Examining the characteristics of logging road-associated landslides induced by 2018 Hokkaido Eastern Iburi Earthquake

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1. INTRODUCTION

The effect of anthropogenic activities has been intensively discussed in geomorphic hazard studies over past few years (Sidle et al., 2017). Much concern is now focused on the side effects of anthropogenic activities on forest management issues such as deforestation and logging road construction (Sidle and Ziegler, 2012). Landslide events are a particular concern as they can magnify the widespread damage to the Earth's surface, which is already affected by natural phenomena (e.g., storms and earthquake). Thus, the effects of anthropogenic forest management on landslide events needs to be assessed to better understand how the extent of landslide damage has shifted from natural triggers to anthropogenic ones as well as to create mitigation strategies for preventing subsequent disasters.

Cut-fill roads are one of the most common types of anthropogenic footprints that induce landslides. Logging roads can trigger landslides on road-cut slopes, fill slopes, and hillslopes by rerouting hydrological pathways, as well as altering strength and loading on hillslopes (MacDonald and Coe, 2008). The effect of logging roads on landslide characteristics differs depending on the road prism characteristics, i.e., the fill slope and cut slope. For instance, Wemple et al. (2001) revealed that logging roads in Western Cascades, Oregon, can exacerbate landslide occurrence vary as landslides initiated from hillslopes that intercept mid-slope roads (0.11 landslides/km), landslides initiated from fill slopes (0.15 landslides/km), and landslides that undercut at cut slopes (0.01 landslides/km). Despite being well documented, these findings regarding landslide–logging road interactions were mostly based on rainfall-induced landslide cases.

Anthropogenic activities associated with road construction, such as hillside cutting, may be the greatest challenge due to their extensive damage to ecosystems that are periodically subjected to large earthquakes. Martino et al. (2019) found that 704 landslides triggered by 2016 Central Italy earthquake associated with road cuts, causing traffic disruptions. While the results of many quantitative and qualitative studies have shown that hillside cutting in mountains may result in landslides due to seismic activity, such investigations have not considered the increased anthropogenic activity associated with logging roads, especially regarding earthquake-induced landslides.

To clarify whether past anthropogenic activities may have contributed to earthquake-induced landslides, we examined the interaction between logging roads and landslides caused by the 2018 HEIE. The objectives of this study are: (1) analyzing the characteristics of landslides caused by the 2018 HEIE, including frequency, density, size, and topography using geostatistical analysis; and (2) examining the effect of road prisms on the earthquake-induced landslide characteristics by categorizing road-associated landslides on the basis of the landslide initiation point, road interception, and road cut.

2. STUDY AREA AND METHODOLOGY

This study was conducted in the Habiugawa watershed (39.8 km2), Atsuma, Hokkaido Prefecture, Japan, located 10 km northwest from the epicenter of the Eastern Iburi earthquake (Fig. 1a, b). The mean annual precipitation and air temperature are 997 mm and 6.7°C, respectively, according to AMeDAS Atsuma data (1976–2019). Soil depth in this area ranged from 1 to 4 m. The Tarumae volcano was the most recent contributor to the pyroclastic deposits in the area including Tarumae b (Ta-b: 1667 A.D.), c (Ta-c: 2.5 ka), and d (Ta-d: 8.7–9.2 ka). The study area is covered mostly by secondary forests, including deciduous forests (e.g., Betula platyphylla, Quercus mongolica), mixed-conifer forests, and conifer plantations such as Larch (Larix kaempferi) and Todo fir (Abies sachalinensis) (Fig. 1c). Logging roads in the study area were mainly constructed with cut-fill method. The width, age, and density of the logging roads vary with the elevation and their position on the hillslope. Abandoned logging roads are dominant since most were constructed only for temporary use to support various forestry activities including harvesting and re-planting. As a result, many of the roads are fully covered with Sasa dwarf bamboo due to the lack of maintenance (Ritonga et al., 2021).

The LiDAR–DEM derivatives (0.5 m) and high-resolution orthophoto (0.2 m) taken five days after the landslide occurrence were used to extract landslides as polygons and logging road networks as polylines. In this study, only landslide scars (i.e., open failure plans with a smooth surface roughness) were used for geostatistical analysis.

We estimated the interaction between landslides and logging roads by determining whether each landslide was associated with the road prism using the ArcGIS Pro 2.9 geographic information system software package. Landslides may interact with road prisms under three main conditions: (1) landslide initiation at the fill-road surface, (2) landslide scar intercepted by road at mid-slope, and (3) landslide initiation immediately below the cut slope. To define these categories, we first extracted three points from each landslide polygon representing the maximum (Max), center (Mid), and minimum elevation (Min) points of the landslide. The GIS

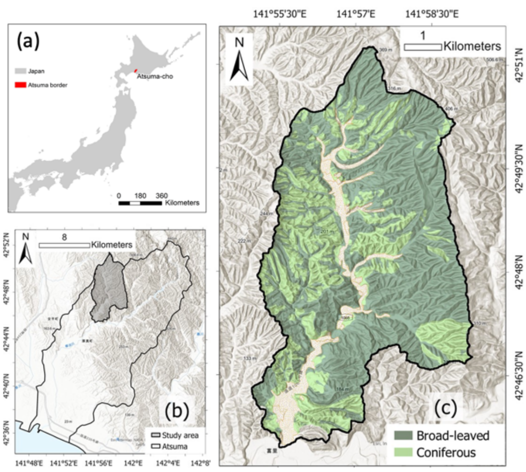

Fig 1. Locations of the study area; (a) Hokkaido prefecture in Japan with Atsuma basin in the southern part of the island; (b) Atsuma basin facing the Pacific Ocean in the southern part, (c) Habiugawa watershed (39.8 km^2)

