Development and Applications of Multi Hole Suction Pipe

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1. Introduction

There are several countermeasures against sedimentation in a dam reservoir (Table-1). A sedimentation dam traps sediments that flow into a dam and a sediment bypass tunnel routes turbid water as well as sediment downstream of a dam. The sediments, which have been already deposited in a dam reservoir, may be dredged, released from the bottom gate of the dam (flushing), or removed by some sediment-removing facilities such as Hydro suction Sediment Removal Systems (HSRS), which utilize the water head difference to initiate sediment suction flow.

HSRS may be classified into two types depending on whether the sediment-suction devices are movable or fixed in their location. Although none of these systems has been applied for the actual sediment removal project in Japan, several systems have been proposed and their applicability has been investigated. Examples of fixed-type HSRS are: Hydro-P which applies continuous suction slits; Multi Hole Suction Pipe (MHSP) which applies multiple suction holes separately located along the main suction pipe; and the system that utilizes a sheet covering the reservoir bed around the suction pipe aiming to extend the sediment-suction area. Among these systems, this paper focuses on the development and applications of MHSP proposed by authors.

2. Development History of MHSP

The goal of our research group, Water Resources Sedimentation Technology (WRST), is to develop and improve technologies that reduce or remove sediments accumulated in a dam reservoir. For example, WRST has been engaged not only in the development of conventional dredging but also in slurry transportation technologies such as U-shaped conveyer and pneumatic transport system. In 2001, besides these technologies, we started the investigations of HSRS originally aiming for the removal of deposited sediment in Miwa Dam without causing serious environmental damages at downstream of the dam. Miwa Dam is located along Mibu River in the watershed of Tenryu River. HSRS is one of the preferable sediment-removal systems at Miwa Dam because the system utilizes the

Table-1 Countermeasures against sedimentation in a dam reservoir

	Movable suction	Fixed suction	The conventional machine dredge (for reference comparison)
Sand Collection	Floating body + Siphon dredge Hydro−J method SY method etc	Transport sediment by lowering the reservoir water level	pump dredger + mechanical pump
Suction		Orifice type discharge pipe discharge pipe with dispersed type slit Hydro-P method MHSP method Flexible slit discharge pipe with sheet etc	
Derivery	Pipe or Ship transport	Pipe	Pipe or Hopper barge
Storage	Storage outside at a reservoir or Temporal storage in a reservoir	----	Sedimentation pond
Down-stream discharge	---- (Discharge during flood)	Concentration control Discharge during flood	---- (Recycle or disposal)

Table-2 Development history of MHSP

Year	Experiment	Investigated features
2001	Lab. experiment	physical mechanisms around suction holes
2002	Lab. experiment	applicability of multiple separate suction holes
2003	Lab. experiment	MHSP / extension of suction area (shut & open device by sliding-cover, water jets around holes) / development of numerical model / design of system in the actual field
2004	Field study at Miwa Dam	Field-scale experiment wit sediment collected from Miwa Dam. MHSP with 300mm-diameter.

natural water head difference, i.e. clean energy, to initiate the suction flow.

In 2001, WRST carried out laboratory experiments to investigate the physical characteristics of the sediment-suction holes and proposed a new HSRS that has separate multiple suction holes located along the bottom of a straight pipe. In 2002, WRST carried out additional laboratory experiments to capture the physical mechanisms of the proposed HSRS and to investigate measures to enlarge the sediment trap area and also to prevent blockage of the system. In 2003, we modified this system by opening the upper-end of the suction pipe and placing it in the water above the sand bed so that the system can intake pure water from this upper-end opening. This modification worked to prevent blockage of the system as the supplied pure water decreases the slurry density and instead increases the flow velocity. We called this system as Multi Hole Suction Pipe (MHSP) and, through a number of laboratory experiments, further investigated the theoretical mechanisms of the system and explored possible improvements of the system. For example, we confirmed the effectiveness of "shut and open device," which shuts and opens the suction hole by a sliding-cover attached at the hole. By shutting the downstream suction holes, this shut and open device extends the "effective length" of MHSP, within which the system effectively intake and transport the slurry without causing blockage problems. Water-jet installed around the suction holes were also effective to fluidize the sediment accumulated around the suction hole and hence to enhance sediment suctions. Based on these experimental data, furthermore, we developed one-dimensional numerical model to predict the inflow rates at each suction hole as well as flow velocity distributions along the suction pipe.

