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Blockage of a Slurry Pipeline

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Die Verstopfung einer Feststoff-Rohrleitung
L'obstruction d'une canalisation destinée au transport de matières solides
La obstrucción de una tuberia para el transporte de sólidos
スラリパイプラインの閉塞
泥浆管道的阻塞
انسداد خط انابيب الملاط . بقلم ني . تاكاوكا .

Summary

The Ministry of Construction plans to dredge the Tsurumi River and to transport the dredged material by a slurry pipeline. As this pipeline is planned to cross the mouth of the river and the channel, the possible blockage in this submarine pipeline should be investigated before construction.

In this paper, the measures taken against a possible blockage of this pipeline are reported. At first, flow tests were carried out in a horizontal and submarine model pipeline in order to obtain the characteristics of dredged slurries.

Then, the blockage prevention method by the detection of critical velocity, the removal method of alien substances by an expanded pipe and the calculation method for the required pressure to restart the deposits which are formed at the lower part of the vertical section in the pipeline at shutdown are considered.

After these studies, the 4.5 km pipeline near the mouth of the river has operated since December 1979.

Nomenclature

A_s	projected area of particle	(m²)
a	ratio of plug diameter to pipe diameter	(—)
C_D	drag coefficient	(—)
C_v	volumetric concentration of slurry	(—)
C_{vs}	volumetric concentration of deposit	(—)
D	inner diameter of pipe	(m)
D_e	inner diameter of expanded pipe	(m)
d_s	mean particle diameter	(m)
d_{sa}	equivalent sphere diameter of particle	(m)
g	acceleration of gravity	(m/s²)
H	height of vertical pipe	(m)
h_T	height of deposit	(m)
K	constant in equation (9)	(—)
l	length of pipe	(m)
n	exponent in equation (9)	(—)
ΔP	pressure loss of slurry	(Pa)
ΔP_c	pressure loss of slurry at V_c	(Pa)
ΔP_f	pressure loss of carrier fluid	(Pa)
ΔP_s	additional pressure to restart deposit	(Pa)
R_e	Reynolds number defined by equation (13)	(—)
R_{eB}	Reynolds number defined by equation (2)	(—)
V	mean velocity	(m/s)
V_c	critical velocity	(m/s)
V_s	volume of particle	(m³)
γ_f	specific weight of carrier fluid	(N/m³)
γ_s	specific weight of solid particle	(N/m³)
θ	angle of inclination of pipe	(deg.)
λ	friction factor of carrier fluid	(—)
λ_B	friction factor defined by equation (2)	(—)
μ_B	plastic viscosity of Bingham fluid	(Pa.s)
μ_f	viscosity of carrier fluid	(Pa.s)
μ_s	coefficient of friction	(—)
ν	kinematic viscosity of carrier fluid	(m²/s)
ϱ_s	specific gravity of solid particle	(—)
τ_{so}	friction force per unit area	(N/m²)
τ_y	yield stress	(N/m²)
ϕ	coefficient of pressure loss	(—)
ψ	modified Froude number	(—)

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I. Introduction

In a blockage accident of a slurry pipeline, an enormous labor and cost are required to detect its location and to restore it. Especially in the case of buried or submarine pipelines, the blockage problem is fatal to the system. Therefore, experiments on the prevention of a blockage should be carried out before the planning and design of the slurry pipeline.

The Ministry of Construction has planned to dredge the Tsurumi River and to transport the dredged material by a slurry pipeline whose outline is shown in Table 1 [1]. As this pipeline is planned to cross the mouth of the river and the channel shown in Fig. 1, the possible blockage in this submarine pipeline should be investigated before construction.

The causes of a blockage seem to be the following:

1. Decrease of velocity or increase of concentration
2. Inflow of alien substances or large particles
3. Shutdown of the pipeline at emergency.

This paper details the methods that were used to ensure that blockage was prevented.

At first, flow tests were carried out in a horizontal and submarine model pipeline in order to obtain the characteristics of dredged slurries.

Transport volume	600,000 m³/year								
Pipe line	Length : 14 km								
	Pipe size : 609.6$^{\phi}$ X 24.5^{t}								
Booster pump	Type : Single stage, single suction, centrifugal pump								
		Dredger	BP 0	BP 1	BP 2	BP 3	BP 4	BP 5	BP 6
	Flow rate m³/h	3350	3350	3350	3350	3350	3350	3350	3350
	Head m	69	42	42	69	52	52	42	42
	Power kw	1700	1000	1000	1700	1250	1250	1000	1000

Table 1: Summary of the Tsurumi River dredged slurry pipeline

Then, the preventive method of a blockage by the detection of the critical velocity, the removal method of alien substances by the expanded pipe and the estimating method of the restart pressure were considered.

