# Landslide Displacement Observation in A Mountainous Area using Temporal Geo-spatial Data Acquired from Drone Mapping

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***Abstract*:** *With the advancement of drone autonomous flight performance and observation sensor technology, terrain-following mapping techniques have been widely applied, enabling stable mapping and 3D terrain model generation with consistent ground sampling distance (GSD), even in mountainous areas with steep slopes and elevation differences. Furthermore, the introduction of smart oblique imaging, which combines conventional nadir and oblique aerial imaging, has significantly improved the accuracy of drone mapping and 3D terrain models in mountainous regions. This study proposes a methodology for periodic landslide disaster monitoring in mountainous areas by utilizing state-of-the-art drone photogrammetry technologies, such as terrain-following mapping, smart oblique imaging, and time-series mapping analysis.*

*Keywords:* *Time Series, Drone Mapping, Landslide, Ground Displacement Monitoring*

## Introduction

In September 2022, Typhoon Hinnamnor triggered widespread slope failures in the Mt. Toham region of Gyeongju, Gyeongsangbuk-do Province. Approximately 24 distinct landslides were recorded, damaging transportation routes, agricultural land, and forested slopes. In July 2023, prolonged torrential rainfall caused over 2 trillion KRW in damages nationwide, particularly concentrated in the central regions such as Chungcheong and Gyeongbuk. More recently, in July 2025, a five-day rainfall event resulted in at least 30 fatalities and extensive infrastructure failures, including inundated residential areas, collapsed farmlands, and damaged transportation networks across Sancheong, Gapyeong, and Seosan.

The recurrence of such events demonstrates a clear need for high-resolution and high-frequency monitoring frameworks. Traditional post-disaster assessment methods—such as expert-led ground surveys and aerial reconnaissance—are time-consuming, costly, and often hazardous due to inaccessible terrain conditions. Satellite-based monitoring, although valuable for regional assessments, lacks the spatial resolution (typically 10–30 m for Sentinel-2 or Landsat) and revisit frequency required to capture localized slope failures in near-real time (Casagli et al., 2017). Thus, there is a pressing demand for cost-effective and precise approaches to monitor landslide-prone slopes with sufficient spatial detail and temporal consistency.

Unmanned aerial vehicle (UAV) photogrammetry has recently emerged as a transformative technology for natural hazard monitoring. Equipped with high-resolution RGB and multi-spectral sensors, UAVs enable rapid acquisition of imagery with centimeter-level ground sampling distance (GSD). Structure-from-Motion (SfM) photogrammetry allows these images to be processed into digital surface models (DSMs), digital terrain models (DTMs), and dense point clouds, providing unprecedented detail in topographic representation (Westoby et al., 2012). The integration of real-time kinematic (RTK) positioning further reduces reliance on ground control points (GCPs), ensuring positional accuracy within a few centimeters even in rugged environment.

Two key innovations particularly enhance the applicability of UAV photogrammetry in mountainous regions:

- Terrain-following flight planning ensures a uniform GSD across highly variable terrain, reducing scale distortions and improving DSM quality.
- Smart oblique imaging, which combines nadir and oblique perspectives, increases overlap on steep slopes and improves 3D reconstruction fidelity in areas with large elevation differences (Nesbit & Hugenholtz, 2019).

These advances have proven especially beneficial for disaster-prone terrains where slope instability occurs on complex geomorphological surfaces.

Numerous studies have demonstrated the effectiveness of UAV-based photogrammetry for landslide investigation. For instance, Lucieer et al. (2014) used UAV imagery to quantify erosion rates in Tasmania, while Giordan et al. (2018) highlighted UAV photogrammetry as a rapid-response tool in post-earthquake landslide mapping in Italy.

Despite these advances, several limitations remain unresolved:

- Temporal monitoring: Most studies focus on single-event assessments rather than systematic, time-series monitoring across multiple seasons.
- Steep terrain challenges: Vertical imaging alone is insufficient to capture slope geometry in mountainous areas, leading to underestimation of volumes and slope angles.
- Integration with geospatial analysis: Few studies have combined UAV photogrammetry with geographic information system (GIS)-based change detection for quantitative assessment of displacement.

These gaps highlight the need for robust workflows that combine UAV photogrammetry, oblique imaging, and time-series geospatial analysis to provide continuous monitoring of slope stability.

The objective of this research is to establish a comprehensive UAV-based framework for monitoring rainfall-induced landslides in mountainous environments. Specifically, this study aims to:

- Apply terrain-following flight planning and smart oblique imaging for high-accuracy 3D reconstruction of landslide-prone slopes.
- Assess the positional accuracy of datasets generated from different photogrammetric software (Pix4Dmapper, Agisoft Metashape, DJI Terra) using RTK-enabled UAV imagery validated against GNSS checkpoints.
- Conduct time-series analysis through orthoimage comparison and point cloud profiling to detect potential slope displacement.
- Evaluate the feasibility of UAV-based monitoring as a tool for disaster risk reduction and early warning in Korea's mountainous regions.

