Sea Experiment on Tele-operation System of Underwater Excavator

Tsukasa Kita[a], Taketsugu Hirabayashi[a], Atsushi Ueyama[b], Hiroshi Kinjo[c], Naoki Oshiro[c], and Nobuyuki Kinjo[d]

[a]Frontier technology and engineering Department, Port and Airport Research Institute, Japan
[b]Kyokuto Co., Ltd, Japan
[c] Faculty of Engineering, University of the Ryukyus, Japan
[d]Okinawa General Bureau, Japan
E-mail: mailto:kita-t@p.mpat.go.jp,

Abstract –

We have developed a remote operation support system for underwater excavators and conducted Sea experiments. Underwater excavators have been operated by divers boarding on them. Their main task is levelling rubble mounds of port structures in Okinawa, Japan. However, in recent years, remote control is required due to the decrease in the number of the divers. Therefore, we have been developing tele-operation support system for underwater excavators. This system integrates three elemental technologies such as "Underwater Information Presentation" that serves as a display interface, "Measurement Method of Mound Shape" and "Attachment for levelling works operated with simple input". So far, we conducted elemental tests of each technology underwater and on land to confirm their usefulness.

In this report, we performed experiments using this system in the sea. First, the elemental test of the attachment was performed by boarding operation of divers. The purpose of the attachment is to perform levelling works without difficult input for position adjustments in order to improve the work efficiency of remote operations. The purpose of the tests is to evaluate the performance of the attachment alone. The measurement items are the varies of mound height and the working time. As the results, the attachment was confirmed to be able to submerge the mound and the operability in the sea is the same as that on land. Next, a remote operation test simulating levelling works was conducted to measure the work accuracy and the work efficiency. As the results, by adding a mechanism to move stones to depressions, this system is demonstrated to level the mound from unevenness of ±30 cm to that of ±10 cm. In addition, it is confirmed that the working times with the system depends on the operators' experiences of tele-operations more than that of boarding operations.

From the above, the proposed system is demonstrated to be useful for levelling works of mounds by tele-operated underwater excavators.

Keywords –

Tele-Operation; Underwater Construction; Port Construction;

1 Introduction

Underwater excavators have been adopting for a long time in port constructions in Okinawa, Japan. They are similar in shapes and mechanisms to those on land. However, their hydraulic systems are powered by electric motors. Therefore, they have cables to supply the electric power for the motors from ships. They have been controlled by divers on their cockpits in the sea.

Their main task is levelling works of rubble mounds underlying port structures. They perform the works by pressing the backs of buckets against the mounds or moving stones to depressions (shown in Figure 1).

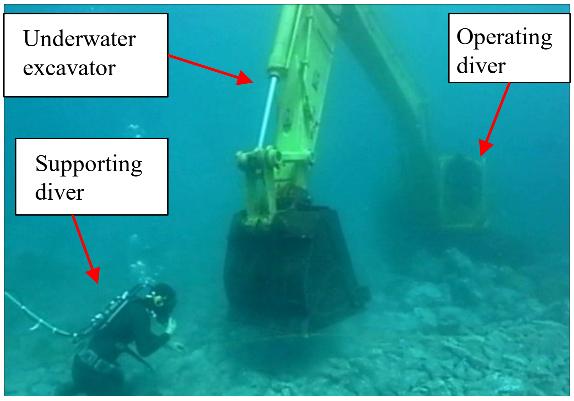

Figure 1. Conventional Levelling work of mound by divers using underwater Excavator

At present, there are two problems. One is that these operations require huge efforts for the safety management. Muddy sea water in construction sites prevents operators from grasping conditions of mounds. Thus, they have to be supported by other divers. The supporting divers change positions of stakes and check unevenness of the mounds. Therefore, they have to stay nearby the vehicles. For this reason, safety checks must be conducted Strictly. Secondary, the work productively is not high due to work suspensions caused by restrictions on dive times or sea conditions. Due to these backgrounds, in order to improve the safety and the efficiently, remote-controlled constructions are required.

Therefore, we have been developing a tele-operating support system for underwater excavators.

