Control morphology to the landslide Induced Earthquake: Case Study Padang Pariaman, Sumatra

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Abstract

The September 30, 2009, Padang earthquake has induced huge landslide in Padang Pariaman Regency, West Sumatera, Indonesia. Earthquake induce landslide occasionally occurred in tephra with a thick pumice deposit. The thickness and characteristic tephra contents of pumice, slope, presence of clay layer to the sliding surface are the main factors controlling landslide occurrences. Other factors are morphology and tectonics conditions. The present lithology and morphology play important factors controlling of landslide occurrences within this area. This study aimed to identify the level of tectonic activity in Padang Pariaman, West Sumatra by morphotectonic index analysis such as ; the stream-gradient index(SL), drainage basin asymmetry (Af), valley floor width–valley height ratio (Vf), drainage density (Dd), and mountain-front sinuosity (Smf). Geomorphic aspects were analyzed by using geomorphological index to identify the tectonic activity of the study area. The lineament of stream segments will be compared with the azimuth of joint and azimuth of landslide crown using statistical test to determine the relationship between these variables. Based on morphometric measurements it's known that the study area has an active tectonic activity level and the river channel give significant parameter to the landslide occurrences. In this paper we will describe landslide triggered by earthquake in the Padang Pariaman, West Sumatra from morpho-tectonics of view.

Keywords: landslide, geomorphology, tectonics, river channel.

1. Introduction

According to Heath (1988) and Varnes (1996), the factors controlling landslide occurrences must consider the conditions of geomorphological / slope, geological, soil or rock, hydrogeological and land use. Keefer (2000) showed that the geotechnical parameters as friction angle and cohesion cannot explain the distribution and density of landslides. He also showed that landslide caused by earthquakes more correlated with the characteristics of engineering geology and geomorphology than geotechnical parameters. Lin (2008) showed 88 percent of earthquake-induced landslides due to Chi Chi earthquake do not relate directly with river channel. Wang, (2010), based on laboratory test using ring shear apparatus, the result indicates that the pumice layer from landslide location at Pariaman is very strong even in the saturated condition and the slope can remain stable during rainfall. Faris (2014), the result from cyclic triaxial show that pumice layer posible to failure without increasing water pore presure, in dry condition, small earthquake with PGA of 0.05 g would only probably excites minor landslide. the high probability of catastrophic landslide that could happen in the area even if earthquake with PGA as small as approximately 0.15 g occurred during rainfall result Warmada (2012) conclude the high degree of weathering which possibly overprinted by alteration in Padang Pariaman district produces large amount of clay minerals, especially smectite and illite. The presence of smectite and/or illite in the weathered zone may become important trigger of landslide occurrences within this area.

West Sumatra September 30, 2009 earthquake with magnitude scale 7.6 Mw had triggered landslides at approximately 154 sites caused 244 people killed and dozens of houses buried. Landslide occurred within 52 miles ($\pm$ 84 km) radius from the epicenter of the earthquake, mostly affected the whole of West Sumatra Province area. In Pariaman and Agam regencies especially Tandikat and Damarbancah area were severely damaged. Geologically, this area is composed mostly of pyroclastic deposits and these landslides occurred in strongly weathered volcanic terrain. Despite earthquake mostly induced landslides in West Sumatra area, but there are some factors which have important role, namely morphology and tectonical conditions. In this paper describe controlling factor of Padang Pariaman landslide from morphology and tectonics point of view.

2. Methodology

Field survey was conducted in Pariaman District to identify the dimension and stratigraphy as well as to map the distribution of landslides. In order to make clear the characteristic of the landslide, topography analysis using IFSAR were carried out. GIS Analysis is performed to assist the morphometric and slope analysis. The flowchart of the methodology to analysis factor controlling landslide is shown in Fig.1.

