Influence of Long-Term Increasing Trend of Maximum Hourly Rainfall on Slope Stability in Forested Area of Aso, Japan

Aril ADITIAN[1*] and Tetsuya KUBOTA[2].

In July 2012, the city of Aso in Kumamoto Prefecture experienced extreme heavy rainfall counting up to 106 mm/hr. The immediate result of heavy rainfall in these regions took the form of numerous landslides and debris flows. This rainfall-induced landslide claimed casualties of more than 20 lives. Field investigations were conducted on three slopes in Aso to collect data from the field. Rainfall increasing trends were statistically investigated using Mann-Kendall rank correlation and Sen's slope estimator in order to obtain the yearly rate of increasing maximum hourly rainfall trends. Numerical analysis (Finite Element Method) was employed in this study to elucidate the influences of increasing maximum hourly rainfall to forest slope stability. The obtained results indicated that the maximum hourly rainfall in Aso has been increasing at the yearly rate of 0.52 mm/hr/year. The increase of maximum hourly rainfall is surely has negative influences in term of slope stability. Therefore, under this increasing rainfall rate, it is possible for many forest slopes to become unstable and prone to landslide disaster in the near future.

Key words: Landslides, Rainfall, FEM, Slope Stability

1. INTRODUCTION

The increasing rainfall pattern that might be induced by climate change is being observed worldwide and being studied for its influence on triggering landslides, this phenomenon is especially obvious in the northern part of Kyushu Island, Japan. (*Kubota*, 2010). Rainfall is the major agent in triggering landslides, it is more frequent compared to earthquake and slope undercutting (*Crozier*, 1986). The relationship between rainfalls and slope stability is widely recognized, however drawing a distinct line of the relative roles of the antecedent rainfall (the rain that falls in the days preceding the landslide events) and the triggering rain (the rain that falls at the time of the landslide events) has proved to be difficult (*Rahardjo*, 2001).

In 2012, the city of Aso in western Japan experienced heavy rainfall from July 11 to July 13 counted up to 656 mm with the intensity of 493 mm/day and 106 mm/hr. This tremendous amount of rainfall translated into countless traces of debris flows and landslides. By employing numerical analysis (Finite Element Method), this paper aims to quantify the increasing rainfall in the city of Aso throughout the last decades and to quantify its effects to slope stability in forest area.

2. STUDY SITE

Aso is located in the northern part of Kumamoto prefecture, three slopes were selected as case studies, which are as follow:

1. Aso Teno 1 (131^{o} 6 '54''E, 32 ^{o} 58' 46''N)
2. Aso Teno 2 (131^{o} 7 '56''E, 32 ^{o} 58' 27''N)
3. Aso Nakasakanashi (131^{o} 9 '1''E, 32 ^{o} 56' 26''N)

The study site is located in the Kumamoto Prefecture, Japan. The city of Aso experienced numerous landslides and debris flows during the record-breaking rainfall on July 2012. Three slopes were taken as case studies for the effect of increasing rainfall induced by climate change to the forest slope stability. The average annual rainfall of the study site is 2831 mm/year (*Japan Meteorological Agency*, 2013) with most rainfalls on June and July.

The geological features of the study site are represented by mainly unconsolidated deposit of diluvium gravels, sands, muds, and volcanic ash. On the forested slopes of Aso region, broadleaved tree species, such as *Quercus crispula*, *Cornus controversa* and *Prunus jamasakura* as well as coniferous species such as *Chamaecyparis obtuse* and *Cryptomeria japonica* are common. (*Paudel*, 2007).

[1] Laboratory of Forest Conservation and Erosion Control, Kyushu University (Hakozaki 6-10-1, Higashi-ku, Fukuoka, 812-8581 Japan)

[2] Dept. Forest Environment Science, Faculty of Agriculture, Kyushu University (Hakozaki 6-10-1, Higashi-ku, Fukuoka, 812-8581 Japan)

