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Vertical Multi-Holed Double-Pipe System: A New Sediment Suction Method Utilizing a Natural Head

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ABSTRACT:
At present, the sediment removal method using a suction pipe is the subject of research as an effective method for discharge of accumulated sediment in dam reservoirs. Vertical Multi-Holed Double-Pipe System is one of these methods and has been researched by the authors for the application to an actual reservoir. This system is expected to reduce the cost of removing sediment accumulated repeatedly around a local place such as the neighborhood of the intake. This paper explores the following topics: methods and results of the laboratory tests of the system; the hydraulic design method based on the laboratory tests; and the estimation of sediment concentration in the discharge flow.

Keywords: sediment removal, suction pipe, vertical multi-holed double-pipe system

1. INTRODUCTION

At present, the hydro-suction sediment removal system is researched as an effective method for discharge of accumulated sediment in dam reservoirs. The method is to discharge sediment to the lower reaches of the dam utilizing the natural head between the reservoir water level and the outlet of the pipe.

This paper presents a new hydro-suction sediment removal system called “Vertical Multi-Holed Double-Pipe System (Maeda, K., et al. 2015).” The purpose of this system is periodical sediment removal at a local area such as the neighborhood of a water intake facility. The vertical multi-holed double pipe is composed of an outer pipe and an inner pipe, which enable the system to suck sediment continuously by negative pressure occurred between the two pipes.

This paper investigates the following three topics. First, laboratory tests using a small model and quasi-full-scale model were carried out in order to estimate the suction ability. Secondly, the hydraulic design method was established from the test results. Finally, the estimation method for sediment concentration in the pipe based on the flow and pressure was established.

2. OUTLINE OF VERTICAL MULTI-HOLED DOUBLE-PIPE SYSTEM

Conceptual figures of installation of Vertical Multi-Holed Double Pipe System and its hydraulic mechanism are shown in Fig. 1 and Fig. 2, respectively. The system is composed of an outer pipe and inner pipe. The outer pipe is equipped with suction holes on its side, while the inner pipe is equipped with suction holes with gates on its side. This structure has a clearance between the outer and inner pipes, which makes it possible to suck the sediment continuously even if the pipes are buried in sediment. The sediment removal area by this system is not very large because the pipe is fixed on the dam body. However, this system is expected to reduce the cost of removing sediment accumulated repeatedly around a local place such as the neighborhood of the intake.

The system is installed on the dam body. First, the pipe flow reaches steady state in a few minutes after the valve is opened. Next, the system begins to suck the sediment after the higher and lower suction holes on the inner pipe are opened. After the start of sediment discharge, the system is expected to suck sediment through the suction holes using the water head difference. After discharge of the sediment is completed, its surface becomes hemiconical shaped centered by the vertical pipe. The slope gradient is determined by the underwater angle of repose.

3. LABORATORY TEST USING A SMALL MODEL AND ESTABLISHMENT OF THE HYDRAULIC DESIGN METHOD

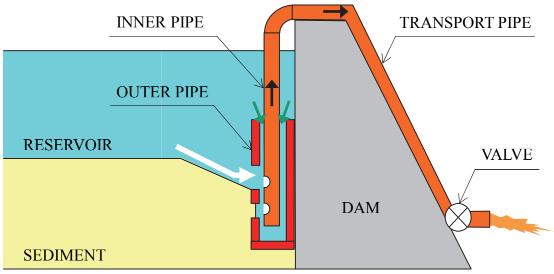

Figure 1. Conceptual figures of installation of the Vertical Multi-Holed Double Pipe System.

