The 1 January 2024 Noto Peninsula co-seismic landslides hazards: Preliminary results

Christopher Gomez[1,2,*]

[1] Kobe University, Faculty of Oceanology, Laboratory of Sediment Hazards and Disaster Risk, Japan
[2] Universitas Gadjah Mada, Department of Geography, PSBA Laboratory, Yogyakarta, Indonesia
[*] Corresponding author: christophergomez@bear.kobe-u.ac.jp

ABSTRACT

On the first day of 2024, a strong Mw.7.6 earthquake followed by a tsunami shook the Noto Peninsula (Japan) located on the coast facing the Sea of Japan. It resulted in numerous casualties, infrastructures and dwelling destroyed. The earthquake also triggered an estimated 5,000 coastal and mountain co-seismic mass-movements, from which 930 were identified by aerial photographs and digitized from the emergency aerial photographs (2/1/2024). The goal has been to provide a preliminary assessment of their distribution and characteristics. The medium surface of the landslides was found to be 1,749 m^2, with numerous small < 50 m^2 landslides and at least one large deep-seated landslide (0.8 km × 1 km). The mountain landslides were concentrated around two clusters, which were not close to the epicentre, but around 7 km and 10 km from the epicentre. From a disaster-risk perspective, the 1/1/2024 Noto Peninsula earthquake is typical of a 'coastal earthquake' where the coastal landslides, even sparse collapsed on the main artery of the peninsula, the ring road, isolating communities and hampering the disaster relief process.

KEYWORDS

co-seismic landslides; Japan; Noto earthquake; geomorphology

Received: 3 June 2024
Accepted: 23 July 2024

Gomez, C. (2024): The 1 January 2024 Noto Peninsula co-seismic landslides hazards: Preliminary results. AUC Geographica 60(1), 1–8
https://doi.org/10.14712/23361980.2024.11

1. Introduction

On 1 January 2024, while local inhabitants had gathered for the New Year celebration and the "Oshogatsu yasumi", a Mw. 7.6 earthquake (N37.5, E137.2) shook the Noto Peninsula (Fig. 1) and sent seismic waves that were felt in the majority of the main island of Honshu.

Near the epicentre, the intensity reached the maximum level (JMA 2024): 7 on the Japanese Earthquake Intensity Scale (Alcantara-Ayala et al. 2022). It resulted in a first estimated 100 casualties as per 6 January, and 168 on the 8 January in the Noto Peninsula alone, with these numbers likely to rise even further.

1 January was not a "freak" single event. The Noto peninsula has been seismically active during the measurable historical period, with raised shorelines, the 1720–1950 shoreline being up to < 40 cm a.s.l., the 1430–1665 shoreline around 60 cm a.s.l., and the 1025 to 1235 shoreline between 80 cm and 100 cm a.s.l. (Shishikura et al. 2009). The 2024 event is not the first destructive event of the 21st century in the peninsula. The 25 March 2007 earthquake and tsunami caused one casualty, injured 338 and impacted around 33,700 dwellings (Sakai et al. 2008). Triggered by a known submarine fault (Katagawa et al. 2005), it resulted in a first estimated Mw 6.6 (Sakai et al. 2008) to 6.7 (Kato et al. 2008) < 20 cm wave tsunamigenic event (Tanioka 2008), with horizontal and vertical displacements both < 20 mm overall (Hashimoto et al. 2008) and with local uplift of 50 cm (Shishikura et al. 2009). This event had been the largest event in 100 years for the peninsula (Nakajima 2022). This "single" event ended after a set of aftershocks, but in 2018 a long-lived swarms or clusters of earthquakes was identified, with a high density of events (Nakajima 2022). In May 2018, a swarm of four years began. It generated > 20,000 Mw > 5.0 earthquakes (Amezawa et al. 2023). Such event has been attributed to the migration of the hypocentres and the fluid supply combined with the permeability of the environment (Amezawa et al. 2023), making the Noto peninsula an earthquake-prone area.

