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Debris flow velocity due to the collapse of natural dam

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Abstract. Natural dam on Way Ela river was a landslide formation of Ulakhatu mount located at Negeri lima village, Distric Leihutu, Ambon island on 13th July 2012. The natural dam blockage the valley for 300 m wide and 200 m height with total 1,000 m dam area and providing 87 million m³ volume of water storage. Slope failure trigger by slide area on the deeper surface structure leading to landslide. High risk landside increased by the high rainfall intensity of 432 mm/day and causing the failure of natural dam Way Ela. This study aimed to analyse debris flow velocity of the landslide of natural dam. Analysis performed based on debris during using geometric slope with empirical model system. PMF *Synder-Alexeyev* and GAMA-1 method and PMP frequency analysis equation method demonstrated that rainfall intensity data along with recurrent period of 100 years of Q_{peak} resulting debit volume of 448.85 m³/d. Furthermore, velocity estimation also showed that on 215.66 elevation high, allowable slope degree of (*i*) 0,005 %, average width of Way Ela river of 79.97 m and Manning's grain roughness of 0.004 μ m would resulting debris flow velocity of 10.98 m/s, and distance from the landslide centre point to the river mouth was 2.5 km. Those data leading to achieve arrival flow time to the residential area of 3.8 minutes. This study results potential as a base data for disaster mitigation due to high risk of debris flow velocity presented by Way Ela river.

1. Introduction

Natural dam on Way Ela river was a landslide formation of Ulakhatu mount which is located at Negeri lima village, Distric Leihutu, Ambon island on 13th July 2012 night. The natural dam blockage the valley for 300 m wide and 200 m height with total 1,000 m² dam area and providing 87 million m³ volume of water storage and avalanche volume estimated to 10 million m³. This study aimed to analyse debris flow velocity when the landslides occur by considering causa and mechanism of landslides mass movement. Analysis outcome presented in form of frictional coefficient estimation, rate arrival time and travel distance of landslides material. Outcome data potentially aimed as model to evaluate compounding risk of landslides on the studied area as well as disaster mitigation.

2. Study location

Way Ela river is a small and short river flowing through Maluku Province. Its mouth end on Banda sea and forming small fertile delta located on coordinates 3.64 LS 127.98 BT. As time flow, the delta occupied by a population which administratively termed as Negeri Lima village, subdistric Leihutu, and Distik Central Maluku. Way Ela natural dam extended 2.5 km toward the upstream of Negeri Lima village (Figure 1).



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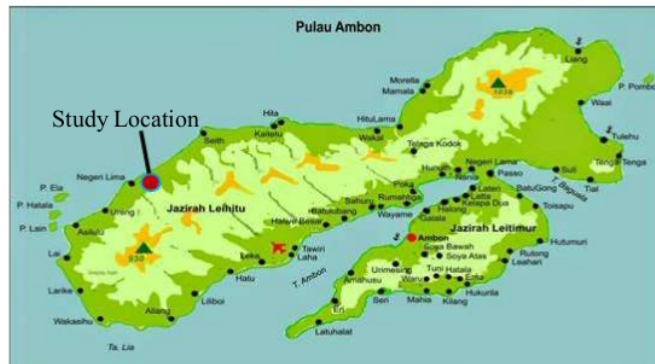


Figure 1. Ambon island map.

Geological landscape around natural dam Way Ela commonly performed from discontinuity [1]. The discontinuity is a straight fracture which demonstrated general direction (southwest-northeast) and straight fracture normal. The nearest straight fracture facing northwest or toward DAS (drainage basin) Way Ela upper coarse or 5 km extend from Way Ela natural dam. These straight fracture also predicted as normal (southwest-northeast). Based on Regional geologic map scale 1:250.000 and mechanical process of natural dam breakage, it is predicted that there were five lithology type happens on natural dam Way Ela as presented on figure 2.



Figure 2. Map of natural dam geology distribution skeleton way ela.

3. Methodology

3.1. Debris Flow

Debris flow is moving mass of high sediment concentration on the river water that travels down a steep slope. The mass often contains larger rocks and driftwood. The flow moving on high velocity with destructive force risking human by significant damage and fatalities not only to the environment but also to human properties. Sediment movement by mass flowing and individual sediment movement are natural [2]. Both movements affected by the same factors such as debit flow, basic steepness, and basic material characteristic of the sediment. Force domination of the sediment movement is different, as well as individual sedimen movement by water pressure and mass sediment movement by gravitational force [2]. One form mass sediment movement is the flow of debris on this research is.

