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*Discharge from a Hydraulic Pipeline*

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## AIMS & SCOPE OF THE JOURNAL

The *Journal of Dredging* is published by the Western Dredging Association (WEDA) to provide dissemination of technical and project information on dredging engineering topics. The peer-reviewed papers in this practice-oriented journal will present engineering solutions to dredging and placement problems, which are not normally available from traditional journals. Topics of interest include, but are not limited to, dredging techniques, hydrographic surveys, dredge automation, dredge safety, instrumentation, design aspects of dredging projects, dredged material placement, environmental and beneficial uses, contaminated sediments, litigation, economic aspects and case studies.

# ACOUSTIC MEASUREMENT OF SUSPENDED SOLIDS FOR MONITORING OF DREDGING AND DREDGED MATERIAL DISPOSAL

J.M. Land[1] and R.N. Bray[2]

## ABSTRACT

A reliable method has been developed for the measurement of suspended solids concentrations using Acoustic Doppler Current Profilers™, in addition to their design capability of measuring current speed and direction. The method has been used to study sediment plume generation and decay around dredging and dredged material disposal operations in Europe and SE Asia, in addition to studies of natural sediment transport.

The combination of detailed profiling of suspended solids and water currents from a moving survey boat permits very rapid and detailed coverage of the affected area. Sediment losses and transport rates can be measured with a high degree of confidence. This paper summarises the basic principles of the method and presents several examples of its application

## INTRODUCTION

Both dredging and disposal are dynamic operations in which sediment is put into suspension from a moving vessel (or a moving part of that vessel), usually into flowing water. A very large number of measurements are required in order to adequately define the extent of these often large sediment plumes, and the variation of concentration within them, particularly in active hydrodynamic environments. Studies of the amount of sediment put into suspension, and of the subsequent decay of sediment plumes, are thus difficult to undertake using conventional techniques such as water sampling and turbidity meters because they rely on point measurements. This, in turn, gives rise to difficulties of quantification and can sometimes, e.g. during environmental monitoring of operations, even result in confusion as to the true source of the sediment being observed.

During the last decade, Doppler current profilers have become widely used to measure the speed and direction of water currents. They do so by measuring the Doppler shift of acoustic pulses emitted from four transducers arranged in a 'Janus' formation (Figure 1), usually at an angle of 20° or 30° to the vertical. The pulses are backscattered from particles suspended in the water column. If the particles are moving relative to the axes of the transducer beams, they are received by the transducers at a frequency which is different to the transmission frequency. Computation of the Doppler shift enables the speed of the particles along the axis of each beam to be derived and combination of the data from the four splayed beams enables the speed and direction to be determined relative to the instrument itself.

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[1,2] Directors, Dredging Research Ltd, Bargate House, Catteshall Lane, Godalming, Surrey, GU7 1LG, UK.

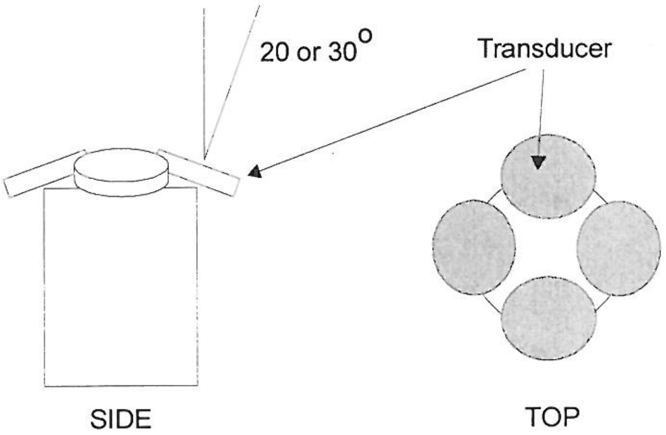

Figure 1. Typical transducer arrangement on a Doppler current profiler.

The profilers which have led to the development of the method described here are Acoustic Doppler Current Profilers™ (ADCPs) manufactured by RD Instruments of San Diego, CA. ADCPs are fitted with internal compasses and, in some cases, have the ability to track their progress over the seabed ('bottom-tracking'). The speed and direction of the current can thus be related to earth coordinates. External compasses and navigation systems may also be interfaced with the instruments.

These particular instruments, in addition to measuring current speed and direction, have the facility to measure the relative intensity of the backscattered acoustic signal. This provides a qualitative measure of the relative concentrations of the scatterers in the water column. This capability has often been used to assist with the positive location of sediment plumes in order to facilitate conventional measurements but there are few published accounts of the use of this data in a reliable quantitative sense.

Backscatter data are obtained at the same vertical and horizontal (or time) resolution as the current data and can be selected by the operator within limits which depend on the specification of the instrument being used. Vertical measurement intervals used in the work described here generally range between 0.25 and 1.00m. Complete profiles of data are usually obtained at time intervals of between 1 and 3 seconds. At sailing speeds of typically 2 $ms^{-1}$, this equates to profiles at intervals of between 2 and 6 metres.

The method which has been developed here (which is called The Sediview Method™) uses the relative backscatter intensities measured by the ADCP to provide estimated suspended solids concentrations. These, in combination with the data on current speed and direction, permit the detailed study of large-scale or dynamic sediment movement processes. The method was originally developed in Hong Kong during studies of the dredging and disposal operations required for the New Airport and other infrastructure developments (Land et al., 1997). It since been used in Germany and the UK for similar work and for studies of natural sediment movements. Broadly similar work has also been undertaken in the USA by others, e.g. Kraus (1991), Thevenot and Kraus (1993) and Ogushwitz (1994).

## BASIC PRINCIPLES OF THE METHOD

### Acoustic Theory

The acoustic theory on which the method is based has been developed by a number of workers, e.g. Thorne et al. (1991) Sheng and Hay (1988), Richards et al. (1996). However, the majority of successful applications have used relatively short-range, bottom-mounted devices for detailed studies of near-bed sediment transport processes. The study of sediment plumes from dredging and disposal operations requires the use of ADCPs over comparatively long ranges. Water depths of 20-30 metres are typical and data has, on occasions, been required in depths of up to 60 metres. In such circumstances, the minimisation of range-dependent errors becomes critical.

The Sediview Method™ is based on conventional theory but is highly dependent for its accuracy on detailed corrections for range-dependent attenuation of the signal due to absorption by the water and also scattering and absorption by the sediment.

The theoretical water absorption coefficient profile through the water column can be computed using measured profiles of water temperature and salinity and the appropriate corrections made to the backscatter data. However, due to inevitable local variations of water chemistry, most methods of computation provide only approximations.

Similarly, an approximation of attenuation due to scattering and absorption by the sediment can be derived if the particle size distribution, density and compressibility of the sediment are known but these are often difficult to obtain. The Sediview Method™ therefore incorporates an iterative approach in order to derive both the water absorption and sediment attenuation coefficients using approximations as a starting point.

The attenuation due to the sediment is a function of the sediment concentration, which is unknown and which may vary considerably through the water column. An iterative procedure, based on a top-down computation, is thus required to derive the concentration estimates. Direct inversion methods of computation (e.g. Lee and Hanes, 1995) are not used because they are largely dependent on assumptions which are rarely satisfied in the types of study described here which involve measurement over long ranges in suspensions which are not the result of natural processes.

### Practical Application

The acoustic theory has been found to work well in a wide variety of environments but its successful application is entirely dependent on the following:

1) knowledge of the temperature and salinity profile at the measurement site;

2) detailed knowledge of the performance characteristics of the ADCP and the manner in which the performance can change with time, even over the space of a few minutes;

3) careful mounting of the ADCP to avoid air bubbles created by the passage of the survey boat through the water and ensuring that the sailing speed is less than that which gives rise to noise caused by water passing over the transducers;

4) frequent acquisition of calibration data (preferably water samples) combined with thorough analysis of that data to identify and define temporal and/or spatial trends in the sediment regime, e.g. variation of particle size with depth, or periodic flocculation and deflocculation of fine sediments.

Knowledge of the performance characteristics of the instrument is critical. Each instrument is unique and must be calibrated. In particular, the relationship between the received signal strength and decibels must be established with a high degree of accuracy. The effects of variations of temperature and supply-voltage on performance must also be established accurately.

In all of the work described here, the ADCP has been mounted over the bow of the survey boat or against the side (Figure 2). In addition to ensuring that the ADCP is not affected by air bubbles, the maximum safe sailing speed of the vessel, above which passage of water over the transducers gives rise to noise, must be established by means of detailed noise tests. Interfering noise caused by other equipment on the boat (e.g. echo sounders, sonars) must also be investigated and eliminated.

Calibration data are usually obtained using both siltmeters and water samplers. The calibration is site-specific, in addition to being instrument-specific, and can vary dramatically if the characteristics of the suspended solids change during the course of the work. For this reason, it is usual to collect calibration data at very frequent intervals (e.g. 10-30 minutes) through the work. Single water samples and siltmeter observations can easily be obtained from shallow depths while the vessel is underway, thus avoiding disruption of data collection, in order to monitor and quantify such variation.

More detailed data sets designed to establish depth-related calibration parameters can be obtained at less frequent intervals by stopping the boat and obtaining profiles of data throughout the water column. However, great care is required when collecting calibration data from stationary or drifting boats in order to avoid air bubbles formed as the boat rolls. Even a very gentle rolling motion is sufficient to generate bubbles which will interfere with an instrument mounted close to the hull of the boat.

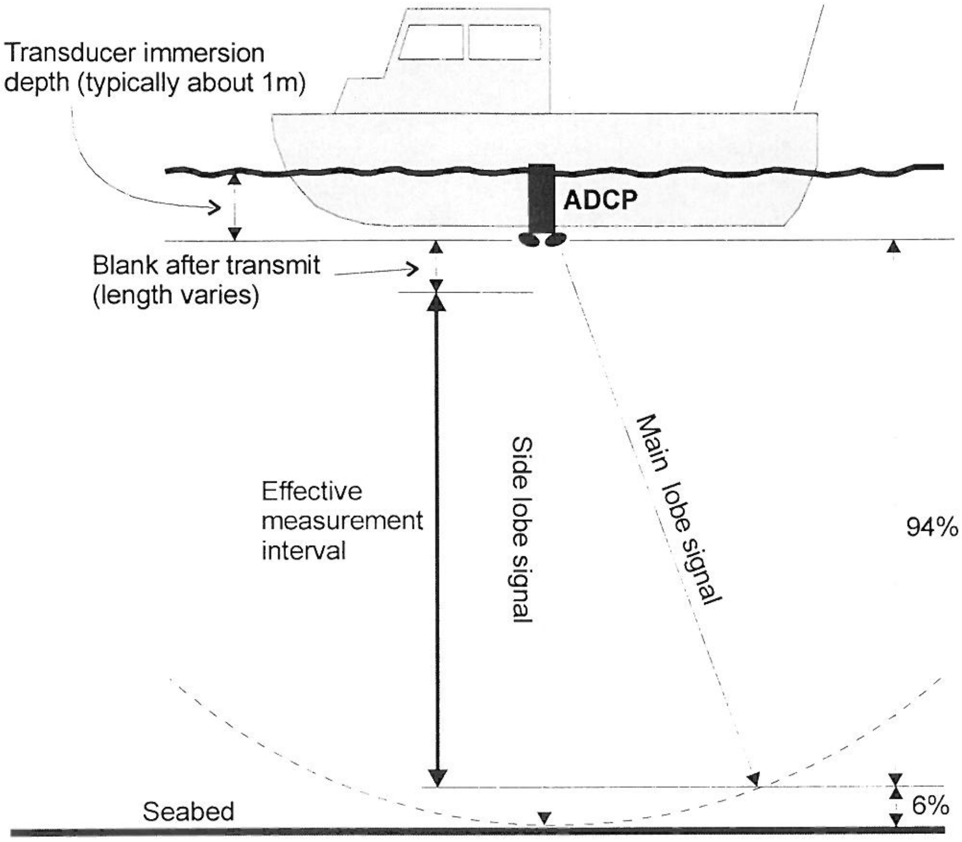

Figure 2. Typical ADCP deployment arrangement from a survey boat showing effective measurement range for ADCP with 20° beam angle.

## Limitations

Inevitably, there are limitations to the method which arise from several factors:

1) air bubbles entrained in newly-formed plumes may give rise to spurious data;
2) rapid variation of particle size can result in erroneous concentration estimates if insufficient calibration data are available;
3) acoustic energy will be backscattered from any particulate matter, not only sediment;
4) the computation of the concentration estimates becomes extremely sensitive as concentrations rise above about 2,000 mg/L;
5) high concentrations very close to the transducers can give rise to spurious data;
6) data cannot be obtained at the surface because of the necessity to fully immerse the transducers and because the instrument cannot measure within about 1 metre of the transducers (varies according to specification);
7) valid data cannot be obtained from very close to the seabed due to interference from signal side lobes (approximately the lowest 6% of the water column in the case of instruments

with transducers mounted at 20° to the vertical). The range over which valid data can be obtained is schematically illustrated in Figure 2.