Unfortunately, as it is often the case in hilly and mountainous areas, earthquakes are often associated with co-seismic landslides (e.g. in Greece, Italy, Japan, New-Zealand, Chile, Nepal, etc. (Towhata et al. 2022). Their size and number are usually scaled with the magnitude of the earthquake (Malamud et al. 2024) and the distance to the epicentre (Keefer 2000). Furthermore, earthquake-triggered landslides can be further enhanced by antecedent or concurrent precipitation as it reduces the shear strength of material, as it was notably observed during the 2018 Iburi Earthquake in Hokkaido for instance (Gomez and Hotta 2021). Comparatively however, co-seismic landslides in the Noto Peninsula have historically been small and scarce: in 2007, despite of a Mw 6.6–6.7 earthquake occurring after rainfalls (50 mm over three days), only 61 landslides were recorded for the whole Noto peninsula for past events (Goto 2007), compared to the ~7,000 landslides recorded in Hokkaido for the Iburi-earthquake (Murakami et al. 2022). Contrasting with the co-seismic landslides in the Iburi area, the

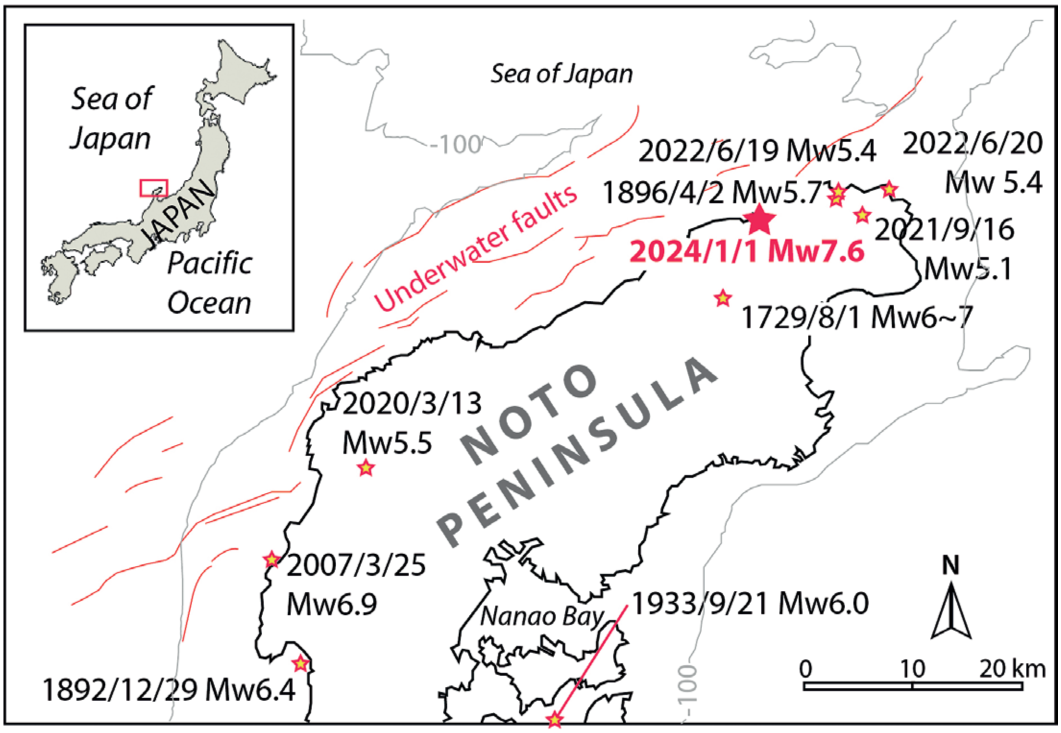

Fig. 1 The 2024 earthquakes and the major recorded historical earthquakes.

landslides travelled shorter distances, characteristics that can be attributed to the local conditions (Okada et al. 2008).

Because each earthquake and its geographical setting produces different types and distribution of co-seismic landslides, documenting each set of events brings us closer to understanding the unfolding of such hazards. Consequently, the present contribution investigates the geometry and the spatial distribution of co-seismic landslides that occurred because of the Mw. 7.6 earthquake of January 2024.

2. Methods

The present research has been occurring while the earthquake sequence was ongoing (with the latest strong motion earthquake recorded on the 3 June 2024 around 6:30 in the morning). As reconstruction has not begun yet, the author took the decision to base this preliminary work based on remote sensing data solely.

2.1 Ethical disaster investigation

As the disaster is unfolding and field-work should not trump the suffering of local populations, the present contribution is solely based on remote-sensing data, in order not to accentuate the burden on local communities. This methodological approach is motivated and in line with the "manifesto" (Power, Prestige & Forgotten Values: A Disaster Studies Manifesto 2024).

2.2 Data source and processing

On 2 January 2024, the Japanese government took a set of aerial photographs of the Noto Peninsula for emergency management purposes. From this dataset, 235 cloud-free photographs were selected. The set of photographs was then stitched together using structure from motion (Agisoft, Metashape-Pro software) and geodetic points of the peninsula (www.gsi.go.jp). As structure from motion reconstructs the elevation as well as it collates the photographs, the generated topography was also used to rectify the images and generate an orthophotograph.

