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Point Cloud Data from Different Measurement Methods in Road Embankments

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Abstract: *In Japan, UAVs and 3D point cloud data are being introduced and utilized for simple and efficient maintenance and management of a wide area for earthwork structures that extend over a considerable distance due to i-Construction advocated by the Ministry of Land, Infrastructure, Transport and Tourism. By acquiring UAV and 3D point cloud data at the time of construction, it can be used as continuous data in case of deformation after construction or for daily inspections. However, the current standards don't sufficiently verify the effects of different measurement methods on earthwork structures and their characteristics. Therefore, point cloud data were acquired on the slope of a road embankment including a reinforced soil wall using three different methods: a laser-mounted UAV (laser UAV), a laser-unmounted UAV (UAV), and a terrestrial laser scanner (TLS). As a result, the TLS was able to acquire high-density point clouds for the steep slope of the reinforced earth wall, while the laser UAV was able to acquire high-density point clouds for the entire slope with a long extension, showing differences in point cloud density depending on the target earthwork structure. The laser UAV was able to acquire point clouds evenly throughout the entire extension, but the UAV showed differences in point cloud density on the left and right sides of the slope, centered on the road pavement surface, and the TLS tended to depend on installation position.*

Keywords: 3D point cloud data, Unmanned aerial vehicle (UAV), Terrestrial laser scanner (TLS)

1. INTRODUCTION

In Japan since 2016, the Ministry of Land, Infrastructure, Transport and Tourism has been promoting i-Construction, an initiative that aims to enhance productivity at construction sites by utilizing information and communications technology (ICT) and other digital technologies for all project processes, from pre-construction surveys and measurements to design, construction, and product maintenance. Starting in 2023, the use of building/construction information modeling and management (BIM/CIM) has become standard practice for government-managed civil engineering projects and other construction works, driving the adoption of three-dimensional models, including those using point cloud data [1]. For earthwork structures, which often extend over considerable distances, unmanned aerial vehicles (UAVs) and three-dimensional point cloud data are being introduced and utilized to enable simplified and efficient maintenance and management across large areas. Specifically, capturing UAV aerial imagery and point cloud data immediately after the completion of construction allows for the simplified and quantitative management of positional information and the assessment of post-construction changes.

Kikuchi et al. [2] summarized the accuracy characteristics of various point cloud methods, noting that laser detection yields insufficient point cloud data on steep natural slopes, while terrestrial laser scanning (TLS) struggles with insufficient data density on gentle slopes. Nagaya et al. [3] reported that increasing the UAV overlap rate improves point cloud accuracy for a given imaging area. They pointed out that factors such as slope and overlap rate in aerial imaging patterns affect the laser hit rates and the reproducibility of generated models. However, current Japanese standards [4], [5], [6] have not yet sufficiently verified the impact and characteristics of different measurement methods when they are applied to earthwork structures.

In this study, therefore, we acquired point cloud data using three methods—one involving a laser-equipped UAV (laser UAV), one involving a non-laser UAV (conventional UAV), and one involving a terrestrial laser scanner (TLS)—on the slopes of

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road embankments with a reinforced soil wall and a reinforced embankment. This report addresses onsite constructability, the density and characteristics of the collected point cloud for each earthwork structure, and the applicability of each method.

2. SURVEY SITE

The survey site was a slope with vegetation on a high-standard road embankment. This embankment has a three-layered structure with a planned height of 16.0 m, a gradient of 1:1.8, and an approximate length of 160 m (Photo 1). The target section includes a reinforced soil wall with a planned height of 4.6 m and a vertical face, and a reinforced embankment with a planned height of 10.7 m and a slope of 1:0.6. Poles for reducing bird roadkill are installed along the embankment crest, and wire ropes are installed along the median strip.



Photo 1. Road embankment at the survey site (photographed from the origin side)

3. ANALYSIS METHOD

The laser UAV used was the DJI Matrice 350, the conventional UAV was the Autel Robotics Evo II, and the TLS was the TOPCON GLS-2200.