In 2004, WRST performed a field experiment of MHSP at Miwa Dam using the sediments deposited in the dam and confirmed the overall performance of MHSP in the actual filed-scale. Through the field experiment, we also verified the applicability of the numerical model, which was newly developed for predictions of hydrodynamics of MHSP in the field scale. The numerical model is now utilized to determine the optimum design of MHSP based on given conditions such as available water head difference, characteristics of deposited sediment, and required discharge rate of the sediment, etc.

3. Advantages of MHSP

Primary advantages of MHSP are outlined as follows:

(1) The system efficiently utilizes the natural clean energy of water head difference.
(2) Since the entire system is based on a simple pipe-flow structure, cost of the system is relatively low.
(3) No sediment disposal area is necessary since the system discharges sediments directly to the downstream.
(4) Upper-end opening of the discharge pipe enables the system to retain high flow velocity and to prevent blockage of the system.
(5) Water-jet at the suction holes fluidizes and breaks up the ambient sediment and enhances the efficiency of the sediment suction.
(6) "Shut and open device" extends the effective length of MHSP

Figure-1 illustrates how MHSP may be applied in a dam reservoir and Figure-2 shows the detailed structure around the suction holes.

4. Laboratory Experiment

In 2003 and 2004, we performed laboratory experiment and investigated the physical mechanisms of MHSP. Outlines and primary outcomes of the experiment are summarized in the following sections.

4.1 Outline of the experiment

The experiment uses a basin with 0.7m deep, 1.0m wide, and 8.5m long. MHSP was 52mm in diameter and made of transparent vinyl chloride so that one can observe the features of sediment suction. This MHSP is 1/6-scale of the MHSP used for the field experiment discussed later. Round suction holes were separately opened along the bottom of the pipe with diameter of 23mm, i.e. 1/5 of the pipe diameter. Distance between each adjacent hole was set to be 350mm so that the ratio of open and closed area becomes 1:15 as proposed by Michiue and Oda (1986). The down-end discharge opening of the pipe was set in the air and a valve, pressure gauge, γ-ray density meter, and flow meter are installed near the discharge opening. Water head difference was changed by adjusting the elevation of the discharge opening. Overflow gate was installed in the basin so that the water level of the basin is stabilized. The basin was filled with either quartz sand or silt. Characteristics of the quartz sand

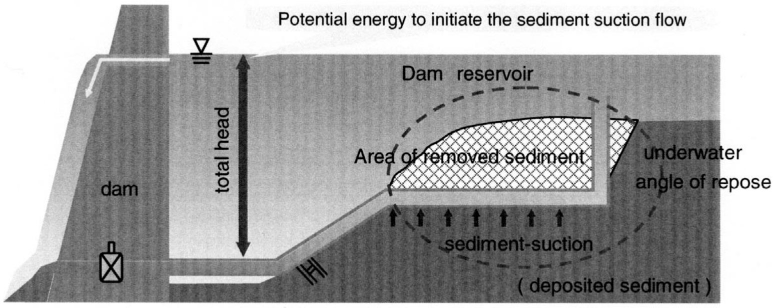


Figure-1 Application image of MHSP in a dam reservoir

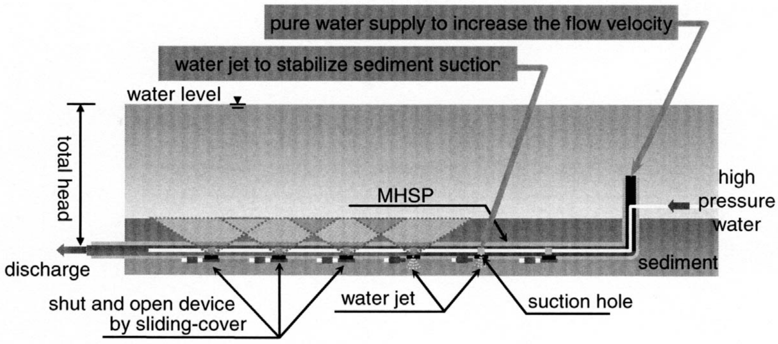


Figure-2 Illustration of MHSP

and silt are summarized in Table-3 and Figure-4. In the case of silt, deposited sediments were not fully consolidated. In addition to the measurement facilities near the discharge opening mentioned above, five pressure gauges were installed between each suction holes and another flow meter was installed near the upper-end opening of the pipe. Ultra-sonic distance measurements device was also installed to measure the spatial bed elevations. Figure-3 shows the cross view of the experimental facilities.

