A method for predicting shallow landslide area in managed and unmanaged forests

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In recent years, with the decline of forestry in Japan, unplanted areas left after clear-cutting have increased rapidly. As shallow landslides occur frequently in clear-cut and unplanted areas, this study newly constructed a landslide risk prediction model, an improvement of a previous model [Kuroiwa and Hiramatsu, 2004], that considers the forest condition, especially whether the forest root system is decayed or developed following forest harvesting. Using this model, we calculated the shallow landslide area ratio in the Miyagawa Dam basin. It was possible to predict the shallow landslide area ratio with high accuracy compared with previous model application. Thus, the proposed model successfully predicted changes in shallow landslide areas of the basin by considering forest harvesting and rainfall.

Key words: Clear cutting, landslide risk, shallow landslide, replanted, unplanted

1. INTRODUCTION

In Japan, forest harvesting has declined in recent years due to the faltering prices of lumber and increased management costs. Following forest clearing, through a few decades to a few years, many sites were not replanted, and more unplanted areas are found each year. Unplanted areas do not benefit from the protection provided by forest cover, and the frequency of landslides has been increasing [e.g., Yanai and Terazawa, 1998; Preston and Crozier, 1999; Koyama et al., 2009; Kuroiwa and Hiramatsu, 2010]. To carry out sensible forest management and land erosion control in the future, there is a need to track forest harvesting and regeneration in these regions in real time and develop a predictive method for sediment yield by shallow landslides (shallow landslide area) considering forest harvesting. Prediction methods for shallow landslide areas need to be simple and practical if they are to be used more regularly for land erosion control master plans.

Several methods for predicting shallow landslide areas considering rainfall have been proposed [e.g., Uchiogi, 1971; Yoshimatsu, 1977; Wu and Sidle, 1995; Dhakal and Sidle, 2003; Shuin et al., 2012; Pradhan et al., 2016], and studies focusing on the forest condition as a potential predisposing factor of shallow landslides have been carried out using various approaches. By the statistical approach, landslide occurrence prediction methods considering the presence or absence of forest, forest age, and types of trees have been demonstrated [e.g., Azami, 1997; Sakuda et al., 2007]. Most of these studies have focused on the relationship between forest condition and landslide occurrence. Some studies have tested tree root strength, which can affect the risk of shallow landslides [e.g., Kitamura and Namba, 1981; Abe, 1998]. Physical models have been used in combination with infinite slope analysis models to calculate the risk of landslide occurrence, by considering the mechanical strength of the surface soil with its root system, i.e., effective soil cohesion [e.g., Tsukamoto, 1987; Sidle, 1991, 1992; Wu and Sidle, 1995; Dhakal and Sidle, 2003; Abe et al., 2004; Kurokawa et al., 2007]. Sidle [1991, 1992] proposed the net root strength model based on root cohesion in response to vegetation management and, using this model, assessed the change in slope stability depending on forest harvesting and methods of forest management. Imaizumi et al. [2008] discussed the effects of forest harvesting on the occurrence of landslides and debris flows using the same model. These studies focused on the relationship between root system strength and slope stability.

Many methods for predicting sediment yield have been proposed [e.g., Mizuyama et al., 1990]. Imaizumi and Sidle[2007] clarified the linkages between sediment supply and sediment transport processes in
the Miyagawa Dam basin, Mie Prefecture. Sediment yield prediction methods in the basin were advanced by these studies; however, the methods were not intended to be predictive of the sediment yield of the basin with consideration of forest harvesting. In the Miyagawa Dam basin, there has been an increase in the number of shallow landslides due to the increased amount of clear-cut and unplanted areas [e.g., Numamoto et al., 2004]; the same situation also exists in other basins in Japan [e.g., Numamoto et al., 2002; Koyama et al., 2009]. Thus, it is important to construct a prediction model for shallow landslide areas with consideration of forest harvesting.

Previous research [Kuroiwa and Hiramatsu, 2004] examined the Miyagawa Dam basin in Mie Prefecture and proposed a model for assessing sediment yield by shallow landslides (shallow landslide area) using the number of years since clear-cutting and the condition of replanted or unplanted; they confirmed that the model is generally valid for landslides. However, although this model considered landslide risk and whether replanting had occurred, it did not account for real phenomena such as the decay of tree roots and the process of forest growth.

In this study, we improved the previous model [Kuroiwa and Hiramatsu, 2004] by considering whether the root system is decayed or developed, as a result of forestry practices. From this, we constructed a landslide risk prediction model considering the forest condition. This model was then used to predict shallow landslide area sites.