2.3 Information Extraction and calculation

The orthophotograph was then imported in the QGIS Geographical Information System environment to hand-digitize the clearly identifiable landslides. From the digitized polygons, the landslides length and width were calculated using an oriented bounding box, and the direction of the oriented vector was determined by extracting the altitude of the edges of the bounding box. The results from GIS were then exported to the Python environment, where the data was handled as a panda dataframe to conduct the descriptive statistics used in the present contribution (the table data is available upon request), that explains the type of landslides that occurred.

2.4 Secondary data

This contribution also relies on secondary data. The geological map of the Noto peninsula (Yoshikawa et al. 2020) as well as the earthquake information that was collected from the Japanese Meteorological Agency (2024).

3. Results

3.1 The majority of the landslides is < 100 m long

The 1 January 2024 earthquakes triggered at least (digitized landslides) 930 co-seismic landslides. Their mean length reached 132 m for a median length of 94 m. Despite a number of small-size events (a quarter is shorter than 54 m) the maximum length exceeded a kilometre (Tab. 1). The mean area of landslides is 5,353 m^2 and the largest one 373,962 m^2.

From this set of landslides, a majority is < 200 m long (Fig. 2). The smaller landslides have a ratio of length/width > 2.0 while the larger landslides are less elongated (Fig. 2). The mean length of the landslides with a ratio length over width > 2.0 have lengths that are on average < 184 m. Despite valley confined landslides, the length/width ratio does not exceed 3.24, coinciding with the visual recognition of numerous shallow translational landslides that travelled short distances.

3.2 Landslides concentrated between 7 and 10 km away from the epicentre

The spatial distribution of the co-seismic landslides of the 1 January 2024 shows two hotspots (summarized in Fig. 6). They are concentrated in two areas of Tertiary terrain: (1) between the Iizuka formation (Siliceous siltstone) and the Awagura formation (volcanic

Tab. 1 Statistical characteristics of the digitized 930 landslides (as per 2/1/2024).

	Area [m²]	Width [m]	Length [m]	Perimeter [m]
mean	5,353	66	132	395
std	15,543	63	127	365
min	23	4	8	31
25%	742	29	54	174
50%	1,749	45	94	287
75%	4,788	81	154	471
max	373,962	868	1,078	3,701

