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Pipe Size Effect on Hydraulic Transport of Jumoonjin Sand – Experiments in a Dredging Test Loop

Abstract

The diameter of a slurry pipeline is an important factor in a design and an operation of a pipeline and pump system connected with a dredger. However, the effect of pipe diameter on the slurry flow behaviour (frictional head losses, specific energy consumption, deposition limit velocity) is not well understood. Moreover, there is a lack of experimental data that could be used to study the pipe size effect on slurry flow behavior and thus on efficiency of slurry transport operation. Recently, tests were carried out in the dredging test loop of Hyundai Institute of Construction Technology with an aim to collect information on the effect of pipe size on pipeline characteristics (I-V curves and specific energy curves) for aqueous slurries of the Jumoonjin sand (a medium to coarse sand with $d_{50} = 0.54$ mm). The measurements were carried out in straight horizontal pipelines of three different diameters – 155 mm, 204 mm, 305 mm. The article describes and analyses results of these tests. It is reprinted from the *WODCON 2004 Proceedings* in Hamburg, Germany, with permission.

Introduction

The diameter of a slurry pipeline is an important factor in a design and an operation of a pipeline and pump system connected with a dredger. However, the effect of pipe diameter on the slurry flow behaviour (frictional head losses, specific energy consumption, deposition limit velocity) is not well understood. Moreover, there is a lack of experimental data that could be used to study the pipe size effect on a slurry flow behaviour and thus on the efficiency of a slurry transport operation.

HYUNDAI DREDGING TEST LOOP

The Hyundai Dredging Test Loop was completed in 2001 with an objective to investigate both the effect of a pipe size and the effect of pipe bends on slurry flow

NOMENCLATURE

c_u	uniformity coefficient of sand	[-]
c_v	curvature coefficient of sand	[-]
C_{vd}	delivered volumetric concentration	[%]
C_{vi}	spatial volumetric concentration	[%]
d_{50}	mass-median particle diameter	[m]
D	pipe diameter	[m]
l_w	hydraulic gradient of water	[-]
l_m	hydraulic gradient of mixture	[-]
k	pipe-wall roughness	[m]
N_{Fr}	Froude number of pipe flow	[-]
Re	Reynolds number of pipe flow	[-]
S_m	relative density of mixture	[-]
S_w	relative density of water	[-]
V_m	mean velocity of mixture	[m/s]
γ	density of water/mixture	[kg/m ³]
λ	friction coefficient	[-]

Abbreviations

r.p.m.	revolutions per minute
RSE	relative solid effect
SEC	specific energy consumption
SEM	scanning electric microscope

properties in pipelines. The test loop is a part of the Civil Laboratory of Hyundai Institute of Construction Technology in Yongin-city near Seoul in Korea. Basically, the dredging test loop consists of the engine connected with the centrifugal slurry pump, the pipe circuit with parallel pipe sections and the measuring system.

Circuit

Figure 1 shows a schematic diagram of the dredging test loop. The entire circuit is 160 metre long and it is composed of a vertical U-bend, horizontal pipelines, 45° and 90° bends, a cyclone tank and 12 main control valves. The vertical U-bend is 13 m long and positioned downwards from the level of the pump station. The steel pipe of the U bend has a diameter 204 mm. Horizontal sections of the circuit are equipped with



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Choong-Ki Chung

After receiving a PhD in civil engineering from Northwestern University, Illinois, USA in 1991 and spending a year as a post-doctoral fellow in the same institute, Prof. Choong-Ki Chung joined the faculty of civil engineering at Seoul National University (SNU) in 1992. He is in charge of the SNU soil mechanics laboratory and has performed research on engineering properties by lab and field testing. In addition, he is interested in developing GIS-based a geotechnical information system and field monitoring system.



Vaclav Matousek

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parallel pipes of different diameters: 155 mm, 204 mm, 305 mm (circular steel pipes with nominal diameters 150, 200 and 300 mm) and 200 mm (rectangular steel pipe).

Each horizontal circular pipe has a 80-cm long perspex section for visual observations and taking photos (see Figure 1). There are 45° bends and 90° bends mounted to the circuit at the end of the horizontal pipes. Using the bends and the ball valves the flow is directed to one of the parallel horizontal pipes. The entire circuit contains 49 taps and sedimentation pots at every pressure measuring point.

A cyclone tank is used to introduce solids in the circuit and collect the solids after a test. The cyclone has the diameter 2 metre and the height 3 metre. Inside the cyclone is a wire mesh screen that helps sand to settle down. The cyclone is equipped with 5 control valves and a 15 cm long perspex tube beneath the ball valve at the cyclone outlet. This helps to observe whether the inflow of sand to the circuit is steady.

The centrifugal pump used in the test loop is the JOOHO dredging slurry pump with the 4-blade impeller of the diameter 0.45 metre and the diameters of pump inlet and outlet 0.3 metre and 0.25 metre, respectively. The pump is driven by a HMC 255kW diesel engine equipped with BOSCH governor and turbocharger. The engine is connected with the centrifugal slurry pump by V belts. The speed of the pump can be controlled within the range of 530 to 2,000 r.p.m. Figure 2 shows the pump performance curve when clean water was transported.