These limitations are rarely a problem if they are understood and care is given to the interpretation of the data. However, there may be occasions when they preclude the successful use of the technique. It may not be appropriate, for example, in areas which are significantly affected by particulate waste from outfalls, where there is very dense marine traffic giving rise to aeration of the near-surface waters and in areas affected by organic 'snow'. It should also be noted that the water column may contain air bubbles for several hours after severe storms.

The impossibility of measuring in the near-bed zone (about 1.2 metres above the bed when working in 20 metres of water) is a very real limitation because, frequently, that is where a large proportion of the sediment transport takes place. If data are required close to the bed, the ADCP data can be supplemented by using rapid-profiling siltmeters deployed from the boat as it moves slowly. Sufficient data can sometimes be obtained in this manner, without disrupting ADCP data collection, to enable broad 'rules of thumb' to be developed concerning the near-bed solids distribution. This data can be incorporated into the processing to provide a seamless data set.

## Accuracy

The accuracy of the Sediview concentration estimates depends on the:

1) type of instrument used, particularly whether it is a broadband or narrowband ADCP;
2) extent to which environmental parameters (i.e. water temperature, salinity and the nature of the sediment itself) vary, and have been measured, during data collection;
3) degree of effort expended in data collection and calibration procedures.

Broadband ADCPs are able to measure relative backscatter intensity (in instrument counts) to provide concentration estimates which are theoretically accurate to within ±2% for a single 4-ping data ensemble. Narrowband instruments are less accurate and concentration estimates based on a single data ensemble are unlikely to be better than about ±25%. However, both errors are truly random and large data sets would not be systematically biased by them.

Far greater errors, which can be systematic, can be encountered due to variations of the environment in which the measurements are made and because calibration procedures have not been rigorously undertaken. The former can largely be avoided by frequent sampling and measurement of water temperature and salinity during the survey. On occasions, the variations (particularly of sediment size and composition) will be such that errors are almost unavoidable. However, in this respect, it should be noted that turbidity meters are subject to broadly similar problems.

The greatest errors of all can result from inadequate calibration procedures. In particular, the derivation of the correct conversion from instrument 'counts' to dB is critical; errors arising from the use of the wrong conversion can, in theory, approach an order of magnitude.

Overall, it has been found that, using broadband instruments, with careful data collection and analysis, individual concentration estimates can be derived which are generally within about ±25% of the concentrations measured on contemporaneous water samples. Over the course of five years fieldwork experience, the overwhelming impression gained has been that the majority of such 'residual errors' are not, in fact errors, but are largely due to the inevitable impossibility of achieving perfect temporal and spatial synchronisation of measurements made using two or more different methods. Some examples of comparisons between Sediview estimates and water sample concentrations are provided in the case histories described below.

During the work summarised in this paper, a high degree of accuracy has been achieved using both broadband and narrowband ADCPs with operating frequencies of 300, 600 and 1200 kHz. Data have been obtained in water depths of up to 60 metres and in concentrations of less than 1 mg/L up to about 2,000 mg/L.

### Data Processing

The iterative procedures required to establish accurate values for the water absorption and sediment attenuation coefficients and the site- and instrument-specific calibration constants are tedious. In addition, when all of the calibration components have been established with the required degree of accuracy, the processing of the ADCP data using the top-down method of computation, is very laborious. For this reason, a sophisticated software package has been developed. In addition to making calibration procedures relatively easy, and enabling very rapid processing of the data, the software can be used to detect and partially auto-correct certain errors in the raw data (e.g. loss of bottom-track, default error values etc.), edit data files and vessel trackplots and analyse and output data in a variety of formats. Analytical routines can utilise both the current and solids concentration data and include temporal and spatial averaging and computation of solids fluxes. Data output options include colour contour plots and graphs of concentration, flux and water current, ribbon and vector plots, and ASCII data files which can be used in other applications.

## PLUME GENERATION DURING DREDGING OPERATIONS

### Overflow Plume from Trailing Suction Hopper Dredgers

Overflow plumes from trailing suction hopper dredgers (or from barges being loaded using cutter suction dredgers) are probably the greatest single source of sediment release during dredging operations. Overflow is a necessary component of most sand-dredging operations if economic load factors are to be achieved. It may also assist in increasing the efficiency of some operations in muddy materials (excluding the obvious extreme case of pure agitation dredging). As such, overflow from trailers involved in capital and maintenance works, and in aggregate dredging, is frequently a key issue in the environmental impact assessment and later monitoring of dredging projects (e.g. Whiteside at al. 1995).

The use of ADCPs permits rapid collection of data throughout the water column over a wide area. When used in combination with float-and drogue-tracking, data on plume size, concentration, sediment flux away from the dredging site and the area affected by the plumes can be obtained. Figure 3 shows examples of the decay of depth-averaged solids concentrations in the cores of two overflow plumes during sand-dredging operations in Hong Kong. The trailers were working a deposit of muddy sand with a fines content (<60μm) of typically 20-30%. The data show a rapid decay of plume concentration. Background concentrations in the area were of the order of 1 - 3 mg/L and the plumes decayed to near-background levels after about 3 hours, except close to the bed where elevations of the order of 2-3 mg/L were detectable up to 12 km from the site and 8 hours after they were generated.

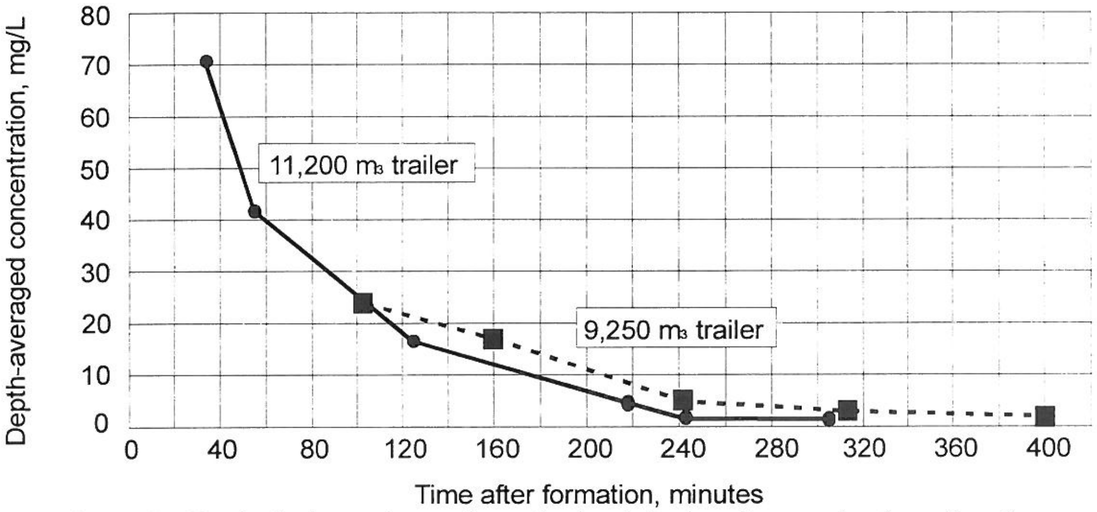

Figure 3. Typical plume decay data obtained during the monitoring of trailer dredging with overflow during sand-winning operations.

Figure 4 illustrates the increase of the width of the plumes which were formed in natural water depths of about 30 metres. The considerable increase in width, from a nominal initial 50 metres to more than 1 km after about two hours, is greater than can be accounted for by diffusion and is largely due to the plumes acting as large density currents, even at very low concentrations.

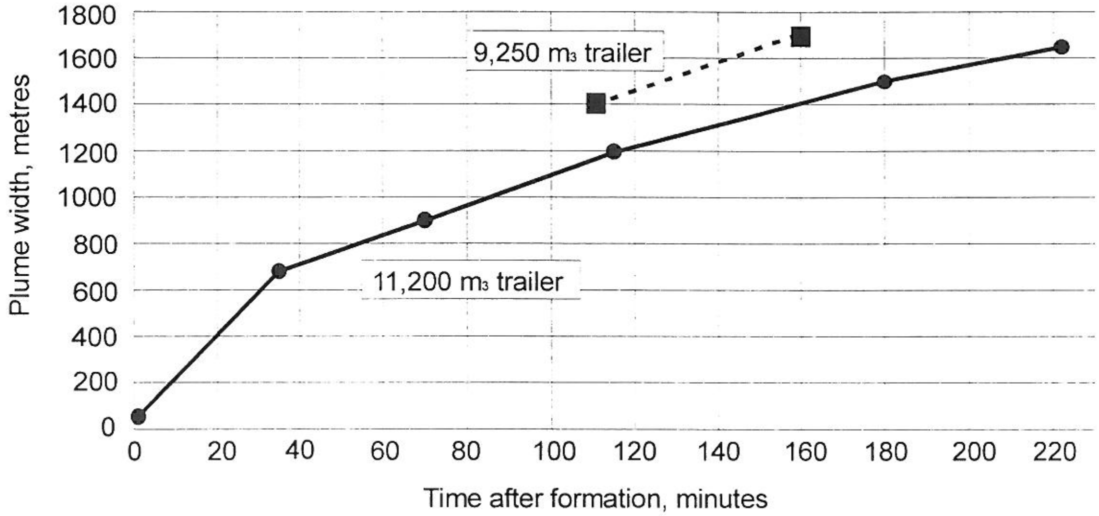

Figure 4. Increase of near-bed width of plumes formed during overflow from trailers (same data set as Figure 1).

### Sediment Plume Generation During Water Injection Dredging

Trials of the water injection dredging method were recently undertaken in the Köhlfleet Basin in the Port of Hamburg, Germany. These were monitored using a combination of acoustic profiling and a high-range profiling siltmeter. The latter was used to investigate the formation of thin, near-bed, high-density suspensions beyond the profiling range of the ADCP. The observations were made over a period of five days following four days measurement of background conditions.

The data showed that, in this particular case, the combination of the morphology of the basin and the mixed nature of the sediment prevented the formation of effective density currents to transport all the displaced material away from the dredging site. However, the weak tidal currents transported sufficient fine sediment put into suspension in the main water column to make the operation successful. Due to the high and very variable background sediment concentrations which characterise the River Elbe, it was not possible to identify sediment which had passed out of the basin into the main river and it was concluded that the water injection operations had no discernible effect on the sediment regime beyond the immediate dredging site.

## PLUME GENERATION DURING DISPOSAL OPERATIONS

### Disposal from Trailing Suction Hopper Dredgers

Disposal by simple bottom-discharge from trailing suction hopper dredgers has been studied on several occasions in Hong Kong and in the UK. In most cases, the objective was to define the extent of the resulting sediment plume but the case described here was intended to establish the percentage loss of material during disposal. A secondary objective was to collect data on the temporal decay of the plume which could be used to refine mathematical models used for predictive purposes.

Six discharge events were monitored using two survey boats equipped with 1,200 kHz narrowband ADCPs. One boat sailed repeated transects across the plume, from clear water to clear water, perpendicular to the current direction and at a distance of 300 metres down-current of the discharge site in order to measure the losses during discharge. The second boat sailed transects perpendicular to the path of a drogue which was released at the discharge site as the dredger emptied in order to establish the rate of decay of the plume. The losses of material at a nominal range of 300 metres from the discharge site varied considerably and are summarised in Table 1.

The dredged material was similar for all six events and comprised 30% clay, 55% silt and 15% predominantly fine sand. However, the split-hull dredger dredges mud at a high density and discharged very quickly, giving rise to the small losses. The twin hopper dredger discharged its load of low density material comparatively slowly and had to flush the hoppers in order to fully discharge, giving rise to much larger losses.

Table 1. Summary of sediment losses observed during discharge from trailer dredgers in 30-45 m of water (losses measured at 300 m range from discharge point).

| Dredger | Mass of solids discharged, tonnes | Hopper density, $tm^{-3}$ | Loss, % |
|---|---|---|---|
| Split-hull | 1,829.6 | 1.425 | 0.86 |
| | 1,753.1 | 1.409 | 2.09 |
| Twin hopper, bottom valves | 2,282.4 | 1.200 | 8.42 |
| | 1,969.6 | 1.167 | 6.87 |
| | 1,380.3 | 1.121 | 5.33 |
| | 1,986.3 | 1.168 | 8.74 |

Figure 5 shows the depth-averaged solids concentrations observed by the tracking boat in the lower half of the water column (about 15 metres) following a discharge from the twin hopper trailer. The plot clearly shows the extent of the area affected by the plume and the decay of solids concentration as the plume moved away from the discharge site.

Figure 6 shows the concentrations, averaged over a distance of 50 metres in the core of the plume, plotted against time, for all of the monitored discharge events, clearly demonstrating the different results achieved by the two types of vessel.

