A SLOPE STABILITY ASSESSMENT IN THE TROPICS

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ABSTRACT

Landsliding is one of the most damaging natural disasters in the mountainous and hilly terrain in the tropics. Landslides occur frequently in the rainy season, which shows that it is the main triggering factor. But how much rain for how long period causes landsliding in the humid tropics is not yet clear. The study tries to understand the relationship between rainfall intensity and duration for triggering landslides. The study uses historical landslide inventory and long term climatic data to define rainfall thresholds. The result shows that for triggering a landslide antecedent rainfall of up to five days and minimum rain of 37 mm is required on the day of slope failure. Slope susceptibility to failure depends very much on terrain hydrological condition which is influenced by soil type and land use practices. Study shows that sloping areas having soils with high clay content are more susceptible to slope failure.

INTRODUCTION

Landsliding, defined as movement of a mass of rock, debris or earth down a slope (Cruden, 1991; Dai et al., 2002), occurs when the shear stress of the material is higher than its shear strength (Pack et al., 1998; Pack et al., 2001; Van Westen et al., 2009), and it normally occurs on steeper area especially in the mountainous and hilly region. This movement is influenced by various factors, such as slope gradient, soil properties, ground water table, geomorphology, land use change (Karsli et al., 2008), rainfall and also by human intervention such as deforestations, undercutting of slope for road construction or expansion of settlement areas. In addition to these, landslide also occurs as an effect of other natural disasters, such as earthquake and volcanic activity. Slope failures can be caused by combination of both factors, human and natural, mentioned above (Highland et al., 2008). The disaster related to landsliding cannot be avoided, however the impact can be significantly reduced by understanding the process so that proper mitigation measures can be implemented in time (Daag, 2003). In Indonesia landsliding occurs in a yearly basis which causes lots of property damages and also loss of human lives. It is reported that during the period 1998 – 2007, 569 landslide events took place which caused 1,362 fatalities, 315 people injured, around 1,100 people missing, and around 170,000 people were evacuated (BNPB, 2009). Moreover, these landslides also damaged around 42,000 houses, 290 public facilities, 420 km road, and around 387,000 hectares of crops, plantation, and forest.

Similar study by Marfai et al. (2008) reveals that between 1990 and 2005 1,112 people died and 395 people were wounded due to landslides in the island of Java. The study also reports the increase of landslide events on a year by year basis due to deforestation, excavation for construction materials (rock and soil), and expansion of settlement in unstable slopes. Rainfall can be considered as one of the main triggering factors in landslides, since most of the landslides are reported to occur during the rainy season (Shrestha, 2004; Marfai et al. 2008; Dahal et al., 2008; Sengupta et al., 2009). Antecedent rainfall influences the saturation of soil and groundwater level making the slope unstable (Van Asch et al., 1999; Guzzetti et al., 2007; Sengupta et al., 2009; Crosta, 1998). Besides, the presence of water in the soil or rock supplements the overall weight of the slope, which increases the shear forces causing the slope less stable (Smith et al., 2008) .

Landsliding is one of the most damaging natural disasters in the tropics due to heavy rain. Although rainfall has long been well known as the main cause of landslides, however, the relationship between landslide and rainfall (intensity and duration) is still unclear and it seems to vary from one region to the other (Van Asch et al., 1999; Glade et al., 2000; Guzzetti et al., 2007; Dahal et al., 2008; Guzzetti et al., 2008; Hasnawir et al., 2008; Zˆezere et al., 2008; Sengupta et al., 2009). For minimising damage and for preventive measures, it will be important to know the rainfall thresholds for landslides in the humid tropical environment. The present study shows how long term rainfall data can be analysed in relation to historical landslide data to derive rainfall thresholds (critical intensity or duration of rainfall) for the initiation of landslides. The study was carried out in Central Java, Indonesia.

