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Predisposition Factor of Safety of Landslide Dams from Typhoon Talas, Kii Peninsula, Japan

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Abstract
Landslide dams are less frequent than other landslides, and their very existence is often very-much short-lived, because the temporary dam tends to collapse rapidly. Because of the resulting lack of evidences, there has been less research done on this topic, although the potential catastrophe they can be at the origin of needs assessment. For this purpose, the present contribution aims at differentiating landslides that trigger dams against those that do not inside a group of valleys of the Kii peninsula in Japan, where landslides occurred after the typhoon Talas in 2011. Using topographic map before the event and LiDAR data in its aftermath, the authors have calculated the factor of safety (FS) of different landslides in the same valleys, comparing the data of landslides that created dams against those that did not. The results show that landslides that triggered dams seemed to have a higher FS than those that did not. The authors suggest that it is because larger landslides are needed and thus appear more stable, but also because at the location where the slopes are stable, the riverbed can incise further instead of growing horizontally, and thus the sediments damming the channel have more chances to block it (as it is narrow) and stop the river from flowing.

Keywords: landslide predisposition facts, landslide dams.

1. Introduction

Landslides (Hadmoko and di Mauro, 2012) and landslides' dams are a major threat across mountainous regions of the world, with the potential of sudden dam-breach, which in turn have the potential to lead to downstream floods. Moreover, recreational mountaineering and climate change have increased the disaster risk due to mass movements (Purdie *et al.*, 2015).

The largest contemporary landslide dam on Earth is the Usoi dam, produced in 1911 in Tajikistan, with a lake as deep as 505 m. Other smaller-size landslides can be found in most countries with mountainous areas: in Turkey, the Tortum dam is 180 million m3 dam, impounding a 6.77 km2 surface lake (Duman, 2009). Across the world, Costa and Schuster (1991) recorded 463 landslide dams, and more recently Korup (2002) recorded more than 130 for New Zealand only and Yan (2006) found 388 for China alone, suggesting that the data first provided are very conservative. More recently, Peng and Zhang (2012) compiled a database with 1,239 landslide dams, demonstrating the difficulty of working with landslide dams, because they are often temporary features, which are often drained when possible. Peng and Zhang (2012) have demonstrated that 87% of landslide dam fails within one year, while 71% within 1 month and a bit more than half within a week, and that the failure occurs by either overtopping (90%), piping (8%), and slope failure (1%). Interestingly, they also demonstrated that this distribution does not compare well with the man-made earth and rockfill dams. Consequently, morphological indices of valley dams (Stefanelli *et al.*, 2016) and statistical approaches (Shen *et al.*, 2020) are being employed to improve scientific understanding of the longevity of landslide dams and when they are most likely to break.

Because of the difficulties, Science still faces with fully physical simulations for prediction of frequency and runout (e.g. Huang *et al.*, 2015; Cama *et al.*, 2015), remote sensing (Gomez and Purdie, 2016; Lissak *et al.*, 2020) combined with statistical and geostatistical methods has been widely used (Saputra *et al.*, 2015). These methods have especially led to empirical predictors relying on geometric factors (e.g., volume, area, runout, and distance to river, H/L ratio, type, and lithology) and the statistical relations between these parameters (Fan *et al.*, 2014). The relation between the translated volume of material and the deposition extend has been found to be a power law relating the area of the landslide A [m2] to the volume V [m3], so that: V = 0.316A1.361, with a R2 of 0.906 (Chen *et al.*, 2014). In Hokkaido (North Japan), the relation between the width (W) and the length of the deposit (L) also showed that for earthquake-triggered landslides in the immediate aftermath of a typhoon. The relation was almost scale-invariant with L=2.2492W1.0296 (R2=0.89). Moreover, in Hokkaido the runout was exceptionally long (Gomez and Hotta, 2021), with a H/L ratio between 0.15 and 0.5 for relatively small landslides. This H/L ratio - or Fahrboschung - was calculated to be F=0.3521-9*10EXP-06D (Gomez and Hotta, 2021). By comparison, the Naga landslide (Catane *et al.*, 2019), and the Zhaotong rock avalanche of 1991 (Xing *et al.*, 2020) show Fahrboschung of 0.17 to 0.25, which at equal volume in Hokkaido would lead to a Fahrboschung of 0.028. It shows that in between locations and events, there are great disparities, but at the same time the research corpus also suggests that for a single type of events in homogeneous valleys and lithologies, comparable geometric relations can also be expected.

