Deep-Seated Landslides and Landslide Dams
Characteristics Caused by Typhoon Talas at Kii Peninsula, Japan

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Kii Peninsula was severely damaged by Typhoon Talas in September 2011, causing in many landslide disasters, material loss and casualties. Looking back to the history, this area was also severely damaged by typhoon in 1889. Thus this area seems very prone area to landslide disasters. This research is studying the topographical features of 34 deep-seated landslides that occurred in September 2011, and trying to figure out the special characteristics of landslide dams. The results show that landslide dams are likely to occur if the landslide having riverbed gradient between 0-30º and confluence angle of 60-110º. Based on the regression results, landslide dams are having equivalent coefficient of friction more than 0.25 which means that the travel length of the landslide material less than 4 times of the height difference between top of the landslide area and inundation area. Correlation between equivalent coefficient of friction, landslide type and characteristics need to be studied further in order to find the condition for formation of landslide dam, so that a clear distinction of which type of disaster a landslide would likely to form can be obtained.

Key words: deep-seated landslide, landslide dam, characteristics, typhoon talas, Kii Peninsula

1. INTRODUCTION

There are many different factors that trigger landslides, namely prolonged and excessive rainfall, earthquakes, and snow melts. Mass movement involves flowing, sliding, toppling or falling movements, and generally combination of several types of movements [Varnes, 1978]. Landslides occur as a single disaster or multiple disasters which occur simultaneously in a period of time (hours or days). Landslide as a result of weakened self-retainability of the soil under the influence of rainfall or earthquake forms in many types of disasters, namely shallow landslide, debris flow, deep-seated landslide, landslide dam, slump, etc. Each type of landslide form has different characteristic and condition for formation.

Most common types of mass movement that form landslide dams are rock and soil slumps, slides (mud, debris, and earth flows) and rock and debris avalanches [Schuster & Costa, 1986]. Landslide dam is common phenomenon in Japan, due to unstable slope and narrow valley which widely spread in Japan, in conjunction with frequent hydrologic, seismic and volcanic occurrence [Swanson et al., 1866]. On steep narrow valley which bordered by high rugged mountains, even small volumes of landslide material will easily form landslide dam, thus landslide dam mostly occur on this type of area [Costa & Schuster, 1988]. Such dams are much less common in broad open valleys, but in areas where rivers have incised lacustrine or marine deposits, slides and slumps or quick-clay failures have formed landslide dams [Evans, 1984 and Clark, 1947 in Costa & Schuster, 1987].

Historical documents and topography have revealed the formation of many landslide dams, some of which broke and caused major damage in Japan [Tabata et al., 2002]. Damming of rivers by landslide dam hold a great threat, the dam breaking which is mostly due to overflowing will cause large surges or debris flow that is dangerous to population in downstream area [Mizuyama et al., 2004].

Kii Peninsula is a large peninsula located in the main island in Japan, the Honshu Island. Due to its location which protruding into the Pacific Ocean as shown in Figure 1, this area is commonly the hit by the typhoon. Topographically, this area is occupied with steep mountains, thus when typhoon or heavy
Fig. 1 Kii Peninsula.

rainfall hit this area, landslides occur in many location and causing severe damages.

Kii Peninsula was hit by Typhoon Talas (Typhoon No. 12) from 2nd to 4th September 2011 which cause precipitation more than 1,500 mm, about half of the annual precipitation of Kii Peninsula that is about 3,000 mm. The typhoon caused more than 3000 landslides in Mie, Nara and Wakayama Prefectures, including thousands cases of slope collapses, debris flows, deep-seated landslides, and landslide dams, and also numerous casualties and property damage. Large-scale landslides occurred frequently due to heavy rainfall in this area, particularly in 1889 this area were catastrophically damaged by the collapse of many landslide dams [Fujita, 2012].

In 1889, Kii Peninsula was also severely damaged by typhoon which leads to many deep-seated landslide disasters and landslide dams. The typhoon brought rainfall over 1000 mm between 19 and 20 August 1889 and caused more than 33 landslide dams. Most of the dams were collapsed and caused more severe damages [Inoue et al., 2012].