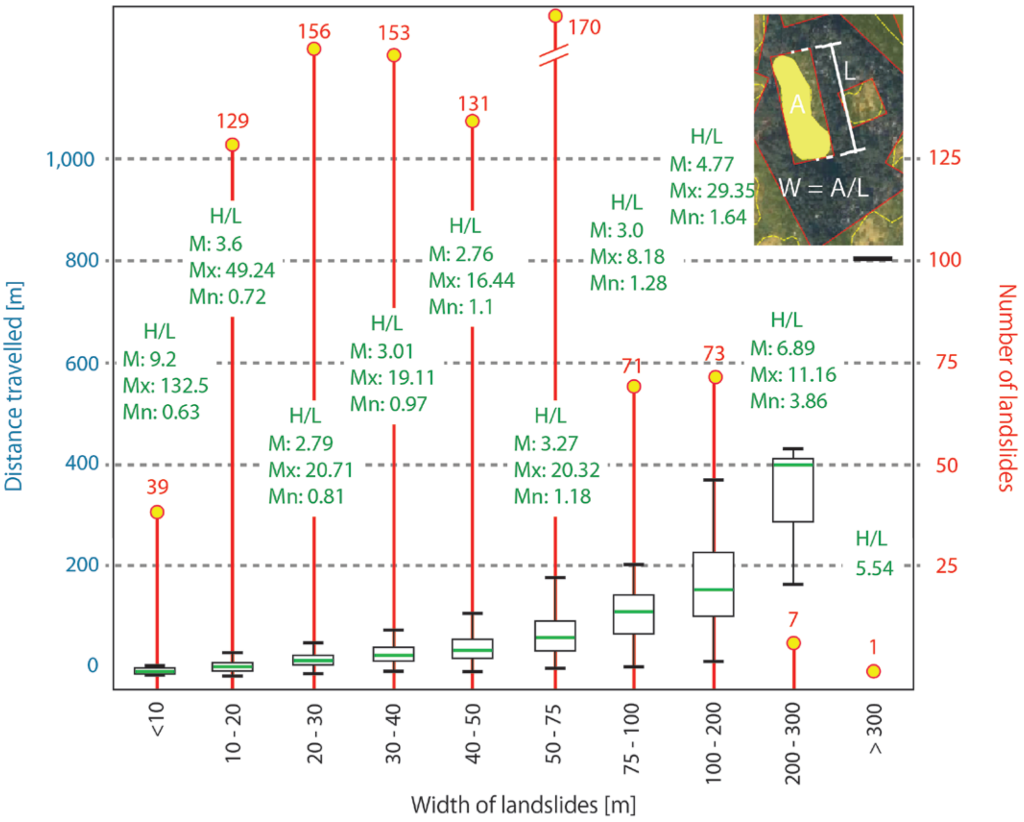

Fig. 2 Landslides length by classed width (the red plots and number in black is the number of landslides per class; the blue number on the left of the bar plot is the mean length per class, and the green horizontal number is the ratio of mean length over mean width).

rock intercalated with siltstone) and (2) in the Horyuzan formation (mixture of Dacite volcanic rocks with siltstone and conglomerate). The two concentrations of landslides are both at a ~10 km distance from the epicentre (Fig. 3). The coastal landslides are sparser and of smaller magnitude than the one in the West, as they occurred mostly in the Awagura and the Iizuka formations (Fig. 3).

In the Awagura hot-spot of landslides, the largest event (Fig. 4) occurred and it is more than a kilometre wide and about 800 m wide (estimated from aerial photographs to be Length: 1078 and Width: 868 m).

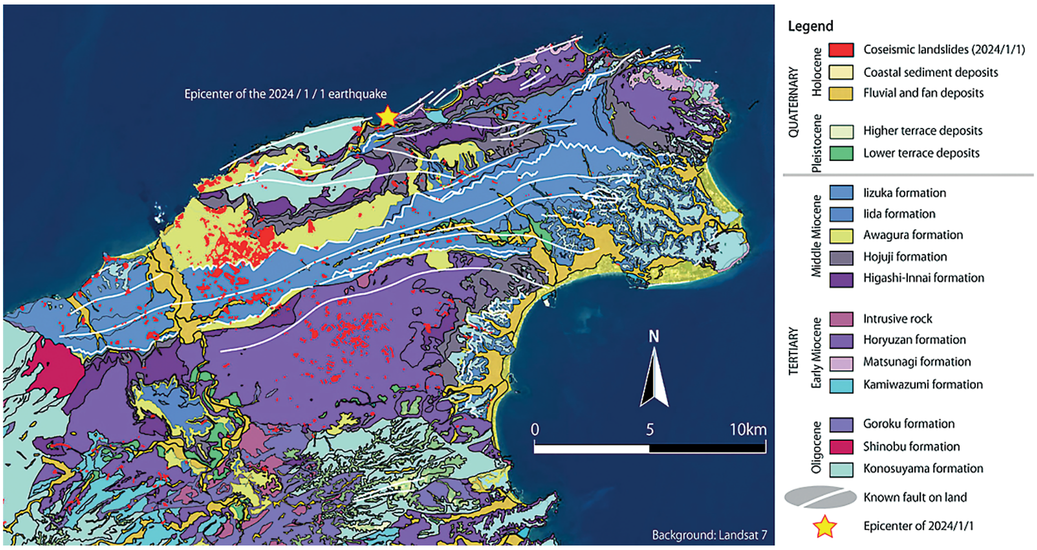

Fig. 3 Spatial distribution of the 1 January 2024 landslides across the geological structure of the Noto Peninsula (Map drawn from the Geological map of Japan (Yoshikawa et al. 2020) and the digitized 2024 landslides (GSJ 2024); please note that the coloring was adapted for improved readability).

