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Defining Surface Deformation Boundaries Using ICP and Clustering: 2024 Noto Peninsula Earthquake

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Abstract: The 2024 Noto Peninsula Earthquake caused widespread slope deformations in northeastern Noto, where complex geological formations and weak sedimentary layers triggered large-scale mass movements. This study proposes a quantitative and reproducible method for analyzing internal deformation structures by combining Iterative Closest Point (ICP) analysis and Hierarchical clustering using multi-temporal S-DEM data. The ICP analysis was used to align pre- and post-event point clouds and derive high-resolution displacement vectors on a 10M grid, enabling the extraction of fine-scale deformation features. Hierarchical clustering was then applied to classify the displacement field based on spatial and kinematic parameters, objectively delineating coherent deformation blocks. The resulting clusters correspond well with geomorphologically interpreted scarps and sliding masses, demonstrating that the proposed approach effectively identifies block boundaries and internal variations. Patterns of uplift and subsidence further suggest secondary sliding behavior within the moving body. This ICP-clustering framework provides a robust basis for quantitatively segmenting slope deformations and statistically interpreting their internal kinematics following large earthquakes.

Keywords: ***DEM, ICP, Landslide.***

Introduction

Multi-temporal DEMs reveal pre/post-earthquake change, but meter-scale meshes fragment displacement estimates and impede block-level interpretation. We introduce a quantitative, reproducible method to objectively delineate block boundaries and statistically clarify the internal structure of mass movements from the Noto Peninsula Earthquake.

Overview of the study area

The study area is located southeast of the Ohtani Loop Bridge in Suzu City, northeastern Noto Peninsula, Ishikawa Prefecture, as shown in Figure 1. The local geology comprises limestone–siltstone of the Houjuji Formation (JC), siliceous silt of the Iida Formation (DP), and rhyolitic pyroclastic rocks of the Kurikura Formation (AT). Given this complex geological setting, the stratum in this area is inferred to have undergone progressive fracturing due to tectonic deformation (Figure 2).

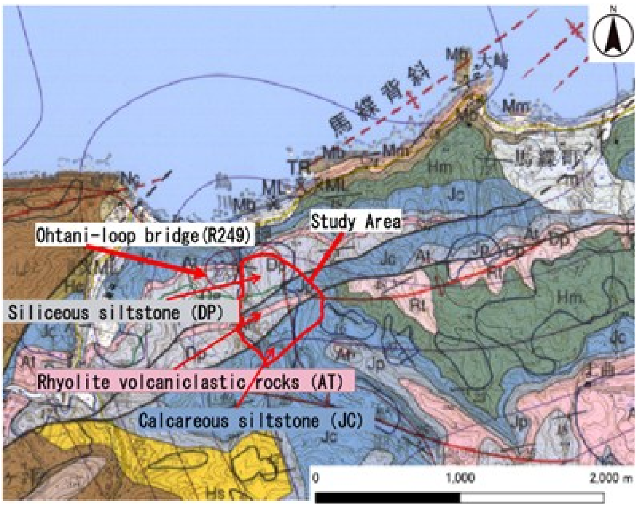

Figure 1, Study area and geological map.

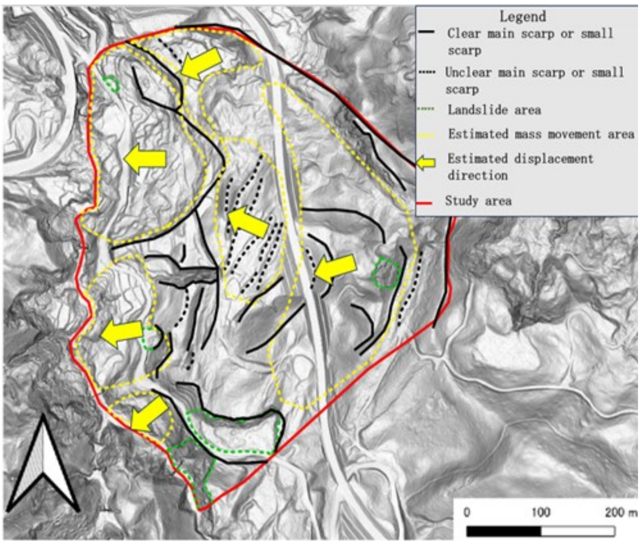

Figure 2, Geomorphological interpretation map.

Methodology

This study conducted displacement-vector analysis by two-temporal point-cloud data. To extract sheet-like deformation behavior within the mass movement and quantify its boundaries, we applied two approaches: Iterative Closest Point (ICP) analysis and hierarchical clustering.