- a. Base slope (Groove or valley) $> 15^\circ$
- b. Material on slope or valley of the forming debris flow.

- c. Large quantities of water that can saturate the deposit of sediment material [4]
- d. High rainfall

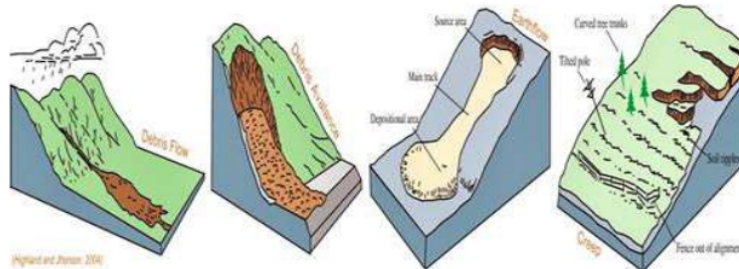


Figure 3. Illustration the debris flow.

3.2. Erosion and sedimentation

Define sediment as a disintegrated product and decomposition of rocks. Disintegration covered all process involving damage, fracture, or destruction of material being in smaller size or particles without changing chemical substance. Decomposition refer to carbonation process, hydasy, oksidation, and solution. While Erosion is phenomen where solid material (sediment, soil, rocks, and other particles) become eroded by air, water, or ice transportation under rainfall characteristics on soil and others material forced by gravitational force. High intensity rainfall and labile, random and unsolidified slide material on the upper coaster composing potential landslide sequence and might form new natural dam. Alluvial fan contain sand- gravel material sediment with a flat morphology is formed on the river mouth. Those morphology causing water flowing migration or uncontrollable (braided river). Sediment transportation in this study is basic sediment transportation (bed load) [5, 6, 7].



Figure 4. Debris flow Condition post crumbling natural dam.

3.3. Discharge flow

Debit flow is water flow rate (in the form of volumetric water) which passes per unit time. In the International system unit (SI) debit the volume represent on meter cubic per second unit (m^3/s). Point analysis were emphasized on basin area system debit, and all contributory component observed and analyse in detail [8]. Water availability analyses aimed to determine debit planning which is a debit origin from the randomly landslides flowing to the river. Natural dam Way Ela debit (Q) gained from

rainfall intensity data with recurrent period of Q100, and calculated with some metode such as PMF Synder-Alexeyev, GAMA-1 and PMP Analysis Frequents method which resulting flooded debit for use as supporting data on calculating whole debris flowing rate.

3.4. *Flow speed*

On landslides location with H height debris mass moved on downslope area. By referring to energy law balance, hydrolic radius could found with method as follow [9].

Wet cross section equation

$$A_e = (b + m.h) h \tag{1}$$

With :

- A_e = Wet section Area
- b = River width
- m = River Slope
- h = Into the water

Roving wet channels

$$P = b + 2h \sqrt{(1 + m^2)} \tag{2}$$

With :

- P = Wet roving
- b = River width
- m = River slope
- h = Into the water

Hydraulic Fingers

$$R = A_e/P \tag{3}$$

With :

- R = Hydraulic fingers
- A_e = Wet area
- P = Wet around

$$V = 1/n (R)^{2/3} (i)^{1/2} \tag{4}$$

With :

- Vd = Debris flow speed
- N = Manning roughness
- hd = Deep debris flow
- I = River slope

4. Result and discussion

Landslides mass movement on landslip area commonly caused by gravitational force and component weight force in parallel with inclined plane surface, and the rainfall water absorbed onto the soil due to prolonged rainfall [11]. Debit flooded on natural dam failure have been checked with Hydrograph synthesis unit, rainfall frequency analysis is statistic analyses of rain interpretation used to determine rain recurrent period on certain period of year. In this study the daily rainfall data gained from Pattimura rainfall station between 1981 to 2013.

Based on matching test from both data, distribution of log-Pearson 3 was the best to represent rainfall intensity on Way Ela area. Log-Pearson 3 distribution provided best result on Chi quadrat test as well as given the smaller discrepancy compared other distribution on the smaller quadrat test.

