HOKKAIDO UNIVERSITY

Title	Rapid Debris Volume Estimation Using UAV-Based 3D Point Clouds : Validation Experiments and Application to the 2024 Noto Peninsula Earthquake
Author(s)	Wang, Xin; Dang, Ji
Relation	Proceedings of the 10th International Symposium on Reliability Engineering and Risk Management (ISRERM 2026), June 28 - July 1, 2026, Sapporo, Japan
Citation	Proceedings of the 10th International Symposium on Reliability Engineering and Risk Management (ISRERM 2026)
Issue Date	2026-07-01
Doc URL	https://hdl.handle.net/2115/100457
Type	conference paper
File Information	C000151_1.pdf

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

10th International Symposium on Reliability Engineering and Risk Management (*ISRERM 2026*),
28 June-01 July 2026, Sapporo, Japan
Kitahara, T., Miyamori, Y. & Beer, M. (editors)

Rapid Debris Volume Estimation Using UAV-Based 3D Point Clouds: Validation Experiments and Application to the 2024 Noto Peninsula Earthquake

Xin Wang[1,] * and Ji Dang[2]

[1]*Division of Architecture and Civil Engineering, Ashikaga University, Tochigi, Japan.*
E-mail: wang.xin@g.ashikaga.ac.jp
[2] *Dept. of Civil & Environment Engineering Graduate School of Science and Engineering, Saitama, Japan.*
E-mail: dangji@mail.saitama-u.ac.jp

Rapid and accurate estimation of debris volume is crucial for effective disaster response and recovery planning. In recent years, unmanned aerial vehicles (UAVs) combined with photogrammetry-based 3D point cloud reconstruction have emerged as promising tools for large-scale damage assessment. However, the reliability of debris volume estimation is affected by multiple factors, including UAV flight conditions, point cloud generation methods, and parameter settings in data processing, which remain insufficiently validated. This study proposes a practical framework for rapid debris volume estimation by integrating controlled validation experiments and real-world application. First, a series of experiments using an artificial debris model composed of stacked cardboard boxes were conducted to quantitatively evaluate the influence of UAV flight altitude, flight path, modeling approaches, and ground estimation parameters on volume estimation accuracy. Second, the proposed methodology was applied to UAV data acquired in the Ukai district of Suzu City following the 2024 Noto Peninsula Earthquake to assess its applicability under complex field conditions. The results demonstrate that circular flight paths and tiled point cloud models with smoothing significantly improve estimation accuracy and stability. In real disaster scenarios, the presence of uneven terrain, dispersed debris, and boundary ambiguity introduces additional challenges that are not fully captured in controlled experiments. Based on these findings, practical guidelines for reliable debris volume estimation in post-disaster environments are discussed.

Keywords: UAV, debris volume estimation, 3D point cloud, photogrammetry, disaster assessment, 2024 Noto Peninsula Earthquake.

1 Introduction

Large-scale natural disasters such as earthquakes and floods often generate massive amounts of debris, posing significant challenges to emergency response and recovery operations. Rapid and accurate estimation of debris volume is essential for planning debris removal, allocating resources, and ensuring the efficiency of rescue activities. However, conventional ground-based survey methods are time-consuming, labor-intensive, and often impractical in hazardous environments.

Recent advances in unmanned aerial vehicles (UAVs) and photogrammetry have enabled efficient acquisition of high-resolution aerial images, from which dense three-dimensional (3D) point cloud models can be reconstructed. These technologies provide a promising approach for large-scale and rapid assessment of disaster-affected areas. Several studies have explored the use of UAV-based point clouds for damage mapping and debris estimation, demonstrating their potential for practical applications (e.g., Sithole and Vosselman,2004; Nex and Remondino, 2014; Zhou et al., 2018]) Despite these advancements, the accuracy and reliability of debris volume estimation remain highly dependent on various factors, including UAV flight conditions, image acquisition strategies, point cloud reconstruction methods, and parameter settings in data processing. In many existing studies, these factors are not systematically evaluated, making it difficult to establish standardized workflows for practical use. Furthermore, there exists a gap between controlled experimental validation and real-world disaster applications. While experimental studies can isolate individual factors affecting estimation accuracy, actual disaster environments involve complex conditions such as uneven terrain, dispersed debris, and ambiguous boundaries between debris and surrounding structures.

