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Possibilities of Using UAV for Estimating Earthwork Volumes during Process of Repairing a Small-Scale Forest Road, Case Study from Kyoto Prefecture, Japan

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Abstract: Although forest road networks are an important infrastructure for forestry, recreation, and sustainable forest management, they have a considerable effect on the environment. Therefore, a detailed analysis of the various benefits and associated costs of road network construction is needed. The cost of earthwork in road construction can be estimated based on the change in topography before and after construction. However, accurate estimation of the earthwork volume may not be possible on steep terrain where soil placement is limited. In this study, an unmanned aerial vehicle was flown under the tree canopy six times during a road repair work to measure the changes in topography using structure from motion analysis. Comparing the obtained 3D model with the measurement results from the total station, the average vertical error and root mean square error were −0.146 m and 0.098 m, respectively, suggesting its good accuracy for measuring an earthwork volume. Compared to the amount of earthwork estimated from the topographic changes before and after the repair work, the actual earthwork volume was 3.5 times greater for cutting and 1.9 times greater for filling. This method can be used to calculate the earthwork volume accurately for designing forest road networks on steep terrain.

Keywords: small-scale forest road; UAV; Structure from Motion (SfM); earthwork volume; under tree canopy

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1. Introduction

Forest road networks can be used for timber production, recreational activities, and preventing the spread of pests and fires [1]. However, constructing a road network on sloping terrain increases the risk of slope failure due to heavy rainfall and the fragmentation of wildlife habitat [2]. For designing an optimal road network layout, it is necessary to comprehensively evaluate candidate routes from the economic and environmental perspectives by setting objective variables, such as the construction and maintenance cost, effect of incurring a minimal cost for timber harvesting and transportation, social benefits related to recreation and disaster prevention, and the risk of damaging environmental health.

The cost–benefit evaluation in designing a forest road network requires a complex analysis, as the benefits of road construction are diverse; additionally, the costs should be calculated while considering the environmental risks [3]. Several methods, such as the analytic hierarchy process, have been proposed to evaluate the optimal route planning to maximize the benefits and minimize the costs of various construction objectives [4–8]. Recently, the precise microtopographic data obtained using an airborne laser scanner (ALS) have been used for forest road construction, because the construction cost is related to the amount of earthwork. Many studies have proposed designing forest road networks with minimal earthwork using high-resolution digital elevation model (DEM), because the routes with less earthwork are economical and discharge less sediment into the environment [9–14]. Aruga et al. [15] comprehensively studied a route selection method that combines the prediction of surface erosion and discharge of the related sediment into streams with the amount of earthwork. Ghajara et al. [16] developed a model in which the total cost of road construction may be estimated with an accuracy range of ±6.5%, assuming that the total construction cost is determined by six factors: clearing operations, embankments, pavements, gradings, culverts, and ditches. These studies have enabled us to estimate the cost of road construction precisely based on the difference in shape change between the landform before and after the forest road construction. Particularly, earthwork volume accounts for a large portion of the cost of small-scale road construction on sloping terrain [17,18], so these models have already been put to practical use as a route selection method to reduce road construction costs [19].

On the other hand, small-scale road construction operations, mainly earthwork operations, often occur on slopes, where there needs to be more space for temporary soil storage. It is necessary to repeatedly excavate, temporarily place, and fill soil in a limited area. Therefore, it is difficult to predict and quantify the amount of earthwork performed since it is difficult to ascertain all of the earthwork performed simply by comparing the shape of the soil before construction with the shape of the completed ground. It is necessary to conduct surveys during construction to grasp the precise amount of earthwork that changes with time. However, accurate quantification has been impractical.

Recently, however, with the development of unmanned aerial vehicles (UAVs), various sensors, and analysis technology, it has become possible to perform high-frequency surveying from the sky without stopping construction work [20]. The two surveying methods using UAVs are as follows: (1) obtaining a 3D model of the ground surface via structure from motion (SfM) analysis [21] based on images taken using an onboard camera and (2) measuring the distance to the ground surface using an onboard laser scanner. As the first method requires inexpensive sensors, it has recently been widely used for surveying.

