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Solids Transportation in a Long Pipeline Connected with a Dredge

Abstract

Extensive field measurements on a dredging installation with a pipeline that is approximately 10 km long and has three booster stations in series, have shown that, contrary to expectations, density fluctuations in slurry flow generated in a system inlet are not flattened. Whilst passing along the pipeline with pumps in series, they are transformed into long density waves with high amplitude.

This phenomenon is typical for dredging operations because it is effective only in long pipelines with slurry flow of continuously fluctuating density. Only on-line measurements at several measuring sites along the whole conveying system can detect the phenomenon. For this reason it has not been explicitly observed and analysed yet.

A mechanism for material aggregation and the development of an internal structure of slurry flow in a long pipeline are analysed under a condition of continuously fluctuating slurry density. Data are interpreted by using the physical two-layer model to verify factors arising from the analysis of a process of material aggregation. To enable a simulation of the phenomena observed in the slurry pipeline connected with a dredge, a recommendation for a physical model configuration is submitted.

The data interpretation issues are verified experimentally in a laboratory circuit. MeaVli data are published with permission of Royal Boskalis Westminster N.V. This paper was first published in the proceedings of the WODCON, *Dredging Benefits,* Volume 1, pp. 55-73. It is reprinted here with permission in a revised version which includes verification by laboratory tests.

Introduction

An unsteady state of solids flow has interesting effects on the internal structure of mixture flow in a long conveying pipeline. From these a process of material aggregation along a long pipeline and the behaviour of solid particles settled at the bottom of a pipeline are of a major interest. An aggregation process may have an influence on the efficiency and safety of the system

Winner of the IADC Award, Mr Vaclac Matousek, is pictured here (right) with Mr Peter Hamburger, Secretary General of the IADC, at the IADC booth at the Europort Exhibition which ran simultaneously with the World Dredging Congress.

IADC Award 1995

Presented during the XIVth World Dredging Congress and Exhibition, Amsterdam, The Netherlands November 14-17 1995

At the XIVth WODCON held in Amsterdam in November 1995, Mr Vaclav Matousek was presented the IADC Award by Dutch Minister of Transport Mrs. A. Jorritsma who officially opened the WODCON.

Mr Matousek received his MSc from Czech Technical University in Prague in 1986. After working at the Czech Academy of Sciences, in 1992 he came to Delft University of Technology where he joined the Faculty of Mechanical Engineering and Maritime Technology as a PhD student in Dredging Technology.

Each year at a selected conference the IADC grants an award to a paper written by a young author. The Paper Committee of the conference is asked to recommend an author who must be under 35 years of age, and whose paper makes a significant contribution to the literature on dredging and related fields. The purpose of the award is “to stimulate the promotion of new ideas and encourage younger men and women in the dredging industry”. The IADC Award consists of US$ 1,000, a certificate of recognition and publication in *Terra et Aqua.*

operation. Prediction of the aggregation process together with an accurate estimate of the critical velocity in a pipeline may lead to a more effective control of the diesel engines and other types of drive used by the drive of a conveying system.
The phenomena characteristic for the development of an internal structure of unsteady solids flow in a long pipeline can be described and simulated in a simplified way by a physical model.

MEAVLI DATABASE: FIELD MEASUREMENTS ON A LONG CONVEYING SYSTEM

Field measurements on a long conveying system composed of the dredge *Groningen* (Figure 1) and a long slurry pipeline with three booster stations in series *(Zaandam, Jagersplas, Duinjager)* were carried out by the Department of the Technology of Soil Movement of Delft University of Technology and the dredging company Royal Boskalis Westminster N.V. during works on the project "de Vlietlanden". A database collected in 1981 (rather huge with its almost 2 GB of information in a mainframe storage) has been named MeaVli (Measurements Vlietlanden) database. The purpose of the dredging project was to supply material, dredged from the bottom of the artificial lake Vlietlanden, to the construction of the new highway junction Prins Clausplein near The Hague. A fine to medium sand with a mean particle diameter varying approximately from 150 to 300 μm was conveyed in a long pipeline the major part of which was horizontal and of DN650. The system was fed by the deep-dredger *(Groningen,* Gr) and driven by one water-based *(Zaandam,* Za) and two land-based booster stations *(Jagersplas,* Ja; *Duinjager,* Du). During a twelve-day experimental programme a large set of data, containing measured data of pumps *(Groningen, Jagersplas* and *Duinjager)* and pipeline operational parameters, was collected.
This database is unique experimental material, monitoring the real processes in a full-scale long slurry pipeline with unsteady flow of sand-water mixture. It covers the time-continuous on-line observations of the most important parameters along the entire long conveying system during a dredging operation. The process of field measurements, the measurement techniques and an organisation of a collected database have been described elsewhere (Duizendstra, 1987a,b,c; Matousek, 1994; de Vries, 1981).

Two types of experimental measurements were carried out on a dredging installation and two types of data files were acquired during the field measurements:

- Data files (A): a time continuous on-line measurement of pumps and pipeline operational parameters of the entire system of a dredger, pipeline sections and three booster stations in series (acquired data files have 45 channels)
- Data files (B): a time continuous on-line measurement of solids velocity profiles in the pipeline cross section at one measuring place on the slurry pipeline; in conjunction with basic integral slurry flow parameters in the pipeline (acquired data files have 14 channels).