As mentioned earlier, the accuracy of laser UAVs and conventional UAVs is known to vary depending on slope gradient and overlap ratio [2], [3]; additionally, the direction and altitude of aerial photography are known to affect accuracy. Therefore, this study compared three patterns of aerial photograph data: data captured only longitudinal to the road, data captured only transverse to the road, and data captured both longitudinal and transverse to the road. Regarding aerial photograph altitude, since flights at a constant aircraft altitude (home position altitude) vary depending on the location, it is generally recommended to conduct aerial photography at a constant ground-level altitude, flying along the terrain. Due to equipment specifications, only the laser UAV performed two aerial photography patterns: one at a constant altitude and the other at a constant height relative to the ground. As shown in Table 1, a total of 14 patterns were captured using the laser UAV and six patterns using the conventional UAV. The point cloud density and characteristics resulting from each aerial photography pattern were compared to determine differences. Point clouds were generated using DJI Terra V5.0.1 for the laser UAV analysis and Pix4D Mapper for the SfM-MVS analysis using the continuous photos acquired by the conventional UAV.

Table 1. Aerial survey patterns for laser UAVs and conventional UAVs

	Over Lap	Side Lap	Aerial photography direction	Altitude
Laser UAV-a	80%	30%	Longitudinal direction only	Above Ground Level
Laser UAV-b				Constant altitude
Laser UAV-c		60%	Longitudinal direction only	Above Ground Level
Laser UAV-d				Constant altitude
Laser UAV-e			Transverse direction only	Above Ground Level
Laser UAV-f				Constant altitude
Laser UAV-g			Longitudinal direction + Transverse direction	Above Ground Level
Laser UAV-h				Constant altitude
Laser UAV-i		80%	Longitudinal direction only	Above Ground Level
Laser UAV-j				Constant altitude
Laser UAV-k			Transverse direction only	Above Ground Level
Laser UAV-l				Constant altitude
Laser UAV-m			Longitudinal direction + Transverse direction	Above Ground Level
Laser UAV-n				Constant altitude
Conventional UAV-a	80%	60%	Longitudinal direction only	Constant altitude
Conventional UAV-b			Transverse direction only	
Conventional UAV-c			Longitudinal direction + Transverse direction	
Conventional UAV-d		80%	Longitudinal direction only	
Conventional UAV-e			Transverse direction only	
Conventional UAV-f			Longitudinal direction + Transverse direction	

4. RESULTS AND DISCUSSION

4.1 Differences in the characteristics of point clouds according to differences in measurement methods

Fig. 1 shows the color point clouds (left column) and point cloud densities (right column) acquired by each method, displayed as if viewed from directly above the site. In each subFig., the road pavement surface runs through the center from bottom to top, with slopes extending along the road section on the left and right. The bottom of each subFig. represents the origin side of the road, and the top represents the terminal side. The aerial photography patterns for the laser UAV-b and the conventional UAV-f are illustrated as representative examples of laser UAVs and conventional UAVs, respectively. Table 2 shows the minimum and maximum point cloud densities for each data acquisition pattern across the entire structure, the reinforced soil wall, and the reinforced embankment. Furthermore, while no point cloud gaps were observed for the wall surfaces

