International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-5, January 2020

Validation of High-resolution and Simple River Monitoring Technique using UAV-SFM Method

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Abstract: ***This study tested the accuracy and precision of the UAV-SfM method, an automated photogrammetry technique called SfM (Structure from Motion) using multiple pictures taken by UAV (Unmanned Aerial Vehicle), in a section of Saba river, Yamaguchi, Japan. The method was applied in the submerged area as well as in the exposed area, taking into account the refraction at the water surface, for the first time in domestic rivers. When the resultant DEM (Digital Elevation Model) is considered as the map of riverbed elevation, the RMS (Root Mean Square) error and R^2 (coefficient of determination) of UAV-SfM were 0.165 m and 0.93, respectively. In pixels with thick algae cover, large apparent overestimations reaching 0.351 m at maximum were observed because UAV-SfM actually measures the algae surface elevation, not the riverbed elevation. Error analyses also showed that the refraction correction method adopted in this study is working well in spite of its simplicity.***

Keywords : ***Underwater photogrammetry, fluvial topography, Digital Surface Model, drone.***

I. INTRODUCTION

River bathymetric data, which includes information about the depths and shapes of the river channel plays an important role in various management and research activities. In river systems, these data are important in management and research applications such as the river channel planning and design [1], numerical analysis of deposition and bank erosion [2], and river habitat evaluation [3]. Traditionally, these data were obtained mainly by on-site surveying techniques such as ground-based measurement using tape measures, leveling equipment, and global positioning systems (GPS) devices [4]. However, these techniques are time-consuming, and labor-intensive, and are therefore often limited in spatial coverage. For example, regular surveys are generally performed once every few years for Japan domestic first-class rivers at intervals of about 200 m along the river channel. Furthermore, these techniques only offer measurements of depth at specific points, rather than giving continuous coverage.

In river channels, there is no perfect method for exhaustive bathymetric mapping. Conventional ship sounding is time-consuming and constrained by ship access. Single-beam echo-sounding from a boat is limited by its small spatial footprint on the river bed. Airborne light detection and ranging (LiDAR) is too costly to a wide area.

To supplement these approaches, the recent development of Structure-from-Motion (SfM) photogrammetry techniques, which is a semi-automatic image-processing-based computer vision technology, has provided the opportunity for low-cost bathymetric data acquisition. This method greatly reduces the level of expertise and ability required to extract high resolution and accurate bathymetric data, using cheap consumer-grade digital cameras mounted on small Unmanned Aerial Vehicles (UAVs) (e.g. drones).

The monitoring of both exposed and submerged areas in river channels using this method is increasingly in demand in order to generate a highly accurate fluvial topographic map. The suitability of the method for land topographies has already been demonstrated and it has become clear that the UAV-SfM method has high accuracy and precision in monitoring exposed areas [5]. In contrast, the applicability of this technique in the submerged area is limited by the water surface refraction effect [5-8]. The refraction effect causes in-water measurements to be appearing shallower than the reality and reduce the accuracy of the bathymetric map. To solve this problem, a simple refraction correction procedure has been developed by [5]. This procedure proposes using the refractive index of water (1.34) as the correction factor to convert the apparent water depth into real water depth.

This study is concerned with the technical aspects of using high-resolution UAV-SfM technique to generate the accurate digital elevation models (DEMs) of river channels. There are two main aims: (1) assessment of the representation of exposed areas using UAV imagery and SfM method; and (2) assessment of the representation of submerged areas using the same imagery, UAV-SfM method, and water surface refraction correction model. In this study, the UAV-SfM method was applied for the first time in a river channel in Japan.

Manuscript published on January 30, 2020.
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In the following, the field survey and analysis method is explained in Section 2, and then the results of the evaluation of the accuracy and characteristics of errors are shown and discussed in Section 3.