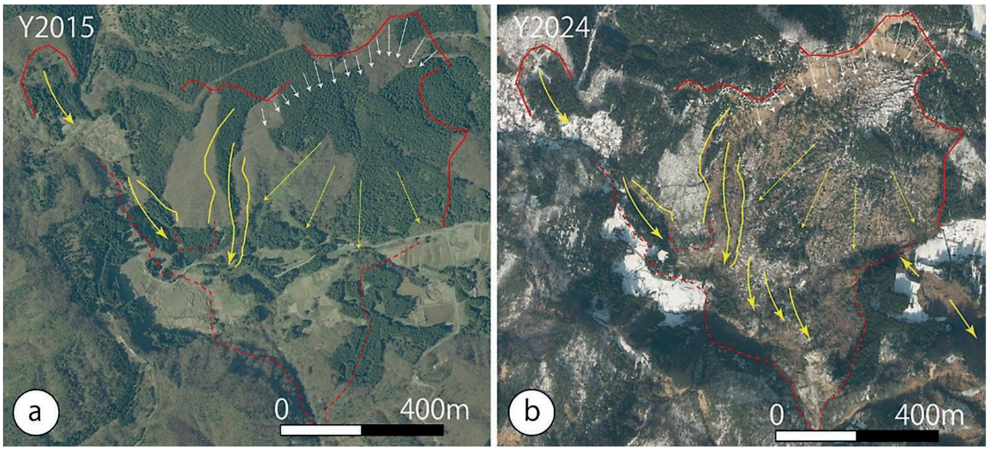

Fig. 4 The largest deep seated landslide, located in the Awagura formation. The red lineaments are the visible crown of the landslides, while the yellow arrow shows direction of spread. The dotted red line represents the toe of the landslides, and white arrows are the locations where the sliding plane is now visible.

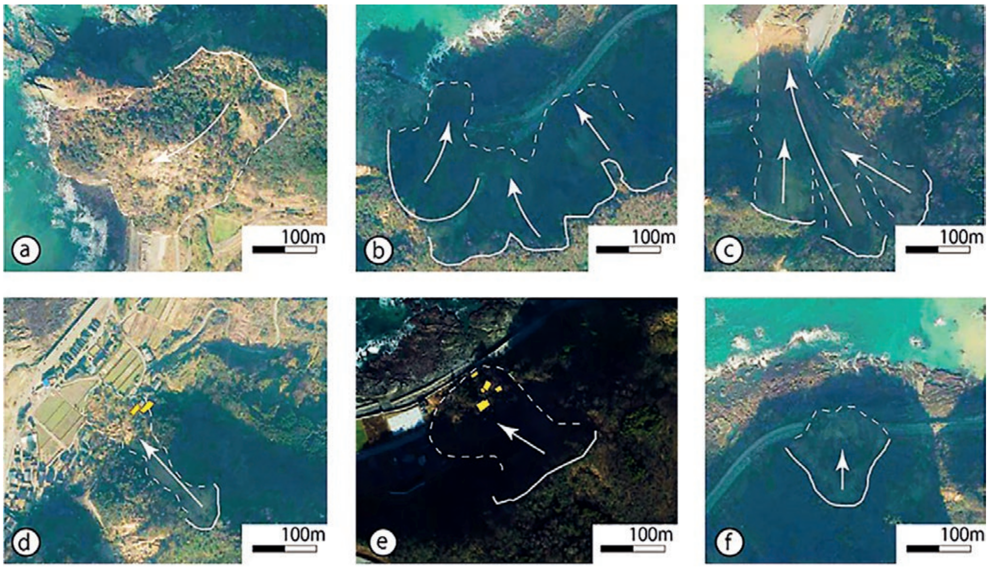

Fig 5. Coastal landslides cutting the “ring-road” of the island to the West of the Epicentre. The Yellow boxing marks dwellings that have been buried by the landslides.

The entire slope travelled over the agriculture terraces at its toe (Fig. 4). The event contrasts with the majority of the smaller-scale co-seismic landslides that often occurred as valley-constrained earth-flows (Tab. 1).

The coastal landslides that cut the road reach 300 and 400 m in length from the crown to the toe of the landslide. Translational landslide on complex or curved failure plane (Fig. 5a,f) have been observed as well as shallow landslides on sliding planes parallel to the surface (Fig. 5b–e). The material remained relatively cohesive at places (Fig. 5d–f) while some other slides created deposits that reveal a granular-flow or rock avalanches. These different slides exist within a single rock formation and similar topographies, with different types of events juxtaposed to one another (Fig. 5b: the event on the left is a rock avalanche, while the two other events on the right have a deposit that are more compacts.

Only 1.7% (i.e. 16 events) of the total number of landslides cut the coastal road, covering lengths between 17 m and 566 m length, for an average length of road cut of 179 m for each event. The size of the coastal landslides however is larger than the average, because in the mountainous areas numerous smaller landslides also took place.

4. Discussion

The co-seismic landslides triggered by the 2024/01/01 earthquake are concentrated at two locations, centred on 7 km and 10 km distances from the epicentre (Fig. 6).

