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Engineering Geological Challenges Following the 2024 Noto Earthquake, Japan

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Abstract: The 2024 Noto Peninsula (Noto-Hanto) earthquake significantly impacted infrastructure and communities in Central Japan, unveiling critical engineering geological challenges. To our knowledge, this paper presents the first systematic field survey conducted eight months after the mainshock, focusing on the post-disaster phenomenon and their recovery states. Through ground visits, satellite imagery analyses, and high-resolution DEM differencing, we identified persistent deep-seated gravitational slope deformation (DGSD) undermining tunnel stability, land uplift, structural collapses from soil liquefaction, and several landslides, with rural areas experiencing severe impacts. Our observations reported that the crustal uplift has permanently altered hydrological regimes and DGSD remains active beneath major tunnels, inducing tunnels spalling. Slope failures have progressed under cumulative rainfall loading, and tunnel linings show evolving structural distress linked to both DGSD and residual seismic damage. Lateral spreading, ground upheaval, ground settlement, sinking of utility poles, and the presence of sand ejecta are found as the major indicators of liquefaction. The study also evaluates the efficacy of current mitigation and restoration efforts. The Ishikawa`s structured, community-focused model demonstrates a clear path toward more efficient, resilient recovery, despite lingering delays in damage repair work. This study further emphasizes the significance of proactive, long-term disaster risk reduction to minimize future earthquake-related impacts.

Keywords*: The 2024 Noto Earthquake, Post-disaster Assessment, Seismic hazards, Liquefaction, Landslides*.

Introduction

On January 1, 2024, as the people of the Noto Peninsula were celebrating the New Year, a sudden and powerful Mw7.5 earthquake with an epicenter at a depth of 16 kilometers struck, turning a joyful day into a tragic one (USGS 2024). Such a strong tremor was caused by a large thrust faulting, up to nearly 10 meters of slip, that expanded more than 150 kilometers along the fault zone (Fukushima et al. 2024). Figure 1 shows the tectonic setting around Japan and the location of the 2024 Noto earthquake's epicenter. The intense seismic activity caused significant crustal deformation and triggered regional cascading hazards (Fukushima et al. 2024; Gomez 2024; Kataoka et al. 2024).

Two factors made this earthquake unusual: (a) an active seismic swarm resulting from the upward migration of crustal fluids and (b) much larger shaking than expected for an earthquake of its size and depth (Toda and Stein 2024). This unusual event has been linked to the accumulation of underground fluids due to a reverse fault stress field, as suggested by the focal mechanism analysis (Ishikawa and Bai 2024). The cracks in the earth's crust were oriented horizontally as the fluids flowing underground in deep areas could not rise and spread over a wide area in the horizontal plane. A recent geochemical study provided insight into the upwelling of deep fluids from the uppermost mantle that triggers the seismic swarm activity. The noble gases and their isotopes have been used as geochemical indicators to determine the origin of the fluids associated with the swarms and their upwelling. Gas samples collected from boreholes around the seismic source region are characterized by anomalously high 3He/4He ratios (~3.9 RAcor), indicating infiltration of mantle fluids from the subcrustal lithosphere (Umeda et al. 2024).

The major earthquake and subsequent tremors caused several geological engineering issues, including land uplift, structural collapse due to soil liquefaction, tunnel collapses, and landslides (Kataoka et al. 2024). The earthquake caused the collapse of old wooden houses with heavy roofs. The highways, railways and Noto airport runway were damaged. The earthquake induced many slope failures along the steep shores and mountainous terrain. These impacts are discussed in detail in the report available (Suppasri et al. 2024).

Although several rapid response studies documented the immediate impacts of the 2024 Noto earthquake (e.g., Suppasri et al. 2024; Ishikawa et al. 2024), no published report has evaluated the post-disaster state of the affected region. To address this gap, we conducted a focused field excursion on August 3-4, 2024, approximately eight months after the main shocks, during which we visited key sites across Ishikawa Prefecture to document engineering geological challenges and ongoing recovery efforts. The material presented here synthesizes publicly available data released by national and international earthquake institutes, mass media reports, and the author's field observations and measurements. To our knowledge, this is the first systematic survey of post-disaster phenomena in the Noto Peninsula at an eight-month interval. Because our focus was on analyzing post-disaster state and secondary hazard evolution of the affected area rather than exhaustive damage mapping, this paper highlights key sites where liquefaction-induced damages, sustained crustal uplift, and deep-seated gravitational slope deformation (DGSD) are the major issues that continue to threaten infrastructure, livelihoods, and the environment.

