USE OF UAVS IN RESIDUAL DISPLACEMENT MEASUREMENT FOR MOORING FACILITIES AFTER EARTHQUAKE

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Abstract

Because mooring facilities are used as a base for transporting relief supplies and personnel in the event of an earthquake, it is necessary to assess the damage to such facilities and judge whether they can be used as soon as possible. In the case of a tsunami after an earthquake, such as the 2011 Tohoku Earthquake, the damage was so extensive that the facility could not be entered until the warning was lifted. The use of unmanned aerial vehicles (UAVs) is considered useful in the initial investigation of such disasters, and UAVs have been used in recent earthquakes and heavy rainfall disasters in Japan and abroad. Although UAVs are typically used for inspections in post-earthquake investigations using on-board cameras, image processing can also be applied to evaluate the displacement of facilities after an earthquake by calculating the difference between the embedded coordinate values of photographs before and after the event. The accuracy of UAV photogrammetry varies significantly depending on various conditions such as the type of UAV and camera, flight and photographic conditions, and the location and shape of the target facility of interest. Therefore, the authors conducted a field test at a port facility to confirm the accuracy of the displacement measurement through UAV photogrammetry and to extract problems in the measurement. The results show that UAV photogrammetry can be used to measure the displacement of a mooring facility on the centimeter scale, even from 120 m above the ground, if the image processing is corrected by the reference points.

In this study, the applicability and accuracy of UAV photogrammetry to measure the residual displacement to determine the availability of the mooring facilities after an earthquake were investigated. In coastal areas where many mooring facilities are located, a liquefaction-induced ground flow may occur during a large earthquake, and the reference points for a UAV photographic correction may move and therefore cannot be used after an earthquake. In a situation in which reference points are unavailable, the measurement error of the UAV photogrammetry is large and a quantitative displacement measurement is difficult. In real-time kinematic (RTK) positioning, which can be used to evaluate the relative distance from the reference station, the ground displacement of the mobile station can be evaluated by placing the reference station in a structure where no ground displacement occurs. It was found that the use of a UAV with an RTK positioning available increases the accuracy of the coordinate measurements, with a maximum error of 6.5 cm, even without a correction using the reference point in the image processing. This means that even if the ground is displaced by an earthquake and the reference point is unavailable, the displacement of the facility can be measured. In addition, in principle, RTK positioning can be used to ignore the crustal deformations generated by large earthquakes, making it suitable for post-earthquake residual displacement measurements.

Keywords: mooring facility, earthquake damage, unmanned aerial vehicle, global navigation satellite system

1. Introduction

The author's research group has developed *Berth Surveyor*,[1] a tool to help achieve a quick determination of the availability of mooring facilities to use them for the transport of emergency supplies and personnel for rescue activities by ships after an earthquake. This tool uses the Real Time Kinematic-Global Navigation Satellite System (RTK-GNSS), hereafter referred to as RTK positioning, which is a satellite positioning system that sends positioning information from GNSS at a reference station to a measurement point as correction information, and uses such information to correct errors at the measurement point. The accuracy of the coordinate measurement when applying this method is approximately 1–2 cm. The equipment necessary for the measurement can be installed after a disaster, and the power source can be a generator or a battery, and thus even in the event of a disaster, the amount of displacement necessary for determining the availability of the facility can be measured with high accuracy without being affected by a blackout or interruptions in the communication facilities. However, in the event of a large-scale earthquake and tsunami, the area affected by the disaster is extensive, and it becomes impossible to enter the facilities when a tsunami warning is issued. Therefore, the use of unmanned aerial vehicles (UAVs) is expected as an efficient survey method.

In this study, as a method for evaluating the residual displacement during an earthquake, a method using images photographed by a UAV is discussed. With this method, three-dimensional point group data containing the coordinate information is created through the processing of images photographed by UAVs before and after an earthquake, and the amount of displacement is calculated from the difference in the positional coordinates of the target facility before and after the event. In such a survey method using images photographed by UAVs, the accuracy varies significantly depending on various conditions such as the type of aircraft and camera, flight and photographic conditions, and the location and shape of the target facility. Therefore, an on-site field experiment was conducted on a mooring facility to confirm the accuracy of the displacement measurement method and to understand the issues involved in the measurement, assuming that the UAV can be used to measure the displacement quickly and efficiently after a disaster. During the experiment, a device that simulates the displacement of a quaywall (hereinafter referred to as the quaywall model) was installed at the mooring facility to simulate the measurement conditions close to the actual disaster situation, and the residual displacement during the earthquake was simulated by moving the model. In addition, the constraints and measurement accuracy during the disaster are discussed, including the assumption that reference points that have been measured before the earthquake are moved and cannot be used after the earthquake.

2. Experimental conditions

2.1 Measurement equipment

Two types of UAVs were used with different flight methods: a rotary-wing and a fixed-wing, as shown in Table 1. In addition to the differences in flight methods, the major difference is the presence or absence of RTK positioning. In this study, a fixed-wing UAV capable of RTK positioning was used for the survey to confirm the usefulness of RTK positioning. To compare the accuracy of the displacement measurement, a direct measurement method with a GNSS receiver capable of RTK positioning (hereinafter referred to as RTK-GNSS) was also used (Photograph 1).

