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DEBRIS-FLOWS IN PENINSULAR MALAYSIA: TOPOGRAPHY, GEOLOGY, MECHANISM AND SEDIMENT DISCHARGE

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ABSTRACT

Debris-flows caused the highest number of deaths amongst the many types of landslides in Malaysia due to its high velocity, and the travel distance that it covers. As such, 8 events which occurred from 2001 till 2007 were chosen to ascertain the preparatory and triggering factors for debris-flows in Peninsular Malaysia. Site investigations and laboratory tests were conducted and documented in 2010 with detailed description of the debris-flow channels which are useful for deduction of the debris-flow mechanism and sediment discharge estimation. The influences of slope gradient, catchment area and geology on the initiation and deposition of debris-flows are examined and sediment discharge volumes are estimated based on field investigation and calculated based on Japanese guidelines. It is concluded that for the study sites, the bed gradient of initiation zones are more than 20^o while the catchment area ranges from $0.2km^2$ to $3.5km^2$. The gradient of the banks along the flow path are typically close to 50^o forming a V-Shape channel. All initiation locations occurred in weathered granitic rock and are also near to metamorphic formation. The particle size comprises of 75% cobbles and boulders and 25% sandy silt which is typical of weathered granite. The most prevalent mechanism of debris-flow in Peninsular Malaysia is gully bed erosion. Landslide induced debris-flows and collapse of natural dam are also possible. The potential sediment discharge volumes estimated based on the field studies show similar trend with the data in Japan with a sediment yield of about $14{,}200m^3$ per event per km^2 of catchment area.

Keywords: debris-flows, initiation, gradient, catchment area, geology, mechanism, sediment discharge.

1. INTRODUCTION

Debris-flows, or sometimes referred to as mud-floods in Malaysia, are fast-moving landslides which generally occur on steep natural terrains during periods of heavy rainfall [7]. They consist of loose soil, rocks, and tree trunks combined with water, forming slurry that flows downslope. Typical velocity of debris-flows, as reported by Highland *et al.* [9] ranges between 16 to 56 km/h. Due to their relatively high density and viscosity, debris-flows can displace boulders, may carry away vehicles and other objects as large as bridges and locomotives.

Debris-flows can also be extremely destructive to life and property. Thousands of lives are loss worldwide in any given year due to this disaster. In such a case in December 1999, debris-flows claimed 30,000 lives in Vargas, Venezuela. Since 1961, about 740 fatalities due to landslides were recorded in Malaysia, out of which more than half were due to debris-flows. For example, in 1996, a debris-flow incident in Keningau, recorded 302 fatalities and destroyed close to 5,000 houses (Figure-1). In the same year, another debris-flow incident in Pos Dipang claimed 48 lives [17]. Other cases in Malaysia were reported by Hussin *et al* [10].

Due to their destructive nature, the Public Works Department (PWD), Malaysia carried out a study in 2010 to investigate the factors that caused some of the major debris-flows in Peninsular Malaysia. Eight sites were chosen due to the availability of physical details and that the effects of the debris-flows could be observed then. Table-1 lists the study locations and the date of debris-flow occurrences. Out of these chosen events, the events in Genting Sempah and Gunung Pulai claimed 20 and 5 lives, respectively while the incidence in Gunung Tempurung injured a motorist. All debris-flow events chosen for this study resulted in road closures from a few hours to several weeks.

Figure-1. The debris-flow in Keningau which was triggered by the Gregg Typhoon on 26th December 1996.

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Table-1. Debris-flow sites studied by PWD in 2010 [21].

Date of Occurrence	Location	Coordinates
15-Nov.-07	**Km 4 to 5 Gap-Fraser's Hill Road (FT148)**	**N 3.71639 E 101.75833**
30-Jun-95	Km 38.6 Kuala Lumpur-Karak Highway (Genting Sempah)	N 3.35342 E 101.77583
28-Dec-01	Gunung Pulai, Kulai , Johor	N 1.59342 E 103.54283
10-Nov-04	Km 302 North South Expressway (Gunung Tempurung)	N 4.41569 E 101.20928
10-Nov-03	Section 23.3 to 24.10 Kuala Kubu Bharu - Gap Road (FT55)	N 3.63633 E 101.74261
2-Nov-04	Km 52.4 Lebuh Raya Karak (Lentang)	N 3.39625 E 101.89542
3 Jan-09	Section 62.4, Lojing-Gua Musang Road (FT185)	N 4.60369 E 101.46569
12-Apr-06	Km 33 Jalan Simpang Pulai - Cameron Highlands Road	N 4.55972 E 101.33492

2. SIGNIFICANCE OF THIS STUDY

In Malaysia, almost all debris-flows initiates on natural terrains as opposed to other forms of landslides which occur mostly on man-made slopes. Investigation along the channel's bed would be very challenging and most studies, therefore, rely heavily on aerial photos and topographic maps from the Land and Survey Department. This study, however, involved detailed topographic survey and field investigations along the main channel up to the initiation areas, if reachable, which took 1 to 7 days for each site. By doing so, field tests could be conducted, and samples could be obtained for laboratory tests.

With the triggering and preparatory factors of debris-flows in Malaysia made known, the study will support the landslide hazard and risk assessment initiatives being carried out by various government agencies. This paper, therefore, consolidates the key findings by Ghazali [7] and PWD [21] and focuses on the spatial aspects of the study. The temporal aspects or rainfall threshold of the 8 study sites have been published by Kasim [18].

3. METHODOLOGY AND EQUIPMENT

Topographic surveys were conducted by a licensed surveyor so that a base or route map could be prepared for the field works during which, topographical and geological conditions were noted at various sections along the routes or channels. Aerial reconnaissance by a helicopter was carried out to take aerial photographs and plan for the field works. A field investigation form was established so that the elevations, coordinates, cross sections, and geological information were adequately recorded.

Site investigation for all 8 sites was carried out from 2nd June 2010 till 7th July 2010. Equipment used during the field works were hand-held GPS, range finder with 0.1m accuracy, geological hammer and compass. Probe tests were terminated at 100 blows per 30cm, which is equivalent to a bearing capacity of 435kN/m^2, at the initiation, flow path and deposition areas so that the thickness of movable sediment in the channel could be estimated. Particle size distribution which included large boulders was conducted at Fraser's Hill to determine the composition of the debris material. Soil samples obtained using hand augers up to 1.2m depth were sent to the laboratory for classification tests while petrography tests were conducted on the rock samples.