2 Tele-operation Support System

An outline of our system is shown in Figure 2.

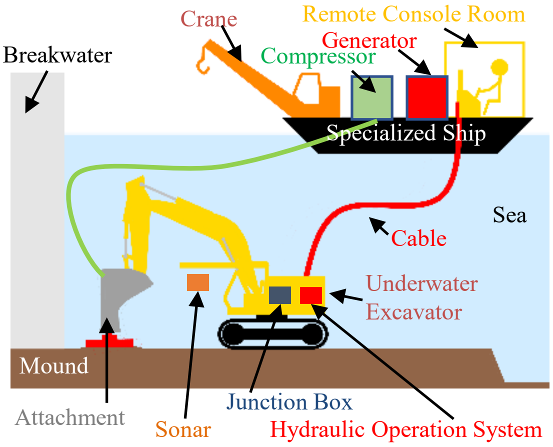

Figure 2. Image of Tele-operation system of underwater excavator

Tele-Operation of underwater excavators is implemented by installing proportional solenoid valves in the pilot hydraulic circuits. Operators use remote consoles on ships, and control the valves by electric signal. Then, the flow rates of the pilot circuits vary and drive the main spool valves. In this way, the flow rates of hydraulic oil are controlled, and operate the hydraulic cylinders.

In addition, we proposed Tele-operation Support System composed of three elemental technologies which are "Underwater information presentation", "Measurement Method of Mound Shape", and "Attachment for levelling works operated with simple input" (shown in Figure 3).

2.1 Underwater Information Presentation

This is an interface that shows work information to remote operators on a ship. It is difficult to visually recognize the position and the orientation of a underwater construction equipment from the ship due to turbidity.

Therefore, the posture of the excavator is calculated with data measured by sensors installed on the vehicle. stroke sensors for cylinders, a gyro sensor, an inclinometer, a geomagnetic compass, a depth gauge, an underwater acoustic positioning device, an encoder etc. are installed (shown in Figure 4).

On the ship, there are a remote console and 3 monitors showing cross-sectional views, bird's-eye views and top views (shown in Figure 5). In addition to them, design information input in advance are also displayed (shown in Figure 6). This allows the operators to work without directly watching the work area in the sea.

So far, an installation test has been performed in actual construction site to verify the robustness of the underwater information presentation alone [1]. In the test, an operating diver ridded on an underwater excavator and performed the conventional levelling work of a mound. The information presentation monitor was installed in the

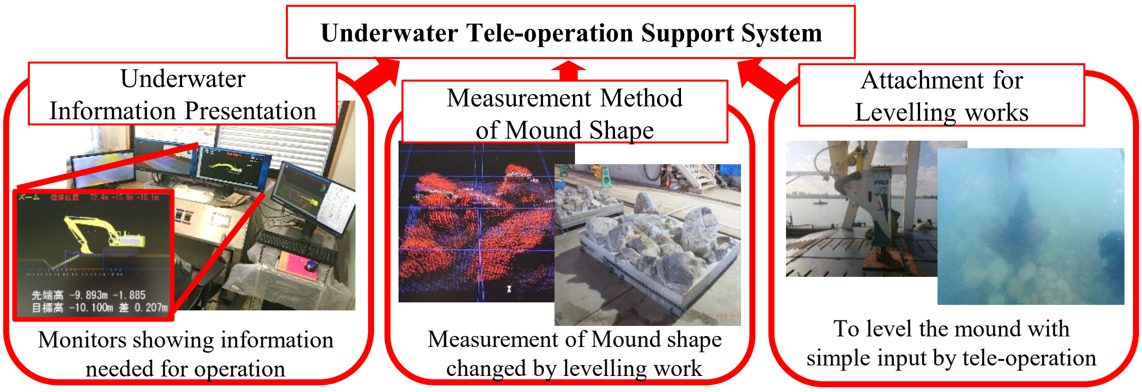

Figure 3. Three elemental technologies for Underwater Tele-operation Support system