To address these challenges, this study aims to develop a reliable and practical framework for debris volume estimation by integrating validation experiments and real disaster application. Specifically, controlled experiments using an artificial debris model are conducted to systematically evaluate key factors influencing estimation accuracy. The validated methodology is then applied to UAV data acquired in the Ukai district of Suzu City following the 2024 Noto Peninsula Earthquake. By comparing experimental findings with field application results, this study provides insights into the applicability, limitations, and practical considerations of UAV-based debris volume estimation.

2 Methodology

2.1 *Overall workflow*

The overall workflow of the proposed debris volume estimation method consists of four main steps: (1) UAV-based image acquisition, (2) 3D point cloud reconstruction, (3) ground surface estimation and debris extraction, and (4) volume calculation. A structure-from-motion (SfM) approach is employed to generate dense point clouds from aerial images, followed by geometric processing using an open-source library.

2.2 *UAV data acquisition*

Two types of UAV datasets were used in this study: controlled experimental data and real disaster data. In the validation experiments, aerial images were acquired at low altitudes (5 m and 10 m) using different flight paths, including circular (around) and linear (above) trajectories. These conditions were designed to evaluate the influence of image acquisition strategies on reconstruction quality.

In the field application, UAV surveys were conducted in the Ukai district of Suzu City after the 2024 Noto Peninsula Earthquake. Images were captured at an altitude of approximately 116 m, covering an area of about 0.5 km². A total of several hundred high-resolution images were collected within a short flight duration.

2.3 *Point cloud reconstruction*

Three different approaches were employed for generating 3D point cloud models:

(1) Direct generation from images
(2) Generation via tiled 3D mesh models
(3) Tiled models with additional smoothing processing

The second approach enables uniform point density by controlling the pixel size during model conversion, while the third approach further reduces noise and irregular surface fluctuations. The reconstruction process was conducted using photogrammetry software, and high-density point clouds were generated for subsequent analysis.

2.4 *Ground estimation and debris extraction*

Ground surface estimation was performed using the RANSAC-based plane fitting algorithm implemented in the Open3D library. The algorithm identifies a dominant planar surface within the point cloud by iteratively sampling subsets of points and estimating plane parameters.

After estimating the ground plane, points located above the plane were classified as debris. To improve robustness, statistical outlier removal was applied to eliminate noise points based on the distance distribution of neighboring points. Additionally, voxel-based downsampling was used to reduce computational cost while preserving geometric features.

2.5 *Volume calculation*

The debris volume was calculated using a Delaunay-based 2.5D triangulation method. The extracted debris points were projected onto a horizontal plane, and a triangular mesh was constructed. The volume was then obtained by integrating the vertical distance between the mesh surface and the estimated ground plane.

This method provides a balance between computational efficiency and estimation accuracy, making it suitable for rapid assessment in post-disaster scenarios.

3 Validation experiments

To evaluate the accuracy of the proposed method, a controlled experiment was conducted using an artificial debris model. The model consisted of 162 cardboard boxes stacked to form a mound with a known volume of approximately 6.5 m³ as shown in Figure 1. This setup allowed direct comparison between estimated and true volumes.

The results indicate that UAV flight conditions significantly affect the quality of the reconstructed point cloud. Circular flight paths (around) provided better coverage and more stable reconstruction compared to linear paths (above), even with fewer images. Lower altitude flights improved spatial resolution but also increased the risk of noise due to limited viewing angles. The locations of camera are shown in Figure 2.