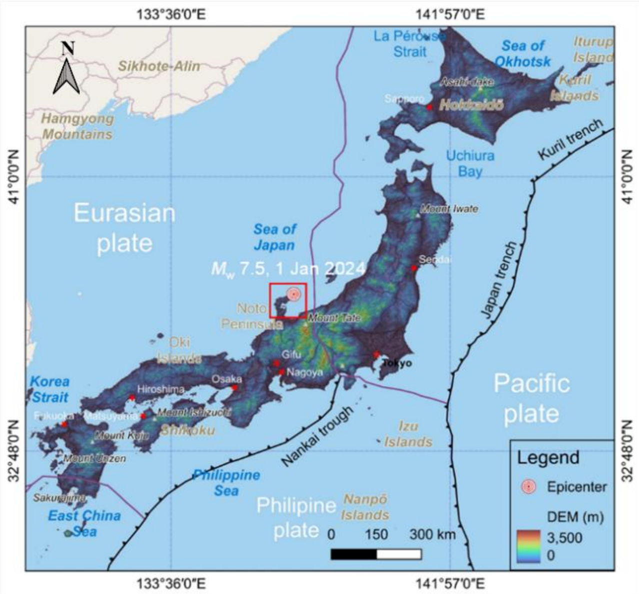

Figure 1, Tectonic setting in and around Japan.

Engineering Geological and Seismological Context

Japan has a very complex tectonic setting resulting from the convergence of several tectonic plates. Philippine Plate subducting beneath the Eurasian Plate at Nankai Trough and the Pacific Plate subducting beneath the North American Plate at Japan Trench has caused several major earthquakes and tsunamis (Seno et al. 1993). The Noto Peninsula is the largest Peninsula along Japan's Sea, situated at the convergence of the Eurasian and Pacific Plates. It extends towards the northeastern part, characterized by low-relief erosion surfaces and marine terraces. The geological framework of the Peninsula is dominated by pre-tertiary basement rock, primarily composed of Hida metamorphic rocks, and the Tertiary Formation is composed of Funatsu granitic rocks. Exposed basement rocks characterize the southern region, whereas Neogene formations dominate the central and northern parts of the Peninsula, demonstrating the geological transition from older to younger succession (Honda et al., 2008).

The Noto Peninsula has a history of seismic activity and has been subjected to complex tectonic processes. Four significant events have been recorded in this region, including coseismic uplift in 1025-1235, probable aseismic motion in 1430-1655, coseismic uplift associated with a pair of ca. Mw6.4 earthquakes in 1892 and Noto earthquake Mw6.7 in 2007 before the 2024 Noto earthquake (Shishikura et al., 2009). Several research studies have revealed the presence of active fault systems that traverse the Noto Peninsula. During this field observation, an active fault of the surface earthquake was observed along the Wakayama River in the northern part of Suzu city (Figure 2).

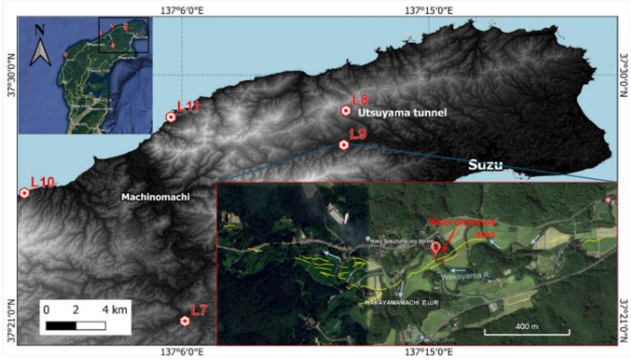

Figure 2, Surface earthquake active faults along the Wakayama River in the northern part of Suzu city (yellow line indicates active faults from Geospatial Information Authority of Japan 2024).

A series of minor to medium-sized earthquakes followed by aftershocks in the same area over a short period without a main event are recognized as earthquake swarms. Umeda et al. (2024) mentioned that the 2024 Noto Earthquake followed a prolonged period of intense earthquake swarms that had been ongoing beneath the northeastern part of the Peninsula for more than five years. Multi-year cluster-like pattern with shorter inter-event times has been observed during the swarm, which originates in the southern part of the Peninsula and it migrates towards the northeastern region along the Noto Peninsula (Wang et al. 2024). Additionally, they also discussed the occurrence of low-frequency seismic tremors within the region resulting from volcanic or hydrothermal activity beneath the surface.