Data description and registration way

We used the dataset derived from LAS data for the eastern Noto region of Ishikawa Prefecture, covering both pre- and post-earthquake periods. Initially, Nakanihon Air Co. processed this data to create a DEM. Subsequently, Nakanihon Air further refined the DEM into an S-DEM (Substratum Digital Elevation Model). Finally, to reset the uplift caused by the earthquake, we registered the S-DEM with our survey results. Then, we applied wide-area ICP, effectively removing regional crustal deformation and retaining local signals (e.g., landslides).

ICP (iterative closest point) analysis

ICP estimates earthquake-related displacement by registering pre- and post-event 3D point clouds. It iteratively translates and rotates the post-earthquake cloud to minimize nearest-neighbor distances to the reference, yielding per-point displacement vectors. By aligning entire surfaces while preserving local structure, ICP offers higher-precision deformation than DEM differencing or mesh-based methods and retains fine topographic detail. Here, a 10-m grid was used, and vectors were computed for each cell.

Hierarchical clustering

To capture spatial variability in the point-cloud–derived displacement field, we apply hierarchical clustering. Each observation is described by its X–Y position, displacement components (dx, dy, dz), and magnitude (dl). Using Ward's minimum-variance criterion, clusters are agglomerated to minimize within-cluster variance. The result is a data-driven delineation of spatially coherent blocks, statistically extracting boundaries where deformation trends and the magnitude of the displacement vector (dl), representing the combined amount of the displacement.

Results and discussion

Figure 3 summarizes deformation. Panel (1) maps displacement vectors and magnitudes, with white arrows for mean directions; (2) shows hierarchical clustering at k=5; (3) depicts subsidence/uplift from the z-component. Clusters 1–2 coincide with the clear head scarp near the riverbed and the sliding mass (cf. Figure 2), indicating agreement between local vectors and cluster-derived patterns. Cluster 4 shows scattered vectors, mainly from ICP nearest-neighbor matching that can flip directions; even so, (3) indicates net subsidence there. Panel (3) also reveals upslope subsidence and downslope uplift, implying a secondary slide toward the river followed by subsidence in the rear of the mass movements. Future work will improve clustering accuracy and point-cloud registration.

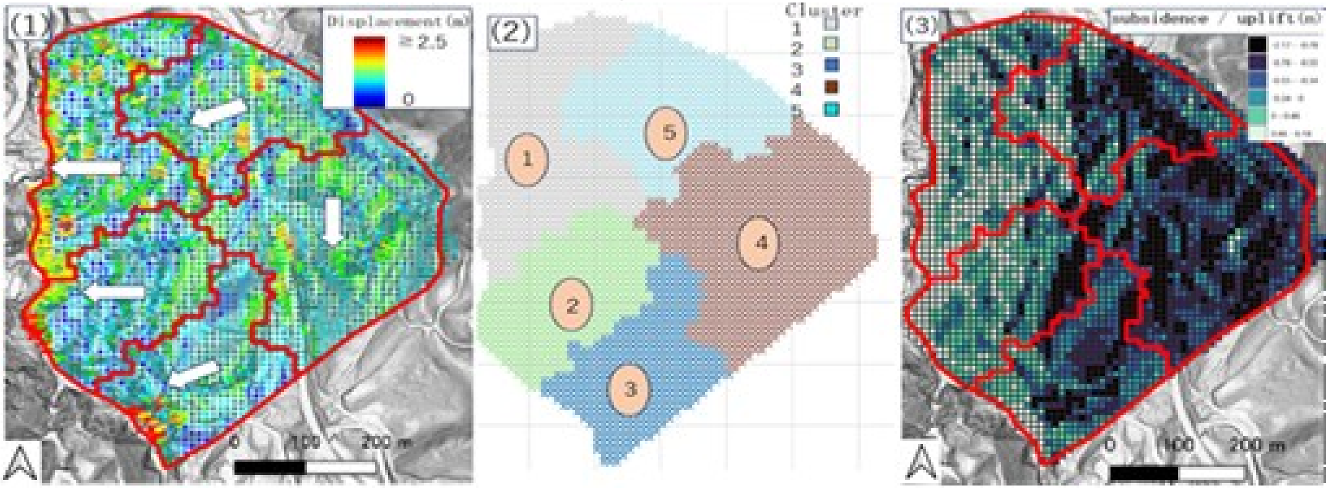

Figure 3, (1) Displacement vector (2) Clustered area by k=5 (3) Subsidence and uplift.

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