2.2 Installation of quaywall models

Five models of the quaywall made of wood veneer were set up in parallel to simulate the residual displacement of the quaywall (Photograph 2 and Fig. 1). To simulate different displacements caused by an earthquake during this experiment, each model was set to displacements of 5, 10, 20, 50, and 16 cm horizontally and vertically, and moved by a prescribed amount of displacement while being measured with a measuring tape.

Table 1 – UAV information and survey results

Name Product name	Rotary-wing UAV Phantom 4 Pro		Fixed-wing UAV eBee RTK	
Appearance				
Information of UAV				
RTK positioning	No		Yes	
Weight [kg] (including camera)	1.39		0.73	
Camera model	1 inch 20 MP (Standard)		18.2 MP (Sony WX)	
Camera orientation	Directly below		Directly below	
Gimbal	Yes		No	
Maximum length [cm]	35 (excluding propeller)		96 (Wingspan)	
Survey results				
Photography timing before or after moving	Before	After	Before	After
Flight height [m] (height to the ground)	100	100	120	120
Overlap rate [%]	90	90	75	75
Side lap rate [%]	60	60	80	80
Number of images photographed [images]	159	159	103	109
Flight Duration [min]	7	7	19	17

Photograph 1 – Survey using RTK-GNSS method with GNSS reciever. Coordinates are measured at the center of the anti-aircraft sign on the quaywall model.

Photograph 2 – Installation of the model of quaywall (after moving). The prescribed displacements of the model are 5, 10, 20, and 50 cm horizontally and 16 cm vertically from the front.

The on-site field experiment was conducted at Tsuruga Port in Shiga Prefecture, Japan. A 230-m long berth was targeted for the survey, and the models of the quaywall were installed in a part of the berth, and the displacement was evaluated at the position of the models (Figs. 1 and 2). Images were photographed by the UAVs before and after the models were moved a prescribed amount, and the difference in coordinate values before and after the movement was defined as the amount of displacement. The RTK-GNSS, which has a

measurement accuracy of approximately 1–2 cm, was used to measure the center of the anti-aircraft sign on the model, to compare the accuracy with that of the UAV. The UAV was flown automatically, and a flight altitude of over 100 m was set as a problem-free flight condition, considering the height of the cargo-handling equipment at the neighbor berth and buildings within the vicinity, and the measurement condition was set to cover a wide area of multiple berths in one flight.

2.3 Reference station for RTK positioning

For the RTK-GNSS, the reference station was set at a distance of 2.3 km from the quaywall, assuming an actual operation, as shown in Fig. 1. Because the RTK-GNSS evaluates the relative distance between the reference and the measurement points, the effect of the crustal movement can be eliminated from the measured values if the amount of crustal movement that occurs during a large earthquake is the same for both points. In other words, if the displacement is evaluated from the comparison of the coordinates before and after the earthquake, the crustal movement will be included, and the amount of residual displacement necessary for determining of the availability of the facilities cannot be evaluated. The UAV equipped with RTK positioning (fixed-wing type) used the same reference station as the RTK-GNSS.