Field Survey and Methodology

Eight months after the main shock, we conducted a comprehensive two-day field survey across the earthquake-affected regions of Ishikawa Prefecture. Our approach combined direct site visits and aerial imagery analysis to evaluate the seismic impacts on infrastructure and natural landscapes. This integrated methodology enabled us to investigate the scientific and engineering geological dimensions of the damage caused by the earthquake. Table 1 presents the data source used to prepare various thematic layers.

During our survey, we assessed the extent of damage and evaluated the progress of restoration efforts. Several maps were created within the QGIS environment, allowing us to visualize and interpret the observed damage more effectively. A 10 m DEM from the Geospatial Information Authority of Japan was used to overlay point data on the collapsed areas. We recorded the coordinates of damaged homes, road blockages, and fissures, measured visible displacement when possible, and photographed each site for later georeferencing. When debris blocked access, we relied on aerial imagery to identify additional slides and estimate their extent. In addition to our field observations, we critically reviewed previously published scientific articles and news reports from various media outlets to comprehensively understand the situation.

Table 1, Summary of tools, data sources, resolutions, and observation types used during the field survey

Tools and techniques	Source	Resolution/accuracy	Purpose
Digital elevation model (DEM)	Geospatial Information Authority of Japan (GSI)	10 m × 10 m grid	Map collapse zones, uplift, and subsidence
QGIS	QGIS 3.34	10 m×10 m grid	Create thematic maps and layer integration
Landslide topography distribution map	National research institute for earth science and disaster resilience	1:50,000 (landslides of ≥150 m width are only presented)	Analyze landslide distribution
Prefecture boundary	Geospatial Information Authority of Japan	n/a	Provide administrative boundary
Literature and media review	Peer-reviewed papers, local news outlets	n/a	Contextualized field data against initial rapid-response findings, verified timelines of recovery efforts and identified gaps in existing reports

Key Engineering Geological Issues

Soil liquefaction and associated damage

Liquefaction emerged as a major geotechnical concern in most of the earthquake-affected areas. It generally occurs when seismic vibrations destabilize loosely packed, water-saturated fine sand to silt sediments near the surface, significantly reducing ground strength. The major indicators of liquefaction are shown in Table 2. Inland regions of the Noto Peninsula, containing sand deposits from nearby dunes, were severely impacted by liquefaction due to the strong tremor. Along the coast, fine sand susceptible to liquefaction seems to have been carried by seasonal winds from the Sea of Japan. In contrast, on the landward side, where winds are blocked, fine sand was likely deposited in hilly regions, making the ground on the landward side more vulnerable to liquefaction compared to the seaside (Suppasri et al. 2024).

In Uchinada Town, the Saida Bridge has collapsed due to ground subsidence, disrupting the connection between the structure and the ground (Figure 3). The area, a floodplain located at the neck of Kahokugata Lagoon, has experienced significant subsidence due to sand liquefaction. Traffic on this bridge has been completely halted since the event. Lateral stress caused the bridge's northern side to pop up, displacing the abutment with a 36 cm lateral crack toward the south and a vertical movement of 12 cm, leading to the buckling of the bridge's middle section, which remains visible today. Figure 4 further illustrates liquefaction-induced engineering geological issues. Mizuno et al. (2024) reported the damage to the twin bridges (Naka-Noto Agriculture Bridge and Noto Island Ohashi Bridge) that connect Noto Island and the Peninsula. Additionally, a two-day emergency survey conducted using a microtremor array revealed ground shaking lasting approximately 4–5 minutes, which resulted in several liquefaction-induced damages in Uchinada Town. These included lateral spreading over approximately 2.7 hectares, ground upheaval, ground settlement, lateral displacement in the northwest to southwest direction, sinking of utility poles, and the presence of sand ejecta.

During the 2011 Great East Japan Earthquake, liquefaction was observed in reclaimed lands and old river channels. However, in the case of the 2024 Noto earthquake, liquefaction occurred in areas where sand deposits and sand dunes had accumulated, particularly on the landward side, making the land more susceptible to subsidence and dry slope failure where most of the structural damage resulted from the liquefaction of deeper sandy strata. This phenomenon was especially damaging in Uchinada town.

Figure 3, Damages in the Saida Bridge, Uchinada (Bridge offset vertically over tens of centimeters) (date of photographs taken: August 3, 2024).