Considering that this area seems a deep-seated landslide prone area and deep-seated landslide material might forming into other type of disaster, this research aims to analyze the landslide material movement of deep-seated landslides occurred at Kii Peninsula and its influencing topographical factors so that the characteristics of deep-seated landslides can be understood. Furthermore, factors that influencing the formation of landslide dam can be found in order for further landslides prediction and mitigation.

2. METHODOLOGY

Landslide is generally influenced by several aspects, namely the geology of collapsed material, volume of material, topography, and human activity. Collapsed material of deep-seated landslide cause three types of hazard, namely (1) collapsed materials flow down through the river to downstream area, (2) collapsed materials deposit in the river course and causing water inundation, and (3) collapsed materials not flow down to downstream and not blocking the river course. Kikuchi [2013] studied the shallow and deep-seated landslides characteristics in Kii Peninsula namely slope inclination, distance of collapsed area from valley, angle and direction of confluence of collapsed material and stream, and stream order. This research is continuing Kikuchi’s research in order to find more characteristics of landslides in Kii Peninsula specifically on deep-seated landslide cases and the formation of landslide dam.

In this research, deep-seated landslides classified into three types based on its material movement, namely debris flow, landslide dam, and other. Deep-seated landslides formed landslide dam if there is deposition of material in the river course ahead and the material deposition is not forming a wide or long deposition, but piling up vertically with the height of more than 10 meters. Landslides changed into debris flow if the material flows down to through the river with travel length more than twice of its landslide length. Other than those two types of landslide’s material movement classified as other, those landslides might be small landslide dams with height less than 10 meters or landslide dams that washed away by the flash flood soon after its formation.

Main data of these researches were DEM (Digital Elevation Model) which obtained from Geospatial Information Authority of Japan (GSI) and aerial photographs of research area. The DEM data, as shown in Figure 2, was elaborated to topographical features such as slope aspect, contour, stream flow direction, stream order, upstream watershed area, etc. The landslides areas were obtained by interpreting aerial photographs and comparing the photographs before and after the Typhoon Talas. These landslides areas then used as clipping feature to cut the topographical features in order to obtain special features on each landslide area.

Factors that affecting landslides and material movement type in this research area are average slope inclination, distance to valley, stream order, and confluence angle [Kikuchi, 2013].
On this research, characteristics of the deep-seated landslides were observed further including riverbed gradient, slope height, upstream watershed area, equivalent coefficient of friction and characteristics correlation was investigated through multiple regression analysis.

Equivalent coefficient of friction was used as the dependent variable in the regression analysis. As for average slope inclination, stream order, distance to valley, confluence angle, riverbed gradient, upstream watershed area, and slope height were considered as independent variables. The multicollinearity between independent variables was checked and several variables were eliminated in order to avoid multicollinearity.

3. RESULT AND DISCUSSION

Kikuchi [2013] found 393 landslides on the research area, including 34 deep-seated landslides which classified into 13 debris flows, 12 landslide dams, 9 others and the rest are shallow landslides as shown in Figure 3.

The classification of shallow landslide and deep-seated landslide was based on material volume of the landslide. Landslide with material volume less than 100,000 m$^3$ were classified as shallow landslides, while landslides with material volume more than 100,000 m$^3$ were classified as deep-seated landslides.

However, the characteristic of landslide that can directly obtained from ArcGIS and DEM data is landslide area, thus the empirical relationship by Guzetti [2009] below was used to transform the landslide area characteristic into landslide material volume.

$$V = 0.074 \times A^{1.45}$$

where

- $V$ : landslide material volume (m$^3$)
- $A$ : landslide area (m$^2$)

Based on the empirical relationship above, landslides with area more than 16,909 m$^2$ were classified as deep-seated landslide while the other classified as shallow landslide.

The landslides in Kii Peninsula mostly occur in $30^\circ$-$40^\circ$ of slope inclination, regardless the type of the landslide. Regarding the distance from valley, most of the landslides occur at less than 100 m distance from the valley, landslide dams mostly occur at 100-200 m distance whereas debris flows mostly occur at 100-250 m distance. Character distinction between landslide dam and other type of landslides could not clearly observe in this factor.