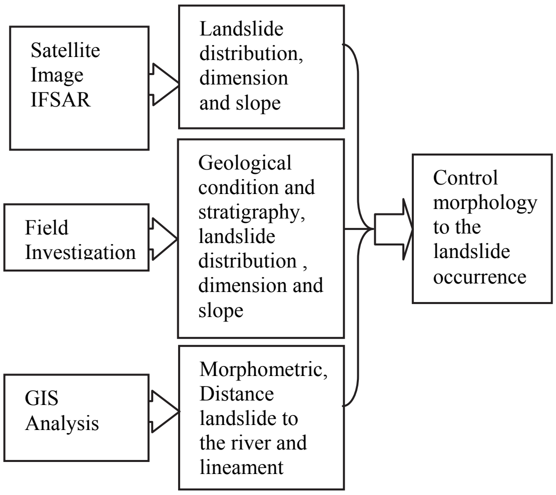


Fig. 1. Research Methodology

3. Regional Geology

Geologial condition of research area based on volcanostratigraphy shows the landslide at West Sumatra landslide occurred dominantly on Tephra Malalak (Pribadi, 2007). Tephra deposit from Tandikat which consists of pumice lapilli, ranging from 2 – 10 cm in diameter, slightly consolidated. Landslide predominantly occurs in this rock type due to unconsolidated, very loose structure, easy collapse and eroded, pores are larger and has high permeability. Several landslide and rockfall occurred at andesite of Maninjau lake caldera. The elongated form of the caldera could indicate a prolonged period of eruption during right lateral displacement on the Great Sumateran Fault, also the tephra Malalak to overlie the Maninjau volcanic rock.

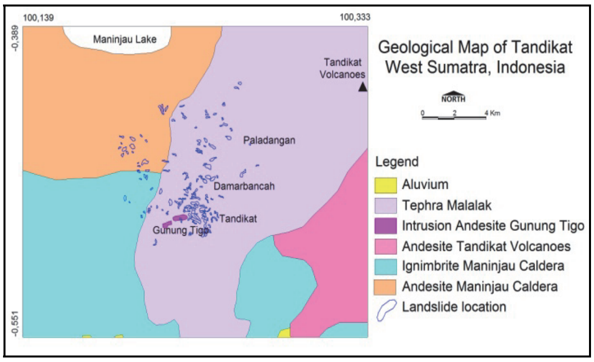


Fig 2. Geological condition of research area based on volcanostratigraphy (Pribadi, 2007)

4. Analysis and Result

4.1. Landslide distribution

GIS Analysis and field survey in Pariaman District found 154 landslide sites due to West Sumatra earthquake on September 30, 2009 (Table 1 and Fig 3). Landslide concentrated at Manggur Gadang rivers and around the lineaments (fault), and occurred on the slopes of 15^{o} - 45^{o} (Table1). Field survey found out flowsliding characteristic at gentle slope (Fig. 3a) and Tephra deposit consist pumice layer overlying the clay (Fig 4b). The SEM and XRD analysis found out that clay minerals, especially halloysite (Table 2 and Fig 5) formed due to tephra alteration. It is strongly controlling factor of landslide occurrences within this area.

Table 1 Landslide occurrences at 5° interval

Slope (°)	Number of Landslide	Slope (°)	Number of Landslide
>5 – 10	4	>30 – 35	22
>10 – 15	17	>35 – 40	4
>15 – 20	33	>40 – 45	3
>20-25	40	>45 – 50	1
>25-30	29	>50 – 55	1

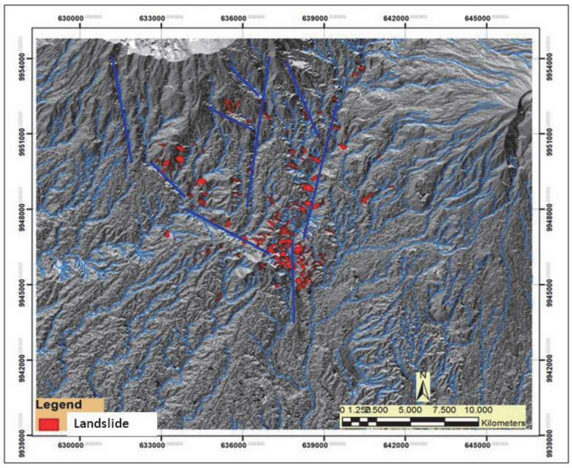


Fig 3 Landslide distribution and morphological lineaments in research area.

