The January 1st 2024 Noto Peninsula Co-seismic Landslides Hazards: Preliminary Results

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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 at least 930 coastal and mountain co-seismic landslides that were digitized from the emergency aerial photographs (2/1/2024), in order to provide a preliminary assessment of their distribution and characteristics. The medium surface of the landslides was found to be 1749 m$^2$, with numerous small < 50 m$^2$ landslide and at least one large deep-seated landslide (0.8 km x 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 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.

Introduction

On January 1st 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$^1$: 7 on the Japanese Earthquake Intensity Scale$^2$. It resulted in a first estimated 100 casualties as per January 6th, and 168 on the 8th in the Noto Peninsula alone, with these numbers likely to rise even further.

January 1st 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 above sea level, the 1430–1665 shoreline around 60 cm a.s.l., and the 1025to 1235 shoreline between 80cm and 100 cm above sea level$^3$. The 2024 event is not the first destructive event of the 21st century in the peninsula. The March 25th, 2007 earthquake and tsunami caused 1 casualty, injured 338 and impacted around 33,700 dwellings$^4$. Triggered by a known submarine fault$^5$, it resulted in a first estimated Mw 6.6$^4$ to 6.7$^6$ <20cm wave tsunamigenic event$^7$, with horizontal and vertical displacements both < 20 mm overall$^8$ and with local uplift of 50 cm$^3$. This event had been the largest event in 100 years for the peninsula$^9$. 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$^9$. In May 2018, a swarm of four years began. It generated > 20,000 Mw > 5.0 earthquakes$^{10}$. Such event has been attributed to the migration of the hypocentres and the fluid supply combined with the permeability of the environment$^{10}$, 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.$^{11}$). Their size and
number is usually scaled with the magnitude of the earthquake\textsuperscript{12} and the distance to the epicentre\textsuperscript{13}. 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\textsuperscript{14}. 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\textsuperscript{15}, compared to the ~ 1,800 in Hokkaido. To the contrary of the co-seismic landslides in the Iburi area, the landslides only travelled short distances, characteristic attributed to the local conditions\textsuperscript{16}.

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 as a result of the Mw. 7.6 earthquake of January 2024.

**Results**

**Half of the landslides are < 100 m long**

The January 1st, 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 (Table 1). The mean area of landslides is 5353 m\(^2\) and the largest one 373,962 m\(^2\).

<table>
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</table>
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.

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

The spatial distribution of the co-seismic landslides of the January 1st, 2024 shows two hotspots (summarized in Fig. 6). They are concentrated in two areas of Tertiary terrain: (1) between the lizuka formation (Siliceous siltstone) and the Awagura formation (volcanic rock intercalated with siltstone) and (2) in the Horyuzan formation (mixture of Dacite volcanic rocks with siltstone and conglomerate). The two concentration of landslides are both at a ~ 10 km distance from the epicentre (Fig. 3). The coastal landslides are rare and of smaller magnitude than the one in the West, as they occurred mostly in the Awagura and the lizuka formations (Fig. 3).

In the Horyuzan 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). 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 (cf. Table 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. 5-a, f) have been observed as well as shallow landslides on sliding planes parallel to the surface (Fig. 5-b,c,d,e). The material remained relatively cohesive at places (Fig. 5-d,e,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. 5-b: 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.

**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).
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 & 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 (e.g. the 2018 Iburi earthquake co-seismic landslides), 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.

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$^{14}$, 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 runout are also smaller: in Kaikoura the longest was 2.7 km$^{19}$.

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 multihazard and eventually a disaster$^{20}$. Arguably, the January 1st 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 failure 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$^{19}$, 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.

Methods

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).

**Data source and processing**

On January 2nd, 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.

**Information Extraction and calculation**

The orthophotograph was then used in QGIS Geographical Information Software to digitize (by hand) 930 landslides. The landslides length and width were calculated using an oriented 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).

**Secondary data**

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

**Declarations**

**Competing Interests statement**

The author declares no competing interest.

**Data availability statement**

The data that support the findings of this study are available from the authors (christophergomez@bear.kobe-u.ac.jp) upon reasonable request, and secondary data are available from the Geological Survey of Japan (www.gsj.go.jp) and the Japanese Meteorological agency (www.jma.go.jp) but restrictions may apply.

**Author Contribution**

The author conceptualized, gathered and processed the data and prepared and wrote the manuscript on his own.
References


Figures
Figure 1

The 2024 earthquakes and the major recorded historical earthquakes.
Figure 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).
Figure 3

Spatial distribution of the January 1st, 2024 landslides across the geological structure of the Noto Peninsula (Map drawn from the Geological map of Japan and the digitized 2024 landslides; please note that the coloring was adapted for reading and do not strictly follow the Geological map).

Figure 4

Y2015  

Y2024
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.

Figure 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.
Figure 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.)