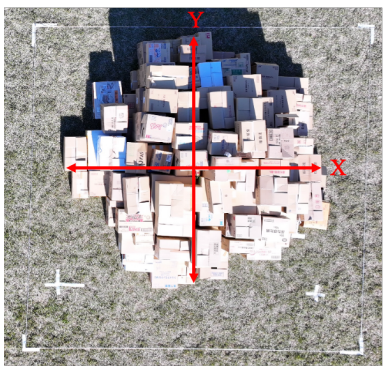


Figure 1. The artificial debris model

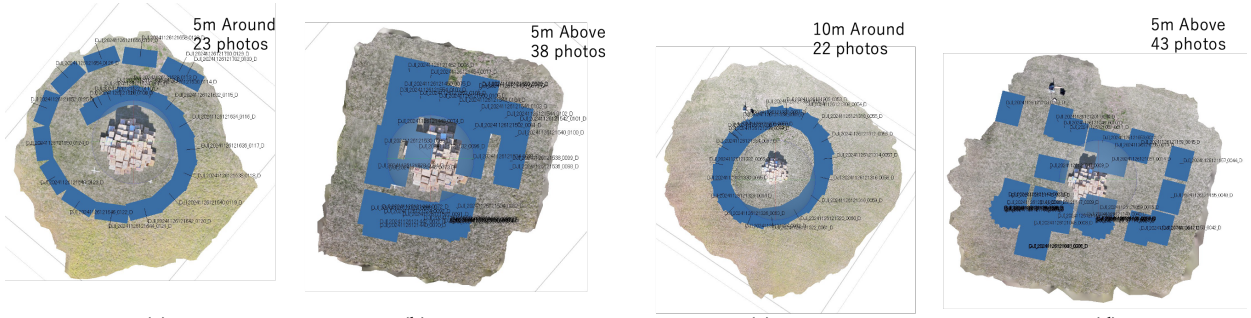


Figure 2. The locations of camera



Figure 3. Textured 3D model generated from point cloud data

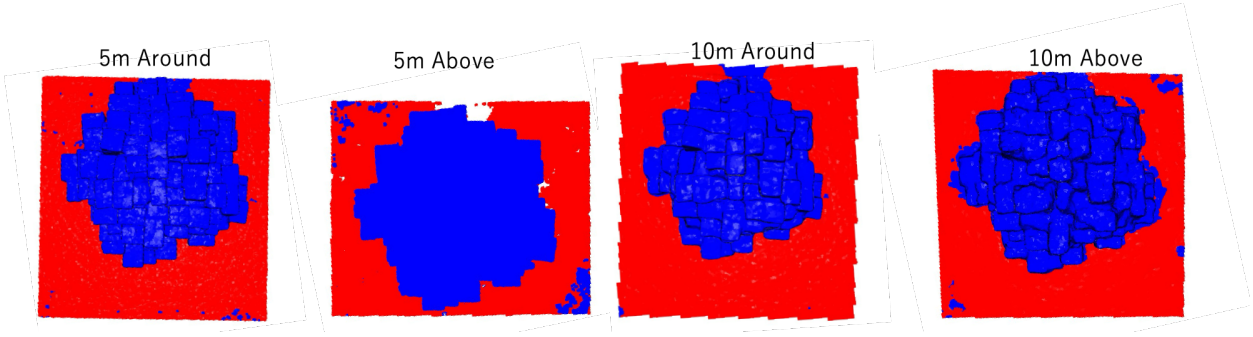


Figure 4. Classification of ground surface and debris based on plane estimation

The textured 3D model generated from point cloud data are shown in the Figure 3. Among the three modeling approaches, the tiled model with smoothing produced the most stable and accurate results. Direct point cloud generation often resulted in uneven point density and local defects, while the tiled approach improved uniformity. The smoothing process effectively reduced noise, leading to more reliable volume estimation.

The estimation accuracy was also influenced by parameters used in ground plane estimation and noise filtering. In particular, the threshold distance for plane fitting and the number of neighboring points in outlier removal played important roles. Improper parameter settings could lead to overestimation or underestimation of debris volume. The results of classification of ground surface and debris based on plane estimation are shown in Figure 4.

The experimental results demonstrate that:

I. Flight path selection is critical for reconstruction quality
II. Tiled point cloud generation with smoothing improves stability
III. Proper parameter tuning is essential for accurate volume estimation

These findings provide a validated basis for applying the method to real disaster scenarios.

4 Application to the 2024 Noto Peninsula Earthquake

The proposed method was applied to UAV data collected in the Ukai district of Suzu City, which was severely affected by the 2024 Noto Peninsula Earthquake (Misumo et al.,2024). The area includes collapsed buildings, scattered debris, and complex terrain conditions. The textured 3D model of the Ukai district of Suzu City after the 2024 Noto Peninsula Earthquake is shown in Figure 5.

Debris regions were manually identified and extracted from the full point cloud. Ground surfaces such as roads and open spaces were included to ensure accurate plane estimation. The extracted point clouds were then processed using the same workflow as in the validation experiments.