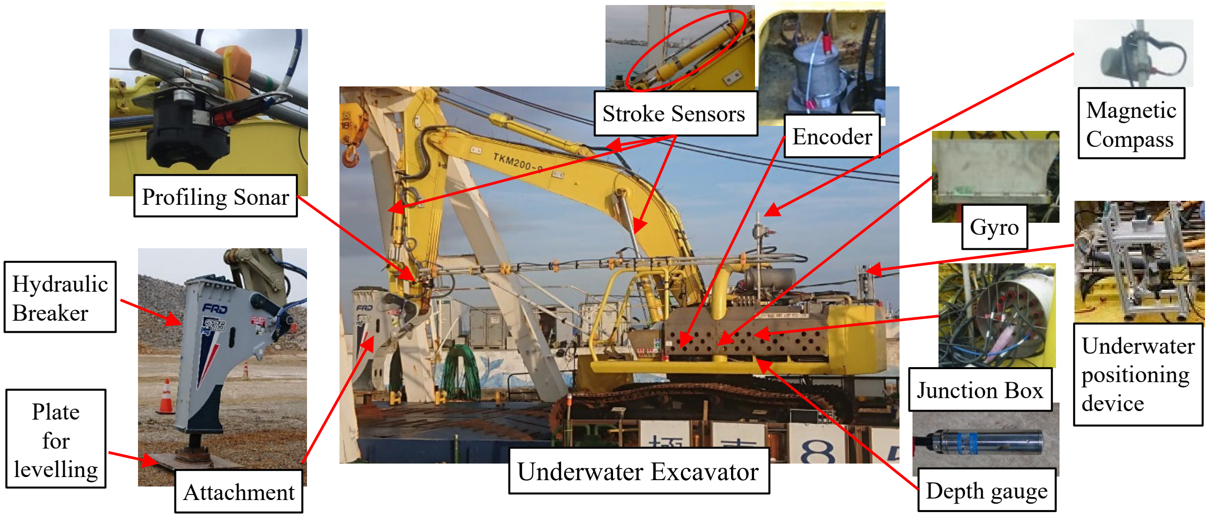

Figure 4. Sensors installed on excavator for underwater information presentation system

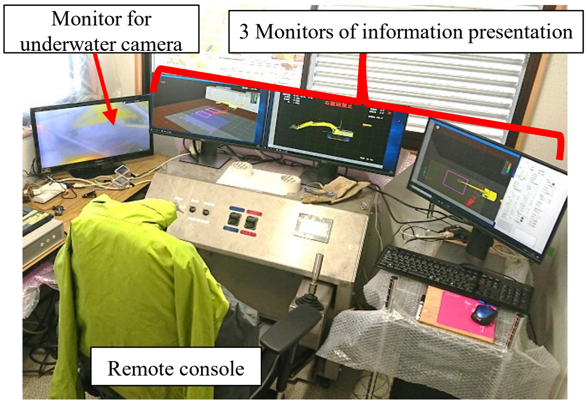

Figure 5. Monitors for underwater information presentation system on remote console room

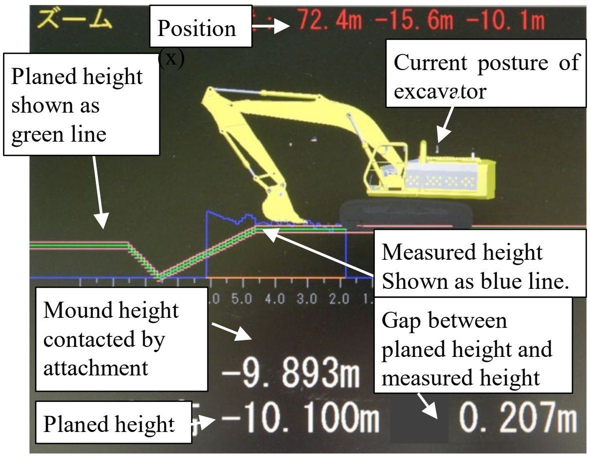

Figure 6. Cross section view of underwater information presentation system in remote console room