Measuring system

The dredging test loop is equipped with 17 measuring devices. The measuring system contains tachometers, flow meters, density meter, absolute pressure and differential pressure transducers and manometers.

The flow rate of slurry through the circuit is measured using two instruments both mounted to the descending pipe of the vertical U-bend. One instrument is the ABB magnetic flow meter and the other the CONTROLTRON ultrasonic spectra flow meter. The density of the flowing slurry is determined using the BERTHOLD radiometric (Cs137) density meter mounted in the ascending pipe of the vertical U-bend (Figure 3).

The absolute pressures at both the inlet and the outlet of the pump and in several points along the circuit are measured by the WYKEHAM-FARRANCE pressure transducers and the GDS pressure controllers and simultaneously by the absolute-pressure manometers. The pressure drops over the 2-metre long measuring sections in both vertical and horizontal pipes are measured using the SENSOTEC 1-psi capacity differential pressure transducers and differential manometers. Two AUTONICS tachometers and

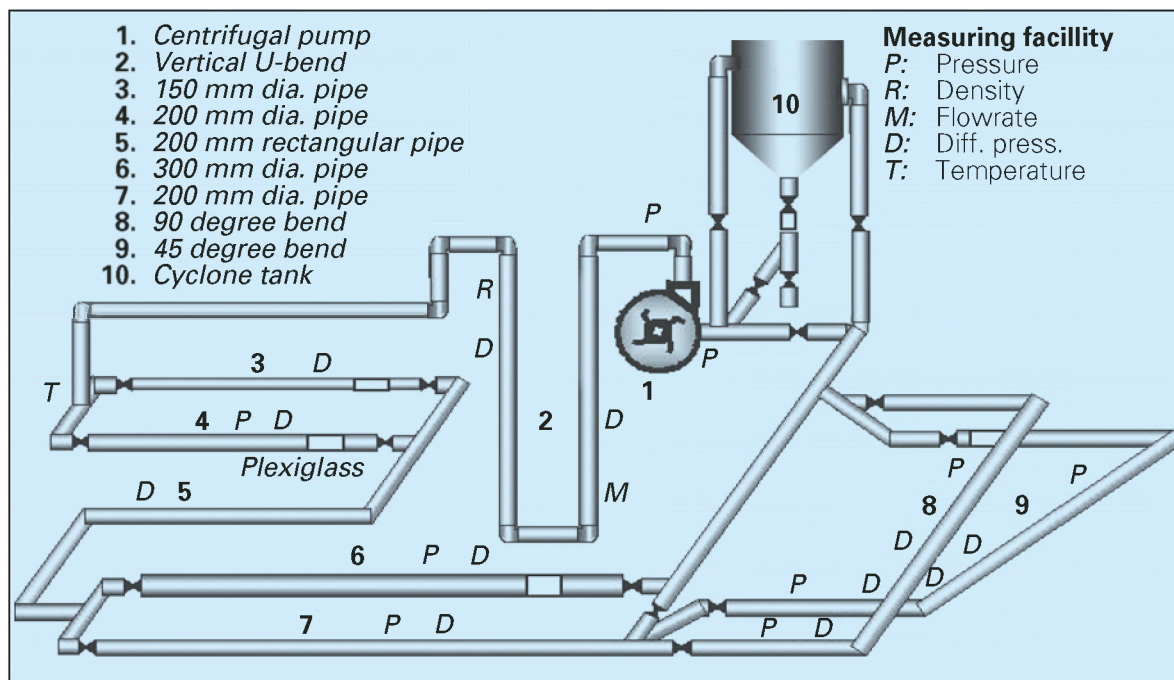


Figure 1. Schematic diagram of the new dredging test loop.

proximity sensors on the pulley of V-belts sense the speed of both the pump and the engine.

The data acquisition system is composed of two WYKEHAM-FARRANCE data loggers and a noise filter to store simultaneously electric signals from all transducers and to convert the electric signals into digital data collected in data files of the ASCII format. Figure 4 shows the booth with the remote-controlled data acquisition system.

EXPERIMENTS

Tested solids

The material tested was the Jumoonjin sand that is the Korea Standard Sand. Three tonnes of the Jumoonjin sand were used in this study has the specific gravity (G_s) 2.65. Figure 3 shows the particle size distribution and Figure 4 shows the Jumoonjin sand photography from a scanning electric microscope (SEM).

Test methodology

Before each test run, all sensors were checked on calibration and if necessary recalibrated so that the measurement was as accurate as possible. During a test run the slurry flow rate was controlled by variation of the pump speed. The slurry density was controlled by the ball valve at the outlet of the cyclone tank. Once the required concentration of solids in the circuit was reached the valve was closed.

The flow of solids through the circuit was steady. There was no significant variation in density along the circuit.