Detailed engineering geological maps which summarize the observations from the field works were then produced for all sites. Catchment areas and cross sections along the channel were determined based on the topographic maps while debris-flow mechanisms were deduced from information obtained from this investigation and other researchers. Sediment discharge volumes were determined using the Japanese guidelines [1, 14, 15] and compared to the debris-flow data in Japan.

4. GRADIENT AND CATCHMENT AREA

For the 8 sites being studied, the elevation vs chainage (measured from the road) are plotted in Figure-2 so that the average gradient of the main channel, defined as the slope from the road to the initiation point (along the channel), and the gradient at the initiation zones could be determined. The initiation points, as indicated in this figure, are then decided based on the engineering geological maps produced for the sites and aerial photos. It is concluded that the average bed gradient ranges from 10^o to 39^o while the gradient for the initiation areas ranges from 22^o to as high as 50^o. Based on the debris-flow occurrences in Japan, Osanai *et al* [22] proposed the most probable initiation, flow and deposition sections based on gradients as depicted in Figure-3. The initiation areas of debris-flows are typically found on slopes steeper than 15^o while deposition areas are found on gentler slopes. Sediments tend to deposit in areas where the gradient is less than 10^o and only fine particles may travel beyond 2^o.

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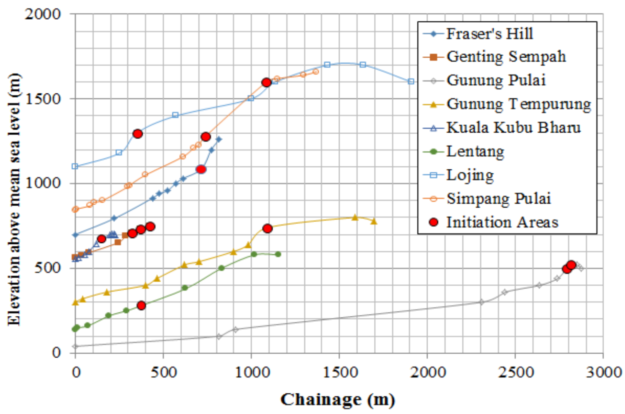

Figure-2. Elevation vs chainage along the channels.

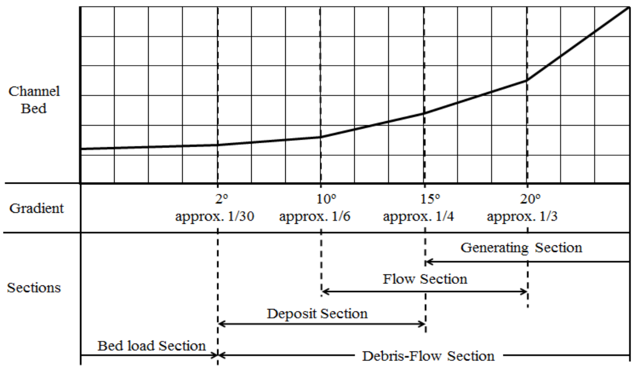

Figure-3. Debris-flow behaviour based on channel bed gradient [22].

The figure below summarizes the gradients and the behaviours proposed by [22]. All the sites have initiation gradients steeper than 20^o and as the average gradient are equal or higher than 10^o, their debris were able to reach and sever the roads downstream. Due to the gentle average bed gradient at Gunung Pulai, however, most of the heavier debris, such as boulders, had deposited before reaching the road that only trees were observed at the bridge (Figure-5). All the initiation and deposition zones of the 8 sites, therefore, agree well with the trend anticipated by [22].

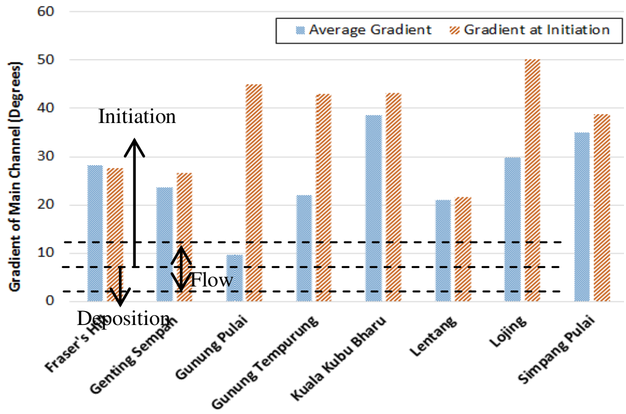

Figure-4. Average and intiation gradients and the debris-flow behaviours proposed by [22].

Figure-5. Tree trunks deposited at the bridge downstream due to the debris-flow at Gunung Pulai.

Possible relationship between catchment area and the average gradient of the main channel is shown in Figure-6. A steeper gradient would require less runoff, hence smaller catchment area to initiate a debris-flow. The data were compiled by Gartner *et al* [5] for debris-flow incidents with various rock formations that occurred in the aftermath of wildfires. The heavy curve line indicates threshold conditions and the dashed vertical line emphasizes that debris-flows were not observed beyond the outlets of the basins larger than about 25 km^2 for wildfire-related debris-flows. Also plotted on the same graph are the data points from this study. It should be noted, however, that the creation of hydrophobic layer during fires inhibits the infiltration of rainfall, hence leads to increased rates of runoff [4]. As such, the threshold line for debris-flows which are not induced by wildfires should be higher, i.e. larger catchment area with the same bed slope gradient.

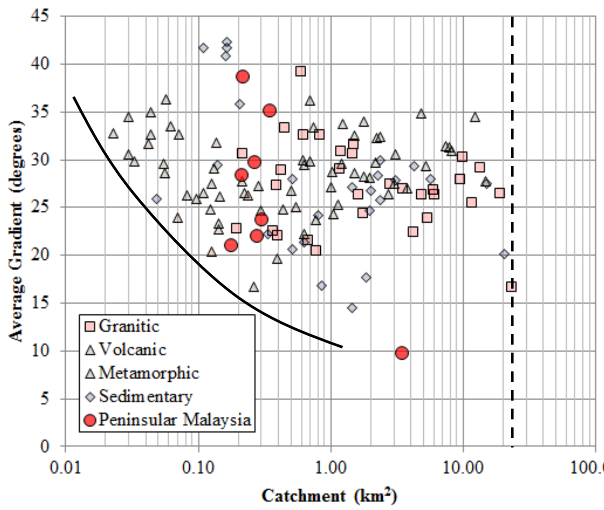

Figure-6. Relationship between catchment area and the average channel gradient with different geology for wildfire-related debris-flows in the USA [5], compared to the data points from this study.