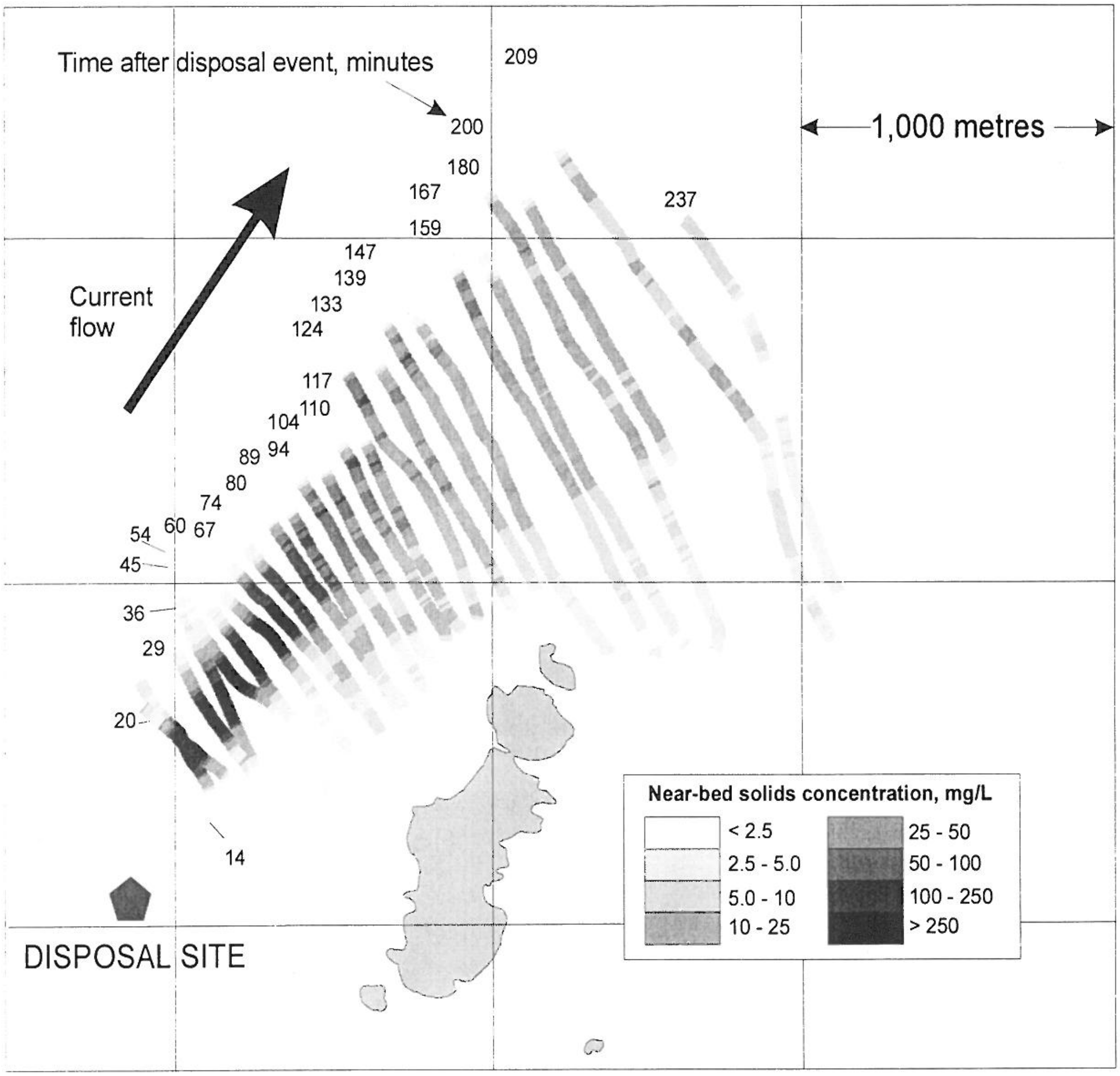

Figure 5. Extent of area affected by a sediment plume formed in Hong Kong waters during bottom-discharge from a trailing suction hopper dredger.

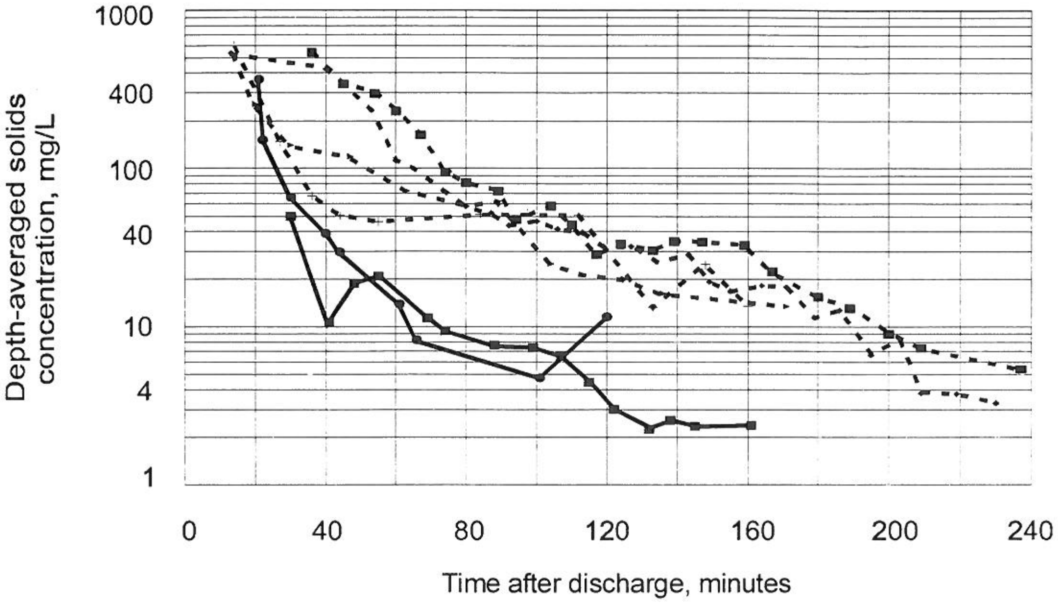

Figure 6. Decay of sediment plumes created during bottom-discharge of dredged mud from a split-hull trailer (solid line) and a twin-hopper trailer with bottom valves (broken line). Concentration is depth-averaged over the lower 15 metres of the water column.

## Disposal from Barges

Disposal from barges has been studied in Germany and Hong Kong. The Hong Kong studies were mainly aimed at establishing the percentage loss of sediment to suspension during discharge but data has also been obtained of the decay of the plumes. The losses observed following six dump events are summarised in Table 2. A further three events which took place close to slack water gave rise to no measurable losses.

Table 2. Sediment losses observed during discharge of barges into submarine pits.

| **Volume, $m^3$** | **Dry Density, $t\ m^{-3}$** | **Mass of solids discharged, t** | **Average current speed, $m\ s^{-1}$** | **Loss, %** |
|---|---|---|---|---|
| 400 | 1.235 | 494 | 0.07 | 2.218 |
| 1000 | 1.039 | 1039 | 0.25 | 1.193 |
| 600 | 0.718 | 431 | 0.10 | 2.806 |
| 600 | 0.751 | 450.6 | 0.22 | 3.112 |
| 970 | 0.751 (est) | 899 (est) | 0.40 | 1.149 |
| 400 | 1.235 (est.) | 494 (est.) | 0.35 | 2.176 |

The number of measured events is limited but the results tend to confirm what might be expected from the processes which operate to disperse material following discharge, i.e:

- percentage losses are greatest with fine materials of low density;
- percentage losses from dump events involving large volumes are smaller than those involving small volumes.

There was no discernible relationship between current speed and the magnitude of the losses, except that no losses were observed when there was no current. This was interpreted to indicate that, unless there is no current whatsoever, the losses are determined mainly by the amount of sediment which is initially stripped from the descending jet of material during discharge which is a function of water depth, material properties, the size of the barge and the speed of discharge. Over short distances, the current speed has a minor effect on the loss due to the comparatively slow rate of decay of the plume and merely determines the length of time which the plume takes to pass out of the pit. This suggests that, if percentage losses during dumping into pits must be minimised, the pits must be very large and discharge should take place as far upstream as possible and/or that care should be taken to ensure that large barges are used, discharge is completed as rapidly as possible and that the density of the dredged material should be as high as possible.

Figure 7 is a typical profile through a plume which had escaped from the pit, which was approximately 4 metres deeper than the surrounding seabed. Maximum concentrations, close to the bed, are slightly in excess of 500 mg/L. The profile was sailed along the edge of the pit, 150 metres from the discharge point and 37 minutes after discharge

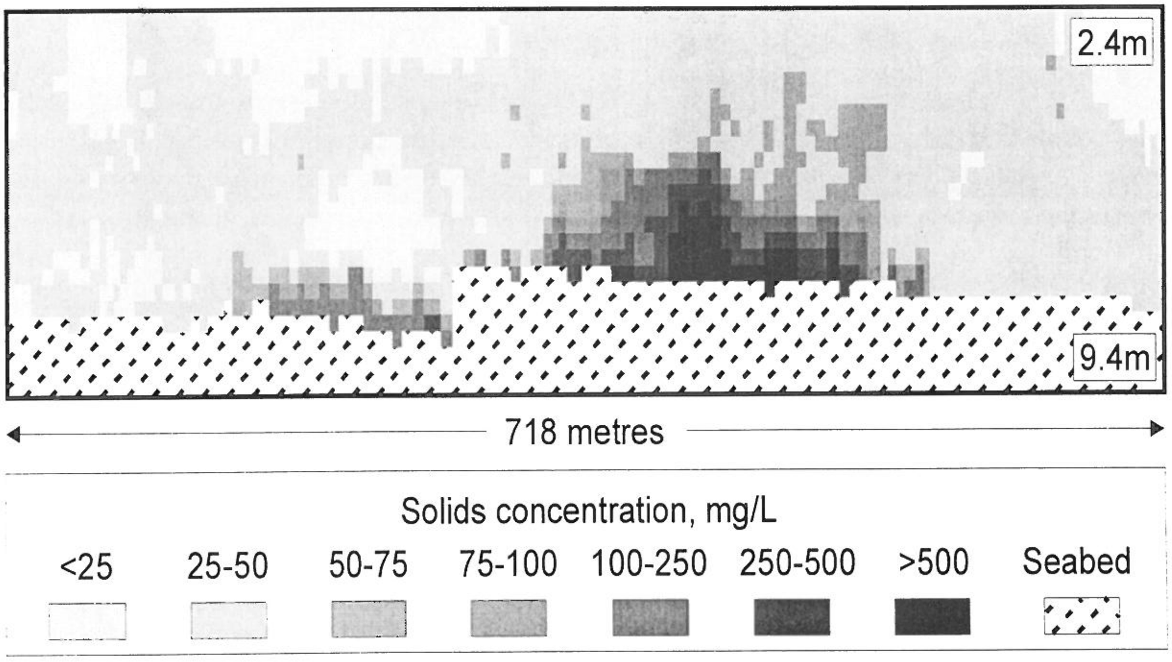

Figure 7. Sediment plume escaping into shallow water from a submarine pit after disposal from a 1,000 $m^3$ split barge.

## APPLICATION TO THE STUDY OF NATURAL SEDIMENT TRANSPORT

The method described here could be applied to the studies of natural sediment regimes:

- For establishing natural background conditions and their variation prior to dredging and disposal operations (or any other works in aquatic environments);
- For calibration of mathematical models; and
- For studies of pollutant transport.

An example of the last application is included here because it illustrates the extent to which the problems associated with acoustic measurements can be overcome when working in suspensions which periodically flocculate and when the particle size of the suspended solids varies with depth and/or current speed.

### Natural Sediment Flux in the River Mersey, UK

The UK Environment Agency require accurate measurements of sediment transport in the River Mersey for their studies of pollutant movement in the estuary. Two series of measurements during neap and spring tides were made in 1995 using the Sediview Method. Each comprised a series of transects across the river at intervals of approximately 15 minutes. After each transect, during the return journey to the starting point, sets of 2 or 3 water samples were taken at different depths at three locations.

Current flows and solids concentrations in the Mersey are very variable and can be high. At times, the current speed makes it impossible to obtain water samples immediately under the survey vessel and the sampler often trails up to 20 metres behind the boat. An added difficulty is that the fine sediment readily flocculates at slack water. The majority of the sediment has a particle size of less than 20 microns but, in the absence of turbulence, forms flocs which may be up to 1.5 mm in diameter. This has a dramatic effect on the acoustic response. However, frequent sampling during the surveys permitted the derivation of a time-variable calibration which substantially eliminated the errors arising from this source.

Figure 8 shows a comparison between the Sediview concentration estimates and the concentrations obtained from laboratory analysis of water samples which were obtained at ranges of between 2 and 22 metres from the ADCP transducers. No samples have been omitted from the data set, despite the gross difficulties of ensuring spatial correlation.

The same data are plotted in Figure 9 against a time axis from which it can be seen that there is a good correlation between the two measures of concentration. The data permitted detailed estimates to be made of both river discharge and sediment flux during the tidal cycle. The discharge and solids flux measured during the neap tide survey are plotted in Figure 10. Analyses suggested that, assuming no error in the current measurements, the accuracy of the flux estimates were within 1% of the true values.