4.2 Observed features of MHSP for quartz sand

Through the experiments, applicability of MHSP for quartz sand was verified. Overall characteristics of MHSP for sand-discharge are summarized as follows:

- The system successfully discharged quartz sand when the depth of the sand above MHSP is less than five times of pipe diameter. Required discharging time depended on the sand depth above MHSP.
- As sand is discharged, following characteristics of geometry change of the sand bed was observed (Picture-1 and Figure-5). Seepage failure first occurs around the suction holes. The area of the seepage failure is extended to the sand surface and starts to form a vertical water path along the water flow (piping). Area of this vertical water path is horizontally enlarged until the slope of the sand bed reaches to the angle of repose. The earlier the piping occurs, the more efficient is the sand discharge.
- Sediment concentration and flow velocity of the discharged slurry was measured. Average volumetric concentration of the sand was relatively low and was ranged from 2 to 5 percent.

Bed geometry after discharge of quartz sand was downward-cone-shape with slope of 35-degree. This knowledge of sand-bed geometry can be used to estimate the total volume of sand to be discharged by multiple suction holes.

Table-3 Sediment characteristics

quartz sand	
d_{50}	0.07 (mm)
density ρ_s	2.642 (g/cm^3)
wet unit weight ρ_s	1.936 (g/cm^3)
dry unit weight ρ_d	1.505 (g/cm^3)
permeability κ	1.12×10^{-3} (cm/s)

Miwa sediment	
d_{50}	0.01 (mm)
density ρ_s	2.76 (g/cm^3)
liquid limit W_L	40.7 (%)
plastic limit W_P	32.3 (%)
plasticity index I_P	8.4

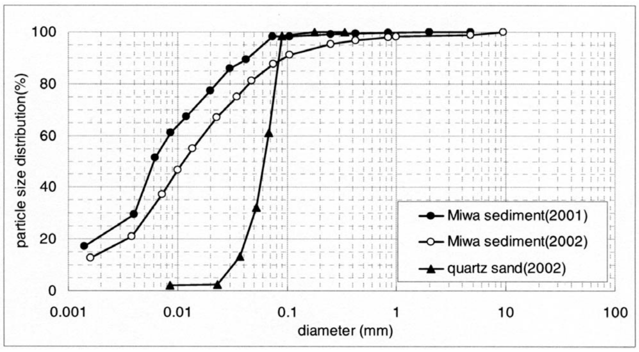


Figure-4 Diameter distributions of sediments used for the experiment

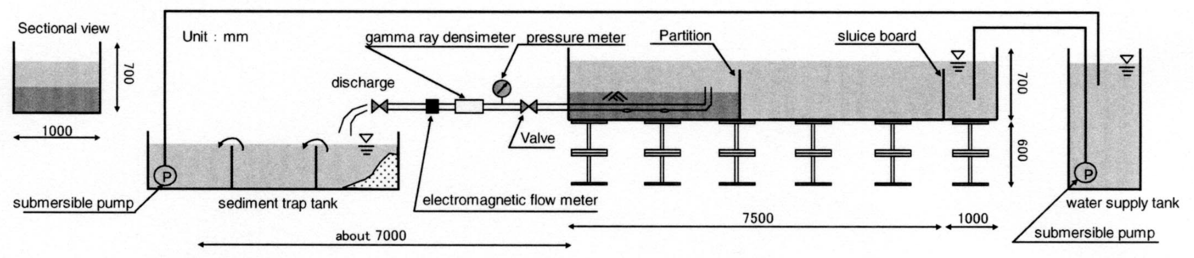
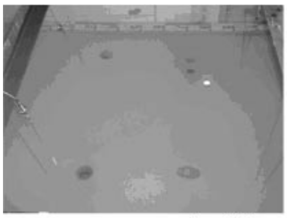
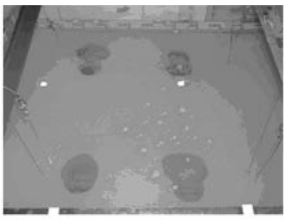