*Corresponding author. E-mail: aril@kyudai.jp

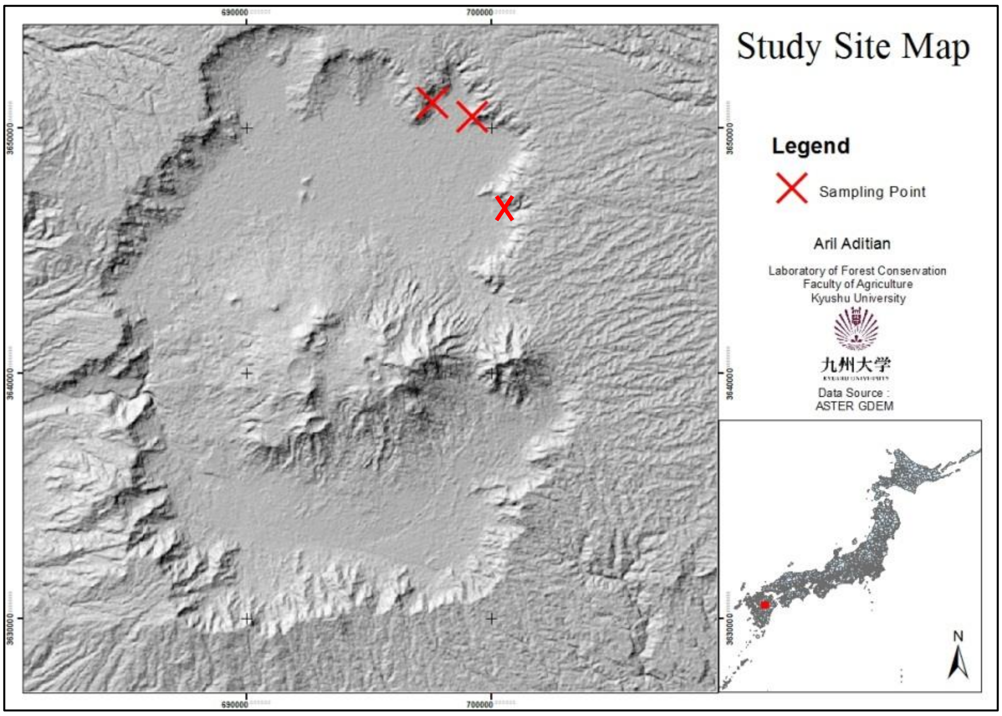

Fig. 1. The location of the research area

Fig. 2. Top – Aso Teno #1, middle – Aso Teno #2, bottom – Aso Nakasakanashi in July 2012

3. METHODS

3.1 Data collection

Field investigations were conducted during the year of 2012 to collect data from the field. Four soil samples were collected from each slope for the direct shear test in the laboratory. Two samples were also collected for permeability test.

Collecting soil samples for slope stability analysis is a very important and crucial task. Soil sampling is difficult particularly when attempting to get representative sample from the entire area. In this study soil samples were taken from several parts of the slope (the bottom, middle, and top) above the slip surface for the direct shear test. Two samples from different depth were also collected for the permeability test. The samples were collected using sample cylinders in the undisturbed forms.

Rainfall data were collected through the AMeDAS network of Japan meteorological agency. For the Aso region, data were obtained from Aso-otohime weather station. Data were collected from 1978 – 2012 from the Aso-otohime weather station.

3.2 Rainfall statistics

The Mann-Kendall test is applicable in cases when the data values *xi* of a time series can be assumed to obey the model

$$X_i = f\ (t_i) + \varepsilon_i \qquad (1)$$

where *f(t)* is a continuous monotonic increasing or decreasing function of time and the residuals ε_i can be assumed to be from the same distribution with zero mean. It is therefore assumed that the variance of the distribution is constant in time.

We want to test the null hypothesis of no trend, *Ho*, i.e. the observations *xi* are randomly ordered in time, against the alternative hypothesis, *H1*, where there is an increasing or decreasing monotonic trend. In the computation of this statistical test we exploit both the so called S statistics given in Gilbert (1987) and the normal approximation (Z statistics). For time series with less than 10 data points the S test is used, and for time series with 10 or more data points the normal approximation is used

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & if\ S < 0 \end{cases} \qquad (2)$$

The presence of a statistically significant trend is evaluated using the Z value. A positive (negative) value of Z indicates an upward (downward) trend. The statistic Z has a normal distribution. To test for either an upward or downward monotone trend (a two-tailed test) at α level of significance, H_0 is rejected if the absolute value of Z is greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables.