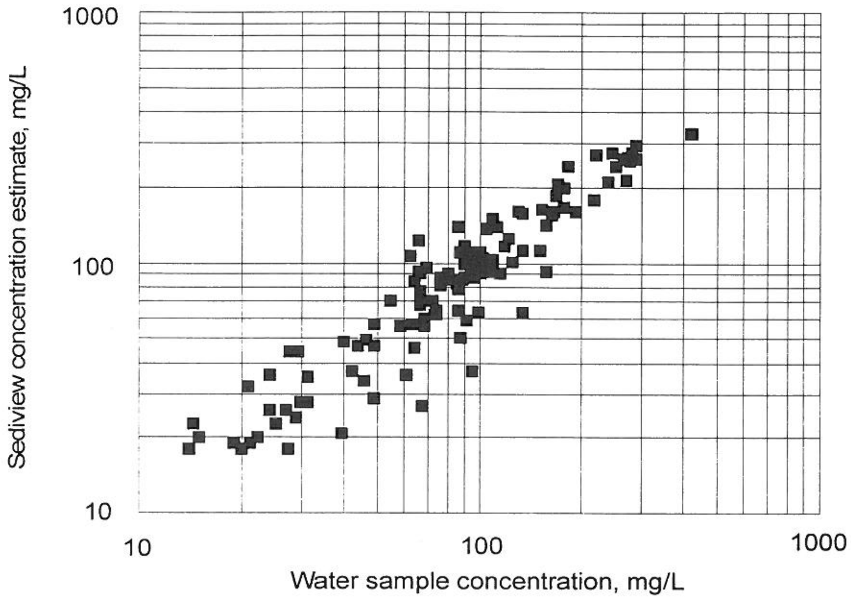

Figure 8. Comparison between Sediview concentration estimates and water sample concentrations, River Mersey, UK

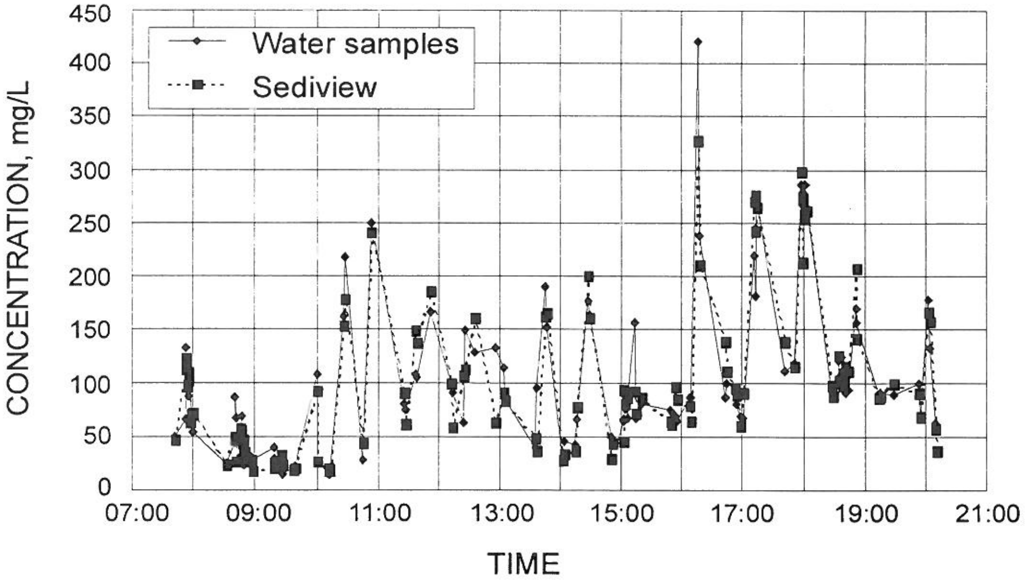

Figure 9. Time series plot of Sediview concentration estimates and water sample concentrations, River Mersey, UK.

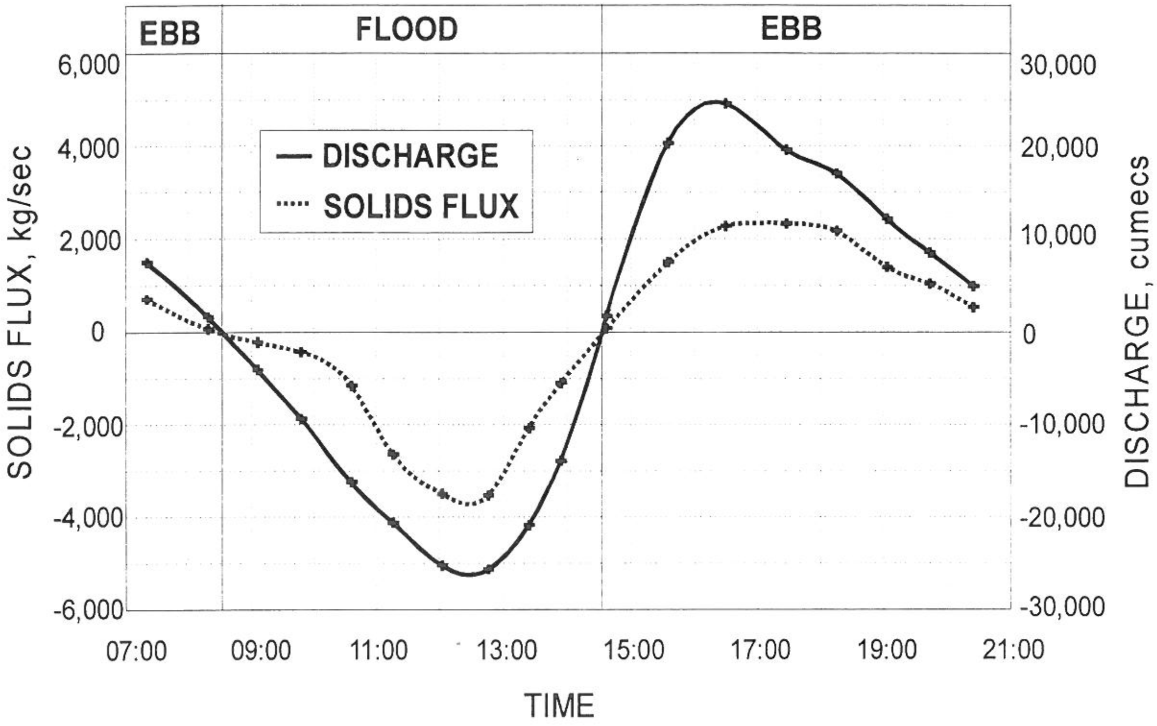

Figure 10. River discharge and solids flux during a neap tide cycle, River Mersey, UK.

## CONCLUSIONS

Despite some limitations arising from instrument design and performance and the extent to which site conditions may influence measurements, the combined measurement of suspended solids concentration and current speed and direction using ADCPs has been developed to the point where a high degree of accuracy can be obtained. The data-collection power of this method permits large-scale, dynamic sediment transport processes to be quantified at a level of detail which is difficult to achieve using other methods. This approach has been used to study the migration and decay of sediment plumes from dredging and dredged material disposal, and natural sediment transport in estuaries.

## ACKNOWLEDGEMENTS

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# EXPERIMENTAL INVESTIGATION OF SLURRY FLOW MECHANISM IN A PIPELINE

Vaclav Matousek[1]

## ABSTRACT

A recent study showed and analyzed phenomena that occurred in a long dredging pipeline as a result of slurry density fluctuation generated in the pipeline inlet (Matousek, 1996). The proposed theoretical explanation of the observed phenomena had to be verified experimentally by tests during which important flow parameters could be sensed at various controlled slurry flow conditions. Therefore, extensive experiments were conducted using a 150-mm diameter laboratory pipe loop. The experiments included visual observations of a deposition-limit velocity and measurements of frictional head losses and concentration profiles for aqueous slurries of different sizes of sand and gravel. The wide range of tested solids (sand and gravel from 0.2 to 5 mm), slurry velocity (2 – 8 m/s) and delivered volumetric concentration (10 – 36 %) permitted the detection of the behavior of slurry flow in a pipeline under very different flow conditions. A measure of a flow stratification and slip between phases were found to be of substantial importance for an identification of prevailing mechanisms of flow of settling slurry in a pipeline. This paper discusses experimental work conducted at the Delft University of Technology and reviews the most interesting observations. On the basis of laboratory experiments, proposals for the modeling of settling slurry flow in a pipeline are given.

## INTRODUCTION

In dredging practice, empirical correlations are used to predict design parameters for pipeline transport. These correlations provide the hydraulic gradient (i.e. a measure of energy dissipation) in a pipeline flow and the deposition-limit velocity (the minimal value of the mean slurry velocity for which the operation is safe and efficient). However, these correlations are not capable of simulating dynamic effects of unsteady flow occurring during a dredging operation (Matousek, 1996). This can be accomplished only by using a physical model that reproduces the flow mechanism in a pipeline. Empirical correlations may reflect the phenomena occurring in a dredging pipeline but they do not reflect the physical mechanisms governing those phenomena.

Traditional experiments completed on dredging installations provide only a limited number of flow parameters: the pressure drop over a long pipeline section, expressed as the hydraulic gradient $I_m$, the mean mixture velocity, $V_m$ and the mean delivered concentration of solids in a pipeline, $C_{vd}$. These are not sufficient to detect mixture flow mechanisms and thus to verify a physical model. Verification of a physical model requires the detection of prevailing mechanisms governing a mixture flow. A physical model requires that a number of flow parameters be

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[1] Assistant Professor, Delft University of Technology, DEP, Section of Dredging Technology, Mekelweg 2, 2628 CD Delft, The Netherlands

measured to detect the flow mechanism and to verify the model based on a description of the flow mechanism. A physical model cannot be considered to have been verified by experimental tests that do not include measurements of concentration profiles in a pipeline cross section.

## EXPERIMENTAL OBJECTIVE

One aim of the experimental work, completed in the laboratory of the Chair of Dredging Technology of Delft University of Technology, was to observe the behavior of slurry flow in a pipeline in a way that would show not only the effects of slurry flow as energy dissipation and solids deposit formation but also the reasons for these effects. This made it necessary to measure the flow characteristics appropriate to the detection and analysis of mechanisms governing the process of slurry flow in the pipeline. Furthermore, the measured characteristics had to be appropriate for the verification of the components of a physical model (Matousek, 1998). Two types of flow parameters were measured:

- the integral flow characteristics; the measured values represent the mean values of a quantity in a pipeline cross section (slurry velocity, delivered and spatial concentration of solids, pressure)
- the local flow characteristics in a pipeline cross section (local concentrations at different vertical positions in the pipeline cross section and local solids velocity near the bottom of the pipeline).

A further aim of the experimental work was to collect a sufficiently representative database to verify a physical model over a wide range of slurry flow conditions. The experimental program was focused on slurries and pipeline configurations typically handled in dredging, i.e. on aqueous sand mixtures and gravel mixtures flowing in horizontal and inclined pipelines. Steady flow conditions were characteristic of the tests in the laboratory circuit.

## EXPERIMENTAL SET UP

The circuit DN150 (Figure 1) in the laboratory of the Chair of Dredging Technology of Delft University of Technology consists of a 24-m long test loop that can be inclined from horizontal to vertical positions, an 18-m long vertical U-tube, the connecting pipes and the sump tank by means of which solids are introduced into the pipeline and in which solids are stored at the end of each experimental run. During measurements the tank can be bypassed. The entire pipeline circuit has a diameter of 150 mm and is 65 m long. A centrifugal pump driven by a 164 kW diesel engine with variable speed serves the system.

The test loop is composed of a wide U-bend and two 10.55-m long straight pipes. These two pipes of the test loop are called the ascending pipe and the descending pipe to indicate the flow direction in the pipes when the test loop is inclined. Each pipe contains one measuring section. Both measuring sections are 3 m long and are equipped with a differential pressure transmitter and a radiometric density meter. This permits simultaneous measurement of slurry flow characteristics in both the ascending and the descending pipes. Measuring sections are placed in

