Debris Flow Numerical Simulation Model Comparison with Field Events in Kuala Kubu Baru and Lentang, Malaysia

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Abstract. Debris flow is one of Malaysia's natural disasters which could cause casualties and serious infrastructure damage. Precisely predicting the factors associated with the occurrence of debris flow such as the run-out lengths, velocities and thickness of alluvial deposits can greatly mitigate damage, minimize or even avoid the aftermatts of the occurrence. Applying numerical simulation models explaining debris flow deposition would be a valuable tool in forecasting potential debris flow activity and providing criteria for designing protective measures. Comprehensive studies of available records of past debris flow events from relevant sources and site investigations have been carried out in order to assemble field information for the particular debris flow event in Malaysia. A number of calamitous debris flow events occurred in Malaysia have been closely observed and studied. The well-documented events, i.e. Lentang and Kuala Kubu Baru debris flow disasters occurred on 2nd November 2004 and 10th November 2003, respectively were simulated using the Kanako 2D (Ver.2.04) simulation model software. The results obtained from the numerical simulation model were compared with the real events in order to evaluate their predictive capabilities. The results showed an accuracy of more than 93% was obtained from the simulation model as compared to the real in-situ measurements. A positive simulation result will become a valuable method to predict potential debris flow hazard behavior of the same type and characteristics.

1. Introduction
Debris flow is a geomorphological hazard that usually occurs in mountainous areas and capable of washing down houses and infrastructures with sudden and fast-moving mixtures of water, sediments, woods and large boulders. Subsequently, the catastrophes eventually resulted in casualties and damage to properties. The two basic criteria for debris flow initiation are the presence of loose abundance debris, and the high rainfall intensity [1]. Malaysia is a tropical area that receives heavy rainfall nearly all year round. The rainfall is mostly brief and intense, while prolonged rainfall occurs annually during two monsoon seasons, namely from May to September known as the Southwest Monsoon and from November to April known as the Northeast Monsoon. Most of the major debris flow events in Malaysia occurred in November and December during the wet period of the year.
A number of calamitous debris flows have been reported in Malaysia. Incidents of debris flow in Malaysia are investigated and recorded only when human lives or infrastructures are impacted. Since 1994 until present, there have been at least 15 incidents of killer debris flow tragedies whereby at least 137 people have been killed [2]. Research on the after-disaster investigation related to debris flows in Malaysia is currently still very confined within the areas where the debris flow has occurred. Estimating the runout distances, velocities, flow depths and volumes of alluvial deposits on fans plays a major role in assessing the hazards from debris flows and is capable of mitigating calamities, minimizing or even avoiding the impact due to the occurrence of the incident. Velocities and flow depths are the factors that need to be evaluated for designing structural counter measures. The travel distance, which is controlled by the gradient, and the volume of the debris are amongst the critical factors that determine the extent of damages [3]. Assessing the debris flow distance travelled from the initiation of the deposits to their lowest point on an alluvial fan is of utmost importance to delineate the areas at risk due to the flow of debris [4].

Numerical models for describing the progression and deposition of debris flows have been developed. These models require detailed field data before they can be applied, as each model must be calibrated for predictive purposes before it is practically useful. The use of computational simulation models that portray the deposition of debris flow would be a valuable method for forecasting possible future debris flow behaviour [5]. However, most of the current models have not been adequately checked with real field events. The lack of research is due to the lack of input criteria, such as topographical and hydrological data [6]. Accurate delineation of the channel and fan topography is required to obtain a good replication of the observed deposition pattern. In this study two locations of debris flow event in Malaysia were analysed. The Kanako 2D model is used to compare the calculated volumes of debris that were generated, transported and deposited with those estimated by the field investigations or with the records made at the time of the event. To test the computational simulations predictive capabilities of debris flow, their results were correlated and compared with the field events.

2. Study Area

Based on the geological map of Peninsular Malaysia published by Malaysian Department of Meteorology, the two selected study sites, namely Kuala Kubu Baru and Lentang debris flow areas are geographically located at the latitude 30° 38’ 07.4” North and longitude 101° 44’ 28.4”, and latitude 30° 23’ 43.2” North and longitude 101° 53’ 23.9”, respectively. They are placed within the Main Range Granite, part of the granite body that is classified into the late Mesozoic Orogenic granite (Figure 1). The sites are primarily underlain by granite with varying grades of weathering.

Figure 1. (a) Geological Map of Peninsular Malaysia. Location of (b) Kuala Kubu Bharu and (c) Lentang (Source from Meteorology Department of Malaysia)
2.1. Kuala Kubu Baru
Kuala Kubu Baru debris flow occurred on 10th Nov 2003. The catastrophe had caused damage to the main road linking two districts and the road was closed to all vehicles for 15 days for debris clearing. The stream along which the debris flow occurred has an average gradient of about 33° and flows within a narrow valley ranging from 1 to 6 m wide while the hill slope on both banks of the stream generally has gradients between 44° to 46°. The debris flow elevation, ranging from 550 m to 670 m, covers the length of approximately 200 m. With catchment area of 0.2 km², the total volume of the transported material has been estimated to be about 3,990 m³ comprising boulders in various sizes, mud, and tree trunks. These materials were deposited on the road and had caused the road shoulder to collapse. The average size of boulder is 0.1 m.