To evaluate the phenomena observed in a pipeline, both types of acquired data files have to be analysed. Data files (A) detect a phenomenon of a material aggregation in slurry flow when transported in a long pipeline. Data files (B) describe, in a simplified way, an internal structure of solids flow with slurry density fluctuations in the pipeline and they are the basis for an analysis of the phenomenon detected in data files (A). A relationship between the velocity of solid particles at the bottom of the pipeline and slurry density in the

Nomenclature

c_v	local volumetric concentration at some position in pipe cross-section	[1]
C_{cod}	delivered volumetric concentration of solids in contact load	[1]
C_{vd}	delivered volumetric solids concentration in pipe cross-section	[1]
$C_{vp}(C_{vi})$	spatial volumetric solids concentration in pipe cross-section	[1]
C1	volumetric concentration of solids in upper layer	[1]
C2	volumetric concentration of solids in lower layer	[1]
d	particle diameter	[m]
d_s	mean particle diameter	[m]
d_{50}	mass-median particle diameter	[m]
D	internal diameter of a pipe	[m]
I_m	friction loss of slurry flow in a pipe	[mH_2O/m']
V_b	solids velocity at the bottom of a pipe	[m/s]
V_m	mean velocity of mixture	[m/s]
V_s	mean velocity of solids	[m/s]
V_s1	mean velocity of solids in upper layer	[m/s]
$V_s2(V_2)$	mean velocity of solids in lower layer	[m/s]
γ	vertical distance defining a position in pipe cross-section	[m]
Y_b	thickness of bed layer	[m]
α	angle defining a position in pipe cross-section	[deg]
ρ_m	density of mixture	[kg/m^3]

Abbreviations

DIM	Data Interpretation Model
DTI	Data Transfer and Interpretation
PSD	Particle Size Distribution
SRC	Saskatchewan Research Council
2LM	Two-Layer Model

pipeline can also be correlated for approximately constant mean slurry velocity from data files (B).

Phenomena Observed in a Long Slurry Pipeline

Two interesting phenomena were observed in the pipeline when MeaVli database had been processed:
- an aggregation of material into long density waves with a high amplitude within a slurry stream in a long pipeline (Figure 2);
- a variation in velocity of solid particles at the bottom of a pipeline as a result of fluctuating slurry density in a pipeline (Matousek, 1995c).

During dredging operations slurry density varies in time and space along the entire long pipeline of a conveying system. The controlled global operational parameters of the system (slurry flow rate through the conveying system, rpm of pumps) are assumed to be maintained at an approximately constant level during the whole operational period of the system. That was also the case during the field measurements of the MeaVli project.
A fluctuating density which enters the system and moves through the pipeline is detected at three measuring sites along the pipeline length by the radioactive density meters and interpreted as the moving density waves in the pipeline. A material aggregation phenomenon, which is observed along the long pipeline, is demonstrated by a transformation of density waves which are moving along the pipeline. From analysis of MeaVli pumps data (torque and rpm measurements at the Gr, Ja, Du pumps) the influence of a pump performance on density waves transformation has been observed to be negligible. An aggregation mechanism is active in the pipeline.
When unsteady solids flow in a long pipeline is modelled by means of basic hydrodynamic equations, including transport and turbulent dispersion effects (Basco, 1977), the fluctuating slurry density entering the system is assumed to be gradually flattened and become almost constant in time and space along the pipeline. This mechanism may be effective in a short time and length scale and may cause a flattening of short-time density fluctuations behind a dredge pump (compare Gr and Ja density signals of Figure 2). Over a longer time and length scale (more suitable for a description of the process in a pipeline which is more than 10 km long, in which each particle needs almost one hour to reach its destination from the bottom of a lake) a mechanism of slip between phases may be prevailing. With respect to the specific flow conditions in a long slurry pipeline connected with a dredge, it is believed that a process of material aggregation is caused by the variable slip in an unsteady solids flow along the long pipeline. It is a product of an instability of solids flow along the pipeline. More detailed analysis of the phe-

Figure 1. Suction dredger Groningen *at work.*

nomenon has been published previously (Matousek, 1995a), so only a brief description is given here.
Slurry density, a major variable parameter of the transport system, produces an unsteady solids flow along the pipeline even when a slurry flow is considered steady. Stability of solids flow in steady slurry flow in a pipeline of constant pipeline diameter is characterised by constant mean solids velocity in pipeline cross section along the whole long pipeline.
Because a relationship between slip and slurry density is expected (different level of mutual particles hindrance), mean solids velocity varies in different pipeline cross-sections throughout the pipeline. This V_s variability along the pipeline causes a relative material transfer among moving density waves, which results in a transformation of density waves. To evaluate an aggregation mechanism the parameters characterising the mean slip in the pipeline cross section must be evaluated. These parameters are V_s and V_m or C_{vd} and C_{vp}. For MeaVli data processing this means a requirement to determine V_s from measured velocity profiles in a pipeline cross section for all flow conditions occurred. Then a ratio V_s / V_m, called slip ratio and considered as a parameter describing a mechanism of a material aggregation in slurry flow in a long pipeline, can be evaluated. To accomplish this, a physical model, described below, is used to process the MeaVli data.