## Methodology

### a. Study area

The study was conducted in the Mt. Toham region of Gyeongju, located in Gyeongsangbuk-do Province, southeastern Korea (Figure 1). Mt. Toham rises to an elevation of 745 m above sea level and is characterized by steep slopes, highly dissected ridges, and a mixture of granite and metamorphic rock formations. The terrain exhibits slope angles frequently exceeding 35–40°, rendering the area particularly susceptible to rainfall-induced slope failures. During Typhoon Hinnamnor in September 2022, the Mt.

Toham area experienced at least 24 reported landslide events of varying sizes, ranging from shallow debris flows to deeper-seated rotational failures. These events resulted in the partial blockage of mountain roads, soil erosion in agricultural fields, and localized damage to cultural heritage sites around Gyeongju. A deep-seated landslide site near Hwangyong-dong (Parcel 116-5) was selected as the study area due to its large affected surface, steep inclination, and continuing risk of slope instability. Geological surveys indicated highly fractured bedrock and weak soil horizons, both of which increase susceptibility to landslide reactivation under heavy rainfall or seismic loading.

The site was therefore considered representative of rainfall-induced slope hazards in Korea's mountainous regions. Its complex topography, frequent extreme weather exposure, and potential socioeconomic impacts made it an ideal location for testing UAV-based monitoring methodologies.


Figure 1: Location of the study area: Mt. Toham in Gyeongju, Korea.

## b. Methodology

In the time-series landslide observation method of this study, the first step was to select and extract fixed reference points on the ground which were clearly identifiable in the imagery, considering the challenging accessibility of the mountainous terrain. The subsequent step involved utilizing the ortho-photo maps and 3D terrain cross-section data generated through drone-based mapping to monitor centimeter-level positional changes over successive observation periods. This approach enabled the analysis of the potential for further landslide occurrences based on temporal changes in the terrain morphology.

From September 2024 to August 2025, approximately 2,000 aerial photographs were acquired and processed into ortho-images, point clouds, and 3D models. Inaccessible terrain required reference features such as large boulders or dead trees for positional consistency. The generated 3D models were then compared over time to monitor centimeter-level displacements.

**c. Used drone and Data Acquisition**

A DJI Matrice 350 RTK unmanned aerial vehicle was selected for this study due to its robust stability in mountainous flight conditions, extended flight endurance, and compatibility with high-resolution sensors. The platform was equipped with a Zenmuse P1 optical payload, featuring:

- Sensor resolution: 45 megapixels (full-frame CMOS sensor)
- Lens focal length: 35 mm with mechanical global shutter
- Image size: 8,192 × 5,460 pixels
- Ground sampling distance (GSD): 1.15 cm/pixel (nadir) and 2.14 cm/pixel (oblique) at 120 m altitude

The RTK module provided real-time correction signals, reducing positioning errors to sub-decimeter accuracy. This allowed data collection without an extensive network of ground control points (GCPs), thereby saving field time and ensuring higher operational efficiency.

UAV flights were conducted across six campaigns from September 2024 to August 2025, capturing seasonal variations and enabling time-series monitoring. The DJI Pilot 2 software was used to design automated flight missions. To ensure consistency, identical flight parameters were applied across campaigns, including:

- Altitude: 120 m above ground level
- Forward and side overlap: 80% / 80%
- Flight speed: ~10 m/s

Figure 2: DJI Matrice 350 / Built-in Zenmuse P1

Both nadir and oblique imaging strategies were employed. The nadir images supported ortho-photo generation, while oblique images enhanced 3D reconstruction of steep slopes and vertical scarps. In total, 2,086 images were acquired across the six missions. Weather conditions were carefully monitored, and flights were conducted only under low wind (<5 m/s) and favorable visibility to ensure data quality (Table 1).

Table 1: Flight Planning for Drone Mapping

| Imaging Method | Flight Height (m) | Imaging Angle (°) | Overlap Rate (%) | Coverage (㎢) | Num. of Images | GSD (cm/pixel) |
|---|---|---|---|---|---|---|
| Obli. & Nar. terrain follow | 120 | Nadir: 90<br>Oblique: 45 | 80 | 0.14 | 2,086 | Nad. 1.15<br>Obli. 2.14 |

## Results and Discussion

The experimental results are presented in three parts: (i) accuracy assessment of UAV photogrammetric datasets, (ii) 3D model generation and site characterization, and (iii) time-series change detection. Together, these results validate the effectiveness of RTK-enabled UAV photogrammetry for monitoring landslide-prone terrain.