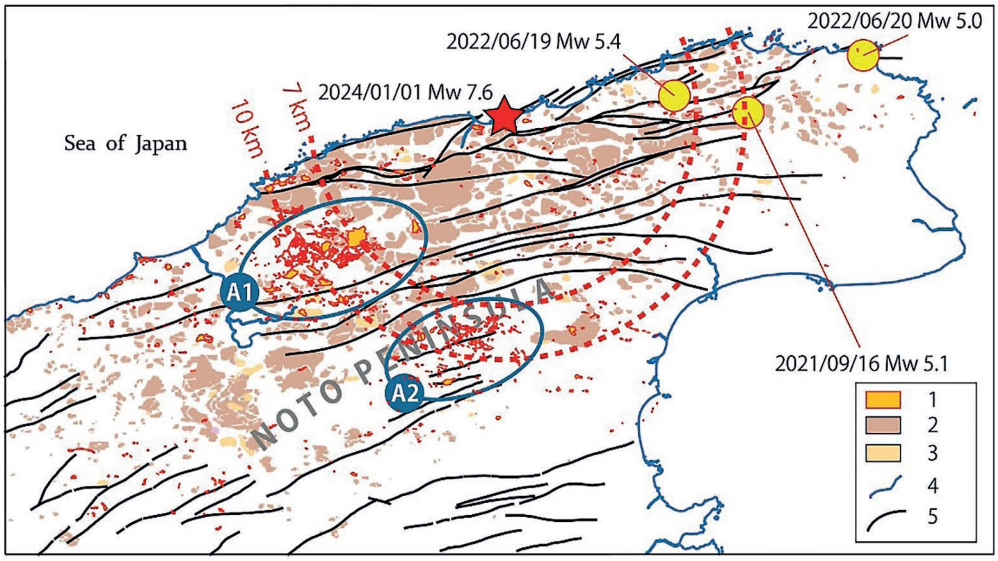

Fig. 6 Synthesis map: The January 2024 co-seismic landslides are not controlled by past- and active landslides.
(1: Landslides digitized for the present study; 2: Existing active landslides; 3: Potential active landslides; 4: Coastline of the Noto Peninsula; 5: Known faults on land. The red star shows the 2024 earthquake epicentre, and the yellow circle the previous ones in 2022.
Zones A1 and A2 are the areas where landslides are zones of landslides concentration.

The cluster A1 occurred mostly in the Awagura formation, while A2 is in the Horyuzan formation. Despite a large number of mapped landslides and potential landslides, the 2024 co-seismic landslides mostly occurred in new areas. Except for the largest landslide and its surrounding (Fig. 4 and in A1, Fig. 6) the co-seismic landslides occurred in previously unaffected (or unmapped) areas. The present set of co-seismic landslides present at least two oddities, when compared to other events in the scientific literature. Keefer (2000) describes a spatial density of landslides that is correlated with the distance to the epicentre as it is often the case, but for the Noto Peninsula co-seismic landslides, they are centred in two areas that are around 7 km and 10 km from the epicentre. By comparison with the 2018 Hokkaido co-seismic landslides that were concentrated in the Iburi mountains, the results show that they are concentrated in two main geological formations, which may show either the role of the formation in amplifying the seismic waves, either the role of the topography and the geomorphological specificities. Another hypothesis that may be stressed here, like for the Iburi earthquake is the position and orientation of the main faults and how they communicate the seismic energy to the surface.

The landslides are also showing a mixture of shapes. The 2018 Iburi earthquake generated landslides all close to the relation $LD = 2.2492\ W^{1.0296}$, where LD is the length of the deposit and W is the width of the deposit (Murakami et al. 2022), but for the co-seismic landslides of the Noto Peninsula, such relation could not be observed, even after dividing them in classes (Fig. 2). Compared to the co-seismic landslides of the coastal earthquake of Kaikoura (Mw 7.8), the runouts are also smaller: in Kaikoura the longest was 2.7 km (Massey et al. 2018).