Table-2 provides the values of gradients and areas determined from this study while Table-3 provides

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the length and geometry of the debris-flow channels. It was observed that the banks are very steep, i.e. close to 50^o, that V-shape channels are normally formed (Figure-7). This is believed to be an important preparatory and sustaining factor for debris-flow.

Table-2. Values of average bed and initiation gradients gradients and catchment area.

Site	Average Bed Gradient (Degrees)	Initiation Gradient (Degrees)	Catchment (km^2)
Fraser's Hill	28	28	0.21
Genting Sempah	24	27	0.31
Gunung Pulai	10	45	3.51
Gunung Tempurung	22	43	0.28
Kuala Kubu Bharu	39	43	0.22
Lentang	21	22	0.18
Lojing	30	50	0.27
Simpang Pulai	35	39	0.35
Average	26	37	0.67

Table-3. Channel's length and average geometries.

Site	Total Length (m)	Left Bank Gradient (Degrees)	Right Bank Gradient (Degrees)	Width (m)
Fraser's Hill	1,000	48	40	13.0
Genting Sempah	548	59	53	8.4
Gunung Pulai	2,820	43	47	16.2
Gunung Tempurung	813	55	53	8.3
Kuala Kubu Bharu	388	46	44	12.9
Lentang	452	44	41	11.5
Lojing	605	41	42	10.8
Simpang Pulai	463	49	50	7.9
Average	886	48	46	11.1

Figure-7. A typical V-shape channel of the study sites.

5. GEOLOGICAL AND SOIL CONDITIONS

The geological characteristics based on the site investigation and petrography tests are summarised in the Table-4. All the debris-flows in this study were initiated from weathered granitic rock. When the locations of the study (Table-1) are superimposed on the geology map of Peninsular Malaysia (Figure-8), the locations are found to be located along the main range and within the granitic formation. Another interesting observation is that all the sites in this study are also close or next to metamorphic formation. At least 2 sites, i.e. Genting Sempah and Simpang Pulai, even have channels that flow along the contact of metamorphic and igneous rocks as shown in Figure-9a and 9b. The site furthest from a metamorphic formation is Lentang which is estimated to be just 4km away from such lithology. In general, lithology is important as it is a major factor in describing the activity of debris-flows [16].

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Table-4. Summary of Geological Conditions.

Site	Geology at Initiation Area	Geology Along the Channel
Fraser's Hill	Granite - IV to VI with high seepage	Igneous (Plutonic) - Dry
Genting Sempah	Granite - IV to VI with seepage	Igneous (Volcanic) & Metamorphic - Stream & seepage at banks
Gunung Pulai	Granite - V to VI	Igneous (Volcanic) & Metamorphic - River & natural dam
Gunung Tempurung	Granite – not reachable	Metamorphic - Stream with cliff at contact zone
Kuala Kubu Bharu	Granite - III to V	Igneous (Plutonic) - Intermittent stream & sabo dam
Lentang	Granite - II to III	Igneous (Plutonic) - Stream with seepage and scarps at banks & sabo dam
Lojing	Granite - III to V	Igneous (Plutonic) - Dry but with seepage at toe of channel
Simpang Pulai	Granite - III to IV	Igneous (Plutonic) & Metamorphic - Stream with seepage at banks and cliff at contact zone

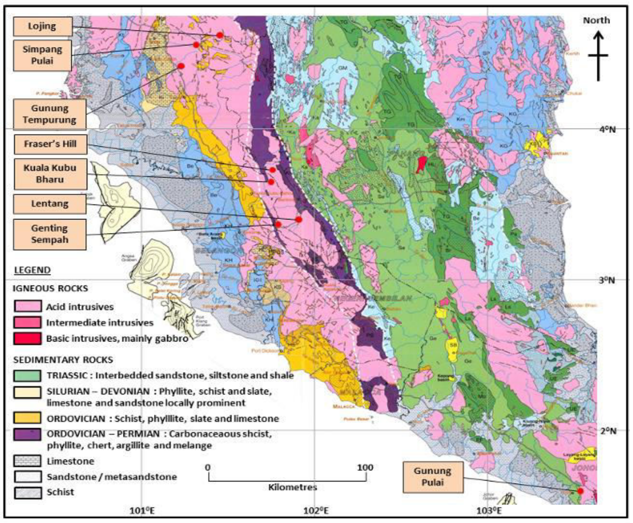

Figure-8. The debris-flow study locations superimposed on the geology map of Peninsular Malaysia [6].

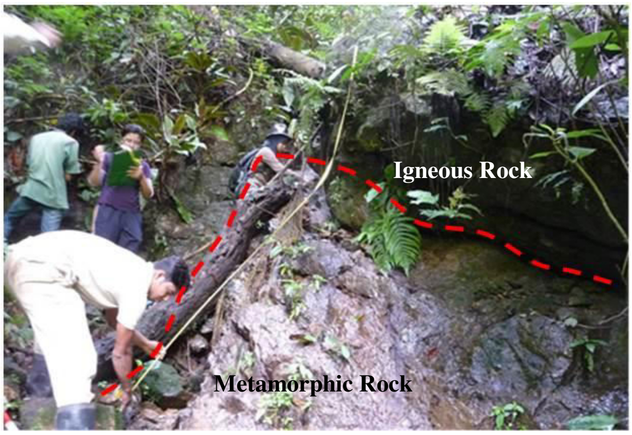

Figure 9a. Contact between igneous and metamorphic rocks at Genting Sempah.