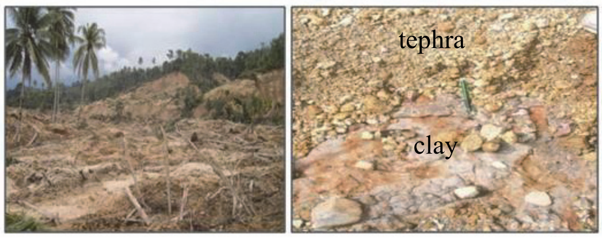


Fig 4 (a) The main scarp of the Tandikat flowslide, the slope angle was about 35 degree; (b) clay layer underlie pumice layer from tephra Malalak

Tabel 2 Mineralogical contents of sliding surface of landslide.

Ref. Code	Score	Compound Name	Displacement [°2Th.]	Scale Factor	Chemical Formula
00-029-1487	21	Metahalloysite	0.000	0.380	$Al_2 Si2 O_5 (OH)_4$
01-083-2465	34	Silicon dioxide $-alpha	0.000	1.047	SiO_2
00-041-1486	27	Anorthite, ordered	0.000	0.718	$Ca Al_2 Si_2 O_8$

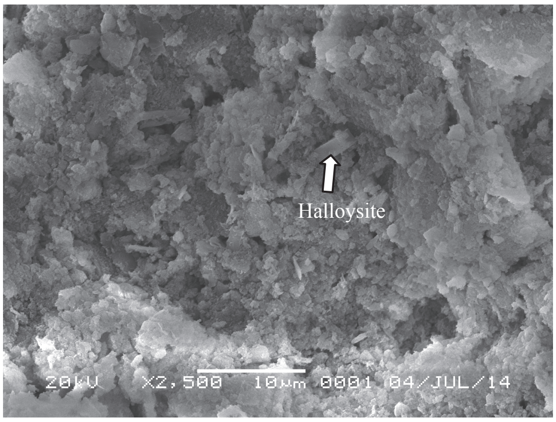


Fig.5 SEM analysis on the sliding surface

4.2. Distance of landslide to the river

Based on GIS analysis show that, most of earthquake trigered landslide in Pariaman connect directly with river channel, mostly landslide occurred on the distance 0-100 m (Table 3). Based on 65 % landslide that random seleceted from GIS, show that 49 landslide occurred on the range 0-100 to the river channel. The meaning is the landslide also controlled by cutting slope by rivers erotion other than lithology and stratigraphy.

Table 3 Distance landslide to the river

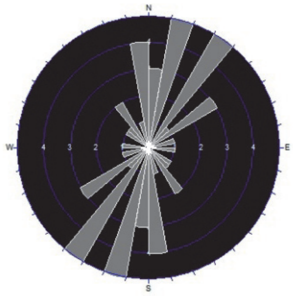
Distance landslide to the river	Landslide Area	Landslide Occurrences
0-100	106114	49
100-200	68082	24
200-300	53247	11
300-400	29642	12
400-500	19111	2
500-600	9843	3

4.3 Correlation between landslide crown azimuth and river segment

Due to part to topografic site effect, most of earthquake trigered landslide in Chi-Chi earthquake not connect directly with river channel (Lin, 2008). In Pariaman case the landslide connect with river segment and the landslide material reach the river, especially Manggur Gadang river. The measurement of landslide crown azimuth with the river segment at Pariaman showed that 97% the direction of the landslide crown azimuth correlated with the direction of the river segment and majority of landslides reach the river (Fig. 6 and 7). It suggests that landslide condition is controlled by slope cutting due to erosion and local tectonic in this area as well as morphology or morphometric aspects. It can be concluded that the tectonic possibly has an influence in landslide occurrence in this area.

(a)

(b)



(c)

Fig. 6 Rosette diagram river (a) river segmen at Manggur Gadang, (b) Azimuth fault/linieament at Manggur Gadang River (c) azimuth landslide crown at Manggur Gadang. All of diagram show relatively parallel.