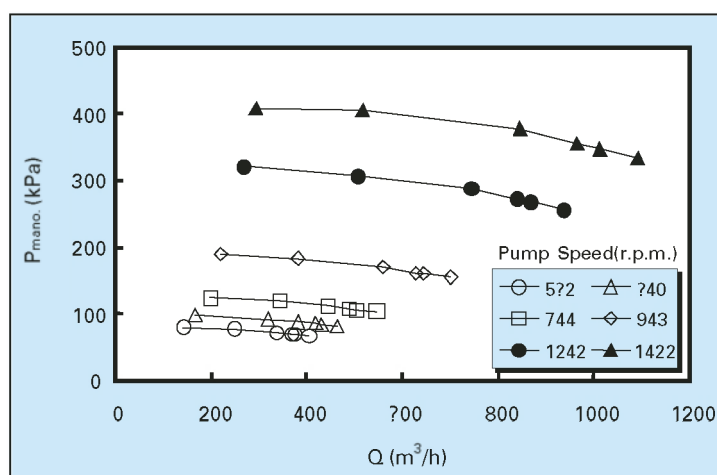


Figure 2. Pump performance curve of the JOOHO dredging slurry pump.

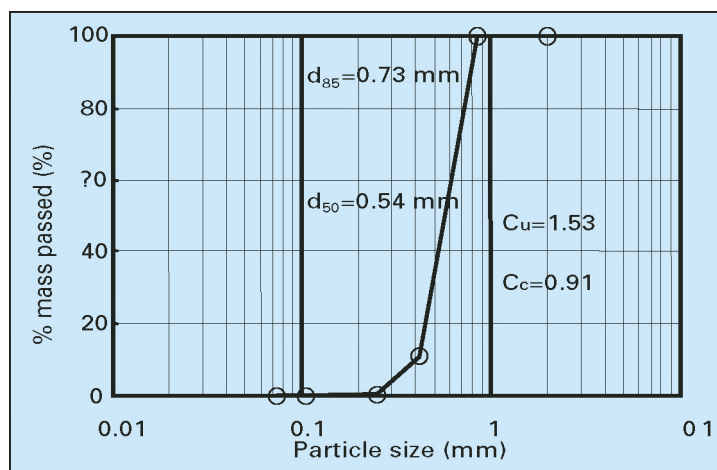
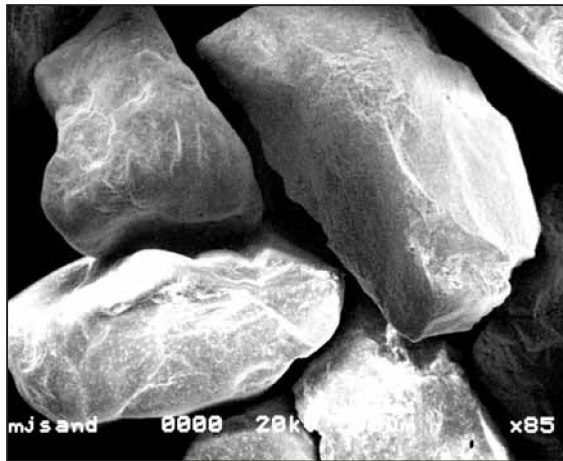
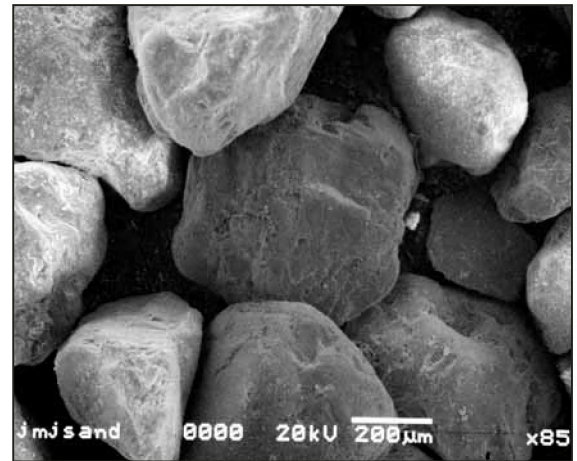


Figure 3. Particle size distribution.



a) Sands before tests



(b) Sands after tests

Figure 4. Photos of Jumoonjin sand taken by scanning electric microscope.

One test run contained measurements of slurry flow parameters at different chosen mean slurry velocities from low mean velocity to high. During the measurement at one velocity the material circulated approximately 30 times through the circuit. When the entire run (one concentration, various velocities) was finished, more sand could be added to get higher slurry density and continue with the next test run. During the measurements photos of the flow patterns were taken by a digital video camera in the perspex tube mounted in the horizontal pipe section. At the end of the test runs the sand was collected in the cyclone tank again so that the circuit remained sand free.

Summary of test runs

In the 204-mm pipe the mean velocity of slurry was

maintained between 1.68 m/s to 5.47 m/s, only velocities higher than the deposition limit velocity occurred in the pipe. The test runs were carried out for the volumetric concentrations of sand within the range 3.3% to 25.8%. The pump speed varied from 530 to 1,433 r.p.m., the r.p.m. increment per step (installing a new value of the mean velocity of slurry in the circuit) was about 100 r.p.m.

