

## LANDSLIDES AND DEBRIS FLOWS AT KHAO PHANOM BENJA, KRABI, SOUTHERN THAILAND

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**ABSTRACT:** A detailed investigation of the characteristics of the 2011 catastrophic landslides of Khao Phanom Benja, Krabi, Thailand was conducted. The landslides on the slope faces of the high relief granitic mountain led to devastating debris flows of large rock boulders that buried houses in the foothill area. The unfavorable orientations of four major joint sets of the mountain created high kinematic instability of rock wedge slides along the stream channel direction as well as rock wedge formation on the channel walls in the eastern sides of the mountain. Weathering and joint opening in the areas of slopes and stream channels increase the vulnerability of rock slides, in particular for a prolonged heavy rainfall. The heavy rainfall and stream channel flow on slab block of rock slope erosion along stream bank caused down bank slope failure. The increasing upward water pressure caused the increase in uplift force behind the rock block and rock wedge failure. In addition, the hazard zone delineation of debris flows deposition was mapped out using a MATLAB codenamed as FLOWS. Majority of slides on the eastern slopes of the mountain were granitic rock slide modes while soil slide and surface erosion on the residual soil to completely weathered sedimentary rock were the predominant modes of failure on the western and northern slopes in lower areas at foothills of the mountain. As found in this investigation the factors influencing landslides and debris flows in 2011 at Khao Phanom Benja, Krabi, southern Thailand were not only limited to the prolonged rainfall but also to slope gradient, rock types and weathering degree, discontinuity characteristics.

**Keywords:** *Landslide, Debris flow, Rock failure, Rock discontinuity*

### 1. INTRODUCTION

The most dangerous devastating landslide is debris flow of which slope materials become saturated with rainwater resulting in slope failures and mass movement by flowing water along streams towards foothills. In Southern Thailand Peninsula, the reported incidents of catastrophic landslides and debris flows have increased significantly in recent years owing to increased human settlement and land use changes in hilly areas. Landslides and debris flow occurred mostly after periods of heavy rainfall, such as the debris flow event of Ban Kratoon of Nakhon Si Thammarat Province in 1988 that claimed 373 lives and property damages around US\$ 280 million [1,2]. Subsequently, incidents of landslides in Southern Thailand have been frequently reported. In 2011, disastrous landslides and debris flow occurred again. Exceptionally heavy rainfalls in the late rainy season caused widespread slope failures in neighboring Surat Thani, Nakhon Si Thammarat and Krabi provinces. Numerous villages in these provinces were damaged by debris flows with the most affected area being around the Khao Phanom Benja National Park of Krabi Province as shown in Fig.1, where a lot of slope failures on the steep mountain slopes of granitic rocks led to destructive debris flows along stream channels and alluvial fan as shown in Fig. 2.



Fig. 1 The study location at Khao Phanom Benja

The characteristics of the debris materials suggested that their sources were predominantly from rock slope failures rather than soil slope failures as commonly reported in early cases of a landslide in Southern Thailand. The incident of the 2011 catastrophic debris flow at Khao Phanom Benja was not the first time. Similar incidents occurred in the past and the last one occurred 50 years ago in 1962. This paper presents the results of the investigation in term of geological structures, causes, characteristics of landslides and debris flows that occurred in this high relief mountain area.



Fig. 2 Debris flow looking upstream at the outlet

## 2. INVESTIGATION AREA AND GEOLOGIC SETTINGS

Khao Phanom Benja is a high relief mountain that lies in a north-south direction. The highest peak is at 1,397 m above MSL where steep rock cliffs of granite exist with no vegetation cover.