To these inherent difficulties, landslide dams add further challenges to their predicting, as it is the case for secondary- and multi-hazards (Saputra *et al.*, 2021). Indeed, in a geologically "homogeneous region", only a small proportion will block valleys and generate impoundments. For instance, out of the approximately 30,000 landslides generated by the 12 May 2008 Sichuan Earthquake, only 257 blocked rivers to form impounded lakes (Cui *et al*., 2009; Peng and Zhang, 2012). Moreover, landslide dams generated by rainfall-induced landslides tend to collapse in 82% of cases, while earthquake-induced landslides tend to be more stable (57% collapse) under the pressure of the impounded water (Kuo *et al.*, 2011), further emphasizing the difficulty in predicting potential for impoundments and downstream floods.

In the light of this research body, which suggests that in homogeneous terrain, and for a homogeneous triggering event, the variability is site specific and eventually linked to the morphology of the slope, the objective of this work has been to test whether the factor of safety (Fs) could be used as a factor to determine whether a landslide could turn into a dam or not. Such work would then allow for pre-event assessment of the slopes from high-resolution topographic data, prior to further engineering invasive investigation.

2. Research Method

To reach the present objective, the research was conducted at the Kii peninsula, located to the south-west of Honshu Island, Japan (Figure 1), where a set of landslides have occurred following the landfall of typhoon 12 or Typhoon Talas, on September 3rd, 2011 (Figure 2). The local topography is characterized by elevation not exceeding 1,500 meters, but with slopes commanding topographic gradients of 500 m to 800 m locally, with gravel-bed rivers resulting for the tectonically active area. Erosion is an important shaping factor of these reliefs as they are cut from shale with blocks of chert and greenstones alternating with sandstones, dating back to 80~90 million years. This material was generated as part of the Ryujin accretionary prism, created by the subduction of the tectonic plates, and dated to be Middle Miocene in igneous rocks with signs of remobilization during the late Maastrichtian based on U-Pb dating (Hoshi *et al*., 2022).

This typhoon was the second catastrophic event after the 1889 typhoon, which brought 1000 mm of rainfall to the Kii Peninsula (Kharismalatri *et al*., 2017). The geology belongs to the Miyama Formation of the Hidakagawa Group, which is part of the Chalk Shimanto Belt and is composed mainly of chert, greenstones, and alternating sandstone and shale (Kinoshita *et al.*, 2013).

Using 8 landslides, triggered by the typhoon 12 (or Typhoon Talas), four of which became landslide dams (Figure 3), the authors reconstructed the topography prior to the landslide using the 1989 topographic maps 1/25,000 and the new topographic profiles in the center of the landslide scar from LiDAR data, in order to measure the depth of the slide by subtracting one from the other. The alignment of both dataset was performed using the open-source software Cloud-Compare and QGIS, based on 86 and 99 control points for the two map tiles used in the present study. In both cases, the alignment error was 3.24-11 and 9.14-12 and deemed to have no significant effect on the results. The 1989 map were used as a confirmation that the local slope was in continuation to the surrounding ones that did not collapse. This way the edge of the landslide measured from the LiDAR data were interpolated to the missing areas from which the pre-landslide topographic profile was generated (the data are provided in appendix as a csv file).