II. METHOD

A. Field Survey

In this study, the test site was located at the main section of Saba River, Yamaguchi Prefecture, Japan. This site is located about 8.5 km from Saba River Estuary with the length of the section is about 250 m. Fig. 1 shows a mosaic aerial photograph (orthophoto) of the test site.

The first survey was conducted on January 6, 2016, land-to-air signs were installed and surveyed by using Real-Time Kinematic-Global Positioning System (RTK-GPS: Trimble R4 GNSS). A total of seven air signs were installed in the test site, two on the right bank side and five on the left bank side. Aerial photography was then performed using a stock camera attached on a small, lightweight, quad-copter UAV (a DJI Phantom 4). The UAV was flown 25 m above ground level (at the drone's home point) to give approximately 1 cm ground resolution of imagery. The resulting image footprint size was approximately 64 m x 48 m. Aerial images were collected with a high level of overlap (> 75 %) to allow subsequent image matching during SfM processing. The total number of images collected at the test site was 270.

In addition, the RTK-GPS survey was conducted again on March 17, 2016, at the point shown in Fig. 1 as an additional survey to evaluate the effect of bottom sediment on SfM accuracy. In this survey, each survey point was photographed directly from the water surface with a digital camera and visually judge of the bottom sediment type. In visual judgment, the bottom sediment is classified into three types: algae, sand, and gravel. In special cases, if the gravel occupied more than 50% of the whole picture, the bottom sediment type was classified as gravel, while if it is less than 50%, the bottom type was classified as sand.

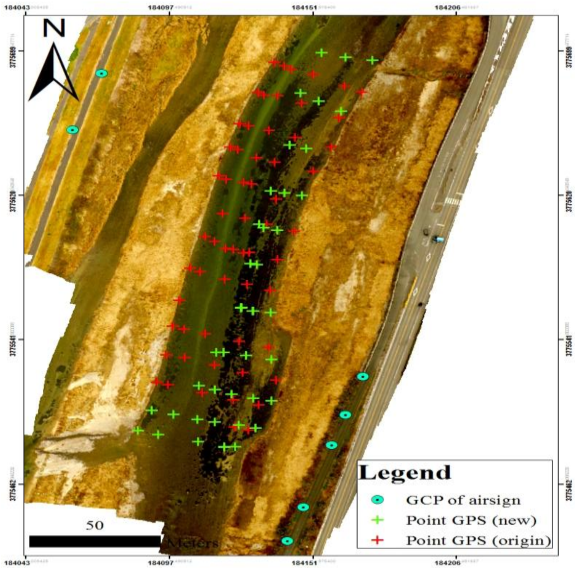

Fig. 1. Orthophoto and survey point of test site.

B. Generation of Digital Elevation Model of Riverbed

Based on the aerial photographs obtained from the field survey and the survey results of the air signs, a digital elevation model of the river bed was created according to the workflow in Fig. 2. In this study, PhotoScan (Agisoft) software was used for the general SfM image processing, and ArcGIS 10.2 (ESRI) was used for the subsequent processing. For the spatial interpolation, two-dimensional interpolation using a cubic polynomial model was applied.

Regarding the correction of the water surface refraction effect, the correction factor by [8] and [9] has the disadvantage that the correction factor varies with the position of the drone cameras. Although aerial photographs at multiple positions are used to estimate the actual 3D coordinates of each feature point, it is not clear which position should be used to calculate the correction coefficient. Therefore, in this study, a simple correction method which does not depend on the camera position was applied [1]. In this method, the correction coefficient is the relative refractive index of water to the air (1.34). In other words, the true water depth was estimated by multiplying the apparent water depth with the relative refractive index.