To estimate the true slope of an existing trend (as change per year) the Sen's nonparametric method is used. The Sen's method can be used in cases where the trend can be assumed to be linear. This means that *f(t)* in equation (1) is equal to

$$f(t) = Qt + B \qquad (3)$$

where Q is the slope and B is a constant.

To get the slope estimate Q in equation (10) we first calculate the slopes of all data value pairs

$$Q_i = \frac{X_j - X_k}{j-k} \qquad (4)$$

Where j>k.

3.3 Finite element analysis

In this study the slope stability analysis was performed using FEM with strength reduction technique. The soil was modelled according to Mohr-Coulomb failure criterion for its mechanical properties and Van Genuchten Model for its hydraulic properties.

Slope stability analyses were conducted using GUSLOPE ver 1.00 computer code developed at Gunma University. The method of analyses was Finite Element Method (FEM) performed with strength reduction technique. The slope stability analyses were coupled with seepage analyses to compute the effect rainfall to slope stability.

GUSLOPE ver 1.00 computer code was employed in this study. FEM were conducted with three different scenarios:

- No Rainfall
- Actual Rainfall of July 2012
- Without Increasing Maximum Hourly Rainfall (reduce the peak value of each rain event by the rate of increment according to Sen's slope estimator)

The output of the simulation is Factor of Safety (FS). Factor of Safety of a slope is the ratio of resisting forces to driving forces. FS lower than 1.00 denotes that the slope is not stable, thus prone to landslide. FS 1.00 or more denotes that the slope is in a stable condition.

The stability analyses were coupled with seepage analysis to gain comprehensive understanding on the effect of rainfall to slope stability.

4. RESULTS

4.1 Geotechnical aspects of the slopes

Soil samples were analyzed in the laboratory for its geotechnical properties. The result of the soil analyses are presented in the table 1.

Table 1. Soil Strength Parameter

	Unit Weight (kN/m^3)	Cohesion (kPa)	Angle of internal friction (^{o})	Permeability coefficient (m/s)
Aso Teno #1	24.7	15	58	$2.03x10^{-4}$
Aso Teno #2	24.6	4	47	$1.03x10^{-6}$
Aso Nakasakanashi	15	2	26	$8x10^{-6}$

From the obtained result, Aso Teno 1 and Aso Teno 2 exhibit similar properties in term of unit weight. However the cohesion value between this two slopes are different, Aso teno 1 cohesion value is 15 kPa while Aso teno 2 cohesion value is 4. The angles of internal friction (φ) of these two slopes are relatively high at the 58 degrees for Aso Teno 1 and 47 degrees for Aso Teno 2. Generally, soil with these kind of properties belong to the categories of clay which typical value is ranging between 0 – 48 kPa.

The soil of Aso-Nakasakanashi exhibits unit weight of 15 kN/m^3, with cohesion value of 2 kPa. The angle of internal friction (φ) is 26 degrees. These characteristics show that the soil of Aso-Nakasanishi is those of silty clay.

Generally, the silty clay soil shows properties of unit weight between 16 – 20 kN/m^3, cohesion (c) ranging between 0-48 kPa, and angle of internal friction (φ) between 20-34 degrees. Clay usually generates good shear strength due to its elastic properties.

The permeability coefficient (k) of Aso Teno 1 is $2.03x10^{-4}$ m/s, which denotes that in this slope the rate of permeability is moderate. Aso Teno 2 permeability coefficient is $1.03x10^{-6}$ m/s which denotes that the rate of permeability is low. The soil of Aso-nakasakanashi also exhibits the same moderate permeability rate at the 6 orders of magnitude which is $8x10^{-6}$ m/s.

Generally, with the permeability coefficient ranging between 4-6 orders of the magnitude, slopes of Aso, in term of permeability can be consisted of stratified clay deposits or mixtures of sand, silt, and clay.

Many factors affect soil permeability. Sometimes they are extremely localized, such as cracks and holes, and it is difficult to calculate representative values of permeability from actual measurements. The size of the soil pores is of great importance with regard to the rate of infiltration (movement of water into the soil) and to the rate of percolation (movement of water through the soil). Pore size and the number of pores closely relate to soil texture and structure, and also influence soil permeability.