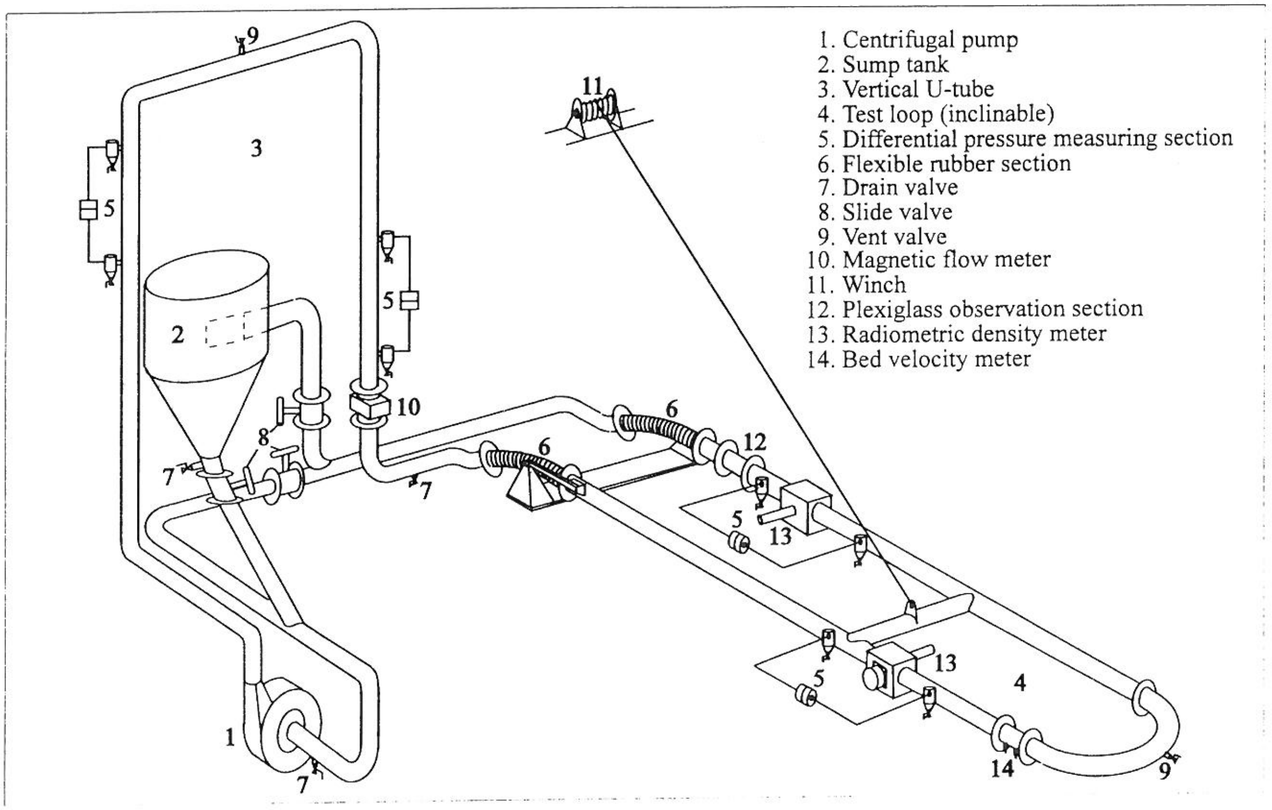


**Figure 1. Laboratory circuit with the 150-mm pipe.**

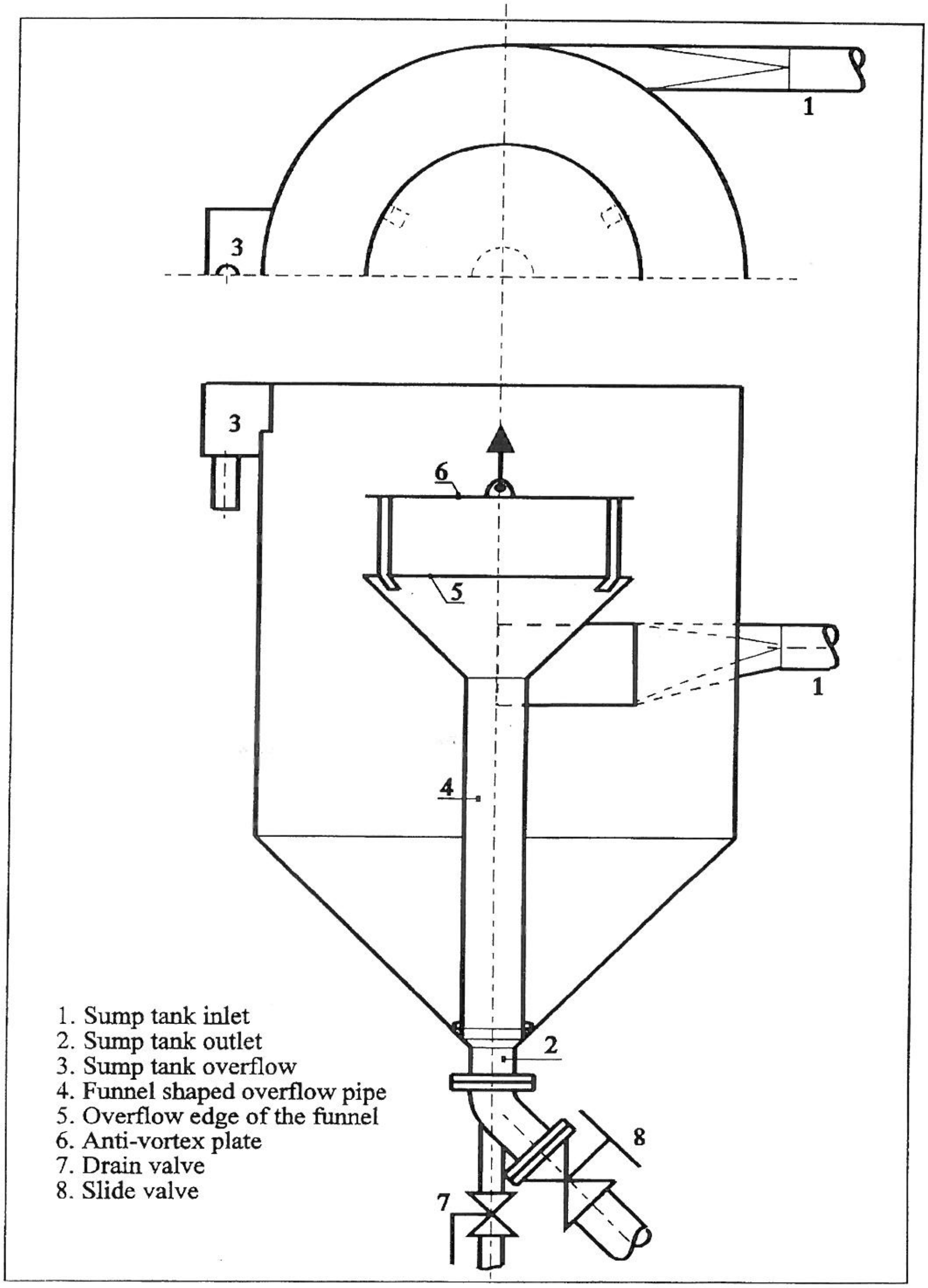


**Figure 2. The sump tank of the laboratory circuit.**

the straight pipes in such way that the slurry flow structure in the sections is not affected by bends and other sources of flow disturbance.

The vertical U-tube also contains 3-m long measuring sections in both the ascending and descending limbs of the U-tube. A flow meter is installed in the descending limb 0.5 m behind the end of the measuring pipe. The height of the U-tube is 9.45 m when measured from the axis of a horizontal pipe on which the U-tube is vertically mounted.

The sump tank is open to the atmosphere. It is equipped with a funnel-shaped overflow pipe, which can be lifted within the tank (Figure 2). The elevation of the pipe regulates the path of the slurry flow through the tank. At the end of an experimental run the movement of the funnel permits the separation of solids from slurry and their storage in the tank. Two different positions of the funnel determine two different flow modes in the tank. When the funnel is lifted up so that its overflow edge is above the slurry level in the tank, the slurry flows directly through the tank leaving it by an outlet in the tank bottom. In this case slurry does not flow through the funnel. The second position of the overflow pipe is reached by letting the funnel sink to the tank bottom so that the bottom of the overflow pipe rests on the tank outlet. The funnel is entirely submerged in the slurry and slurry can reach the tank outlet only via the overflow at the top of the funnel. The overflow edge is positioned above the level of the tank inlet. The solids that tend to settle in the slurry are therefore collected in the tank and quickly separated from the carrier fluid streaming through the overflow back to the pipeline circuit.

The feeding of the pipeline circuit with solids at the beginning of an experimental run is achieved by lifting the funnel to open the tank outlet for the sediment deposited on the bottom of the tank. When the tank inlet is closed and water circulates in the pipeline circuit through a bypass, there is no flow through the tank and the solids from the bottom of the tank flow only by gravity to the circuit. Feeding is slow (it takes about 10 minutes) and steady, and this prevents the creation of unsteady slurry-flow conditions in the circuit. Constant delivered concentration is reached along the entire circuit.

## EXPERIMENTAL METHODOLOGY

Manometric pressure gradients and concentration distributions were measured for different solid sizes, various slurry flow conditions (controlled by measured mean slurry velocity, $V_m$, and delivered concentration, $C_{vd}$) and pipe inclinations. In the final stage of the experimental program a bed velocity meter was developed and incorporated into the measuring system. The temperature of the water in the circuit was maintained within a narrow range (near 21°C) by regulation of the gland-water flow rate at the centrifugal pump. A small amount of gland water always entered the system at the centrifugal pump and the same amount of water left the system via the overflow at the edge of the sump tank.

### Differential Pressure over a Pipeline Section

Pressure differences over the 3-m long measuring sections are measured by Fisher-Rosemount differential pressure transmitters (Model 1151DP). The differential pressure is sensed as pressure-induced deflection of a diaphragm in the δ-cell of the instrument. The pressure is transmitted from the measuring point to the diaphragm of the transmitter via a medium, e.g. clear water, in a hose. The pressure transmission must not be disturbed by impurities or air bubbles in the hose. For this reason, transparent PVC hoses are used to connect the differential pressure transmitters to sedimentation pots in order to detect the presence of air bubbles or sediment deposits. A sedimentation pot is mounted on the slurry pipe wall to cover a tap (of diameter 3 mm) in the pipe wall. The taps are located on the upper part of the pipe perimeter. The sedimentation pots prevent the penetration of solid particles from the slurry pipe into the PVC hoses and to the δ-cell. A valve at the top of the pot permits the venting of air from the pot and the hose. Vent valves are also available at the pressure transmitter. The sedimentation pots are connected to a pressurized water-supply circuit so that the pressurized water can be admitted to the pots to remove any incidental air bubbles, to clean the sedimentation pots and to flush the taps. Calibration of each pressure transmitter was completed by adjusting zero differential pressure and known differential static pressure on the transmitter diaphragm. Static pressures from water columns of known heights in a transparent PVC hose were exerted against an atmospheric pressure at the diaphragm. There is a linear relationship between differential static pressure and the transmitter output current (mA). The instruments appeared to be very reliable, accurate and stable in all conditions that occurred in the circuit during the tests.

### Slurry Velocity

The Krohne magnetic-inductive flow meter, Altometer TIV 50, is used to measure the mean slurry velocity in the laboratory circuit. The magnetic flow meter is a practical application of Faraday's law of electromagnetic induction. When an electrically conducting liquid moves through a magnetic field, a voltage proportional in magnitude to liquid velocity is induced at 90 degrees to both the field and direction of motion. The induced voltage is proportional to the flow velocity only and is unaffected by density, viscosity, pressure or temperature of the liquid. The measured velocity is the mean velocity in a pipe cross section. Mounting the instrument on a vertical pipe allows the interpretation of the measured velocity as the slurry velocity because the slip velocity between phases is considered, and also verified by experiments, to be negligible in the vertical pipe for all solids tested during the experiments. Furthermore, the accuracy of measurement in a vertical pipe is not affected by distortion of velocity distribution in the pipe cross section. Calibration of the instrument was conducted and certified by the manufacturer.

### Delivered Concentration

The inverted, vertically mounted, U-tube is used as the counter-flow meter to determine the slurry density in the pipeline. This device is often used in laboratory and field installations because it is simple to construct and operate. A careful description of the measuring principle, together with an analysis of measurement accuracy under different conditions is given by Clift and Clift (1981). Differential pressure is measured over the equally-long sections in the ascending and the descending limbs of the vertical U-tube. Pressure drop due to friction is considered independent of solids concentration and equal in both pipe sections. Averaging measured differential pressures from both sections eliminates the influence of wall shear stress (and thus of friction) and the average pressure drop can be attributed to the hydrostatic pressure exerted by a slurry column in a pipe section. The calculated slurry density of the slurry column is the average slurry density for both limbs of a U-tube. It is interpreted as the average spatial concentration in a vertical U-tube. When the absolute value of slip velocity is assumed identical in the ascending and descending limbs, the slip effect is also eliminated by averaging the measured differential pressures. The mean delivered concentration in a pipeline is then obtained by the counter-flow meter.

The experimental tests showed that slip is practically negligible in a vertical pipe for all solids used. Almost identical values for concentration were obtained from measured concentration distributions in both the ascending and descending sections of the vertical U-tube and from the counter-flow meter. Thus, the concentration obtained from the vertical U-tube is considered the mean delivered concentration of solids in the experimental circuit.

## Concentration Distribution in a Pipeline Cross Section

The local value of slurry density in a pipeline cross section is sensed by a radiation density meter Berthold LB 367 with a Cs-137 source. The absorption of a radiation beam passing through a pipeline between a radioactive source and a transmitter is represented by the ratio of beam intensity at the source and at the transmitter. It is an exponential function of the absorption coefficients of the media and the lengths of the beam for each medium through which the beam is passing. The values of absorption coefficients for liquid and solids are nearly proportional to their densities thus the attenuation of the radiation beam is a function of slurry density in the beam path (Shook and Roco, 1991).

A two-point calibration was conducted in the pipeline with a beam directed to the center of the pipeline cross section. The change in radiation intensity was measured for a water-filled pipeline and a water-filled pipeline with glass plates of known volume and specific gravity. The specific gravity of the glass was very similar to that of sand and gravel. The results were processed by the instrument software and the absorption coefficients were determined automatically. Furthermore, the instrument was calibrated for a water-filled pipeline at each vertical position in the measuring pipe cross section in which it was also planned to measure slurry density. To eliminate the influence of pipe wall wear on the values of measured local concentrations, the instruments were recalibrated for each position several times during the long period of the experimental work.

