3.4 FRICTIONAL HEAD LOSS (HYDRAULIC GRADIENT)

3.4.1 Definition

Flow resistance is given by the amount of mechanical energy dissipated in a slurry flow when flowing through a pipeline. The mechanical energy balance along a pipeline section - expressed by the Bernoulli equation - shows that energy dissipation in a steady slurry flow is characterized by the pressure difference along a horizontal pipeline section of constant diameter. The resistance is evaluated as

- the *pressure drop* $\Delta P = P_1 - P_2$ (differential pressure over a pipeline section confined at the inlet by the pipeline cross section 1 and at the outlet by the pipeline cross section 2) [Pa],

- the *pressure gradient* $\frac{\Delta P}{L}$ (pressure drop over a pipeline section divided by the length L of a pipeline section between cross sections 1 and 2) [Pa/m] or

- the *hydraulic gradient* $\frac{\Delta P}{\rho_f g L}$ due to friction, also termed the frictional head loss (I_m) (head that is lost owing to friction is divided by the length of a pipeline section, L), which is dimensionless and expresses the pressure gradient by the ratio of meter liquid column and meter pipeline length.

Head, $\frac{\Delta P}{\rho_f g}$, is a measure of the mechanical energy of a flowing liquid per unit mass. It is expressed as the height of the fluid column exerting the pressure, which is equivalent to the pressure differential over a pipeline section.

The sum of the hydraulic gradient due to friction in straight pipeline sections, the hydraulic gradient due to minor losses in fittings (see Chapter 7) and the geodetic gradient (the potential energy gain or loss in a mixture from different geodetic heights at an inlet and an outlet of a pipeline, see Chapters 6 and 7) determine the amount of energy which has to be fed by pumps to mixture flow in a pipeline.

3.4.2 Pipeline-resistance curve

A relation between the mechanical dissipation due to mixture flow through a pipeline and the mean mixture velocity is expressed in a pipeline-resistance curve. This relates the head $\frac{\Delta P}{\rho_f g}$ (in meter water column) lost due to friction in a straight pipeline with the mean mixture velocity V_m (see Fig. 3.2).

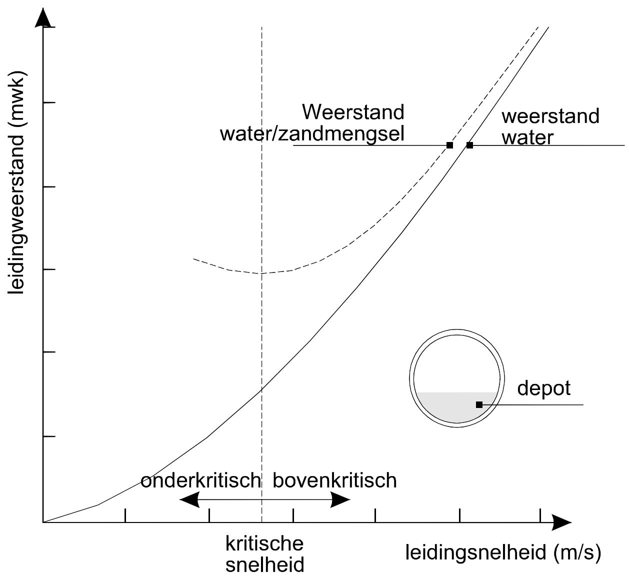

Figure 3.2. A typical course of a pipeline-resistance curve for water flow and mixture flow.

