Development of the Pilot System for Test of Excavating and Ore lifting of Seafloor Polymetallic Sulfides

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It is estimated that seafloor polymetallic sulfide deposits are abundant in the waters around Japan. As Japan is a country with few natural resources, these deposits are considered to be promising mineral resources. To exploit these deposits, Japan Oil, Gas and Metals National Corporation (JOGMEC) conducted a pilot test for excavating and ore lifting in the waters off Okinawa and successfully performed continuous slurry ore lifting from seafloor polymetallic sulfide deposits for the first time anywhere in the world. Having been commissioned by JOGMEC, a consortium which we represent (the members are: Mitsubishi Heavy Industry, Ltd.; Mitsubishi Shipbuilding Co., Ltd.; Nippon Steel & Sumikin Engineering Co., Ltd.; National Institute of Maritime, Port and Aviation Technology; Shimizu Corporation; Sumitomo Metal Mining Co., Ltd.; Fukada Salvage & Marine Works Co., Ltd.; and Mitsui Miike Machinery Co., Ltd.) built a test system and carried out the pilot test by operating the test system and making measurements. We were responsible for building an ore collecting test machine and a submersible pump unit, both of which are the pivotal components of the test system. This report describes their development and summarizes the pilot test.

1. Introduction

Figure 1 illustrates the pilot test. The ore collecting test machine developed from the mining support vessel moves to where ore has been piled. Then, the mining support vessel moves while reeling out an umbilical cable to connect a flexible hose to the ore collecting test machine.

The ore lifting support vessel, is moved to come directly above the ore collecting test machine and connects a flexible hose to the ore collecting test machine. The ore lifting support vessel then moves away from the ore collecting test machine and the mining support vessel, while descending the subsea pump unit down in the sea until a catenary of the flexible hose is formed. The submersible pump unit should be eventually settled at a level of approximately 50 m above the ore collecting test machine.

Ore, which has been piled in advance by the excavating test machine of Mitsui Miike Machinery, is dredged by the ore collecting test machine and is transported via a flexible hose to the submersible pump unit, from which it is lifted up to the ore lifting support vessel.

We were responsible for building the ore collecting test machine and the submersible pump system. This report describes the development of these components in the pilot testing system and summarizes the excavating and ore lifting pilot test.

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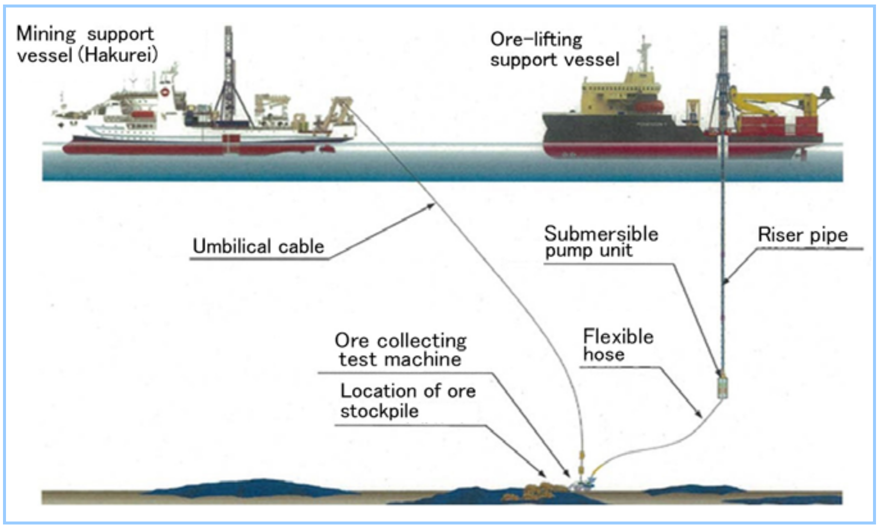

Figure 1 Schematic diagram of the pilot test system
The excavation and ore lifting test was carried out by simultaneously deploying two ships (i.e., the mining support vessel and the ore lifting support vessel).

2. Development of the ore collecting test machine

2.1 Ore collecting test machine modification plan

Before the pilot test, we built a Mining Element Engineering Test Machine with the aim of obtaining technical data related to the seabed mining unit. Completed in 2012, the Mining Element Engineering Test Machine underwent testing including offshore trials, and both technical data and subsea operation data were collected. The ore collecting test machine used in the pilot test was a modified unit of this Mining Element Engineering Test Machine. **Figure 2** shows the modifications that have been made.