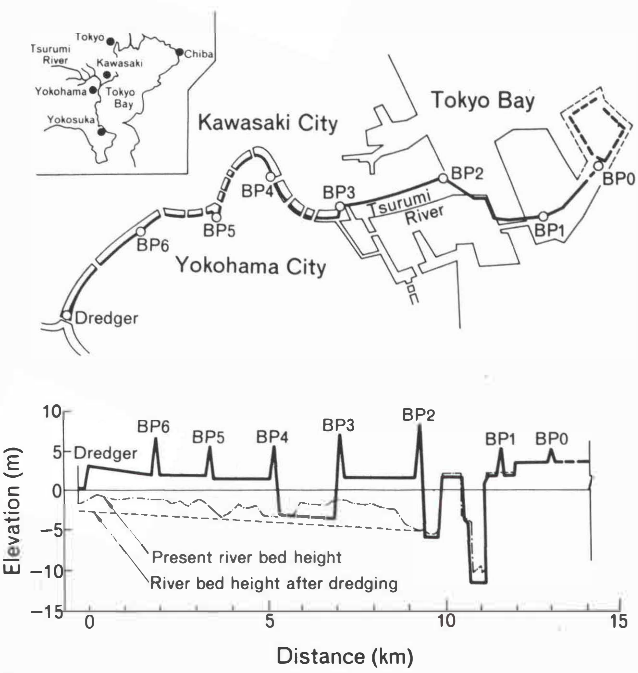


Fig. 1: Profile of the Tsurumi River dredged slurry pipeline

2. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 2. The flow tests were carried out using a horizontal pipeline and submarine model pipeline shown in Fig. 2 (a) and (b), respectively. The former is a stainless steel pipe with inner diameter of 78.8 mm and the test section for measuring pressure loss is 9 m in length after a 7 m entrance section. The latter is a polycarbonate transparent pipe with inner diameter of 77.0 mm and the pressure loss was measured at the section P.T. 1—P.T. 2 and the section P.T. 3—P.T. 4 which included bends with curvature radius of 390 mm (about 5 D).

In the removal experiment of alien substances, a 3 m acrylic transparent pipe with inner diameter of 156 mm was installed in a 3 inch test loop and the velocities at which the alien substances stopped in the expanded pipe were measured.

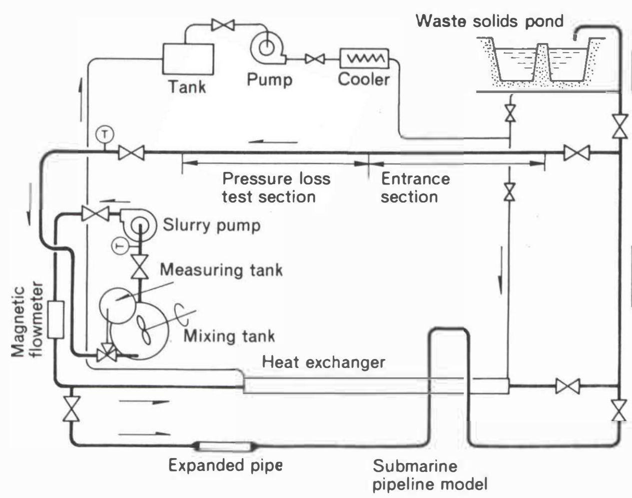
In the restart experiment, the deposit was formed in the vertical transparent pipe with inner diameter of 77.0 mm or 156 mm as shown in Fig. 2 (c) and the pressures required for restarting the deposit with the flow of clear water were measured.

Samples used in the experiments were three kinds of Tsurumi River sand. The particle size distributions are shown in Fig. 3 and the mean particle diameter and specific gravity are shown in Table 2.

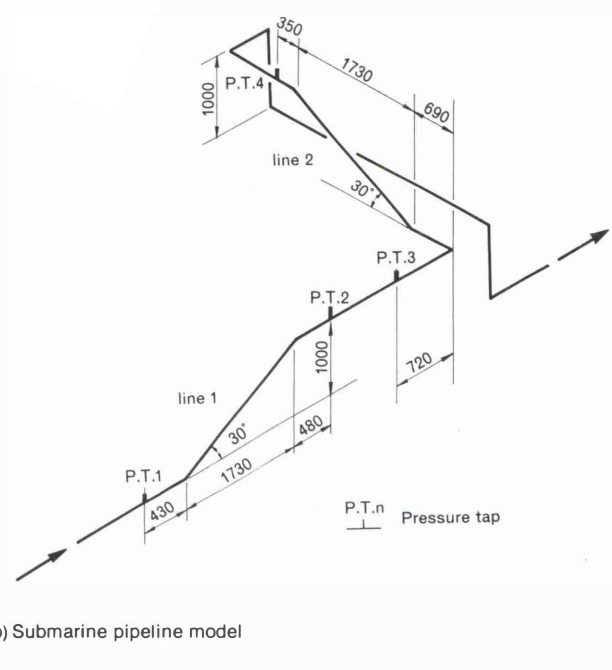
Sample No.	d_s mm	d_{max} mm	Cumulative % of −37 μm	ρ_s
No. 1	0.026	7.2	59.2	2.36
No. 2	0.132	4.0	20.9	2.43
No. 3	0.77	20.0	0.0	2.68

Table 2: Properties of sand used in the experiments

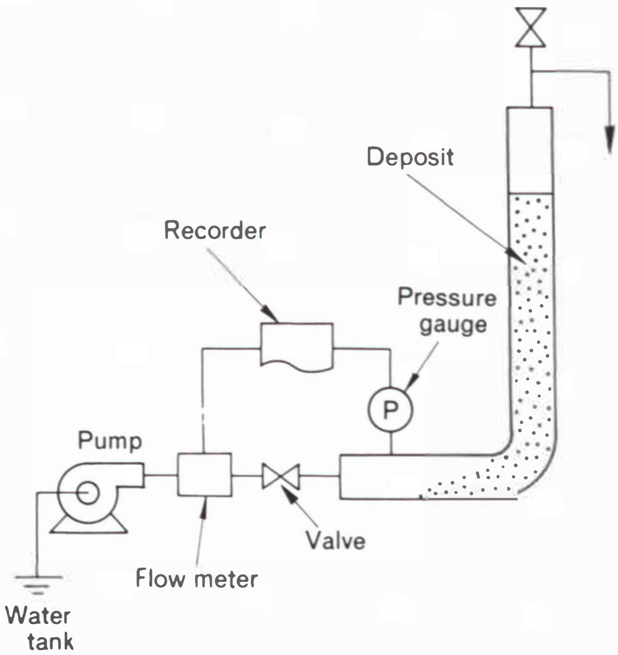
Fig. 2: Schematic diagram of experimental apparatus