MATERIALS AND METHODS / EXPERIMENTAL

Study Area

Study area is located in a watershed in Wonosobo District, Central Java Province – Indonesia (Figure *1*). The watershed is located between 7º11'' - 7º36'' S and 109º43'' - 110º04'' E and the elevations varies from 185 – 1,100 m above sea level with surface area extending 11,183 Ha. The study area consists of mountainous region in eastern and north-eastern part of the catchment and gently sloping to hilly/undulating region in the lowlands.

Agriculture is the main occupation of the people. Five land cover/land use types exist: forest cover in the mountainous areas, shifting cultivation on the steeper slopes, rainfed and irrigated rice near the river and its tributaries and mixed orchard in the footslope areas. Crops grown are cassava, banana, coffee, kapulaga (Amomum cardamomum), etc. The fast growing Sengon tree (*Albazia falcataria*), introduced by The Indonesian Ministry of Forestry in early 1990s can be found throughout the study area. There are few settlements in the area.

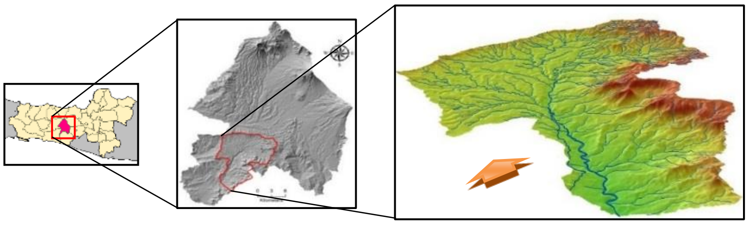

Figure 1: The Study Area

The monthly precipitation in the study area ranges from 34 – 511 mm with mean annual rainfall of around 3500 mm. The rainy season begins in October and continuous to April in the following year. About 50 % of annual rainfall is received during the period January to April and 30 % in October to December (Figure *2*).

Landslides occur mainly in the rainy season. Historical data shows that Wonosobo, one of regencies in Central Java Province, has stricken by landslides frequently which damages houses and infrastructures including loss of human lives. The last recorded landslides occurred on 23th/24th January and on 26th/27th February 2009. According to local people, the landslides occurred due to prolonged rainfall (Anonymous, 2009a).

Landslide Inventory

Land slide data of the study area for the period 2001 to 2008 was available as shown in Table 2 (Anonymous, 2009). The available landslide historical data was classified. Landslide types being used in this research are deep-seated rotational landslides and creep caused by environmental factors, meanwhile the human induced landslides due to under cutting of slopes for constructing road and settlements were left out. During fieldwork the landslide type (environment or human induced) was verified and their geographical position was noted using GPS. Head of landslide scarp was taken as the position of geographic coordinates for the landslides. Data on the date of slope failure was also recorded through interview with local people.

Rainfall Data

Daily rainfall data from the study area was available for the period 1980 – 2008 (Kaliwiro and Wadaslintang rainfall stations) and for the period 1980 – 2002 (Limbangan station). Because of the presence of few rain gauses in the area, the data from the nearest station was used to correlate rainfall with the landslide event. Total 24-hour rainfall (mm) or continued precipitation of many days at a station was considered the event rainfall for the corresponding landslide event (Dahal et al., 2008).

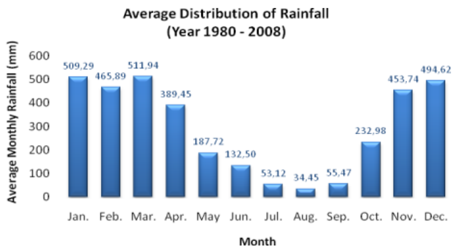

Figure 2: Average monthly rainfall in the area

Table 1: Historical Data of Landslide in Indonesia in year 1998 – 2007

Year	Landslide Number	Victims (People)			Damages			
		Deaths	*Injured*	*Evacu-ated*	*House (Unit)*	*Public Facilities (Unit)*	*Roads (Km)*	*Crops, Plantation, Forest (Ha)*
1998	19	41	32	-	380	4	2	138
1999	9	58	-	-	365	10	-	-
2000	94	167	-	-	1,386	-	-	780
2001	29	15	3	-	175	4	-	3
2002	44	136	21	12,908	3,603	2	56	5,322
2003	103	311	92	95,799	13,968	32	225	363,023
2004	53	139	8	44,997	4,788	169	31	15,515
2005	41	209	29	6,113	13,997	35	110	1,331
2006	73	196	52	9,489	2,392	12	3	491
2007	104	90	78	1,271	974	24	-	654
Total	569	1,362	315	170,577	42,028	292	427	387,257