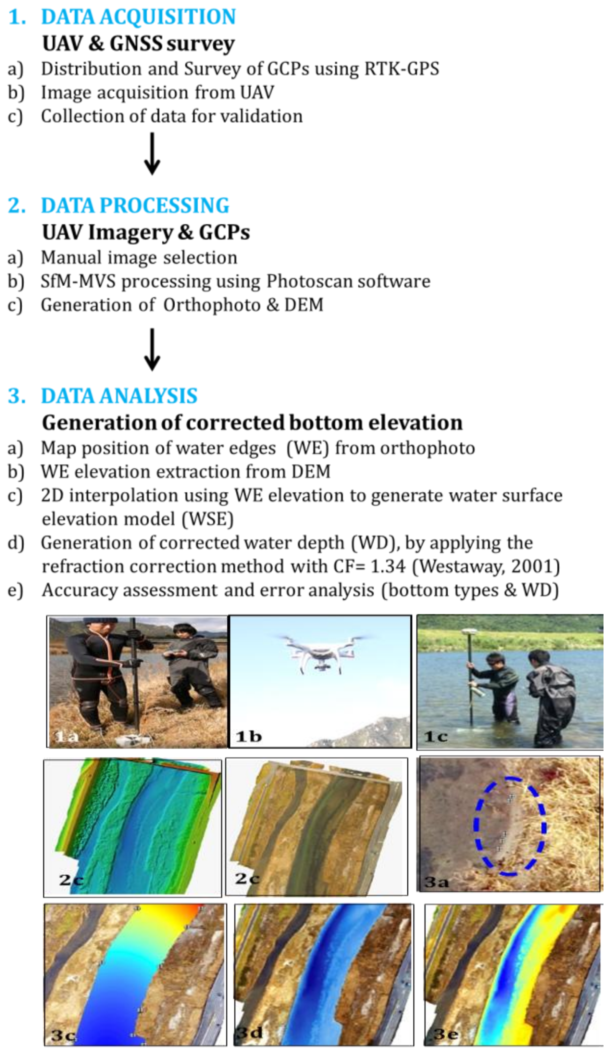

Fig. 2. Workflow of UAV-SfM method for generating DEM of riverbed.

C.Accuracy Assessment and Error Analysis

To evaluate the accuracy and precision of photogrammetry, the measured elevation of the validation points (the underwater points where the world coordinates were measured by RTK-GNSS, Fig. 1) were compared with the elevation of the pixel of the digital elevation model containing the point. The difference between these elevations was defined as the error of river bottom elevation estimation by UAV-SfM. It should be noted that the estimation error calculated by this definition includes an apparent error caused by the mismatch between the survey point and the pixel due to the horizontal coordinate estimation error by UAV-SfM. As the statistics of estimation error, we evaluated the standard deviation, which is an index of precision, the mean, which is an index of accuracy, and the RMS (root mean square), which is a statistic that comprehensively evaluates precision and accuracy.

Furthermore, the relationship between the estimation error of river bed elevation with the bottom sediment, water depth, and river channel direction was investigated, and the cause of the error was considered.

III. RESULT AND DISCUSSION

A. Digital Elevation Model

Fig. 3 shows the digital elevation model (before applying the water surface refraction correction model) obtained by the UAV-SfM method. Fig. 4 shows the digital elevation model (after applying the water surface refraction correction model) for the submerged area. From this Figure, it can be observed that the river channel topography from the embankment to the submerged areas is expressed in detail. This river section has a reverse slope, and it is not an error that the elevation is high on the downstream side.