According to Kataoka et al. (2024), liquefaction induced by this earthquake can be compared to that of the Niigata Earthquake in 1964, as both events exhibited liquefaction caused by seismic waves interacting with a combination of various geomorphic and geological factors.

Ground uplift and coastal changes

In December 2020, a seismic swarm began in the Noto Peninsula, initially confined to a small area associated with upwelling fluids through a shallow fault zone at a depth of around 16 km (Nishimura et al. 2023). This activity escalated significantly with a Mw6.5 earthquake in 2023, linked to the same mechanism (Kato 2024).

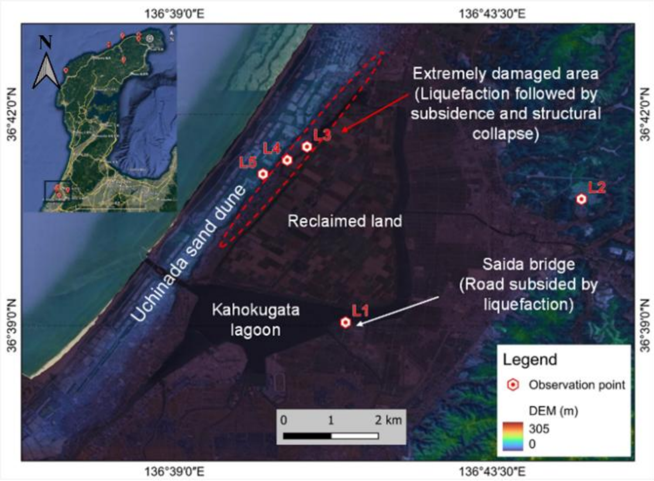

Figure 4, Liquefaction-related engineering issues observed along the coast of Saidamachi, Iwasaki, and Midorigaoka (L1 to L5 represents the observation site location).

The fifty seconds of violent shaking on the Noto Peninsula has uplifted and shifted the land northwest. The field observations indicated that the seafloor in the western part of Wajima City has been uplifted by approximately 4 m, resulting in the formation of a new marine terrace (Figure 5). This uplift was also confirmed by 2.5 D analysis, pixel offset analysis, and SAR interferometry analysis conducted by the Geospatial Information Authority of Japan using ALOS-2 data (Geospatial Information Authority of Japan 2024). The presence of wave-cut terraces and cliffs further evidences the extent of coastal uplift. Additionally, sea organisms such as oysters, bivalves, gastropods, and shellfish that were attached to the seawall and uplifted clearly indicate the pre-earthquake sea level, which can be observed at the Kaiso fishing port.

Coseismic crustal deformation caused by the 2011 Great East Japan Earthquake resulted in horizontal displacements of up to 5 m and vertical displacements of approximately 1 m near the epicenter (Kamiyama et al. 2017). Similarly, the 2016 Kumamoto Earthquake on Kyushu Island induced horizontal displacements of about 1.6 m and subsidence of nearly 2 m, as determined through Phased Array type L-band Synthetic Aperture Radar-2 (PALSAR-2) pixel tracking and Interferometric Synthetic Aperture Radar (InSAR) analyses (Himematsu and Furuya 2020). Global Navigation Satellite System (GNSS) observations recorded around 2 m of southwest-directed displacement and 1.3 m of uplift in Wajima. Meanwhile, Advanced Land Observing Satellite-2 (ALOS-2) data revealed 4 m of uplift and 2 m of westward displacement in Wajima City, along with 2 m of uplift and 3 m of horizontal displacement in northern Suzu City. In Suzu's northern region, reverse faulting caused approximately 2 m of land uplift, elevating the Wakayama River bed and leading to the damming of the river, which has since formed a preserved pond. These crustal deformations are part of a series of active faults distributed along the Wakayama River, which crosses its meandering path. At one observation site in Suzu City, the fault intersects the road perpendicularly, emphasizing the geomorphic impact of the earthquake-induced surface ruptures (Figure 6).

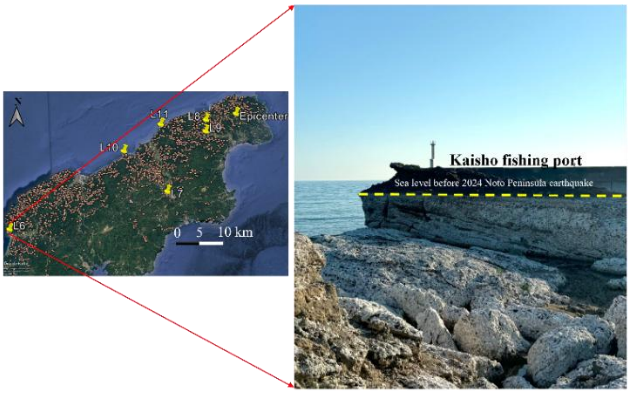

Figure 5, Kaiso fishing port uplifted by the Noto Peninsula Earthquake (date of photographs taken: August 3, 2024).