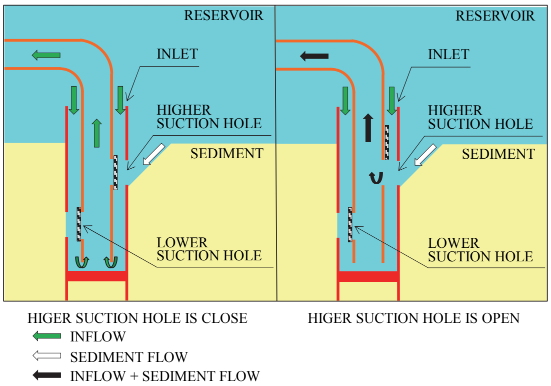

Figure 2. Hydraulic mechanism of Vertical Multi-Holed Double Pipe System.

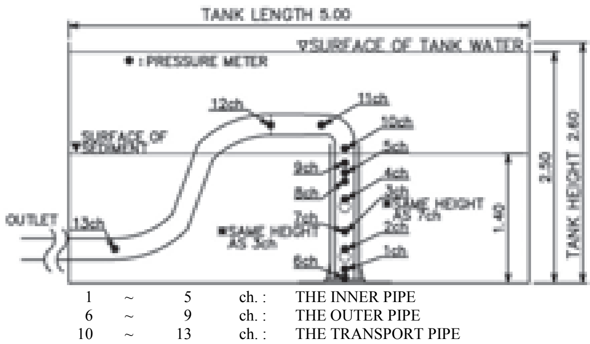

Figure 3. Profile of the experimental facilities and installed positions of the pressure meters (m).

Table 1. Diameter conditions

Case	Inner pipe(m)	Outer pipe(m)	Suction holes(m)
1	0.2	0.3	0.12
2	0.2	0.4	0.12
3	0.2	0.4	0.20

Table 2. Results of the laboratory test

Case	Average flow (L/sec)	Suction ability (m^3/h)	Max sediment concentration (%)
1	54.1	13.2	17.4
2	63.0	8.5	4.0
3	58.0	9.5	17.4

3.1. Conditions of the laboratory test

The authors carried out the laboratory test using a small model in order to estimate the suction ability. The profile of the experimental facilities and the installed positions of the pressure meters are shown in Fig. 3. The measured values of pressure meter were used for verification of the hydraulic design method. The tank used for the laboratory test was 5 m in length, 2.6 m in width, and 2.6 m in height. The authors installed the small model of the system in the tank, and buried it in the sediment whose thickness was 1.4 m. The sediment removal laboratory test was carried out keeping the head about 4.4 m. The items of measurement and observation during sediment discharge were as follows: 1) suction pipe pressure by the pressure meter; 2) suction pipe flow by the electromagnetic flow meter; 3) sediment concentration at the outlet of the suction pipe by sampling of water; and 4) observation of the flow in the suction pipe by video camera. After sediment discharge, the quantity of discharge sediment was estimated by measuring the surface of the remaining sediment. The diameter of the inner pipe was fixed as 0.2 m. The diameters of the outer pipe and the suction holes were varied as shown in Table 1. The suction abilities of the system in each case were estimated.

3.2. Results of the laboratory test

The results are shown in Table 2. The findings obtained from the laboratory test are as follows:

- When the diameter of the inner pipe is the same, the velocity head around the suction holes and the sediment suction ability are greater when the diameter of the outer pipe is smaller than when the diameter is larger (from the comparison between Case 1 and Case 2).
- When the diameters of both the inner and the outer pipes are fixed, the sediment suction ability is greater when the diameter and the suction area of the suction holes are larger than when they are smaller (from the comparison between Case 2 and Case 3).