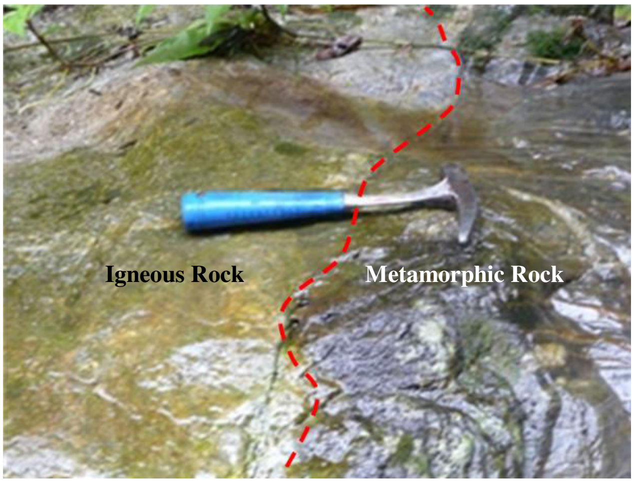

Figure 9b. Contact between igneous nd metamorphic rocks at Simpang Pulai.

In addition to the visual observations, the rock types were further confirmed by petrography tests conducted by Ghazali [7]. The tests indicated that 2 sites are underlain by igneous-volcanic rock while the others are of igneous-plutonic rock. Rocks obtained at some of the channels are confirmed to be metamorphic. Figures 10a to 10c show the petrography results for Genting Sempah and Gunung Tempurung indicating these rock types.

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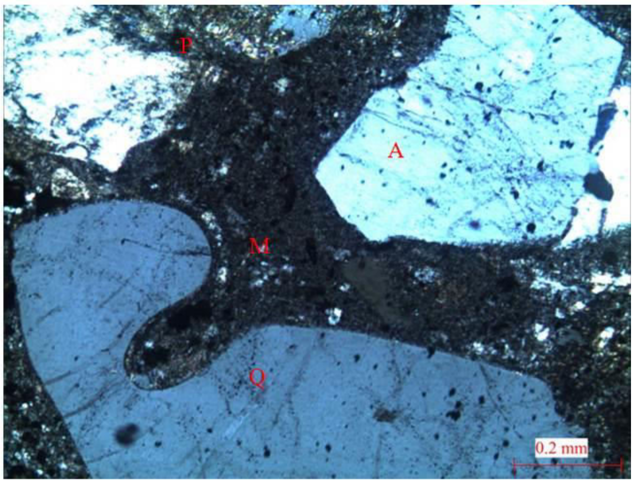

Figure-10a. Microscopic image of Genting Sempah - Quartz showing indentation on mineral indicating igneous volcanic rock. Q=Quarzt, P=Plagioclase, A=Alkaline Feldspar, M=Matrixs.

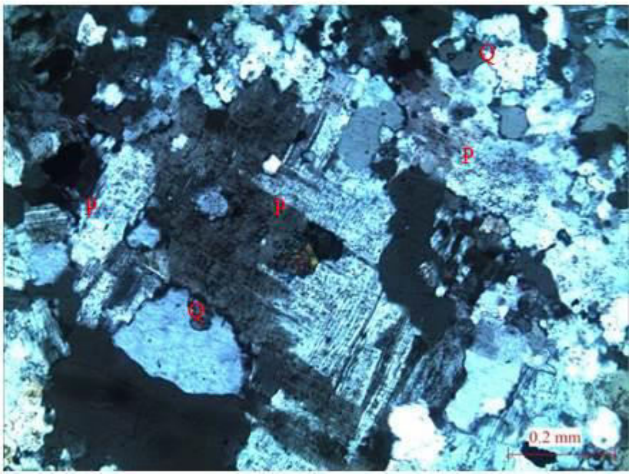

Figure-10b. Microscopic image of Gunung Tempurung - Subhedral plagioclase with polysynthetic twinning indicating fine grained igneous plutonic rock. Q=Quartz, P=Plagioclase.

Samples from hand augers obtained from various locations, e.g. scarps, initiation areas and deposition areas, were tested to obtain their physical properties and soil classification. The average values obtained from the initiation and deposition areas, as summarised in Table-5 suggests that regardless of the locations where the samples were obtained, the soils are predominantly silty sand, which is typical of weathered granite. Also included are the maximum boulder or cobble sizes observed. Knowing the grain size distribution and its details may suggest the flow density (and flow nature) and the material exchanges (incision or deposition) at various locations along the debris-flow channels (Li *et al.* 2015). Classification tests indicate an average liquid limit of 47% with the average plastic limit found to be the same as the moisture content, i.e. 30% (Table-6). The density of the solid particles is on average 2,640kg/m^3.

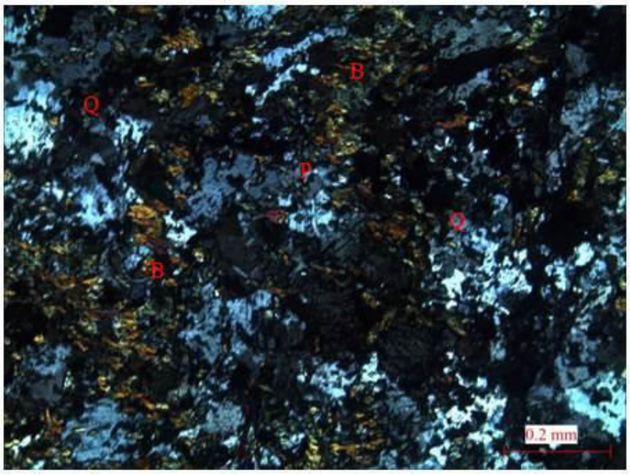

Figure-10c. Microscopic image of Gunung Tempurung - Presence of biotite as matrix besides quartz and plagioclase minerals indicating low grade metamorphic rock, i.e. phyllite. Q=Quartz, P=Plagioclase, B=Biotite.

Table-5. Average particle size distribution for soil samples taken from the initiation and deposition areas and the size of boulders and cobbles observed.

Site	% Gravel	% Sand	% Silt	% Clay	Rock Size (mm)
Fraser's Hill	8	47	29	17	500
Genting Sempah	17	48	22	13	380
Gunung Pulai	19	53	19	10	150
Gunung Tempurung	26	25	28	22	500
Kuala Kubu Bharu	0	50	26	25	200
Lentang	5	63	21	13	250
Lojing	8	47	29	17	300
Simpang Pulai	16	46	26	13	100
Average	12	47	25	16	298

Table-6. Average moisture content, specific gravity and Atterberg limits of soil samples.