In the aftermath of the 2011 Earthquake that shook Canterbury and the coastal town of Christchurch in New Zealand, professor Deirdre Hart coined the term “coastal disaster” during one of her oral intervention. The idea acknowledges the particular characteristics of settlement and the role of the coastal geomorphology and sedimentology (estuarine sediments, loose Quaternary sediments, etc.) combined with coastal settlements (sea-side roads, blue-edge real estate) on the making of a coastal multihazards and eventually a disaster (Hart et al. 2018). Arguably, the 1 January 2024 earthquake that shook the Noto Peninsula is one these events as well, and the co-seismic landslides concur with this idea. As in Christchurch, only a few failures on the lifeline that could not be built with redundancies in coastal areas, resulted in a slower response and a difficult recovery, once cut by co-seismic landslides. In the mountain area of the Noto Peninsula, the rupture of the access roads has had a similar effect. A comparable issue also arose in 2016, in the aftermath of the Kaikoura earthquake in New Zealand, where coastal co-seismic landslides cut the main coastal road as well as the train track (Massey et al. 2018), although the Kaikoura earthquake triggered more than 10,000 landslides (about 10 folds compared to the Noto Peninsula). Consequently, the 1/1/2024 Noto Peninsula co-seismic landslide distribution of co-seismic landslides is at odd with traditional models and seemed to have occurred in areas where previous landslides have not occurred. The difficulty to understand the geometry and distribution of co-seismic landslides is also a reminder that a large amount of data concerning soils and geology were notably created for resource mapping, but not to understand hazards, and there is certainly a need to develop new method to refine the mapping of soils and geology in the same way that point cloud has done for topography or radar for rainfalls.

5. Conclusion

The 2024/1/1 earthquake that struck the Noto peninsula is the latest event in a series of recent and historical earthquakes that were directly recorded or that can be evidenced from the large number of secondary landslides, which cover the peninsula. The co-seismic landslides concentrated in two areas, away from the epicentre, which makes the event atypical compared to others found in the scientific literature. The event also emphasized the channel to sustainable development in seismically active peninsula and islands, where the coastal road is a lifeline trapped in between potential tsunami damages on one side and the landslides on the other side.

Acknowledgements

The author is in dept to the company KokusaiKogyo, which provided verification data for this work as well as the Japanese government, which made the aerial photographs used in the present contribution available at a very early stage for recovery and the supporting scientific and engineering efforts. The author would also like to thank two anonymous reviewers for their careful reading and contribution that led to an improved manuscript.

References

Alcantara-Ayala, I., Gomez, C., Chmutina, K., van Niekerk, D., Raju, E., Marchezini, V., Rom Cadag J., Gaillard, J. C. (2022): Disaster Risk, Routlege, https://doi.org/10.4324/9781315469614-3.

Amezawa, Y., Hiramatsu, Y., Miyakawa, A., Imanishi, L., Otsubo, M. (2023): Long-Living Earthquake Swarm and Intermittent Seismicity in the Northeastern Tip of the Noto Peninsula, Japan. Geophysical Research Letters 50(8), e2022GL102670, https://doi.org/10.1029/2022GL102670.

Gomez, C., Hotta, N. (2021): Deposits' Morphology of the 2018 Hokkaido Iburi-Tobu Earthquake, Mass Movements from LiDAR & Aerial Photographs. Remote Sensing 13(17), 3421, https://doi.org/10.3390/rs13173421.

Goto, S. (2007): On slope disasters by the Noto Hanto Earthquake in 2007. Prompt reports of geodisasters by the Noto Hanto Earthquake in 2007. The University of Tokyo, 20–26 (in Japanese).

GSJ – Geological Survey of Japan (2024): Online map of landslides of Japan. Available online: https://gbank.gsj.jp/owscontents/howto.html accessed on 9. 1. 2024 (in Japanese).

Hart, D. E., Giovinazzi, S., Byun, D.-S., Davis, C., Ko, S. Y., Gomez, C., Hawke, K., Todd, D. (2018): Enhancing resilience by altering our approach to earthquake and flooding assessment: multi-hazards. Proceedings of the 16th European Conference on Earthquake Engineering, Thessaloniki, Greece, 1–13.

Hashimoto, M., Takahashi, H., Doke, R., Kasahara, M., Takeuchi, A., Onoue, K., Hoso, Y., Fukushima, Y., Nakamura, K., Ohya, F., Honda, R., Ichiyanagi, M., Yamaguchi, T., Maeda, T., Hiramatsu, Y. (2008): Postseismic displacements following the 2007 Noto peninsula earthquake detected by dense GPS observation. Earth, Planets and Space 60, 139–144, https://doi.org/10.1186/BF03352775.

JMA – Japanese Meteorological Agency (2024): Earthquake information 2024/01/01 16, 24. Available online: https://www.data.jma.go.jp/multi/quake/quake_detail.html?eventID=20240101162429&lang=jp accessed on 9.1.2024 (in Japanese).