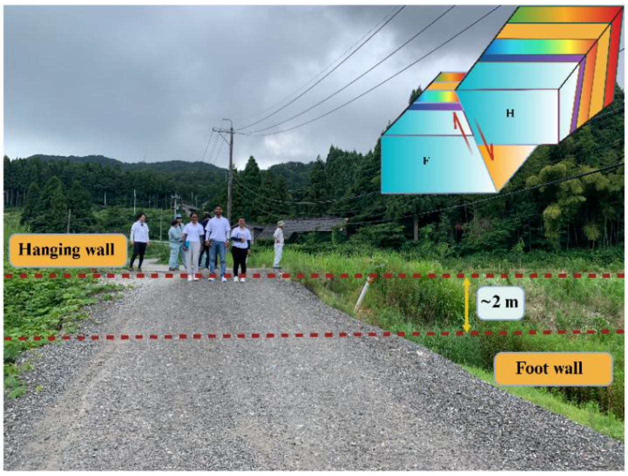

Figure 6, Land uplift of approximately 2 m by reverse faulting along the Wakayama River in Northern Suzu city (F and H represent footwall and hanging wall, respectively) (date of photographs taken: August 4, 2024).

Structural Collapse and Tunnel Failure

The Noto region experienced significant damage to structural stability due to the severe shaking of the earthquake, as well as the impacts of liquefaction and landslides, reminding of prior calamities such as the Haiti earthquake in 2010 (DesRoches et al. 2011), the Gorkha earthquake in 2015 (Liu et al. 2021), and the Kumamoto earthquake in 2016 (Setiawan et al. 2017). This study assessed damage to houses, indicating that the typical architectural style comprises wooden structures with timber mud walls and dark roof tiles. Numerous wooden houses either completely collapsed or incurred significant damage. Traditional two-story timber-framed houses experienced considerable damage during the 2024 Noto earthquake due to lateral movement, analogous to the destruction witnessed during the Kobe earthquake in 1995 (Yamazaki and Murao 2000) and the Tohoku-Oki earthquake in 2011 (Uchida and Bürgmann 2021).

On August 21, the official website of Ishikawa Prefecture announced updated damage statistics: 5,190 buildings collapsed, 16,231 residences sustained partial damage, and 60,426 structures displayed varying levels of damage across the Prefecture (Disaster Prevention, Safety and Security, Ishikawa Prefecture, 2024). In the Wajima and Suzu regions, many houses were destroyed or significantly tilted due to substandard construction practices. In the Uchinada region, numerous residences were damaged due to subsidence, lateral spread, and slope failures induced by liquefaction. Figure 7 illustrates some representative collapsed wooden buildings observed in the study area. The Saida Ohashi Bridge in Uchinada has been unusable due to lateral displacement caused by liquefaction. This phenomenon has similarly impacted other notable structures, including the Noto Island Ohashi Bridge and the Twin Bridge linking Noto Island with the Peninsula (Mizuno et al. 2024).

Figure 7, (a) Completely collapsed building along Wajima city; (b) tilted building; (c) building inspection certificate; and (d) inspection certificate attached to a building suffered with uplift and subsidence (date of photographs taken: August 3, 2024).

In Japan, mountain tunnels are constructed with earthquake-resistant stability; however, earthquakes with great magnitude result in either fully buried or unstable concrete tunnel lining. In the case of mountainous tunnels, earthquakes provoke landslides and damage the tunnel (Pai and Wu 2021). Otani tunnel (782 m length and 6.5 m width) is part of the Otani road (7.8 km), a National Route R249 in Suzu city, closed in many sections after the earthquake. The Otani tunnel was constructed within a DGSD zone in the Utsuyama region. Deep-seated landslides including DGSD and shallow slope failures, are primarily triggered by strong ground shaking. The 2024 Noto earthquake triggered a landslide around the area, disturbing the stability of the Otani tunnel resulting in the tunnel spalling about 100 m. The movement caused by the earthquake triggered the landslide and moved the whole mass laterally around 40 cm on the roadway towards the Karasugawa loop bridge. The spalled tunnel lining concrete was kept in front of the tunnel mouth on the roadside. Even eight months after the disaster, the expressway connecting Suzu City and Otani-Cho remained obstructed due to the tunnel collapse and slope on R249. Likewise, Maura-machi in Suzu City is one of the disaster-struck locations that suffered from a large-scale collapse near the Osaka tunnel on National Highway 249. The tunnel entrance is completely obscured by the debris from the landslides and slope failure. The condition of the Osaka tunnel can be observed before and after the earthquake of 2024. The 2024 Noto earthquake has majorly damaged roads such as National Highway 249 and Prefectural Road 1, which are partially closed and take time to be repaired fully.