Table 1. Pattimura rainfall station data 1981-2013.

Year	Rainfall (mm)	Year	Rainfall (mm)
1981	232	1995	179
1982	140	1996	231
1983	135	1997	97
1984	431	1998	162
1986	70	2005	101
1987	113	2006	166
1988	455	2007	263
1989	233	2008	170
1990	307	2009	97
1991	145	2010	224
1992	106	2011	188
1993	150	2012	360
1994	133	2013	432

Table 2. Statistical parameters pattimura station rain data.

Parameters	Value	Logarithmic parameters	Value
Average ($X_{average}$)	200,04	$X_{average, log}$	2,25
Standard deviation (S)	107,23	S_{log}	0,21
Coefficien variation (Cv)	1,87	Cv_{log}	0,09
Coefficien skewedness (Cs)	1,18	Cs_{log}	0,37
Coefficien Sharpness (Ck)	3,38	Ck_{log}	2,44

Rainfall intensity value for log-Pearson distribution 3 (and others) for different recurrent period ³ can be seen in table 3.

Table 3. Rainfall for various distributions at various reperiods.

Re-Period (year)	R_{Normal} (mm)	$R_{Log-normal}$ (mm)	R_{Gumbel} (mm)	$R_{Log-Pearson 3}$ (mm)
2	200,04	177,20	182,42	171,95
5	290,28	267,77	277,18	264,70
10	337,45	332,27	339,92	337,59
25	387,75	418,25	419,19	443,64
50	420,25	485,28	477,99	533,41
100	449,48	554,71	536,37	632,93
1000	531,39	806,87	729,25	1050,71

One of PMP calculation method is Hersfield method, calculation rule for rainfall maximum is allowable Hersfield method. Calculation following the below formulation.

$$X_M = \bar{X}_p + K_m \cdot S_p \tag{5}$$

With :

X_M = Maximum rain value may

\bar{X}_p = Average of the annual maximum daily rainfall data series

K_m = function value of the rainy duration and the average annual maximum rainfall

S_p = Deviation from the maximum annual daily Rain data series
 Debit flooded plan subsequently compared with debit flooded plan PMF based on frequency analysis, debit flooded plan based on PU, and debit plan PMF Hersfield method. On normal condition debit flooded represent as follow:

Table 4. Discharge flood PMF from various hydrographs with PMP hersfield.

PMP (Hersfield)	HMS-Snyder	Snyder-Alexeyev	Nakayasu	SCS	HSS ITB 1	HSS ITB 2	GAMA-1	Rasional
Q_{peak} (m ³ /s)	612.20	742.92	917.07	574.65	340.96	461.77	826.8	1216.12

Table 5. Discharge flood PMF from various hydrographs with PMP frequency analysis.

PMP Log-Pearson 3	HMS-Snyder	Snyder-Alexeyev	Nakayasu	SCS	HSS ITB 1	HSS ITB 2	GAMA-1	Rasional
Q_{peak} (m ³ /s)	437.10	530.46	654.81	410.31	243.45	329.72	499.7	868.34

Table 6. Discharge flood PMF from various hydrographs with PMP Isohyet PU.

PMP PU	HMS-Snyder	Snyder-Alexeyev	Nakayasu	SCS	HSS ITB 1	HSS ITB 2	GAMA-1	Rasional
Q_{peak} (m ³ /s)	277.40	336.57	415.47	260.34	154.47	209.20	374.6	550.95

By considering GAMA-1 dan Snyder method as a method justified by SNI 2415:2016 on rule of calculation of debit flooded plan, both method then chosed for comparison with a result of debit value which nearly resemble debit value from Creager Method.

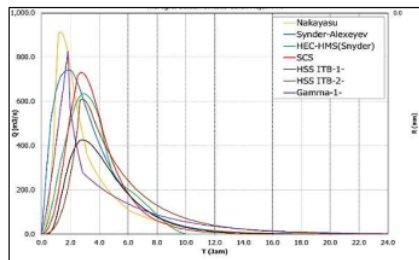


Figure 5. PMF hydrograph graph with rain reperiod of Hersfield PMP.