Some parts of the area at the valley are covered mainly by colluvium and talus. The terrain is covered by Phyletic rocks, which is formed by various metamorphism activities. The phyletic rocks were uplifted due to tectonic activities. The exposed rock outcrops are predominantly of Porphyritic Granite, with fine to coarse grain sizes. The weathering grade in the initiation area is V and VI. There were no exposed boulders in this area. The soil types found in this site are of Sandy Silt, Silty Sand and Sandy Silt. An average thickness of soil layers with the potential for failure is between 3.0 m to 3.3 m, as determined by the Mackintosh Probe test with 100 blows. The maximum elevation is 667 m a.s.l and the total run-out distance has been measured to be as high as 195 m from the point of initiation to the toe of deposition.

2.2. Lentang
Lentang debris flow occurred on 2nd Nov 2004 during the Northeast Monsoon season. The disaster had caused temporary closing of the Karak Highway, heading towards Kuala Lumpur. The MTD Prime Sdn. Bhd. highway authority took a few days to clear the whole site of dirt, rocks, and timber. This incident occurred on a slope towards Kuala Lumpur at KM 52.4. Debris is believed to have originated upstream and then gushed down the channel and flowed onto the road. The stream along which the debris flow occurred has an average gradient of about 35°. It has a narrow valley ranging from 2 m to 10 m while the hill slope on both banks of the stream generally has gradients between 30° to 45°. Near the downstream area, the slope is very steep with gradient reaching to 30°. The debris fall from the 160 m and 350 m elevations occupies the total length of out about 550 m. The estimated amount of debris moved was 2,600 m³. The average size of boulder is 0.1 m.

Fine to medium grain granite is the type of outcrop that is exposed at the site. The outcrop exposed during observations is weathered granite of grade II to III. The existing channel system is large and decreasing in size downstream. Water seepage was found in the left channel facing upstream. There is an upstream channel with no water and there are relatively small size boulders compared to those found downstream. Tectonic activity is quite composite in this area which has resulted in the formation of fault structures such as the Bentong fault and meta-sediment rock in the surrounding area. Weathering grade upstream is between III to IV and the boulders were very loose.

Debris flow consisted mostly of water and gravel without many large boulders, as no damage to the trees was found in the channel. The debris spilled out to the road with driftwoods and gravels content. Sabo dam was already built before the debris flow incident occurred. Flash flood type of flow may have occurred in the upper stream, washing out the fan deposits in the area from the first Sabo dam to the end of the channel.

3. Method of Numerical Simulation Model
Kanako is a debris flow simulation modeling algorithm fitted with a graphical user interface (GUI) to simplify the numerical computational analysis and to be more user-friendly when simulation is being carried out [7][8]. In order to simulate the debris flow event, KANAKO 1D and KANAKO 2D have been used. KANAKO 1D is a one-dimensional model that considers only the upstream and downstream directions of the river model and reproduces the flow and piling up progression of the debris. Figure 2a and Figure 3a show the elevation of the debris flow and the upstream distance from the debris flow. KANAKO 2D is used for the alluvial fan area. Figure 2b and Figure 3b show the road as alluvial fan
area impacted by the debris flow. In general, to perform simulation of debris flow occurrence, fundamental and preliminary investigation data are needed to prepare the input data. Simulations are usually performed in two stages: (1) performing reproduction simulation to calibrate the input data such as hydrograph; (2) performing predictive simulation to assess the risk in case of rainfall occurrence with specific return period of interest. In some cases, a third step is required to check the effectiveness of counter measures such as the provision of Sabo dams.

The basic 2-D debris flow equations are shown below. The same equations are applied in 1-D debris flow simulations, without the terms of y-axis direction. The equations on momentum, equations on continuation, equations on riverbed deformation, equations on erosion/deposition, and riverbed shearing stress are referred to [9]. The staggered scheme and variables arrangement are utilised based upon [10].

The continuation equation to account for the total volume of debris flow is:

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = iz$$  

(1)

Here, all the sediment material average grain-size includes both groups of larger and smaller grain-size ones. The x-axis flow phenomenon (flow-direction) utilises a momentum equation as follows:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial H}{\partial x} - \frac{\tau_x}{\rho h}$$  

(2)

Where $H = h + z$

The y-axis direction of flow phenomenon (cross-direction) uses an equation of momentum, as follows:

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial H}{\partial x} - \frac{\tau_y}{\rho h}$$  

(3)

To determine the difference in the bed surface elevation, the equation is as follows:

$$\frac{\partial z}{\partial t} + i = 0$$  

(4)