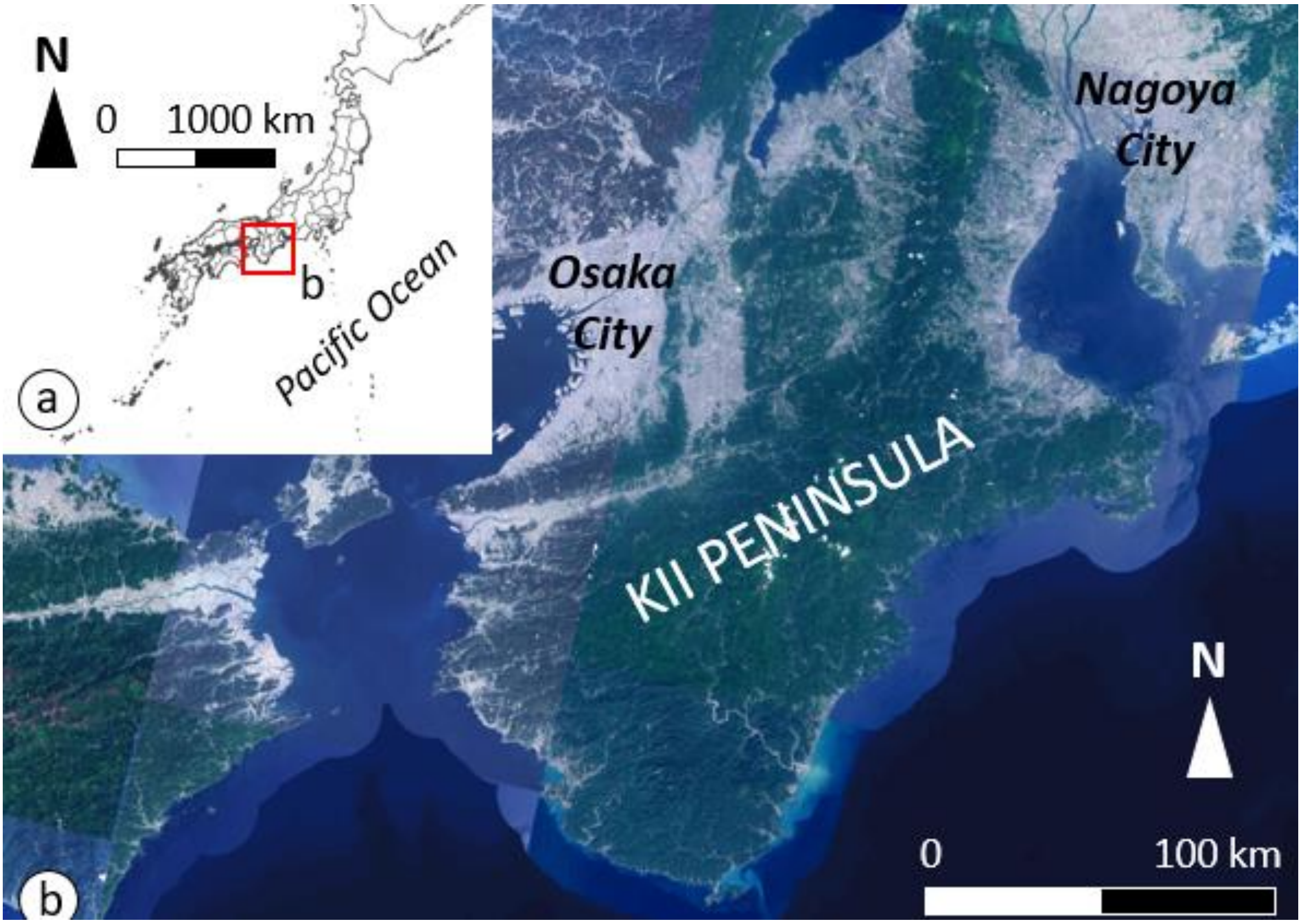

Figure 1. Regional Map of the research area (a) map of Japan with the survey region squared in red, (b) Kii Peninsula located in between Osaka City and Nagoya City.

In order to link the landslide to predisposition factors of stability, the authors have used the infinite slope model, for which the unit density of material was tested at 20 kN/m3 (γ) was used as a simplification of the local material. The stability of slopes using the infinite slope method is based on the shear strength equation:

$$\tau_c = C' + \sigma' \tan \varphi' \qquad (1)$$

Where τ_c is the shear strength, C^' is is the cohesion, σ^' is the normal stress on the potential failure surface and φ' is the angle of friction. If we simplify the concept by omitting the pore pressure and water intake to compare slopes using the factor of safety (F_s), the equation can be reduced to:

$$F_s = \frac{C'}{\gamma H \, cos^2 \beta \tan \beta} + \frac{\tan \varphi'}{\tan \beta} \qquad (2)$$

Where H is the depth at which the failure occurs, and β is the slope angle of the failure plane. This equation was computed in the open-source software Hyrcan, using the method of slice (http://www.geowizard.org/download_hyrcan.html). Iteratively, Hyrcan tests the potential failure planes at different depths. The highest probability of failure corresponds to the “lowest” factor of safety, which once calculated was compared to the landslide failure plane, so that the authors could define whether – or not – the location of the simulated failure plane corresponded to the actual failure plane following the September 2011 rainfall landslides.

