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Factorial analysis of lateral flow induced damage in Uchinada Town due to the 2024 Noto Peninsula Earthquake, Japan

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ABSTRACT: The 2024 Noto Peninsula Earthquake caused widespread liquefaction and significant ground deformation across Ishikawa Prefecture. Uchinada Town, located approximately 100 km south of the epicenter, experienced particularly severe damage, especially in low-lying coastal and reclaimed areas. This study focuses on the Muro district of Uchinada Town, where intensely localized lateral flow occurred. To investigate the deformation mechanism, field surveys including boring investigations, Standard Penetration Tests (SPT), and Piezo Drive Cone (PDC) tests were conducted. Results revealed that the subsurface primarily consists of fine, loose sand highly susceptible to liquefaction under seismic loading. The area's gentle slope and catchment topography promoted groundwater accumulation, resulting in a shallow groundwater table (~1 m depth) that further contributed to the severity of lateral flow. PDC tests identified a continuous weak soil layer (N-value 0–1) along the reclamation side of Prefectural Route 8, corresponding with the most severe lateral spreading. Liquefaction was found to initiate at shallow depths (1–2 m), causing extensive surface displacement. These findings emphasize the importance of detailed geotechnical assessments related to liquefaction damage and highlight the necessity for effective mitigation strategies in similarly vulnerable coastal zones.

KEYWORDS: Earthquake, liquefaction, lateral flow.

1 INTRODUCTION

The 2024 Noto Peninsula Earthquake, which occurred on January 1, 2024, caused severe liquefaction damage in Ishikawa Prefecture and its surrounding areas. Uchinada Town in Kahoku District, Ishikawa Prefecture, located approximately 100 km south of the epicenter, suffered significant liquefaction damage, accompanied by pronounced lateral flow (Yasuda, 2024 and Toyota et al., 2024). Uchinada Town is an urban area situated on the inland outer edge of the Uchinada Sand Dunes and the Kahoku Lagoon reclamation area (see Figure 1).

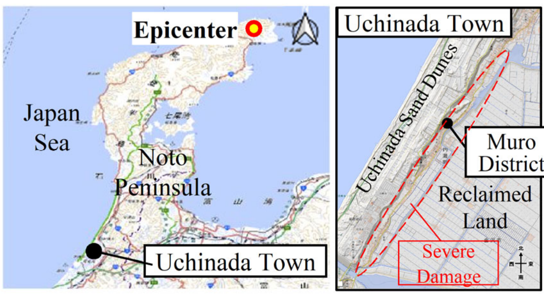

Figure 1. Location map of the Muro district

Liquefaction damage was prominent along Route 8, which runs along the outer edge of the Uchinada Sand Dunes, leading to ground deformation, as well as lateral flow toward the Kahoku Lagoon reclamation area. In the Muro district of Uchinada Town, localized and significant lateral flow occurred toward the Kahoku Lagoon reclamation area. Subsidence due to lateral flow and house displacements of up to approximately 12 meters were observed (Hazarika et al., 2024 and Kubota et al., 2024). Uchinada Town has a characteristic historical background related to land reclamation using dune sand during the development of the Kahoku Lagoon reclamation area. To facilitate post-disaster recovery and reconstruction, risk assessment for similar damage, and proposals for pre-disaster mitigation measures, it is crucial to clarify the disaster mechanism of the localized lateral flow damage that occurred in the Muro district. This paper reports the results of field investigations and soil tests conducted by the authors to elucidate the disaster mechanism of localized lateral flow in the Muro district of Uchinada Town, including grain size analysis, boring surveys, Standard Penetration Tests (SPT), and Piezo Drive Cone (PDC) tests. Additionally, based on the field survey results, this study presents an analysis of the deformation mechanism of localized lateral flow in Uchinada Town.

2 LIQUEFACTION DAMAGE IN MURO

Figure 2 illustrates the extent of lateral flow damage and the locations of representative cracks in the Muro district. In this district, intense lateral flow occurred on the gentle slope toward the Kahoku Lagoon. This resulted in the displacement of revetments, accompanied by waterway blockage.