Based on the stream order, debris flows mostly occur at first stream order, means at the headwaters area of the stream, while landslide dams mostly occur at second or third stream order. The stream order factor is indirectly describing riverbed gradient factor, where the first order stream has steeper angle rather than second or third order. Kikuchi [2013] also considered confluence angle between landslide area
and river as one of influencing factors of landslide dam formation. Most of landslide dams occur when the angle of confluence of collapsed material and river is about 60-110°, while debris flows mostly occur at 0-40°.

In this research, other characteristics were analyzed, specifically on deep-seated landslide cases which were classified into three types based on its material movement. The landslides which classified as “other” were mostly having the potential of being landslide dams, but no deposition of materials found at the river ahead the landslide area. This condition might be caused by flash floods that wash away the material deposition soon after its formation due to the landslide’s location on main river. It also that the volume of landslide material relatively small compared to the wide of river ahead and the deposition was not so high, thus the landslide could not be considered as landslide dam. Figure 4 shows the two examples of landslides that classified as other.

Figure 4 Examples of other type of landslides.

Characteristics of deep-seated landslides were studied with focusing on those three types and other characteristics that not yet been studied in prior research by Kikuchi, namely riverbed gradient, slope height, upstream watershed area, and equivalent coefficient of friction.

Riverbed gradient was measured by dividing the difference in elevation between two points on a stream by the distance between those two points. It can be expressed as meters per kilometer, percentage, or angle. High gradient indicates a steep riverbed, rapid flow of water and more ability to erode, where usually the valley is steep and narrow V-shaped. Whereas low gradient indicates gentler riverbed, slower water flow, have wider valley, usually forming a meander and may be able to carry only small amounts of very fine sediments.

The results show that streams with 0-5° of gradient are tend to form landslide dams, whilst streams with 15-20° gradient are likely to form debris flows. This result is corresponds with the general characteristics of riverbed gradient, where higher riverbed gradient tend to have rapid flow, thus the landslide mass will be easier to flow down to downstream. While on 0-5° of riverbed gradient, the landslide material will be deposited on the stream ahead, because the water flow is slow and unable to erode the landslide material. Slope height of the landslides areas was also observed, calculated from the valley area to the top of the slope, where all landslide types are mostly occur on 200-300 meter of slope height.

Confluence angle was measured by drawing imaginary line around the middle of the landslide area to the river ahead. The meeting angle between this imaginary landslide line and the upstream river is considered as confluence angle in this research, as shown in Figure 5. Generally, landslide with small confluence angle will tend to form debris flow, since landslide material can easily flow down into the river. While bigger confluence angle will cause the landslide material to deposit at the river and form landslide dam.

Figure 5 Example of confluence angle (α) measurement
Figure 6 shows the correlation between confluence angle and riverbed gradient where landslides within 10-30° riverbed gradient and 0-40° confluence angle area are tend to form debris flow, whilst landslide within 0-10° of riverbed gradient and 60-110° of confluence angle area are tend to form landslide dam. The area outside these two factors is ambiguous area, it could not clearly decided whether the landslide occurred in this area will turn to landslide dam or debris flow. This separation of landslide dam and debris flow formation area could not represent the general condition of landslide dam formation in Japan, it is only represents the condition at Kii Peninsula.

In order to understand formation of landslide dam, multiple regression analysis was done on each type of landslide material movement and also on general condition. Characteristics used in the regression analysis were topographical factors such as average slope inclination ($x_1$), stream order ($x_2$), distance to valley ($x_3$), confluence angle ($x_4$), riverbed gradient ($x_5$), upstream watershed area ($x_6$), slope height ($x_7$) and landslide area ($x_8$). Multicollinearity between each factors were checked before the regression analysis done.

The dependent variable for the regression was equivalent coefficient of friction ($\Sigma H/\Sigma L$) which is an indicator of the run-out distance and degree of fluidization of falling material. Smaller equivalent coefficient of friction means that the landslide material flows to downstream and inundated farther from the landslide area, while bigger equivalent coefficient of friction means that the landslide material flows not so far and might deposited near the landslide area.

Multiple regression analysis was done on each type of deep-seated landslide’s material movement and also on general condition, where all the deep-seated landslides considered as one general type without classifying it into three types. The results of the multiple regression analysis are showed below.