Source: National Disaster Management Agency (2009)

Rainfall Frequency Analysis

To determine the recurrence of extreme rainfall events causing slope failures and landsliding, Gumbel Distribution model, known as Extreme Value Distribution Type I, was used. This method calculates return period of particular rainfall intensity, or vice versa, based on yearly maximum precipitation in a certain period. The resulted formula from linear trend line is used to derive the intended return period or rainfall intensity (Wilson, 1969). This method is one of the most widely used probability density function (pdf) that calculates extreme values in hydrological and meteorological studies (Kotz et al., 2000; Subyani, 2009).

Rainfall Threshold Analysis

Rainfall thresholds analysis which i used in this study are intensity – duration (ID) thresholds and antecedent rainfall thresholds calculated empirically. ID thresholds are used to define the lowest boundary of rainfall intensity (mm/day) and the minimum duration that triggers landslide. The relationship between rainfall and landslide can be obtained by means of simple power law method.

In intensity – duration (ID) thresholds, a database consisting of rainfall intensity (mm/day) and rainfall duration (day) of landslide events is first made. The two data sets were then used to generate a scattered graph, in which rainfall intensity is used as y-axis and duration as x-axis. By choosing simple power law method, a trend line can be added and the graph shows the equation of rainfall threshold. Generally, intensity – duration (ID) thresholds is presented by the following equation;

$$I=aD^b \quad (1)$$

where, I: intensity, D: Duration, and a and b: constants. To study the effect of previous rainfall intensity, antecedent rainfall thresholds of 3, 5, 10, and 15 days was determined. The approximate minimum antecedent threshold is defined by the equation:

$$T=R_0+aR_c-b \quad (2)$$

where, T: thresholds, R_0: rainfall intensity of failure day, a & b: constants, and c: cumulative rainfall of 3, 5, 10, and 15 days before failure. The constants (a and b) are visually identified after constructing a scatter plot showing daily precipitation amounts and cumulative rainfall amounts (3, 5, 10, and 15 days).

Terrain Susceptibility To Landslides

To study terrain susceptibility to landsliding soil infiltration, permeability, moisture content, and soil texture were used. Infiltration tests were carried out in the field in different land use types in various landforms (denudated hill, denudated mountain, and foot slope). In the same locations, soil samples were collected for laboratory analysis.

The measured infiltration rate is used to generate predicted infiltration rate (f) (Wanielista et al., 1997) and to generate cumulative infiltration (F). The cumulative infiltration (F) shows how much water is infiltrated into the ground, as well as the soil thickness affected by the infiltrated rainfall. These conditions are related with the increase in unit weight which eventually decreases the shear strength of a particular slope.

To calculate the slope stability SINMAP (Pack et al., 1998; Pack et al., 2001) was used. SINMAP underlies its theory based on the infinite slope stability model that balances the destabilizing components of gravity and the stabilizing components of friction and cohesion. The pore pressure due to soil moisture reduces the effective normal stress, which trough the angel of friction is related to shear strength (Pack et al., 2001). The model calculates the safety factor (SF) expressing the ratio of stabilizing forces (shear strength) to destabilizing forces (shear stress) on a failure plane parallel to the surface (Deb et al., 2009). The safely factor is calculated using:

$$SF = \frac{C_r+C_s+\cos^2\theta[\rho_s g(D-D_w)+(\rho_s g-\rho_w g)D_w]\tan\phi}{D\rho_s g\sin\theta\cos\theta} \quad (3)$$

where Cr is root cohesion (N m^{-2}), Cs is soil cohesion (N m^{-2}), θ is slope angle (°), ρs is wet soil density (kg m^{-3}), ρw is the density of water (kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), D is the vertical soil depth (m), Dw is the vertical height of the water table within the soil layer (m), and ϕ is the internal friction angle of the soil (°). θ is the arc tangent of the slope S, expressed as a decimal drop per unit horizontal distance.