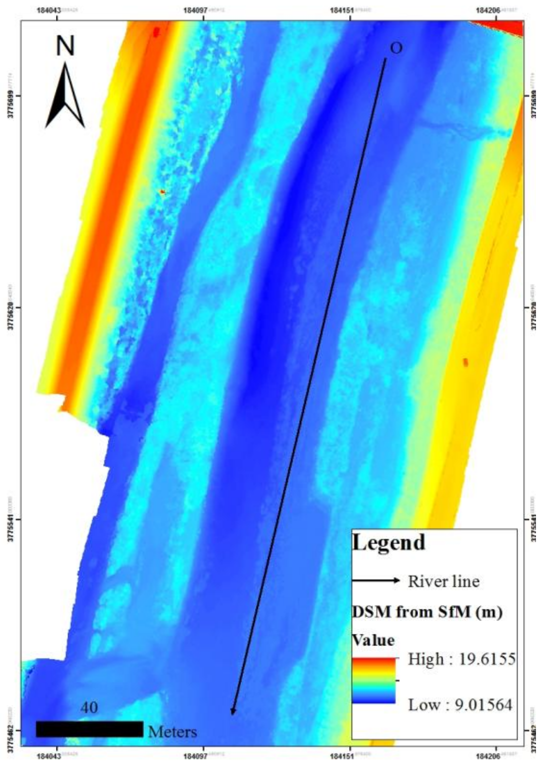

Fig. 3. DEM obtained by UAV-SfM photogrammetry (before refraction correction).

B. Validity of UAV-SfM in Exposed Areas

Table I shows the statistic of the estimation error of the exposed areas. The RMS of the estimation error for horizontal and vertical coordinates was about 0.017 m (computed by combining the X and Y components from the original data in Table I) and 0.013 m, respectively. It is of the same order as the general error in RTK-GNSS measurements and demonstrates the success of our UAV-SfM procedure.

Besides, as illustrated in Fig. 5, there was no clear relationship between the coordinate's estimation error and the river channel position (coordinates on the axis in the direction of the arrow with "O" in Fig. 3 as the origin). These results suggest that it is possible to accurately estimate the position and orientation of the camera and to accurately determine the land location even from aerial photographs including water surfaces with refraction.

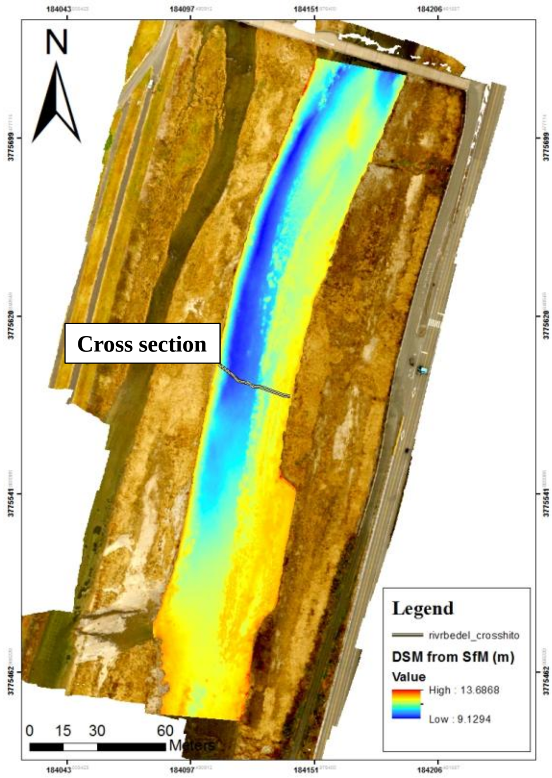

Fig.4. Digital elevation model obtained by UAV-SfM photogrammetry (after correction).

Table-I: Statistic of estimation errors for air sign coordinates

Coordinate	Mean (m)	Standard deviation (m)	RMS (m)	The number of data
X axis	0.004	0.002	0.004	7
Y axis	-0.002	0.017	0.017	7
Z axis (elevation)	0.005	0.012	0.013	7

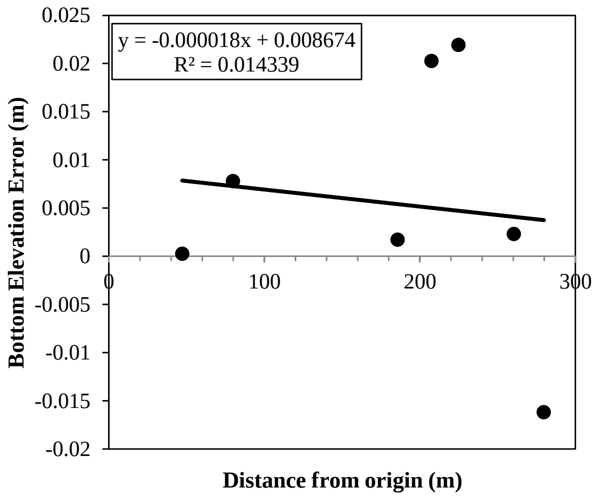

Fig. 5. Relationship between estimation errors of bottom elevation and river channel position.