Figure-3 Cross-view of experimental facilities

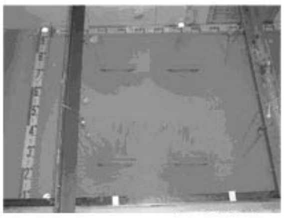


(1) 1 minute



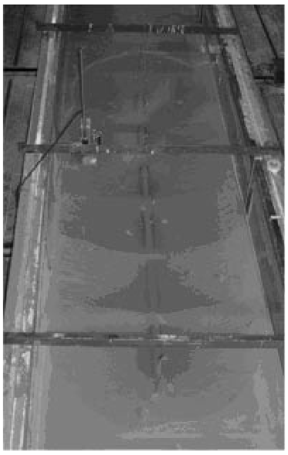
(2) 5 minute

(3) 10 minute

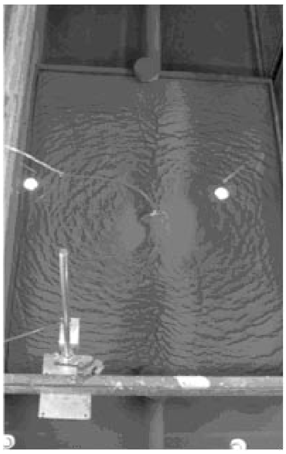


(4) 15 minutes (equilibrium state)

Picture-1 Geometry change of the sand bed after initiation of suction flow



quarts sand



silt collected from Miwa Dam

Picture-2 Bed geometry after discharge

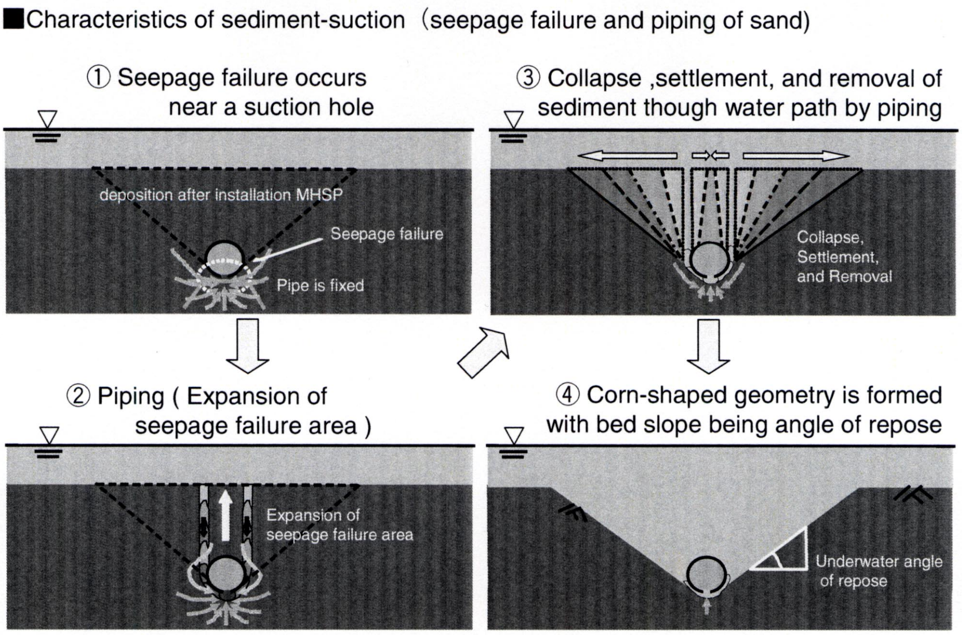


Figure-5 Characteristics of geometry change of the sand bed

- Effective length of the suction pipe was about 1.4m, which corresponds to four suction holes in this experiment.
- Following supplemental facilities were effective to enhance the sediment discharge.
  1) Upper-end opening of the pipe that supplies pure water and increases the flow velocity and decreases the slurry density.
  2) Water jet around the suction hole that fluidizes ambient sediment.
  3) Shut and open device by sliding-cover extended the effective length of the suction pipe. In this

experiment, the effective length was extended up to eleven suction holes, i.e. was nearly tripled by applying this shut and open device.

- One-dimensional numerical model was developed for predictions of hydrodynamics of MHSP. The developed numerical model provides predictions of pressure and flow velocity inside the pipe from the input data of water head difference as well as dimensional features of MHSP.

4.3 Observed features of MHSP for silt

The system also discharged the silt collected from Miwa Dam if the consolidation time was short and deposited silt was retained to have relatively high fluidity. As the fluidity of the deposited silt goes down (moisture content of 50% in this experiment), however, MHSP sometimes failed to intake the silt around the suction holes. Compared to the experimental case for quartz sand, average concentration of slurry was higher, ranged from 5 percent to 15 percent. Bed geometry remained plane and the entire bed level was lowered as MHSP discharges the silt.