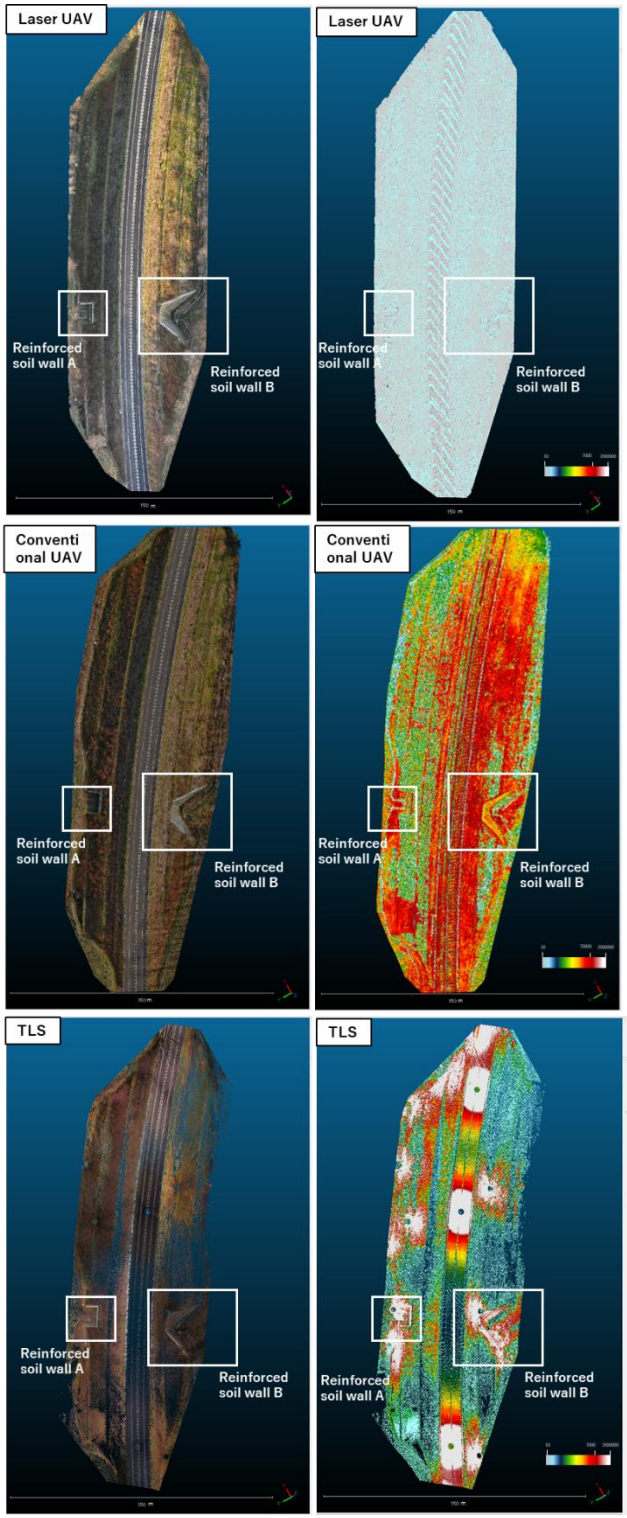


Figure 1. Point clouds of the target section acquired by each method (Top: Terminal side, Bottom: Origin side)

of the reinforced embankment, gaps were identified for the reinforced soil wall depending on the aerial survey pattern; these are also summarized in the table.

From Fig. 1 and Table 1, it can be said that the differences in point cloud characteristics associated with each measurement method are more pronounced than those associated with differences in aerial survey patterns. Therefore, we first describe the characteristics of point clouds obtainable by each measurement method. In each subFig. of Fig. 1 with a color scale, the gray indicates point cloud densities of 100 points/m² or less, while the gray to light blue indicates densities exceeding 100 points/m² up to 400 points/m². In the range exceeding 400 points/m², cooler colors indicate lower point cloud densities, warmer colors indicate higher densities, and white indicates even higher densities. The standard values specified in Japan's requirements for laser UAVs [4] are 10 to 100 points/m2 for terrain acquisition in areas with low vegetation impact and 100 points/m2 for product management and digital mapping at level 1000 (equivalent to a scale of 1:1000). The standard point densities for conventional UAVs [5] are classified as low at 0.01 points/m², standard at 4 points/m², and high at 100 points/m². While national specifications for TLS do not include density requirements [6], a separate manual [7] issued by the Chubu Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism specifies 4 points/m² for pre-construction initial surveys and 100 points/m² for product management. Thus, 100 points/m² can be considered a standard value for any measurement method.