Four representative debris types, as shown in Figure 6, were analyzed:

I. Type 1: Compact debris with clear boundaries
II. Type 2: Large debris with well-defined ground surface
III. Type 3: Dispersed debris with irregular distribution
IV. Type 4: Debris adjacent to buildings with unclear boundaries

Accurate volume estimation was achieved for Types 1 and 2, while Types 3 and 4 posed challenges due to discontinuous surfaces and ambiguity in boundary definition.

The field application revealed that some factors identified in the experiments, such as modeling method and parameter settings, remain important. However, additional complexities in real environments, including uneven terrain and debris dispersion, significantly affect estimation performance.



Figure 5. Textured 3D model of the Ukai district of Suzu City after the 2024 Noto Peninsula Earthquake

5 Discussion

While validation experiments provide controlled conditions for accuracy assessment, real disaster environments involve multiple uncertainties. Factors such as terrain slope, occlusion, and heterogeneous debris distribution introduce errors that are not fully captured in simplified models.

Based on the results of this study, the following guidelines are recommended:

I. Use circular UAV flight paths for stable reconstruction
II. Apply tiled modeling with smoothing for noise reduction
III. Include surrounding ground areas when extracting debris
IV. Carefully adjust parameters based on point cloud characteristics
V. These practices enhance both accuracy and robustness in practical applications.

The current approach relies partially on manual selection of debris regions, which limits scalability. In addition, the method may struggle with highly dispersed or overlapping debris. Future work will focus on automated debris detection using machine learning and improved modeling techniques for complex terrain.

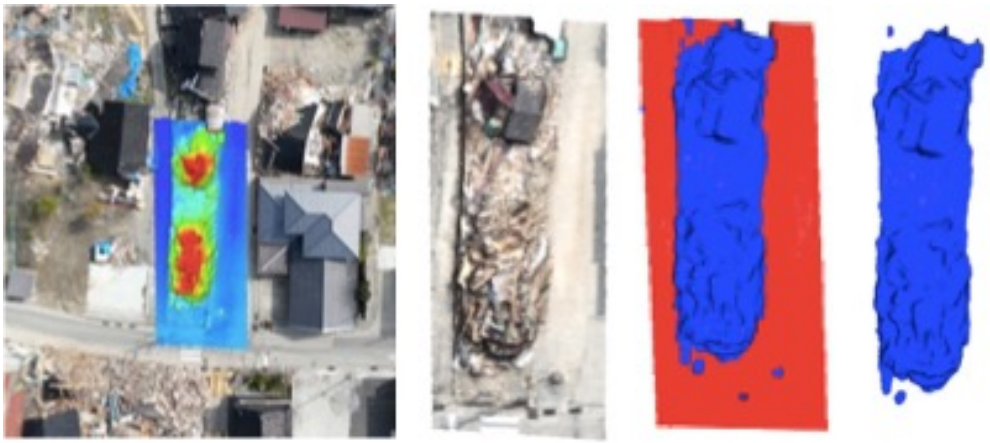
6 Conclusions

This study proposed a framework for rapid debris volume estimation using UAV-based 3D point clouds, integrating validation experiments and real disaster application.

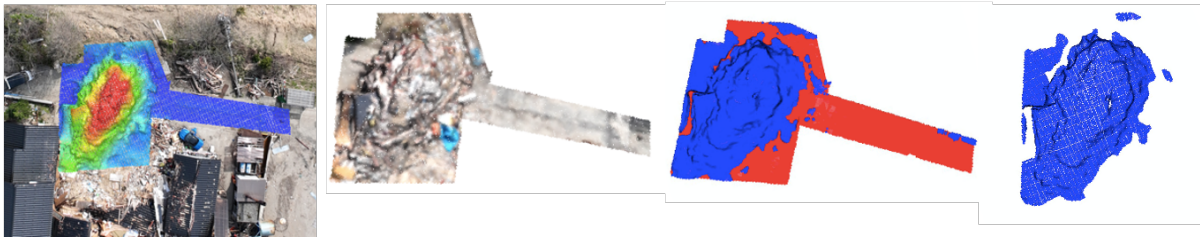
The validation experiments demonstrated that UAV flight conditions, point cloud generation methods, and processing parameters significantly affect estimation accuracy. In particular, tiled modeling with smoothing and appropriate parameter settings improved both accuracy and stability.