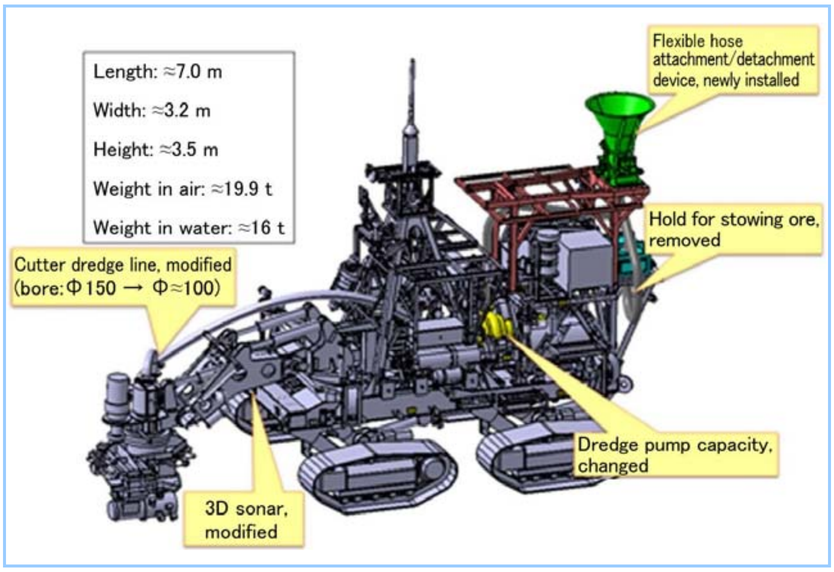

Figure 2 Modifications made to the Ore collecting test machine
The dredge pump and line of the Mining Element Engineering Test Machine were modified and a device to connect the flexible hose was newly installed.

(1) Excavator dredging head

A 2-axis cutter head, which was the excavator dredging head of the Mining Element Engineering Test Machine, is also used as the excavator head of the ore collecting test machine. The 2-axis cutter head can be rotated and consists of two spinning cutter drums positioned opposite to each other. With the rotational and spinning movements, excavated ore is gathered at the center of the excavator head where the dredging mouth is positioned. The excavated ore is then sucked through the mouth for slurry transport. The bore of the dredge line in the ore collecting test machine has been changed to ϕ ≈100 from ϕ 150, making it consistent with the riser pipe (inner diameter of ≈100 mm).

(2) Dredging system

In the Mining Element Engineering Test Machine, dredged ore is stowed in the hold at the rear of the machine and is recovered by the ship together with the machine itself. However, in the case of the ore collecting test machine, dredged ore is slurry transported via the flexible hose to the submersible pump unit which is positioned 50 m above the ore collecting test machine. The slurry flow velocity is to be maintained at the level required for lifting ore. The flow rate and head of the dredge pump have been adjusted according to the modifications made in the piping system of the ore collecting test machine.

The dredge line bore size of the ore collecting test machine is $\phi \approx 100$. After the hold for stowing ore was removed, the dredge line was connected to a flexible hose attachment/detachment device. The flexible hose can be attached to the ore collecting test machine by dropping the metal fitting at the end of the flexible hose from above into the cone of the attachment/detachment device, and fixing the metal fitting with a hydraulic cylinder. An abrasion-resistant rubber hose with an inner diameter of $\phi \approx 100$ is used as the flexible hose.

2.2 Dock test

The dock test was conducted to examine the dredged slurry transport performance of the modified ore collecting test machine. **Figure 3** illustrates the dock test. In this test, the ore collecting test machine dredged crushed rocks that were placed in the ore pallet at the bottom of the dock, and transported them as a slurry via a flexible hose to the mining tank at dockside. The flow rate, pressure and slurry concentration were measured at the onshore measurement site after setting up a pipe for measurement.