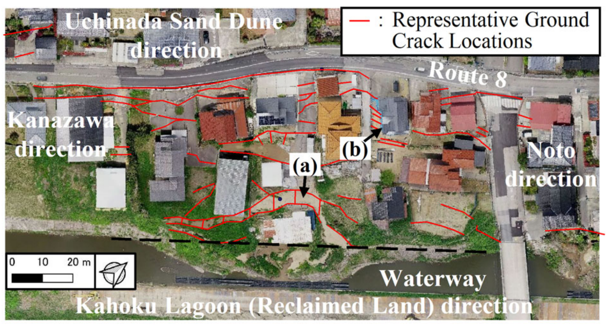

Figure 2. Lateral flow in the Muro District

Moreover, Figure 3(a) shows a house that was displaced approximately 12 meters toward the waterway due to lateral flow. On the other hand, Figure 3(b) shows a house that remained undamaged by lateral flow because of ground improvement piles. While subsidence and lateral flow were observed in the surrounding ground, the house itself showed no significant damage.

(a) (b)

Figure 3. A house in the Muro District

3 TOPOGRAPHY AND GEOLOGY OF MURO

Uchinada Town is located on the inland outer edge of the Uchinada Sand Dunes, a transverse dune approximately 1.5 km wide. The Muro district of Uchinada Town is situated on the southeastern side of the dunes, in the reclaimed land area. In this district, large-scale land reclamation and embankment projects were carried out in the 1970s, resulting in the conversion of Kahoku Lagoon into reclaimed land. Additionally, due to embankment construction associated with the reclamation project, the Muro district was filled with dune sand up to the vicinity of the former shoreline. Consequently, in the gently sloping area on the Kahoku side of Route 8, where significant lateral flow damage was observed, the surface layer consists of reclaimed soil.

4 FIELD SURVEY AND SOIL TESTING

4.1 *Types of Field Survey and Soil Test*

Three different surveys and a test were conducted in the Muro district: Boring Survey, Standard Penetration Test (SPT), Piezo Drive Cone (PDC) Test and Grain size analysis. Figure 4 shows the locations where the field surveys were conducted and Table 1 and Figure 5 and show sampling locations of the grain size test.

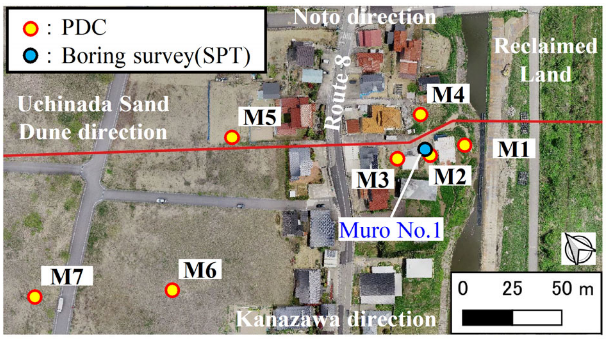

Figure 4. Field Survey Locations in the Muro District

Table 1. Sampling Locations of the Grain Size Test

No.	Sampling sites
1	Sand dune(no liquefaction damage)
2, 3	Sand boiling location
4	Sand boiling location (Elementary school ground)
5	Sand boiling location
6, 7	Muro district residence

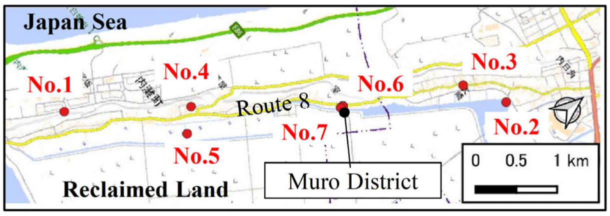

Figure 5. Sampling Locations of the Grain Size Test

1. Grain Size Analysis: Samples were collected from both the top of a dune where liquefaction did not occur and sand boil locations.
2. Topographic Analysis: The topography and groundwater conditions in the Muro district were analyzed based on elevation data (5m DEM) obtained before the disaster and existing geological survey results.
3. Boring Survey and Standard Penetration Test (SPT): The purpose of the boring survey is to understand the ground composition of the Muro district, where significant lateral flow damage was observed. Additionally, the purpose of the Standard Penetration Test (SPT) is to determine the N-values of the ground.
4. Piezo Drive Cone (PDC) Test: The Piezo Drive Cone (PDC) Test measures pore water pressure through dynamic penetration and estimates the N-value and fine content (Fc) to evaluate the soil's liquefaction resistance.

4.2 *Results of Field Survey and Soil Test*

4.2.1 *Grain Size Analysis*

Figure 6 shows the grain size analysis of sand samples from Uchinada Town. Sample No. 1 was taken from a site without any signs of soil liquefaction, while the other samples were collected from locations exhibiting sand boils. The grain size distributions at the dune top and sand boil locations were similar, both classified as highly liquefiable sands.