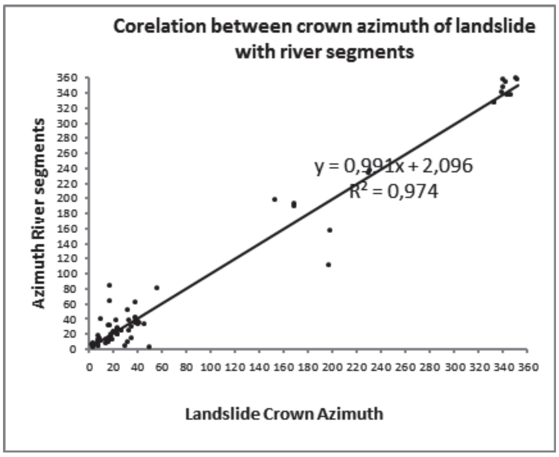


Fig. 6 Correlation between azimuth of landslide with river segments

4.4. Morphometric indices

The study area also had an experienced on land earthquake on January 20 to 25, 2003, with a 3.3 magnitude scale and have caused 80 houses damaged at this area, but no landslide occurrences at that time. Landslide area due to West Sumatra earthquake was located parallel on drainage pattern or river channel. The flow pattern was developed in a longitudinal slope conditions with a rather steep, and it is possibly controlled by geological structures. Geomorphic indices is useful to identify tectonic parameters, include the stream gradient index (SL), drainage basin asymmetry (Af), Valley floor width-valley height ratio (Vf) and mountain front sinuosity (Keller and

Pinter, 1996). Most of these obtained- indices are used to identify river basins in Naras, Manggur Gadang and Manggur Kecil Sub Watershed.

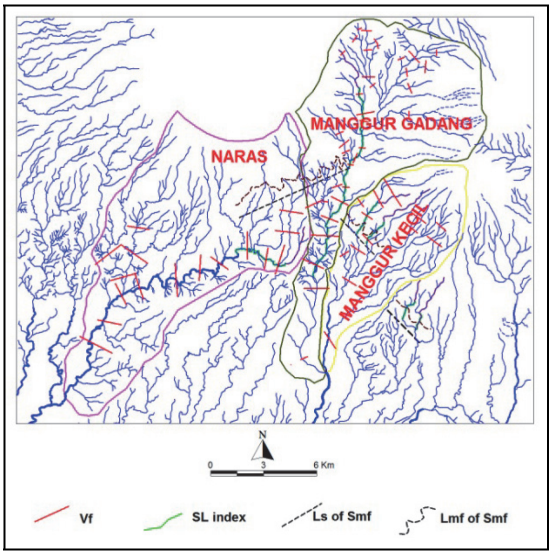


Fig.7. Location measurement of Morphometric indices at Naras, Manggur Gadang and Manggur Kecil Sub Watersheed, Pariaman District

4.4.1 Stream length gradient index (SL)

The SL index can be used to evaluate relative tectonic activity (Keller and Pinter, 2002). Although an area on soft rocks with high SL values indicates recent tectonic activity, anomalously low values of SL may also represent such activity when rivers and streams flow through strike-slip faults. SL indices are defined as:

$$SL = (\Delta H/\Delta L) \times L \qquad (1)$$

where; ΔH is change in altitude, ΔL is length of a reach, and L is the horizontal length from the watershed divide to midpoint of the reach. We calculated SL along rivers using a digital elevation model which is extracted from a digitized 1:25000 topographic map and using GIS to perform its average value for each sub-basin. The values were classified into three categories: 1 (SL≥500), 2 (300≤SL<500) and 3 (SL<300) (El Hamdouni et al., 2007). The result of the classification is shown in Table 8.

Table 4 SL Value

No.	ΔH (m)	ΔL (m)	L (m)	SL
1	645	12210	15040	794,4963
2	215	13170	15740	256,9552
3	204	2229	4296	393,1736
4	230	1617	5227	743,4818
5	165	1288	2594	332,3059
6	180	975,7	3643	672,0713

4.4.2 Drainage basin asymmetry (AF)

The asymmetry factor (AF) of catchments was used to detect possible tectonic tilting at the scale of the whole range. The AF is defined as (Keller and Pinter, 2002):

$$AF = A_R/A_T \times 100 \qquad (2)$$

where A_R is the area of the basin to the right (facing downstream) of the trunk stream, and A_T is the total area of the drainage basin. Values of AF above or below 50 indicate that the basin is asymmetric (Table 5). Af is close to 50, if there is no or little tilting perpendicular to the direction of the master stream. Af is significantly greater or smaller than 50 under the effects of active tectonics or strong lithologic control. Af values were grouped into three classes: 1 (AF≥65 or AF<35); 2: (35≤Af<43 or 57≤Af<65), and 3 (43≤Af<57) (El Hamdouni et al., 2007).