4.1.1 Laser UAV

The point cloud acquired by the laser UAV was predominantly gray to light blue throughout and exhibited the lowest point density among the three methods (Fig. 1, Table 1). Fig. 1 shows that the majority of the slope appears light blue, while the majority of the paved surface appears gray, indicating a tendency for higher point cloud densities on the paved surface. Furthermore, on the paved surface, the point cloud densities vary as if diagonal lines are running from left to right. This variation coincides with the spacing width of two or three bird roadkill prevention poles, suggesting that the poles caused the differences in point cloud density. Furthermore, Table 1 shows that when the side overlap rate was low, the point cloud density tended to vary depending on direction from which the aerial photographs were taken. The point cloud density was lowest in the longitudinal direction, followed by the transverse direction and then by the combined longitudinal and transverse directions. For patterns other than the laser UAV-m and the laser UAV-n, the point cloud densities were higher for flights at variable ground clearance than at a constant 50m altitude. However, the data acquisition greatly improved when the side overlap rate or photography direction was changed. Therefore, the factors that most greatly affect point cloud density are considered to be these, in ascending order: side overlap rate, photography direction, and ground clearance. It is known that accuracy becomes uneven on high slopes exceeding 15m [8], [9] and that the greater is the elevation difference on the slope, the greater is the impact of that

difference. However, the elevation difference at the survey site was minimal, and its contribution was considered less significant than those of other factors.

4.1.2 Conventional UAVs

The point cloud acquired by the UAVs predominantly consists of data that correspond to warm colors, with no gray to light blue tones, indicating that a high density of 400 points/m² was achieved (**Fig. 1**). Differences in point cloud density are observed between the left and right slopes, centered along the road pavement surface. The right slope predominantly shows red tones, while the left slope exhibits yellow to red tones. The difference in point cloud density is likely due to the influence of solar radiation direction [10], [11]. The road extends southeastward and sunlight was shining from the southwest at the time of imaging, likely causing the difference in point cloud density between the left and right slopes. Furthermore, high-density white points are also observed on the paved surface, indicating that, similar to the results for the laser UAVs, higher-density point clouds were acquired on the pavement than on the slopes. Additionally, within the slopes, high-density point clouds are concentrated in berm areas, which suggests that higher densities occur in flat areas without significant gradients. In the conventional UAV results presented in Table 1, the point cloud density from the UAV-e aerial survey pattern is clearly excessive compared to the others and is therefore considered an error. The point cloud density of UAV-c, which captured data in both the longitudinal and the transverse directions, is higher than that of UAV-a (longitudinal only) and UAV-b (transverse only). However, the density for UAV-f (longitudinal and transverse directions) is lower than that of UAV-d (longitudinal only). These observed differences in point cloud density based on capture direction indicate the need for comparative analysis using a wider variety of aerial capture patterns.

4.1.3 TLS

The characteristics of point clouds acquired by TLS were often influenced by equipment placement (**Fig. 1**). Specifically, the point cloud density was highest near the TLS and decreased in a concentric pattern. Consequently, gaps in the point cloud were observed both immediately beneath the TLS and in areas far from the equipment. On the pavement surface, the point cloud density was lower at the median strip. Reports indicate that when measuring large, columnar objects with TLS, point cloud gaps may occur due to device characteristics and the surface rigidity of the measured object [12]. Therefore, wire rope posts, being columnar structures, are considered difficult to capture with point clouds.

Table 2. Minimum and maximum point cloud densities by data acquisition pattern for the overall area, the reinforced soil wall, and the reinforced embankment

	All	Reinforced soil wall A		Reinforced soil wall B
	Point cloud density(points/m^2)	Point cloud density(points/m^2)	Presence or absence of point cloud gaps	Point cloud density(points/m^2)
Laser UAV-a	1-513	19-207	Wall gaps in the wall running transversely across the road	90-227
Laser UAV-b	1-500	17-178	Wall gaps in the wall running transversely across the road	92-195
Laser UAV-c	1-938	17-248	Wall gaps in the wall running transversely across the road	105-291
Laser UAV-d	1-898	16-258	Wall gaps in the wall running transversely across the road	106-292
Laser UAV-e	1-1489	14-230	Wall gaps in the wall running longitudinally across the road	85-468
Laser UAV-f	1-1229	12-214	Wall gaps in the wall running longitudinally across the road	73-399
Laser UAV-g	1-1729	19-283	No Wall gaps	76-562
Laser UAV-h	1-1521	29-230	No Wall gaps	113-536
Laser UAV-i	1-1486	7-244	Wall gaps in the wall running transversely across the road	113-275
Laser UAV-j	1-1448	15-245	Wall gaps in the wall running transversely across the road	108-276
Laser UAV-k	1-1654	25-217	Wall gaps in the wall running longitudinally across the road	98-442
Laser UAV-l	1-11505	9-265	Wall gaps in the wall running longitudinally across the road	114-459
Laser UAV-m	1-1734	23-288	No Wall gaps	64-534
Laser UAV-n	1-1818	36-260	No Wall gaps	116-610
Conventional UAV-a	1-4833	2-2691	Wall gaps in the wall running longitudinally across the road	279-3459
Conventional UAV-b	1-4816	5-2965	Wall gaps in the wall running transversely across the road	257-3518
Conventional UAV-c	1-5578	218-3618	Partial gap	1032-4006
Conventional UAV-d	1-6740	6-3653	Partial gap	759-4376
Conventional UAV-e	1-1548266	1-170	Wall gaps	28-1700
Conventional UAV-f	1-5638	29-3258	Partial gap	931-3740
TLS	1-278396	6086-58076	Partial gap	16-91280