### a. Accuracy Assessment of UAV Photogrammetric Datasets

Accuracy validation was conducted by comparing UAV-derived coordinates against GNSS-surveyed checkpoints. Five independent checkpoints were located along National Road 945, adjacent to the landslide site. These checkpoints were measured with dual-frequency GNSS receivers ensuring centimeter-level reference accuracy.

The Root Mean Square Error (RMSE) values for each drone mapping software and campaign date are summarized in Table 2.

On September 13, 2024, the following results were obtained:

- Pix4Dmapper: RMSEs of 0.019 m (X), 0.028 m (Y), and 0.241 m (Z).
- Metashape: RMSEs of 0.013 m (X), 0.030 m (Y), and 0.356 m (Z).
- DJI Terra: RMSEs of 0.009 m (X), 0.086 m (Y), and 0.122 m (Z).

On October 25, 2024, results showed similar trends:

- Pix4Dmapper: 0.024 m (X), 0.012 m (Y), 0.308 m (Z).
- Metashape: 0.030 m (X), 0.045 m (Y), 0.878 m (Z).
- DJI Terra: 0.014 m (X), 0.012 m (Y), 0.110 m (Z).

These results highlight two key findings:

- Horizontal accuracy was consistently within 0.02–0.03 m for all software, well within the tolerances required for engineering-scale monitoring.
- Vertical accuracy exhibited greater variability, with DJI Terra outperforming other platforms. Its elevation RMSE of ~0.11–0.12 m was approximately three times smaller than Metashape's ~0.35–0.87 m errors.

Table 2: Accuracy Assessment Results of RTK Drone mapping (25-Oct. 2024)

| CPs | Pix4Dmapper | | | Terra | | | Metashape | | |
|---|---|---|---|---|---|---|---|---|---|
| | dX(m) | dY(m) | dZ(m) | dX(m) | dY(m) | dZ(m) | dX(m) | dY(m) | dZ(m) |
| 1 | -0.021 | 0.047 | -0.314 | -0.003 | -0.190 | 0.263 | 0.020 | -0.045 | 0.548 |
| 2 | -0.009 | 0.017 | -0.236 | 0.004 | -0.009 | 0.019 | 0.003 | -0.012 | 0.035 |
| 3 | -0.031 | 0.009 | -0.222 | 0.016 | -0.017 | 0.059 | 0.006 | 0.024 | 0.577 |
| 4 | -0.016 | 0.013 | -0.223 | 0.003 | 0.004 | 0.018 | 0.020 | 0.002 | 0.004 |
| 5 | 0.001 | -0.035 | -0.188 | 0.009 | 0.028 | -0.035 | 0.007 | 0.042 | -0.016 |
| RMSE | 0.019 | 0.028 | 0.241 | 0.009 | 0.086 | 0.122 | 0.013 | 0.030 | 0.356 |

Several factors contributed to accuracy variation:

- Pix4Dmapper exhibited slight vertical biases, possibly due to interpolation methods in dense point cloud generation.

- Metashape struggled with steep, shadowed slopes, resulting in larger elevation discrepancies.
- DJI Terra benefited from seamless integration with DJI flight metadata and optimized calibration routines.

Overall, the results confirm that DJI Terra provided the most reliable outputs for subsequent analysis, particularly in elevation-sensitive applications such as landslide monitoring.

**b. Ortho-image and 3D Model Generation**

High-resolution ortho-images were generated for each campaign at a GSD of approximately 2 cm. The mosaics displayed clear delineation of slope morphology, including scarps, talus deposits, and drainage channels. Field validation confirmed that visible features in the ortho-images corresponded with observed ground conditions.

Dense point clouds and DSMs revealed detailed topography of the landslide site. Vegetation filtering allowed extraction of DTMs, which emphasized bare-earth slope geometries. Figure 3 illustrates examples of ortho-images and 3D models for the Hwangyong-dong site.

The 3D models facilitated quantitative assessment of slope metrics:

- Average slope angle: 35~40°.
- Maximum slope angle: ~47° in scarp regions.
- Landslide area: ~1.8 ha delineated from DSMs.
- Collapse volume: 21,244 m³, estimated using cut-and-fill analysis between DSM and DTM.
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(a) Ortho-image (b) 3D Model

Figure 3. Ortho-image (left) and 3D Model (right) of Landslide Site

**c. Time-Series Change Detection**

The core objective of this study was to assess the feasibility of UAV-based time-series monitoring. Two complementary approaches—ortho-image comparison and point cloud profiling—were employed to detect potential displacement.