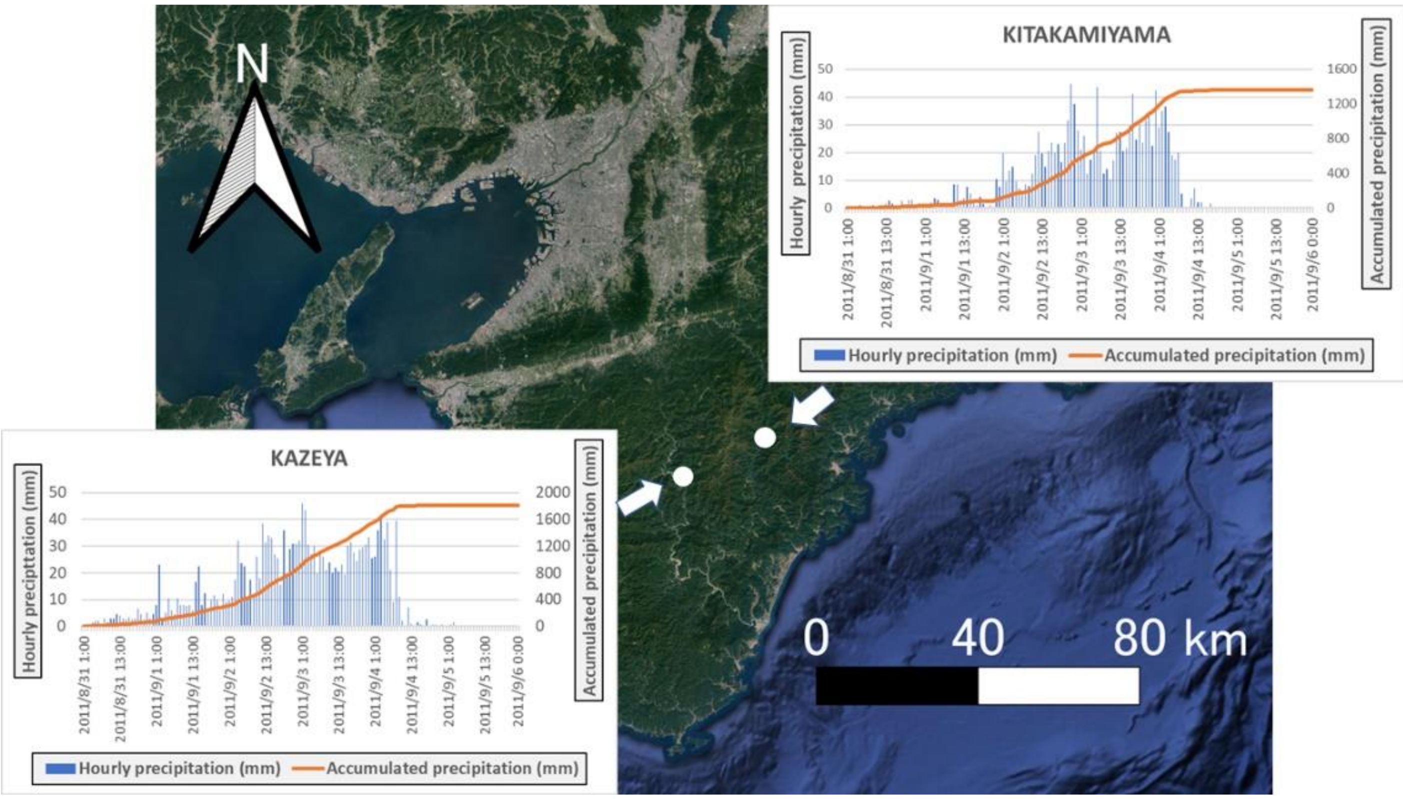

Figure 2. Rainfall Record of the 2011 Talas Typhoon (Typhoon 12) over the Kii Peninsula.