a) Recirculating test loop



b) Submarine pipeline model



c) Apparatus used in start-up experiments

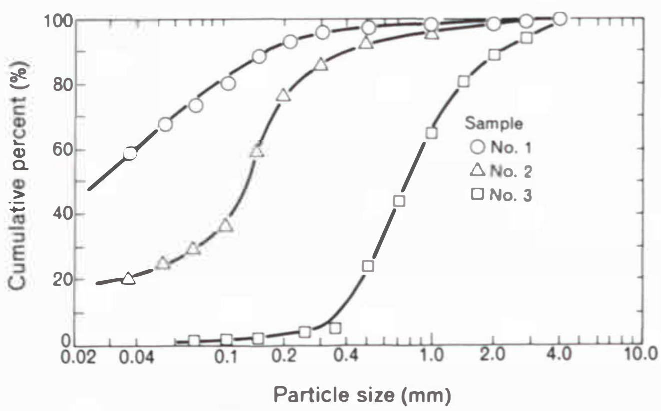


Fig. 3: Particle size distribution

3. Flow Tests

3.1 Flow properties

Figs. 4 and 5 show the flow properties of samples No. 1 and 2, respectively. As sample No. 1 slurries seem to be non-Newtonian fluid, data are arranged as Bingham fluid using Tomita's method [2]. Reynolds number and friction factor are defined as follows:

$$Re_B = \frac{\gamma_f V D}{g \mu_B} \left(\frac{a^4 - 4a + 3}{3} \right) F(a) \quad (1)$$

$$\lambda_B = \frac{\Delta P}{l} \quad \frac{2 g D}{\gamma_f V^2 F(a)} \quad (2)$$

where

$$F(a) = \frac{9}{5} \quad \frac{5 + 6a - 11a^2}{(3 + 2a + a^2)^2} \quad (3)$$

The relation between λ_B and Re_B is shown in Fig. 6.

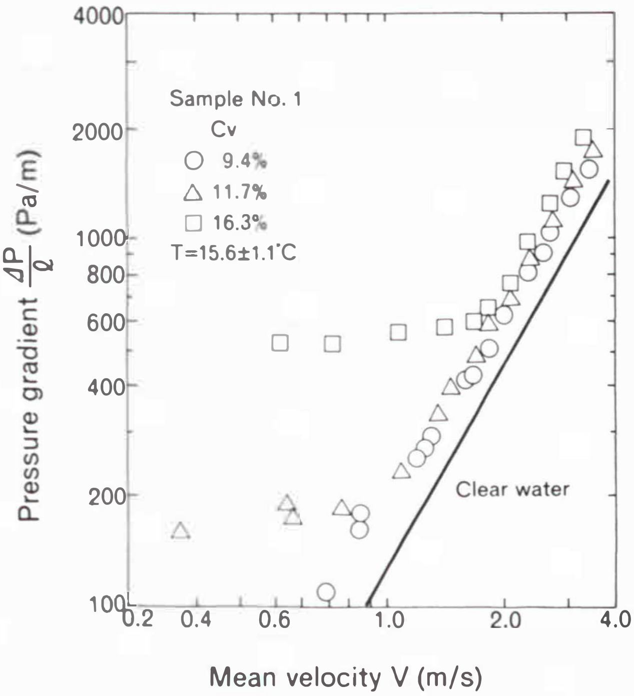


Fig. 4: Relationship between pressure gradient of sample No. 1 slurries $\Delta P / l$ and mean velocity V

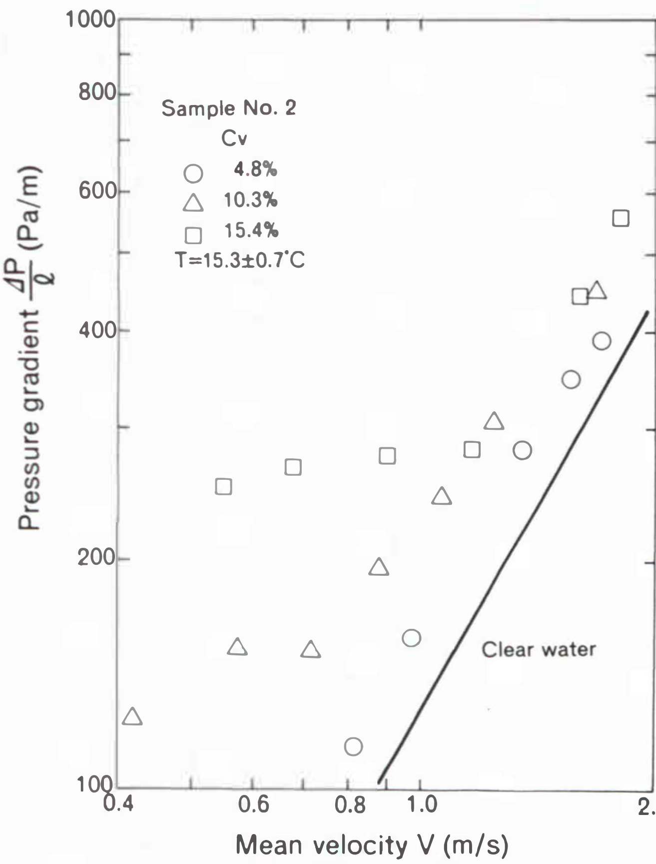


Fig. 5: Relationship between pressure gradient of sample No. 2 slurries $\Delta P / l$ and mean velocity V