According to particle size distribution (PSD) curves from slurry samples collected during MeaVli measurements the PSD of dredged material is rather wide. A transported material (of particle diameter d_{50} approximately 0.2 mm) contained a portion of sand coarser than 0.6 mm (approx. 10% of the total amount of a transported material) but also a silt finer than 0.075 mm (approx. 12% of a transported material). PSD together with a flow regime causes a certain degree of slurry flow stratification in the pipeline cross-section. The stratification has been observed in the MeaVli pipeline, as it is seen from a shape of measured solids velocity profiles (Figure 3).
The structure of a stratified flow in the pipeline matches the pattern of a physical two-layer model (2LM) developed originally by Wilson. Its physical background has been published (e.g. Wilson, 1988;

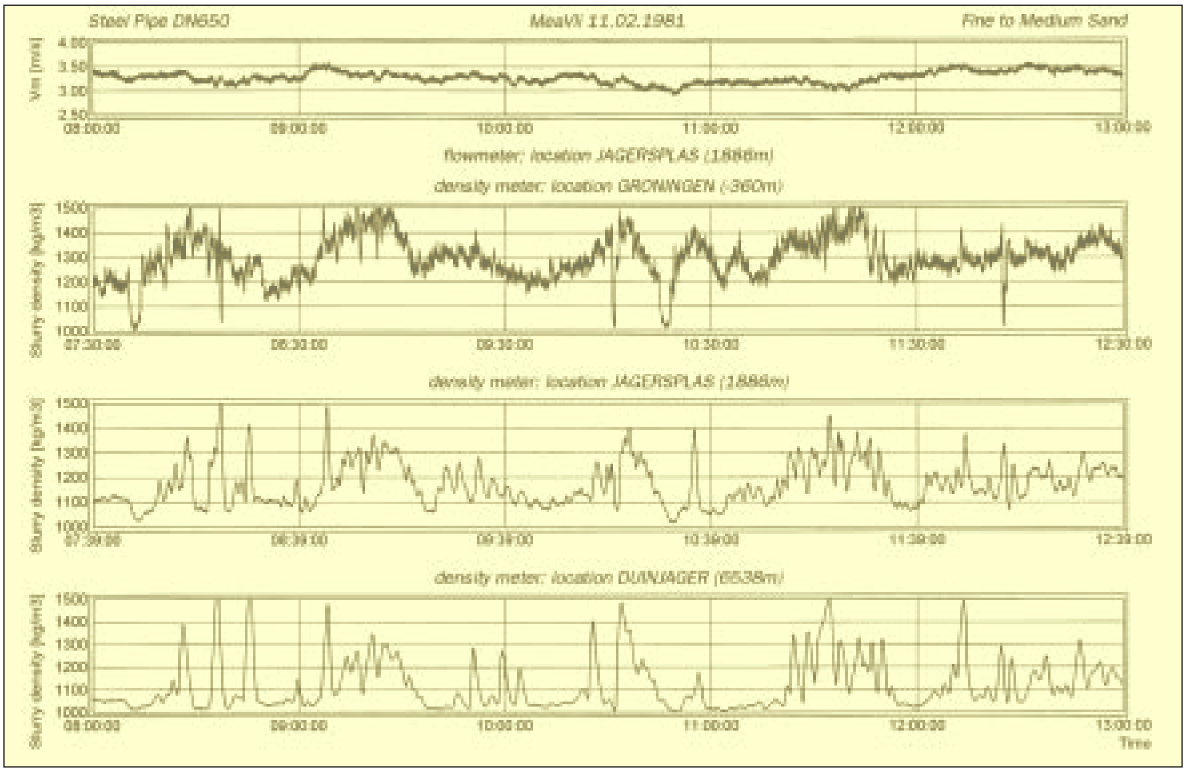


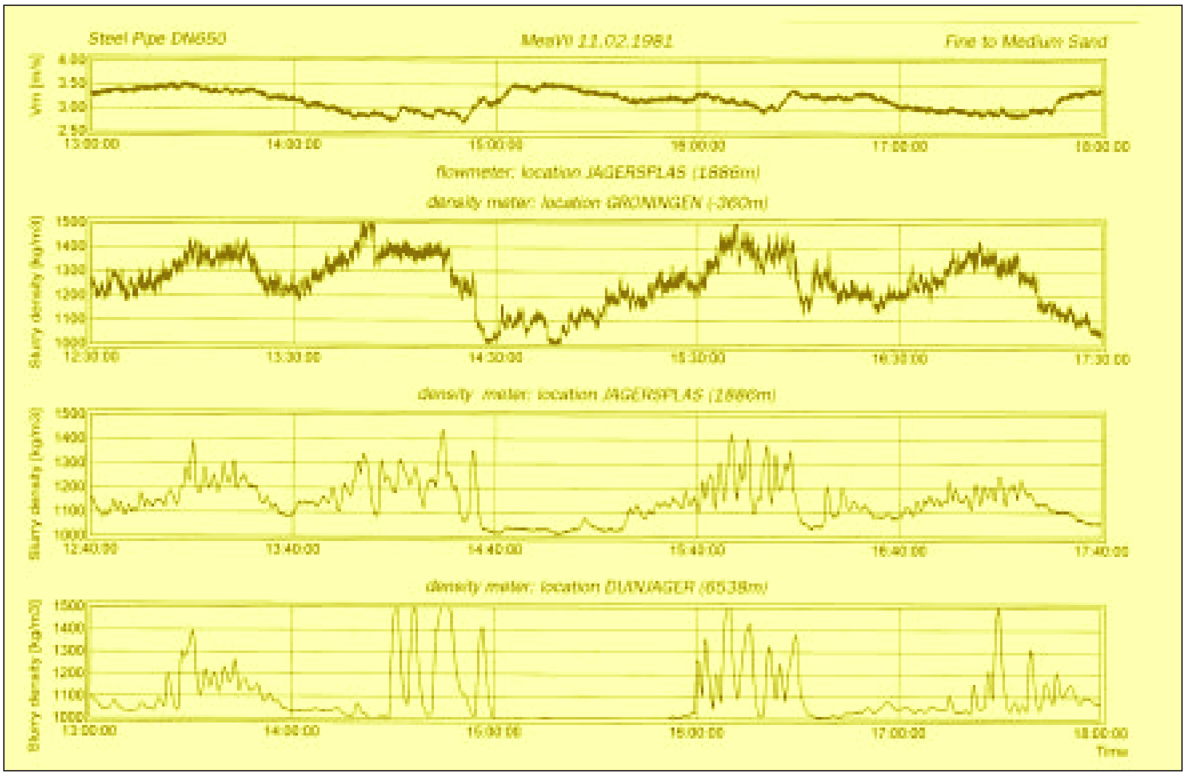
Figure 2. Density waves measure along DN650 pipeline, left, from 8:00 to 13:00 hrs and, right, from 13:00 to 18:00 hrs.