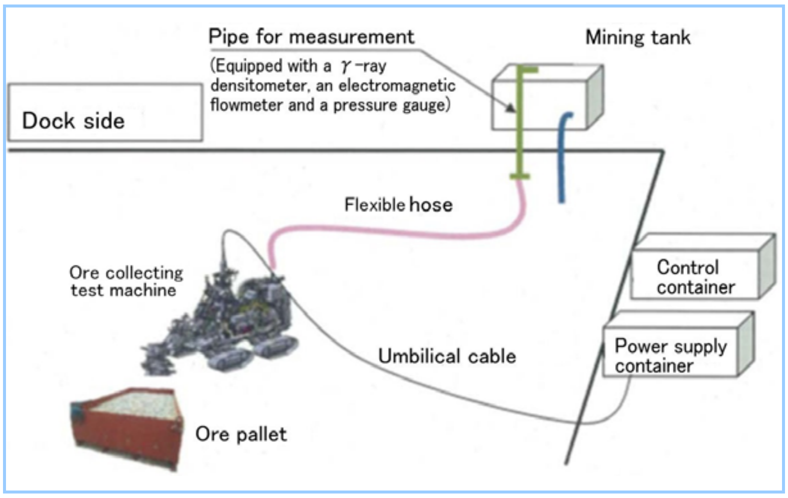

Figure 3 Dock test overview
An ore pallet was placed at the bottom of the dock. The ore collecting test machine excavated/dredged and slurry-transported the dredged ore to the mining tank at dockside.

Figure 4 presents a scene from the dock test. The following knowledge was acquired from the results of the test.

(1) It is possible for the ore collecting test machine to excavate/dredge and lift the dredged ore through the flexible hose.

(2) Although the depth of excavation and the boom swing speed are the two factors that determine the concentration of slurry, the concentration can be controlled by adjusting the depth of excavation. The influence of boom swing speed is small.

(3) The ore collecting test machine needs to be fitted with a γ-ray densitometer, because it is necessary to know the concentration at the time of excavation to realize stable control over the concentration (Subsequently, a γ-ray densitometer was installed).

(a) Ore collecting test machine (with the jumper hose attached)   (b) Onshore measurement site and the mining tank

Figure 4 Dock test
(a) The ore collecting test machine, moving in the air with the flexible hose attached to the flexible hose attachment/detachment device
(b) The onshore measurement site and the mining tank at dockside. The pipe allocated for measurement is the vertical part of the piping erected from the water surface. The mining tank is placed at dockside.

3. Development of the submersible pump system

3.1 Submersible pump design

The basic operating conditions for consideration are as follows:

(1) Ore: ore particle diameter of up to 30 mm, with the average relative density of excavated ore being 3.2 (a maximum of 4)
(2) Sea area and the depth of installation: up to 1,700 m deep
(3) Riser pipe: rigid (steel) pipe, with an inner diameter of ≈100 mm
(4) Slurry volume concentration: a target value of roughly 10%

A centrifugal multi-stage pump is used as a submersible pump. When using a single pump unit, the riser pipe is subject to twisting force (torque) because of the rotational inertia of the pump. Therefore, we have built a structure in which two pump units are combined in such a way that they counteract each other’s rotational inertia. A 6-stage submersible pump is employed as one of the two units. To balance the thrust, 3-stage impellers are arranged opposite each other. The minimum passage size of the submersible pump is 50 mm.

3.2 Submersible pump system

Figure 5 gives a configuration of the submersible pump unit. It measures 3 m (L) x 3 m (W) x 7 m (H) and weighs approximately 28 tons in the air.

The submersible pump unit consists of two pumps placed in parallel with one rotating clockwise and the other counterclockwise, thereby enabling them to counteract each other’s torque. Installed on the top of the submersible pump unit is a riser adapter to connect to the riser pipe, which is supported by a gimbal structure. When the pump is turned off, ore in the riser pipe will be discharged by the stone ejection mechanism. A negative-pressure prevention device is installed at the inlet of the submersible pump, which prevents the occurrence of negative pressure by opening a bypass valve at the time of the occurrence of an interruption in the flow of the flexible hose. The flexible hose is attached at the bottom of the submersible pump unit via the flexible hose detachment device, by which the flexible hose can be detached from the unit when it cannot be disconnected from the ore collecting test machine. The number of rotations of the submersible pump is controlled by the inverter on the ship, while monitoring the voltage and current. For the monitoring of the conditions of the submersible pump unit, the flow rate, concentration and pressure are monitored on the ship, whereas pressure monitoring is carried out at both the upstream and downstream sides of the subsea slurry pump unit.

Power supply to the submersible pump unit is carried out using an umbilical cable. The umbilical cable has two motor power supply lines and a single control power supply line (a total of three lines). The motor is supplied with high voltage power that is boosted to 6000 V.