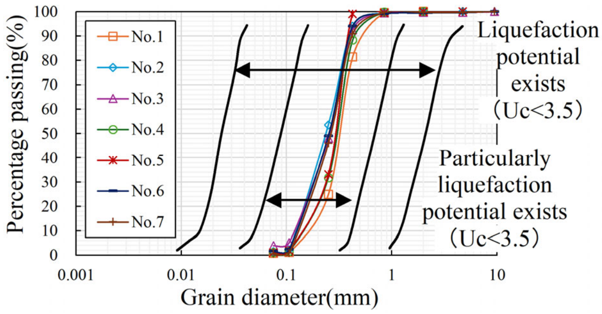

Figure 6. Grain Size distribution of Samples Collected in Uchinada

4.2.2 *Topographic Analysis:*

Figure 7 presents a contour map based on pre-disaster elevation data. The Muro district exhibits a gradual surface incline directed toward the Kahoku Lagoon reclamation zone, forming a concave landform characteristic of a catchment area.

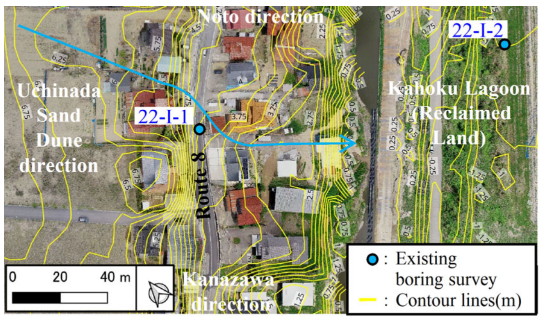

Figure 7. Contour map created using pre-disaster elevation data

Additionally, existing geological surveys recorded groundwater levels at approximately 1 m depth (Table 2). Furthermore, post-disaster investigations confirmed flooding, as shown in Figure 8. This suggests that groundwater tended to accumulate in this region, resulting in a higher groundwater level compared to the surrounding areas.

Table 2. Groundwater levels observed in existing geological surveys

Existing Boring Survey	Groundwater Level
22-I-1	GL-1.34m
22-I-2	GL-1.24m

Figure 8. Ponding conditions in Muro District

4.2.3 *Boring Survey and SPT*

Figure 9 illustrates the results of the boring survey and SPT at Muro-No.1. The identified soil layers are a reclaimed layer (Fs) (0–4.5 m), a dune sand layer (ds1) (4.5–6.7 m), and an alluvial clay layer (Ac) (6.7–9.5 m). The *N*-values of ds1 (13–20) were higher than those of Fs (4–6), while Ac (0–3) indicated extreme softness. The groundwater level was confirmed at 1.0 m, indicating a highwater table.

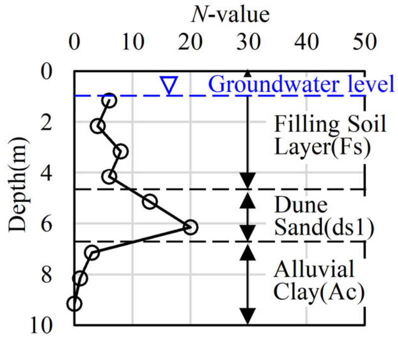

Figure 9. Boring Survey and SPT Results at Muro-No.1

4.2.4 *PDC Test*

Figure 10 illustrates the converted *N*-values derived from the PDC test (hereinafter referred to as *Nd*-values), along with the corresponding fine content (Fc). Also, it presents the soil classification based on these results. Both the reclaimed soil layer (Fs) and the dune sand layer (ds1) on the reclamation side primarily consist of sandy soil layers with minimal fine-grained content. Beneath these sandy soil layers, a weak alluvial clay layer (Ac) with *Nd*-values of 10 or less is distributed. Figure 11 presents a visualization of the *Nd*-values obtained from the PDC test, categorized by color. In the area from Route 8 to the reclamation side, where significant deformation due to liquefaction-induced lateral flow was observed, the *Nd*-values at depths of 0–2 m at survey points M2 to M4 were approximately 0, indicating an extremely loose state.