Wilson *et al.,* 1992). When accepting the simplifications of internal structure of solids flow assumed by the two-layer model (constant velocity and concentration distribution within each layer), the model version for heterogeneous flow can be used for an evaluation of the phenomena observed in the MeaVli pipeline. The model operates with a simplified two-layer distribution of velocity and concentration in a pipe cross-section. Bed velocity can be evaluated and slip can be determined by the model in this flow pattern.

DTI and DIM: Experimental Data Interpretation Based on a Two-Layer Model

A relation between slip and slurry density which would verify an assumption that material aggregation is caused by slip can be accomplished by processing data files (B). These contain solids velocity profiles, mean slurry velocities and related slurry densities passing the pipeline cross-section. The solids velocity profiles were derived from measurements at one measuring site (location Jagersplas) in the pipeline. Profiles are constructed from local solids velocities at α = 0, 20, 30, 40, 60, 90, 135 and 180 deg. measured continuously by acoustic Doppler velocity meters. Slurry density, measured by a radiometric method (γ-ray radiometric density meter with a beam directed to the center of the pipeline cross-section) in a down coming vertical section of the pipeline as a mean value for the pipeline cross-section, provides a value of delivered volumetric concentration C_{vd}. To evaluate V_s from measured velocity profiles, the solids concentration distribution must be known. Since it was not measured this must be reconstructed by an appropriate data interpretation model (DIM) to which the physical two-layer model is implemented. DIM is a module of a data processing programme Data Transfer and Interpretation (DTI) which executes all operations required for an interpretation of data from an experimental database. A procedure of the data interpretation has been described elsewhere (Matousek, 1995c).

A set of 3 mass balance equations of the two-layer model are used to get C1, C_{vp} and V_s from measured parameters transformed to the two-layer pattern. Then the slip ratio is calculated (V_s/V_m or C_{vd}/C_{vp}). The rule for a split of solids flow into two layers is examined by DTI. It is expressed as the stratification ratio C_{cod}/C_{vd}. C_{cod} is determined from 2LM parameters.
All interpreted data plotted in Figures 4 and 5 have been processed by DIM based on the two-layer flow composition. Data files (A) and (B) contain measurements from different measuring days, so density waves presented in Figure 2 were measured at other times than velocity profiles and integral parameters from which slip values were processed. But since the operation conditions (properties of transported material, mean velocities and slurry densities, pumps revolutions) of the dredging installation were maintained at an approximately constant level during all measuring days, the same processes are supposed to occur in slurry flow in the pipeline in each particular measuring day.



Description of the Observed Phenomena by the Interpreted Data

Slip Ratio in a Pipe Cross-Section

Results of data interpretation (Figure 4) verify the existence of the relationship between the slip and slurry density in a pipe cross section and support the hypothesis that there is a slip effect on the material aggregation along the long pipeline characterised by density wave transformation. While V_m is considered constant in time, V_s varies according to slurry density in various pipeline cross sections along the long pipeline of the constant diameter.

An Explanation of a Variable Slip in a Pipe Cross-Section: Variable Mutual Force Interaction Between Two Layers

Slip was evaluated by 2LM, therefore constant velocity and no slip is expected within each layer. Different slip is caused by different mutual shift between two layers in a pipeline. This shift is a product of a force interaction between contact (bed) layer and suspended layer in a pipeline.

A relation between V_s2 and ρ_m processed by DTI and plotted (Figure 4) explains why the slip ratio has been found to increase with slurry density. There is an effect of density variation on solids velocity at the bottom of a dredging pipeline. When mean slurry velocity is approximately constant, measured velocity profiles show that particles at the bottom of the pipeline (in a contact layer) are sliding faster in a mixture of higher density than in that of lower density (Figure 3). This can be explained by a mechanism of force balance within a two-layer flow structure. A higher driving force acts on the bed layer and promotes its sliding in a mixture of higher density in the pipeline. Increasing slurry density has following impact on the acting forces in a pipeline section with stratified flow. A denser suspended flow (higher C1) in upper layer produces higher shear stress at the interface between two layers and so the higher driving force acting via the interface to the bed. The finest portion of the transported material (approx. d_s<75 μm) contributes directly to the fluid and increases carrier (water + finest particles) density. An increase in carrier density has an effect of increasing buoyancy on the solid particles. The increased buoyancy reduces the submerged weight of the bed load which is in mechanical contact with pipeline wall and therefore decreases the bed resistance by mechanical friction between particles in bed and a pipe wall. The effect of the contribution of the finest particles to the carrier on slurry flow behaviour has been measured and published, see e.g. SRC experiments with sand + clay in DN315 pipeline (Shook, 1988).