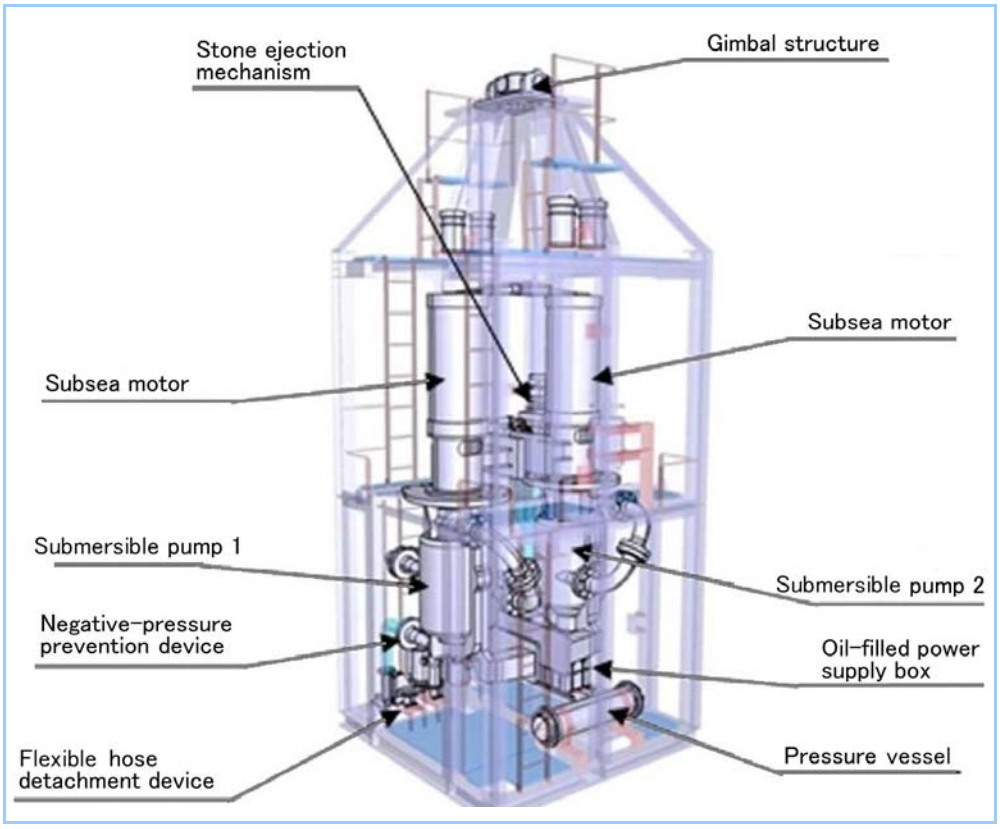

Figure 5 Submersible pump unit configuration
The submersible pump unit mainly consists of the submersible pumps, pressure vessel, stone ejection mechanism, negative-pressure prevention device, and flexible hose detachment device.

4. Pilot test

The pilot test was commenced in mid-August 2017. The ore collecting test machine was on board the marine resource research vessel "Hakurei," while the submersible pump unit was on board the ore lifting support vessel. The two vessels separately navigated toward the waters off Okinawa and rendezvoused at the test location. The test starts with the ore collecting test machine landing on the seabed at the test point (where crushed ore has been piled beforehand) and being connected to the flexible hose coming down from the submersible pump unit, which is followed by the formation of a catenary. After operating the test system using seawater (i.e., without ore) as a preliminary check, the slurry ore lifting test was commenced.

Figure 6 is a photograph of the submersible pump unit. It is mounted on the moon pool hatch cover of the ore lifting support vessel. The hatch cover will slide open to drop the unit in the sea through the moon pool. **Figure 7** shows the process of attaching the flexible hose. While ROV continues to monitor the positioning of the flexible hose, it is adjusted in 10 cm intervals using the dynamic positioning system (DPS) from the ore lifting support vessel. The tip of the flexible hose is moved until it is located directly above the cone of the flexible hose attachment/detachment device of the ore collecting test machine. The flexible hose was thus connected. Floats are also attached to the flexible hose from where it is connected to the ore collecting test machine up to the point approximately 10 m away from it, thereby preventing mutual interference between the flexible hose and the ore collecting test machine.

To collect data, the slurry ore lifting test was conducted by lifting slurry ore for several minutes and repeating about a dozen times. The test started from slurry at a low concentration and was continued by gradually increasing the amount. The concentration at the time of excavation and dredging was primarily controlled through the depth of excavation by the ore collecting test machine. The highest concentration in the ore lifting test was produced by excavating to the depth of 100 mm and approximately 6% was recorded as the average concentration in the riser pipe. Monitoring the γ-ray densitometer, which is mounted on the ore collecting test machine, enables the concentration to be regulated to a certain extent. When a sudden, increased concentration is observed, it can be suppressed by swinging the boom and stopping excavation further down. The γ-ray densitometer of the ore collecting test machine was useful when controlling the concentration.