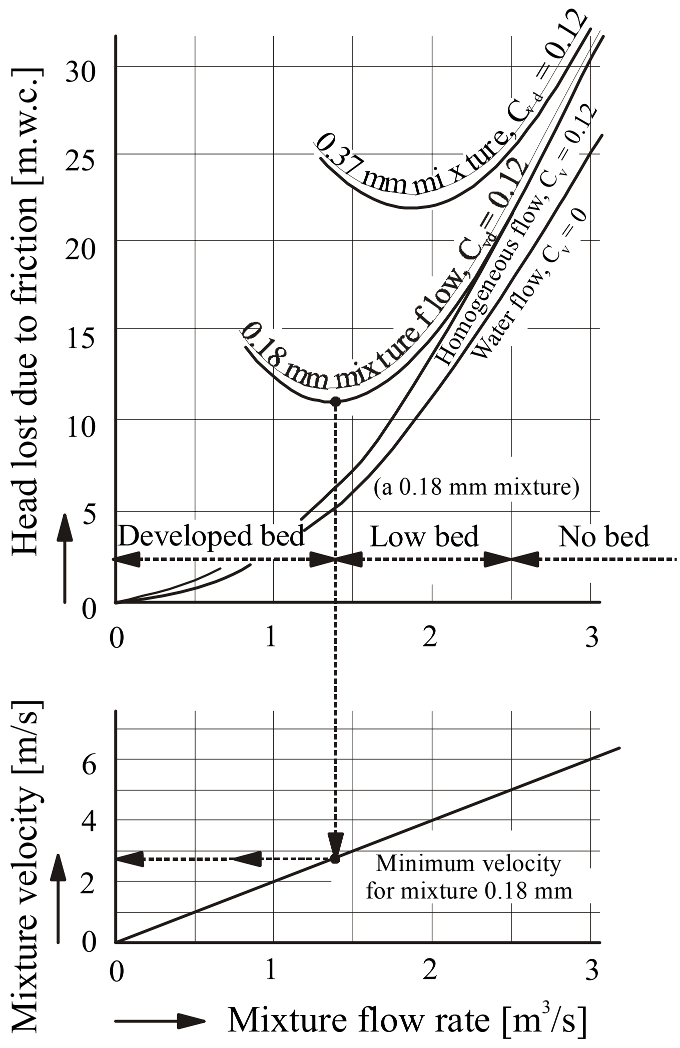

Figure 3.3. Typical courses of a resistance curve for various sand mixtures (in a 800 mm pipeline).

3.4.3 Course of a pipeline-resistance curve

3.4.3.1 Theoretical considerations

A course of a resistance curve within a wide velocity range indicates different flow patterns that occur in a pipeline. A resistance curve for water flow in a pipeline is a parabolic curve. The pseudo-homogeneous flow of fine solids is represented by a parabolic curve also, only the gradient of a curve is higher (see Fig. 3.3).

Heterogeneous flows are characterized by resistance curves that exhibit the minimum at so called "minimum velocity" (see Figs. 3.3 & 3.4). A descending curve section at velocities below the minimum velocity indicates a developed stationary or sliding bed.

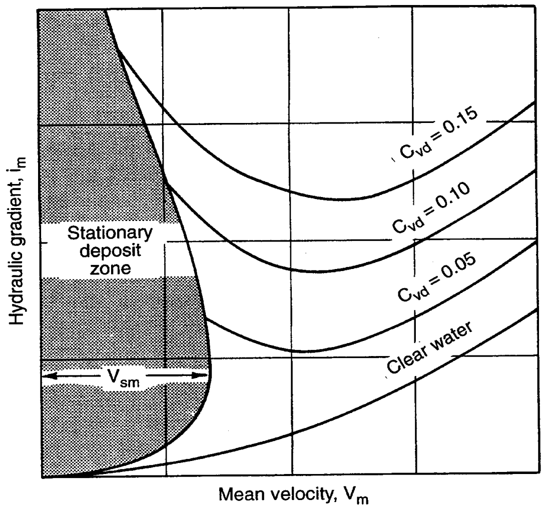

Figure 3.4. Resistance curves and stationary-bed zone.

A threshold velocity between a stationary bed and a sliding bed is illustrated on Fig. 3.4 (the threshold velocity V_{dl} is sensitive on the concentration of solids in a pipeline). If the velocity increases above the minimum velocity value the bed gradually dissolves (particles gradually loose their mutual contacts and they become suspended by a carrying liquid).

3.4.3.2 Experimental observations

The Figure 3.5 shows resistance curves (representing here the hydraulic gradient due to friction in a 1-meter horizontal pipe versus mean mixture velocity) for flows of different soil sorts in a 150-mm pipeline of a test loop in Laboratory of Dredging Technology of Delft University of Technology. Shapes of measured resistance curves are very different for various sand and gravel sorts. Furthermore, shapes of measured resistance curves are very sensitive to concentration of solids in tested mixture flows.

Generally, flow friction increases with both the particle size and the concentration of solids in a pipeline. A shape of a pipeline-resistance curve is very different for fine solids and coarse solids:

- A resistance curve of a fine sand (0.10-0.12 mm sand) indicates a slightly stratified heterogeneous flow within a velocity range 1.5 – 4.0 m/s. At velocities higher than 4.0 m/s the flow may be considered pseudo-homogeneous.

- The curves for a medium sand (0.20-0.50 mm sand) indicate a considerable flow stratification near the deposition-limit velocity and a gradual bed dissolution within a velocity range 3 – 5 m/s. The pseudo-homogeneous flow regime is reached at velocities higher than 6 m/s.