cockpit and was used by the diver as a reference for operation. As a result, there was no failure of equipment such as sensors. However, the position measured by the sensor was not correct. The horizontal distance between the ship and the equipment was several meters, but the measured results were often over a hundred meter. This is due to the characteristics of the underwater acoustic positioning system. This system installs a reference station on the ship and a target station on the vehicle. The position is detected by performing triangulation with sound waves between the stations. In this experiment, the sound waves may be blocked by the bubbles from the diver's breathing. Thus, the sound waves may not reach the reference station directly from the target station. At that time, the wave reflected on existing caissons or the seabed may be measured and mistakenly recognized as the direct sound wave. For the reasons, it is considered that the measured values differ from the actual positions. In the experiments conducted in this study, in order to mitigate the effect of bubbles, the installation position of the underwater acoustic positioning system was moved to the rear end of the body.

2.2 Measurement Method of Mound Shape

The height of mounds changes from moment to moment due to the works. Therefore, it is necessary to measure the mound height during the levelling works. We implemented two methods in the system. One is the way using a profiling sonar. Profiling sonars are time-of-flight distance meter using sound waves. Acoustic sensors are less susceptible to turbidity than optical devices such as laser scanners. Therefore, sonars are often used for underwater measurements.

From this measurement, the difference between the mound surface and the target height can be calculated.

The calculation result is shown on the monitors of underwater information presentation and serves as a substitute for the stake. This eliminates the need for the supporting divers to stay in the sea for the staking. This is essential for remote control constructions. In this study, M3 sonar (from Kongsberg Maritime Ltd.) was adopted in consideration of the time required for measurement. The sonar measures the coordinates of 128 points on one cross section up to 40 Hz.

The profiling sonar was installed as shown in Figure 7. The measurements are performed at each time when a certain range end. The sensor was moved with the rotations of the upper part of the excavator to measure the height of the mound surfaces.

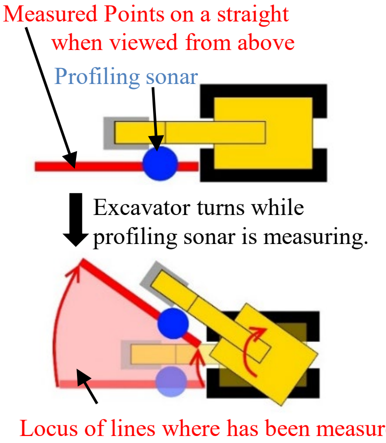

Figure 7. Top view image of position where Profiling sonar installed and the method to measure the height of mound surface

In order to confirm the measurement accuracy, an elemental test was conducted in a water tank [2]. The profiling sonar measured the flat bottom surface of a water tank and mound model in the tank. The mound model was made of rubble stones which are same size as stones of actual rubble mounds in Okinawa, Japan.

As the result, it was apparent that it is possible to recognize the shape of the bottom surface. However, we cannot grasp the contour shape of each stone. This is because the gap between stones could not be measured accurately. In addition, it cannot measure the height under the tip of the arm. Therefore, we cannot judge the completion whether the pressed points get within the acceptable hight. Hence, we examined another way to measure the mound height.

Another method for measuring the height of mounds is to measure by contacting the tip of arms of excavators against mounds. When the attachment is pressed against mounds, the height of the tip calculated by the information presentation system is same as the mound height. It has been shown from the results of previous experiments that this method can measure the mound height with an average error of 31 mm. However, this method can measure only one point in one measurement. Hence, it is not suitable for surface measurement. Therefore, we use the two measurement methods properly depends on the purpose.

2.3 Attachment for levelling work operated with simple input

For the purpose of improving the work efficiency, we examined an attachment that can level mounds without delicate input based on detailed topographic information.

So far, a remote operation test was conducted with a combination of elemental technologies which are "Underwater Information Presentation" and "Measurement Method of Mound Shape". In the test, a stone placed on a flat floor was grasped with a fork grab and moved to a predetermined place. we evaluated the working time depends on the observation method. As a result, it takes 1.8 times longer to perform the work with the profiling sonar, compared with the case of directly visual observation on land. It is considered because the contour of the stone is unclear, and it takes time to perform the operation of positioning for gripping. Therefore, we developed "attachment operated with simple input" for the purpose of improving the work efficiency.