Figure 6 Submersible pump unit
The submersible pump unit is mounted on the moon pool hatch cover of the ore lifting support vessel.

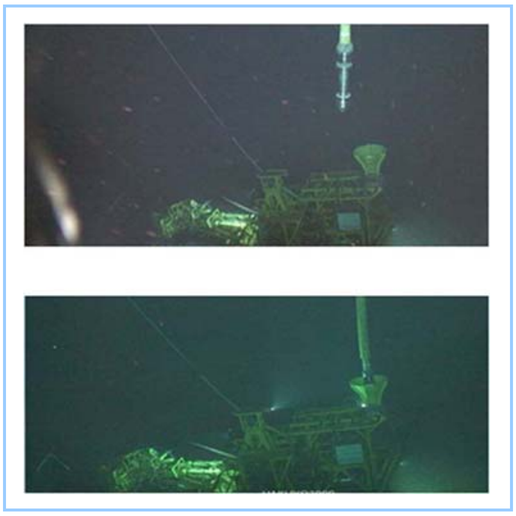

Figure 7 Ore collecting test machine and the flexible hose before and after attachment
The flexible hose was being manipulated by monitoring through ROV to get it closer and attach to the ore collecting test machine on the seabed (above).
Immediately after the flexible hose was successfully attached to the ore collecting test machine on the seabed (below).

Figure 8 is an example of the slurry ore lifting test results. It takes about 7 minutes to raise ore to the ship after being dredged by the ore collecting test machine. During this time, the concentration in the riser pipe increases and the pressure loss in the riser pipe increases. Although the number of rotations of the submersible pump can be controlled either manually or automatically, automatic control has been selected because it is impossible to manually handle load fluctuations during slurry ore lifting. Figure 8 also shows the automatic flow rate control results, which confirms its capability of steadily maintaining the flow rate in the neighborhood of the target level regardless of riser pipe pressure loss fluctuations caused by varying concentrations in the riser pipe. During the ore lifting test, the flow rate was successfully maintained within the approximate range of the target level (140 m^3/h) ± 5 m^3/h.

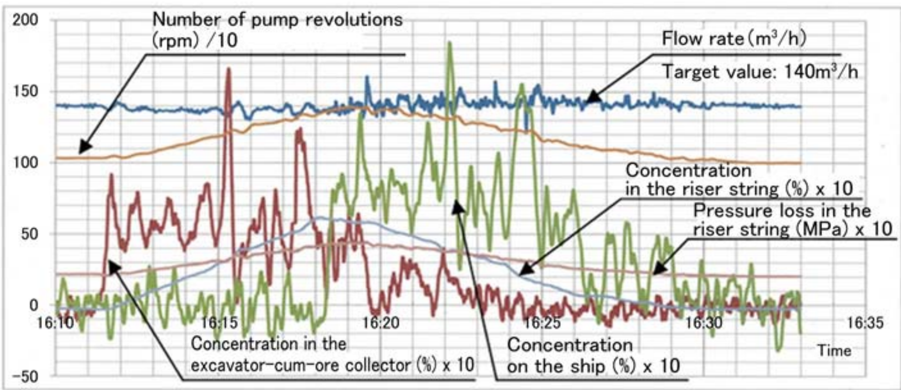

Figure 8 Slurry ore lifting test and automatic flow rate control results
As the slurry concentration changes, the pumping load changes. However, the flow rate was successfully maintained in the neighborhood of the target level by following the load change and automatically adjusting the number of pump revolutions.

5. Conclusion

In the pilot test (conducted between mid-August and late September 2017), continuous slurry ore lifting from seafloor polymetallic sulfide deposits was successfully performed for the first time in the world. A total of approximately 16 t of ore and simulated ore were lifted to the ship. The pilot test provided us with operation data on the submersible pump performance, raiser pipe pressure loss, automatic flow-rate control, etc. Such data has brought us useful knowledge and is valuable for further developing commercial mining systems.

The pilot test was performed by JOGMEC under the commission of the Japanese Ministry of Economy, Trade and Industry (METI). We would like to express our appreciation to those in METI and thank everyone who has taken part in the test.

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