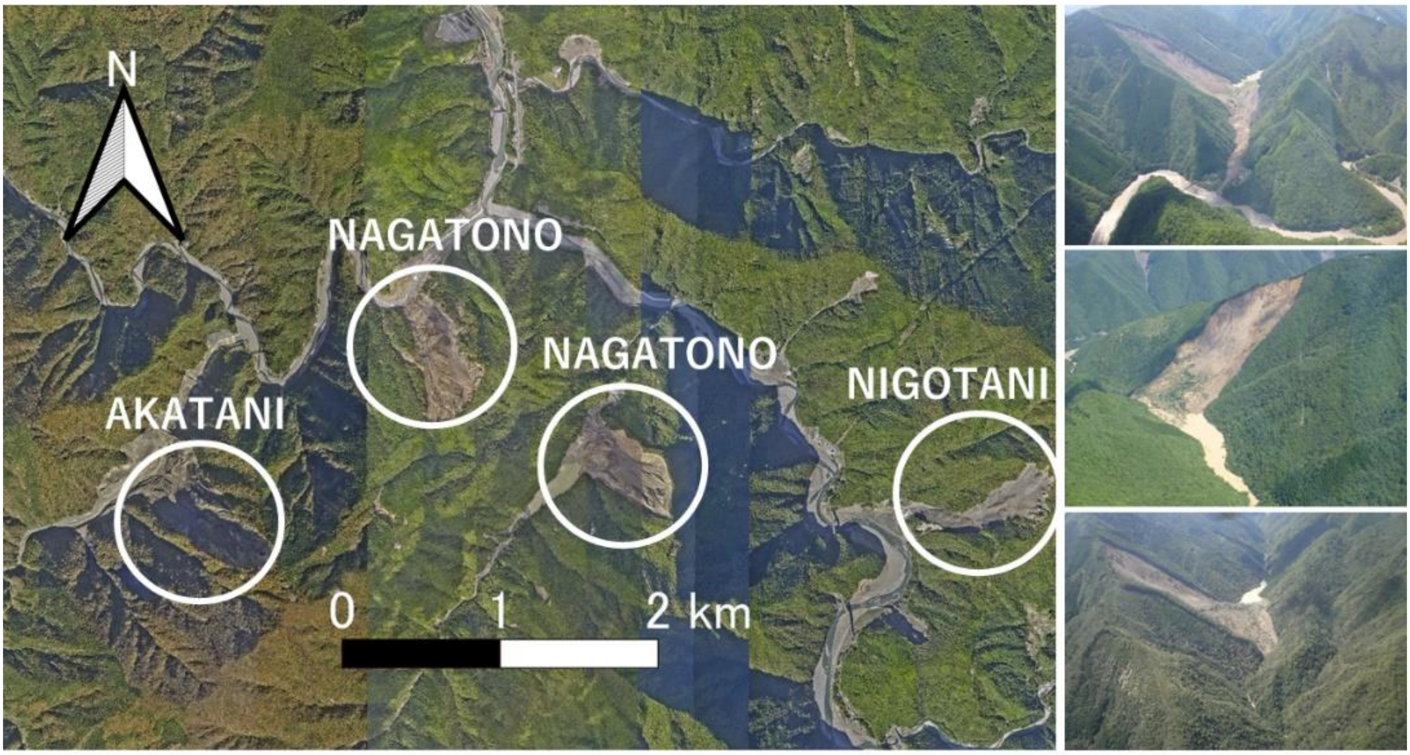

Figure 3. Aerial oblique photographs of the four studied landslides triggered by typhoon 12 in Nara prefecture, on the Kii Peninsula (source: MLIT).

3. Results and Discussion

3.1. Results

The 8 simulated landslides show depths (H) varying between 0.017 m and 83.160 m. The deepest simulated landslide found a depth of 83.160 m at AKATANI② location. The actual landslide depths varied between -0.073 m and 76.900 m, and the local discrepancy vary from 0 m to 44.696 m locally, with an underestimation of the sliding plane at AKATANI① landslide (Figure 4). At AKATANI and NAGATONO landslide, the lower part of the sliding plane does not correspond to the simulation, because accumulation occurred in the valley, and such accumulation could not be taken into account.

For the landslides that did not trigger a landslide dam, the depths varying between 0.009 m and 45.120 m. The deepest simulated landslide found a depth of 45.120 m at NIGOTANI① location. The actual landslide depths varied between -4.748 m and 58.500 m, and the local discrepancy vary from 0 m to 35.398 m locally, with an underestimation of the sliding plane at NIGOTANI② landslide (Figure 5).