5. Field Experiments

Through the laboratory experiment, we confirmed the applicability of MHSP especially for the discharge of sand in a laboratory scale. Applicability of MHSP for discharge of silt in an actual scale, however, still remains unclear. In order to investigate this feature, we carried out a field experiment at the east bank of Miwa Dam (Figure-6) from December 2004 until February 2005. Miwa Dam is located in the river system of Tenryu River, Nagano. The experiment used the actual silt deposited in Miwa Dam whose fluidity was relatively high.

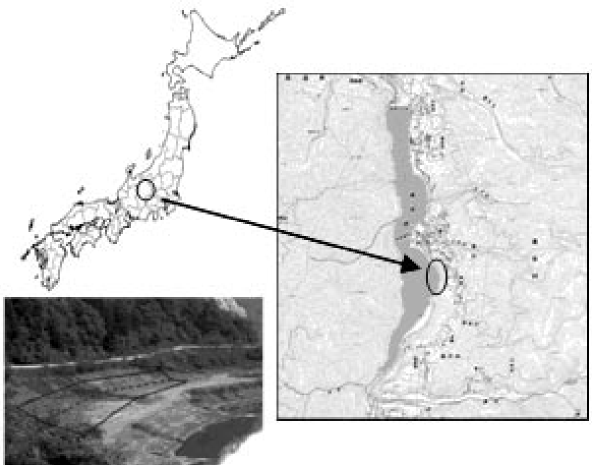


Figure-6 Field study site

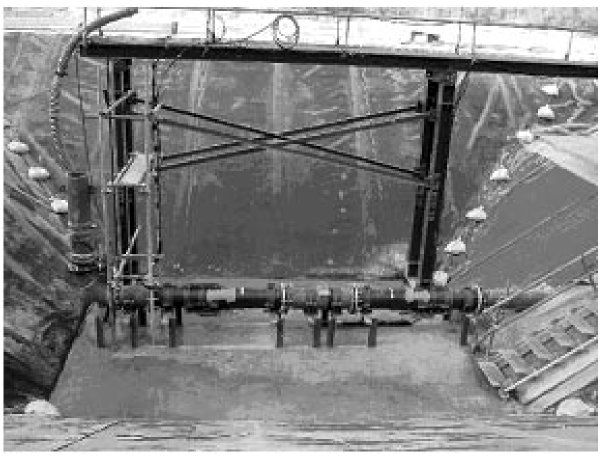
5.1 Outline of the experiment

We first developed a 3.75m-deep basin with horizontal dimensions of 4mx6m near the bottom and 9mx11m near the surface and installed MHSP (Pictures 3 and 4) near the bottom of the basin. Diameters of the main pipe and suction holes were set 300mm and 134mm, respectively. In this basin, we spread the silt collected from the dam reservoir until the surface elevation of the silt reaches to 1m above the bottom of MHSP. Moisture contents of the silt was measured and controlled before the silt was spread in the basin. The basin was then filled with water and the surface water elevation was stabilized by overflow gate. The length of the discharge pipe from the down end suction hole to the discharge opening was 40m and the diameter of this discharge pipe was D=300mm. Elevation of the discharge opening of the pipe was adjusted so that the total water head difference becomes 1, 2, 3, or 4m depending on the experimental cases.

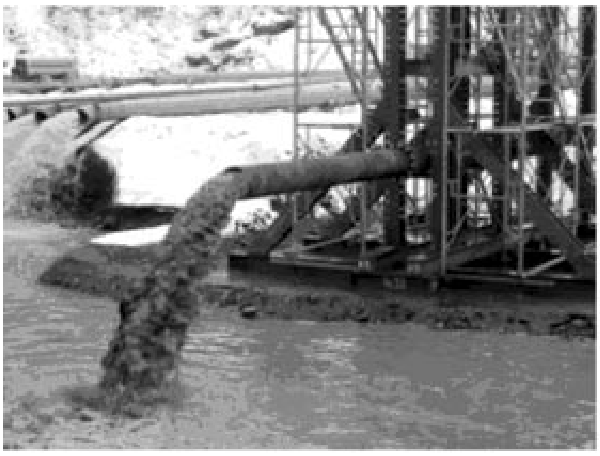
In all experimental cases, we first shut both suction holes and let the pure water flow in the pipe from the upper end opening. After the flow rate was stabilized, we opened one or two suction holes depending on the experimental cases and measured the time-varying velocity, pressure, and the density of the slurry flow. Figure-7 shows the positions of five pressure gages, a γ-ray density meter, and three acoustic Doppler current profilers. Procedures of the experiment are summarized as follows.