After the earthquake, the landslide in the Utsuyama area impacted on the stability of the Otani tunnel, leading to the tunnel liner spalling (Figure 8). The spalled lining materials have been mocked out of the tunnel and kept on the roadside. The landslide caused the ground to slip laterally around 40 cm on the road and the Otani loop bridge (Figure 8d).

Figure 8, (a) Otani tunnel damaged by the sliding mass; (b) schematic diagram of liner spalling; (c) concrete liner mocked out from the tunnel; and (d) lateral slip observed along the roadside near the tunnel entrance (date of photographs taken: August 4, 2024).

The route between Suzu City and Otani-Cho remains closed due to the tunnel collapse, even eight months after the disaster. Similarly, the Osaka Tunnel on the northwest side of Mauramachi has been entirely covered by landslide debris and slope failure, rendering the tunnel entrance unrecognisable today (Figure 9).

Figure 9, Collapsed Osaka tunnel before and after the 2024 Noto earthquake [date of photograph taken (after): August 4, 2024].

Earthquake-induced landslides

The 2024 Noto earthquake has triggered numerous landslides, some of which were examined during field investigations (Figure 10). Emergency aerial images from January 2 2024, revealed approximately 930 coseismic landslides in mountainous and coastal regions, with a mean area of 5,353 m^2 and the largest one covering 373,962 m^2 (Gomez 2024). In total, the 2024 Noto earthquake caused over 2,300 landslides across a large area. Although this total is substantial, it is comparatively lower than other recent events of similar or greater magnitude: the 2002 Mid-Niigata Prefecture earthquake (>5,000 landslides), the 2018 Hokkaido Iburi earthquake (~6,000 landslides) (Loi et al. 2024), the 2016 Kumamoto earthquake (~3,467 landslides) (Xu et al. 2017), and the 2011Tohoku earthquake in 2011 (~3,477 landslides) (Wartman et al. 2013). Table 2 compares the sediment-related disasters triggered by the 2024 Noto earthquake with previous major earthquakes.

Earthquake-induced landslides can be categorized into several types, including rock falls, shallow landslides and dry debris flows, deep-seated landslides, and cut-fill slope failures, as described by Dahal (2015). In the study area of Wajima City, numerous deep-seated landslides, typically characterized by subsidence and the spreading of the upper part of a rock slope, along with outward movement or bulging at the base's slope, were observed. These landslides have also blocked the highway, necessitating the construction of alternative transportation routes. In Tsubata, Kahoku District, a significant landslide displaced a large mass of earth, exposing the foundations of houses and increasing their vulnerability. To mitigate further damage, plastic sheeting has been applied to the exposed land to prevent rainfall infiltration, thereby reducing the risk of additional movement or collapse. Areas prone to landslides face a high risk of secondary disasters due to future rainfall on unstable sediment and driftwood accumulated on slopes and in mountain streams. Consequently, the government actively implements emergency landslide countermeasures in these high-risk areas.

Earthquake-induced sediment movement poses a critical hazard in seismic regions, as intense ground shaking can trigger landslides, debris flows, and large-scale hillslope failures. The 2024 Noto earthquake caused around 420 cases of sediment movement within the Ishikawa Prefecture, 18 in Niigata Prefecture, and 13 in Toyama Prefecture, which resulted in numerous casualties damaging 57 infrastructures completely, 33 destroyed partially and 17 partially damaged (Ohno et al. 2024). Recent study also identified hillslope slumps exceeding 15 km in spatial extent; the first time such large-scale slumps and their associated toe scarps were quantified using satellite imagery (Fukushima et al. 2024). A four-day field investigation by the International Consortium on Geo-disaster Reduction (ICGdR) team revealed that most coseismic landslides in the affected area were controlled by preexisting geological features, such as large joint systems or secondary faults within original slopes, and predominantly occurred in mudstone units (Peng et al. 2025). Fukushima et al. (2024) documented meter-scale slope movements along flexural faults and activation of secondary inland faults, indicating synchronized ruptures.