The magnitude of the forces and their mutual relation is dependent on the position of the interface between two layers in a pipe cross-section. Processing of the profiles shows that a variation in Y_b is confined to the lowest part of a large pipeline, even for very different slurry density in the pipeline cross-section. For most of the profiles (especially when V_m does not drop below 2.9 m/s) it is maintained at approximately constant value. The assumption of a relatively small variation of Y_b with slurry density is supported by a wide PSD of transported material. Only the coarsest portion of

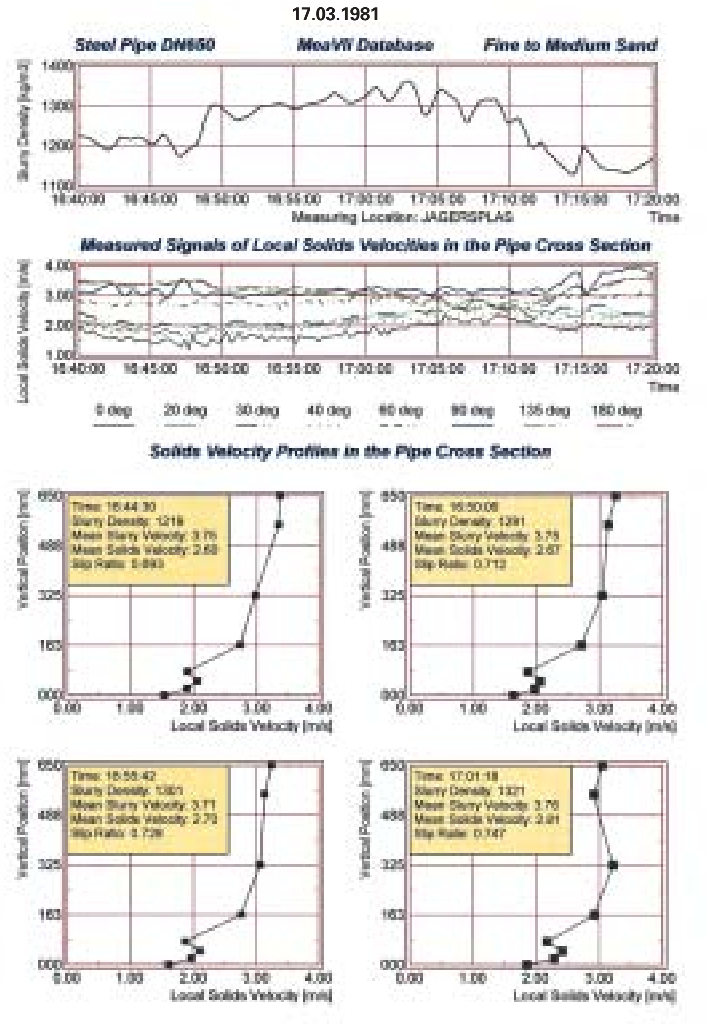


Figure 3. Solids velocity distribution in non-stationary solids flow in the DN650 pipe.

transported material contributes to the contact load and the rest remains suspended above the bed or (in case of the finest material) contributes directly to the carrier. With some degree of idealisation it can be predicted that flow is separated into two layers immediately at the beginning of the entire horizontal pipeline and a stable flow pattern is maintained along the whole pipeline length; coarser particles are transported within the bed of approximately constant concentration and thickness. The bed is sliding slowly (with a variable velocity) at the bottom of the pipeline and it is continuously passed by faster upper layer containing suspended solids in a variable concentration. Slurry density variation in pipe cross section is realised exclusively within the upper layer and it is expressed by C1 variation. A material aggregation effect is realised within the lower layer where accelerated bed within denser slurry flow gradually accumulates the material from slower bed before the forehead of the high density wave.

The computer analysis of 2LM parameters, as V_s1, V_s2 and slip ratio, reconstructed from MeaVli database has been done for both Y_b=const. (Y_b/D=0.117) and variable Y_b determined by DTI from the shape of measured velocity profiles. The results obtained do not differ significantly and both show the same sort of a relationship between parameters, as described here. Determined by DIM, the stratification ratio appears to be weakly dependent on the slurry density in the pipeline cross-section for C_{vd} higher than approx. 9% (Matousek, 1995c). This parameter is decisive for a correct prediction of slip and bed velocity in a pipeline by the two-layer model. Over-estimation of the layer of the contact load in a dense mixture flow gives too high Y_b and diminishes V_s2, expressing velocity of solid particles at the bottom of a pipe in 2LM.