Successive ortho-images from September and October 2024 were co-registered with GNSS checkpoints to ensure consistency. Visual and quantitative comparisons revealed no significant changes in stable reference features such as large boulders and exposed bedrock. Vegetation areas exhibited minor differences due to seasonal variations in canopy cover, but these did not correspond to geomorphic changes.

Point cloud transects were extracted along slope-normal directions. Profiles compared cross-sections of the terrain at two time steps.

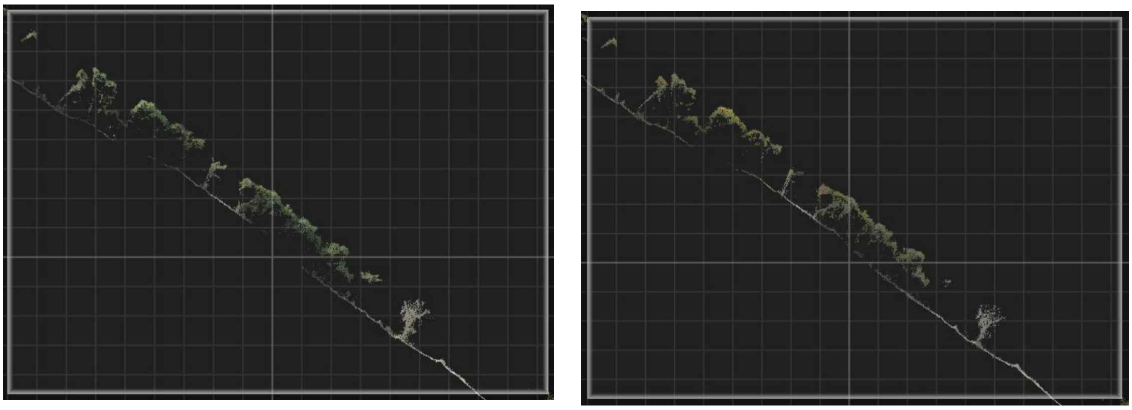
Results indicated:

- Minor elevation differences (<5 cm) attributable to vegetation growth and seasonal litter accumulation.
- No discernible subsidence, bulging, or crack widening in the main landslide body.
- Stable slope geometry across the 12-month monitoring period.

These findings suggest that while the site remains geo-morphologically sensitive, no measurable reactivation occurred during the study period. Repeated cut-and-fill calculations across all six campaigns consistently estimated landslide volume near 21,000–22,000 m³. This consistency further confirmed the absence of large-scale mass movement during the monitoring timeframe.


(a) Bedrock (b) Fallen tree trunk

Figure 4. Ground Target-based Displacement Analysis



(a) 3D Terrain Cross-section (13-Sept. 2024) (b) 3D terrain Cross-section (25-Oct. 2024)

Figure 5. Ground Displacement Monitoring Using 3D Terrain Cross-sectional Analysis

**d. Data Visualization and Interpretation**

High-resolution ortho-images (2 cm GSD) were invaluable for visual interpretation. For instance, tension cracks near the scarp crest were visible in ortho-photos, enabling preliminary assessment of slope stability risks. Such detail would not have been attainable with satellite imagery. 3D mesh models derived from dense point clouds provided immersive visualization of terrain conditions. These models enabled interactive exploration of slope morphology, which could be leveraged by local authorities for hazard communication and decision-making. All ortho-images and DSMs were integrated into a GIS platform for spatial analysis. Layers included slope angle maps, aspect classification, and hydrological flow paths. This integration demonstrated the potential for combining UAV data with broader geospatial datasets in multi-hazard risk assessments.

**e. Summary of Findings**

The results can be summarized as follows:

- UAV-based photogrammetry achieved centimeter-level horizontal accuracy and sub-decimeter vertical accuracy, validating its reliability for landslide monitoring.
- Ortho-images and 3D models provided detailed slope metrics, with a collapse volume of ~21,244 m³ identified.
- Time-series monitoring across six campaigns revealed negligible displacement, confirming slope stability during the observation period.

- DJI Terra outperformed other photogrammetric platforms in vertical accuracy, highlighting the importance of software selection.
- UAV-derived datasets proved highly compatible with GIS-based hazard assessment frameworks, underscoring their operational value.

**Conclusions**

This study demonstrated the applicability of advanced drone photogrammetry and time-series analysis for monitoring landslides in mountainous regions.

Approximately 2,000 drone images were acquired between September 2024 and summer 2025, generating 3D terrain models and ~2 cm resolution maps. These enabled time-series displacement monitoring through 2D ortho-images and 3D models.

The study area showed an average slope of ~35–40°, a landslide-affected area of ~1.8 ha, and a collapsed volume of 21,244 $m^3$. No significant displacement was detected during the observation period.

The findings suggest that RTK drone-based photogrammetry is effective for high-precision landslide monitoring in mountainous regions and can support disaster management and early-warning systems.

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