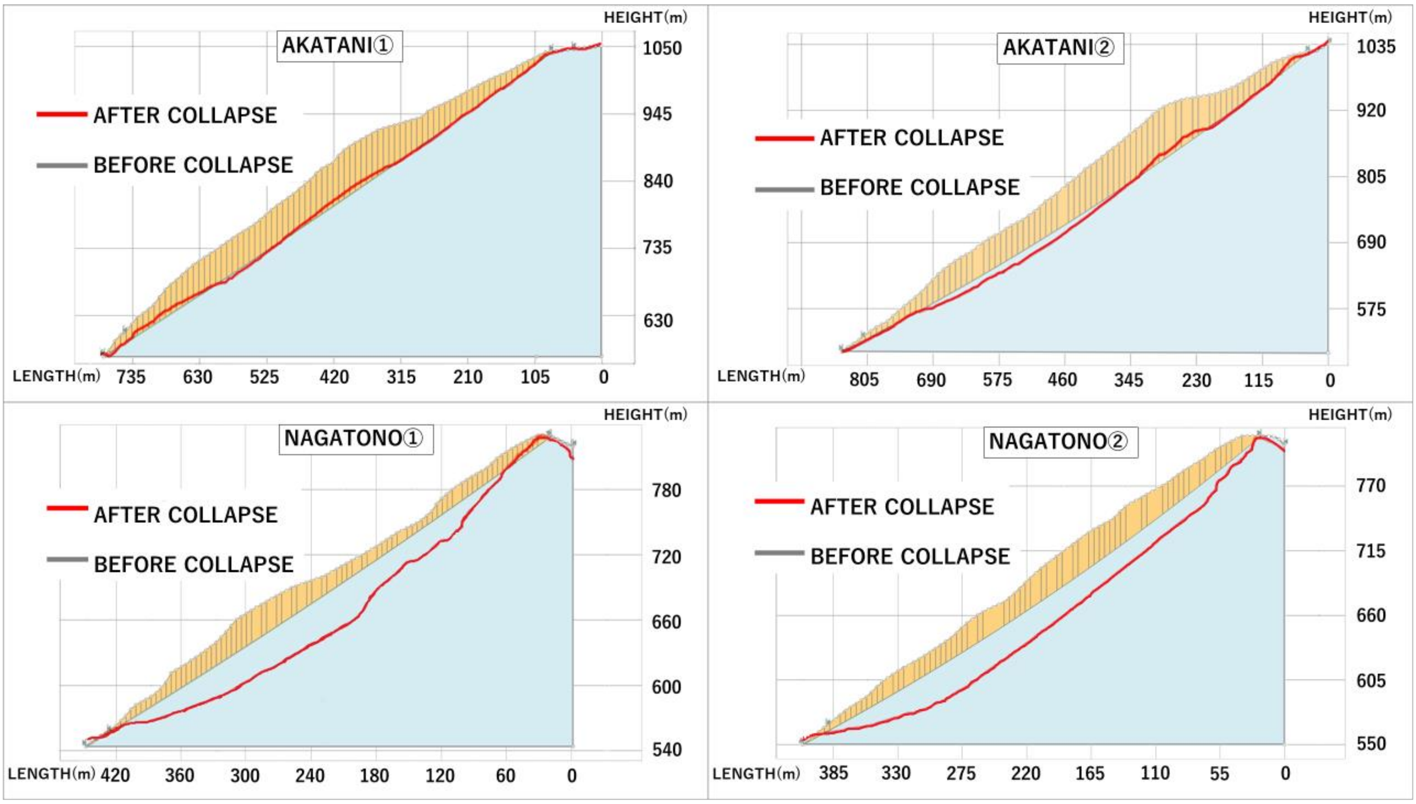

Figure 4. Profiles of the landslides that triggered landslide dams, with the simulated landslide and the actual sliding plane. The orange-coloured slices reveal the slicing method used to solve the factor of safety on the slope.