3.3. Establishment of the hydraulic design method

For the purpose of hydraulic design for the full-scale facilities of Vertical Multi-Holed Double-Pipe System, the hydraulic design method for sediment transportation was established and verified by the results of the pressure meters, which is based on Bernoulli's equation (Eq. 1).

$$H = \frac{1}{2g}\left(\frac{Q}{A}\right)^2 + \frac{p}{\rho g} + z + \sum h_L \,, \qquad (1)$$

where,

- H: Total head (m)
- g: Gravity acceleration (m/s^2)
- Q: Pipe flow (m^3/s)
- A: Pipe section area (m^2)
- p: Pipe pressure (Pa)
- ρ: Flow density (kg/m^3)
- z: elevation head (m)
- h_L: Head loss (m)

The forth term of the right-hand side in Eq. 1 was headloss, composed of shape loss and friction loss. Friction loss h_f is shown in Eq. 2. When the pipe flow contains sediment, the value of h_f increases because friction loss coefficient λ increases as shown in Eq. 3.

$$h_f = \lambda \frac{1}{2g}\left(\frac{Q}{A}\right)^2 \frac{L}{D}, \tag{2}$$

$$\lambda = \lambda_w + \lambda_s = \lambda_w(1+\phi C), \tag{3}$$

where,

- h_f: Friction loss (m)
- λ: friction loss coefficient
- L: Pipe length (m)
- D: Pipe diameter (m)
- λ_w: Friction loss coefficient in flow
- λ_s: Additional friction loss coefficient in sediment flow
- ϕ: Pressure loss coefficient
- C: Sediment concentration (%)

Pressure loss coefficient ϕ was determined by Kazenskij's equation (Eq. 4), in which particle size distribution can be taken into consideration (Kazanskij, I. 1978). The other loss is estimated based on the references(Anderson, A.G., et al. 1948, Okano, M., et al. 2004).

$$\phi = 180 D^{0.5} V^{-3}\left(\overline{Fr_{xj}^{\ 1.5}}\right)^{0.5}, \tag{4}$$

Where,

$\overline{Fr_{xj}^{\ 1.5}} = \sum (Fr_{xj})^{1.5} X_n / 100$

- Fr_{xj}: Froude number based on diameter and settling velocity
- X_n: Weight percentage based on particle size distribution
- V: Mean velocity

The calculated (solid line) and measured (closed circle) values of the pressure head in the pipe are shown in Fig. 4. The lower suction hole is installed between 2 ch and 7 ch. As the cross-section area of the pipe varies, the calculated value of the pressure head also varies greatly along this section. Except for the above-mentioned section and that the calculated pressure head at 11 ch was a little higher than the measured value, the calculated higher values of the pressure head coincided with the measured values. On the whole, it was confirmed that the hydraulic design method could reproduce the pressure head along the pipe.

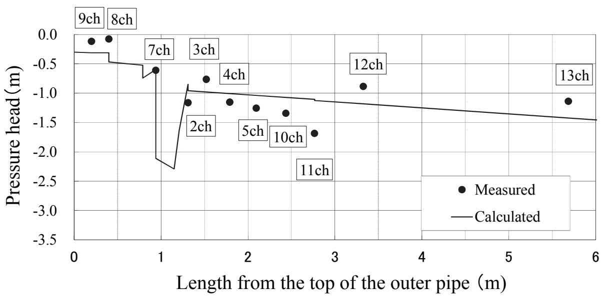

Figure 4. Comparison of measured and calculated values.

4. LABORATORY TEST USING A QUASI-FULL-SCALE MODEL AND ESTIMATION OF SEDIMENT CONCENTRATION

4.1. Conditions of the laboratory test

Aiming to apply the system to an actual reservoir, the authors carried out a laboratory test using a quasi-full-scale model based on the results of the laboratory test using a small model. As the thickness of the sediment layer in actual dams is about 5.0 m, the scale of the quasi-full-scale model is from about 1/3 to 1/2 for the model that is installed at an actual dam. The profile of the quasi-full-scale model and installed position of measurements are shown in Fig. 5. The facility specifications of the quasi-full-scale model are shown in Table 3.

In order to avoid pipe blockage depending on increasing sediment concentration in the suction pipe, the quasi-full-scale model has another pipe called the "water supply pipe." The pipe can supply the water from the surface of the water tank to the suction pipe. Therefore, the water supply pipe is used to reduce the sediment concentration in the pipe when the sediment concentration in the pipe is excessive.