C. Accuracy of River Bottom Elevation

Fig. 6 shows the scatter plot of the estimated bottom elevation (before and after applying refraction correction of water surface) by UAV-SfM against the measured bottom elevation by RTK-GNSS. Based on this Figure, systematic overestimation error due to the effects of water surface refraction can be reduced by applying the simple refraction correction techniques. As the results of the statistical error, the mean error of the bottom elevation after the correction was -0.068 m (slightly underestimated trend) and the RMS error was 0.165 m. The coefficient of determination of the linear regression was 0.93. Overall, the UAV-SfM approach provides finer resolution datasets (0.03 m) with high accuracy of the estimated bottom elevation of the river bed.

On the other hand, based on the visual interpretation of the photograph, the two points with the largest estimation error (0.351 m and 0.333 m, Fig. 6) were located in the distribution area of algae. In this area, a few tens of centimeters thick algae have been confirmed. The significant overestimation in this area is due to UAV-SfM estimates the surface elevation of algae as the actual bottom elevation, while the RTK-GNSS measures the actual bottom elevation.

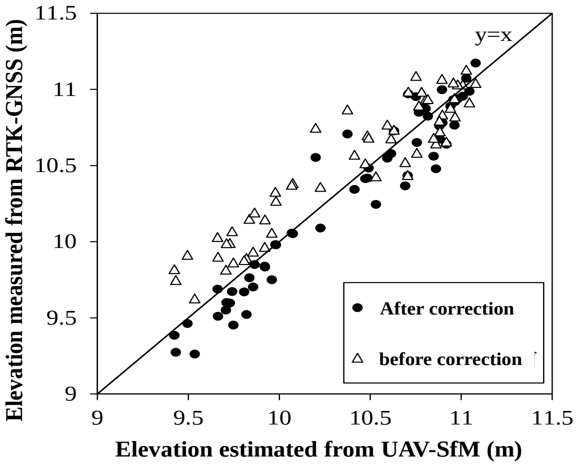

Fig. 6. Scatter plot of the estimated bottom elevation before and after applying refraction correction by UAV-SfM against measured bottom elevation by RTK-GNSS.

D. Relationship between Elevation Estimation Error and Various Conditions

Influence of bottom sediment

Fig. 7 shows the scatter plot of the elevation of algae top/ bottom measured by RTK-GNSS against the estimated elevation obtained by UAV-SfM. This Figure shows that photogrammetry is more consistent with the surface elevation than the bottom elevation of the algae, as expected from its principle.

Table II shows the statistics of elevation estimation error by bottom sediments for the additional survey. From this Table, it can be seen that the RMS of the estimation error for the algae is almost the same as that of sand when the elevation by photogrammetry is regarded as the surface height. The absolute value of the bias component (mean) is about half that of sand, and the variation component (standard deviation) is about the same as that of sand. Therefore, it can be seen that photogrammetry can be estimated with the same level of accuracy as sand, no need to worry about algae if the attention is paid to measuring surface height.

As can be seen from Table II, the highest RMS error among the three categories of sediments was gravel, and the RMS error of gravel was about twice that of algae and sand. Both the bias component and the variance component were the largest among the three categories. One reason is that the difference in elevation between the upper and lower gravel is large. For example, the mismatch between the survey point and the pixel of the digital elevation model due to the horizontal coordinate estimation error of about several pixels (within 0.1 m) by photogrammetry is likely to cause a large apparent elevation estimation error.