UAVs are indispensable for earthwork estimation in the construction industry owing to their speed and efficiency [22]. Akgul et al. [23] compared the results of earthwork volume estimation of small-scale roads using DEMs created by fixed-wing UAV and Network real time kinematic global navigation satellite system (NRTK-GNSS). It was revealed that the UAV-based method was more cost-effective and accurate than NRTK-GNSS. Buğday [24] used UAVs and SfM analysis to create 5 cm mesh data after road construction in a forest area and showed that post-evaluation of earthwork volumes is possible. Hrůza et al. [25] operated a UAV at a speed of 1 m/s and 1 frame/s from an altitude of 4–6 m to create a point cloud with an average of 3.2 points/cm^2 and accuracy with a root mean square error (RMSE) of 0.0198 m for use in inspection work on asphalt-paved forest roads. Hrůza et al. [26] also reported that SfM analysis was performed on asphalt paved road surfaces using photographs taken from a height of 1.5 m above the ground and that the accuracy was higher than various LiDAR methods. Many other studies have been conducted for use in the calculation of earthwork quantities at construction sites [27–29].

Although SfM analysis using UAVs is used for constructing forest road network, previous studies have used data obtained from locations higher than the tree canopy. In the SfM analysis, identifying the same object in images taken from multiple locations is necessary. The ground surface in forests cannot be photographed due to the obstruction caused by standing trees. Therefore, flying the UAV under the tree canopy is necessary for performing a detailed analysis of the changes in the amount of earthwork during construction. An automatic flight is difficult under the tree canopy, as stable global navigation satellite system (GNSS) reception and positioning accuracy cannot be ensured. Consequently, manual operation with advanced flight techniques is required in such conditions. Therefore, few studies have been conducted by flying UAVs under the canopy to obtain detailed information of forests [30,31].

In this study, we attempted to quantify the changes in topography by taking six UAV mapping and conducting an SfM analysis at a small-scale forest road repair site, where it is relatively easy to fly UAVs even under the tree canopy because earthwork is performed in a narrow area with few standing trees. At the same time, we compared the accuracy of the topography measurement with that of a total station. The obtained data were used to verify whether it was possible to estimate the amount of earthwork at each stage of the repair work. A forest road repair site was chosen for this study, instead of a forest road construction site, because the earthwork is concentrated in a small area in forest road repair sites; therefore, it is convenient to collect data and obtain accurate evaluation.

2. Materials and Methods

The measurement test was conducted at a 2.5 m wide road repair site in Kizugawa City, located in the southern part of Kyoto Prefecture, Japan. The length of the road is 706.3 m, and it was constructed in 2020 as a branch line from a larger forest road. This road was constructed using the Ohashi-type road construction method, which assumed that 3–5-ton class excavators and 2–3-ton trucks will be used in the construction [32]. The logs used to make the retaining wall with log structure were used for the frame to distribute the loads [33].

Repair work was conducted from 22–25 August 2022 to repair a defective embankment near the middle of this line caused by heavy rainfall in May 2021. According to official rainfall data in the neighboring city of Kyotanabe, the total rainfall from 16–22 May was 204.5 mm, 160 mm of which was concentrated over two days. The road was carefully constructed with logs on the upper part of the embankment and the roadbed, but the bedrock was exposed in the affected area, making it challenging to form the embankment.

The repair consisted of first creating a simple road to access the lower part of the missing embankment and then reshaping the embankment with logs from the valley flowing under the lower part of the road embankment to the upper part of the road. A rectangular plot with a length of about 30 m and a width of about 16 m was set along the work road in the repair work area, and this was used as the analysis range.

UAV photography was conducted six times: once before the repair work (morning of 22 August), four times during the repair work (afternoon of 22 August, morning of 23 August, afternoon of 23 August, and morning of 24 August), and once after the repair work (13 September). A DJI Mavic3 drone was used for photography. We used PiX4Dmapper (Pix4D S.A., Prilly, Switzerland) for the SfM analysis. ArcGIS 10.8.1 (ESRI Inc., Redlands, CA, USA) and QGIS 3.16.7 (QGIS Development Team, 2021) were used for earthwork volume estimation.