Mixed-particle-size sand was used as the sediment material for the laboratory test. The 50% particle diameter is about 0.4 mm. The particle size distribution curve is shown in Fig. 6. The water tank used for the laboratory test was 6.0 m in length, 4.7 m in width, and 5.0 m in height. The authors installed the quasi-full-scale model of the system in the tank and buried it in the sediment whose thickness is 2.2 m. The sediment removal laboratory test was carried out keeping the head about 4.4 m. The items of measurement and observation during sediment discharge are as follows: 1) suction pipe pressure by the pressure meter; 2) suction pipe flow by the ultrasonic flowmeter; 3) sediment concentration at the outlet of the suction pipe by sampling of water; and 4) observation of the flow in the suction pipe by video camera. After sediment discharge, the quantity of discharge sediment was estimated by measuring the surface of the remaining sediment.

4.2. Results of the laboratory test

The results of the test are shown in Fig. 7: suction pipe flow including water supply pipe flow; water supply pipe flow; sediment concentration at the outlet of the suction pipe; and sediment thickness around the suction pipe. After opening the higher suction hole, the sediment

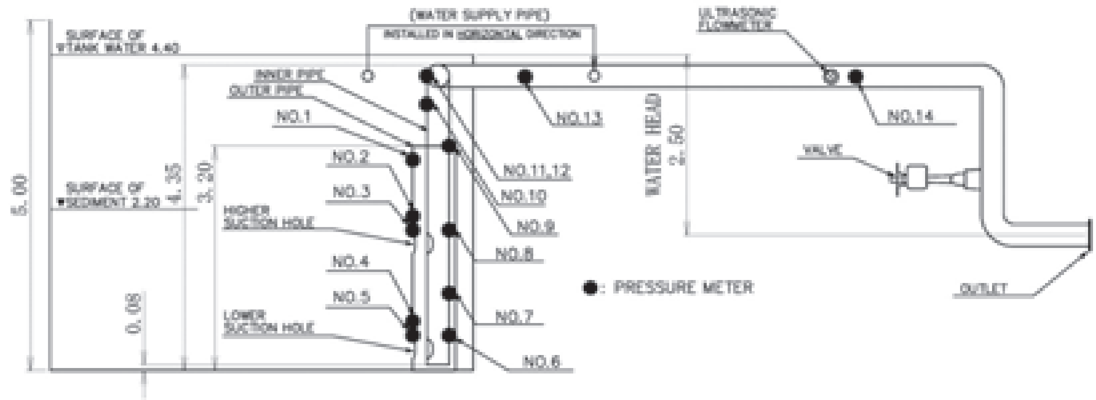

Figure 5. Profile of the quasi-full-scale model and installed position of measurements (m).

Table 3. Facility specifications of the quasi-full-scale model

Inner pipe	Diameter	0.30 m
	Height	4.35 m
Outer pipe	Diameter	0.60 m
	Height	3.20 m
Suction holes	Diameter	0.28 m
	Higher height	1.36 m
	Lower height	0.17 m
Water supply pipe	Diameter	0.15 m
	Length	4.0 m
Transport pipe	Diameter	0.30 m
	Total length	10.8 m

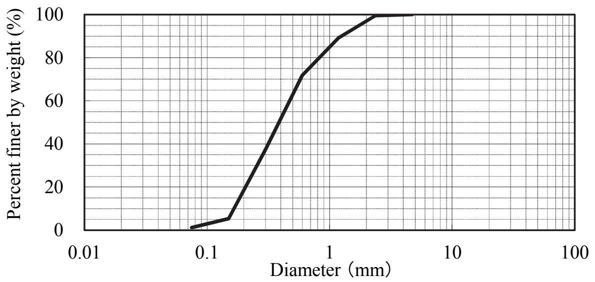

Figure 6. Particle size distribution curve of sediment material.