- The resistance curves for coarse sand (0.50-1.00 mm sand) indicate that an interaction between a developed granular bed and suspension flow above the bed governs a flow behavior at velocities not far above the deposition-limit threshold. The bed is sheared due to a fast current of suspension above the bed within a range of mean velocity values near the deposition-limit velocity. Bed shearing results to a relatively low friction loss. Bed shearing is gradually dumped if velocity increases (3 – 4 m/s) and the compact bed is restored – friction increases rapidly. The bed is disintegrated and a portion of solids resuspended if the velocity grows further (4 – 7 m/s).

- The resistance curves for a gravel flow (3.0-5.0 mm gravel) show that the frictional head loss drops when the steady sliding of a granular bed is reached by increasing velocity above the velocity range in which an unstable sliding-stopping bed was observed (2.2 – 3.5 m/s). A further increase in the mean velocity does not provide a decrease of the difference between the frictional loss values for mixture and for water. This is an indication that the sliding bed is not disintegrated even at high mean mixture velocities. The flow remains stratified.

The Figure 3.5 shows also that the values of deposition-limit velocity, V_{dl}, vary with the concentration and that the deposition-limit velocity differs from the minimum velocity in flows of high concentrations of solids. The value of the deposition-limit velocity coincides with the minimal velocity ($V_{dl} = V_{min}$) only if the initial sliding of the bed and the initial disintegration of the bed occur at the same velocity. $V_{dl} < V_{min}$ if the bed is thick enough to slide *en bloc* before it starts to be initially disintegrated.