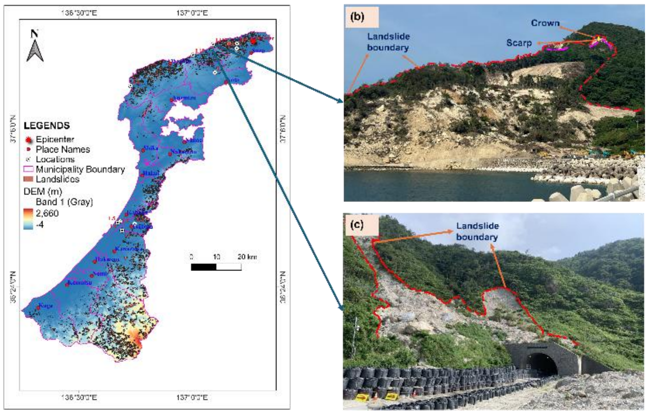

Figure 10, (a) Landslide distribution map along the Noto Peninsula; (b) large landslide mass covering the Osaka tunnel entrance; and (c) tunnel damaged by the landslide mass (date of photographs taken: August 4, 2024).

Cut and fill slope failures are also serious engineering concerns in the affected regions. Many roadside slopes in mountainous areas have suffered from these failures, primarily due to improper excavation practices and the instability to place or filled material on the slopes. Poor compaction and weathered-filled materials might have caused the fillings to slide downward. Another reason for this slide could be ~40 mm/day precipitation the day before the earthquake occurred. Road pavement buckling and lifting during earthquakes is very common in cut-and-fill engineering practices, which can lead to differential settlement. A similar pattern of extensive damage was observed during the 2016 Kumamoto earthquake, where the road pavements were constructed on liquefiable soil or fill materials experienced differential settlement, which created an undulating structure in the pavement (Kuribayashi et al. 2021).

Evaluating the Road to Recovery: Mitigation and Restoration Efforts

The aftermath of the 2024 Noto earthquake has left intensely damaged Ishikawa Prefecture with extensive recovery challenges. The direct field observations indicated that the damage repair progress has been markedly slower than in previous major earthquakes (Itatani et al., 2024). This delay may stem from the Prefecture's unique geography, characterized by its narrow and elongated north-south topography and limited road connectivity. Figure 11 presents a detailed January–August 2024 timeline of utility restorations, housing interventions, and infrastructure repairs.

Although essential utilities such as electricity and water supply have been restored, and temporary houses have been made available for the displaced residents, additional temporary houses are still being constructed in Wajima and Suzu city.

Table 2 Comparative summary of the 2024 Noto, 2016 Kumamoto, and 2011 Tohoku earthquakes

Parameter	Noto Earthquake, 2024	Kumamoto Earthquake, 2016	Tohoku Earthquake, 2011
Magnitude (Mw)	7.6	7.0	9.0
Houses damaged	5,190 buildings collapsed; 16,231 partially damaged; 60,426 with varying damage levels (Disaster Prevention, Safety and Security, Ishikawa Prefecture 2024).	198,000 (completely destroyed: 8642, half: 34,389, partially: 155,227) (Takeda and Inaba 2022)	~128,530 completely or half destroyed; 240,332 partially destroyed or damaged (Kazama and Noda 2012)
Sediment disasters (slope failure and landslides)	>2,300 landslides (Gomez 2024)	3,467 landslides (Xu et al. 2017)	3,477 landslides (Wartman et al. 2013)
Ground uplift magnitude	~4 m vertical uplift (field verification)	~1.6 m horizontal uplift and ~2 m subsidence (Himematsu and Furuya 2020)	~5 m horizontal uplift and ~1 m vertical uplift (Kamiyama et al. 2017)
Liquefaction indicators	Lateral spreading, ground upheaval, ground settlement, sinking of utility poles, and the presence of sand ejecta	Sand and water boiling, tilting buildings, road undulation and collapse (Wakamatsu et al. 2017)	Sand boils, floating manholes, tilting and damaged housing, levees collapse, the collapse, subsidence, cracking, and irregularity of road (Kazama and Noda 2012)
Estimated cost of damage	¥1.1 trillion to ¥2.6 trillion (The Japan news 2024)	~¥3.8 trillion (Takeda and Inaba 2022)	~¥16.9 trillion (Kazama and Noda 2012)