1) Collect Miwa silt and control the fluidity of the silt by adjusting the moisture contents of the collected silt.
2) Measure and record the moisture contents of the silt and spread it in the basin.
3) Fill in the water until the surface water reaches to

Picture-3 Overview of field experimental devices



Picture-4 MHSP installed in the pond



Picture-5 Discharge pipe during operation

Picture-6 Geometry change of silt bed after suction

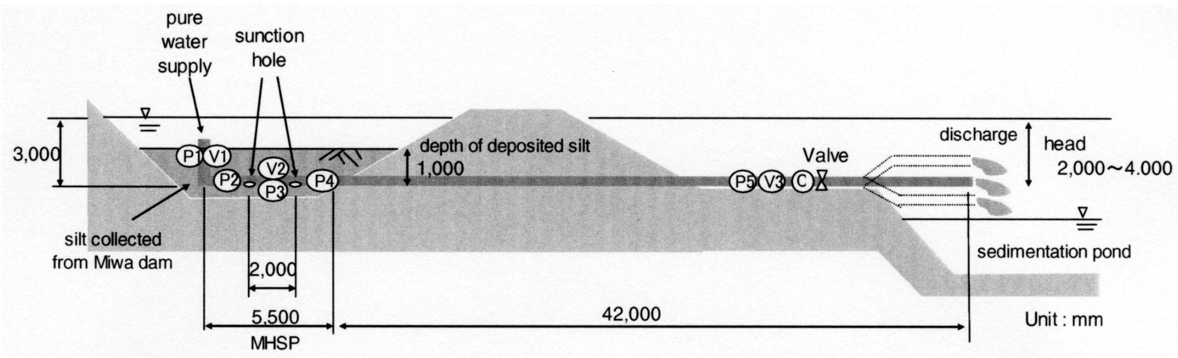


Figure-7 The outline of a field experiment institution

the designed elevation.

4) Open the downstream valve with both suction holes closed.
5) After the water flow was stabilized, open one or two suction holes to begin sediment suction.
6) Measure velocity, pressure, and density of the discharged slurry.

5.2 Observed features of MHSP in the field scale

Through the field experiments, we confirmed that MHSP in the actual field scale can effectively discharge the silt with relatively high fluidity. We should however note that the depth of deposited silt above the bottom of MHSP was kept in 1m in this experiment and further experiments may be necessary to examine the applicability of MHSP when the depth of deposited sand is deeper. Other primary features of MHSP observed in this experiment are as follows:

1) Average density of the discharged slurry was 1.2g/m^3, which corresponds to 11% of volumetric sediment concentration and 2x10^{5}ppm of SS, suspended solid, concentration.
2) Slope of the silt surface after the discharge was around 1:10. This slope may depend on fluidity of the deposited silt.
3) MHSP discharged silt without blockage even when debris such as pieces of wood and plastic bags was mixed in the silt.
4) When the density of the discharged slurry is stable with its peak value (Phase 1 in Figure-8), the

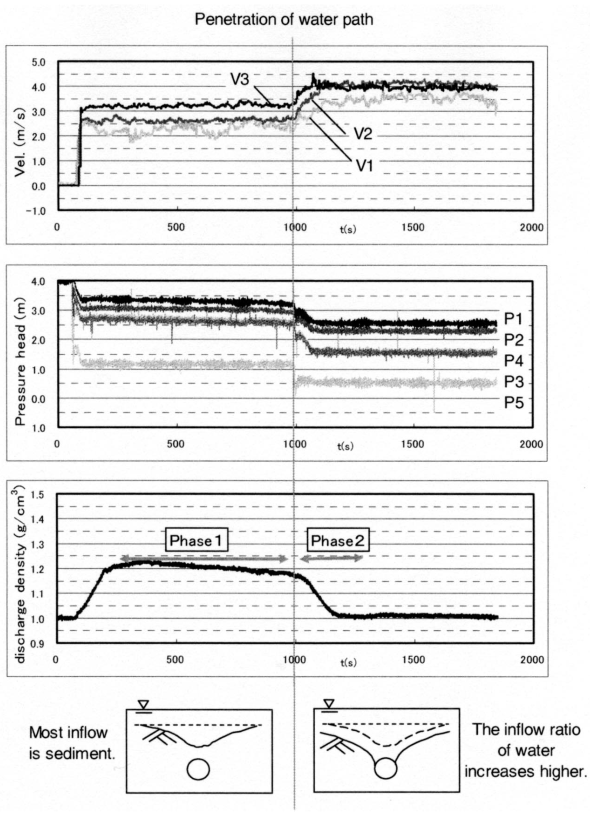


Figure-8 Time varying flow velocity, pressure and slurry density (Head:4m, Deposition thickness:1m, Water ratio:34.6%, 1 suction hole)