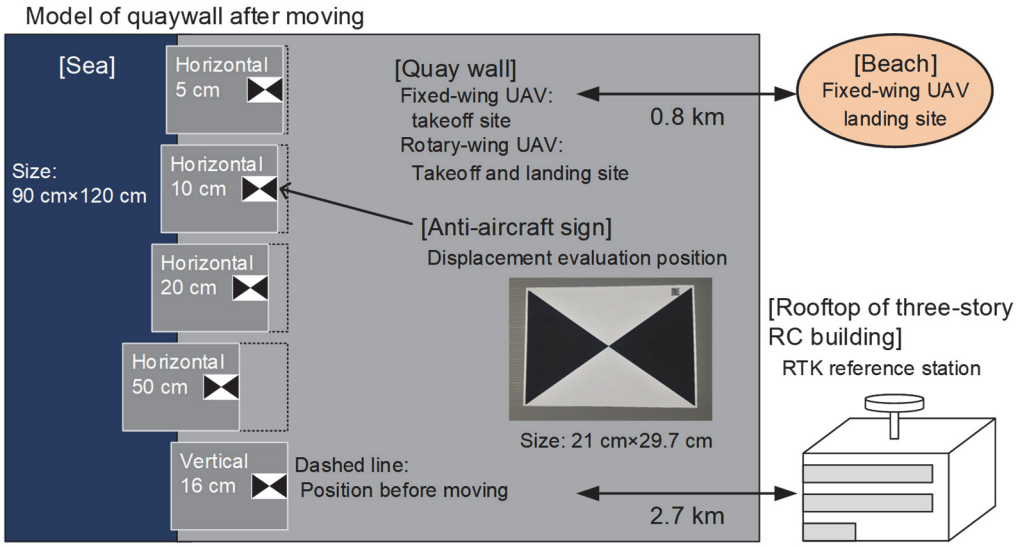


Fig. 1 – Schematic diagram of quaywall model

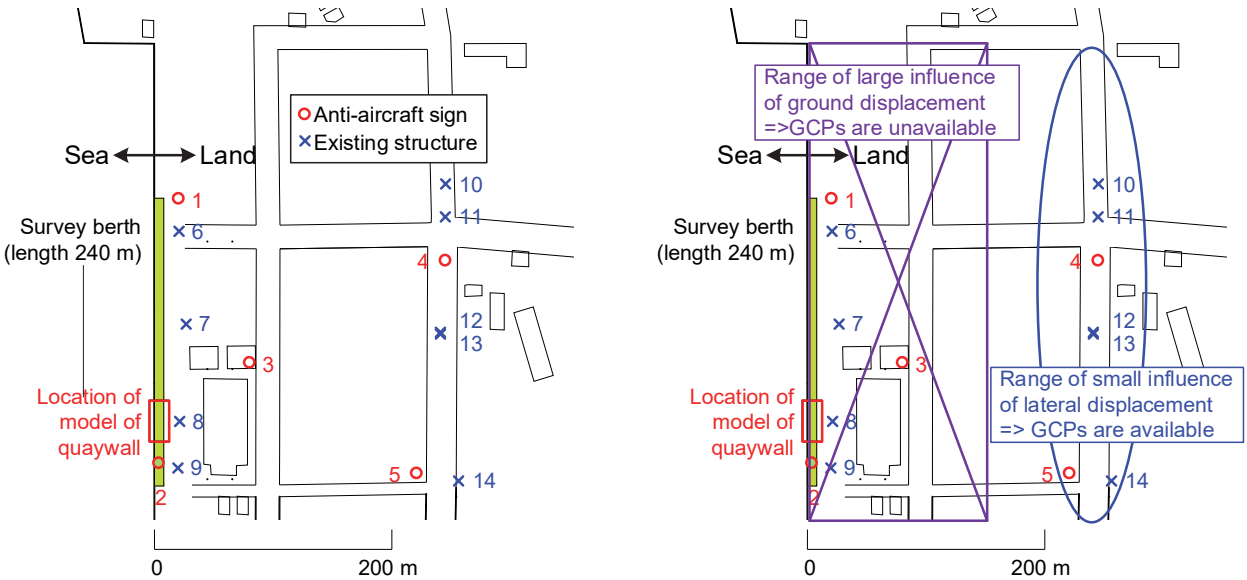


Fig. 2 – Location of quaywall model and GCPs (left) and restriction of GCP use after earthquake (right)

2.4 Restriction of GCP use

In the image processing for creating three-dimensional point group data necessary to obtain the coordinates of the facility, it is necessary to set the ground control points (GCPs) for correction as the known coordinate points. In the manual[2] of public surveying using UAVs, the basic rule is that GCPs should be arranged to surround the measurement object; however, it was difficult to arrange GCPs around the quaywall because it is located on a waterfront. However, it was found that the accuracy of the displacement measurement could be ensured by placing GCPs on the four sides of the photographic area[3].

Fig. 3 shows the relationship between the distance from the waterfront and the horizontal displacement at Port Island during the 1995 Hyogoken-nanbu Earthquake. This displacement distribution was obtained by measuring the widths of the cracks on the ground surface and adding them together. In addition, horizontal displacements of more than 2 m occurred at the quaywall, and the displacements of most of the measuring lines converged at a constant point 150 m from the waterfront. It is clear that when soil liquefaction occurs in reclaimed land, the displacement of the quaywall will affect the area several hundred meters away.

In the case of a large-scale earthquake, the GCPs behind the quaywall are unlikely to be available owing to a ground displacement. When GCPs are moved, it is necessary to measure their coordinates after the earthquake, but it is difficult to enter the site for a coordinate measurement owing to the issuance of a tsunami warning. For the range of influence of the ground displacement, referring to the case of Kobe Port (Fig. 3), if the ground is displaced within a range of 150 m from the waterfront, the GCP on the landward, which is located more than 200 m from the waterfront, will not move. Therefore, it is assumed that only the GCP on the landward side can be used after an earthquake (Fig. 2).