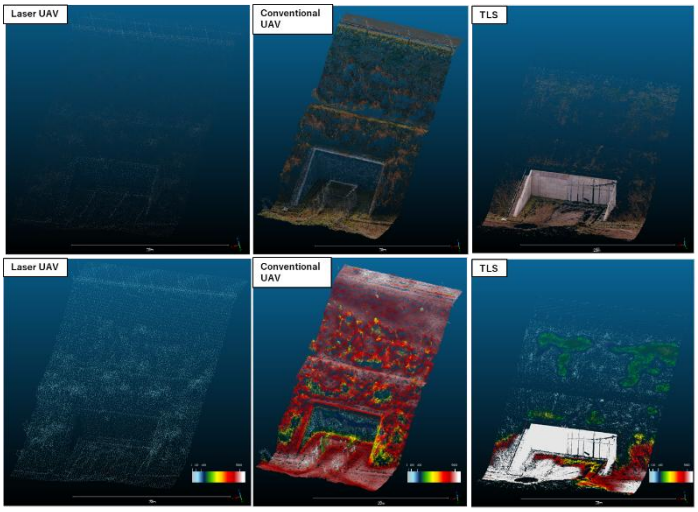


Figure 2. Point clouds of the reinforced soil walls acquired by each method

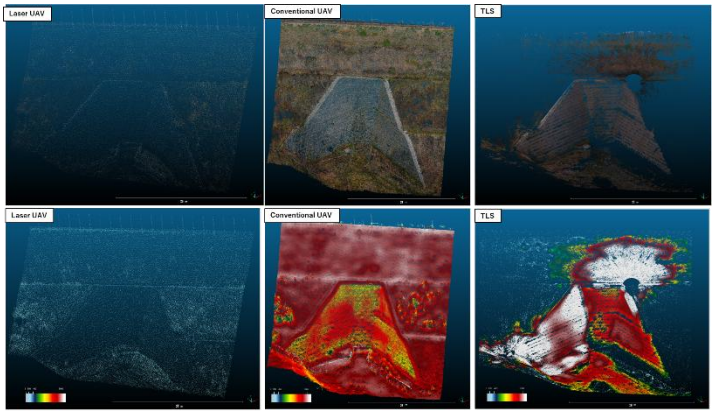


Figure 3. Point clouds of the reinforced embankment acquired by each method

4.2. Characteristics of point cloud density in reinforced so il walls and reinforced embankments

Fig. 2 shows the color point cloud (top) and point cloud density (bottom) of the reinforced soil wall and the slope from the wall to the road pavement surface above it. **Fig. 3** shows the color point cloud (top) and point cloud density (bottom) of the slope from the reinforced embankment to the road pavement surface directly above it.