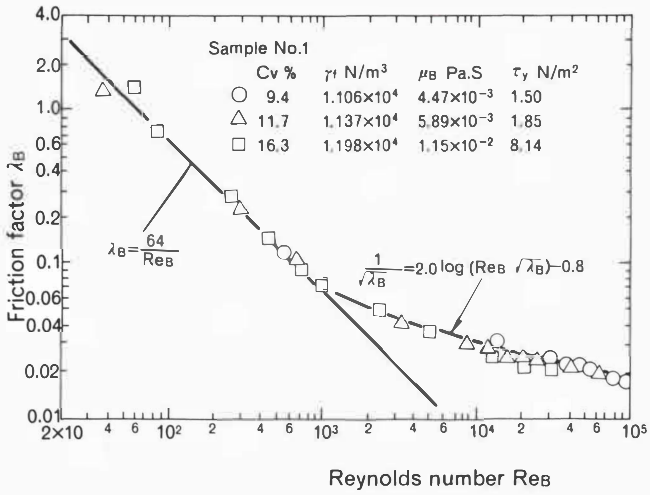


Fig. 6: Relationship between friction factor λ_B and Reynolds number Re_B

On the other hand, sample No. 2 slurries could not be considered as Bingham fluid. So it was assumed that the solid particles excluded sample No. 1 component from sample No. 2 were transported by sample No. 1 slurries. The size distribution of this special solid sample is also shown in Fig. 3. The characteristics of carrier fluid and solid particles of sample No. 2 and 3 are shown in Table 3. In this point of view, the experimental data of sample No. 2 and 3 slurries were plotted in Fig. 7 which shows the relation between the coefficient of pressure loss and the modified Froude number defined as follows;

$$\phi = \frac{\frac{\Delta P}{l} - \frac{\Delta Pf}{l}}{Cv \, \frac{\Delta Pf}{l}} \tag{4}$$

$$\psi = \frac{V^2 \sqrt{C_D}}{g D (\varrho_s - 1)} \tag{5}$$

The results agree fairly well with the experimental equation (6) which was obtained by [3]:

$$\phi = 120 \psi^{-1.5} + \sqrt{\varrho_s} - 1 \tag{6}$$

Fig. 8 shows the relation between the coefficient of pressure loss and the modified Froude number when sample No. 3 slurries are transported in the submarine model pipeline. The relations obtained are expressed by the following experimental equations:

for line 1:

$$\phi = 138 \psi^{-1.27} + \sqrt{\varrho_s} - 1 \tag{7}$$

for line 2:

$$\phi = 60 \psi^{-1.09} + \sqrt{\varrho_s} - 1 \tag{8}$$

It is known from Fig. 8 that the coefficient of pressure loss in line 2 is smaller than that in line 1. The reason for that is as follows: As line 1 has a 5 m entrance section at the upper stream, the flow of slurries becomes constant and heterogeneous. On the other hand, line 2 has a horizontal 90° bend at the upper stream. Solid particles flow in the line 2 as homogeneous flow because of the centrifugal force caused by the horizontal 90° bend.

Sample No.	Carrier fluid			Solid particl			
	γ_f N/m³	μ_f Pa·s	τ_y N/m²	d_s mm	ρ_s	C_D	C_v
No. 2	×10⁴ 1.005	×10⁻³ 1.47	0.003	0.16	2.41	21.5	0.031
	1.035	2.01	0.035		2.34	35.9	0.066
	1.064	2.76	0.142		2.28	62.1	0.098
No. 3	0.980	1.14	0	0.77	2.68	1.38	0.05~0.24

Table 3: Characteristics of sample No. 2 and 3 slurries

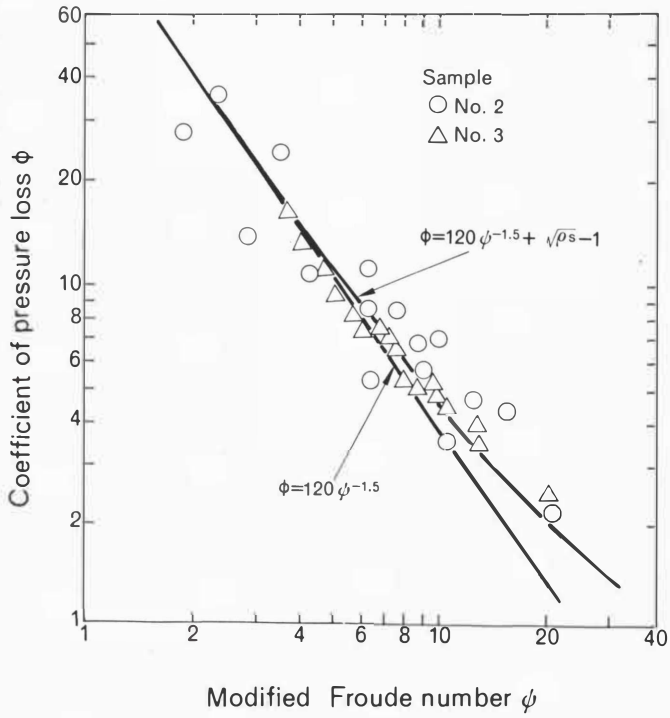


Fig. 7: Relationship between the coefficient of pressure loss ϕ and modified Froude number ψ in the horizontal pipe