Site	Moisture Content (%)	Specific Gravity, Gs	Liquid Limit (%)	Plastic Limit (%)
Fraser's Hill	34	2.65	52	30
Genting Sempah	24		42	29
Gunung Pulai	25	2.65	43	27
Gunung Tempurung	30		50	28
Kuala Kubu Bharu	29	2.64	55	30
Lentang	23		39	27
Lojing	34	2.65	52	30
Simpang Pulai	30	2.63	48	30
Average	29	2.64	47	29

Table-5 is the particle size results conducted on soil samples which were obtained from hand augers. Weathered granite, however, comprises of not just soil ranging from clay to gravel, but also cobbles and boulders which particle sizes are not normally determined in the laboratory. As such, particle size analysis using very large sieves, specially fabricated for this study, were conducted. For large boulders, they are randomly sampled and their dimensions measured. Figure-11 shows the sieve analysis conducted at Fraser's Hill and Figure-12 presents the result by combining the laboratory and field tests.

Figure-11. Particle size distribution determination at site using large sieves.

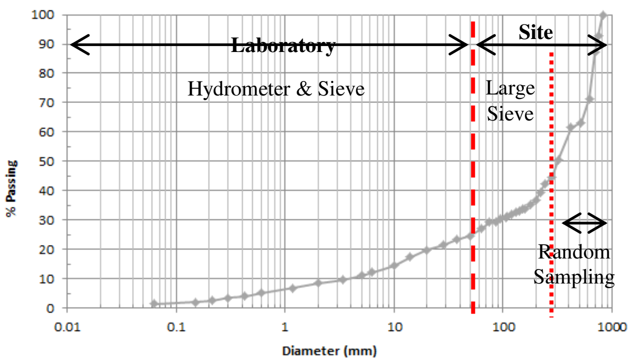

Figure-12. Result of a combination of particle size distribution determination in the laboratory and at site for Fraser's Hill.

Particle size distribution from this combined lab and field tests indicate that only about a quarter of the whole soil and rock formation, by weight, was determined in the laboratory. Cobbles from 300mm to boulders of more than 1m diameter, made up about 50% of the whole weight. This explains why debris-flows are so deadly especially so when they occur in granitic formation, .e.g. the Genting Sempah debris-flow which claimed 20 lives.

6. DEBRIS-FLOW MECHANISMS

Dikau *et al* [2] defined a 'flow', which could comprise of rock, debris or earth as classified by Varnes [26], as one of the landslide mechanism where individual particles travel separately within a moving mass. Takahashi [24] on the other hand refined it as a flow of sediment and water mixture driven by gravity with large mobility due to enlarged void space saturated with water or slurry. Three types of sources and initiation of debris-flow was given by Lorenzini and Mazza [20], and Takahashi [24] include those:

a) Induced by collapse of natural dam,

b) Induced by gully bed erosion,

c) Induced by landslide.

The most probable initiation mechanisms for the 8 sites are classified in Table-7 based on the following evidences:

a) Photographs, including aerial photos, taken immediately after the event and during the course of this study,

b) Relevant newspaper cuttings and case studies by other researchers,

c) Final site investigation report of this study [21],

d) Engineering geological maps prepared by [7].

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Table-7. Classification of debris-flow mechanism for the 8 study sites.

Site	Debris Material	Bed Erosion	Landslide Induced	Collapse of Dam
Fraser's Hill	Boulders		√	
Genting Sempah	Boulders & Tree trunks	√		
Gunung Pulai	Trees			√
Gunung Tempurung	Boulders & Tree trunks	√		
Kuala Kubu Bharu	Boulders & Tree trunks		√	
Lentang	Boulders & Tree trunks	√		
Lojing	Boulders& Trees		√	
Simpang Pulai	Boulders & Tree trunks	√		

Based on 3 case studies, including the one in Gunung Tempurung, Tan and Ting [25] suggested that the occurrence of a natural dam is an important requirement of Malaysian debris-flows. The debris observed are mainly of old dead woods which conformed to the existence and breaching of a natural dam after a heavy rainfall. A key feature of this debris-flow behaviour is the development of a high friction, coarse-grained flow fronts, pushed from behind by nearly liquefied, finer-grained debris [11, 12].

This study concluded that gully bed erosion is the most prevalent mechanism of debris-flow occurrences in Peninsular Malaysia. This is deduced mainly due to the eroded bed observed at the initiation areas. The narrow V-shape channel also makes it possible for rainwater to be concentrated in the channel and the debris to reach the roads or bridges, i.e. the elements at risk. The authors' believe that the breaching of natural dams along the flow path due to obstruction by boulders or tree trunks are likely to occur during the event, but this is not the main triggering mechanism. A good example is the Lentang debris-flow which recurred on 11th November 2015 whereby tree trunks were found within the debris. The engineering geological map produced based on the site investigation from 2nd till 5th June 2010, clearly shows at least 4 locations where the channel was obstructed by tree trunks (Figure-13). Within a period of 5 years more tree trunks might have fallen into the channel.

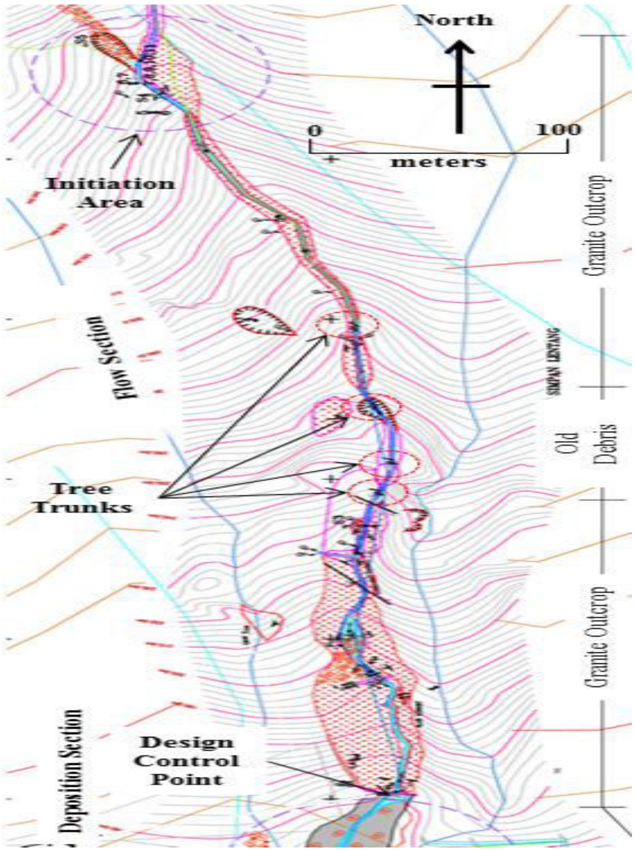

Figure-13. Engineering geological map for Lentang produced in 2013 [7] before the recurrence of another debris-flow at the same location in 2015.