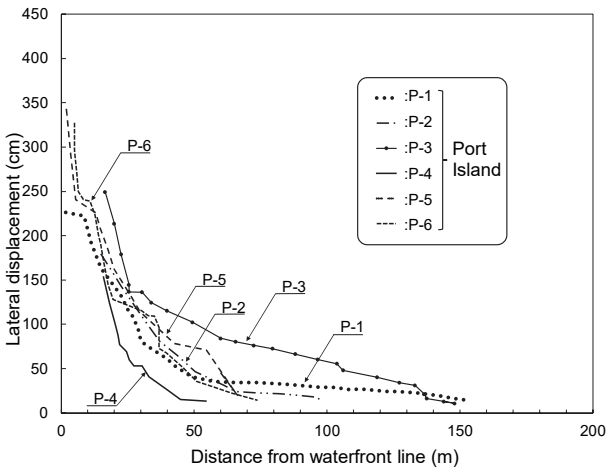


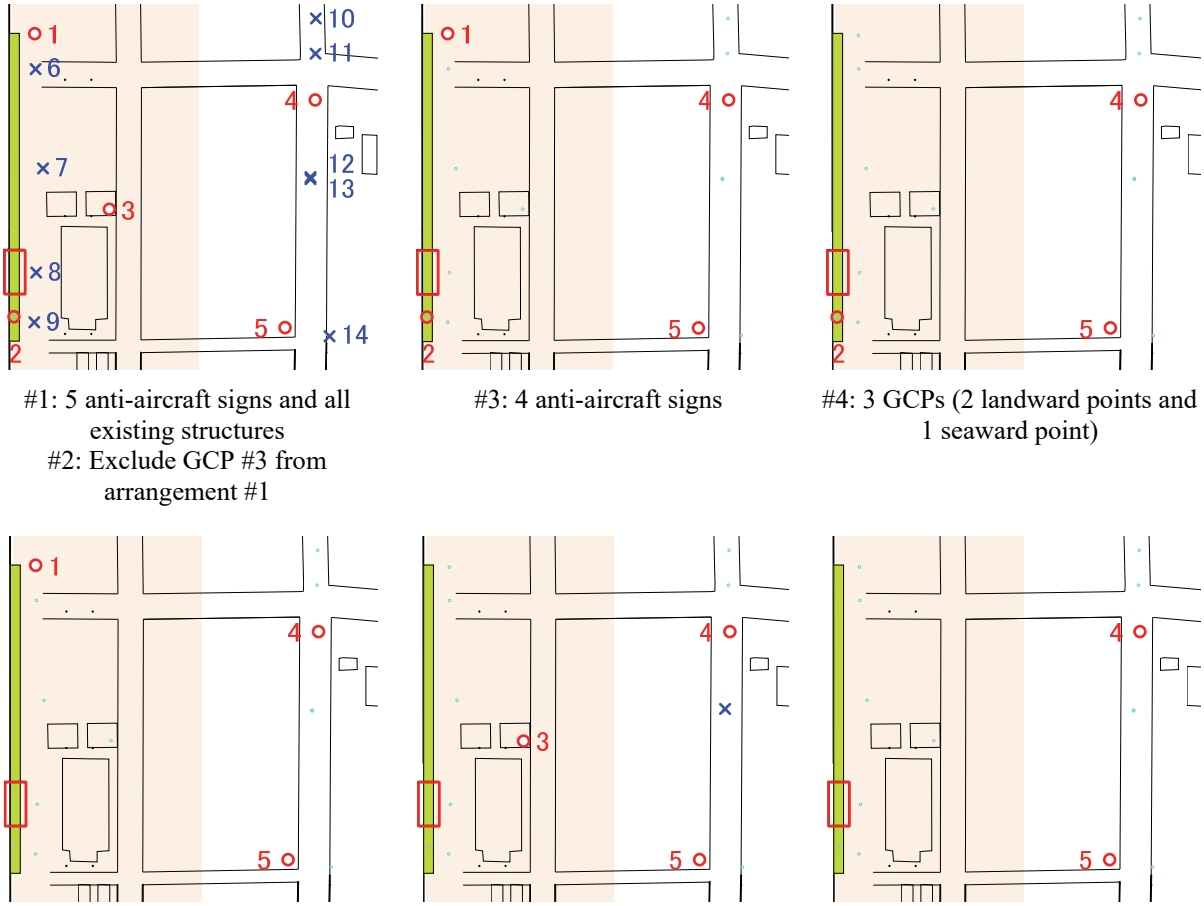
Fig. 3 – Distribution of lateral displacement behind the quaywall[4]

2.5 GCP arrangement

Fig. 4 shows the list of GCP arrangements set during the image processing. In this study, in addition to the anti-aircraft sign, parts of the existing structures were used for the GCP. Many different GCP arrangements were considered added to the two GCPs on the landward that can be available at the time of disaster (arrangement #7). The case of no GCP was set because it was unclear whether image processing was possible without GCPs and whether accuracy could can be ensured after an earthquake. In addition, a fixed-wing UAV capable of RTK positioning can ensure a high measurement accuracy for photographic coordinates without setting the GCP, and thus it was used to confirm whether RTK positioning is advantageous during a disaster. Arrangements #1 and #2 use almost all of the measured GCPs, and are compared with arrangement #3, which is installed only in the four corners of the photography range.

As described below, the image processing of only two points on the landward side, which is assumed to be after a disaster (arrangement #7), resulted in poor orthoimage quality and an inability to identify the coordinate evaluation position, and even when it could be identified, the displacement was on the order of

meters. Therefore, in addition to the two points on the landward side, one additional point was added on the seaward side to create a three-point GCP configuration (arrangements #4, #5, and #6). These three cases with three GCPs are different in terms of the distance between one GCP on the seaward side and the model of the quaywall. These cases correspond to the case in which a person enters the facility at the time of disaster and measures the coordinates of one GCP point, or where a single GCP point is set on a substantial structure that is unaffected by ground displacement, although this is not a realistic condition.