2. STUDY AREA

The study area was the Miyagawa Dam basin in Odai-cho, Taki County, Mie Prefecture, Japan (basin area of 125.6 km$^2$; see Fig. 1). The basin’s elevation varies from 270–1,700 m, and its main river has a length of approximately 26 km and a mean bed slope of 1/18. The lithology of the basin is mainly claysone and sandstone, typical of the Chichibu Paleozoic System south of the Median Tectonic Line. The Miyagawa Dam basin is among the regions with the heaviest rainfall in Japan. It had an average annual precipitation of 3,130 mm during the period from 1958 to 2007. The mean daily maximum precipitation during this period was 346 mm. In 2004, the year of disastrous Typhoon #21, the annual precipitation was 5,135 mm and the precipitation on the rainiest day was 767 mm.

3. CHANGES IN SHALLOW LANDSLIDE AREA AND FOREST HARVESTING IN THE BASIN

3.1 Shallow landslide area

Figure 2 shows the shallow landslide area in the Miyagawa Dam basin over the period from 1960–2004. These values were measured using aerial photographs taken during nine different periods: 1965, 1970, 1976, 1982, 1986–1987, 1992, 1996–1997, 2001, and 2004 [Hiramatsu et al., 2002; Kuroiwa and Hiramatsu, 2004; Kuroiwa and Hiramatsu, 2010]. The occurrence of shallow landslides was determined by comparing all of the aerial photographs in chronological order. Landslides were judged to have occurred when areas without exposed bare ground in an earlier photograph showed bare ground in a later photograph. Only the areas where a landslide began were considered to be shallow landslide areas. These areas were measured from the top of the landslide to the point of maximum landslide width. The shallow landslide area was measured directly from the aerial photographs using tracing paper with a 1-mm grid. We estimated the
landslide years as follows: 1961, 1968, 1975, 1979, 1982, 1990, 1992, 2001, and 2004. These years were determined by considering the annual daily maximum precipitation and the annual precipitation during each period of aerial photography.

Shallow landslides occurred frequently in 1976–1982(1979), 1986–1992(1990), and following the torrential rain caused by Typhoon #21 in 2004. An area of about 0.20 km² was affected during these three periods. As of 2004, the cumulative shallow landslide area was 1.02 km², or 0.81% of the total basin area. Most of the landslides were distributed in Yamatodani and Chichigatani, just upstream from the dam, and in Fudodani in the mid-basin (see Fig.1).

3.2 Forest harvesting in the basin

The aerial photographs taken during the nine periods, which were used to determine the shallow landslide areas, were also interpreted to obtain data about forest harvesting in the basin. The many aerial photos, taken at different times, were compared and the forest areas in the basin were classified into the following three types:

1. Clear-cut area (in hectares)
   The clear-cut area was determined by comparing the aerial photographs from all periods in chronological order. Areas showing forest in an earlier photograph and then showing areas of forest (standing trees) that had been cut in a later photograph were judged to be clear-cut areas. These areas were additionally divided into (2) “clear-cut and replanted area” and (3) “clear-cut and unplanted area.”

2. Clear-cut and replanted area (in hectares)
   This refers to the forest region that was replanted after clear-cutting. We determined the clear-cut and replanted areas by comparing all aerial photographs taken after harvesting. These areas included places where trees were replanted and places where trees had grown, as shown in the chronology of the aerial photographs.

3. Clear-cut and unplanted area (in hectares)
   This is the region without forest after clear-cutting. We determined the clear-cut and unplanted areas by comparing all aerial photographs taken after harvesting. These were the locations other than the “clear-cut and replanted area,” category (2), of the “clear-cut area (1).”

Figure 3 shows changes over time of the clear-cut and replanted areas, clear-cut and unplanted areas, and the ratios of replanted area and unplanted area for the clear-cut areas of the Miyagawa Dam basin. The clear-cut areas marked in the figure with the symbol were newly found in the aerial photographs of 2004 (during the 2001–2004 period). No aerial photographs of the period after 2004 were available; thus, these areas could not be classified into the “replanted” or “unplanted” type. Until 1976, even though about 500 ha or more of forest (about 4% of the basin) had been clear-cut in the previous 5–7 years, most of the land had been replanted; unplanted area represented less than 16% of these areas during these time periods. After 1976, the area of clear-cutting decreased considerably. From the latter half of the 1970s forward, the unplanted area increased, and the percentage of unplanted area of clear-cut area was more than 30%.

As of 2004, the total clear-cut area amounted to 2,996 ha (24% of the basin), and 698 ha, 23% of this area (6% of the basin), was unplanted. Most of the unplanted portion was in Chichigatani, a left-bank tributary of the Miyagawa (see Fig.1).