SINMAP implements mathematically the computation and mapping of a slope-stability index based on surface topography to route flow downslope. The flow is assumed that the subsurface hydrologic boundary (or bedrock-drift boundary) parallels the surface and the soil hydraulic conductivity is uniform. The flow model predicts relative levels of the perched water table for the whole of a watershed area implying subsurface flow through the colluviums or regolith, then is used to assess slope stability (Pack et al., 1998; Deb et al., 2009). The stability index is reclassified into degree of susceptibility from safe to very high susceptible area (Deb et al. (2009)).

The main inputs for the SINMAP are digital elevation data (DEM), landslide inventory map, soil properties, and hydrological parameters. In addition, the following default values were used to run the model: acceleration due to gravity (9.81m/s^2), density of soil (2,000 kg/m^3), density of water (1000 kg/m^3), ratio of transmissivity to recharge rate (2,000 for lower bound and 3,000 for upper bound), soil cohesion (0.0 for lower bound and 0.25 for upper bound), and soil friction angle (30^o for lower bound and 45^o for upper bound).

RESULTS AND DISCUSSION

Landslide – Rainfall Relation

The landslide inventory data for the period 2001 -2008 shows that land sliding occurs on a yearly basis and that the maximum number of landslides occurred during the wet season (Table 2). Landslide incidences correlate positively with precipitation showing high relation, r^2 = 0.898 (Figure 3). The month of December has the highest landslide incidences since it is the wettest month. Similarly December holds the highest probability of landslide occurrence, followed by November, April, January, March, and February, with probability of 0.22, 0.18, 0.15, 0.13, 0.11, and 0.10 respectively. The rest of the other months have lower probability (less than 1%).

From the types of landslides, the rotational type is very common which have deep scars. Rotational deep landslides are influenced by long duration of rainfall which results in more infiltration that allows the steady rise of the groundwater table reducing the shear strength of the affected materials (Van Asch et al., 1999; Tofani et al., 2006; Zˆezere et al., 2008). Short duration of excessive rainfall intensity will exceed infiltration rate resulting in higher surface runoff. The other types are creep in very gentle slope, and debris flow on the steeper mountainous area. The scarps of older landslide, especially shallow landslides, can hardly be identified due to natural resilience and human intervention. The Landslide scars are usually covered by shrubs or grasses making them difficult to delineate, since the area is volcanic, has fertile soil and in the tropics.

Table 2: Landslide Events in Wonosobo District, Year 2001 – 2008

Year	Jan.	Feb.	Mar	Apr	Mei	Jun	Jul	Agust	Sep	Okt	Nop	Des	Total
2001	-	2	2	-	1	-	-	-	1	-	2	2	10
2002	1	1	1	3	-	-	-	-	-	-	5	11	22
2003	7	3	6	2	-	-	-	1	-	9	5	8	41
2004	17	1	2	4	-	-	1	1	-	1	3	15	45
2005	2	5	2	11	2	-	-	-	-	2	7	6	37
2006	9	5	4	13	2	2	1	1	-	2	8	11	58
2007	5	15	7	14	1	1	-	-	4	-	17	20	84
2008	5	6	17	7	-	-	-	-	-	8	17	7	67
Total	46	38	41	54	6	3	2	3	5	22	64	80	364
Avg.	5.75	4.75	5.13	6.75	0.75	0.38	0.25	0.38	0.63	2.75	8.00	10.00	
Perc.	12.64	10.44	11.26	14.84	1.65	0.82	0.55	0.82	1.37	6.04	17.58	21.98	

Source: Badan Kesbanglinmaspol of Wonosobo, 2009.