In this system, we proposed a mechanism to attach a plate to the tip of a hydraulic breaker (shown in Figure 4). Not only the static load of the machine, but also the dynamic load of a breaker pushes down protuberances of mounds to perform levelling works. On the other hand, this attachment does not have the ability to raise the lower part than the plan.

An element test was conducted on this device to perform levelling works on a rubble mound installed in the air, to confirm its performance [3]. As a result, it was revealed that the attachment has an ability to level to bring down to the target height from +30cm height.

In addition, we conducted element tests of the proposed attachment in the sea. The purpose of the experiments was to confirm whether the attachment has the ability to level the mound in the sea and the time required for the work. The experiments were carried out at a rubble mound in Hirara Port in Okinawa, Japan. The top surface had a water depth of about 5 m, and unevenness of ±30 cm.

In the experiment, the attachment was equipped on an underwater excavator TKM200-9 (owned by Kyokuto Co., Ltd) whose operating mass is about 20 tons. A diver boarded on and operated it. The diver had experience of controlling underwater excavators in normal tasks. The work was done according to the instructions of an assistant diver.

The attachment banged the mound for 5 seconds and paused. Then, we measured the mound height. We alternated 5 seconds of beating and measuring for 6 times at the same point. As a result, it was shown that the mound surface could sink 11 cm in 5 seconds and 25 cm in 30 seconds.

In addition, an experiment simulating a continuously work in a range of 2m x 5m was also conducted. In this experiment, we could not recognize the height because we did not stake. Hence, the time for each impact was fixed at 5 seconds. The assisting diver instructed the banging position and the posture of the front part (arm, boom and bucket cylinder). As the result, the working time was the same as the land test if supporting divers guided them. It was confirmed that no deterioration in operability in the sea due to the attachment was observed.

3 Performance test of the remote-control support system in the sea

In order to examine the performance of the remote-control support system, performance tests were conducted in the sea (shown in Figure 8). The experiment was carried out at a caisson mound at Hirara Port. The top is about 8.7m deep. The working areas were 5m x 7m areas on the top of the mound. In the initial state, the top of the mound had unevenness of about ±30cm from the target height. The target of the works is to level unevenness within ±10 cm in the working area.

In the levelling works, the attachment banged a point of the mound until the height gets within the acceptable height. The operator confirmed the completion by watching the cross-sectional view showing the hight of the tip of the attachment contacting with the mound. After that, the attachment was moved to another unlevelled point. The layout is shown in Figure 9. The work procedure is shown in Figure 10.

Figure 8. Captures of sea experiments (left figure; Excavator craned into the sea, right figure; Excavator working without divers on cockpit)

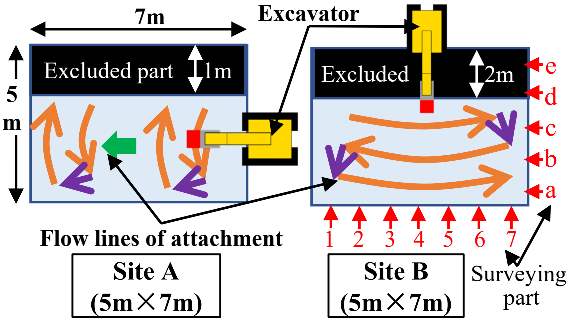

Figure 9. Layout of levelling tests of Site A (left figure) and Site B (right figure)