The soil strength properties will be used in the finite element analysis as the soil material input.

4.2. Rainfall Statistics

Rainfall data were collected to then be subjected in the Mann-Kendal test and Sen's slope estimation.

The results for rainfall time series of Aso-Otohime rainfall trend statistics are presented in figure 3.

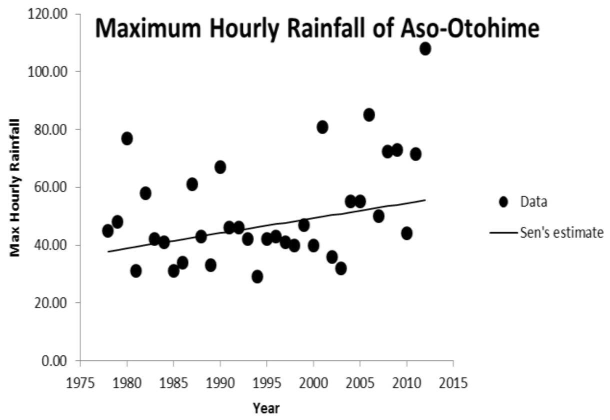

Fig. 3. The long term increasing trend of maximum hourly rainfall in Aso-Otohime.

Based on the Mann-Kendall analysis it is found that increasing trend of Aso-Otohime region is detected at various level of significance for each rainfall time series. For the maximum hourly rainfall, the increasing trend is detected at 0.01 level of significance.

Based on the obtained results, it can be inferred that the Aso-Otohime area is experiencing increase in term of maximum hourly rainfall. Sen's slope estimator was used to estimate the slope of the increasing trend of rainfall. The Q in the table 2 is the Sen's estimator for the true slope of a linear trend. i.e : change per unit time period (in this study a year).

It is obtained that the Q value of the maximum hourly rainfall is 0.52 mm/hr/year, this means that during 1978 – 2012 a total increment of 18.2 mm is happened in Aso-Otohime in term of maximum hourly rainfall.

Detail statistical analysis of rainfall time series (annual rainfall, maximum daily rainfall, and maximum hourly rainfall) in Aso-otohime region is shown in table 2.

Aso-Otohime 1978-2012				Man-Kendall		Sen's slope estimate									
Time series	First year	Last Year	n	Test Z	Signific.	Q	Qmin99	Qmax99	Qmin95	Qmax95	B	Bmin99	Bmax99	Bmin95	Bmax95
Annual Rainfall	1978	2012	35	2.16	*	25.10	-4.28	49.82	1.89	42.45	2392.50	2832.35	1926.02	2758.27	2066.99
Max Daily Rainfall	1978	2012	35	2.37	*	2.40	-0.23	5.30	0.65	4.50	159.60	212.62	111.83	190.90	131.47
Max Hourly Rainfall	1978	2012	35	1.83	+	0.52	-0.18	1.34	-0.01	1.13	37.88	48.18	26.97	45.00	27.62

Table 2. Rainfall trend analysis of Aso-otohime during 1978-2012

The long term increase in precipitation of western Japan such as the increment of 18.2 mm/hr in term of maximum hourly rainfall is obtained statistically by employing Mann-Kendall's rank correlation. This phenomenon is negatively affecting the general slope stability in forested slopes. The apparent increase of rainfall might be due to increasing water vapor from the southern Pacific Ocean driven by the circular geostrophic wind around the pacific high pressure provoked by the increase in ocean surface temperature (*Kubota*, 2010).

4.3. Slope Stability Analysis

Three different scenario were employed for the slope stability analysis, the first one is without rainfall (this scenario is not considering any rainfall effects to the slope), the second one is with the actual rainfall of July 2012 (this scenario is adding the actual rainfall of July 2012), and the third scenario is without increasing rainfall scenario (from the statistical analysis it is found that the increasing trend in term of maximum hourly rainfall is detected, thus the rainfall of July 2012 is assumed to be under the influence of this increasing effect. This scenario aims to gain an insight of a 'what-if there is no increasing rainfall trend' scenario. This was done by reducing the peak value of each hourly rain event by the rate of annual rainfall increment obtained from Sen's slope estimators, which is 0.52 mm/hr/year. The result is presented in figure 4.