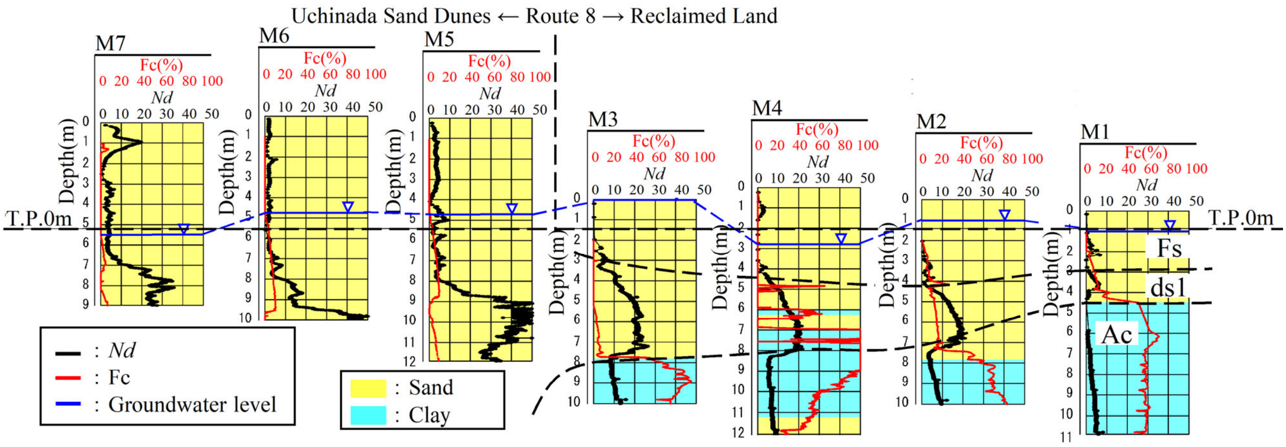

Figure 10. PDC Test Results in the Muro District (Classification of Sand and Clay)

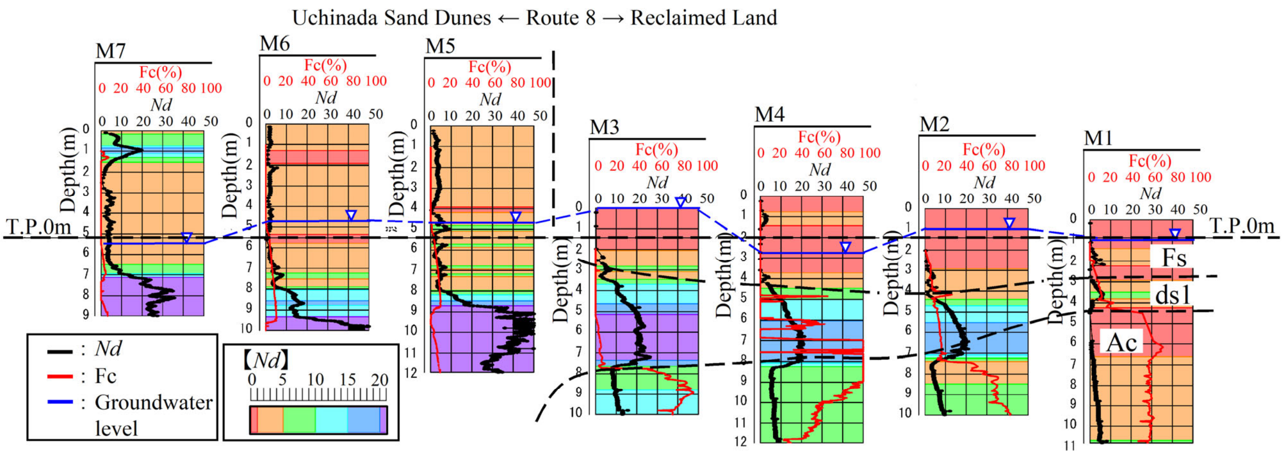

Figure 11. PDC Test Results in the Muro District (*Nd*-Value Categorized by Color)

4.3 *Analysis and Discussion of the Results*

The Muro district consists of the outer edge of the sand dunes facing Kahoku Lagoon, which has been reclaimed using dune sand. On the reclamation side of Route 8, where the reclaimed layer (Fs) is distributed, a continuously loose ground layer with *Nd*-values of approximately 0–1 was observed at depths of around 2–4 m. In contrast, this trend was not observed on the Uchinada Sand Dunes side of Route 8. Furthermore, focusing on the groundwater level, on the reclamation side of Route 8, where significant deformation was observed, the groundwater level was approximately 1 m deep, indicating a highwater table. On the Uchinada Sand Dunes side, where deformation was minor, the groundwater level was approximately 5 m deep, indicating a lower water table.