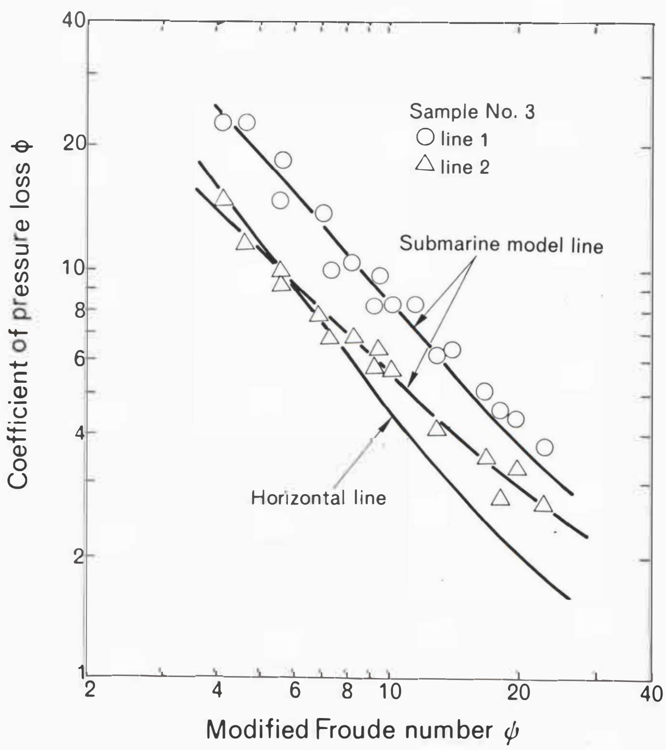


Fig. 8: Relationship between the coefficient of pressure loss ϕ and modified Froude number ψ in the submarine model pipeline

The absolute value of the exponent of ψ in the submarine model pipeline, the inclined angle of which is 30°, is smaller than that in the horizontal pipeline. This shows a similar tendency to the results obtained by Noda [4] from the transportation tests of the settling slurries in inclined pipes.

3.2 Critical Velocity

Since the critical velocity is defined as the velocity at which the pressure loss becomes minimum in the flow curve, the critical velocity of each sample and each line was calculated by the operation of $\partial (\Delta P/l)\ \partial V = 0$ using above experimental results. Fig. 9 shows the relation between the critical velocity and the volumetric concentration.

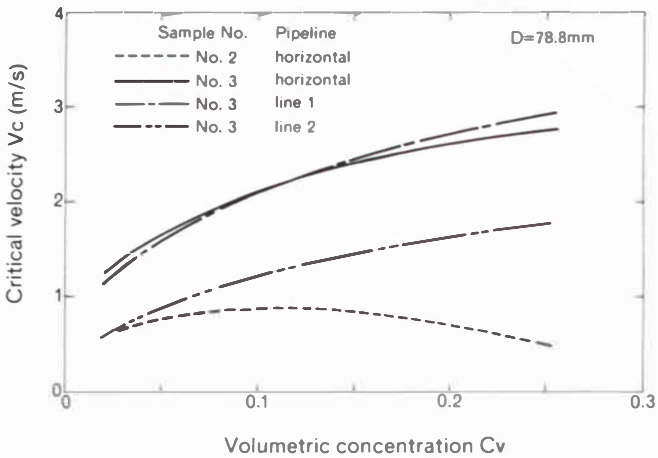


Fig. 9: Relationship between critical velocity V_c and volumetric concentration C_v

The critical velocity of sample No. 2 slurries has a maximum value in the region of 10—12.5 vol % and decreases with the increase of volumetric concentration because the viscosity of the carrier fluid increases with the increase of the volumetric concentration.

The critical velocity in line 2 is smaller than that in line 1 or horizontal pipe because the flow in line 2 is more homogeneous than the others.

4. Preventive Method of Blockage by Detection of Critical Velocity

As mentioned before, the critical velocity changes with the volumetric concentration or the characteristics of solid particles. In the case of pipeline transportation of dredged materials, it is difficult to grasp the typical characteristics of dredged materials. Accordingly, we examined the preventive method of blockage by the detection of the critical velocity without measuring the characteristics of dredged materials.

While the relations between the coefficient of pressure loss and the modified Froude number were obtained as equations (6), (7) and (8), the relation is approximated by the following equation within the range of small ψ.

$$\phi = K\psi^n \tag{9}$$

The pressure loss of slurries is written as;

$$\frac{\Delta P}{l} = \frac{\Delta P_f}{l}(1 + C_v\phi) = \lambda\frac{1}{D}\frac{\gamma_f}{2g}V^2 \times \left[1 + C_v K\left\{\frac{V^2\sqrt{C_D}}{gD(\varrho s-1)}\right\}^n\right] \tag{10}$$

Therefore, the critical velocity is given by equation (11) through the operation of $\partial\left(\frac{\Delta P}{l}\right)/\partial V = 0$,

$$V_c = \left[\frac{-1.75}{2n + 1.75}\,\frac{1}{C_v K} \times \left\{\frac{gD(\varrho s-1)}{\sqrt{C_D}}\right\}^n\right]^{\frac{1}{2n}} \tag{11}$$

where the Blasius equation was used to calculate the friction factor λ.

$$\lambda = 0.3164\ Re^{-0.25} \tag{12}$$

$$Re = \frac{VD}{\nu} \tag{13}$$

Assuming that the pressure loss at V_c is $\Delta P_c/l$, the following equation is obtained by eliminating $C_v K$ from equations (10) and (11).

$$\frac{V_c^{1.75}}{\Delta P_c/l} = \left(1 + \frac{1.75}{2n}\right) \times \frac{2gD^{1.25}}{0.3164\,\gamma_f\,\nu^{0.25}} \tag{14}$$

From the flow property of the settling slurries, it is known that the value of $V^{1.75}(\Delta P/l)$ which is calculated by pressure loss $\Delta P/l$ at arbitrary velocity V becomes larger than that of the right hand side in Eq. (14) when the velocity V is larger than the critical velocity V_c and vice versa.