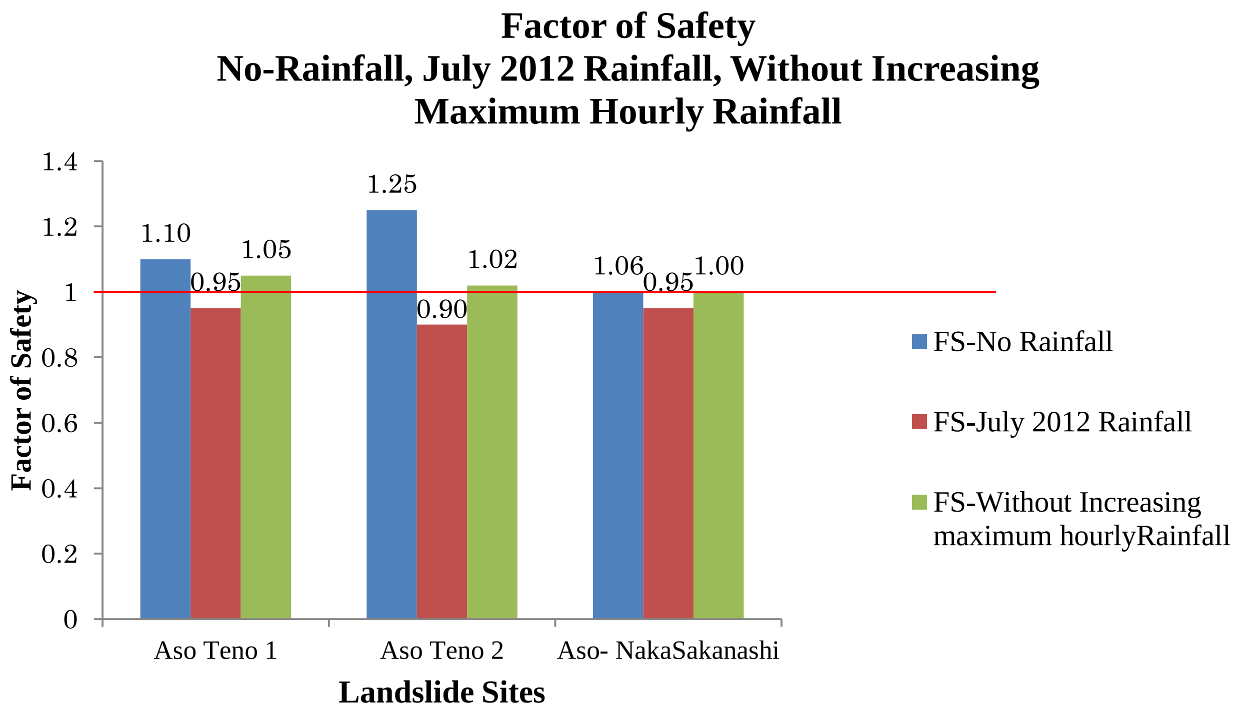

Fig 4. Factor of Safety with three different scenarios (No rainfall, July 2012 rainfall, without increasing rainfall)

All studied sloped showed stable condition when simulated to no rainfall scenario. Aso Teno 1 (FS 1.10), Aso Teno 2 (FS 1.25), and Aso-Nakasakanashi (FS 1.06), However all slopes experiences failure when being simulated to the heavy rainfall event of July 2012: Aso Teno 1 (FS 0.95), Aso Teno 2 (FS 0.90), and Aso Nakasakanashi (FS 0.95), From above result, it can be inferred that all of the studied slopes is becoming unstable after a rainfall event is introduced. Generally, rainfall affects slope stability to a negative direction.

Under the scenario of without increasing rainfall, all Aso slopes are in stable condition. FS increase slightly above the safety threshold of 1.00. : Aso Teno 1 (FS 1.05), Aso Teno 2 (FS 1.02), and Aso Nakasakanashi (FS 1.00). It can be implied that if there is no increasing rainfall effect (that might be induced by climate change) the slopes of Aso are in stable condition. This phenomenon is affecting the general slope stability in forested slopes.