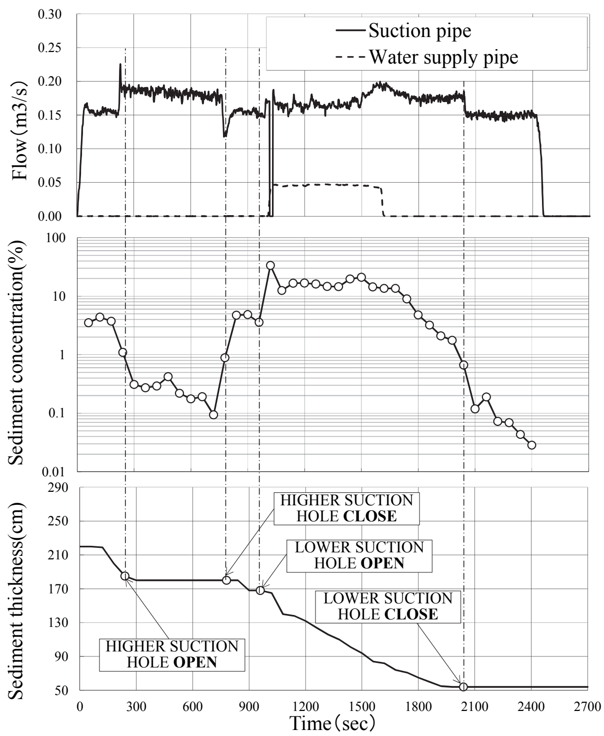

Figure 7. Results of the laboratory test using a quasi-full-scale model.

concentration of the discharge flow and the sediment thickness were not greatly changed in spite of increasing the suction pipe flow. Because the sediment level of the laboratory test was a little higher than the higher suction hole, the hole did not suck much sediment. However, after opening the lower suction hole, the suction pipe flow changed greatly. Because the sediment level of the laboratory test was higher than the lower suction hole, the hole could suck much sediment. Therefore, the suction pipe was almost blocked in response to the rapid increase in sediment concentration in the suction pipe. The sediment concentration of the discharge flow at this time was 33.6%, and the sediment accumulated at the bottom of the horizontal part of the transport pipe. After starting supply from the water supply pipe, the sediment concentration of the discharge flow was reduced to about 10% and the suction pipe flow became steady. After that, the sediment concentration of the discharge flow gradually decreased. The sediment of the laboratory test was continuously sucked until the lower suction hole was closed. The shape of discharge sediment measured at the surface of the remaining sediment is shown in Fig. 8. After discharge of the sediment is completed, its surface becomes hemiconical shaped centered by the vertical pipe. The slope gradient is determined by the underwater angle of repose. At traverse line Ⅳ, the sediment above 0.33 m was sucked. The quantity of sucked sediment was about 15 m^3. The time was 40 minutes until the end of discharge.

4.3. Verification of the hydraulic design method

Based on the results of the quasi-full-scale laboratory test, the hydraulic design method was verified. The calculated value of the pressure head at the transport pipe, which is used to measure the sediment concentration of the

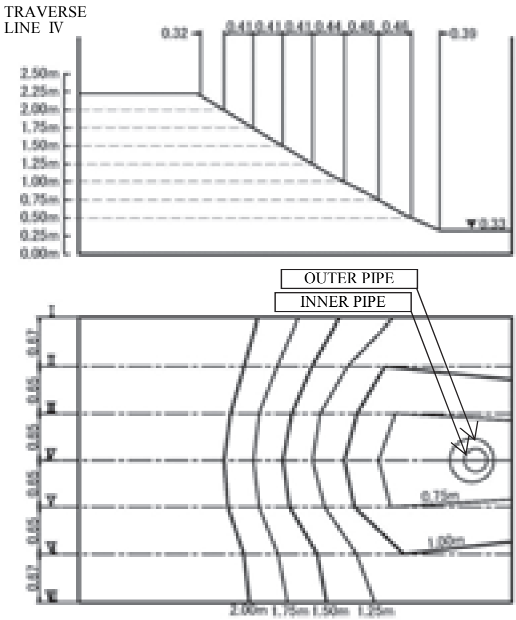

Figure 8. Shape of discharge sediment.