For the 155-mm pipe the test runs were carried out for the sand volumetric concentrations of 7.3% and 21.8% and for the mean velocity between 2.91 m/s to 8.82 m/s. Four volumetric concentrations of sand from 3.3% to 19.8% were tested within the range of the mean flow velocities from 1.2 m/s to 3.6 m/s in the 305 mm pipe. The Table I summarised all test runs discussed in this article.

Table I. Summary of test runs.

Size of pipe	Fluid	γ (t/m ³)	C_{vd} (%)	Pump speed [r.p.m.]									
155 mm	Water Mixtures	0.998	0	536	637	733	833	933	1035	1136	–	–	–
		1.12	7.3	531	637	733	836	925	1028	1127	1229	–	–
		1.36	21.8	530	636	730	832	928	1023	1130	1230	–	–
204 mm	Water Mixtures	0.998	0	533	635	727	828	926	1036	1138	1228	1331	1431
		1.06	3.2	529	623	728	829	931	1036	1132	–	–	–
		1.12	7.2	531	637	733	836	925	1028	1127	1229	–	–
		1.36	21.8	530	636	730	832	926	1023	1130	1230	–	–
		1.41	24.9	534	630	734	826	926	1029	1133	1229	1326	–
		1.43	25.8	–	–	725	828	929	1035	1126	1228	1325	–
305 mm	Water Mixtures	0.998	0	529	629	734	830	924	1034	1136	1228	1330	1429
		1.06	3.3	–	–	726	829	927	1027	1128	1230	1329	1430
		1.12	7.2	–	–	726	829	928	1031	1133	1228	1326	1433
		1.20	12.4	–	–	–	–	928	1030	1126	1228	1329	1425
		1.33	19.8	–	–	–	–	–	1029	1129	1233	1335	1425

TEST RESULTS AND DISCUSSION

Pressure drop as a result of friction in the horizontal pipes

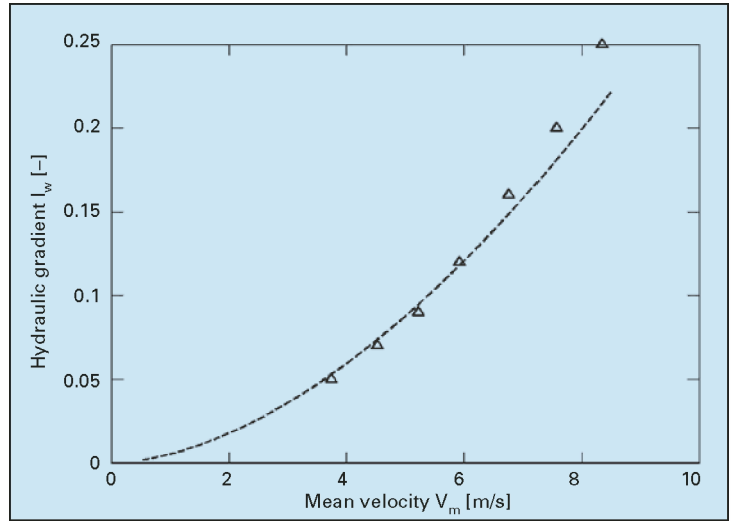
The pressure drop measurements were carried out for flow of water only. The reason was to determine the wall roughness of all three pipes. The water test results and their comparison with theoretical curves are in Figure 5. The water test revealed that both the 155-mm pipe and 204-mm pipe are smooth. Thus the friction coefficient is determined using the Blasius equation $\lambda_f = 0.316/Re^{0.25}$, in which Re is the Reynolds number of the water flow in the pipe. The 305-mm pipe is considerably rougher. The friction coefficient is determined using the universal friction-coefficient equation (Churchill, 1977) for the pipe-wall roughness $k = 250$ micron.

The slurry tests covered different ranges of mean slurry velocities and thus also different flow patterns in the pipes of different diameters. A visual observation of the slurry flow pattern was possible only in the 204-mm pipe. The observation showed that the deposition limit velocity tended to vary with solids concentration in the flow and its value varied between approximately 1.7 m/s for the lowest concentration (3%) and 2.1 m/s for the highest concentration (26%). The pressure drops were measured for the range of mean velocities in the supercritical flow regime, in which a flow is free of a stationary bed. The flow was partially stratified. A portion of particles occupied the granular bed that slid over the bottom of the pipe. The flow patterns in the smaller pipe (155 mm) and in the larger pipe (305 mm) must be estimated according to the trends predicted by a suitable model. In the 155-mm pipe, the range of the tested velocities was broad and the flow was free of the stationary bed at all velocities.