The species of trees in the Miyagawa Dam basin in 2004 were cedar and cypress (43% of the area), evergreen broad-leaved tree forest (30%), deciduous broad-leaved tree forest (20%), and evergreen needle-leaved tree forest (5%), with the remaining 2% area being reservoir area, etc. The tree species of the replanted area were cedar and cypress, and the majority of these trees were in the age range of about 30 to 45 years in 2004.

4. PREDICTION METHOD FOR SHALLOW LANDSLIDE AREA CONSIDERING FOREST HARVESTING

4.1 Landslide risk prediction model considering forest condition

The occurrence of shallow landslides is closely tied to the extent of replanted or unplanted area following clear-cutting. Shallow landslide areas have increased
with the expansion of unplanted areas, and it is an established fact that shallow landslide area decreases with an increase in replanted area [Kuroiwa and Hiramatsu, 2004]. Focusing on this fact, a model of annual variations of landslide risk after clear-cutting was developed.

Previous research [Kuroiwa and Hiramatsu, 2004] modeled the relationship between landslide risk and the number of years since replanting or not planting after clear-cutting. That relationship was assumed to be linear; however, the risk of landslide (slope stability) does not vary linearly with time because slope stability is affected by the decay of tree roots and new growth after deforestation and reforestation [e.g., Abe, 1998; Tsukamoto, 1998].

Kitamura and Namba [1981] summarized the changes in stump strength after clear-cutting and after replanting. According to this work, the curve of stump strength after clear-cutting decreases with time. On the other hand, the curve of stump strength after replanting increases with time. Sidle [1991, 1992] proposed the net root strength model based on root cohesion in response to vegetation management. According to this model, decay, regrowth, and net root strength are defined in the curve. From the above, the changes in slope stability that are affected by root strength are considered to be non-linear.

Based on the above results, this study proposes a new landslide risk prediction model that considers the forest condition, in which yearly changes in slope stability due to forest harvesting are no longer assumed to vary linearly, but rather in a curved manner.

**Figure 4** shows the concept of this model. In Fig.4, \( Ls(t) \) and \( Fs(t) \) represent slope instability rate by clear-cutting and slope stability rate by replanting, respectively. The slope instability rate by clear-cutting \( Ls(t) \) begins to increase \( T_{Ls} \) years after clear-cutting (the number of years at which the effect of clear-cutting begins) and reaches 100% at \( T_{Ls(100)} \) years (time in years at which clear-cutting has no further effect on the forest). The slope stability rate by replanting \( Fs(t) \) begins to increase \( T_{Fs} \) years after replanting (the number of years at which the effect of the replanting begins) and reaches 100% at \( T_{Fs(100)} \) years (time needed for recovery after replanting). These borderline number of years in the model vary; however, the objective variables were set to \( T_{Ls(0)}=0, T_{Ls(100)}=6, T_{Fs}=5, \) and \( T_{Fs(100)}=25 \) years for landslides in the Miyagawa Dam basin [Kuroiwa and Hiramatsu, 2004].

As indicated by the solid line in **Fig.4**, the year-on-year trends (increasing frequency) of slope instability rate \( Ls(t) \) or stability rate \( Fs(t) \) since clear-cutting or replanting are curved. These relationships were modeled with exponential Eqs. (1) and (2):

\[
\begin{align*}
\text{(Slope instability rate by clear-cutting)} \\
& t \leq 6 : Ls(t) = (t/6)^{\alpha} \times 100 \\
& t > 6 : Ls(t) = 100.0
\end{align*}
\]

\[
\begin{align*}
\text{(Slope stability rate by replanting)} \\
& t \leq 5 : Fs(t) = 0 \\
& t > 5 : Fs(t) = (t - 5)/20 \times 100 \\
& t \geq 25 : Fs(t) = 100.0
\end{align*}
\]

where \( t \) is the number of years elapsed since clear-cutting or replanting, \( Ls(t) \) is the slope instability rate at time \( t \) years after clear-cutting, \( Fs(t) \) is the slope stability rate \( t \) years after clear-cutting and replanting, \( \alpha \) is the exponent for the equation for \( Ls(t) \), and \( \beta \) is the exponent for the equation for \( Fs(t) \). When \( \alpha \) and \( \beta \) are both 1, the change of the slope instability rate \( Ls(t) \) and the slope stability rate \( Fs(t) \) are linear (dotted lines in **Fig.4**), as estimated in the previous study [Kuroiwa and Hiramatsu, 2004]. The slope stability rate of clear-cutting and replanting is affected by root strength recovery after forest harvesting and also affected by the weight of the trees [e.g., Tsukamoto, 1998]. The change in \( Fs(t) \) was proposed based on measurements of an actual shallow landslide in a plantation due to the influence of root strength recovery and tree weight. We consider \( Fs(t) \) to be an index of slope stability that takes into account the effects of both root strength recovery and tree weight.