Referring to (1) through (4), h is flow velocity, u is flow velocity in the x-axis direction, v is flow velocity in the y-axis direction, z is bed elevation, t is time, i is erosion/deposition velocity, g is acceleration due to gravity, $\rho$ is interstitial fluid density, $C*$ is sediment concentration by volume in movable bed layer, and are the x-axis and y-axis directions of riverbed shearing stresses, respectively.
4. Results and Discussion

4.1. Kuala Kubu Baru

Figure 4 shows the simulation result that indicates a reasonable difference in value when the volumes estimated by the field investigation are compared to those obtained from the simulation. About 4,270 m$^3$ of total sediment discharge volume passed through the alluvial fan as obtained from the simulation while field data was estimated to be approximately 3,990 m$^3$. The accuracy of the result obtained from the simulation model is about 93 percent as compared to the real in-situ measurements. Conversely, there are slight differences in the volumes obtained. The differences may be due to the estimated geometry values that are being used during simulation.

From the simulation, the deposit tends to occur when the gradient of profile moves from steep to gentle area. Volume of sediment at each calculation point can be obtained from the simulation which shows either a deposition or erosion takes place in the channel during debris flow event. From Figure 4, there are two points of major deposition when the slope gradient decreases which is at 582 m accumulating about 15 m$^3$ of sediment and 558-567 m gathering about 316 m$^3$ of sediment.

From the simulation it shows that after running out of the channel outlet, the debris flows occur in the entire region of the alluvial fan. The maximum sediment thickness is situated at the entrance of the alluvial fan with a thickness of more than 3 m (Figure 5). This indicates that during debris flow incident, roads certainly impassable because they have been filled with 3 m thick of sediments. The alluvial fan area is a narrow road and based on the simulation, at least a 0.04 m flow depth and a maximum flow depth of 0.25 m passes the road (Figure 6).
Figure 4. Volume passed to alluvial fan for Kuala Kubu Baru event

Figure 5. Variation of sediment thickness at Kuala Kubu Baru alluvial

Figure 6. Flow depth at Kuala Kubu Baru alluvial fan area

4.2. Lentang

Figure 7 shows the result obtained from the simulation that indicates a reasonable difference in values when the volumes estimated by the field investigation are compared to those obtained from the simulation. About 2,543 m$^3$ of total sediment discharge volume passed through the alluvial fan as obtained from the simulation while field data calculations estimated approximately 2,590 m$^3$. The accuracy of the result obtained from the simulation model is about 97 percent as compared to the real in-situ measurements. Conversely, there are slight differences in the volumes obtained. The differences may be due to the estimated geometry values that are being used during the simulation.

From the simulation, it can be seen that the deposits tend to occur when the gradient of profile moves from steep to gentle area. Volume of sediments at each calculation point can be obtained from the simulation which shows either a deposition or erosion takes place in the channel during debris flow event. There are six points of main deposition that had occurred which are at: i. 312 m elevations (99 m$^3$), ii. 273 m elevations (210 m$^3$), iii. 250 m elevations (119 m$^3$), iv. 233 m elevations (55 m$^3$), v. 195
m elevations (1042 m$^3$), and vi. 177 m elevations (134 m$^3$) that indicated the gradient suddenly changes to gentler slope (Figure 10). This shows that sediment deposition dominates the entire process of debris flow movement from upstream to downstream.

From the simulation, it shows that the debris flow occurs in the whole area of the alluvial fan after running out from the channel outlet. The maximum sediment thickness is in the range of 1.5 - 1.8 m and located at the outflow of the channel (Figure 8). This indicates that during debris flow incident, road certainly impassable because have been filled with 1.8 m thick of sediment. The alluvial fan area is a 4-lane highway, and based on the simulation, all four lanes will be hit with a flow depth of at least 0.04 m and a maximum depth of more than 0.25 m occurs at roadside drainage (Figure 9).

![Figure 7. Volume passed to alluvial fan for Lentang event](image)

![Figure 8. Variation of sediment thickness at Lentang alluvial fan area](image)

![Figure 9. Flow depth at Lentang alluvial fan area](image)
5. Conclusion
Results obtained from the reproduction simulations have demonstrated a reasonable performance of the simulation model and provide a useful mechanism and outputs that will help in the assessment of the risks as well as in the planning and to provide preventive measures whether in the form of structural or non-structural measures. By comparing between the developed and present numerical models with real events, a reliable decision can be made in evaluating the most suitable and accurate model to determine the total discharge volume, run-out distance, flow depth and thickness of alluvial deposited.

KANAKO Numerical Simulation Models provide comparable and good results in order to predict discharge volume, run-out distance, flow depth and deposits thickness. The results showed an accuracy of more than 93% was obtained from the simulation model as compared to the real in-situ measurements. Hence, simulation by KANAKO has been successful in showing the amount of sediment volumes and processes of deposition and erosion along the channel. Consequently, KANAKO Numerical Simulation Models are suggested to be used as a tool for predicting the behaviour of future debris flow hazard of the same nature and characteristics.

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