As for the Gunung Tempurung debris-flow, although the study team was not able to reach the initiation area due a steep cliff, many tree trunks were found in the channel (Figure-14). Furthermore, an aerial photo taken immediately after the event, provided by the highway operator, clearly showed 2 initiation zones high up the hill. It is highly unlikely that both debris-flows which occurred almost at the same time were triggered by the collapse of identical natural dams.

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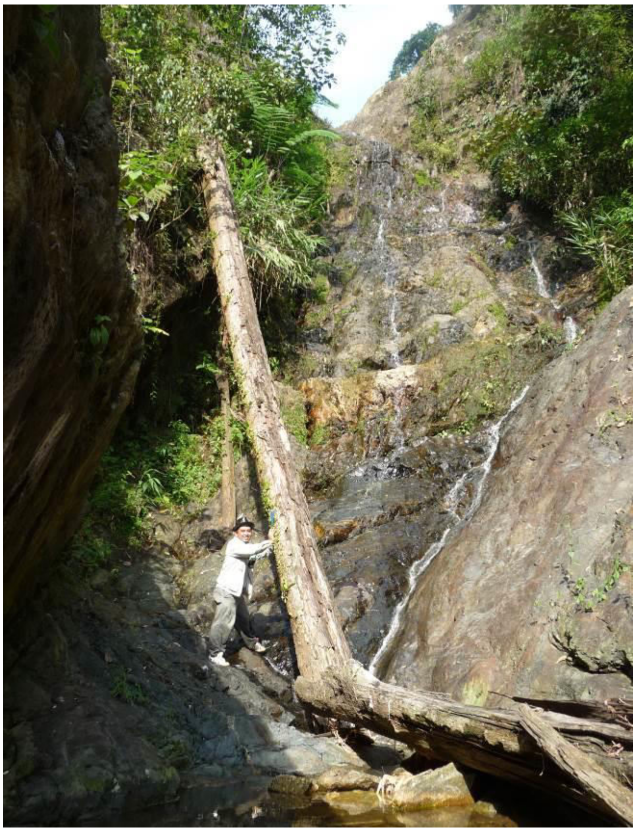

Figure-14. A tree trunk found in a debris flow channel at Gunung Tempurung. The initiation zone further upstream was not reachable due to the cliff.

Landslide induced debris-flows are considered probable when high seepage, or large failures (which might have been rectified) were observed at the initiation areas. Debris-flows for 3 out of the 8 cases studied are most probably landslide induced. The best example would be the Fraser's Hill debris-flow where several rotational slides occurred within a period of 8 months and severed 2 main roads (Figure-15). The flow rate measured from the horizontal drains during the repair work was 730cm^3/s. Another good example is the debris-flows Kuala Kubu Bharu with 2 separate initiation zones and channels which occurred simultaneously during an intense rainfall (Figure-16). The Lojing debris-flow has also been classified as landslide induced based on this study as shown in Figure-17. Although the debris from this event look saturated with tree trunks. A closer look into this photo and another photo taken during the clearing works reveal that the tree trunks are fresh, i.e. with green leaves, and the debris are not wet. The trees were most likely from the slopes along the road and the water was probably from surface runoff.
Collapse of natural dam is considered probable when one was found at site, Figure-18 for example. Another good indication is that the occurrence would probably cause flooding downstream. During the Gunung Pulai debris-flow event, which was triggered by the Vamei Typhoon, tree trunks obstructed the river flow underneath a bridge causing a flash flood comprising of mud and tree trunks which claimed 5 lives.

Figure-15. Several rotational slides which transformed into debris-flows at Gap-Fraser's Hill road.

Figure-16. Two landslide induced debris-flows which were stabilized using soil nails.

Figure-17. Debris deposited at the road at Lojing comprising boulders and tree trunks.

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Figure-18. A natural dam which comprise of boulders and tree trunks was discovered during the site investigation at Gunung Pulai.

7. ESTIMATED SEDIMENT DISCHARGE

Debris-flow hazards are primarily determined by the volumes of debris that reaches the elements at risks. The fundamental factors and characteristics that control the volume and the travel distance of debris-flows are discussed by Japan Geotechnical Society [14]. The basic procedures for estimating the volumes are given in guidelines such as those published by Department of Public Works and Highways and JICA [1]. The procedures proposed by the Japanese guidelines are used in estimating the volume of the debris-flow using topographic data, characteristics of sediments, channel's bed gradient and rainfall data. It can be used, without numerical simulations, in prioritizing the sites that need mitigation measures. Numerical simulations for detail analysis of travel distance and deposition depth may be performed for the sites that are classified as high risk after the first screening stage. The procedures are described in Japanese in the "Manual of Technical Standard for Establishing Sabo Plan for Debris-flow and Driftwood," Technical Note of Japan National Institute for Land and Infrastructure Management, No.364 [15].

The volume of debris-flow (or sediment discharge) for designing countermeasures is referred to as the "design sediment discharge," which is determined based on the results of the field survey, study of topographical maps and the records of the past debris-flow events. The sediment discharge is taken as the smaller of the following two estimates so that the results are not overly conservative for design purposes [1]:

a) Total movable sediments (V_{dyl}) in the catchment area: the total volume that may move by a series of events. The estimate is based on field investigations and topographic maps.

b) Probabilistic volume of sediments (V_{dy2}) per event: the volume transported in one event of debris-flow with specific return period.

The following major steps are generally applied to estimate the volume of harmful debris-flow which refers to the debris that can cause causalities and damage to properties. The volume of debris that does not pose any threat is considered harmless and excluded from the volume to be captured by barriers and dams.