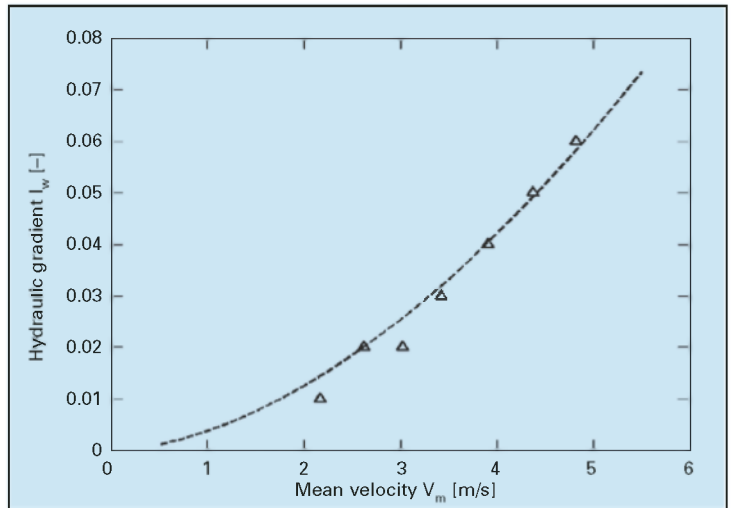
Presumably, there was no sliding bed at the highest velocities. The tests in the 305-mm pipe covered only a narrow range of mean slurry velocities, presumably below the deposition limit velocity. Thus there was always a stationary bed at the bottom of the pipe. Figures 6 through 8 show the plots of the hydraulic gradient data measured for flows of different velocities and concentrations in the three pipes of the laboratory circuit.

Effect of pipe size

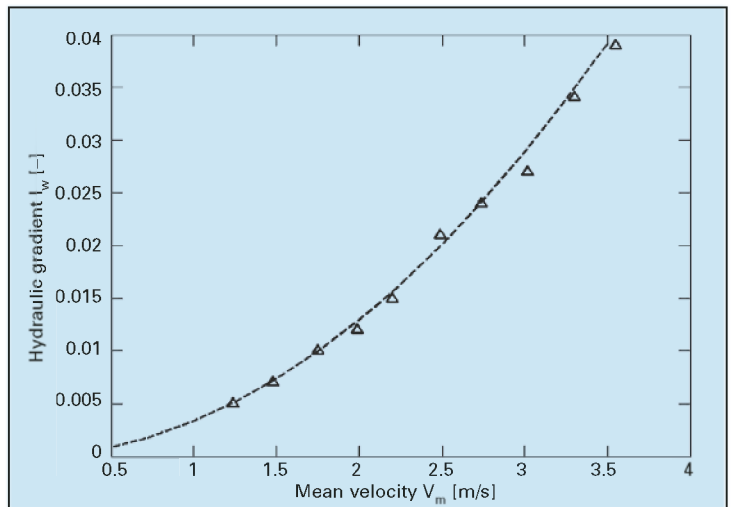
A comparison of the pressure drop data from the Hyundai test circuit with the data and model by Clift *et al.* (1982) on Figure 9 shows very different behaviors. At the low slurry velocities (up to approximately 4 m/s) the values of the relative solid effect $(I_m - I_w)/(S_m - S_w)$ and of the hydraulic gradient I_m of the Jumoonjin sand slurry in the Hyundai test circuit tend to be smaller than those measured and predicted by Clift *et al.* At the lowest velocities near the deposition limit velocity the I_m values are extremely low.



a) I_w - V_m curve for the 155-mm pipe



b) I_w - V_m curve for the 204-mm pipe



c) I_w - V_m curve for the 305-mm pipe

Figure 5. Hydraulic gradients of water transport by using the dredging test loop.

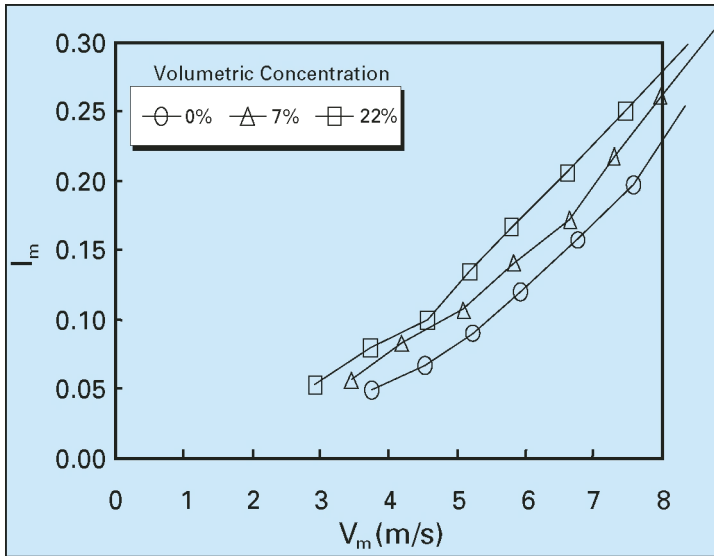


Figure 6. Measured hydraulic gradient in the 155-mm pipe.