Four aerial markers were set up as ground control points (GCPs) to measure absolute coordinates and eliminate distortion of the obtained model. In addition, surveying was conducted at two other open locations in the sky using a survey GNSS receiver (Spectra Precision SP80). Absolute coordinates of the GNSS points were precisely measured using electronic reference points of the Geospatial Information Authority of Japan, and absolute coordinates of the GCPs were calculated using a total station (TS) TAJIMA TT-N45 (TJM Design Co., Tokyo, Japan) from GNSS points. According to the TS specifications, the ranging accuracy, in this case, is "(2 + 2 ppm $\times$ D) mm (for measuring distances of 4 m or more)," with an error of 0.01 mm at a distance of 10 m. The angular accuracy is 5 and the error at a distance of 10 m is 0.24 mm.

The ground height was measured a total of four times using TS during the lunch break on each day when repair work was suspended. The measurement results were compared with the 3D model obtained by SfM analysis from the images taken by the UAV every morning. As the UAV imaging on the 2nd and 3rd days was conducted during the repair work, there was a slight time lag with the TS survey and the topography may have slightly changed. We used 41, 76, 91, and 88 TS survey points for comparison on days 1 (before the repair work), 2, 3, and 4 (after the repair work), respectively. The accuracy of the ground height obtained by the UAV was calculated by the TS measurement points as the validation points, and the results of the TS measurements were true values.

The UAV was operated at two altitudes: close up (3–5 m) and low altitude (7–10 m). In the SfM analysis, 3D models were created using two altitude images at the same time. It captured the area where the repair work was being done, with a flight duration of about 30 min. The UAV was operated manually along the area, and the image was automatically captured at 2 s intervals to ensure a high overlap between images. We also captured images from various directions in the flyable area.

DEMs of the ground surface were created from the 3D model obtained by SfM analysis using a UAV, and the amount of cut and fill at each stage was calculated using the Cut Fill tool in ArcGIS.

3. Results and Discussion

3.1. Generation of 3D Models for Each Phase of the Small-Scale Forest Road Repair Project

The 3D models of each phase were successfully constructed using SfM analysis. The resolution of the generated models ranged from 1.1 cm to 1.4 cm. For example, the 3D models generated from the data taken before, during, and after the work was completed and viewed from various angles are shown in Figures 1–3.

In this test, the flight route of the UAV was not fixed, and the appropriate course for photography was determined manually during the operation. Because the site was located in a valley, which made GNSS reception difficult, and the flight altitude was lower than the height of the surrounding trees, there was a risk of colliding with branches or tree trunks. Under these conditions, GNSS control is insufficient, and UAV flight control technology for real-time obstacle detection using various sensors and SLAM technology is needed.

Figure 1. A 3D model generated by SfM analysis before the repair work started.

Figure 2. A 3D model generated by SfM analysis during the repair work.

Figure 3. A 3D model generated by SfM analysis after the repair work completed.

Because the shooting area differed depending on the shooting session, the area where the 3D model was obtained also differed in each shooting session. There were some differences between the modeled trees and other land objects. However, no inconsistencies in their positions or shapes were observed. Even for the complex and finely patterned subsoil vegetation and soil and stone surfaces, no significant distortions were observed, and it was found that 3D models with clean shapes could be obtained.

3.2. Verification of Height Accuracy of Surface Data Obtained by SfM Analysis by UAV

The elevation values obtained at each point of the 3D model were compared with those measured by the TS. However, measurement by the TS takes time, which causes a significant time lag between drone photography and TS surveying. Therefore, verification of measurement accuracy was limited to four times: the morning of 22 August before the repair work, the morning of 23 August and 24 August during the repair work, and 13 September after the repair work. The results are shown in Table 1 and Figure 4.

Table 1. Height measurement error (m) in SfM analysis compared with the total station survey.

	Mean	Max	Min	RMSE
Before the repair work	−0.102	0.136	−1.333	0.105
During the repair work 1	−0.259	0.290	−0.910	0.162
During the repair work 2	−0.198	0.059	−1.218	0.121
After the repair work	−0.017	0.113	−0.494	0.017
Overall	−0.146			0.098

The overall measurement error averaged −0.146 m, leading to a general tendency toward underestimation. The RMSE was 0.098 m, indicating that elevation values could be obtained with an accuracy of about 10 cm. However, the average error varied greatly from one measurement session to the next. It was −0.102 m before the repair work, and −0.259 m and 0.198 m during the repair work, whereas it was −0.017 m after the repair work, a significant improvement. Lee and Lee [28] reported an RMSE error of 0.11 m in the vertical direction for the SfM analysis using vertical and 45-degree photographs from 50 m altitude at a construction earthwork site. The error in this study was similar, but the accuracy in this study was slightly less at closer distances to the ground surface and in forest areas.