#1: 5 anti-aircraft signs and all existing structures
#2: Exclude GCP #3 from arrangement #1

#3: 4 anti-aircraft signs

#4: 3 GCPs (2 landward points and 1 seaward point)

#5: 3 GCPs (2 landward points and 1 seaward point)

#6: 3 GCPs (2 landward points and 1 seaward point)

#7: 2 GCPs (2 landward points)

Fig. 4 – Arrangement of GCPs for image processing

2.6 Study case setting

The study cases with different combinations of UAV type, RTK positioning, and GCP arrangement were set as shown in Table 2. The contents of the study are divided into three parts, and the focus points of the study are shown below.

(1) Part 1: Combination of GCP and RTK positioning effects

In this part, the effect of the combination of GCP and RTK positioning will be checked. Case 1-2 is the basic condition of the UAV photography, and where a GCP is used to correct the data. Case 1-3 is the case of RTK positioning without a GCP, and the measurement accuracy is checked by setting the suitable condition for the actual disaster.

(2) Part 2: GCP arrangement

In this part, the effects of the GCP arrangement are compared. Although Case 2-6 with two landward points is the only GCP arrangement that can be applied to a disaster, we compare various cases to confirm the effects of the GCP arrangement on the accuracy.

(3) Part 3: Different GCP arrangements before and after the earthquake

It is assumed that all GCPs are available before the earthquake and that the use of GCPs is restricted only after the earthquake. The coordinates of GCP arrangement #2 with all GCPs are used before the earthquake, and the coordinates based on the GCP arrangement of each study case after the earthquake are applied to check the measurement accuracy when different GCPs are used before and after the earthquake.

In the same table, the applicability to an earthquake was evaluated to see if the conditions were set effectively for the ground displacement and crustal movement during the earthquake. In other words, it does not evaluate the measurement accuracy. Only Cases 1-1 and 1-3, which are unaffected by the ground displacement and crustal movement because they do not use any GCPs, were ranked as A. Next, Cases 2-6 and 3-6, which use only two GCPs on the landward side, were ranked as B because these cases are unaffected by ground displacement. The other cases were ranked as C because the GCPs at the seaward side moved during the earthquake and could not be used after the earthquake.

Table 2 – List of study cases

Study number	Case name	Type of UAV	RTK positioning	Arrangement number of GCP		Applicability rank**
				Before	After	
1	Case 1-1	Rotary-wing	No	None		A
	Case 1-2	Rotary-wing	No	1		C
	Case 1-3	Fixed-wing	Yes	None		A
	Case 1-4	Fixed-wing	Yes	1		C
2	Case 2-1	Rotary-wing	No	2		C
	Case 2-2	Rotary-wing	No	3		C
	Case 2-3	Rotary-wing	No	4		C
	Case 2-4	Rotary-wing	No	5		C
	Case 2-5	Rotary-wing	No	6		C
	Case 2-6	Rotary-wing	No	7		B
3	Case 3-1*	Rotary-wing	No	2	2	C
	Case 3-2	Rotary-wing	No	2	3	C
	Case 3-3	Rotary-wing	No	2	4	C
	Case 3-4	Rotary-wing	No	2	5	C
	Case 3-5	Rotary-wing	No	2	6	C
	Case 3-6	Rotary-wing	No	2	7	B

* Same as in Case 2-1
** Applicability rank (applicability to post-earthquake surveys)
A: No need for GCP. Results are unaffected by lateral displacement and crustal movement.
B: Only GCPs 200 m away from the waterfront are used. Results are unaffected by ground displacement, but affected by crustal movement.
C: Results are affected by ground displacement and crustal movement after the earthquake because of the use of GCPs.

3. Experimental results and discussion

3.1 Evaluation of displacement

The difference between the coordinate values of the quaywall model before and after the earthquake extracted by the image processing is called the amount of displacement. Because the quaywall model was moved by a prescribed amount of displacement while measuring with a tape measure, the actual amount of movement of the model and the target value (prescribed amount of displacement) are considered to differ by

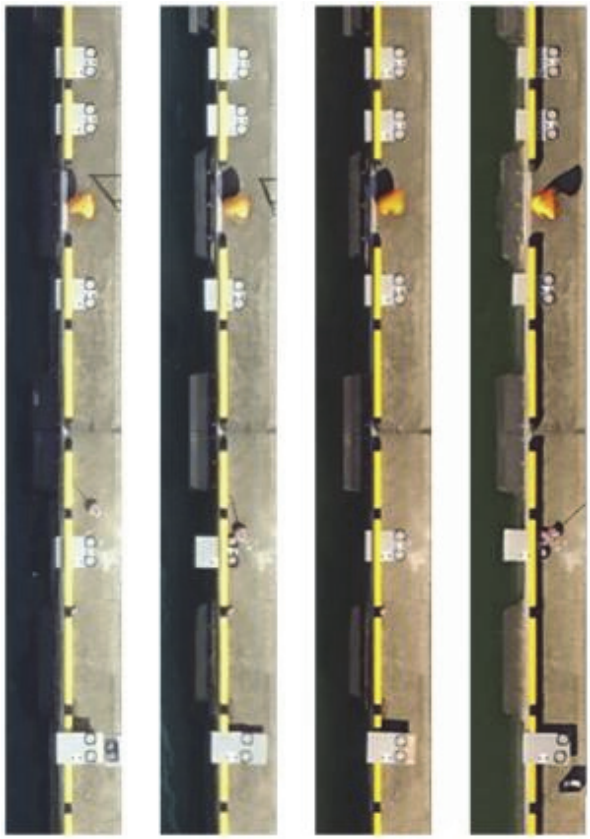
millimeters. To evaluate the accuracy of the measurement, the difference value between the measured displacement in each model and the prescribed displacement is defined as the displacement difference. Next, the absolute maximum value of the displacement difference in each case is defined as the error. The error is then compared between cases, and a smaller error is expressed as having high accuracy. In this study, only the horizontal displacements that are highly correlated with the degree of damage to the quaywall are evaluated.