A Simulation of the Observed Phenomena Using Two-Later Model

To interpret the MeaVli data by 2LM for a concentration and velocity distribution and a slip determination, only the mass balance equations of 2LM are taken into account in DIM module. *To predict* slip ratio and bed velocity (and friction loss per unit length) in a pipe cross-section under various conditions, the two-layer model has to be calculated as a complete set of the balance equations, i.e. a force balance equation for each layer must be included together with a rule for a material division into two layers.
A physical two-layer model was found to be an appropriate model for the analysis of the phenomena monitored in a long pipeline and for the interpretation of MeaVli data. A simulation of the phenomena observed in a pipeline connected with a dredge could be achieved by a two-layer model with reasonable accuracy, if the model could be successfully configured for a heterogeneous (partially-stratified) flow regime. A rule for a determination of a slurry flow distribution into two layers is necessary. A slurry flow distribution is represented by:
a. the geometry of the layers (Y_b)
b. the concentration of suspended and contact layer (C_{cod} transformed to C1, C2).

Consideration of the processed MeaVli database leads to the following recommendation. To configure the model for application to unsteady solids flow of sand in a long dredging pipeline of a large pipeline diameter, the following aspects must be taken into account:
a. thickness of a contact layer does not vary significantly, even for very varying slurry densities; this is caused by rather wide PSD of a dredged material and therefore a sharp flow stratification in a large pipeline; this relatively weak variation in a bed thickness – observed in measured velocity profiles – produces an increase of V_s2 with increasing slurry density as a 2LM output;
b. a stratification ratio is independent of slurry density in the pipe for densities higher than approx. 1150 kg/m^3.

A configured model should provide following outputs for parameters of our interest here:

- V_s2 that increases approximately linearly with slurry density in a pipe cross- section;
- a slip ratio that increases with slurry density in a pipe cross-section.

The validity of a model configuration is tested by an additional measured parameter typical for slurry flow in a pipeline: the friction loss. Friction losses calculated by 2LM are compared with the real losses measured in the MeaVli pipeline. The pressures in the pipeline were measured at the inlet and outlet of Gr, Ja, Du pumps. Therefore friction loss evaluation can be done only for a long pipeline section and only for the mean values of slurry density averaged over the long pipeline section. Values of a friction loss in the Ja-Du pipeline section (4820 m of a pipeline length) is determined as a difference between measured pressure signals when minor losses in the pipeline section and a difference in geodetic heights of the pumps are subtracted. Values of friction losses are predicted by 2LM for model parameters reconstructed from measured velocity profiles. The predicted values match reasonably those acquired from Ja-Du pressure signals (Figure 5).
The non-increasing friction loss with mean slurry density observed in the MeaVli pipeline (in the density range 1080-1270 kg/m^3) is explained by the principles of two-layer model for the flow conditions described above. The contact load contributes predominantly to the slurry flow resistance. When the thickness of the contact layer does not vary significantly with slurry density in a pipe section also the friction loss does not significantly vary.

VERIFICATION BY LABORATORY TESTS

A development of slip ratio in a pipe and of solids velocity at the bottom of a pipe in slurry flow of different densities was investigated in a laboratory circuit. The laboratory facility has been described elsewhere (Matousek, 1995b). Steady solids flow in DN150 pipe was monitored during a set of test runs for slurries of constant delivered concentrations from a range C_{vd} =

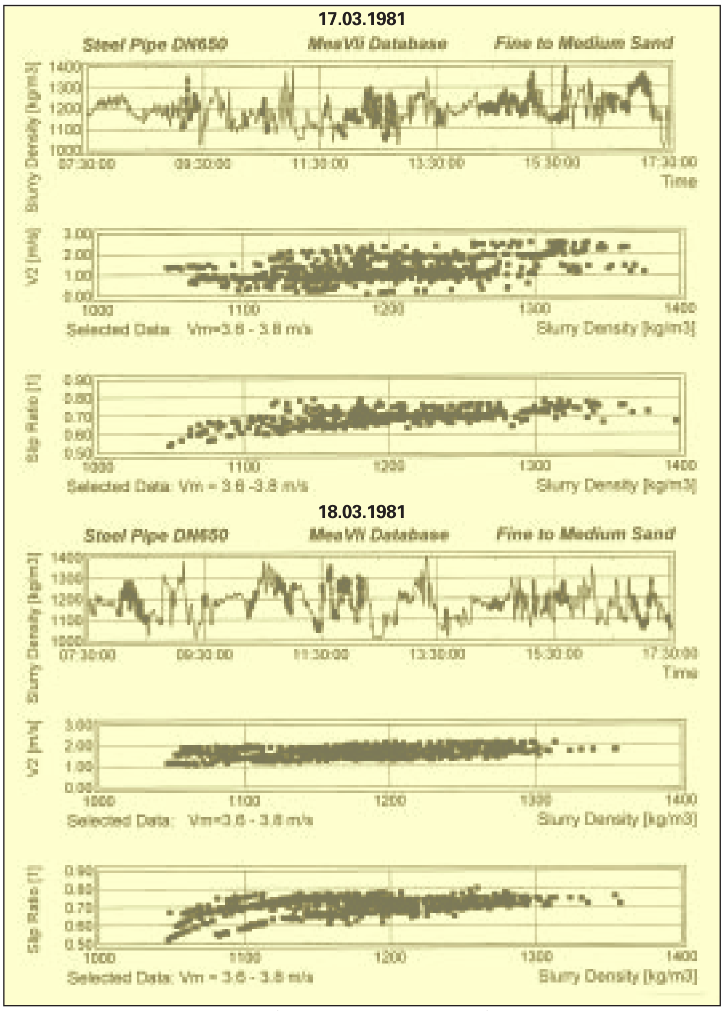
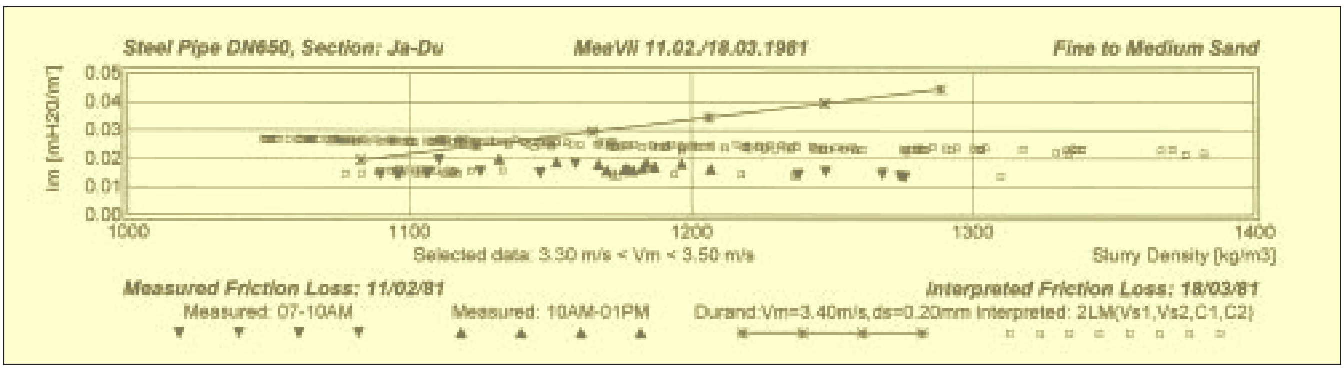