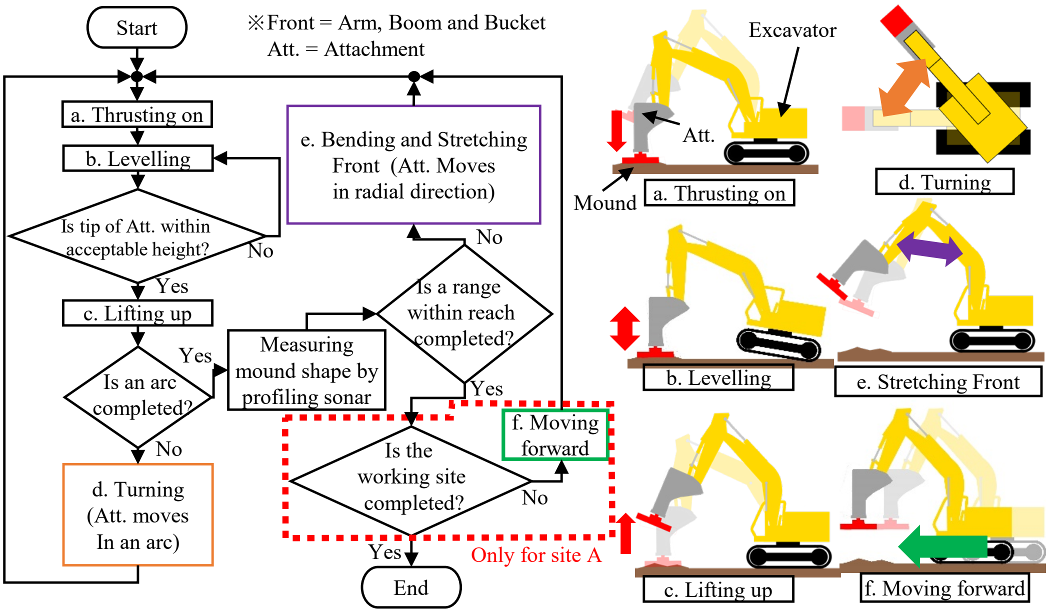

Figure 10. Procedure of levelling tests of mound using tele-operated underwater excavator

The right part of Site A was over 30cm higher than the target height in the initial state. Therefore, it was not possible to make it sink to the target height with the attachment. Therefore, the range was excluded from the evaluation of the work efficiency. On site B, a range in front of the vehicle was excluded from the evaluation. This is because it was out of the working range of the arm.

In Site A, the test is performed by an operator who is an underwater excavator operator and has no remote-control experience. On the other hand, an operator on Site B is not an operator boarding on underwater excavators, but has experiences of remote operations.

3.1 Accuracy of Mound Height

From the results, we assessed the accuracy of the mound height after the works. Before and after the experiment, the mound height was measured by divers using an underwater levelling instrument (shown in Figure 11). Figure 12 and Table 1 show the hight of the Site A after the test. The grey cells in the table are the excluded part. As the results, some points that were higher than the acceptable range remained. The point in yellow circle in Figure 12 is because the initial height was +40 cm from the target. Thus, the attachment could not enough subduct. The part shown in the red circle is because the operator did not bang there due to misunderstanding that it was out of the working range.

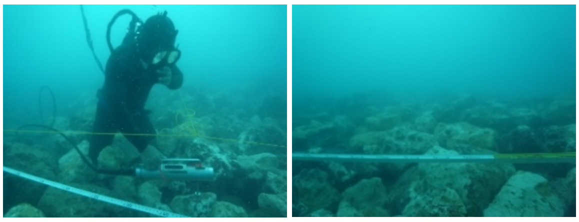

Figure 11. Captures of measurements before (left figure) and after (right figure) experiments

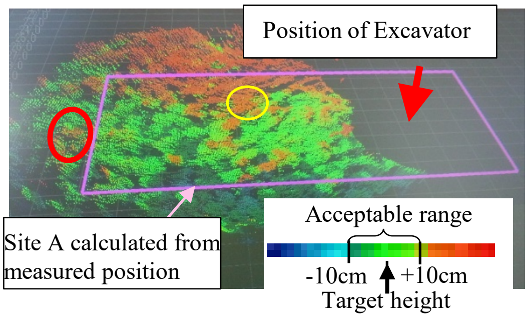

Figure 12. Bird-view of the Site A after experiment shown on monitor of “Underwater Information Presentation”

Table 1. Unevenness from target height surveyed after experiment on Site A

Height [cm]	7	6	5	4	3	2	1
e	23	12	22	21	8	20	25
d	19	10	6	20	5	-2	7
c	14	7	2	-5	-5	6	7
b	2	10	2	4	-3	5	10
a	1	-2	6	-9	9	0	5

The misunderstanding was caused by the measurement error of the horizontal position of the vehicle. That can be dealt with by setting a larger construction range.