3.2 Image processing

More than 100 images photographed by the UAVs (Table 1) were applied for the image processing using Pix4Dmapper software[5] to produce the orthoimages and a digital surface model (hereinafter referred to as DSM), as shown in Figs. 5 and 6. Then, using Global Mapper software[6], the displacement evaluation positions were set from the orthoimages and the coordinate values were extracted from the DSM. The displacement evaluation position was the center of the anti-aircraft sign attached to the quaywall model.

In this study, the resolution of the images was low owing to the high flight altitude of 100 m. However, the enlarged orthoimages showed that the image quality was good enough to identify the center of the anti-aircraft sign. In addition, the difference in the movement of the quaywall model between the prescribed displacement of 5 cm and 10 cm could be clearly judged visually from the enlarged orthoimages (Fig. 6).

Fig. 5 – Orthoimage photographed by fixed-wing UAV before moving. The location of the quaywall model is shown in the square box.



a) Fixed-wing UAV (Before) b) Fixed-wing UAV (After) c) Rotary-wing UAV (Before) d) Rotary-wing UAV (After)

Fig. 6 – Enlarged orthoimage near the quaywall model. The prescribed displacements of the model are 5, 10, 20, and 50 cm horizontally and 16 cm vartically from the top.

3.3 Measurement results

(1) Part 1: Combination of GCP and RTK positioning effects

Table 3 shows a list of the measurement results for part 1 together with the results of RTK-GNSS. Because the measurement dates (flight dates) of the rotary-wing UAV and the fixed-wing UAV were different, and the quaywall model was set up twice, the RTK-GNSS was also applied twice. The error of RTK-GNSS was 13 mm, which is approximately the same as the generally recognized measurement accuracy of the RTK positioning (approximately 1 cm horizontally). In addition, the difference between the two measurement results was calculated before and after the earthquake, but the accuracy was not reduced to half (approximately 2 cm).

The results of UAV photogrammetry are shown for a total of four cases: rotary-wing (without RTK positioning) and fixed wing (with RTK positioning), and the presence or absence of the GCP set during image processing. Fig. 7 shows the error in bold from Table 3. The error was 23 mm for the rotary-wing UAV (Case 1-2) and 58 mm for the fixed-wing UAV (Case 1-4) when the GCPs were set, and the accuracy was higher for the rotary-wing. However, looking at the results other than the maximum value in Table 3, the fixed-wing UAV results were also measured with an accuracy of less than 1 cm. The reason for this difference in accuracy might be due to the blurriness of the images. The fixed-wing UAV has a higher flight altitude and a lower overlap ratio than the rotary-wing UAV, and the camera is fixed to the main body (in the case of a rotary-wing UAV, it is fixed to the gimbal), which is considered to be a disadvantage in the measurement conditions.

Without the GCP, the error of the rotary-wing UAV was more than 1 m, and the measurement error of the positional coordinate became the error of the displacement difference. By contrast, the error of the fixed-

Table 3 – List of measurement results for Part 1

Case name GCP arrangement	Prescribed displacement [cm]	Displacement [m]	Displacement difference* [m]
RTK-GNSS for Rotary-wing UAV	5	0.043	0.007
	10	0.099	0.001
	20	0.189	0.011
	50	0.488	**0.012**
RTK-GNSS for Fixed-wing UAV	5	0.052	0.002
	10	0.113	**0.013**
	20	0.208	0.008
	50	0.492	0.008
Case 1-1 Rotary-wing and no GCP	5	1.151	**1.101**
	10	1.125	1.025
	20	1.024	0.824
	50	0.793	0.293
Case 1-2 Rotary-wing and all GCPs	5	0.046	0.004
	10	0.111	0.011
	20	0.216	0.016
	50	0.477	**0.023**
Case 1-3 Fixed-wing with RTK positioning and no GCP	5	0.115	**0.065**
	10	0.137	0.037
	20	0.225	0.025
	50	0.499	0.001
Case 1-4 Fixed-wing with RTK positioning and all GCPs	5	0.058	0.008
	10	0.106	0.006
	20	0.193	0.007
	50	0.442	**0.058**

* Bold numbers indicate the results with the largest difference from the prescribed displacement.