4.4.3 Drainage density (Dd)

In tectonic studies, drainage density is influenced by the number of fractures in the watershed, the greater the flux density in a watershed is estimated more and more cracks in the watershed. This index is defined as:

$$D_d = L/A \qquad (3)$$

Where L, is total length of the stream in the watershed and A is total area of the watershed

Table 5 AF and Dd Value

Drainage	Ar	At	AF	L	A	D_d
Manggur Gadang	75,78	97,72	77,5481	165,7	97,72	1,69
Manggur Kecil	32,29	49,36	65,41734	104,5	49,36	2,12
Naras	90,11	121,2	74,34818	229,9	121,2	1,90

4.4.4 Ratio of valley floor width to valley height ratio (Vf)

The V_f is defined as the ratio of the width of the valley floor to its average height (Bull and McFadden, 1977) and defined as:

$$V_f = 2V_{fw} / E_{ld} + E_{rd} - 2E_{sc} \qquad (4)$$

where, V_f is the ratio of valley floor width to valley height, V_{fw} is the width of the valley floor, E_{ld} is the elevation of the divide on the left side of the valley, E_{rd} is the elevation on the right side and E_{sc} is the average elevation of the valley floor.

This index differentiates between valleys with a wide floor relative to the height of valley walls with a U-shape compared to narrow, steep valleys with a V-shape. Valleys with a U-shape generally have high values of V_f, whereas V-shaped valleys with relatively low values. Because uplift is associated with incision, the index is thought to be a surrogate for active tectonics where low values of V_f are associated with higher rates of uplift and incision.

Table 6 Vf values

No.	Vw	Erd-Esc	Eld-Esc	Esc	Vf
1A	36,51	79	66	664	0,503586207
2A	93	61	49	797	1,690909091
3A	62	26	83	561	1,137614679
4A	34	66	61	482	0,535433071
5A	89	68	90	408	1,126582278
6A	162	122	71	357	1,678756477
7A	67	78	23	297	1,326732673
8A	84	41	36	268	2,181818182
9A	85	45	26	227	2,394366197
10A	49	40	49	843	1,101123596
11A	57	29	55	1277	1,357142857
12A	58	40	31	1182	1,633802817
13A	78	56	40	1153	1,625
14A	98	87	26	1174	1,734513274
15A	57	47	82	1096	0,88372093
16A	28	39	100	1165	0,402877698
17A	214	201	141	1107	1,251461988
18A	160	83	58	960	2,269503546
19A	228	149	247	1069	1,151515152
20A	42	25	48	1330	1,150684932
21A	137	85	76	940	1,701863354
22A	112	113	74	689	1,197860963
23A	77	70	98	912	0,916666667
24A	45	56	54	697	0,818181818
25A	68	86	45	567	1,038167939
26A	55	90	97	607	0,588235294
27A	115	66	47	466	2,03539823
28A	110	77	72	393	1,476510067
1B	61	50	57	509	1,140186916
2B	37	104	88	457	0,385416667
3B	50	77	28	568	0,952380952
4B	29	22	30	433	1,115384615
5B	54	128	118	875	0,43902439
6B	67	122	113	520	0,570212766
7B	37	88	85	902	0,427745665
8B	31	106	126	944	0,267241379
9B	65	36	93	468	1,007751938
10B	13	42	24	356	0,393939394
11B	31	30	33	140	0,984126984
12B	45	70	123	193	0,466321244
13B	32	29	58	270	0,735632184
14B	13	58	64	281	0,213114754
1C	43	59	47	237	0,811320755
2C	128	70	87	212	1,630573248
3C	70	55	73	195	1,09375
4C	423	81	89	159	4,976470588
5C	148	134	110	121	1,213114754
6C	321	81	104	76	3,47027027
7C	107	50	135	18	1,156756757
8C	311	69	117	14	3,344086022
11C	53	87	79	375	0,638554217
12C	61	79	118	318	0,61928934