In order to avoid multicollinearity, several factors need to be eliminated from the regression results as shown above. The regression results seems quite reliable except for general condition which has $R^2$ only 0.23. Regression results for landslide dam, other and general condition has p-value more than 5% which is might be affected by the small amount of data. Important factors of debris flow are stream order, upstream watershed area and slope height. While for landslide dam, the important factor is average slope inclination. As for other, the important factors are distance to valley, confluence angle, riverbed gradient, and upstream watershed area. For general condition, no important factor found.

Figure 7 shows the correlation between observed and calculated of equivalent coefficient of friction for each type of landslide and general condition. Observed coefficient of friction were obtained from DEM analysis, while calculated friction of analysis were obtained by inputting independent variables into the regression results as shown in equation (2) to (5).

\[
y = 0.0035x_1 - 0.014x_2 + 0.0009x_3 - 1.41 \times 10^{-7}x_6 - 0.00015x_7 + 0.17 \\
(R^2 = 0.79, p-value = 3\%)
\]

\[
y = 0.049x_1 - 0.0015x_4 + 1.86 \times 10^{-10}x_6 - 0.0005x_7 - 0.92 \\
(R^2 = 0.69, p-value = 6\%)
\]

\[
y = -0.024x_1 + 5.11 \times 10^{-5}x_3 - 0.0042x_4 + 0.019x_5 - 7.99 \times 10^{-11}x_6 - 0.00087x_7 + 1.61 \\
(R^2 = 0.95, p-value = 15\%)
\]

\[
y = 0.011x_1 - 0.008x_4 - 3.93 \times 10^{-10}x_6 - 2.01 \times 10^{-6}x_7 + 0.022 \\
(R^2 = 0.23, p-value = 10\%)
\]
Comparison between observed and calculated of equivalent coefficient of friction; (a) by type, (b) general.

**Figure 7(a)** shows that debris flows are likely to have equivalent of friction less than 0.25 (blue area), which means that the travel length of debris flow is at least 4 times longer compared to the height difference of source area and the inundation area. Whilst for landslide dam in red area, it likely to have equivalent coefficient of friction more than 0.25 or in other words, the travel length is less than 4 times of the height difference of source area and the inundation area.

The other type are quite random, some of the landslides in this type has equivalent of friction less than 0.25, while the other are more than 0.25. The other landslides in red area (equivalent coefficient of friction more than 0.25) are deep-seated landslides which located in 2nd or 3rd stream order and having upstream watershed area smaller than the other landslides in blue area. Thus the material’s travel length not so far from its landslide source area. While the other landslides in blue (equivalent coefficient of friction less than 0.25) area having larger upstream watershed area which means larger amount of river flow to wash away the landslide material far to downstream area. This condition is showed in **Figure 8**.

**Comparison between observed and calculated equivalent of friction in general condition** as shown in **Figure 7(b)** seems quite far from the red line, which is 1:1 line to show the reliability of the regression result. Which is normal since the regression result for general condition only has $R^2$ for 0.23. But on the other hand, the landslides based on general condition regression seems having special pattern that need to be studied further. Moreover, travel length of landslide’s material to downstream area also needs to be analyzed for disaster prevention and mitigation planning. Thus these two topics will be studied onwards.

### 4. CONCLUSION

Landslides within 10-30° riverbed gradient and 0-40° confluence angle area are tend to form debris flow, whilst landslide within 0-10° of riverbed gradient and 60-110° of confluence angle area are tend to form landslide dam. Landslides outside these two areas are ambiguous, there is no clarity whether it will turn to landslide dam or debris flow.

Based on multiple regression analysis, the results for debris flow, landslide dam and other are quite reliable. While the regression result for general condition is not so reliable, but it shows special pattern that need to be studied further.

Debris flows are likely to have equivalent coefficient of friction less than 0.25 while landslide dams are likely to have equivalent coefficient of friction more than 0.25. Correlation between equivalent coefficient of friction, landslide type and characteristics need to be studied further in order to find the condition for formation of landslide dam, so that a clear distinction of which type of disaster a landslide would likely to form can be obtained.
REFERENCES