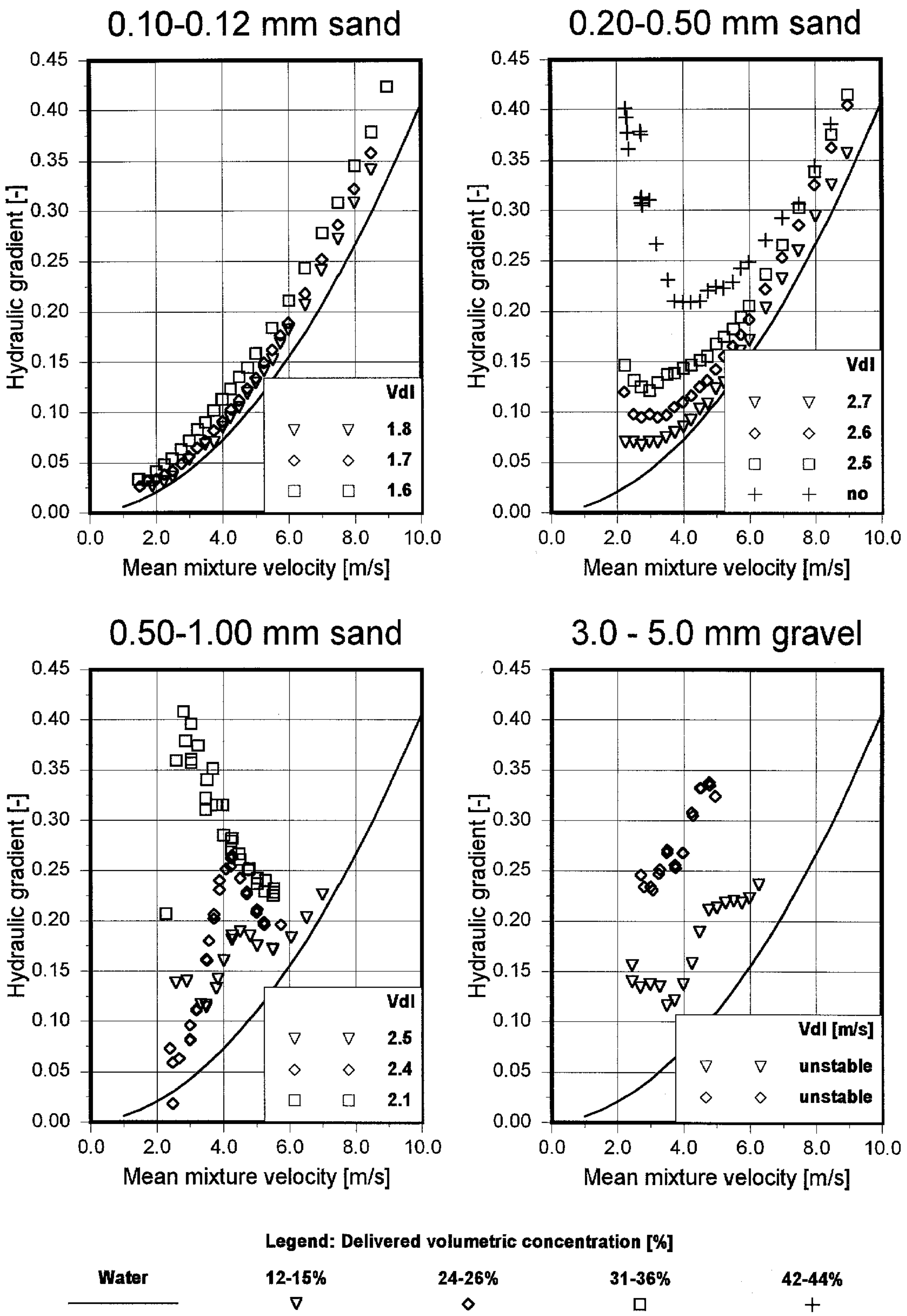

Figure 3.5. Experimentally determined resistance curves and deposition-limit velocities for mixture flows of various materials and various mixture densities. (Data: Laboratory of Dredging Technology, Delft University of Technology)

3.5 SPECIFIC ENERGY CONSUMPTION

3.5.1 Definition

The efficiency of a slurry pipeline is evaluated by means of a parameter called specific energy consumption (SEC). The SEC is an appropriate optimization parameter because it contains both a measure of energy dissipation and of solids load in a pipe flow. The SEC determines the energy required to move a given quantity of solids over a given distance in a pipeline. It is defined as a ratio between the power consumption per meter of pipe and the (dry) solids throughput in a pipe.

Power consumption per meter of a pipe is given by $I_m.\rho_f.g.Q_m$ and solids throughput (mass flow rate of solids) is $\rho_s.C_{vd}.Q_m$.

Then

$$SEC = \frac{I_m g}{S_s C_{vd}} \quad \text{in units} \quad \left[\frac{J}{kg.m}\right] \qquad (3.5)$$

or in more practical physical units

$$SEC = 2.7\frac{I_m}{S_s.C_{vd}} \quad \left[\frac{kWh}{tonne.km}\right] \qquad (3.6).$$

SEC	specific energy consumption	[kWh/tonne-km]
I_m	frictional head loss	[mH_2O/m']
g	gravitational acceleration	m/s^2]
S_s	relative density of solids	[-]
C_{vd}	volumetric delivered concentration of solids	[-].

3.5.2 Specific power consumption

A similar parameter - *specific power consumption* (SPC) - can be derived for flow in a vertical pipe section of a length L that is connected with a pump outlet. The input power to the pipe section is given by the output power of the pump $\rho_f.g.Q_m.H$. The output power of a pipe section is given by the work done to transport the solids (of mass m_s) over a pipe length L in a unit time period Δt. The output power is actually the power supplied to solids and it is expressed as $m_s.g.L/\Delta t$, i.e. $\rho_s.g.Q_s.L$ or $\rho_s.g.C_{vd}.Q_m.L$. The efficiency of the system represented by a pipe section is then

$$\eta_s = \frac{\rho_s.g.Q_m.C_{vd}.L}{\rho_f.g.Q_m.H} = \frac{S_s.C_{vd}.L}{H} \quad \left[\frac{W}{W}\right], \quad \text{i.e. [-]} \qquad (3.7).$$

η_s	efficiency of the pump-pipe system	[-]
L	length of a pipe	[m]
H	pump head	[m]
S_s	relative density of solids	[-]
C_{vd}	volumetric delivered concentration of solids	[-].

The SPC is the inverse of the efficiency. For a horizontal pipe this derivation loses its physical meaning because no potential energy is added to the solids during the flow in a horizontal pipe, thus no work is done on solids. However, the economic significance of the parameter remains valid. The ratio H/L is now the frictional head loss I_m and

$$SPC = \frac{I_m}{S_s C_{vd}} \qquad [-] \qquad (3.8)$$

A comparison of equations gives SEC = g.SPC.