A special support, in which the Berthold radiometric density meter is mounted, enables vertical positioning of a radioactive source and a transmitter in a pipeline cross section. The radiation beam is collimated by a hole in a shield of a lead lined chamber locking a radioactive source. The radiation beam is directed horizontally in the pipeline cross section. By traversing the beam in a vertical direction across the pipeline cross section the chord-averaged density profiles are measured. Values for slurry density are converted to values of the local spatial volumetric concentration of the solids in the pipeline cross section. The concentration profiles are measured in pipeline cross sections located approximately in the middle of the measuring pipe section in both the ascending and the descending pipes of the test loop.

### Slip Ratio

The slip ratio is determined from simultaneous measurements of concentration profiles and the mean volumetric delivered concentration $C_{vd}$ in the pipeline. Integration of the concentration profile $c_v(y)$ gives the mean volumetric spatial concentration $C_{vi}$, hence slip ratio $C_{vd}/C_{vi}$ is determined directly from the measured parameters in the pipeline cross sections.

### Local Solids Velocity at the Bottom of a Pipeline

An instrument to measure solids velocity at the bottom of a pipeline is installed in the ascending pipe of the test loop. It is a modified version of the Wiedenroth & Wetzlar prototype, constructed and tested several years ago in the laboratory of GHS Paderborn in Meschede, Germany. The measuring principle (Wetzlar et al., 1991) is based on the cross-correlation of impedance signals generated by two electrodes mounted in a pipe wall at the bottom of a pipe. The impedance of an electrical field occupying a small control volume of slurry above an electrode is sensed. The impedance varies with the amount of solids passing the electrical field. Some particles or clusters of particles generate characteristic peaks in the impedance signal generated on the electrode.

From the cross-correlation of the characteristic peaks of two similar signals, the time is determined that a solid-particle cluster needs to move from a control volume above the first electrode to that above the second electrode. The velocity of solid particles at the bottom of the pipe is calculated from this time and a known distance between two electrodes.

The technique is practically non-invasive. The surface of the electrode is smooth and it forms part of the surface of the pipe wall. Testing of the system showed that the deviation in velocities sensed by this instrument is within 15% for all sorts (fine and coarse) of the solids tested. This is acceptable when it is realized that the sliding of solids at the bottom of a pipeline is often a very unsteady process.

### Particle Size Distribution and Particle Settling Velocity

Two techniques are used to determine particle size distribution (PSD) in tested solids - the sieving and the sedimentation tests. The sedimentation method has the advantage of direct determination of the settling velocity of the particles, which is the parameter characterizing the solids impact on the slurry flow behavior rather than the particle size. The effect of the concentration of solids in a settling cloud on the particle settling velocity in a sedimentation column is negligible because of small solids samples and thus the low concentration of solids in the settling cloud. The disadvantage of this method is that the length of the sedimentation column

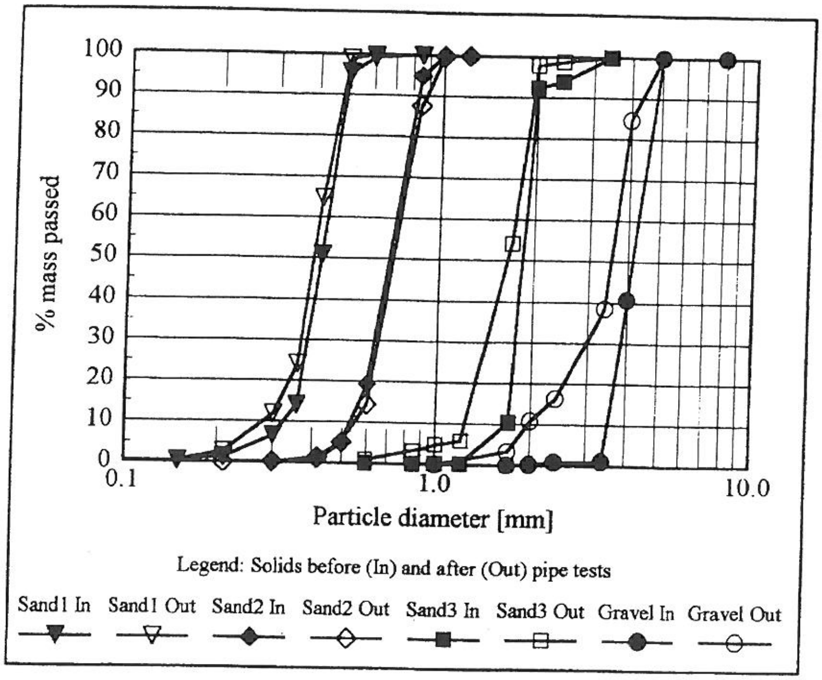


Figure 3a. Particle size distribution of tested solids.

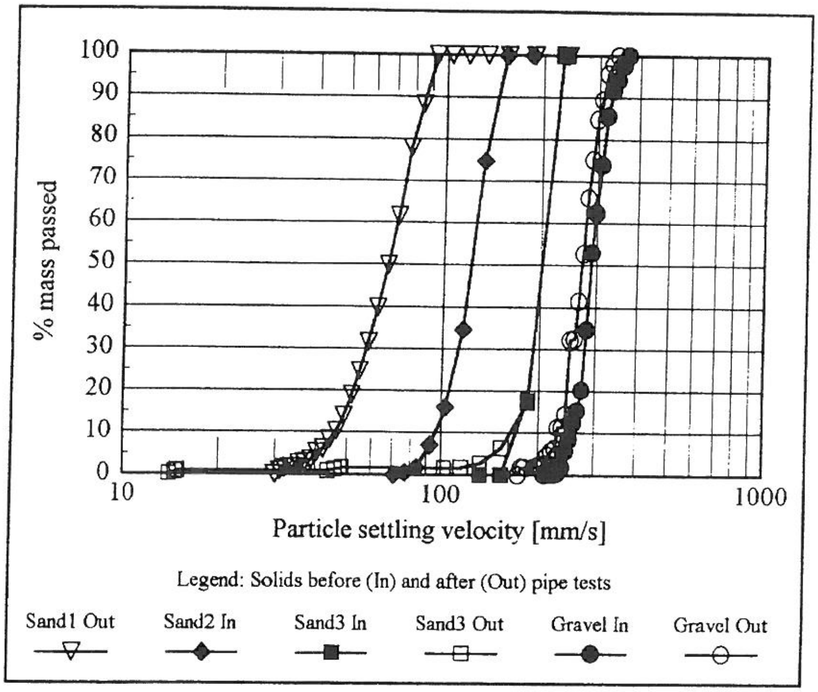


Figure 3b. Particle settling velocity distribution of tested solids.

is too short to test very coarse particles that need only a few seconds to reach the bottom of the sedimentation column.

The PSD curves and curves for the particle settling velocity distribution (PSVD) obtained from tests in our laboratory are shown on Figures 3a and 3b. The tests confirmed that the solids were very narrowly graded. The grading of each type of solid was measured before its introduction into the circuit and after its removal from the circuit at the end of a set of experimental runs. The solid portion became gradually finer and more broadly-graded when it had circulated in the laboratory circuit for a long time. The wear and crushing of the solid particles were primarily due to the contacts of particles with the rotating parts of the centrifugal pump. The pipeline did not contain sharp bends and intrusive fittings that would have accelerated the particle disintegration process. It was observed that coarser particles were subject to higher disintegration rates than finer particles. Even for the coarsest solids, however, the effects of the disintegration process were not so significant that they could have influenced the slurry flow characteristics measured during different experimental runs. The slurry flow tests always started with the lowest solids concentration and portions of new material were added to increase the concentration for the next test run. The first portion might circulate in the system for up to 25 hr and the last-added portion for about 5 hr.

### Coefficient of Mechanical Friction

The mechanical friction coefficient, $\mu_s$, of solids against the pipeline wall should be determined by using a tilting tube according to the proposal of Wilson (1970). Part of the descending pipe in the test loop was adapted to serve as a tilting tube. A value of 29 degrees was typically measured as the angle of the pipe inclination which initiated sliding of the thin bed. This gave the mechanical friction coefficient $\mu_s = 0.55$. It should be noted that this value is not valid for all types of sand and gravel so it is recommended that the coefficient for the solids handled in pipelines should always be determined experimentally.

## EXPERIMENTAL RESULTS

Steady flow was maintained in a laboratory circuit during all experimental runs. Tested settling slurries exhibited the concentration and velocity gradients across a pipeline cross section. The tests were focused on the observation of the influence of different particle size, solids concentration and slurry velocity on the slurry flow behavior.

### Forming of a Stationary Bed

Experiments revealed that the mean slurry velocity ($V_m$) at which solid particles first stopped their sliding and a stationary deposit started to be formed cannot be characterized by one concrete $V_m$ value. The sliding bed was very unstable (particularly in coarser slurries) at mean slurry velocities near the threshold for a stationary bed. A transition between the regime with a stable stationary deposit and the regime with a steadily sliding bed was given by the velocity range of approximately 0.15 m/s. It may be anticipated that the accuracy of the determination of the deposition-limit velocity, $V_{dl}$, by experiments will be of the same order. It was found that the $V_{dl}$, that is the deposition-limit value of $V_m$, was influenced by the particle size and solids concentration in the pipeline. The results of visual observations (Table 1) showed that $V_{dl}$ decreased with increasing particle size $d_{50}$ and $V_{dl}$ decreased with increasing solids concentration $C_{vd}$.

Instabilities occurred at the top of the bed for slurry flow with mean slurry velocities below and near the deposition-limit value, and the bed surface was no longer plane. The instabilities were very weak in the flow of the finest tested material (Sand 1), but in the coarsest gravel flow they led to the development of bed forms occupying a considerable area of the bed. This made observation of the deposition-limit velocity impractical because the bed forms developed might easily block the pipeline near the critical components of the circuit such as bends and other fittings.

**Table 1. Visually observed limit-deposition velocity in the horizontal 150 mm pipeline.**

| solids size [mm] | $C_{vd}$ [-] | $V_{dl}$ [m/s] |
|---|---|---|
| 0.2 – 0.5<br>(Sand 1) | 0.11 | 2.70 – 2.80 |
| | 0.18 | 2.60 – 2.65 |
| | 0.24 | 2.55 – 2.60 |
| | 0.31 | 2.40 – 2.45 |
| | 0.36 | 2.25 – 2.35 |
| | | |
| 0.5 – 1.0<br>(Sand 2) | 0.09 | 2.60 |
| | 0.17 | 2.50 |
| | 0.20 | 2.45 – 2.50 |
| | 0.23 | 2.35 – 2.45 |
| | 0.33 | 2.10 – 2.15 |
| | | |
| 1.4 – 2.0<br>(Sand 3) | 0.08 | 2.00 – 2.10 |
| | 0.21 | 2.00 |
| | 0.24 | 1.90 |

Very weak instabilities in the flow of the finest measured solids (0.2-0.5 mm sand) made it possible to measure the flow parameters for $V_m$ below the deposition-limit value. These measurements showed that the solids concentration in the bed increased rapidly when the bed stopped sliding. Also the frictional head loss, $I_m$, increased rapidly within a narrow velocity range in which the stationary bed began to be formed. A comparison of the shapes of the $I_m$-$V_m$

resistance curves for slurry of different solids concentrations indicates a gradual decrease of $V_{dl}$ value with an increasing solids concentration in the pipeline.

## Energy Dissipation in Slurry Flows

Measured hydraulic gradients $I_m$ showed the following general trends:
(a) compared with the flow containing finer solids at the same $V_m$ and $C_{vd}$, the slurry flow containing coarser particles provides higher resistance, and
(b) when other parameters (as $V_m$ and $d_{50}$) remain unchanged, the friction loss in the slurry flow increases with the slurry density.

The development of $I_m$ with the increasing $V_m$ is shown by the shape of the $I_m$ - $V_m$ curve (also called the resistance curve) obtained during one experimental run (in flow of approximately constant delivered concentration of solids). Resistance curve shapes were observed to be different for flows of solids of different particle sizes. The shape of the curve for the flow of certain material was also found to depend on the solids concentration.

## Specific Energy Consumption

The efficiency of a slurry pipeline is evaluated by means of a parameter called specific energy consumption (SEC). The SEC determines the energy required to move a given quantity of solids over a given distance in a pipeline. It is given as

$$\mathrm{SEC} = 0.2778\frac{I_m g}{S_s C_{vd}} \tag{1}$$

in units of kWh/tonne.km, where $S_s$ is relative density of solids and g is gravitational acceleration, and plotted against solids throughput (the amount of dry solids delivered at the pipeline outlet over a time period) in Figure 4. The lowest values of the specific energy consumption in the laboratory pipeline were found in slurries with the volumetric concentrations of solids higher than 25%, flowing at mean velocities not far above the deposition-limit velocity $V_{dl}$. However, the operation of a pump-pipeline system in this regime of slurry flow is not always practical. When compared with the flow of dilute slurries, the deposition-limit velocity of the flow of highly concentrated slurries is shifted to the lower values of the mean slurry velocity $V_m$ and may become lower than the velocity $V_{min}$ at the minimum of the resistance curve $I_m$ versus $V_m$ for slurry flow of the constant delivered concentration. Operation in the velocity range between $V_{dl}$ and $V_{min}$, in which the flow resistance increases with decreasing mean slurry velocity, is inherently unstable and, in practice, is usually avoided. During observations in the 150 mm pipeline, the deposition-limit velocity dropped below the minimum velocity in sand slurries of the highest measured concentrations ($C_{vd} \approx 35\%$).