Next, \( Ls(t) \) (%) is multiplied by the clear-cut area \( AL \) (ha) to obtain what is here defined as the clear-cutting caused unstable area index \( ALs(t) \) (ha), and \( Fs(t) \) is multiplied by the replanted area \( AF \) (ha) to obtain the replanting caused stable area index \( AFs(t) \) (ha), as shown in Eqs. (3) and (4). \( AFs(t) \) (ha) is then subtracted from \( ALs(t) \) (ha), and this difference is divided by the basin area in ha (a) to find the index of landslide risk \( APht(t) \) (%), as shown in Eq. (5). This \( APht(t) \) is an index for assessing landslide risk due to the effects of clear-cutting, replanting, and leaving the area unplanted.
4.2 Relationship between index of landslide risk $AP_{hr}(t)$ and shallow landslide area ratio

The landslide risk prediction model considering the forest condition proposed in this paper (Fig. 4, Eqs. (1)-(5)) was applied to the Miyagawa Dam basin to obtain an index of landslide risk $AP_{hr}(t)$. Here, the coefficients $\alpha$ and $\beta$ of the objective variable in Eqs. (1) and (2) were set to 10.0 and 0.4, respectively, for landslides of this basin by trial and error. Annual variations in the index of landslide risk $AP_{hr}(t)$ are shown in Fig. 5 along with the actual annual shallow landslide area ratios. The changes in slope stability in relationship to the number of years since clear-cutting (or replanting) are presented together with $AP_{hr}(t)$, the index from the previous model [Kuroiwa and Hiramatsu, 2004] expressing the variation as being linear. In the y-axis title “Shallow landslide area ratio: $s/a$” of Fig. 5, “s” represents the shallow landslide area and “a” represents the study area.

A comparison of the values of $AP_{hr}(t)$, which was calculated based on the landslide risk prediction model considering the forest condition, and the actual trends in shallow landslide area ratio show similarities between the two. In the years of high shallow landslide area ratio, 1979 and 1990, $AP_{hr}(t)$ also shows high values. When examining the period of 1970–1980, when there was a particularly abrupt increase in un-reforested areas in the basin, it is apparent that $AP_{hr}(t)$ consistently tracks the increasing landslide risk associated with the increase in unplanted area. In contrast, the response of $AP_{hr}(t)'$ of the previous model [Kuroiwa and Hiramatsu, 2004] to the sharp increase in unplanted area was muted; $AP_{hr}(t)'$ began to rise gently before the sharp increase of un-reforested area in 1970. There was a time shift between the actual landslide phenomena (shallow landslide area ratio) in the basin and the predictions of $AP_{hr}(t)'$.

**Figure 6** shows the values of $AP_{hr}(t)$ calculated...
using the present model, which considers the forest condition, and the values of AP_{hr}(t)’ calculated using the previous model [Kuroiwa and Hiramatsu, 2004] for slope stability prediction compared with the shallow landslide area ratio proposed in the present study. The present model provides AP_{hr}(t) values that correlate much better with the shallow landslide area ratio than the AP_{hr}(t)’ values of the previous model. The shallow landslide area ratio showed an increasing trend that well matched the increase in AP_{hr}(t).

These results indicate that the index of landslide risk AP_{hr}(t) derived from the clear-cutting and replanted or unplanted landslide risk prediction model considering the forest condition in relationship to the number of years is a useful parameter for describing landslide phenomena in the basin.

4.3 Prediction of shallow landslide areas in the Miyagawa Dam basin

In this section, we propose a prediction model for the shallow landslide area ratio considering rainfall as a trigger for landslides and forest harvesting as a predisposing factor of landslides. The accuracy of the model is subsequently confirmed.

4.3.1 Relationship between shallow landslide area ratio and annual maximum daily precipitation

As a rainfall index of shallow landslides, we extracted the annual maximum daily precipitation. The precipitation station at Miyagawa Dam was selected for the representative precipitation measurements because it had a complete record of measurements dating back to 1961. Figure 7 shows the relationship between the shallow landslide area ratio and the annual maximum daily precipitation.