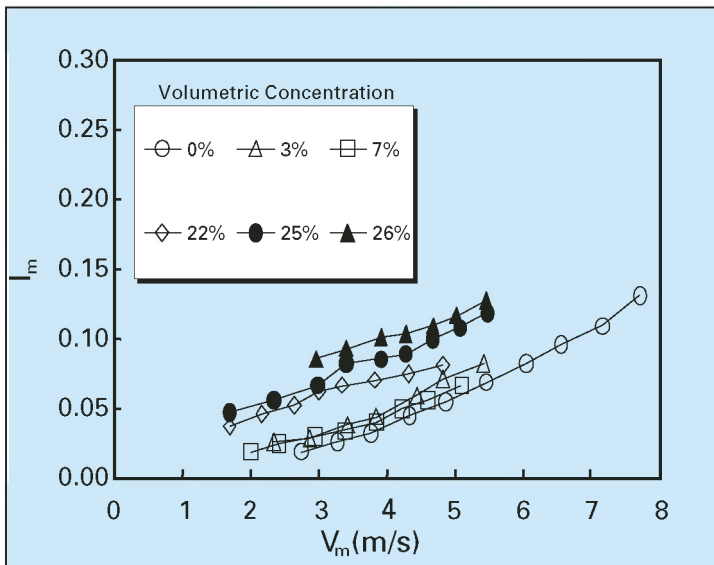


Figure 7. Measured hydraulic gradient in the 204-mm pipe.

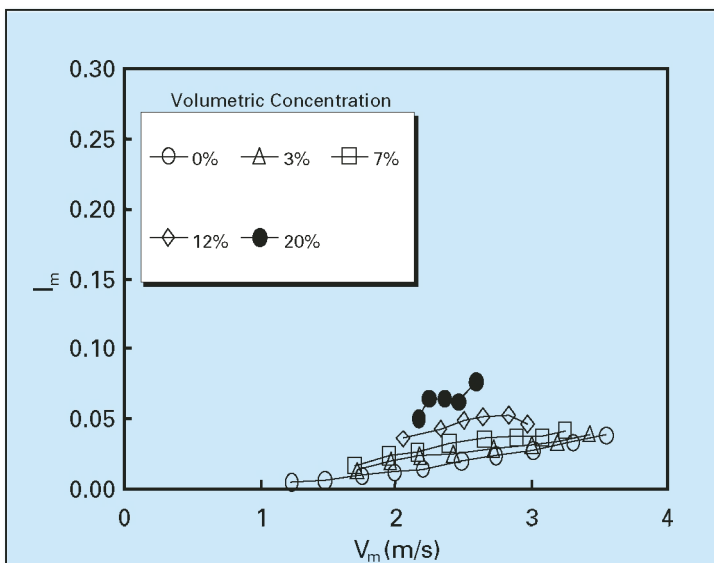


Figure 8. Measured hydraulic gradient in the 305-mm pipe.

A possible explanation of this phenomenon is that the top of the (stationary or sliding) bed in the Hyundai test circuit was sheared off more than it was the case in the Georgia Iron Works pipes during the tests published in Clift *et al.* (1982). A partially stratified flow with a thinner bed obeys lower friction and thus exhibits lower pressure drops (hydraulic gradients). The I_m values for high velocities in the 155-mm pipe tend to be higher than the Clift's data and predictions.

In Figures 10a and 10b the measured hydraulic gradients versus the Froude number $N_{Fr} = V_m^2/(gD)$ are compared for the three different pipes. Interestingly enough the pressure drops in the 305-mm pipe seemed to be higher than in the 204-mm pipe for the flow of the same value of the Froude number and for a similar value of the solids concentration. It is assumed that this effect is associated with the different flow patterns that occur in the flows of the same Froude number in the pipes of the different sizes.

Since the flow in all three pipes is partially stratified (at least for velocities up to approximately 4-5 m/s), it is useful to compare the measured pressure drops with predictions using a two layer model. Basically, the two-layer model predicts the pressure drops for fully or partially stratified flows with a sliding bed at the bottom of a horizontal pipe. The model, which is used for the comparison, was modified and calibrated for flows of various sand slurries in the 150-mm pipe (Matousek, 1997) and recently extended for the use in pipes of different sizes (Matousek *et al.*, 2004).