Step 1: Estimate the catchment area,
Step 2: Determine the areas to be protected,
Step 3: Define the return period of the rainfall intensity for planning the mitigation
Step 4: Determine the control point. The design control point is defined as the location where debris will pass and is usually set in the upstream of the area that need to be protected (Figure-19).
Step 5: Estimate the amount of debris-flow at the control point

Total movable sediments (V_{dyl}) in the catchment area is calculated as follows. The parameters in the equations are estimated by field investigations and topographic maps to evaluate gradients and stream orders. If the sediment discharge data from the past events are available, recorded data may be used for V_{dyl}. The total movable sediments in the catchment (V_{dyl}) is:

$$V_{dyl}=V_{dyl1} + V_{dyl2} \quad (1)$$

$$V_{dyl1}=A_{dyl1} \text{ x } _{Ldyl1} \quad (2)$$

$$A_{dyl1}=B_d \text{ x } D_e \quad (3)$$

where,
V_{dyl}: total movable sediment load (m^3) in the basin area
V_{dyl1}: movable bedload (m^3) in the channel, starting from the control point to the upstream end of the first-order channel
V_{dyl2}: potential sediment volume due to slope failures (m^3)
A_{dyl1}: mean cross-sectional area of movable bedload ($m^{2)}$
L_{dyl1}: distance along the channel to the upstream end of the first-order channel (m) from control point (Figure-19)
$B_{d:}$ mean channel width erodible by debris-flow
D_e: mean depth of bedload erodible by debris-flow

The probabilistic or calculated volume of sediments (V_{dy2}) transported by water with specified rainfall depth is computed by the following equation:

$$V_{dy2} = \frac{10^3 \cdot P_p \cdot A}{1-K_v}\left(\frac{C_d}{1-C_d}\right)K_{f2} \quad (4)$$

where,
C_d: debris-flow concentration
$P_{p:}$ rainfall depth (mm)

A: catchment area (km^2)
K_{f2}: runoff correction ratio
K_v: void ratio.

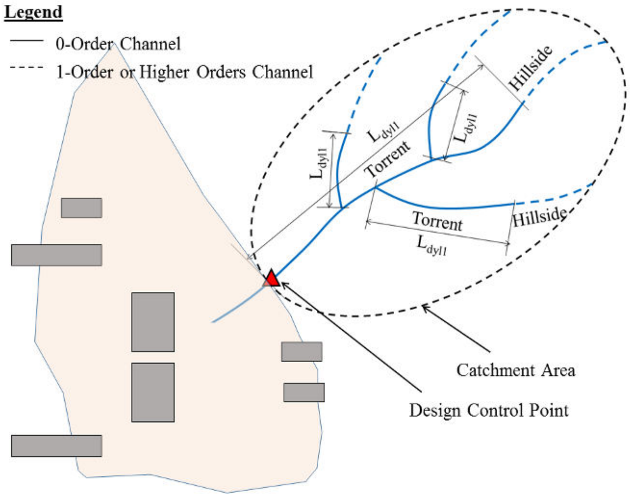

Figure-19. Schematic illustration for design control point and L_{dyl1}.

In determining Pp, the regional-specific rainfall characteristics should be taken into account. Generally 24-hour rainfall is applied to this. The void ratio (K_v) is in general set to 0.4. K_{f2} represents the runoff correction factor which can be calculated using the following equations:

If $A < 0.1km^2$: $K_{f2} = 0.5$ (5)

If $A > 0.1km^2$: $K_{f2} = 0.05\,(\log A - 2.0)^2 + 0.05$ (6)

Debris-flow concentration is computed with the equilibrium concentration equation:

$$C_d = \frac{\rho \tan\theta}{(\sigma - \rho)(\tan\phi - \tan\theta)} \quad (7)$$

where,

σ: density of solid particles (around 2,600kg/m3, in this analysis the specific gravity values in Table-6 are used)
ρ: density of interstitial fluid (around 1,200kg/m3)
φ: internal friction angle of the bedload (usually between 30º and 40º, 35º is typically used)
θ: channel bed gradient (degrees, refer to Table-2)

This equation is called the Takahashi's [23] formula and is typically applied to a bed gradient of 10^o to 20^o. The guidelines specify the upper and lower bounds for the debris-flow concentration, C_d. It is set to 0.9 and 0.3 if the calculated value is higher or lower than these values, respectively.

The total movable volume (V_{dyl}) is taken as the sediment in the channel measured during site investigation. This represents the maximum possible sediment that can be discharged from the channel. The probabilistic sediment that could be discharged (V_{dy2}) are computed for all the 8 sites using the same daily rainfall of 100 mm/day, which is slightly higher than the average 24hrs rainfall of the 8 events, since rain fall intensity with specific return period for each site is not known. As there is only 1 site with an average bed gradient between 10^o to 20^o, a value of C_d equals to 0.6 is used for all the sites.

In addition, the potential volumes are calculated, using the lower and upper bound volume per unit of catchment area according to Table-8, which are based on geological formation. Among the different types of geological formation, weathered granite, although prone to debris-flow, has a lower discharge per unit of catchment area.

Table-8. Sediment discharge per area for different geology in Japan (After Japan Geotechnical Society [14]).

Sediment Volume per Event (m^3/km^2)		
Formation	**Lower Bound**	**Upper Bound**
Granitic rock	50,000	150,000
Volcanic rock	80,000	200,000
Tertiary deposit	40,000	100,000
Heavily fractured rock	100,000	200,000

Results of these calculations are summarized in Table-9 and plotted on Figure-20 for comparison. Except for Fraser's Hill, the sediment discharge values per unit of catchment area are relatively low. Only Fraser's Hill has movable sediment, based on the site investigation, which is higher than the calculated value using the above equations and also slightly higher than the upper bound value proposed by [14]. The large difference compared to the other sites is most likely due to the fact that the debris-flow at Fraser's Hill was actually induced by several large rotational slides. In order words, unlike the other sites, the volume measured for Fraser's Hill was from multiple events of landslides. Based on the chronology of events documented by [7], there were at least 8 large slides that occurred from 16th November 2007 till 3rd July 2008, prior to the site investigation conducted under this study.