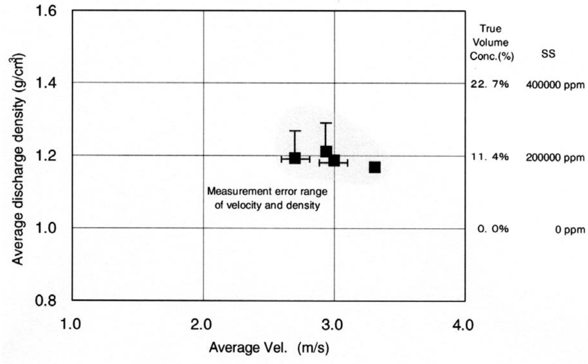
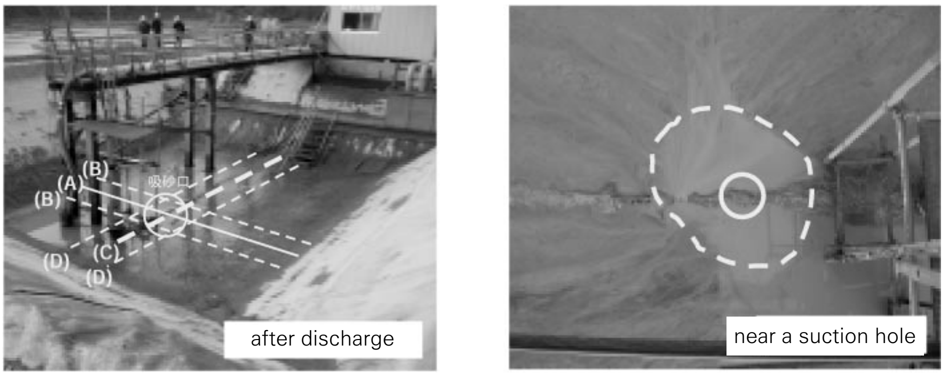
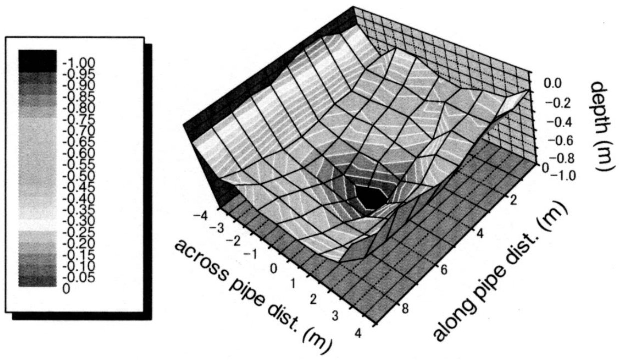


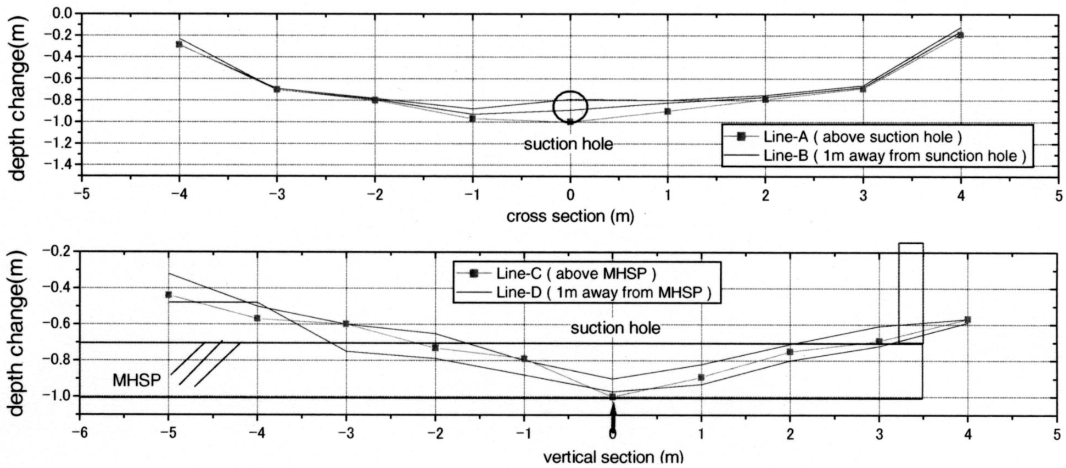
Figure-9 Relationship between average density and average discharge flow velocity