3.5.3 SEC – Production diagram

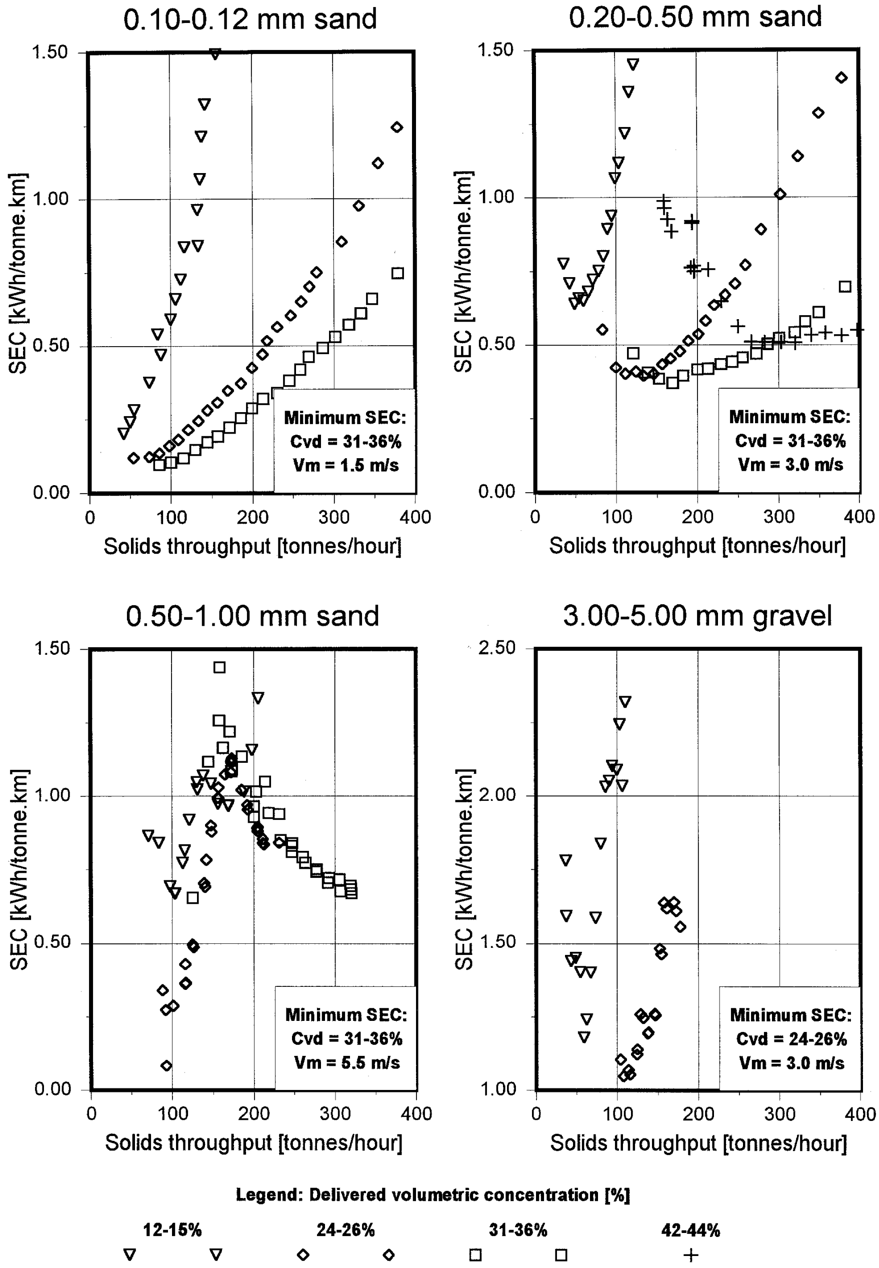

Figure 3.6. Relationship between SEC and production for various sorts of sand and various mixture densities in a 150 mm pipeline.
(Data: Laboratory of Dredging Technology, Delft University of Technology)

The SEC is plotted against solids throughput (the production of solids) in Fig. 3.6 for flows of various solids tested in a 150 mm pipeline of the test loop in the Laboratory of Dredging Technology of Delft University of Technology. The lowest values of the specific energy consumption were found for mixtures of the volumetric concentrations of solids higher than 25%, flowing at mean velocities equal/similar to the minimum velocity, V_{min}.

According to Fig. 3.6 the specific energy consumed to transport medium sand is approximately twice that needed to transport fine sand if transport velocity approaches the minimum velocity in the 150 mm pipeline. The specific energy consumed to transport coarse sand is approximately twice that needed to transport medium sand.

3.6 REFERENCES

Jufin, A.P. & Lopatin, N.A., (1966). O projekte TUiN na gidrotransport zernistych materialov po stalnym truboprovodam. *Gidrotechniceskoe Strojitelstvo*, **9**, 49-52.