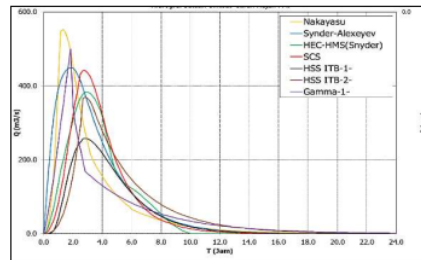


Figure 6. PMF hydrograph graph with rain reperiod PMP frequency analysis.

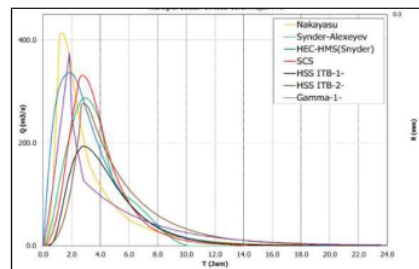


Figure 7. PMF hydrograph graph with rain re-period PMP Ishoyet PU.

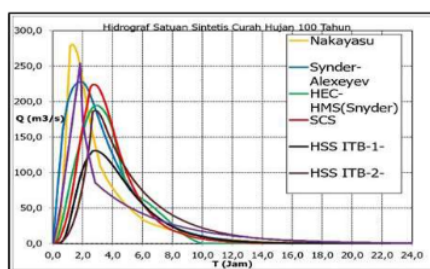


Figure 8. Graph synthesis hydrographs for rainfall reperiod 100 years.

Table 7. Debit peak comparison using creager method.

Method PMP	Method	Qpeak (m ³ /s)
PMP Hersfield	Snyder-Alexeyev	742.92
	GAMA-1	826.8
PMP Analisis Frekuensi	Snyder-Alexeyev	448.85
	GAMA-1	499.7
PMP Isohyet PU	Snyder-Alexeyev	336.5
	GAMA-1	374.6
Condition	<i>Creager Method</i>	425.02

Based on above calculation, method that fulfil requirement was debit PMF Synder-Alexeyev and GAMA-1 from PMP analysis frequency method. Subsequently, for routing Debit flooded PMF analysis frequency Synder-Alexeyev was used, and debit plan value used for spillway was 448.85 m³/s. Table 8 demonstrated characteristic of Way Ela river on the time of natural dam breakage. Debit flooded used rainfall intensity data on the day of dam failure.

Table 8. Characteristics of way ela.

Criteria	Volume
Area of DAS (up to Natural dam)	12.33 km ²
River length from upstream to dam	7.44 km
River length from dam to Estuary	3,35 km
Tilt upstream to early puddle	0.12
Roughness of Manning	0.040
Initial slope of a puddle	3.36 . 10 ⁻²
Emergency discharge capacititation when collapsing (Q ₁₀₀)	448.85 m ³ /s
Rainfall during collapse	432 mm
Into the flow	24 m
Peak elevation collapsed dam	+215.66 m
Long avalanche	1,200 m
Unstoppable Hill Peaks	300 m
Wide Puddle	45.27 ha
Average Puddle Width	300 m

Calculations to know the broad cross section based on equations (1) as follows :

$$A_e = (b + m.h)h = (79.97 + (0.12 \times 24)) \times 24 = 1.988 \text{ m}^2$$

Calculation to know the wet circumference based on the equation (2) as follows:

$$P = b + 2h \sqrt{1 + m^2} = 79.97 + 2(24)\sqrt{1 + (0.12)^2} = 128.31 \text{ m}$$

Calculation to know fingers – finger hydraulic based on equations (3) as follows:

$$R = A_e/P = 1.988/128.31 = 15.49 \text{ m}$$

Calculation to know the flow rate based on equation (4) as follows:

$$V = 1/n (R)^{2/3} (i)^{1/2} = 1/0.040 (15.49)^{2/3} (0.005)^{1/2} = 10.98 \text{ m/s}$$

Calculated debris flow velocity was 10.98 m/s on the maximum elevation of 215.66 m.dpl. This data indicating fastest descendent flow onto crossed points. It was analysed that the landslide was suddenly ceased and subsequently pushed blocked materials to flow down the hill.

5. Conclusion

Rainfall intensity on the day of natural dam break was 432 mm and calculated debit was 448.35 m³/s. Landslide velocity observed suggesting that slide mass moved along river stream, affecting by soil-rocks on wet condition and causing the constant velocity by rain water flowing. It was then calculated that debris flow velocity from landslide center to the river mouth was 10.98 m/s

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