The right hand side of equation (14) is a function of g, D, γ_f, ν and n. γ_f and ν are expressed by a function of the slurry temperature. With regard to the exponent n, the value is more or less different among investigators. Using $n = -1.5$, which is obtained by our experiments in the horizontal pipeline, equation (14) can be written as follows;

$$\frac{V^{1.75}}{\Delta P/l} = 2.634\,\frac{gD^{1.25}}{\gamma_f\,\nu^{0.25}} \tag{15}$$

Hence, it can be judged whether the velocity is larger or smaller than the critical velocity by measuring the velocity V, the pressure loss $\Delta P/l$ and the temperature T of slurry and comparing the left and right hand side of equation (15). In this method, it is not necessary to measure the concentration and the characteristics of the slurry.

The flowchart for this method is shown in Fig. 10. In order to confirm the reliability of this method, the experiment was carried out using a horizontal test loop and micro-computer. Fig. 11 shows the output results from the micro-computer. In this figure, V is the mean velocity, T is the temperature, I is the pressure loss and C_1 and C_2 are as follows;

$$C_1 = 25.8 \frac{D^{1.25}}{\gamma_f \, \nu^{0.25}} \tag{16}$$

$$C_2 = \frac{V^{1.75}}{I} \tag{17}$$

In this experiment we let print *SAFETY* if $C_2 > 1.01\, C_1$, *WARNING* if $0.99\, C_1 < C_2 \leqq 1.01\, C_1$ and *DANGER* if $C_2 \leqq C_1$. Fig. 12 shows the relation between C_2/C_1 and the mean velocity V in order to check the influence of concentration.