The final survey was measured after the repair work had been completed and the area had been compacted. However, before and during the repair work surveys may not have measured the complete ground surface during TS surveying because of the softness of the soil on the ground.

Additionally, there was a considerable time lag between drone photography and TS surveying during the measurements before and during the repair work. This was because the survey was conducted safely so as not to interfere with the repair work as much as possible. In some locations, earthwork, or log construction may have been undertaken after drone flight and before the TS survey.

With this in mind, we discuss the accuracy of the measurements at each stage. The absolute value of the error at the TS measurement points before the repair work is shown in Figure 5a. It is shown in the figure that the error is small on slopes where the soil is visible, and slightly larger errors are observed in vegetated areas and on the shoulders of embankment slopes.

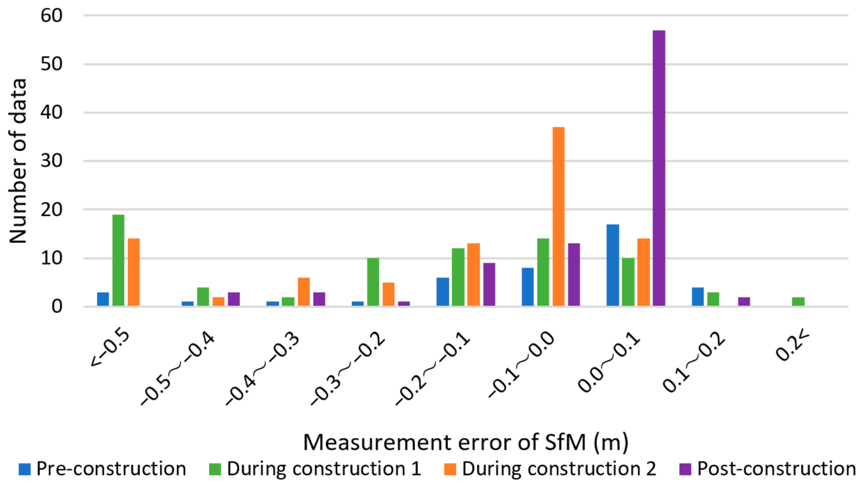

Figure 4. Frequency distributions of height measurement error in SfM analysis.