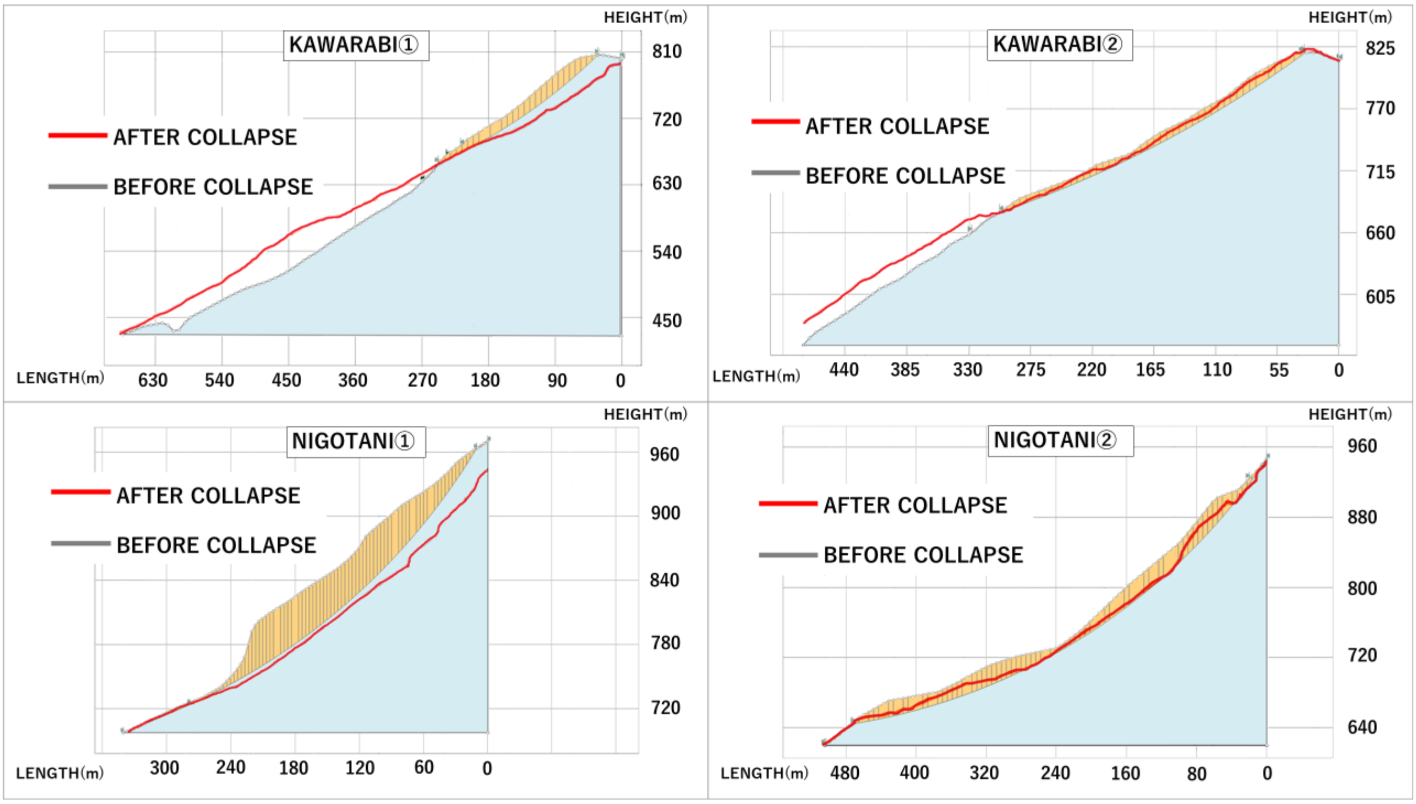

Figure 5. Landslide profiles for which landslide dams did not occur, comparing the simulated landslide against the actual landslide.

The differentiation in typical depth and sheer size of the landslides that triggered landslide dams compared to the normal landslide also exists when comparing the factor of safety for all of them (Table 1). Indeed, the factor of safety of the landslides that triggered landslide dams are comprised between 0.896 and 1.1, while those for landslides that did not trigger landslides, the FS is lower and comprised between 0.692 and 0.877. Consequently, predicting the potential of landslide dams based on soil mechanics and equilibrium approach can be challenging, as the method is not best suited to predict those.

Table 1. Factor of safety of the 8 different landslides. The landslides that triggered landslide dams have a higher safety factor than those that did not trigger landslide dams.