4.2.1. Laser UAV

Fig. 2 shows that the laser UAV-b exhibits low point density (≤100 points/m²) or point cloud gaps in the gray areas shown as the vertical walls. In verifying whether this trend occurs in other aerial survey patterns, point cloud gaps were observed on the reinforced soil walls transverse to the road when the survey direction was only longitudinal along the road (Fig. 2). Conversely, point cloud gaps were observed on the reinforced soil wall longitudinally along the road when the survey direction was only transverse to the road (Table 1). No point cloud gaps were observed when aerial surveys were conducted in both the longitudinal and the transverse directions. This is considered to be an effect of the laser UAV's operating principle. Laser UAVs acquire 360° data, but data accuracy is known to be low in the direction transverse to the flight path [13], [14]. This effect is presumed to be responsible. No point cloud gaps were observed on the reinforced embankment. However, the embankment section with a 1:0.6 slope showed a tendency toward lower point cloud density than that of the 1:1.8 slope embankment (Fig. 3). This is likely because the laser UAV scanning angle is 30°, which makes it easier to acquire data on slopes with some inclination than on vertical walls.

Furthermore, the point cloud density was observed to differ depending on the aerial survey direction. The point cloud density in descending order is as follows: longitudinal and cross-sectional direction, cross-sectional direction only, and longitudinal direction only. This is consistent with the results of Section 4.1.

4.2.2. Conventional UAV

The point cloud density for the reinforced soil walls measured by conventional UAV was 100–400 points/m², which was higher than that obtained by laser UAV (Fig. 2). However, point cloud gaps were observed on the wall surfaces in all aerial survey patterns. Furthermore, with the conventional UAV, when the side overlap rate was 60%, gaps were observed in the point cloud data on the reinforced soil wall longitudinally along the road for the pattern where the aerial survey direction was only longitudinal along the road. Conversely, for the pattern where the aerial survey was only transverse to the road, the point cloud had gaps on the soil wall transverse to the road, yielding results opposite those of the laser UAV. This is thought to be due to the conventional UAV camera gimbal being fixed at -90°. Reports [15], [16] indicate that incorporating oblique photographs is beneficial for steep cliff terrain, such as overhangs. Therefore, including oblique photographs may improve the results. For reinforced embankments, no point cloud gaps were observed in any aerial survey pattern (**Fig. 3**), and the point cloud density was 257 points/m² or higher. This indicates that a high-density point cloud was successfully acquired (Table 2).

4.2.3. TLS

Figs. 2 and **3** show that the TLS exhibited high point cloud densities on the vertical wall close to the installation points. For the reinforced soil walls, the slope break points were also accurately represented as being at right angles. However, some point cloud gaps were observed at the boundary between the reinforced soil walls and the ground (**Fig. 2**). Furthermore, the point cloud density on the slope tended to decrease with

increasing distance from the TLS equipment. For the reinforced embankment, the point cloud density in the embankment section was high, with colors ranging from red to white. However, similar to the results for the reinforced soil wall, some point cloud gaps were observed at the boundary between the reinforced embankment and the ground (**Fig. 3**).

4.3. Comparison of work efficiency and maximum point cloud density among the three methods

Sections 3.1 and 3.2 identified how the impact, characteristics, and trends of point cloud density at structures differ according to the measurement method. We revealed that it is not only data accuracy that can serve as a decision criterion for field implementation; so can operational efficiency metrics like flight time and point cloud processing time. Therefore, in Table 3 we summarized the aerial survey time and point cloud processing time for different aerial survey patterns using laser UAV and conventional UAV.

4.3. Laser UAV

The data acquisition time and point cloud processing time at the site were as follows, in increasing order: laser UAV, conventional UAV, TLS. For the laser UAV, depending on the overlap rate and aerial survey direction, the entire process from data acquisition to point cloud generation was completed in 30 minutes to 4 hours. For the laser UAV, when the overlap was 80%, the side overlap was 60% or less, and only one aerial survey direction pattern was used, the combined flight time and point cloud processing time was under 1 hour. This offers the advantage of the immediate verification of the point cloud data after the aerial survey. In addition to the side overlap rate increasing, the aerial survey time and point cloud processing time increased for certain aerial survey directions. Surveying only transverse to the road resulted in higher point cloud densities than those for surveying only longitudinally (Table 2), but the aerial survey time and point cloud processing time were greater (Table 3). Slight differences in point cloud density were observed between aerial photography at varying ground clearance heights versus at a constant height. Aerial photography at varying ground clearance heights resulted in higher point cloud densities (Table 2), but increased the aerial photography time and point cloud processing time. This confirmed tradeoffs between point cloud density and aerial photography time and between point cloud density and point cloud processing time.