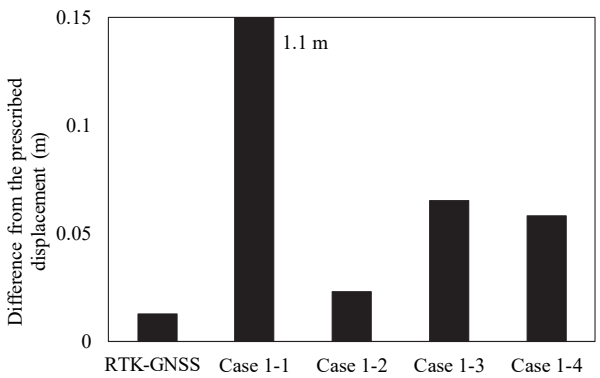


Fig. 7 – Comparison of measurement accuracy in Part 1. Vertical axis: Error in each case. RTK-GNSS: Average of two results of RTK-GNSS. Case 1-1 is 1.1 m above the maximum value of 0.15 m on the vertical axis.

wing UAV was 65 mm, indicating a certain accuracy of the displacement measurement even without the GCP. When evaluating the displacement of a facility from the positional coordinates of three-dimensional point group data, correction by the GCPs is essential during image processing; if RTK positioning is available, a certain level of accuracy can be ensured for a displacement measurement because the coordinate measurement accuracy is high even without correction by the GCPs. In addition, as mentioned earlier, RTK positioning can be used to exclude the crustal movement, and photogrammetry using a UAV capable of RTK positioning is advantageous as a method for measuring the residual displacement of the mooring facilities in the event of a large-scale earthquake.

(2) Part 2: GCP arrangement

Table 4 shows a list of the measurement results for part 2 together with the results of RTK-GNSS, and Fig. 8 shows the error in bold from Table 4. The errror in Case 2-1 using all GCPs was 16 mm, and the error in Case 2-2 placing GCPs at four locations on the four corners of the photographic area was 23 mm, indicating that the measurement accuracy was the same as that of the RTK-GNSS. However, it should be noted that the conditions in both cases were based on the assumption that the GCPs did not move even after the earthquake, as shown in part 1.

In Case 2-6, which assumes that a ground displacement occurs up to 150 m behind the quaywall during an earthquake and that the coordinates of GCPs within this range are unavailable, image processing was performed using two GCPs 200 m away from the quaywall, where the effect of the ground displacement is small. However, owing to the poor image quality of the orthoimages, the displacement evaluation locations could not be identified, or even if they could be identified, the amount of displacement was on the

Table 4 – List of measurement results for Part 2

Case name GCP arrangement	Prescribed displacement [cm]	Displacement [m]	Displacement difference* [m]
RTK-GNSS for Rotary-wing UAV	5	0.043	0.007
	10	0.099	0.001
	20	0.189	0.011
	50	0.488	**0.012**
Case 2-1 4 GCPs and all structures**	5	0.052	0.002
	10	0.105	0.005
	20	0.216	**0.016**
	50	0.498	0.002
Case 2-2 4 GCPs (#1, #2, #4, #5)	5	0.036	0.014
	10	0.123	**0.023**
	20	0.205	0.005
	50	0.484	0.016
Case 2-3 3 GCPs (#2, #4, #5)	5	0.076	0.026
	10	0.127	**0.027**
	20	0.209	0.009
	50	0.517	0.017
Case 2-4 3 GCPs (#1, #4, #5)	5	0.078	0.028
	10	0.114	0.014
	20	0.249	**0.049**
	50	0.531	0.031
Case 2-5 3 GCPs (#3, #4, #5)	5	0.012	0.038
	10	0.041	0.059
	20	0.151	0.049
	50	0.434	**0.066**

* Bold numbers indicate the results with the largest difference from the prescribed displacement.
** Parts of the existing structures

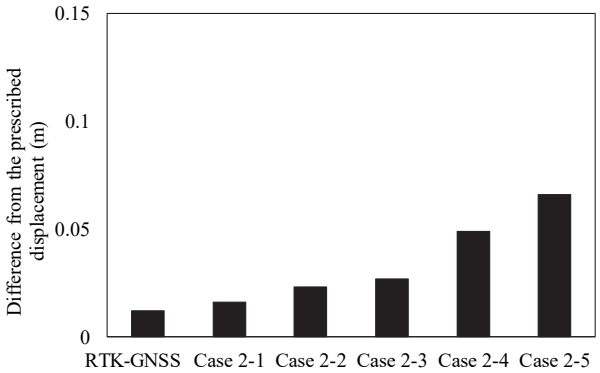


Fig. 8 – Comparison of measurement accuracy in Part 2. Vertical axis: Error in each case. RTK-GNSS: Average of two results of RTK-GNSS.

order of meters. Therefore, the results of the case of the two points on the landward are not shown in Table 4 and Fig. 8.

The error of Case 2-3, in which the GCPs are arranged in a triangular configuration with two landward GCPs 200 m away from the quaywall and one near the quaywall, is 27 mm, which is not significantly different from the accuracy of the quadrilateral configuration cases (Case 2-1 and Case 2-2). However, when the third GCP point was farther away from the model installation position, the error became larger and the accuracy became lower (49 mm in Case 2-4 and 66 mm in Case 2-5).

When the GCP behind the quaywall cannot be used owing to ground displacement during a disaster, it is difficult to evaluate the residual displacement of the mooring facility through UAV photogrammetry. However, if we can set at least one GCP near the facility in addition to the GCP away from the quaywall, we can secure a certain measurement accuracy.