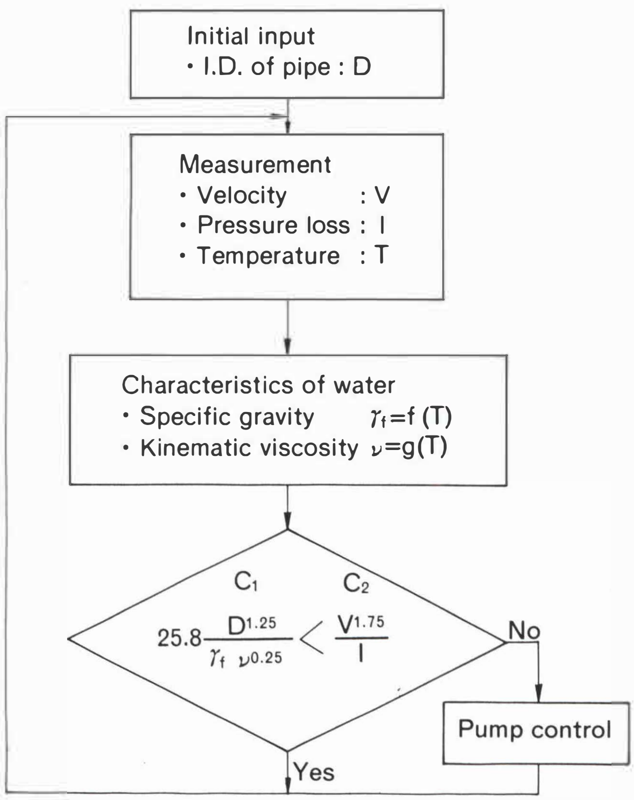


Fig. 10: Preventive method of blockage by detection of the critical velocity

```
****************
*  CHOKE TEST  *
****************

DATE: 1979-07-19
TIME:      16:50

================

V =   3.77 M/S
T =  34.5   °C
I = 205.7 MMAQ

 C1 = 0.03579
 C2 = 0.04955

##############
#   SAFETY   #
##############

----------------

V =   3.45 M/S
T =  34.3   °C
I = 132.1 MMAQ

 C1 = 0.03676
 C2 = 0.04555

##############
#   SAFETY   #
##############

----------------

V =   3.11 M/S
T =  34.0   °C
I = 190.1 MMAQ

 C1 = 0.03670
 C2 = 0.04035

##############
#   SAFETY   #
##############

----------------

V =   2.89 M/S
T =  33.9   °C
I = 174.2 MMAQ

 C1 = 0.03669
 C2 = 0.03675

##############
#  WARNING   #
##############

----------------

V =   2.85 M/S
T =  33.3   °C
I = 173.0 MMAQ

 C1 = 0.03657
 C2 = 0.03515

##############
#   DANGER   #
##############

----------------

V =   2.79 M/S
T =  33.3   °C
I = 172.4 MMAQ

 C1 = 0.03657
 C2 = 0.03487

##############
#   DANGER   #
##############

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Fig. 11: Output results from the micro-computer

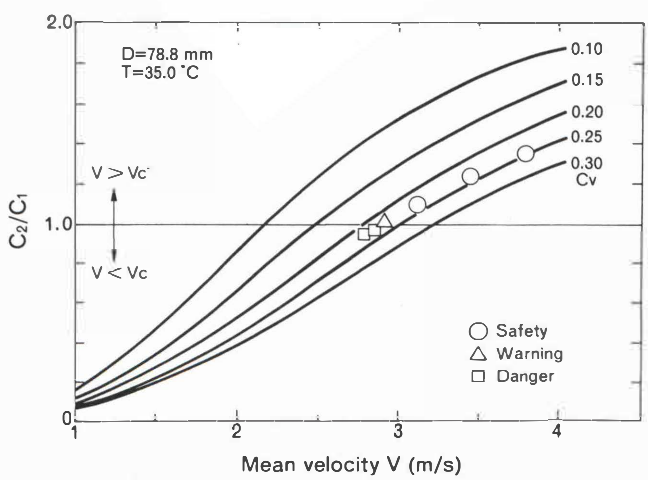

Fig. 12: Relationship between the ratio of C_2/C_1 and mean velocity V

5. Removal of Alien Substances by the Expanded Pipe

Since the dredger always changes location and the space is limited, it is difficult to equip it with an advanced treatment device, such as a mixing tank for concentration control or a screen. Therefore, it was examined that the expanded pipe was installed at the inlet of the slurry pipeline in order to leave only alien substances or large particles in the expanded pipe due to the decrease of slurry velocity there.

Fig. 13 shows the force balance when alien substances stop in the pipe. Forces which act to alien substances are drag

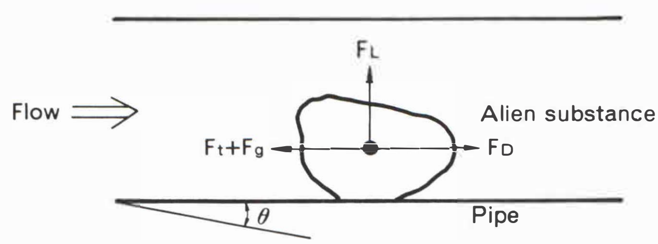

Fig. 13: Force balance

and lift forces caused by flow, friction force between alien substances and pipe wall, gravity and buoyancy. These forces are expressed as follows;

$$F_D = C_{Di} A_s \frac{\gamma_f}{2g} V^2$$
$$= \frac{C_D}{\left\{1-\left(\frac{d_{sa}}{D}\right)^2\right\}^2} A_s \frac{\gamma_f}{2g} V^2 \qquad (18)$$

$$F_L = C_{Li} A_s \frac{\gamma_f}{2g} V^2$$
$$= \frac{C_L}{\left\{1-\left(\frac{d_{sa}}{D}\right)^2\right\}^2} A_s \frac{\gamma_f}{2g} V^2 \qquad (19)$$

$$F_f = \mu_s \{ V_s | \gamma_s - \gamma_f | \cos\theta - F_L \} \qquad (20)$$

$$F_g = V_s | \gamma_s - \gamma_f | \sin\theta \qquad (21)$$

where, C_{Di} and C_{Li} are the drag and lift coefficients based on the interfering terminal settling velocity of alien substances, respectively. C_D and C_L are those based on the free terminal settling velocity. The relation between C_{Di} and C_D, and C_{Li} and C_L are expressed by Смолдыев's equation [5].

The force balance is expressed as follows;

$$F_D = F_f + F_g \qquad (22)$$

and using the equivalent sphere diameter of alien substances, equation (22) can be written as equation (23).

$$\frac{\mu_s \cos\theta + \sin\theta}{C_D + \mu_s C_L}$$
$$= \frac{3}{4} \frac{V^2}{g\, d_{sa} \left| \frac{\gamma_s}{\gamma_f} - 1 \right|} \frac{1}{\left\{1-\left(\frac{d_{sa}}{D}\right)^2\right\}^2} \qquad (23)$$

From the removal experiment carried out in the horizontal expanded pipe, the values of $\mu_s / (C_D + \mu_s C_L)$ were calculated and the results are shown in Table 4.

Alien substance	ρ_s	Max. size mm	Weight g	Mean dia. mm	V_{so} m/s D=77mm	V_{so} m/s D=156mm	$\mu_s/(C_D+\mu_s C_L)$ D=77mm	$\mu_s/(C_D+\mu_s C_L)$ D=156mm
Gravel	2.62	29.1	8	18.0	0.35	0.40	0.36	0.43
		38.3	23	25.9	0.44	0.46	0.44	0.41
		47.1	40	30.8	0.51	0.52	0.55	0.45
		52.5	72	37.4	0.54	0.57	0.60	0.46
		69.8	135	46.2	0.45	0.68	0.47	0.57
Bolt	7.76	65.0	113	30.3	1.09	1.10	0.61	0.49
		110.0	180	35.4	1.29	-	0.82	-