Location	AKATANI①	AKATANI②	NAGATONO①	NAGATONO②
FS	0.859	0.896	0.877	0.852
Location	KAWARABI①	KAWARABI②	NIGOTANI①	NIGOTANI②
Fs	0.811	1.1	0.692	1.02

3.2. Discussion

The present investigation of the predisposition factors for a selection of 8 landslides for which data were accessible, shows that the landslides that trigger temporary dams in river are eventually larger than their other counterparts, but also that the factor of safety is actually higher. The interpretation of the results suggests that landslides that occur less often are then eventually able to remobilize a greater amount of material, but also that the valley floor might play an important control role as well. Indeed, if sediments are continuously supplied to the valley floor, a widening and an adaptation to this situation occurs in the river network. To the contrary, a zone with no or less sediment supply will result in more vertical erosion and a potentially narrower channel, which in turn, during rare events will tend to be more prone to be filled up and to block the valley. Such characteristics, as well as road cuts are both well-known triggering factors of landslides (Ling and Chigira, 2020).

As Cui et al. (2009) expressed, only a few percent of the triggered landslides generate landslide dams. The present finding is in line with these existing findings, because – based on this limited study – their Fs is slightly higher. In other words, slopes that are less stable and prone to progressive erosion and small-scale mass movements are despite of their appearance not the most dangerous, they are most likely to not trigger a large-scale event. This is however not always the case as series of large-scale landslides can also occur and temporarily block rivers (Gomez *et al.*, 2020).

Hadmoko *et al.* (2010) discusses that qualitative, semi-quantitative and quantitative methods have been developed to measure hazards and disaster risks, and so using a broad range of datasets that can characterize the landslides. This logic is based on the concept that previous landslides can be used as a base to characterize future events. This broad concept is verified in the present case as well for landslides that are "dam-genic", because the FS – which is an expression of geometric parameters of the slope in absence of rainfalls - have shown to be of a higher Fs compared to landslides that are not dam-genic. This in turn signifies that, within a certain level, there are geometric parameters - besides the influence of rainfalls - that are sufficient to differentiate large vs small more regular landslides for the Kii peninsula.

The comparison provided in the present contribution however, is based on one single rainfall events, which, if one disregards the spatial variability of rainfall, and so in one single set of geological units. But this realm may not hold in complex and very differentiated geological settings or in the case when rainfalls or earthquake acceleration vary spatially. At present, understanding how one factor play over another one is often difficult, and scientists have often to resort using the simple events in the dataset (e.g., extracting the mass movements with deposits that did not mix with other deposits: Gomez and Hotta, 2021), like it is the case here, but there is still further work to be done on the role of multiple factors together.

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4. Conclusion

In conclusion, we have proven that, before a rainfall event occurs, it was possible for a homogeneous catchment to predict landslides that will be more prone to trigger natural dams against those that have less probability to trigger one. Landslides that can be the source of landslide dams are of larger amplitude and are more difficult to predict, because of their higher Fs values. The investigation found that landslides triggering temporary dams in rivers tend to be larger but have a higher factor of safety, while slopes that are less stable and prone to small-scale movements are not necessarily the most dangerous. The study suggests that previous landslides can be used to characterize future events, particularly for "dam-genic" landslides, but further work is needed to understand the role of multiple factors together in complex geological settings.

Author Contributions

Conceptualization: Rikuto Daikai, Christopher Gomez, Balazs Bradak, Aditya Saputra, Danang Sri Hadmoko; **methodology**: Rikuto Daikai, Christopher Gomez, Balazs Bradak, Aditya Saputra, Danang Sri Hadmoko; **investigation**: Rikuto Daikai, Christopher Gomez, Balazs Bradak, Aditya Saputra, Danang Sri Hadmoko; **writing—original draft preparation**: Rikuto Daikai, Christopher Gomez, Balazs Bradak, Aditya Saputra, Danang Sri Hadmoko; **writing—review and editing**: Rikuto Daikai, Christopher Gomez, Balazs Bradak, Aditya Saputra, Danang Sri Hadmoko; **visualization**: Rikuto Daikai, Christopher Gomez, Balazs Bradak, Aditya Saputra, Danang Sri Hadmoko. All authors have read and agreed to the published version of the manuscript.

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