(3) Part 3: Different GCP arrangement before and after the earthquake

Table 5 shows a list of the measurement results for part 3, and Fig. 9 shows the error in bold from Table 5. When different GCPs were used before and after the movement, the accuracy was low in all cases except Case 3-1. The coordinates include the error caused by the GCP arrangement, and this error is considered to be larger when the number of GCPs is small and they cannot be placed on all sides of the photographic area. Because the displacement is calculated from the difference in the coordinates before and after the movement, the effect of this error is expected to cancel each other out and become small when the same GCP configuration is used. However, if the GCP configuration is different before and after the movement, the error caused by the GCP configuration is different before and after the movement, and thus the effect of the error is not reduced by taking the difference of the coordinates, resulting in a low accuracy result. In particular, in Cases 3-4 and Case 3-5, where three GCPs were used, using the same GCP configuration before and after the movement reduced the error to several times that of the four-corners configuration case,

Table 5 – List of measurement results for Part 3

Case name GCP arrangement	Prescribed displacement [cm]	Displacement [m]	Displacement difference* [m]
Case 3-1***	5	0.052	0.002
	10	0.105	0.005
4 GCPs and all structures**	20	0.216	**0.016**
	50	0.498	0.002
Case 3-2	5	0.077	0.027
	10	0.133	0.033
4 GCPs (#1, #2, #4, #5)	20	0.243	**0.043**
	50	0.523	0.023
Case 3-3	5	0.047	0.003
	10	0.072	**0.028**
3 GCPs (#2, #4, #5)	20	0.174	0.026
	50	0.480	0.020
Case 3-4	5	0.304	0.254
	10	0.356	0.256
3 GCPs (#1, #4, #5)	20	0.494	0.294
	50	0.802	**0.302**
Case 3-5	5	0.148	**0.098**
	10	0.155	0.055
3 GCPs (#3, #4, #5)	20	0.282	0.082
	50	0.586	0.086

* Bold numbers indicate the results with the largest difference from the prescribed displacement.
** Parts of the existing structures
*** The same case as Case 2-1 using the same GCP arrangement before and after the earthquake.

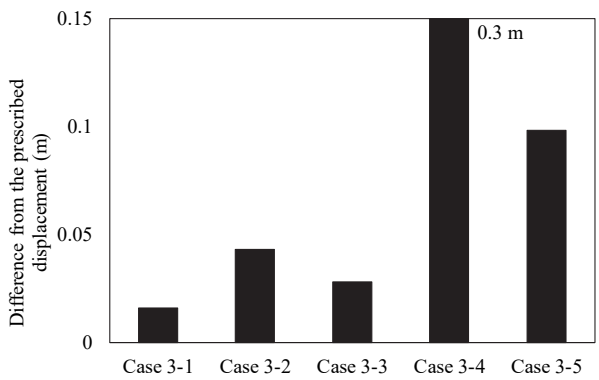


Fig. 9 – Comparison of measurement accuracy in Part 3. Vertical axis: Error in each case. Case 3-4 exceeds the maximum vertical axis of 0.15 m by 0.3 m. Case 3-1 has the same GCP arrangement before and after the earthquake (same as in Case 2-1).

but using a different GCP configuration after the movement significantly reduced the accuracy of the displacement.

If the number and arrangement of GCPs are insufficient to ensure the level of accuracy, using the same GCP arrangement before and after the earthquake can reduce the effect of errors caused by the GCP arrangement and avoid a decrease in the accuracy of the displacement measurement. In other words, the measurement error can be reduced by setting the GCP before the earthquake to evaluate the residual displacement according to the GCP arrangement available after the earthquake.

4. Concluding remarks

The criteria for determining the availability of a facility after an earthquake is highly dependent on the individual characteristics of the facility, such as the structural type and ground conditions. For example, the criterion of serviceability of the quaywalls classified as high earthquake-resistance facilities are a horizontal displacement of 10 cm for gravity type quaywalls and 15 cm for sheet pile type quaywalls[7]. The measurement accuracy of the fixed-wing UAV (with RTK positioning and without GCP) is insufficient for this amount of displacement. If the displacement of interest is approximately 10 cm, the RTK-GNSS should be used. For example, for high earthquake-resistant quaywalls, a residual displacement of 100 cm is often used as a criterion to ensure restorability against Level 2 earthquake ground motions. The measurement accuracy of the fixed-wing UAV (with RTK positioning and without GCP) is sufficient for the initial survey to determine the availability of gravity type quaywalls.

In the case of a large-scale earthquake disaster, crustal movement may occur. In this case, the displacement caused by the crustal movement is likely to be included in the coordinates at the time of photography by the UAV, and in the coordinate values evaluated from the photogrammetry. Displacement owing to crustal movement does not affect the deformation or damage of the facility, and thus it is necessary to remove the crustal movement from the residual displacement to determine the availability of the facility. For example, it is possible to ignore the crustal movement by setting a reference station in the area where the crustal movement is considered to be the same as that of the mooring facility using RTK positioning. By using a UAV equipped with RTK positioning, it is possible to evaluate displacement with a certain level of measurement accuracy, ignoring the crustal movement, without setting the GCP.

5. References

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