In addition, the average height is 0.03m higher than the planed height and the deviation σ was calculated to 0.05m excluding the points in the red and yellow circles. If the mound shape after the work has a normal distribution, 68 % of the mound is within 1σ (-0.02m to +0.08m) in height and 95% of that is within 2σ (-0.07m to +0.13m).

On Site B, 3 survey points were measured -10cm or lower than the planed height. Table 2,3 show the measured height by divers before and after the experiments. Figure 13 shows that measured by the profiling sonar.

The points in black circle in Figure 13 are a missing measurement. The initial height is so low that the sonar cannot measure it hiding behind the rock in front. The points in yellow circles are considered to be the result of striking too much.

Table 2. Unevenness from target height surveyed before experiment on Site B

Height [cm]	7	6	5	4	3	2	1
e	17	30	5	13	28	18	42
d	-6	62	52	32	18	24	22
c	32	31	38	13	38	6	-18
b	-6	35	36	-1	13	33	27
a	-4	24	11	38	21	29	42

Table 3. Unevenness from target height surveyed after experiment on Site B

Height [cm]	7	6	5	4	3	2	1
e	17	34	21	11	30	16	27
d	-11	38	42	29	18	22	5
c	-12	1	-3	6	-1	-10	-17
b	-18	0	0	-2	-15	-5	-1
a	-9	-6	-2	0	-8	2	-2

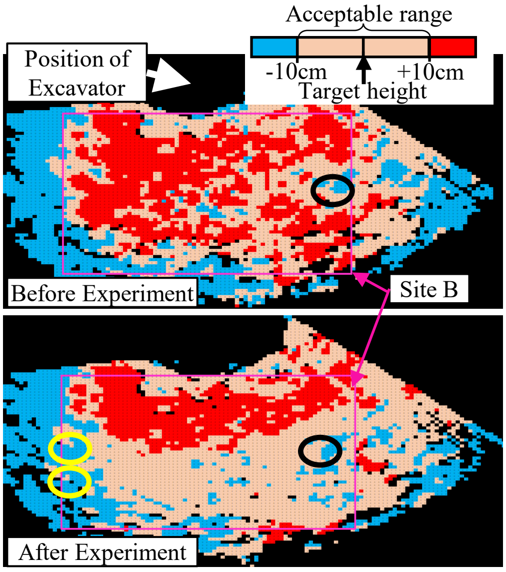

Figure 13. Top view of mound height on Site B measured by profiling sonar before (the upper) and after (the lower) experiment

Since the attachment has only a mechanism that depresses mounds by vibrations, it is necessary to install another function that raises depressions. If the out-of-range points are excluded, the average height is 0.02 m lower than the planed height and the deviation σ is 0.04 m. It means that 95% of the mound is within the range of -0.09 m to +0.05 m in height.

From the results, by taking above measures, underwater excavators with the tele-operation support system seems to have enough performance to level the unevenness of the mounds within ±10 cm from that within ±30 cm.

3.2 Working time

We investigated the work efficiency of the remote operation. The working times in the tests were decomposed into that of each input action. The working time was analysed from the video movie which recorded in the remote-control room on the ship. Figure 14 shows the working times of each items to level one point off.

In the experiment on Site A, the working time was 44 minutes 33 seconds for the work area of about 28 square meters. There are 34 points banged by the attachment, and 0.82 square meters are levelled once.

Site B had the work range of about 21 square meters and had a work time of 20 minutes 39 seconds. The number of banged points is 29, which averages 0.72 square meters.

As the results, the working times of A were longer than that of B in all items. It is considered that the effect of "training for tele-operation" is larger than that of "training of operation of underwater excavators itself". This difference is considered to be due to the fact that the operator engaged in remote operations had empirically predicted and recognized the movement of the equipment with respect to the lever input amount.