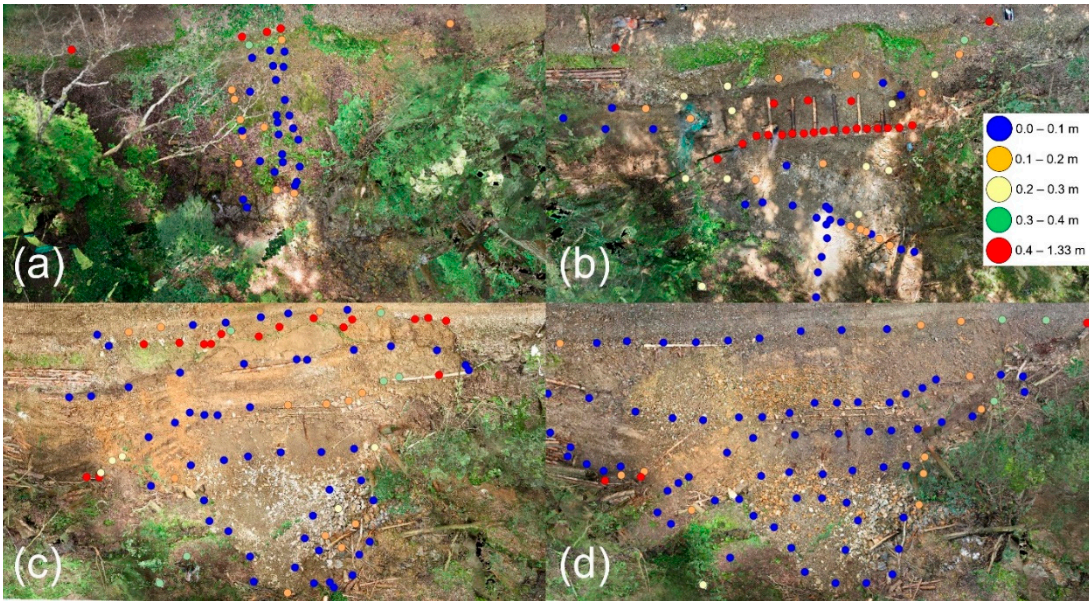

Figure 5. Absolute values of the error at each process of the repair work. (**a**) before the repair work, (**b**,**c**) during the repair work, (**d**) after the repair work.

Similarly, the situation during the repair work is shown in Figure 5b,c, and the situation after the repair work is shown in Figure 5d. It is shown in Figure 5b,c that errors were minor, even during the repair work, in areas where the soil was visible. However, substantial errors occurred in areas where work was being done, such as in areas where wood framing was being installed. A significant error at the shoulder of the embankment is shown in Figure 5c. Still, further verification was needed to determine whether the accuracy of edge detection in the SfM analysis was reduced by this problem or whether the soil tended to move easily at the shoulder of the embankment.

On the other hand, Figure 5d shows that the accuracy was generally good after the repair work, including the shoulders of the embankment. Even on the shoulders of the embankment, most of the errors were lower than 0.1 m. Slightly larger errors were observed in the upper right and lower left parts of the figure, which are close to the vegetation. Together with the edge mentioned above, a more precise analysis of the accuracy in areas easily shaded by vegetation is considered necessary.

3.3. Estimation of Earthwork Volume and Earthwork Allocation Plan

It was suggested by these results that SfM analysis is sufficiently accurate for soil volume calculations in units of cubic meters. However, there was room for further study on the accuracy of measurements under subsoil vegetation and at sharp slope conversion points. Therefore, we calculated the amount of earthwork for cut and fill at each stage. The results are shown in Figure 6.

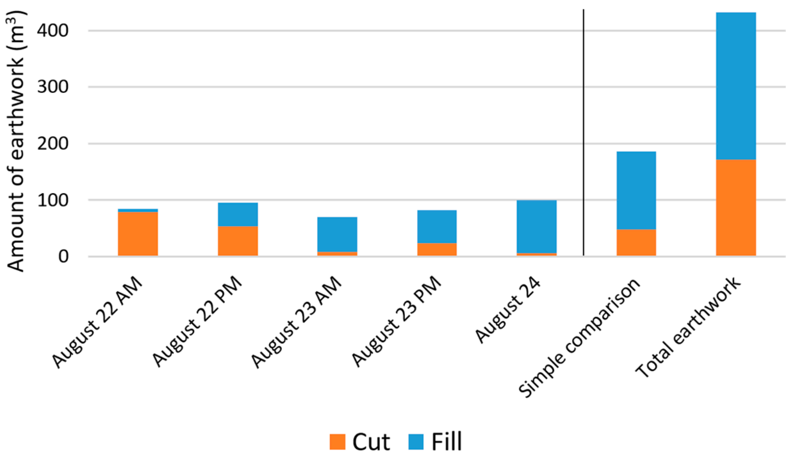

Figure 6. Amount of earthwork for cut and fill at each stage.

It was estimated that 78.6 m^3 of cut soil was generated on the morning of the first day of work (22 August), and another 5.49 m^3 was used as fill. In the early stage of the repair work, it was assumed that much of the cut soil was generated to shape collapsed areas and construct an access road to the lower part of the embankment. In the afternoon of 22 August, the cut, and fill volumes were 54.1 m^3 and 41.4 m^3, respectively. This was consistent with the fact that much soil was used during the formation of the log structure at the base of the fill. On the morning of 23 August, the cut decreased to 8.8 m^3 and the fill increased to 60.9 m^3 when the log structure continued to be installed. The cut soil increased again to 23.6 m^3 and the fill to 58.9 m^3 when the upper portion of the embankment was re-excavated simultaneously with the formation of the fill in the afternoon of 23 August. On 24 August, the last day of the repair work, the cut was 6.2 m^3 and the fill was 93.9 m^3.