Application to the 2024 Noto Peninsula Earthquake confirmed the practical applicability of the method, while also highlighting challenges associated with complex terrain and dispersed debris.

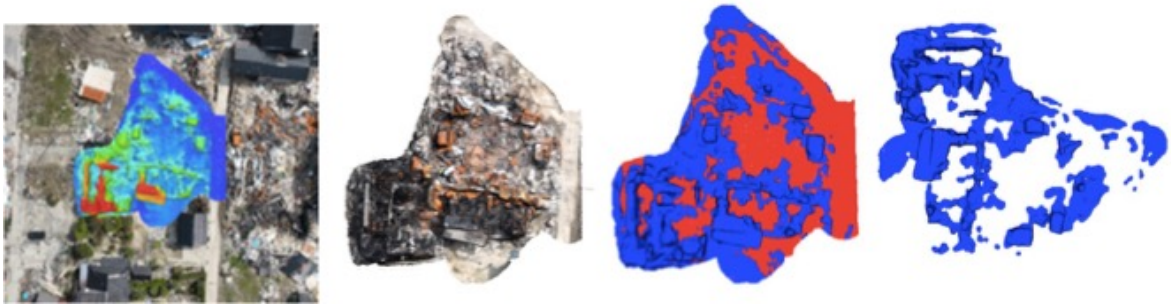
The findings of this study contribute to the development of reliable and efficient debris estimation techniques for post-disaster response and recovery planning.



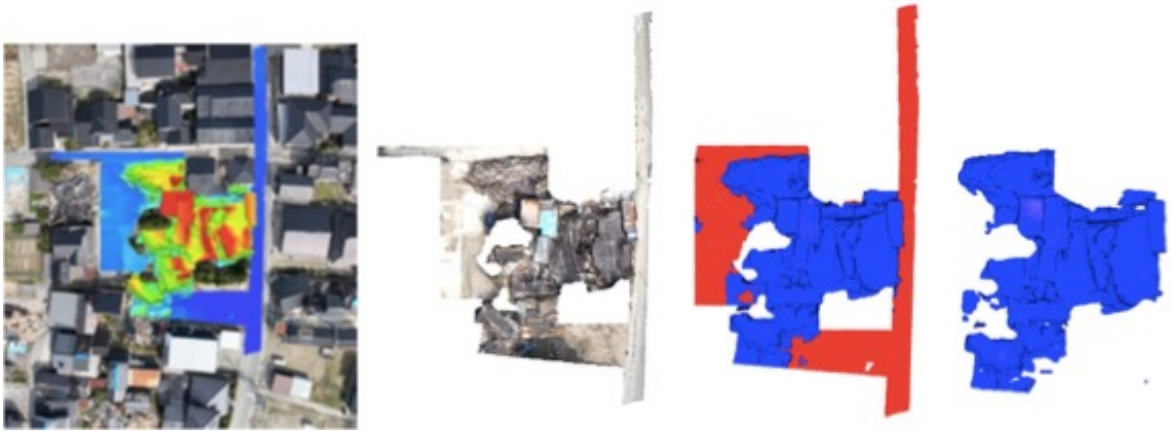
Type 1: Elevation map Point cloud Bottom and debris Debris area



Type 2: Elevation map Point cloud Bottom and debris Debris area



Type 3:Elevation map Point cloud Bottom and debris Debris area



Type 4:Elevation map Point cloud Bottom and debris Debris area

Figure 6. Four representative debris types

References

Sithole, G. and Vosselman, G.: Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds, *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol. 59, pp. 85– 101, 2004.
Nex, F. and Remondino, F.: UAV for 3D mapping applications: A review, Applied Geomatics, Vol.6, No.1, pp. 1-15, 2014.
Zhou, Q. Y., Park, J., Koltun, V. and Labs, I.: Open3D: A Modern Library for 3D Data Processing, arXiv:1801.09847, 2018.
Mizuno, C., Wang, X., Dang, J., A fast survey report about bridge damages by the 2024 Noto Peninsula Earthquake, Earthquake Research Advances, https://doi.org/10.1016/j.eqrea.2024.100312.