In addition, we compared the working time of the boarding-operating work with the supporting diver written in Section2.3. The working times to level depend more strongly on the conditions of the mounds than on the operation method. Therefore, the times of levelling were not taken into account to compare them. Tele-operation support system with highly trained operators was demonstrated to be able to increase the efficiency of the levelling works.

The tele-operating works by operators with great experience of tele-operation is faster than the boarding-operating works in the tests.

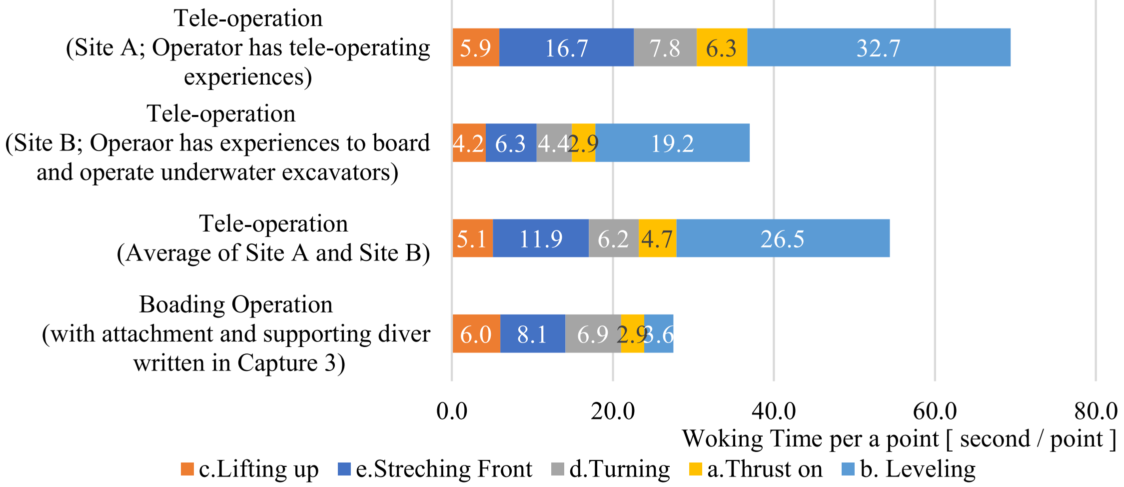

Figure .14 Working times of levelling works using underwater excavator

4 Conclusion

In order to improve the safety and the productivity of underwater constructions, we conducted the study and the sea experiments on remote operation of the underwater excavators.

We proposed a remote operation support system made up of the three elemental technologies. The elemental technologies are ”Underwater Information Presentation,” "Measurement Method of Mound Shape" and "Attachment for levelling works operated with simple input".

In order to assess the performance of the remote-control support system, we conducted the sea experiments simulating the levelling works on the mounds in the sea. The results are shown below.

- The proposed attachment has the ability to level the unevenness of rubble mounds in the sea. The performance to depress mound height was 11 cm in 5 seconds, and 25 cm in 30 seconds.
- Turbidity caused by the attachment is not more terrible than that of conventional works.
- For 28 survey points on Site A, there were 3 points of +10cm or higher than the planed height. Taking measures that set larger work ranges than the target may get rid of the remaining caused by the error of measured position of the vehicle.
- On Site A, the average height was 0.03m higher than the planed height and the deviation σ was calculated to 0.05m without exceptional points.
- For 21 survey points on Site B, there were 3 points of -10 cm or lower than the planed height. It is necessary to add another mechanism to move stones to places whose height are low.
- Excluding exceptional points, the average height after the tests on Site B was 0.02 m lower than the planed height and the deviation σ was 0.04 m.
- Working time was 65 minutes 12 seconds for the total work area of about 49 square meters, which was 45.1 square meters per unit time.
- When the operator with remote-operating experiences performed the simulating task with remote-operating system, the working time is shorter than that performed by the operator with the conventional boarding work. The work efficiency by remote-control is considered to depend on the skill level of the operator.
- By improving the attachment, remote-operated excavators are demonstrated to be able to level unevenness of the top surface of mounds within ±10 cm in the sea.

As the next step, we plan to study and sea experiments on an attachment to move stones into lower place than planed mound.

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