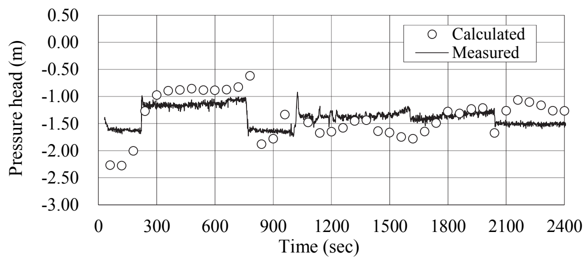

Figure 9. Comparison of measured and calculated values.

discharge flow and the suction pipe flow, and the measured value (11ch) of the pressure head at the transport pipe are shown in Fig. 9. As shown in Fig. 9, the calculated value of the pressure head coincided with the measured value on the whole. Therefore, it was verified that the hydraulic design method can be applied to quasi-full-scale facilities using Vertical Multi-Holed Double-Pipe System.

4.4. Hydraulic design of verification test facilities using the hydraulic design method

The hydraulic design procedure for verification test facilities is shown in Fig. 10. The parameters used for hydraulic design method are shown in Table 4. Basic specification of the verification test facilities was determined using the method. When the method is applied to assumed facilities, it is possible to judge whether it can suck the target sediment or not based on the particle size of the target sediment. In addition to the following parameters used by the method, this method used the parameters shown in Table 4: total head; diameter of the inner and outer pipe; diameter of the suction hole; transportation distance; suction pipe flow; and sediment concentration in the suction pipe.

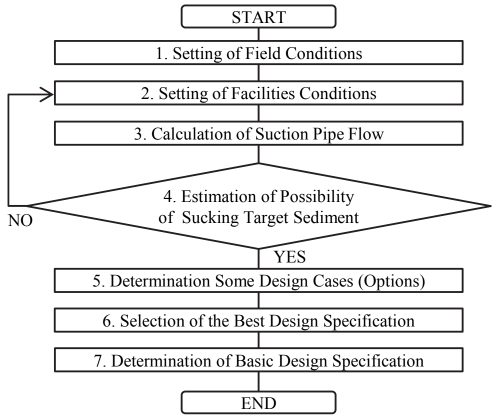

Figure 10. Hydraulic design procedure.

Table 4. Parameters used for the hydraulic design method

Inflow loss coefficient at suction holes (Estimated from results of lab test)		0.1
Shape losses	Inlet	1.0
	Section changed sharply	0.3
	Curve at suction hole	1.0
	Curve at elbow of transport pipe	θ = 90° 3)
Roughness degree of suction pipe		0.013(Steel) 0.0105(Acryl, VP)
Friction loss in sediment flow (α :Correction coefficient)		$Fr_{xi}^{1.5}$=0.50 α=1.65

Table 5. Consideration cases

Item	Case 1	Case 2	Case 3
Total head	2.0 m	3.0 m	4.0 m
Inner pipe diameter	I. 500 mm II. 400 mm III. 300 mm	I. 500 mm II. 400 mm III. 300 mm	I. 500 mm II. 400 mm III. 300 mm
Outer pipe diameter	Inner pipe diameter +300 mm		
Sediment concentration	0%, 5%, 10%		

First, field conditions such as particle size of the target sediment, total head, and so on are set as design criteria. Then, the conditions of the facilities such as diameter of the pipes are set as the design case. Next, suction pipe flow is calculated using the method based on the design criteria. After calculation, the possibility of sucking the target sediment is estimated based on comparison of calculated flow velocity and target sediment diameter. If the assumed facilities can suck the target sediment based on calculated flow velocity, the design case is adopted as an option for the basic specification. The same procedure is carried out for different design cases. The basic design specification is finally selected from the adopted options.