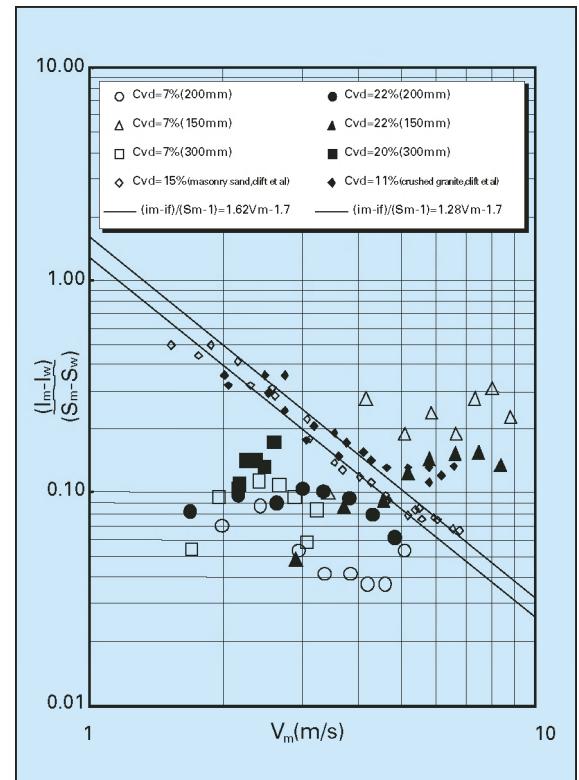
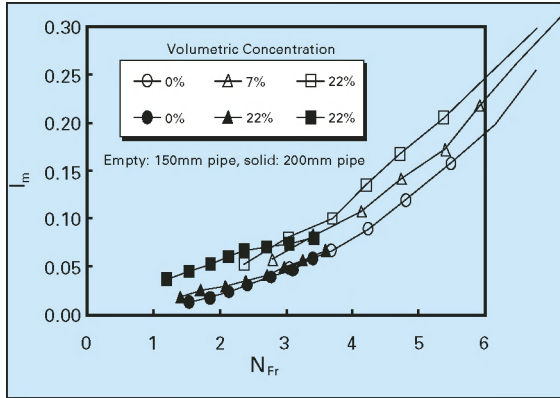
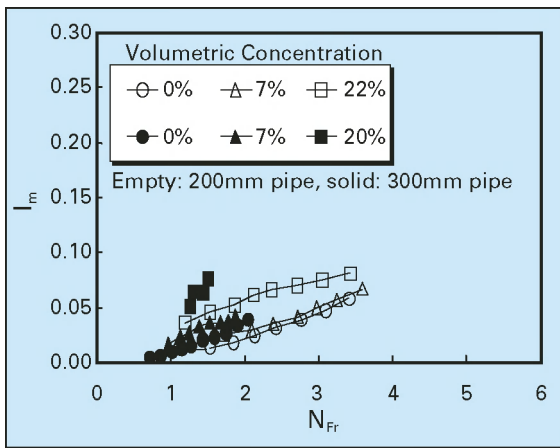


Figure 9. Relative solid effect versus the mean flow velocity.



(a) 155mm and 204mm



(b) 204mm and 305mm

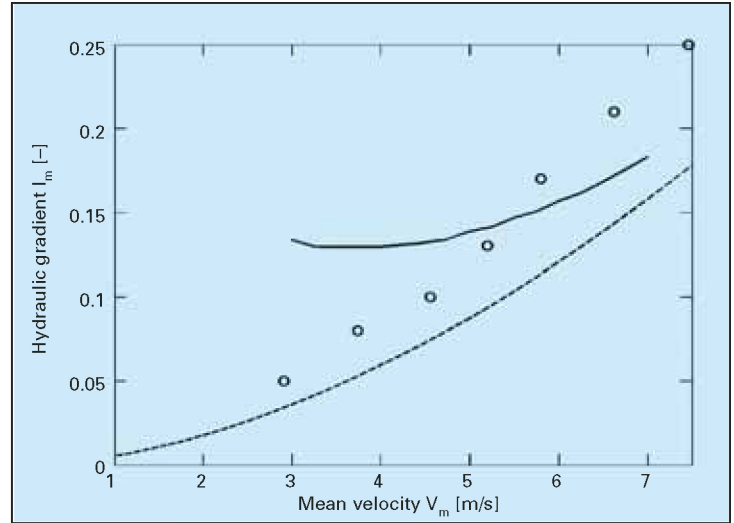
 Figure 10. Comparisons of the hydraulic gradient for two different size pipes (I_m -Froude number curve).

For the pipes of the diameter 155 mm and 204 mm, the model predicts higher hydraulic gradient values than measured (Figures 11a and 11b) at the velocities with the partially stratified flow pattern. Unfortunately, the tests did not provide concentration profiles across the pipes and thus the degree of flow stratification predicted by the model could not be compared with the real situation in the pipes. The measurements of the concentration profiles would indicate whether the extensive shearing of the top of the bed takes place and what are the sources of the extensive shearing-off.

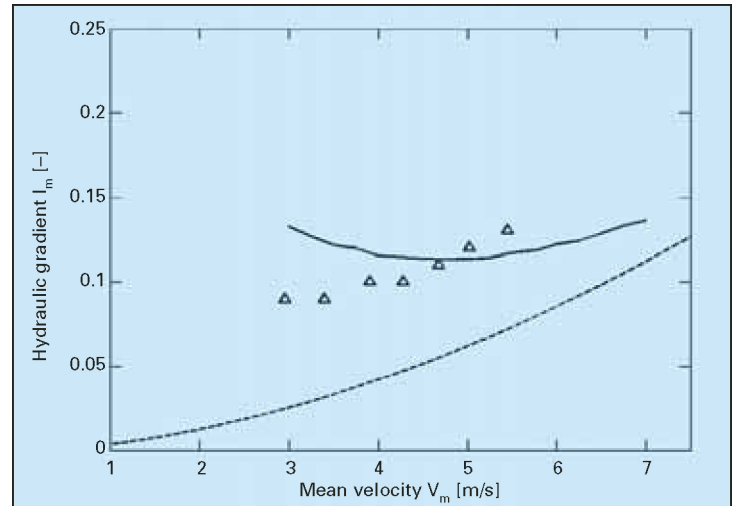
For the 305-mm pipe (Figure 11c) the direct comparison of the data and predictions is not possible (the available data are from the sub critical regime only and the model predicts only super-critical flows of a settling slurry).