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Table-9. Estimated sediment discharge (m^3) from various methods.

Site	Movable Sediment in Catchment, V_{dy1}	Calculated Sediment Discharge, V_{dy2}	Lower Bound for Granite	Upper Bound for Granite
Fraser's Hill	37,522	21,739	10,700	32,100
Genting Sempah	2,723	27,941	15,250	45,750
Gunung Pulai	50,163	136,720	175,500	526,500
Gunung Tempurung	4,508	26,310	14,000	42,000
Kuala Kubu Bharu	5,196	22,172	11,000	33,000
Lentang	2,590	19,200	9,000	27,000
Lojing	3,789	25,643	13,500	40,500
Simpang Pulai	1,752	30,763	17,500	52,500

The low correlation factor for V_{dy1} in Figure-20 is mainly due to the data from Fraser's Hill. If V_{dy1} is divided by 8 for this particular site, so that it corresponds to the value per event, similar to the other sites, a much higher correlation factor is obtained as shown in Figure-21. The sediment volumes based on the site investigations could be considered as the design sediment discharge volume per event (V_{dy}) as the values of movable sediment in the channel for all sites (V_{dy1}) are lower than those calculated using equation (4) (V_{dy2}).

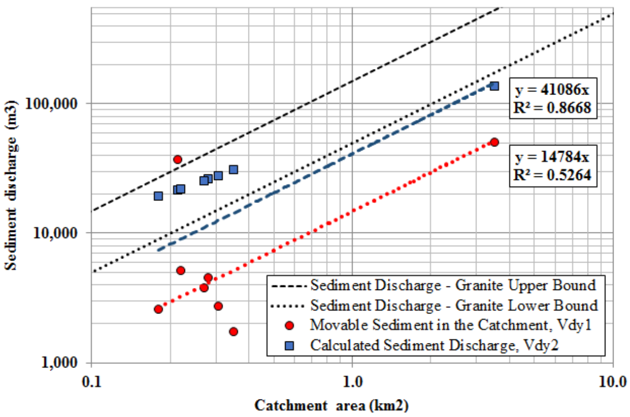

Figure-20. Estimated sediment discharge based on various methods.

Also plotted in Figure-21 are the sediment discharge values for debris-flows in Japan. Similar to the values for the 8 sites in Peninsular Malaysia, most of the data in Japan also show values which are much lower than the lower bound for granite as recommended in Table-8. The trend of the data in Japan is also very similar to the data from this study, i.e. increasing trend with larger catchment area. The dashed vertical lines represent the range of catchment area, i.e. 0.07km^2 to 6km^2, for 80% of the data in Japan. Debris-flow rarely occurs in catchment areas which are too small as water from the rain will not be sufficient to trigger one. It is also rarely triggered in a large catchment, as the water will be dispersed and not having the required concentration. In Malaysia, debris flow in large catchment areas had only occurred most probably twice since the 1990s. In both cases, i.e. at Keningau and Simpang Pulai, they were caused by typhoons which rarely pass through Malaysia.

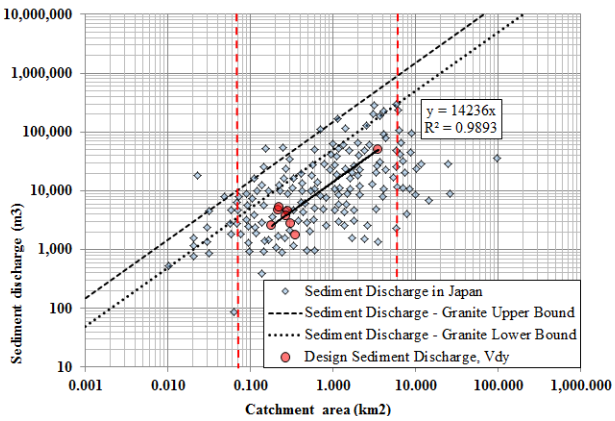

Figure-21. Design sediment discharge per event for the 8 sites compared to the trend in Japan.

8. CONCLUSIONS AND RECOMMENDATIONS

Results of the 8 case studies in Peninsular Malaysia indicate that topography and geology are the major influential factors for the initiation and deposition of debris-flows. The average gradient of the main channel, measured as the angle from the road to the initiation point, ranges between 10^o to 39^o with an average value of 26^o while the gradient at the initiation areas ranges from 22^o to as high as 50^o with an average value of 37^o. Signs of deposition were observed where the channel's bed gradient is close to 10^o. These findings concur with the trend in Japan where generation would probably occur on slopes steeper than 15^o and deposition would probably take place on gentler slopes. A V-shape channel which was observed at almost all the sites is also believed to be one of the important triggering and sustaining factor for debris-flow. Rainwater would easily be concentrated in the channel triggering bed erosion or landslide and the debris would be able to reach the elements at risk or design control point. The catchment area for the 8 sites ranges from about 0.2km^2 to 3.5km^2 which is similar to the range where debris-flows have occurred in the USA and Japan.

All of the debris-flow occurrences in this study initiated in granitic formation and are adjacent or close to metamorphic formation. The soil type is predominantly silty sand which is typical of weathered granite. The actual particle size distribution, however, when large particle sizes are also considered comprise of 75% cobbles and boulders.

Based on the engineering geological maps and photographs taken immediately after the event and during this study, it is deduced that the main debris-flow mechanism for Peninsular Malaysia is gully bed erosion. The natural dams which comprise of boulders and tree trunks that might have been breached during the event should not be considered as the triggering mechanism. The debris-flow at Gunung Pulai, however, is classified as a collapse of natural dam, as such dam was discovered within the channel and the event did cause flooding downstream. Another mechanism that is likely for Peninsular Malaysia is landslide induced debris-flow. A good example is the one in Fraser's Hill which was induced by several large rotational debris slides.

Sediment discharge volumes estimated from field investigation, although relatively lower than what is proposed by the Japanese Guidelines are well within the trend and values in Japan. Based on the 8 sites investigated, a sediment volume of 14,200m^3 per event per km^2 of catchment area may be used for design and hazard assessment purposes. It should be noted, however, that the catchment area for 7 out of the 8 sites are about equal. Only Gunung Pulai has substantially larger catchment than the others. As such, for a more accurate estimate, more sediment discharge data based on different catchment areas are required.

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