Figure 4. 2LM interpretation of measured velocity profiles in the DN650 pipe.

0.09 to C_{vd} = 0.30. Tested solid material was similar to that in MeaVli pipeline, only this was less broad-graded (quartz sand 0.2-0.5 mm). The slip was determined from the parallel measurements of concentration profiles and C_{vd} in the pipe. Integration of concentration profile $c_v(y)$ provided C_{vp}, so slip ratio C_{vd}/C_{vp} was directly obtained from measured parameters in the pipe cross-section. Also local solids velocity at the bottom of a pipe was measured during test runs. Laboratory tests show that:

Figure 5. Friction loss in DN 150 pipeline. Comparison of measured, interpreted and predicted friction losses.



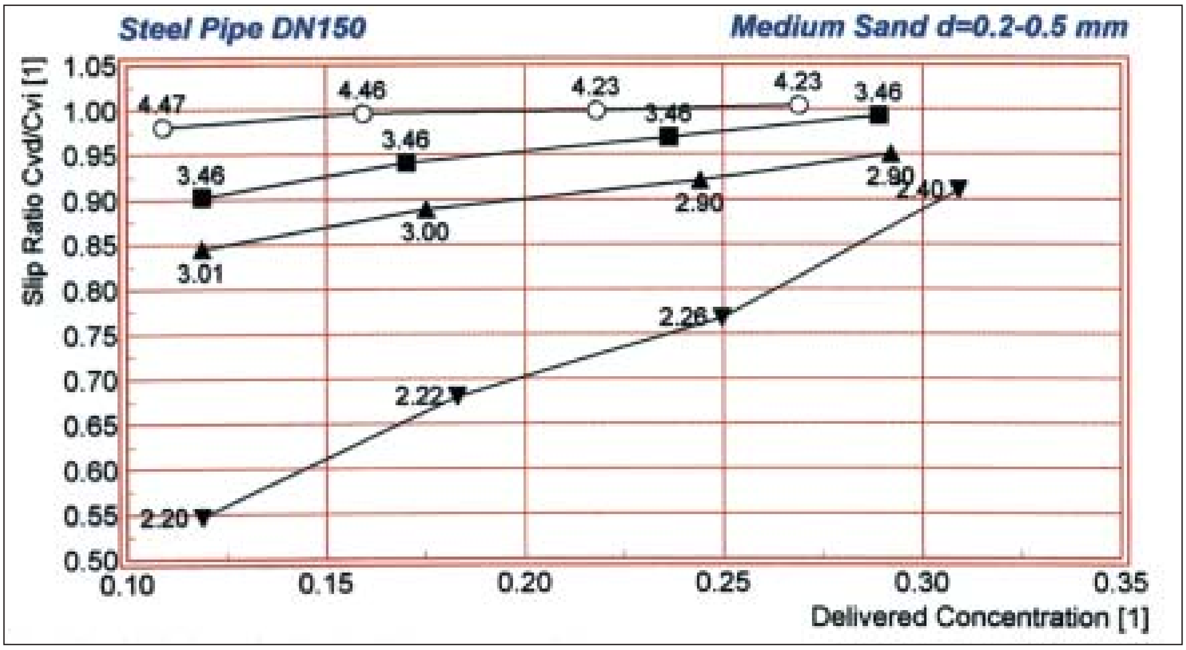
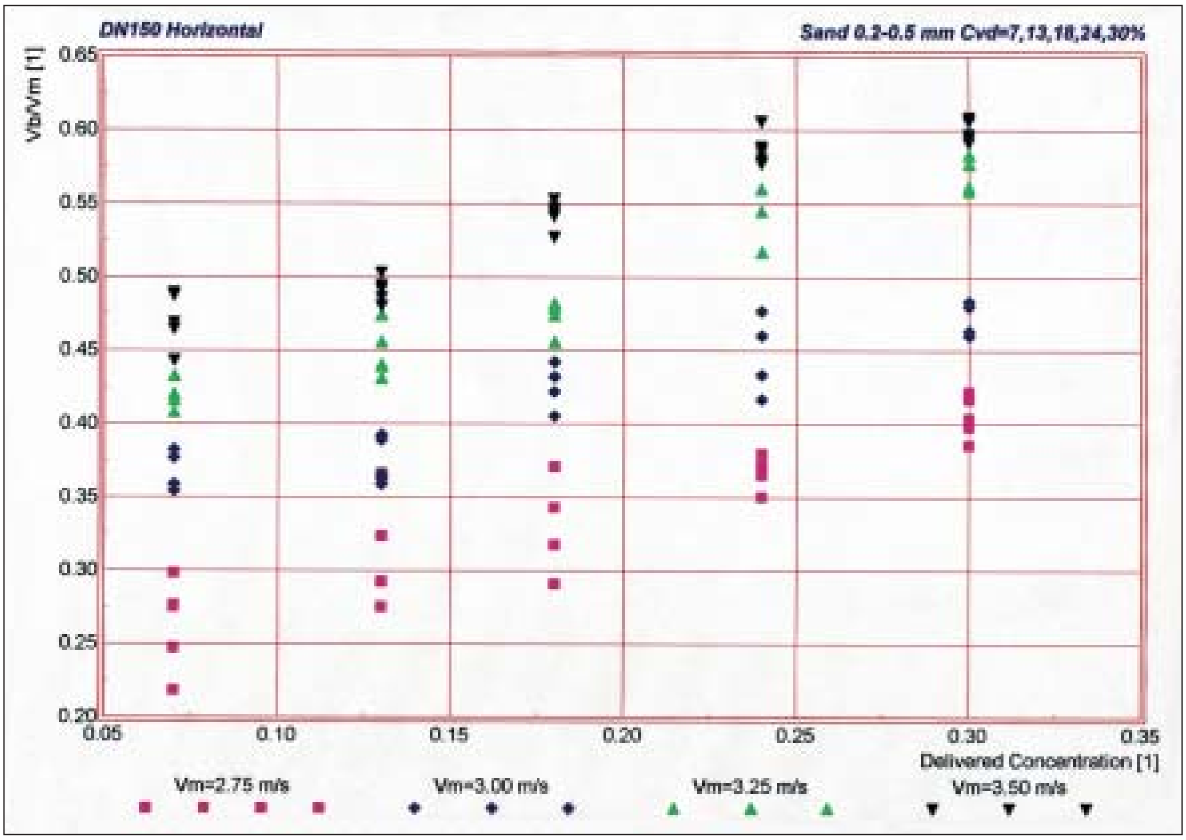