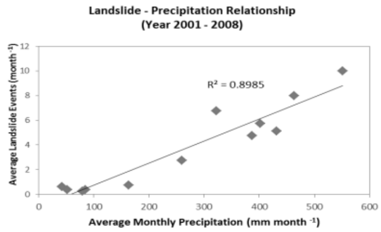

Figure 3: Relationship between precipitation and landslide events

Rainfall Thresholds

Analysis of the rainfall data shows that there can be lot of variations of rain from less than 2.000 mm to 6.000 mm on a yearly basis. Since 1998 annual rainfall shows some declining pattern (Figure 4). On a daily basis, highest precipitation recorded during 1980-2008 is 126 mm which has a return period of 2.42 years. Other two highest daily precipitations are 113 (return period of 1.72 years) and 118 mm (return period of 1.94 years). Thus, there is possibility of high daily rainfall once every 2 years. But for the initiation of a landslide high intensity rain alone is not enough. If it has not been raining in the area for some time slope may not fail.

Using the rainfall data from three rain gauges corresponding with the 28 landslide events, an intensity-duration rainfall threshold for landslide initiation was established. For the rainfall duration threshold day is used instead of hour because only the daily rainfall data was available. The rainfall intensity and duration relationship is defined by the equation $I = 63.683D^{-0.336}$, where I is the rainfall intensity in mm day-1 and D is the rainfall duration in days (Figure 5). The relationship is exponential in nature meaning that it is not necessary to have high intensity rain to cause landslide. A slope may fail at an average precipitation of 20 mm per day if it has been raining for about 20 days. On the other hand a minimum rainfall of at least 37 mm per day is required to trigger landslide if it has been raining for 5 days.

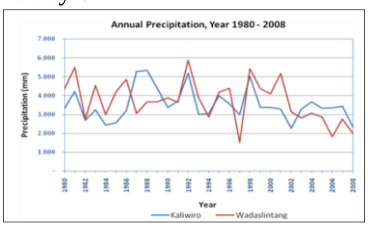

Figure 4: Distribution of rainfall over the years of 1980 to 2008 from the 2 main gauges

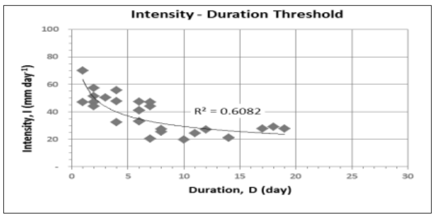

Figure 5: Rainfall intensity-duration threshold curve for landsliding

Effect Of Antecedent Rain

Duration of the rainfall period and the rail intensity are both important in controlling whether certain slope is likely to fail. In Figure 6 landslide events are plotted along with rainfall data which shows that some landslide events correspond to very low rainfall event. In general the landslide events are followed by periods of heavy rainfall which persisted for some days confirming that certain amount of rain is required to saturate the ground surface before the slope fails. During field verification a recent landslide was identified and rainfall data from the nearest station was obtained. Surprisingly only 9 mm rain was recorded on the day of slope failure, but it had been raining in the area for 18 days (with cumulative rain of 309 mm) which was considered the main reason for the slope failure.

To assess the role of antecedent rainfall in triggering landslide, the antecedent rainfall period of 3, 5, 10, and 15 days were considered. The study shows that the correlation between the cumulative rain of the antecedent rainfall period and the rainfall amount of the day when slope fails is only moderate, with r2 of 0.6282 for 3 days and 0.5484 for 5 days (Figure 7). For longer period there is no correlation meaning that any amount of rainfall can trigger the landslide if it has been raining for longer period. This result is similar to the results obtained by Rahardjo et al., (2008) which reports that under tropical rainfall, antecedent rainfall of maximum 5 days prior to day of failure can influence the stability of slopes.

The influence of antecedent rainfall to landsliding is also associated with soil texture. The soil texture in Wadaslintang watershed ranges from clay to loam (Figure *8*) with low permeability, and therefore tends to retain water. Once the soil is saturated the ground water rises up, the debris loose cohesion and it starts to flow.