Specific energy consumption in the pipes

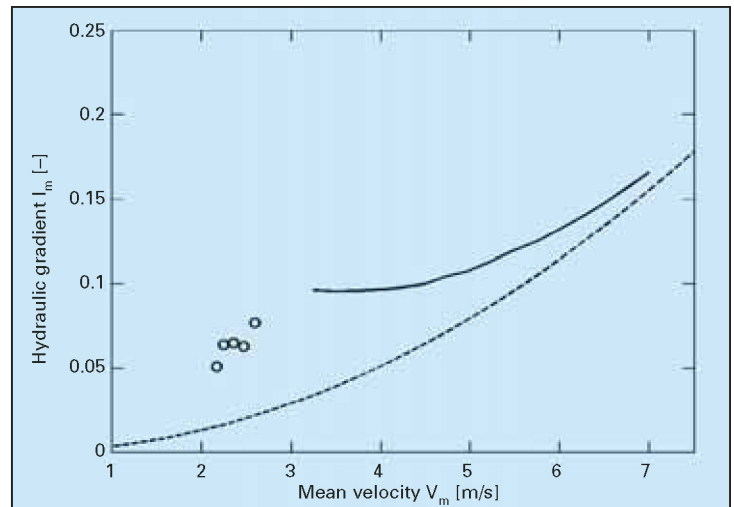
Figure 12 compares the specific energy consumption (SEC), obtained as $2.7I_m/(G_s C_{vd})$, versus solids throughput for the three pipes. In general, the low concentrated slurries (solids concentration of about 7%) exhibit high SEC values for all three pipes.



a) the 155-mm pipe.



b) the 204-mm pipe.



c) the 305-mm pipe

 Figure 11. Two-layer model predictions and measurement results.
Legend: (-) two-layer model; (- -) theoretical water; (o) slurry flow

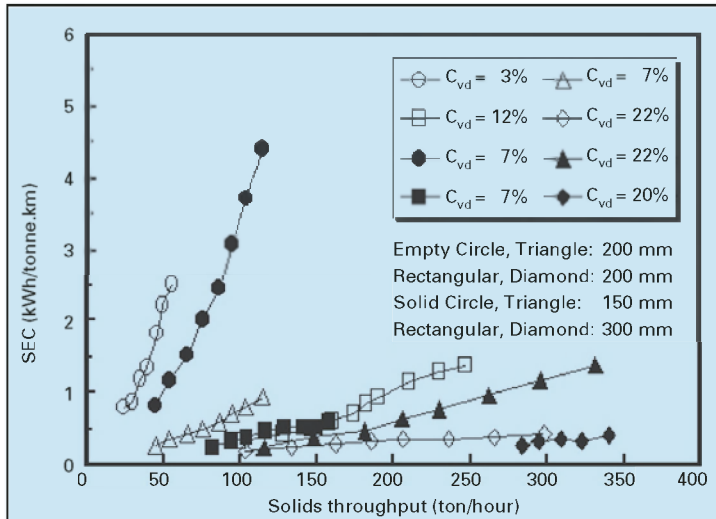


Figure 12. Specific energy consumptions amongst 3-different pipes.

The trends of the curves indicate that at velocities near the deposition limit velocity the SEC would be very similar for flows in all three pipes. The same effect holds for the higher concentrated slurries (solids concentration 22%). The SEC values are very similar in all three pipes at velocities near the deposition limit. However, these values are lower than those for the low concentrated slurry.

The larger is the pipe the smaller is the change in the SEC with the increasing solids throughput. According to the observed trend, an operation at velocities far above the deposition limit velocity could be more efficient in a pipe of a larger diameter than in a smaller pipe. However, the larger pipe requires the higher transport power. The size of the transport pipe has to be optimised considering both the power of the transport facility and the type of the transported soil.

Conclusions

The measurements of the Jumoonjin sand ($d_{50} = 0.54$ mm) in laboratory pipes of three different diameters (155, 204 and 305 mm) showed that a flow pattern has a profound effect on the frictional pressure losses in slurry pipes.

Very low frictional losses have been observed at velocities near and below the deposition limit velocity in all three pipes. Further investigation is required on the internal structure (distribution of solids concentrations) of the flows to find out the reason for the low pressure drops. It is assumed that this is a result of the shearing of the top of the stationary/sliding bed at the low velocities. More detailed tests are required to find the source of the shearing process.

The test results indicate that the specific energy consumption at velocities near the deposition limit velocity is not very sensitive to the pipe size. However, the difference among the pipes of different sizes tends to increase with the increasing velocity in the pipes. For the selection of a pipe diameter in practice, it is necessary to look not only at the specific energy consumption, but also at the required power of the transport facility and other requirements of a dredging project.

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