Figure 6. Slip ration measured in the DN 150 pipe (V_m as a label).

– slip ratio increases with increasing slurry density in the pipe for all V_m at which slip ratio has been measured (Figure 6);
– solids velocity at the bottom of the pipe increases with increasing slurry density for all V_m at which solids velocity has been measured (Figure 7).

Laboratory tests verify a trend in a relation between slip ratio and slurry density identified in the dredging pipeline by MeaVli data interpretation. The tests also confirm a trend in a relation between solids velocity at the bottom of a pipe and slurry density measured in the dredging pipeline. This gives an indication that the

Figure 7. Solids velocity at the bottom of the DN 150 pipe.



same processes occur in partially-stratified flow in the dredging pipe and laboratory pipe. The simplifications chosen for the MeaVli interpretation model do not misinterpret a description of a behaviour of slurry flow in the dredging pipeline.

Conclusions

A process of material aggregation has been detected in a slurry pipeline during a dredging operation. Material aggregation occurs as an effect of unsteady solids flow caused by fluctuating slurry density in a long pipeline. Transported material is gradually accumulated into highly concentrated density waves along the pipeline. This effect is a product of variable slip in different pipeline cross-sections along the slurry pipeline. Slip in pipeline cross-section is related to slurry density just passing the cross-section. The slip ratio V_s/V_m increases with increasing slurry density in pipeline cross-section. The variable slip ratio in partially-stratified flow is caused by variable mutual shift between suspended layer and contact layer in pipeline. The material aggregation effect occurs predominantly in the contact layer.

Velocity of solid particles at the bottom of a slurry pipeline varies with fluctuating slurry density in pipeline cross-section. Particles at the bottom of the pipeline are accelerated within a denser mixture when solids of wide PSD are transported. This is caused by the higher impelling force exerted on a bed load by a denser mixture stream and by a buoyancy effect reducing the submerged weight of bed.
Friction loss in a dredging pipeline may be weakly influenced by variable slurry density when broad-graded solids are transported. The thickness of the contact layer does not vary significantly with slurry density along a pipeline so friction loss, caused predominantly by mechanical friction between contact layer and pipe wall, does not vary significantly as well.

A simulation of the phenomena discussed can be achieved by physical two-layer model when the model is suitably configured. A comparison of trends in parameters obtained from the two-layer model with those measured both in the dredging pipeline and laboratory circuit shows a good agreement and confirms the applicability of the two-layer model to describe and simulate processes occurring in stratified flow in a long pipeline connected with a dredge.

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