4.3.2. Conventional UAV

With the conventional UAV, the entire process from data acquisition to point cloud generation took only a few hours (2 to 6 hours). For laser UAV and TLS, the point cloud processing time was about two to three times the data acquisition time. However, with the conventional UAV, the point cloud processing time tended to be longer for some aerial survey patterns, requiring five to ten times the acquisition time, or more. Furthermore, the point cloud processing time was shorter when the side overlap was set to a high value of 80%. For the conventional UAVs, the aerial photography time was shorter when only transverse aerial photography was performed, yielding results opposite those of laser UAVs. Additionally, the point cloud processing time was shorter when photographs taken in the longitudinal direction and those taken in the transverse directions were used for point cloud processing.

Table 3. Data acquisition time and point cloud processing time for laser UAV, conventional UAV, and TLS

	Flight Time	Point cloud processing time
Laser UAV-a	5m48s	12m27s
Laser UAV-b	5m6s	8m25s
Laser UAV-c	11m32s	29m23s
Laser UAV-d	10m30s	26m45s
Laser UAV-e	19m14s	53m31s
Laser UAV-f	16m10s	45m32s
Laser UAV-g	30m46s	1h28m18s
Laser UAV-h	26m40s	1h12m24s
Laser UAV-i	21m24s	1h54s
Laser UAV-j	19m42s	57m49s
Laser UAV-k	30m22s	1h40m41s
Laser UAV-l	29m14s	1h25m55s
Laser UAV-m	51m46s	3h3m59s
Laser UAV-n	48m56s	3h16m12s
Conventional UAV-a	21m30s	5h1m40s
Conventional UAV-b	16m34s	4h40m50s
Conventional UAV-c	38m4s	2h3m33s
Conventional UAV-d	16m20s	4h8m57s
Conventional UAV-e	21m8s	4h11m21s
Conventional UAV-f	37m28s	3h7m25s
TLS	5h	15h

4.3.3. TLS

TLS exhibited the longest data acquisition time and the longest point cloud processing time. The generation of point cloud data is influenced by the distance between the measuring equipment and the target object, the laser irradiation angle, and the reflectivity of the target object in the case of laser UAVs and TLS [17] and by the number of photographs in the case of conventional UAVs. Therefore, in selecting a method for a site, it is necessary to consider both the desired information and the operational efficiency.

5. SUMMARY

The results of this report are consistent with prior research by Kikuchi et al. [1], showing that point cloud density is low for steep slopes like reinforced soil walls when measured by laser

UAV and is high when measured by TLS. For laser UAVs and conventional UAVs, point cloud density gaps were observed on slopes, and gaps were observed on reinforced soil walls for some measurement directions. Therefore, when point cloud data on long slopes with multiple earthwork structures is acquired, it is necessary to eliminate data gaps and variability by combining measurement methods or dividing the slope into sections for partial data acquisition. Furthermore, since the point cloud density decreased due to the presence of wire rope posts and bird roadkill prevention poles, it is preferable to perform measurements on slopes free of such road accessories during the pre-construction phase.

Surveys using laser UAVs, conventional UAVs, and TLSs are expected to see increased use going forward, as they capture information over an area and reduce working time compared to conventional land surveys. Acquiring point cloud data immediately after construction allows positional information to be stored as data, enabling its use for maintenance task handover and disaster response. However, capturing all of multiple earthwork structures within a long extension in a single acquisition is difficult. It is necessary for both the contractor and the client to understand the characteristics of the data obtainable for each earthwork structure and the differences arising from the acquisition equipment used. Furthermore, while point cloud data is often processed into triangulated irregular networks (TINs) or digital elevation models (DEMs) for use, it is important to bear in mind that, depending on the point cloud density and the height of aerial photography, information between points may be interpolated during processing, potentially resulting in data that differs from reality. Moving forward, we aim to summarize how differences in measurement techniques affect the impact and characteristics of measurements for each earthwork structure when point cloud data are processed into TINs, DEMs, or digital surface models (DSMs).

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