Based on these findings, it can be inferred that in the Muro district of Uchinada Town, liquefaction occurred at a very shallow depth (around 1–2 m) in a continuously loose ground layer with *Nd*-values of approximately 0–1. As a result, lateral flow was induced, leading to extensive damage across the area. Moreover, the groundwater table on the Uchinada Sand Dunes side of Route 8 was comparatively low, measuring approximately 5 meters below the surface. This likely resulted in less severe damage compared to the reclamation side. The factors contributing to the localized and significant lateral flow in the Muro district of Uchinada Town can be summarized as below.

1. Ground Conditions Favorable for Liquefaction:

Based on the results of the grain size analysis and boring survey, the ground materials in the study area primarily consist of fine sand, which is highly susceptible to liquefaction. Furthermore, the area has a gentle slope toward the Kahoku Lagoon reclamation area and forms a catchment topography. The reclamation side of Route 8 experienced more severe damage than the Uchinada Sand Dunes side. The observed disparity is likely explained by the differing groundwater conditions—shallow (approximately 1 m) on the reclamation side, and deeper (about 5 m) beneath the Uchinada Sand Dunes. Considering these factors, it is inferred that liquefaction-induced lateral flow was intensified on the reclamation side of Prefectural Route 8, leading to severe damage.

2. Widespread Loose Surface Soil:

The results of the PDC test indicate that in the Muro district, lateral flow due to liquefaction likely occurred in a section where continuously loose ground with N-values of approximately 0–1 was distributed on the reclamation side of Route 8.

3. Liquefaction at Shallow Depths:

A comprehensive analysis of the field survey results suggests that liquefaction is considered to have taken place at a very shallow depth (approximately 2–4 m) within the reclaimed soil layer in the Muro district. Moreover, due to the high groundwater level and the gentle surface slope toward the reclamation area, lateral flow was induced, leading to widespread damage such as 12 m displacement of the house shown in Figure 3(a).

5 CONCLUSIONS

The following conclusions could be derived based on the field investigations conducted.

- Boring survey results indicate that the fill material in the study area predominantly consists of fine sand.
- Survey results suggest that liquefaction likely occurred at shallow depths, approximately 1 to 2 meters below the surface.
- The soils on the reclamation side of Prefectural Road No. 8 contain a very loose fill layer consisting of sand with *Nd*-values ranging from 0 to 1, as confirmed by PDC test results.
- In the gently inclined terrain of the Muro area, liquefaction is believed to have occurred at shallow depths, resulting in lateral spreading and structural damage. The absence of pronounced manhole uplift in Uchinada Town further supports the conclusion that liquefaction primarily occurred at shallow depths.
- To mitigate liquefaction-induced damage in the region during future earthquakes, detailed and systematic investigations of groundwater levels are necessary to better understand their role in triggering liquefaction. In addition, implementation of economical and efficient ground improvement techniques to enhance the resilience of residential buildings located in such high-risk areas, is of paramount importance.

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7 REFERENCES

Hazarika, H., Ohta, S., Kubota, S., Michi, Y., Sahare, A., Tanaka, T., Ishizawa, T., Murai, M., Fujishiro, T., Matsumoto, T., and Hyodo, T. 2025. Lateral flow in reclaimed land due tolLiquefaction during the 2024 Noto Peninsula Earthquake, Japan ~ Insights from remote sensing and field survey ~, *8th ICRAGEE 2024*, Springer Singapore, Hardcover ISBN 978-981-96-1351-9.

Kubota, S., Ohta, S., Hazarika, H., Matsumoto, T., Tanaka, T., Murai, M., Fujishiro, T., and Michi, Y. 2024. Investigation report aiming to elucidate the mechanism of liquefaction damage in the Muro district of Uchinada Town due to the 2024 Noto Peninsula Earthquake (Part 1). *Journal of Japan Society for Natural Disaster* 43(3), 631-639.

Kubota, S., Ohta, S., Ochi, Y., Imai, T., Hazarika, H., Matsumoto, T., Tanaka, T., Murai, M. 2024. Investigation report aiming to elucidate the mechanism of liquefaction damage in the Muro district of Uchinada Town due to the 2024 Noto Peninsula Earthquake (Part 2). *Journal of Japan Society for Natural Disaster* 43(3), 641-648.

Toyota, H., Nakamura K., Takada S. 2025. Main liquefaction damages in Ishikawa prefecture caused by the 2024 Noto Peninsula Earthquake, *Journal of JGS* 73(1), Ser.No.804, 10-13.

Yasuda, S. 2024. Damage to residential areas caused by liquefaction-induced lateral flow during the 2024 Noto Penin-sula Earthquake and selection of appropriate countermeasures. *Keynote lecture In: 8th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, IIT Guwahati, India.