(1) Picture of silt bed after discharge



(2) Bird's-eye view of silt bed after discharge



(3) Slope of silt bed after discharge (cross and vertical section)

Figure-10 Geometry change after discharge (Picture and Survey result) amount of discharged silt, determined as a product of measured flow rate and the measured silt concentration near the discharge opening, was nearly equal to the product of suction flow rate and the concentration of silt deposited around MHSP. Here suction flow rate was determined as a difference of measured flow rates upper and down side of the suction hole. The concentration of deposited silt was simply determined as 1-n with n=0.6, the porosity of the deposited silt. This observed fact indicates that, in this experiment, the ambient silt with high fluidity directly flew into the suction hole without seepage effects.

5) The numerical model, originally developed based on the laboratory experiment, was also applicable to the real scale conditions.

Based on observations listed in 4) and 5), we can estimate the peak concentrations of discharged slurry as well as time-varying flow rates and pressure distributions in MHSP.

6. Practical Application of MHSP to Dam Reservoirs

Applicability of MHSP in the real scale was confirmed. As discussed above, the newly developed numerical model provides us flow rate of slurry as well as its peak density once following conditions were given: water head difference; sediment characteristics; dimensions of MHSP such as diameter and length. All these information is now readily incorporated to the fundamental designs of the entire MHSP system according to target discharge rate of slurry and local conditions of the dam reservoir. Hinokidani(2005) referred to our work in his paper and pointed out the validity and applicability of the numerical model as a tool to design the practical MHSP system.

Especially for the reservoir which has deposited sand with relatively uniform grain diameters, MHSP may be one of suitable systems to remove this deposited sand. Water jet may be effective to fluidize the deposited sand and to promote piping. Occasional pump may also be helpful to reduce the risk of blockage.

Kashiwai (2005) also admit the future applicability of HSRS, such as MHSP, but pointed out following two limitations of the system. The first limit is that the ability of existing HSRS may be limited up to the sediment discharge of about 105m^3/year. The other limit is that HSRS can be used only during the flood and therefore requires certain supplemental system that can be used for everyday basis and collect deposited sand in the area within which HSRS can entrain the sand.

Presenting MHSP may also be more efficient being combined with other existing sand removal systems. Especially to collect the sand (transport deposited sand within reservoir), for example, combination with following systems may be effective:

1) Dredging
2) Sand transportation by pumping system
3) Use of HSRS combined with sedimentation pond whose water elevation is lower than targeted sand.

In item 2), dredging or MHSP may be applied to collect the transported sand. In order to apply MHSP, however, one may require a pump to yield the pressure difference. Among these options, one advantage of Item 1) may be in that debris can be removed when disposing the dredged sand to the target site and the risk of blockage may be reduced. When designing the entire sand-removal system, one needs to account for various conditions, such as characteristics of deposited sand, targeted volume of removed sand, and available water head difference, etc.

7. Future Works

All the experimental and numerical studies performed by authors have clarified the overall performance and applicability of MHSP. All these knowledge are now incorporated to carry on the fundamental design of the system. In order to apply MHSP in the actual sediment removal project, however, there still remains following problems:

1) Control of the sediment concentration of discharged slurry.
2) Removal of debris to avoid blockage of the system.
3) Establishment of solid methodologies for design, construction, maintenance, and operations of the entire system.

All these problems are essential to apply MHSP to the practical sediment removal project and the research on these problems is on going.

Hinokidani(2005) pointed out that, in the future sand removal project, it is important to design the separate systems depending on the characteristics of removed sand. Characteristics of the sediment may be classified in terms of recyclability as well as impact on downstream environment. In this sense, the present MHSP should also specify the preferable sediment characteristics that can be efficiently discharged so that one can clearly see if the system is applicable when certain sediment conditions are specified.

8. Concluding Remarks

Studies on applicability of MHSP were performed through laboratory, field, and numerical experiments. Through these studies, physical mechanisms and overall performance of MHSP have been cleared while several problems still need to be solved. Development of this kind of new system often requires step by step improvements based on practical applications of the system. The development of the system is on going and we are hoping that, with grateful advices from various contributors, MHSP will be flexibly modified and improved corresponding to individual practical project.

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