Detail results of the slope stability analysis are shown in below figure 5. At the slope of Aso Teno 1 the slip surface was found at the depth of 4 m, while in the case of Aso Teno 2 the slip surface was found at the depth of 2 m. In Aso-Nakasanashi the slip surface was found at the depth of 6 m.

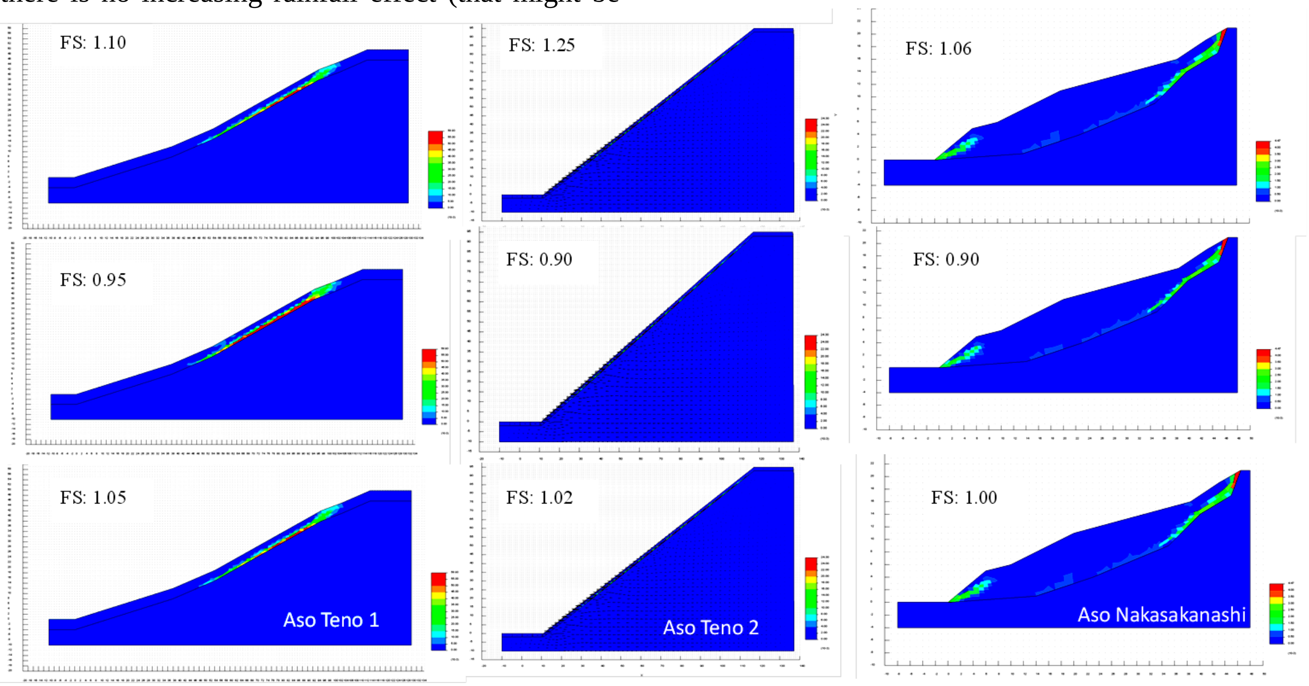

Fig 5. FEM analysis (Top: No Rainfall, Mid: July 2012 Rainfall, Bottom: Without Increasing Rainfall), FS lower than 1.00 means that the slope is unstable while FS higher than 1.00 means that the slope is in stable condition. The brighter the color the higher displacement is in the slope area.

5. CONCLUSION

Based on the presented data and subsequent discussion, the following conclusions are presented: Firstly, the increasing trend of maximum hourly rainfall is statistically detected in Aso city and Yame city. The maximum hourly rainfall during 1978-2012 (Aso) are increased 18.2 mm/hr at the annual rate of 0.52 mm/hr/year. Secondly, the increase of maximum hourly rainfall is surely has negative influences in term of slope stability. Therefore, under this increasing rainfall rate, it is possible for many forest slopes to become unstable and prone to landslide disaster in the near future.

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