Katagawa, H., Hamada, M., Yoshida, S., Kadosawa, H., Mitsuhashi, A., Kono, I., Kinugasa, Y. 2005. Geological Development of the West Sea Area of the Noto Peninsula District in the Neogene Tertiary to Quaternary, Central Japan. Journal of Geography 114(5), 791–810, https://doi.org/10.5026/jgeography.114.5_791.

Kato, A., Sakai, S., Iidaka, T., Iwasaki, T., Kurashimo, E., Igarashi, T., Hirata, N., Kanazawa, T., and the Group for the aftershock observations of the 2007 Noto Hanto Earthquake (2008): Three-dimensional velocity structure in the source region of the Noto Hanto Earthquake in 2007 imaged by a dense seismic observation. Earth, Planets and Space 60, 105–110, https://doi.org/10.1186/BF03352769.

Keefer, D. K. (2000): Statistical analysis of an earthquake-induced landslide distribution: the 1989 Loma Prieta, California Event. Engineering Geology 58(3–4), 231–249, https://doi.org/10.1016/S0013-7952(00)00037-5.

Malamud, B. D., Turcotte, D. L., Guzzetti, F., Reichenbach, P. (2004): Landslides, earthquakes and erosion, Earth and Planetary Science Letters 229(1–2), 45–59, https://doi.org/10.1016/j.epsl.2004.10.018.

Massey, C., Townsend, D., Rathje, E., Allstadt, K. E., Lukovic, B., Kaneko, Y., Bradley, B., Wartman, J., Jibson, R. W., Petley, D. N., Horspool, N., Hamling, I., Carey, J., Cox, S., Davidson, J., Dellow, S., Godt, J. W., Holden, C., Jones, J., Kaiser, A., Little, M., Lyndsell, B., McColl, S., Morgenstern, R., Rengers, F. K., Rhoades, D., Rosser, B., Strong, D., Singeisen, C., Villeneuve, M. (2018): Landslides Triggered by the 14 November 2016 M_w 7.8 Kaikōura Earthquake, New Zealand. Bulletin of the Seismological Society of America 108 (3B), 1630–1648, https://doi.org/10.1785/0120170305.

Murakami, Y., Mizugaki, S., Fujinami, T. (2022): Quantification of sediment and fallen trees generated by landslides in the 2018 Hokkaido Eastern Iburi Earthquake. Journal of the Japan Society of Erosion Control Engineering 74(6), 3–10.

Nakajima, J. (2022): Crustal structure beneath earthquake swarm in the Noto peninsula, Japan. Earth, Planets and Space 74, 160, https://doi.org/10.1186/s40623-022-01719-x.

Okada, Y., Ochiai, H., Kurokawa, U., Ogawa, Y., Asano, S. (2008): A channelized long run-out debris slide triggered by the Noto Hanto Earthquake in 2007, Japan.

Landslides 5, 235–239, https://doi.org/10.1007/s10346-007-0090-3.

Radix. Power, Prestige & Forgotten Values: A Disaster Studies Manifesto. Manifesto/Accord – RADIX: Radical Interpretations of Disasters (radixonline.org) (accessed on 17. 7. 2024).

Sakai, S., Iidaka, T., Iwasaki, T., Kurashimo, E., Igarashi, T., Hirata, N., Kanazawa, T. and the group for the joint aftershock observation of the 2007 Noto Hanto Earthquake. 2008. Highly resolved distribution of aftershocks of the 2007 Noto Hanto Earthquake by a dense seismic observation. Earth, Planets and Space 60, 83–88, https://doi.org/10.1186/BF03352765.

Shishikura, M., Echigo, T., Namegaya, Y. (2009): Evidence for coseismic and aseismic uplift in the last 1000 years in the focal area of a shallow thrust earthquake on the Noto Peninsula, west-central Japan. Geophysical Research Letters 36(2), L02307, 1–5.

Tanioka, Y. (2008): Analysis of the tsunami generated by the 2007 Noto Hanto earthquake. Earth, Planets and Space 60, 123–125, https://doi.org/10.1186/BF03352772.

Towhata, I., Wang, G., Xu, Q., Massey, C. (2022): Coseismic Landslides, Phenomena, Long-Term Effects and Mitigation, https://doi.org/10.1007/978-981-19-6597-5.

Yoshikawa, T., Kano, K., Yanagisawa, Y., Komazawa, M., Joshima, M., Kikawa, E. (2020): Sumisaki, Noto-Iida, and Horyuzan Geological Map, Geological Survey of Japan, AIST.