A simple comparison between before and after the repair work had a difference of 48.6 m^3 for cut and 137.5 m^3 for fill, but when the amounts of earthwork at each stage were added up, 171.3 m^3 for cut and 260.7 m^3 for fill were performed. In the case of civil construction sites, the difference in the amount of earthwork before and after construction and the total amount of earthwork at each stage was not considered to be significantly different. However, it is necessary to temporarily bring in soil from another location or temporarily place cut soil in another location in forest work. The amount of cut and fill soil in this study was about 3.5 times and 1.9 times larger than that measured before and after the repair work. This is a significant error factor in estimating earth work volume and maintenance costs.

The cumulative earthwork volume at each stage is shown in Figure 7. The rate of change in the volume of loosened soil, the change in the volume of soil in the excavation of the ground soil volume (L), was calculated as 1.2 in calculating the amount of earthwork. The rate of change in the volume of compacted soil and the difference in soil volume in forming the ground soil volume into fill (C) was 0.9. The volume of the log structure embedded in the fill was not considered.

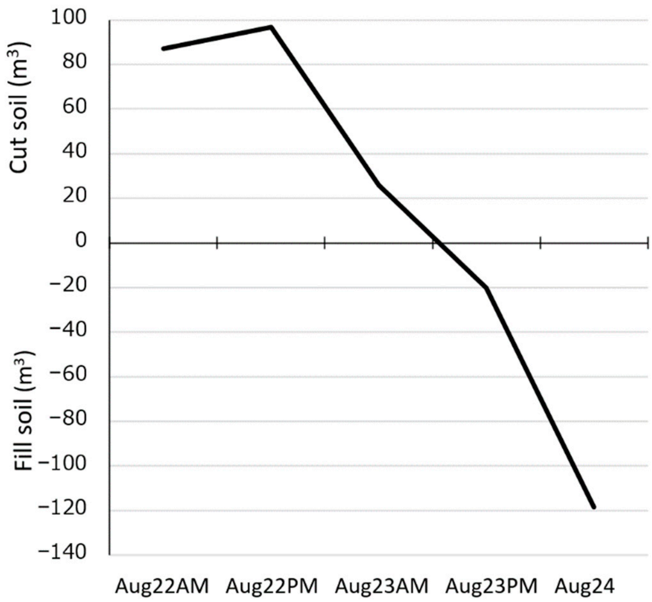

Figure 7. Cumulative amount of earthwork at each stage.

According to this figure, it can be seen that in the early stage of the repair work, when there was much cut soil, there was a maximum of about 100 m^3 of cut soil. Securing a temporary storage place for this cut soil around the work site is necessary. On the other hand, the cut soil forms the embankment, and at some point, the soil for the embankment becomes insufficient. Therefore, it is necessary to secure soil from another location. This amount of fill was considered to be about 120 m^3.

Figure 8 shows a 3D model of the earthwork sections at each stage. The cut and fill areas are shown in blue and red, respectively. In Figure 8f, showing the overall earthwork volume in the lower right corner, almost the entire missing fill area was covered with fill. The cut and fill areas were indicated in each step, making the procedure easy to understand. The entire fill was shown in blue, except for some parts, in Figure 8e. This is because the photographs after the repair work were not taken until three weeks after the completion of the repair work, and it is presumed that the entire fill has tightened and settled.

These results indicate that it may be difficult to accurately estimate the actual volume of earthwork in road construction on steep terrain where there are few temporary soil storage areas based only on the topography change between before and after construction. This study was conducted at a road repair site, and the procedure differed from that of earthwork during road construction. However, while constructing small-scale roads that do not require much artificial structures, the method of excavating the ground once and piling up topsoil blocks may be used to strengthen the road structure [32,33]. In addition to the topographical conditions, the capacity of the temporary soil storage area varies with the construction method. In steep terrain, it is necessary to determine the optimal construction procedures and earthwork volume in each step according to topographic conditions, road standards, and construction methods.