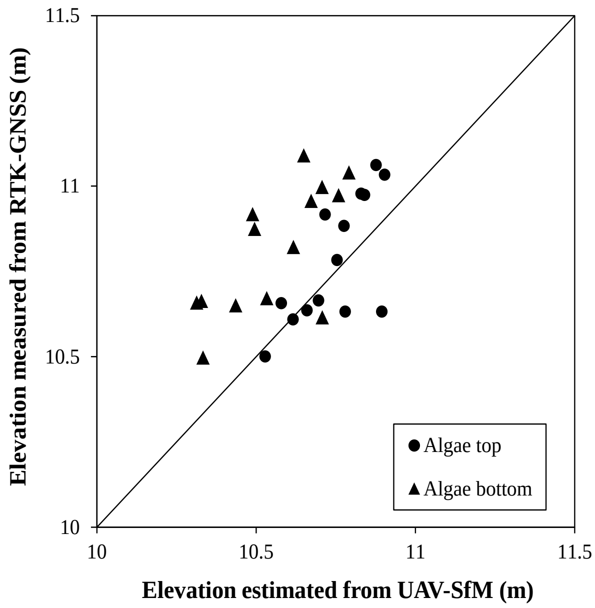

Fig. 7. Scatter plot of the elevation of algae top/ bottom measured by RTK-GNSS against the estimated elevation obtained by UAV-SfM

Retrieval Number: E6926018520/2020©BEIESP
DOI:10.35940/ijrte.E6926.018520
Journal Website: www.ijrte.org

Published By:
Blue Eyes Intelligence Engineering
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Table –II: Statistic of estimation errors for bottom sediments.

Bottom sediment	Mean (m)	Standard deviation (m)	RMS (m)	The number of data
Algae	0.036	0.127	0.132	14
Sand	-0.064	0.129	0.144	16
Gravel	-0.168	0.215	0.273	9
All bottom sediment	-0.052	0.171	0.179	39

Influence of water depth

Fig. 8 shows the relationship between the estimation error of bottom elevation and the water depth by photogrammetry for additional survey points excluding the spot where algae are distributed. The water depth was obtained by subtracting the measured bottom elevation from the water surface elevation estimated by spatial interpolation. According to Fig. 8, there is no clear relationship between the estimation error of bottom elevation with the water depth (the slope of the regression line and the coefficient of determination are small), and the error does not tend to increase as the water depth increases. Overall, there is no problem with the application of the refraction correction technique in submerged areas with various depths.

To illustrate the effect of water surface refraction correction, Fig. 9 shows the bottom elevation profile of river bed (before and after refraction correction) and the bottom elevation points measured by RTK-GNSS in the cross-section (as shown in Fig. 4). From this Figure, it is clear that the water surface refraction correction adopted in this study is working well in spite of its simplicity.

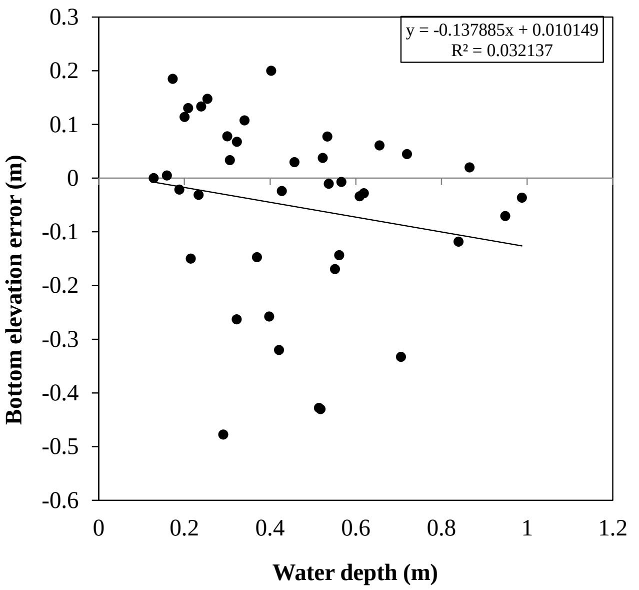

Fig. 8. Relationship between estimation error of bottom elevation and water depth by photogrammetry.