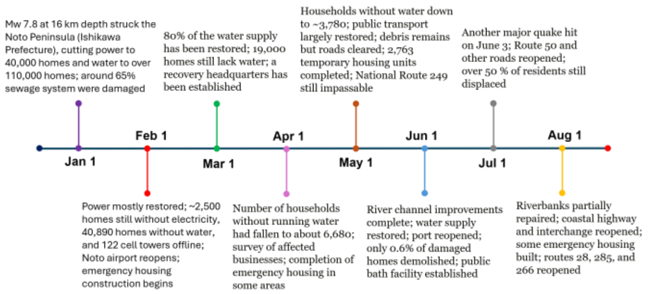

Figure 11, post-disaster recovery timeline (Jan–Aug 2024) in Ishikawa Prefecture after the 2024 Noto earthquake, showing utility restorations, housing, and infrastructure repairs.

Even though the road debris was removed for emergency movements, many collapsed structures remain untouched, and critical infrastructure repairs are yet to progress significantly. Among completely or partially damaged houses, yet many remain standing without being demolished, and as of May 26, only 2% have been demolished and removed (Ishikawa Noto Earthquake Interim Report 2024). Demolition requires specialized skills, but the number of qualified contractors is limited. The reason the demolition process is taking so long is the lack of a number of qualified contractors and adequate worker accommodation. The quake-hit area is still full of rubble, which might be due to delays in damage assessment surveys by the local government. Many tilted houses are still in danger of collapsing. The condition of the houses has been inspected, and inspection certificates are attached to the outer walls to inform residents of their condition (as depicted in Fig. 7).

The fishing port area, which has suffered severe damage and uplift, has rendered the area unstable, halting fishing activities vital to the local community. In many places, landslide-prone regions have been covered with water-resistant tarpaulin; however, long-term management strategies for these vulnerable areas remain lacking.

As recovery continues, the study area emphasizes "building back better". It can be clearly stated that Ishikawa Prefecture's approach introduces a more structured and efficient model for recovery in the affected region. Its clear transition from emergency to permanent housing, and higher levels of community engagement represent significant improvements, despite delays in damage repair (Yang et al 2024). The lessons learned from this earthquake highlighted the critical need for proactive disaster risk reduction measures, ensuring that future earthquakes will have less severe impacts on the people and infrastructure of the region. With scientists warning of the potential for a devastating Nankai Trough megathrust earthquake in southwestern Japan (Fukushima et al. 2023), there is an urgent need for concerned bodies and the local community to prioritize preparedness. Regions characterized by highly saturated, unconsolidated soils such as Kathmandu Valley, Nepal (Subedi and Acharya 2022), and parts of Chile (Verdugo and González 2015), face similar liquefaction hazards during seismic events and the threat of liquefaction demands that both authorities and communities prioritize preparedness now. From Ishikawa's example, three key strategies stand out for earthquake-prone areas: combining quick digital surveys, pre-positioned resources, and community-focused reconstruction. Together these strategies can cut recovery time, boost infrastructure resilience, and protect vulnerable populations. While every disaster has its own distinct characteristics and not every lesson will directly apply, consistently documenting these events builds a valuable knowledge base that enhances future prevention and mitigation efforts.

Conclusion

This study provides a comprehensive update on the current state of the Noto Peninsula and evaluates the damage and engineering geological challenges resulting from the earthquake. The severe tremors caused significant issues, including land uplift, structural collapses from soil liquefaction, tunnel failures, and landslides. The findings highlight that the mountainous terrain of the Noto Peninsula is particularly vulnerable to slope failures, emphasising the need for thorough geological assessments and reinforcement in similar areas to reduce landslide risks. Liquefaction and land subsidence were the major engineering concerns, causing severe damage to human settlements and infrastructure, especially in rural areas. Notably, cut-and-fill slopes along mountainous roads were extensively damaged, indicating a need for seismic-resistant road design. Traditional wooden houses also sustained substantial damage, underscoring the importance of enhancing their seismic resistance and preparing for potential collapses in the affected area and across Japan. The affected area`s structured, community-focused model demonstrates a clear path toward more efficient, resilient recovery, despite lingering delays in repair work. Overall, Ishikawa Prefecture is focused on recovery and rebuilding from the 2024 Noto earthquake. For future resilience, it's crucial to address the engineering challenges revealed by the disaster and ensure that infrastructure and buildings are designed to withstand future seismic events since research has warned about the potential for a megathrust earthquake along the Nankai Trough.

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