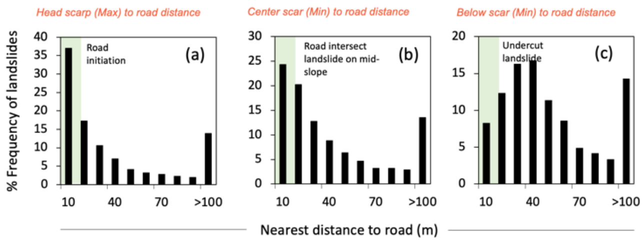

Fig 2. Shortest distance between road polyline and landslide (point): (a) top scar Max points; (b) center scar Mid points; and (c) bottom scar Min points

"Near" tool was used to calculate the shortest distance between those three points to road prisms to no more than 10 m of road polyline. If the distance of Max point from the nearest road polyline was less than 10 m, it was categorized as a fill-slope initiation landslide (*FL*). If the distance of the center point was less than half the landslide length, it was categorized as a mid-slope road intercepted landslide (*ML*). Finally, if the shortest distance below scar from the nearest road polyline was less than 10 m, it was categorized as a road-cut-slope initiation landslide (*CL*). Landslides falling outside these categorizations were defined as natural landslides (*NL*).

3. RESULTS

A total of 2940 landslide scars were identified in the study area using post-earthquake LiDAR datasets and orthophotos of the Habiugawa watershed. The landslide areas (A_L) ranged from 17 m^2 to 3.4×10^4 m^2 (mean = 1617 m^2). Based on topographic characteristics, plan curvature analysis showed that 78% of the landslides were on hillsides with a plan curvature ranging from −4 to 0, with a mean value of −2.1. Meanwhile, the profile curvature was more likely to be distributed from 0 to 4 (71%), with a mean value of 2.2. This indicates HEIE landslides tend to occur on concave landforms.

A total of 446 km of road within 2016 delineated polylines were identified in the study area. Among 2941 identified landslides, 1088 (37%) were fill-slope initiation landslides (*FL*) **(Fig. 2a)** with 762 (70%) of them being right-of-way of road edge (shortest dist. <5 m). There were 1638 (56%) mid-slope road intercepted landslides (*ML*), with the distance ranging from 0-86 m of landslide center point **(Fig. 2b)**, indicating that the roads intercepted the landslide at positions within the landslide at various locations on the hillslope, either on the upper slope or the lower slope. Only 8% of the landslides possibly lost support at the cut slope (*CL*) (dist. = <10 m) **(Fig. 2c)**, with 60% of them located at the base of the cut slope (dist. = 5 m). Based on landslide size, *ML* category were larger (mean = 2027 m^2) compared to *FL* (mean = 1643 m^2). Contrastingly, *CL* were two times smaller (mean = 1100 m^2) compared to *ML*. Of these 2941 landslides, road-associated landslides were more frequent (60%), as well as triggered larger landslides (mean = 1963 m^2) compared to natural landslides or *NL* (mean = 1214 m^2).

4. DISCUSSION

Based on initiation, our finding showed the landslides were mostly fill-slope initiation ones (frequency of 37%; density up to 2.41 landslides/km) is similar to that for rainfall-induced landslides. As evidence, Jakob (2000) showed that the frequency of fill-slope landslides was five times higher (n = 15; *LDR* = 0.05 landslides/km) compared to that of road-cut slides (n = 3; *LDR* = 0.01 landslides/km) in the logged area of Clayoquot Sound, British Columbia, due to excess water input from the roads to the downward slopes. The low infiltration rates on the road surface were apparently caused by vehicle traffic during active logging that had rerouted the water flow pathways to the fill slopes (Sidle et al., 2004). This could lead to excess pore water pressure in the fill-slope during and after storm events, particularly on concave landforms. The terrain in the Habiugawa watershed is covered by volcanic soils, which can retain water for a long period, especially in the clay-rich Ta-d layer (Kameda et al., 2019). We speculated that the road surfaces had already contributed to rerouting the flow pathways during storm events before the earthquake, which would have increased the soil water content in the road fill-downslopes and weakened them.

The landslides in the study area varied in size depending on the road prism. Landslides were largest for those were intercepted by mid-slope road or *ML*, reflected by the domination of medium to large landslides (>1000 m^2). We suggested that the presence of multiple mid-slope roads might have extended the landslide scars further down the slope. In the study area, a single hillslope typically has multiple mid-slope roads for transporting logs from the harvesting site to the main road. However, multiple roads could lead to increased water flow from each fill-road pathway to the slopes located downward slopes. These multiple hillslope roads would thus exacerbate landslide scarring by spreading pore water pressures, particularly in concave hillslopes.

5. CONCLUSIONS

Our GIS analysis revealed that the 2018 HEIE was unique in terms of landslide characteristics, including frequency, density, and size, due to the presence of a dense network of logging roads in the landslide-affected areas. The logging roads likely causes higher road-landslide erosion after an earthquake for a long period given that a greater number of and larger landslides occur in the presence of one or more roads, especially in logged terrain. Overall, our results provide new insight into the location of landslide-prone areas due to anthropogenic activities, such as the construction of logging roads.

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