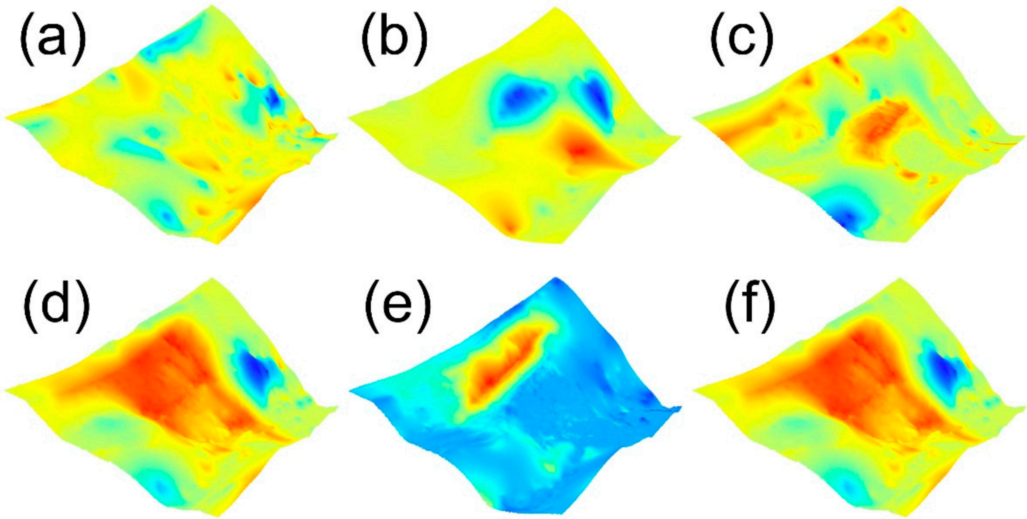

Figure 8. 3D model of the earthwork sections at each stage. (**a**) constructing an access road to the lower part of the embankment and the formation of the base, (**b**) forming the embankment base by earthwork and logs, (**c**) forming the lower part of the embankment by earthwork and logs, (**d**) forming the upper part of the embankment by earthwork and logs, (**e**) shaping the entire embankment, (**f**) overall earthwork.

4. Conclusions

It is shown in this study that SfM analysis using a UAV can be used to quantify the amount of earthwork and record the procedures for repair work on forest roads. The SfM analysis with UAV was an accurate means of measuring landforms comparable to TS surveying, creating detailed 3D models, calculating precise earthwork quantities, and recording detailed area-specific work procedures at each construction stage. Since the earthwork performed at each stage of the work was closely related to the cost of construction, it should be possible to accurately estimate the cost of construction, plan the work, and predict the number of days required for the work, which are deeply related to the cost–benefit analysis of forest roads.

Studying a stable flying method under the tree canopy was necessary as a future issue. However, the drone flight plan must be thoroughly examined when the work area changes by several tens of meters daily. For example, in conditions where a small-scale forest road is being constructed. The method of capturing images must also be verified to enable highly accurate 3D modeling. The drone flight plan must be thoroughly considered, and the method of capturing images must be verified for accurate 3D modeling.

Various measurement conditions, such as light environment, and ground surface conditions, will significantly impact the measurement evaluation, and an assessment of these shooting conditions is also required. The evaluation of soil movement during the construction process will also need to be considered.

This study evaluates only one case of small-scale forest road repair work. It is expected that completely different methods or procedures will be selected for different soil types, topographies, damage conditions, and soil placement locations. Particularly in forests, UAV flight has many obstacles, such as tree trunks and branches. In addition, the GNSS reception environment is poor, making automated flights difficult. In recent years, artificial intelligence drones equipped with sensors to avoid obstacles in real time have appeared [34]. Thus, the automatic flight into forests will be possible soon. In the future, it will be possible to collect a large amount of data on various tasks at various construction sites. It will be possible to formulate optimal road network establishment plans for complex local conditions by converting this information into big data. By collecting a large amount of data under various conditions of small-scale forest road construction and repair works using the methodology of this study, it is possible to estimate precise earthwork volume in road construction and repair works.

The disadvantage of SfM analysis is that it is computationally expensive and takes time to analyze. Still, a characteristic of SfM analysis is that it provides a point cloud with color information. Using color information for object identification is a significant advantage over other methods, such as LiDAR measurements, in forests with many different objects. SfM analysis in forests using UAVs can be used to evaluate the impact of human activities on the environment, such as vegetation change, and sediment transport.

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