Nut	7.76	27.7	30	19.5	0.83	0.87	0.45	0.45
Wood	0.50	53.6	24	45.1	0.29	0.32	0.61	0.41

Table 4: Values of V_{so} and $\mu_s / (C_D + \mu_s C_L)$

Conversely, if these values of alien substances are known the expanded pipe diameter for removal of alien substances is calculated by the following equation:

$$D_e = \left[\frac{4Q/\pi}{\left\{ \frac{4}{3} g\, d_{sa} \left| \frac{\gamma_s}{\gamma_f} - 1 \right| \frac{\mu_s}{C_D + \mu_s C_L} \right\}^{1/2}} + d_{sa}^2 \right]^{1/2} \qquad (24)$$

Fig. 14 shows the relation between the expanded pipe diameter and alien substances diameter in the case that the diameter of the transportation pipe is 560 mm.

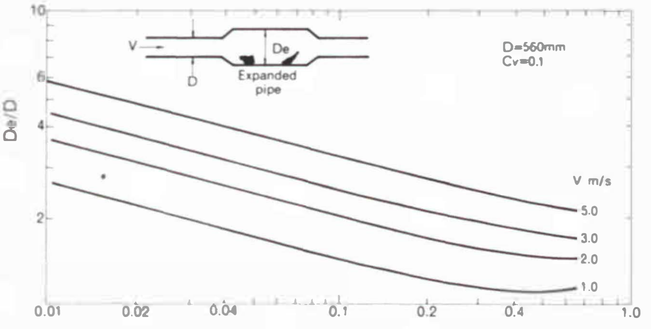

Fig. 14: Relationship between D_e / D and d_{sa} / D

6. Estimating Method of Restart Pressure

Fig. 15 shows the pressure change when the deposit formed at the lower part of the vertical section in the pipeline is restarted. The deposit started moving when the pressure became maximum.

The force balance of deposit at restart is written as follows;

$$\frac{\pi}{4} D^2 \Delta P_s = \frac{\pi}{4} D^2 h_T C_{vs} (\gamma_s - \gamma_f) + \frac{\pi}{4} D^2 H \gamma_f + \pi D h_T \tau_{so} \qquad (25)$$

The first term of the right hand side in equation (25) represents the force to support the deposit, the second term is the static head of fluid, and the third term is the friction force between the deposit and the pipe wall.

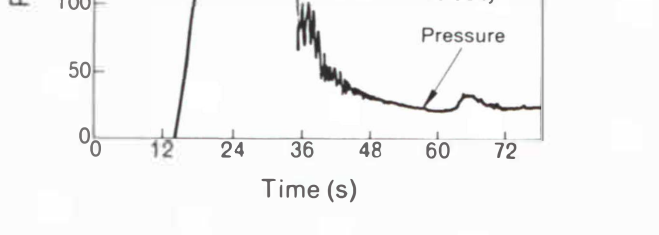

Fig. 15: An example of pressure change in the restart test

The friction force per unit area τ_{so} is calculated from the results of the restart experiment and the relation between τ_{so} and the height of deposit h_T is shown in Fig. 16. There are some scatters in this figure but in our experimental range there is no tendency concerned with the height of the deposit. Therefore the mean values of each case are shown in Fig. 16.

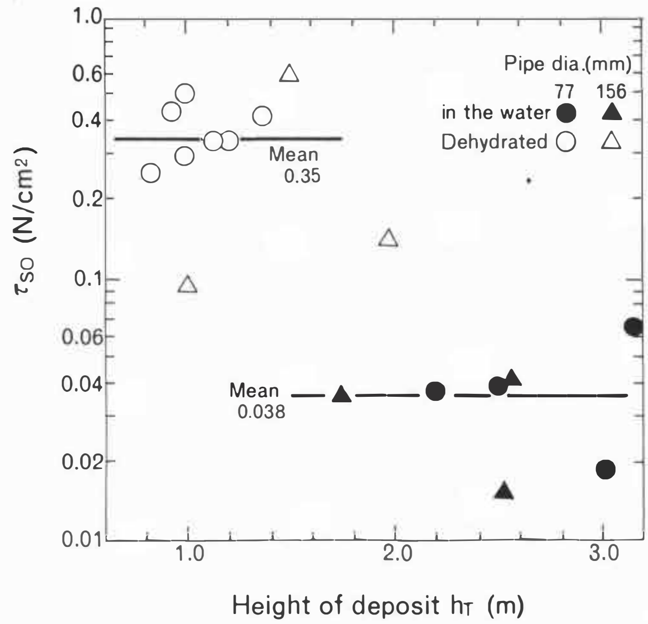

Fig. 16: Relationship between τ_{so} and height of deposit h_T

In the case of sample No. 3, τ_{so} of the deposits which are formed in the water is equal to 0.038 N/cm² and τ_{so} of the deposit which are dehydrated is equal to 0.35 N/cm². It is apparent that the dehydrated deposits are more difficult to restart than the deposits formed in the water.

From equation (25), the required pressure to restart the deposit which is formed at the lower part of the vertical section in the pipeline is expressed as equation (26):

$$\Delta P_s = H\gamma_f + H \frac{C_v}{C_{vs}} \left\{ C_{vs}(\gamma_s - \gamma_f) + \frac{4}{D} \tau_{so} \right\} \quad (26)$$

where

$$\frac{C_v}{C_{vs}} = \frac{h_T}{H} \quad (27)$$

and

C_V = volumetric concentration of slurry
C_{Vs} = volumetric concentration of deposit.

C_{Vs} is equal to 0.5—0.58 in the case that the solid particles settle in the water gently and 0.58—0.7 in the case that the pipeline is vibrated or the deposit is dehydrated.

7. Conclusion

Before building the Tsurumi River dredged slurry pipeline, methods for the prevention of a blockage were examined.

The results obtained were as follows:

1. The prevention of a pipeline blockage is possible by the detection of the critical velocity without measuring the concentration and the characteristics of slurries.
2. The removal of alien substances or large particles which may cause a blockage of a slurry pipeline is possible by installing an expanded pipe at the inlet of the slurry pipeline.
3. The required pressure to restart the deposit which is formed at the lower part of the vertical section in the pipeline at shutdown can be estimated by equation (26).

According to the above results, the Tsurumi River dredged slurry pipeline has been built and the 4.5 km pipeline near the mouth of the river is now in operation since December 1979.

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