4.4.5 Mountain-front sinuosity (Smf)

Mountain-front sinuosity (Smf) is the nodal plane of active faults along the mountain front. It has a simple landscape compared to the slopes in areas dominated by erosion (slopes formed in periods of tectonic stability). Mountain front sinuosity (Smf) was defined by Bull and McFadden (1977) as:

$$Smf = Lmf/Ls \qquad (5)$$

Where Lmf, is total length mountain front and Ls is straight line in front of mountain front.
Smf value for active tectonic zones in arid areas, typically between 1.2 and 1.6, while value for slightly active or inactive tectonic area tend to fall in the ranges 1.8 – 3.4 or 2 – 7 (Bull and McFadden, 1977). El Hamdouni divide Smf into three classes: 1 (Smf<1.1), 2 (1.1≤J<1.5), and 3 (Smf≥1.5) (El Hamdouni et all, 2007).

Table 7 Smf value from different watershed

No.	Lmf	Ls	Smf
1	13,17	6,844	1,924313
2	10,25	6,517	1,57281
3	12,3	6,942	1,771824
4	4,252	2,882	1,475364
5	2,905	2,648	1,097054

4.4.6 Evaluation of relative tectonic activity

Morpho-tectonics parameters are used to evaluate relative tectonic activity in a wider area. The average of the four measured geomorphic indices is used in the study area in order to define the degree of active tectonic. The values of the index are divided into four classes as follow 1—very high (1.0≤Iat<1.5); 2—high (1.5≤Iat<2.0); 3—moderate (2.0≤Iat<2.5); and 4—low (Iat≥ 2.5) (El Hamdouni et al., 2007).

The four class morphometric index for each sub watershed is shown in Table 8. The calculated-geomorphic indexes in this work suggest that Manggur Gadang and Manggung Kecil are tectonically active, with the recent uplift concentrated in the north, east, southeast and southwest. The asymmetry factor (AF) of this area shows a value above and below 50. It means that the drainage basin is asymmetry due to tilting on the drainage basin. When AF = 50, the drainage basin is perfectly symmetric, while values greater or less than 50 belong to asymmetric basins. The SL index shows values ranging 332-794, and the great values indicate that the stream has a steep gradient profile. It suggested that there is an uplifting. Smf index along the area has values < 2 indicating erosion did not occur much. Moreover, most of the Vf and Smf value obtained for Manggur Gadang, Manggur Kecil and Naras sub watershed are low (0.213 to 4.976 for Vf and 1.09 to 1.92 for Smf). Table 1 and 2, which may indicate an area weakly active tectonism. According to Wells *et al* (1988) active fronts will show straight profiles with lower values of Smf, and inactive or less active fronts are marked by irregular or more eroded profiles, with higher Smf values. The high values drainage density and low values of Vf ratio indicate that the area have more fractures and associated with higher rates of incision and uplift. The Smf index is a measure of incision and not uplift; but in an equilibrium state, incision and uplift are nearly matched. Calculation of the index is carried out at a prescribed distance upstream from the mountain front (Silva *et al*., 2003).

Table 8 Tectonic activity of each Sub Watershed

Sub Watershed	**Class**				**Lat**	**Tectonic Activity**
	SL	**AF**	**Smf**	**Vf**		
Manggur Gadang	1	1	3	3	2	Medium
Manggur Kecil	1	1	2	2	1,5	High
Naras	3	1	3	3	2,5	Low

Conclusion

The landslides occurring in Pariaman District were triggered by combination, 30 September 2009 Padang earthquake and rainfall. This landslide located at medium tectonic activity. The stratigraphy under the tephra, slope, presence of clay layer (halloysite contents) to the sliding surface are the main factors controlling landslide occurrences. Geomorphology conditions and control lineaments around Manggur Gadang are important parameter to the landslide occurrences in this area.

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