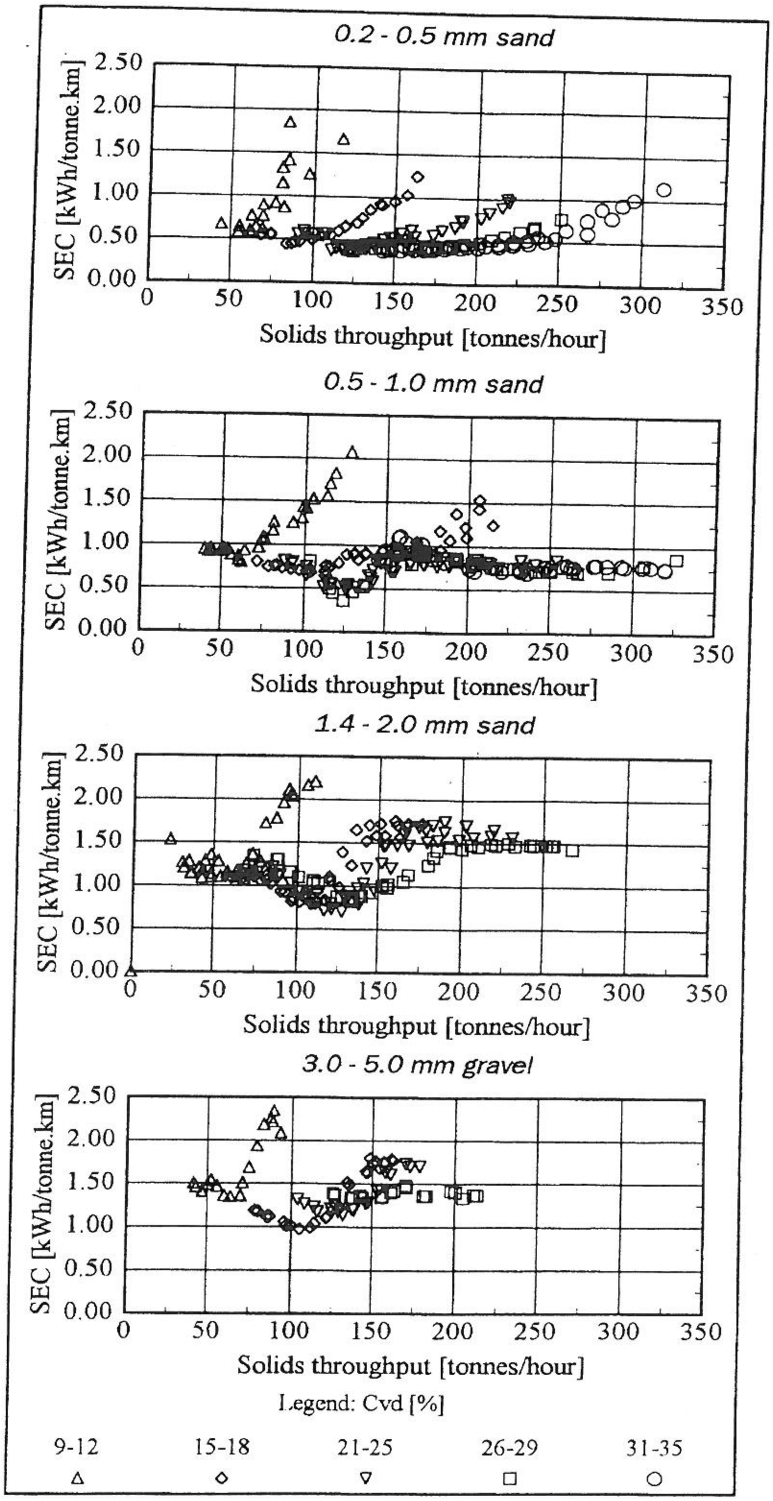


Figure 4. Specific energy consumption (SEC) in the 150-mm slurry pipeline.

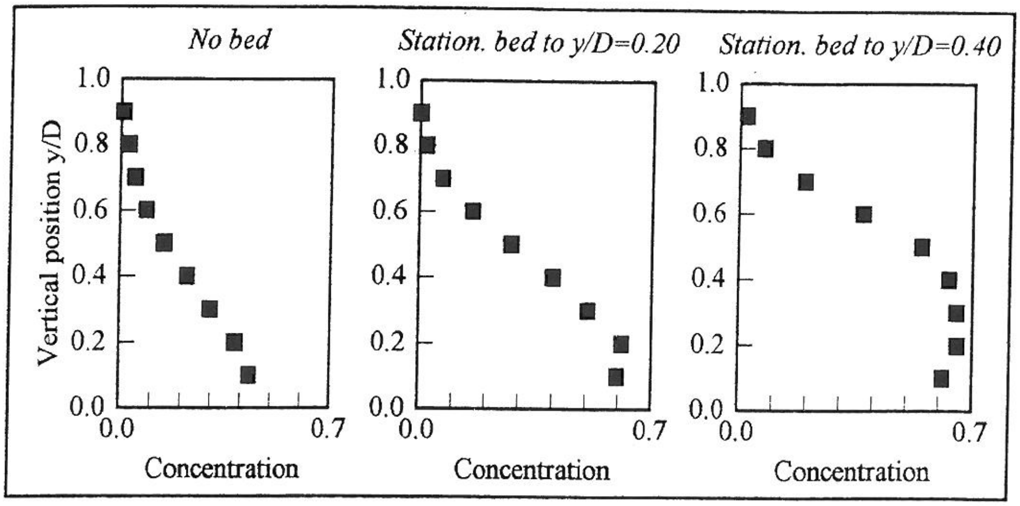
The specific energy consumed to transport coarse sand is approximately twice that needed to transport medium sand in the 150 mm pipeline. This is because energy is primarily dissipated through mechanical friction between the solid particles and the pipeline wall as a result of flow stratification and the formation of a contact bed at the bottom of the pipeline. Flow is more stratified when transported particles are coarser. The granular bed is composed of particles that are not supported by turbulence of the carrying liquid. However, under suitable flow conditions, the top of the granular bed is subjected to shearing and a shear layer is developed in which the inter-particle contacts are sporadic rather than continuous (Matousek, 1997). The development of the shear layer is associated with a drop in the hydraulic gradient $I_m$ and thus with the diminishing of the specific energy consumption in the flow. This effect occurred in mixtures of solid particles coarser than 0.5 mm flowing in a 150-mm pipeline for solids flow rates around 125 tonnes/hour as seen in Figure 4. To profit from the SEC drop resulting from the suspension mechanism caused by inter-particle collisions within the shear layer, the pump-pipeline system must be run at a velocity slightly higher than the $V_{dl}$, but not too close to it.

## Solids Distribution in Slurry Flows

The local concentrations near the bottom of the pipeline may approach a limiting value given by the solids concentration in a loose-poured bed. The measurements showed that this was the case in the stationary beds if they occurred in the test pipeline. Moving beds, however, tended to be less concentrated than stationary beds, even if solids within moving beds remained uniformly distributed. Moving beds with a uniform concentration distribution also exhibited a negligible solids velocity gradient over their height so that they slid *en bloc*. The solids concentration in a stationary bed had values of about 0.60 considered a loose-poured value. This is seen in concentration profiles measured in the Sand 2 slurry on Figure 5. That shows results of a test in a specially adapted test loop during which the bed development in the pipeline was observed under the condition of a gradually decreasing $V_m$ and constant $C_{vd}$; the constant value of $C_{vd}$ was maintained by adding sand to the circuit when the lower $V_m$ was installed. The *en bloc* sliding beds had concentrations of about 0.55 or even less (Figure 5), indicating that even uniformly distributed beds exhibit certain dilation. The local concentrations near the bottom of a pipeline were also found to be strongly dependent on mean solids concentration in the pipeline. Low concentration slurries did not produce a bed of a concentration approaching the loose-poured value even for the slurry velocities only slightly above the deposition-limit value.

The measurement of solids concentration profiles showed that the solids effect ($I_m$ - $I_f$) was strongly dependent on the shape of the concentration profile in a pipeline cross section. Less stratified flow exhibited less resistance. Generally, particle size d, $V_m$ and spatial concentration $C_{vi}$ are the major parameters determining the measure of slurry flow stratification in a pipeline cross section if densities $\rho_s$ and $\rho_f$ are constant. The stream carrying the larger particles requires a higher $V_m$ to overcome the particle settling tendency and keep the particle in suspension. Thus the flow at a certain $V_m$ tends to be more stratified when coarser particles are transported.

Low concentrated slurry flow.



High concentrated slurry flow.

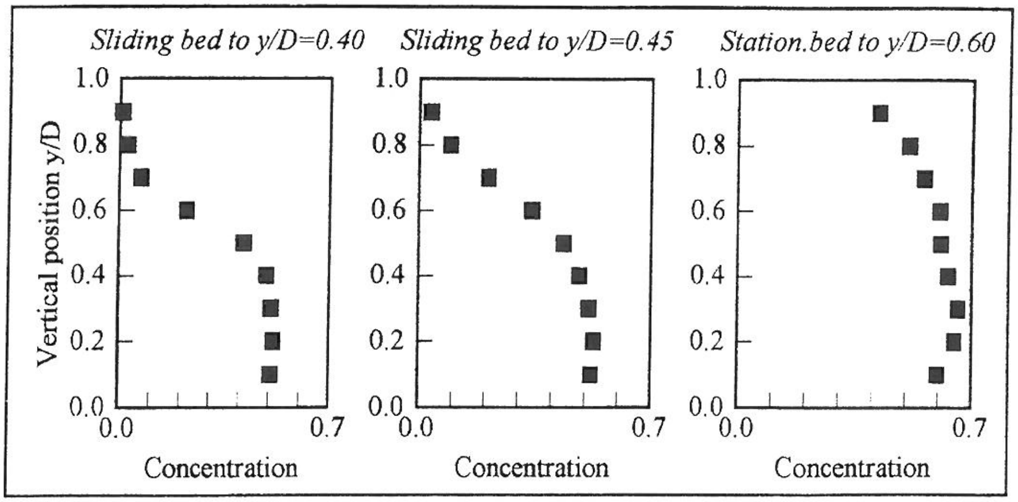


**Figure 5. Stationary and en bloc sliding beds in the horizontal 150-mm pipeline.**

## Slip Between Phases within Slurry Flows

The slip ratio ($C_{vd}/C_{vi} = V_s/V_m$) is a parameter used to describe the slip between the flowing solid and liquid phases in a test pipeline. It was determined experimentally as $C_{vd}/C_{vi}$ from the measurements of the slurry density $\rho_m$ in the vertical U-tube and concentration profiles in the test loop. Measured $\rho_m$ gave $C_{vd}$ and the $C_{vi}$ values that were obtained by integrating the measured profiles over the pipeline cross section area. The slip was found to be strongly related to the degree of flow stratification in a pipeline. The slip ratio approached unity when the concentration distribution became less stratified. Tests in the laboratory circuit revealed the following.

- The slip was always negligible when slurry flow was pseudo-homogeneous (the concentration profile in the pipeline cross section was uniform). This was observed in slurry flows of all tested solids through both the ascending and the descending pipes of the test loop installed in the vertical position. In the horizontally-positioned test loop, negligible slip was detected in flows of the finest tested sand (Sand 1) at the highest testing slurry velocities ($V_m > 5$ m/s). At these velocities a low concentration gradient across the pipeline cross section was measured so the flow could not be considered to be stratified.

- The slip increased with an increasing degree of flow stratification in a horizontal pipe, i.e. the less-uniform concentration profile provided a bigger difference between mean velocities of phases in a pipe cross section.

- The slip tended to be less important (i.e. the slip ratio tended to approach unity) in the slurry flow when solids concentration increased (see Table 2).