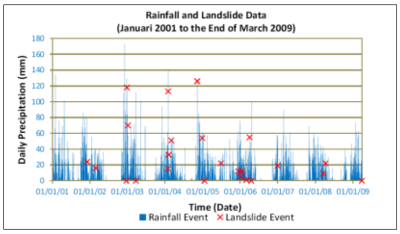

Figure 6: Rainfall and Landslide Data in Wadas Lintang Watershed

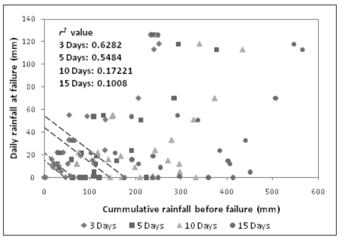

Figure 7: Relationship between daily rainfalls at failure and antecedent rainfall before failure.

Hazard Assessment

Slope stability depends on topography, soil, hydrological parameters and land use. Soils in the area have relatively high clay content (30–70%). When clayey soil becomes saturated with water its weight increases and also it loses its strength (Yalcin, 2007) thus becomes susceptible to landsliding. The higher the clay content, the more prone the soil is to landslide. Jeong et al. (2008), revealed that slope safety factor increases rapidly at clay content less than 10%, beyond that it follows with a more gradual increase or flattens as the clay content increases. Soil infiltration is equally important which depends on soil texture, surface crusting, compaction, structure, soil moisture, organic matter content and porosity. Apart from soil texture many soil parameters are influenced by land use and management practices. In the area mixed garden land use type has the highest infiltration rate followed by pine forest, rainfed ricefield, and settlement respectively (Figure 9). The predicted infiltration rate and cumulative infiltration shows that the shortest time to reach saturated condition is held by rainfed rice fields and followed by settlement, pine forest, and mixed garden. Slope stability assessment shows that 66% of the total area is classified as stable, 19% of the area ranges from moderately to quasi stable, 12 % of the area has probability to fail less than 50%, and 2% of the area tends to fail with the probability of more than 50% (Figure 10).

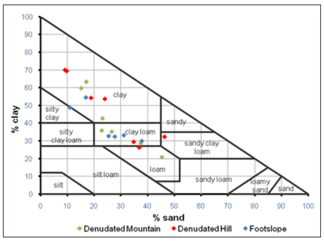

Figure 8: Soil texture in the study area

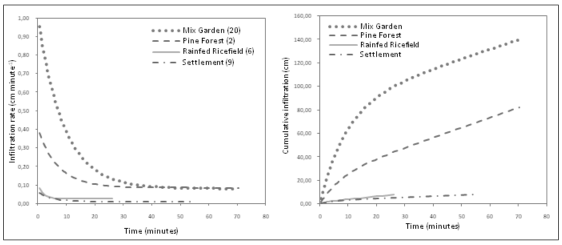

Figure 9: Predicted infiltration rate and cumulative infiltration for various landuse types in the study area

CONCLUSION

The relationship between rainfall intensity and rain duration for landsliding is defined by an exponential function. Landsliding is affected by antecedent rainfall of up to 5 days before the day of failure. The research indicates that a minimum rain intensity of 37 mm per 24 hour is required to trigger landslide if it has been raining in the area for 5 consecutive days. Rainfall of even lower intensity (20 mm per 24 hours) can cause landslide if it has been raining for more than 20 days. The result shows a moderate correlation between the antecedent rain of 3 to 5 days and the daily rainfall at the failure with correlation coefficient of r^2=0.6282, and 0.5484 respectively. The result also shows that excessive rainfall having potential to trigger landslide can occur once in every 2 years.

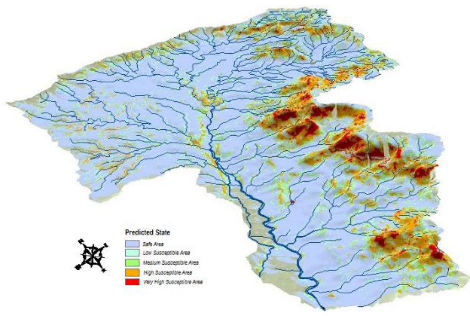

Figure 10: Distribution of Susceptibility Levels and Landslide Locations (not scaled)

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