The authors plan to carry out the verification test of Vertical Multi-Holed Double-Pipe System in actual dams. In order to determine the basic specification of the verification test facilities, 9 sets of conditions of facilities were estimated based on the hydraulic design method. The remaining 5 of 9 sets were adopted as design options. Finally, Case 2-II in Table 5 was adopted based on economical considerations.

4.5. Estimation of sediment concentration at the outlet

When the system is applied to an actual dam, it is necessary to avoid excessive sediment supply to the lower reaches of dam. Therefore, the system is expected to have a function to open and close the suction holes automatically in response to the sediment concentration in the discharge flow. This paper briefly presents the method of estimating sediment concentration of the discharge flow based on laboratory test results using a quasi-full-scale model.

In order to realize this function, the authors established a method for real-time estimation of sediment concentration in the suction pipe. This method is based on the relationship between estimated sediment concentration of the discharge flow and measured pressure of the head and pipe flow, derived from the equation of pipe friction proposed by Turian et al (Raffi, M.T., et al. 1977). When Turian's equation is used, it is necessary to estimate the sediment transport type (Noda, K. 1986) to select the parameters of the equation. Sediment concentration in the discharge flow both measured and estimated by Eq. 5 (Noda, K. 1986, Zandi, I., et al. 1967, Newitt, D.M., et al. 1955, Rubey, W.W. 1933) are shown in Fig. 11.

$$C = \left(\frac{1}{a} \frac{\lambda^s}{\lambda_w^b \cdot C_D^c \cdot \left[V^2 / gD(S-1) \right]^d} \right)^{1/e}, \qquad (5)$$

where,

a,b,c,d,e:	Coefficients based on sediment transport type
C_D:	Drag coefficient
S:	Specific gravity of sediment particle

The estimation was carried out when the pipe flow was steady. As shown in Fig. 11, the estimated value of sediment concentration of the discharge flow coincided with the measured value. Therefore, the authors consider that it is possible to estimate sediment concentration in the discharge flow by using Eq. 5.

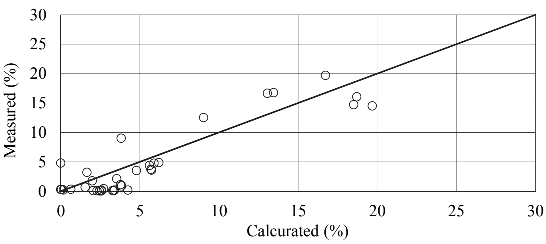

Figure 11. Comparison of measured and calculated values of sediment concentration of the discharge flow.

5. CONCLUSIONS

The followings are the conclusions of this paper:

1. The basic sediment suction ability of the system was estimated by carrying out a laboratory test using a small model. In addition, the hydraulic mechanism of the system was revealed by using hydraulic design method that could calculate the pressure head based on the results of the laboratory test using a small model.

2. The sediment suction ability of the system was estimated by carrying out a laboratory test using a quasi-full-scale model. In addition, the problem of suction pipe blockage was resolved by supplying water, which reduced the sediment concentration in the pipe from the water supply pipe.

3. By applying the hydraulic design method to the results of the laboratory test using a quasi-full-scale model, it was confirmed that the hydraulic design method was valid for quasi-full-scale facilities.

4. The basic specification of verification test facilities was determined by using the hydraulic design method.

5. The estimation method of sediment concentration at the outlets of the suction pipe was presented.

It was found that Vertical Multi-Holed Double-Pipe System was feasible through the laboratory tests with the small model and the quasi-full scale model. In order to confirm further applicability of the system to actual sites, the authors plan to carry out a verification test of the system at an actual dam.

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