The relationship between the two is summarized in accordance with the relationship between the cumulative rainfall and the shallow landslide area ratio proposed by Uchiogi [1971]. The relationship between the shallow landslide area ratio (s/a (%)) and the annual maximum daily precipitation (Rd (mm/day)) in the Miyagawa Dam basin can be approximated by Eq. (6). The coefficients in Eq. (6), 1.637 and the landslide limit precipitation (325 mm/day), were determined using the least-squares method.

\[ s/a = 1.637 \times 10^{-4} \times (Rd - 325)^2 \]  

(6)

4.3.2 Prediction of shallow landslide area ratio considering AP_{hr}(t) and Rd

Here, we constructed a shallow landslide area prediction model considering both the influence of AP_{hr}(t) and the influence of precipitation. The index of landslide risk (AP_{hr}(t)) and the annual daily maximum precipitation (Rd) were analyzed to determine their relationship with the shallow landslide area ratio via multiple regression analysis. A new shallow landslide area prediction model was then constructed using clear-cut area, replanted area, unplanted area, and precipitation as indices. The shallow landslide area ratio s/a (%) in the Miyagawa Dam basin can be approximated by Eq.(7):

\[ s/a = 8.48 \times 10^{-3} \times (e^{0.16 \times AP_{hr}(t)})^{1.12} \times (Rd - 325)^{2.015} \]  

(7)

where s/a is the shallow landslide area ratio (%), AP_{hr}(t) is the landslide risk index (%), and Rd is the annual daily maximum precipitation (mm/day).

Figure 8 shows a calculation of the shallow landslide area ratio s/a (%) using the shallow landslide area prediction model (Eq. (7)). The figure also shows a calculation of s/a’ (%) using the previous linear model [Kuroiwa and Hiramatsu, 2004].

The correlation coefficient for the measured shallow landslide area ratio with the shallow landslide area ratio calculated using the present model is 0.72, which is higher than the correlation coefficient of 0.64 obtained using the previous model.

The reproducibility of the shallow landslide area ratio calculated using the improved model was better than that of previous models, in particular, in the 1960–1990s period during which forest harvesting was actively carried out. When the shallow landslide area ratio was greater than 0.14%, the difference between the calculated value and the actual value was lower using the improved model.

Neither the previous nor the present model was able to predict the measured landslide area after 1990. Imaizumi and Sidle [2007] showed that changes in dam deposits, which can be considered sediment yield and sediment discharge, were positively correlated with
maximum hourly rainfall. The shallow landslides that occurred in 2004 were closely related to the effects of hourly precipitation and slope angle [Kuroiwa and Hiramatsu, 2010]. The difference between the calculated and measured values (Fig. 8) is due to the effects of hourly rainfall (shorter rainfall time than the daily rainfall used in this study) and slope angle. In the future, the prediction accuracy of the shallow landslide area ratio will be improved by adding the factors of hourly precipitation and slope angle to the previous model.

Thus, the shallow landslide area prediction model, Eq. (7), based on the new index of landslide risk APfr(t) proposed here has been shown to have better prediction precision than using the previous model [Kuroiwa and Hiramatsu, 2004].

5. SUMMARY

A new landslide risk prediction model considering forest conditions was proposed with the objective of making improved assessments of year-on-year changes in slope stability after clear-cutting and replanting or leaving the area unplanted, while accounting for site conditions such as climate and tree species. We proposed the "shallow landslide area ratio prediction model" considering annual maximum precipitation (Rd) and the index of landslide risk (APfr(t)) calculated using the new model. A previous model [Kuroiwa and Hiramatsu, 2004] was unable to reproduce accurately the change in the shallow landslide area ratio over the long-term from the past to the present. Using the new model, it was shown to now be possible to satisfactorily predict the changes in the shallow landslide area ratio caused by forest harvesting. In particular, forest harvesting was carried out in a wide area of the basin before and during the 1990 s, and we succeeded in reproducing the shallow landslide area ratio using the new model. As for 1990, as well as for 2004, because the shallow landslide area ratio was relatively large, the prediction accuracy of the new model was only slightly improved compared with that of the previous model.

Using the landslide risk prediction model proposed in this study, it is possible to assess long-term landslide risk and quantitatively consider forest harvesting. In particular, the model is highly useful for basins with a high distribution of plantations. Using the shallow landslide area ratio prediction formula (Eq. (7)), the shallow landslide risk of the basin can be calculated from the clear-cut area and time of replanting. The proposed landslide risk prediction model and shallow landslide area ratio prediction formula can be used for land erosion master plans and forest management.

Future studies will include surveys of other river basins with different climates and different compositions of tree species. The variables α and β in Eqs. (1) and (2) will be set to match the characteristics of the basins, and data will be collected for many different basins. These data will not only allow us to consider relationships between basin site conditions and variations in slope stability but also to investigate how generally this landslide risk prediction model considering the forest condition can be applied.

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