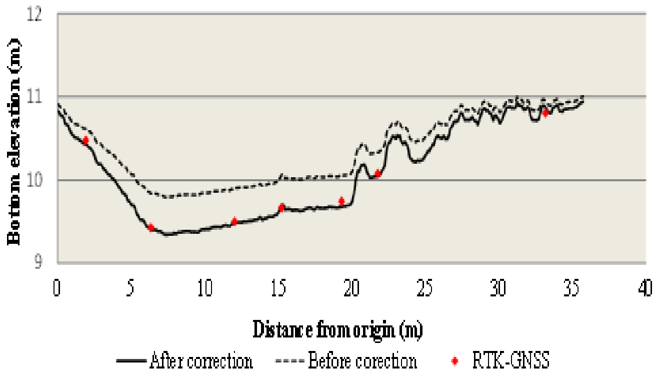

Fig. 9. Elevation profile along the cross section for bottom elevation (after and before correction) estimated by UAV-SfM and bottom elevation measured from RTK-GNSS.

Influence of river channel position

Fig. 10 shows the relationship between the estimation error of bottom elevation and the position of the river channel with the various types of sediments. From this Figure, the UAV-SfM method underestimates the bottom elevation on the upstream side and overestimates on the downstream side.

The trend of the estimation error in the river channel direction is not due to the estimation error of the vertical axis in SfM because it is more than 100 times larger than the trend for the air sign shown in Fig. 5 and the sign is reversed. Furthermore, since the same trend is observed in any bottom sediment, it is not due to bottom sediment, and it is necessary to investigate the main cause in the future.

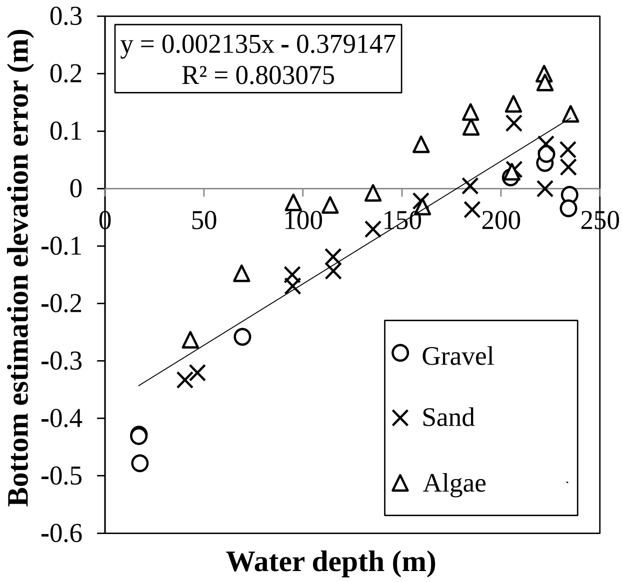

Fig. 10. Relationship between the estimation error of bottom elevation and the position of the river channel with the various types of sediments.

IV. CONCLUSION

In this study, the river channel survey using the UAV-SfM technique was applied for the first time in Japan's domestic river by considering the refraction of light on the water surface. In this study, the accuracy and error characteristics were clarified. The conclusion is shown below.

1. The UAV-SfM technique has potential as a valuable tool for creating high resolution and high accuracy river topography datasets for assessment of fluvial environments.
2. In pixels with thick algae cover, the estimated elevation is suffered from large overestimation error, this is because UAV-SfM measures the algae surface elevation, not the river bed elevation.
3. A simple water surface refraction correction procedure improved the accuracy of the estimated bottom elevation of the riverbed.

In the future, we will investigate the reason for the large error in the bottom of the gravel, the cause of the error in the river channel direction, and the correction method, which could not be clarified in this study. Besides, it is desirable to obtain further knowledge for practical application by applying river surveying technology using the UAV-SfM method to a wider variety of river environments.

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