**Table 2. Slip ratio in the descending pipe of the 150-mm test loop installed in a horizontal position.**

| solids size [mm] | $V_m$ [m/s] | $C_{vd}$ [-] | $C_{vi}$ [-] | $C_{vd}/C_{vi}$ [-] |
|---|---|---|---|---|
| 0.2 – 0.5 (Sand 1) | 3.00 | 0.119 | 0.148 | 0.80 |
| | 3.00 | 0.174 | 0.213 | 0.82 |
| | 3.01 | 0.230 | 0.260 | 0.89 |
| | 3.00 | 0.306 | 0.331 | 0.92 |
| 3.0 – 5.0 (Gravel) | 2.74 | 0.090 | 0.142 | 0.63 |
| | 2.78 | 0.170 | 0.248 | 0.69 |
| | 2.70 | 0.229 | 0.319 | 0.72 |
| | 2.77 | 0.271 | 0.363 | 0.75 |

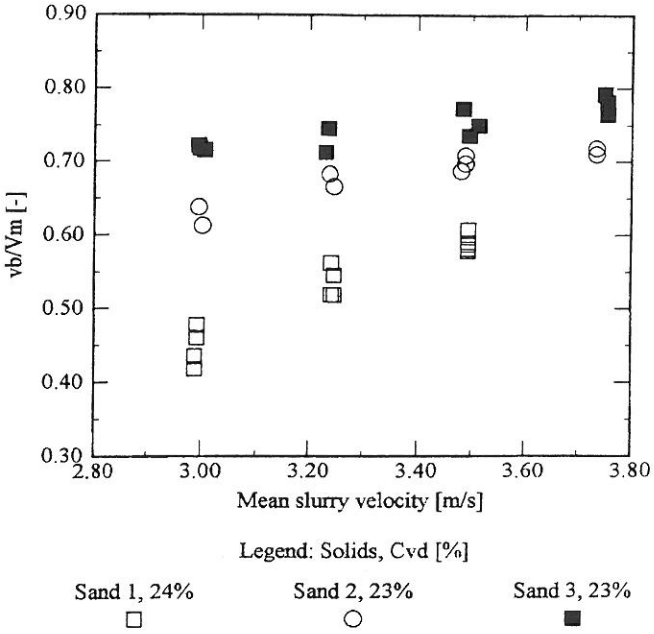


Figure 6a. Solids velocity ($v_b$) at the bottom of the 150-mm pipe for slurries of different transported solids, concentration ($C_{vd}$) and mean slurry velocities ($V_m$).

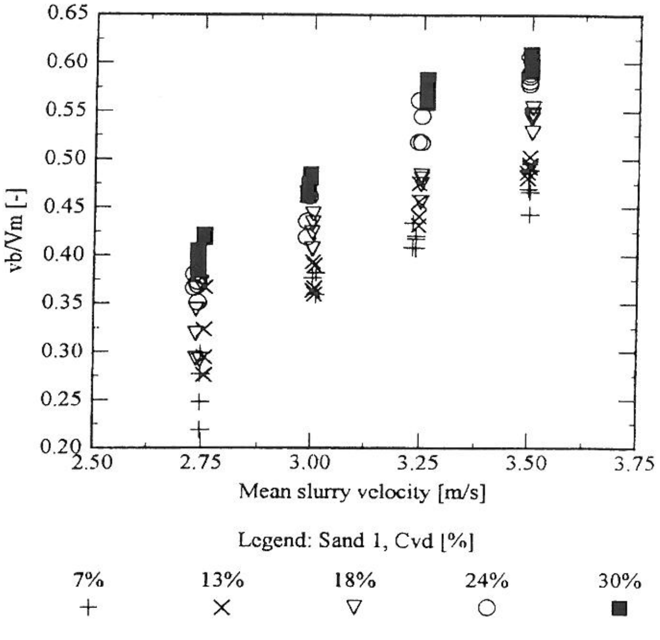


Figure 6b. Solids velocity ($v_b$) at the bottom of the 150-mm pipe for various mean slurry velocities ($V_m$) and solids concentrations ($C_{vd}$).

### Bed Sliding

A granular bed composed of coarser particles slid faster than a bed composed of finer particles in pipeline flows of comparable solids concentrations and mean velocities (Figure 6a). Grains near the bottom of the pipeline slide faster within a highly concentrated slurry flow than within a flow of lower slurry density but the same slurry velocity. This trend was observed in the flows of all materials tested. For Sand 1 slurry flow the trend is illustrated in Figure 6b.

## MODELING

### Frictional Head Loss

#### Semi-empirical correlations

The majority of empirical and semi-empirical models for pipeline flow of settling slurry assumes a linear relationship between the solids effect $I_m$-$I_f$ and the delivered concentration $C_{vd}$ in the form

$$\frac{I_m - I_f}{C_{vd}} = \mathrm{fn}(V_m, D, d, S_s, S_f)$$

in which $I_m$ is the frictional head loss for flow of mixture containing the delivered volumetric solids fraction $C_{vd}$, $I_f$ is the frictional head loss for flow of fluid at the identical mean velocity $V_m$ in a pipeline of diameter D, where d is the solid particle size, $S_s$ relative density of solids and $S_f$ relative density of fluid.

The Wilson & GIW model for partially-stratified (heterogeneous) flow (Wilson et al., 1992) gives a scale-up relationship for friction loss in slurry pipelines of different sizes transporting solids of different sizes at different concentrations. It is based on the assumption that there is a power-law relationship between the relative solids effect $(I_m$-$I_f)/[C_{vd}(S_s$-$1)]$ and the mean slurry velocity $V_m$ that is valid in all slurry flow conditions. The relationship between the relative solids effect and mean slurry velocity is given as

$$\frac{I_m - I_f}{C_{vd}(S_s - 1)} = 0.5\mu_s\left(\frac{V_m}{V_{50}}\right)^{-M} = 0.22\left(\frac{V_m}{V_{50}}\right)^{-M} \qquad (2)$$

in which the coefficient of mechanical friction between solids and the pipeline wall $\mu_s$ is proposed to be equal to 0.44. The exponent M is assumed to depend on the particle size distribution only. According to the latest proposal (Wilson, 1996), $V_{50}$ should be obtained experimentally or estimated roughly by the approximation

$$V_{50} \approx 3.93(d_{50})^{0.35}\left(\frac{S_s - 1}{1.65}\right)^{0.45} \tag{3}$$

in which the particle diameter $d_{50}$ is in mm and the resulting $V_{50}$ is in m/s.

Originally, the model was verified by experimental data for flows of relatively low concentrations ($C_{vd}$ not higher than 0.16). The data herein having a wider range of solids concentrations indicate the influence of solids concentration on the relative solids effect (Figure 7). According to the data the relative solids effect in medium-sand flow may be considered concentration-independent only in the narrow $V_m$ range just above the deposition limit threshold. At higher mean slurry velocities the increase in the relative solids effect with the increasing $C_{vd}$ is no longer negligible. The variation in the relative solids effect is due to both $V_{50}$ and M variation with mean solids concentration $C_{vd}$ in the slurry flow. No common trend is observed in the relationship between $V_{50}$ and $C_{vd}$ but the exponent M seems to decrease with the increasing $C_{vd}$ in slurry flow.

The Wilson&GIW correlation for fully-stratified flow (Wilson, 1996)

$$\frac{I_m - I_f}{C_{vd}(S_s - 1)} = \left(\frac{V_m}{0.55V_{sm}}\right)^{-0.25} \tag{4}$$

in which $V_{sm}$ is the maximum value of deposition-limit velocity, is more appropriate than the heterogeneous model for a 3.0-5.0 mm gravel flow tested during the experiments. This flow tended to be fully stratified, but because of hydrodynamic interaction between a sliding bed and water stream above the bed the entire bed did not slide *en bloc*. Only at the highest measured concentrations ($C_{vd}$ between 0.26 and 0.28) did almost all transported particles occupy the *en bloc* sliding bed.

## Two-layer model

A physical two-layer model recognizes a delivered concentration effect on the relative solids effect. A concrete relationship between the relative solids effect and mean slurry velocity depends on model configuration. Figure 7 compares experimental data with outputs of the model configuration proposed by Matousek (1998).

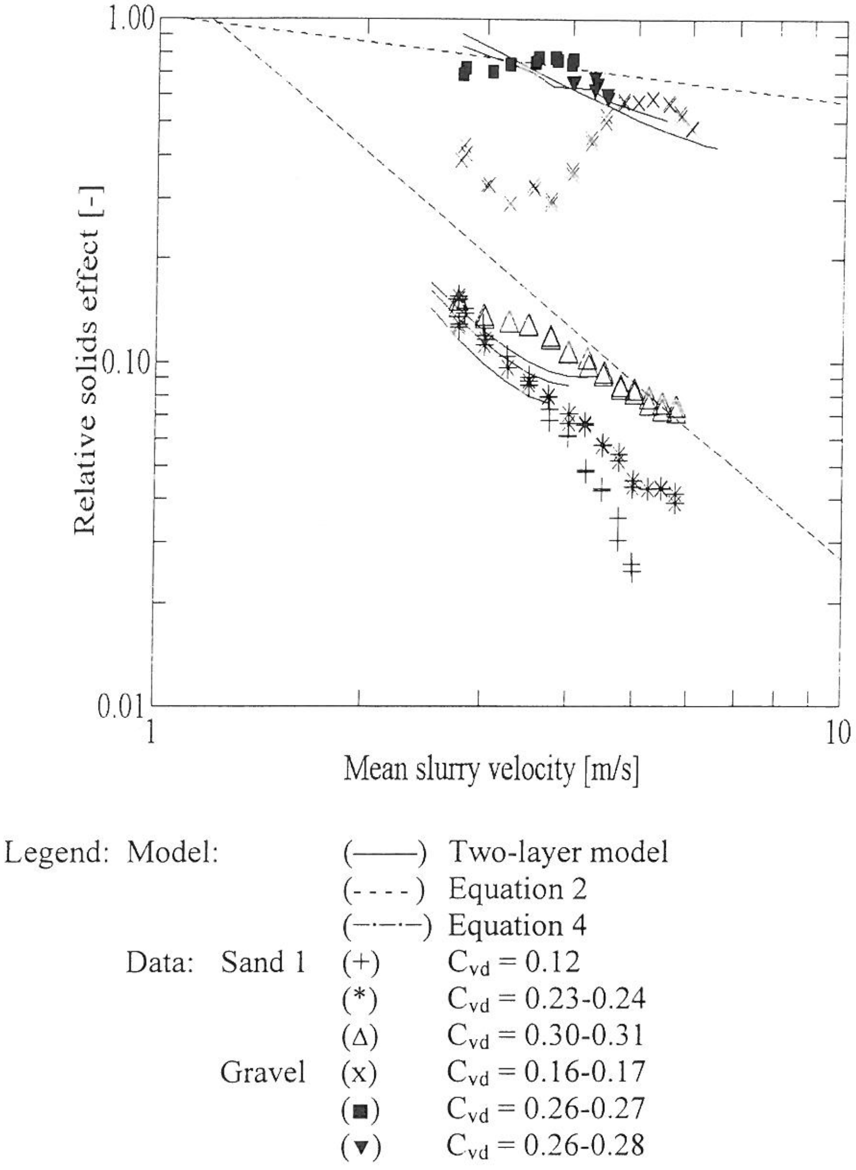


**Figure 7. Measured and predicted relative solids effect for Sand 1 slurry and Gravel slurry at various concentrations of solids.**

### Deposition-Limit Velocity

#### Empirical correlations

Durand and Condolios (1952) submitted a correlation for the deposition-limit velocity $V_{dl}$ in which the effect of solids concentration on the value of $V_{dl}$ was incorporated in a constant $F_L$ determined from a graph $F_L = fn(d, C_{vd})$. According to the graph, it is anticipated that the $V_{dl}$ values will increase with the increasing $C_{vd}$ within a certain range of particle size ($0.1 \text{ mm} < d < 1.6 \text{ mm}$). For particles of sizes outside this range the $V_{dl}$ value is considered to be concentration-independent. The graph was constructed for mixture flows of solids concentrations not higher than 0.15. The laboratory observations do not support the Durand & Condolios predictions.

#### Two-layer model

The measured trends in $V_{dl}$ variation with particle diameter are in accordance with predictions derived from a two-layer model. For particles larger than fine to medium sand the deposition-limit velocity given by the model decreases with increasing particle diameter. This is due to growing interfacial shear stress at the top of a granular bed. The interfacial shear stress produces a driving force acting on the top surface of the bed. A fall in $V_{dl}$ value under the increasing particle size was observed in a laboratory pipeline (Table 1).

The measured trends in $V_{dl}$ variation with solids concentration are also in accordance with predictions by a two-layer model. According to the computational outputs of the model the deposition-limit velocity rises with the delivered solids concentration to a maximum reached at some intermediate concentration value. This concentration value depends on D, d and $S_s$. If the delivered solids concentration rises further, the $V_{dl}$ value drops, approaching zero as $C_{vd}$ approaches the maximum concentration given by the loose-poured value. For flow conditions tested during the experiments the two-layer model anticipates the drop in $V_{dl}$ value for each increase in $C_{vd}$ above the minimum tested value ($C_{vd} \approx 0.10$). The drop in $V_{dl}$ value under the increasing solids concentration was observed in a pipeline (Table 1).

## CONCLUSIONS

The experiments revealed that the transportation of relatively highly concentrated slurries of sand (volumetric concentration up to about 36 per cent) might be safe and efficient. The specific energy consumed to transport sand in a pipeline tends to be lower if the concentration of the sand-water slurry is relatively high. Furthermore, the danger of a pipeline blockage is not increased if slurry is transported at higher concentration. The deposition-limit velocity falls with increasing concentration of solids in a pipeline. This is because the bed slides faster within highly-concentrated slurry flows.

The principles of a two-layer model were found appropriate to describe phenomena observed in partially stratified flows in a laboratory pipeline. A two-layer model is capable of simulating the prevailing mechanisms governing the pipeline flow of settling slurry.

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$$y = a + b + cx^2 \qquad (1)$$

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