The investigation area covered approximately 120 km<sup>2</sup>. Field investigations were concentrated in two areas that were worst affected by the 2011 debris flows incidents, namely Ban Tonharn on the eastern side and Ban Huynumkeaw on the northern side. The mountain was formed by the intrusion of Cretaceous granitic rock through the Permian-Carboniferous sedimentary rocks. A brittle strike-slip fault (strike N5°E) associated with the regional Klong Marui Active Fault traversing Khao Phanom Benja on its western side is shown in Fig. 3. The Klong Marui Fault was a major strike-slip ductile fault zone (strike N35°E) associated with the tectonic plate movement in the Indo-China plate resulting from the collision between the Indian and Eurasian plates during the late Cretaceous to Tertiary Periods [3]. Therefore, the study area was strongly tectonized and the rocks of the Khao Phanom Benja can be expected to consist of numerous fractures and joints that promote weathering process of the mountain slopes as well as landslides. The field investigation indicated that the center area of the mountain consists mostly of steep slopes (30-60 degrees) of granitic rocks flanked by sedimentary rocks on eastern and western sides. Dikes and veins of pegmatite, apatite and quartz are also encountered sparsely in the granitic and sedimentary rock masses. The rocks are mostly fractured with several joint sets affected by granite intrusion and subsequently regional tectonic fault movement.

Mapping of geologic discontinuities along the stream channels and landslide scars revealed orientations of predominant joint sets in the granitic rocks as summarized in stereonet plot in Fig. 4 as well as marked in the geologic map in Fig. 5. It can be seen that there are four major joint sets of

moderately and steeply dipping existent in the mountain slopes.

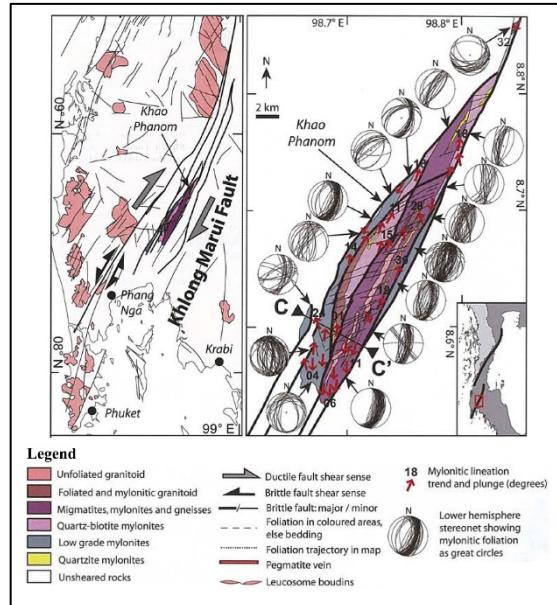


Fig. 3 Khao Phanom Benja and discontinuities mapped at Klong Marui Fault at Khao Phanom, Phang Nga (after Morley et. al. 2011)

The two conjugated sets of steeply dipping (60-80° to East) with a strike more or less in N-S direction. The two sets of moderately dipping (40-50° to N-S direction) with a strike in more or less E-W direction. It is noted that the steeply dipping set with a strike of N5°E is of the same direction with the major fault zone traversing Khao Phanom Benja and the steeply dipping cliff faces of the mountain on the eastern slope are of the same orientation of this set. The orientations of the four major joint sets promote the formation of the cliff face and plane slide of rock blocks toward the east direction and formation of rock wedges along the stream channels flowing eastward and on the channel banks.

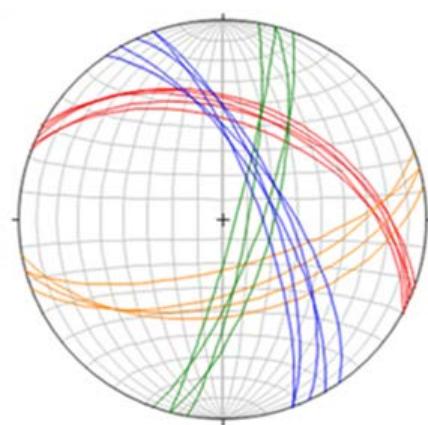


Fig. 4 Major joint sets in granitic rocks

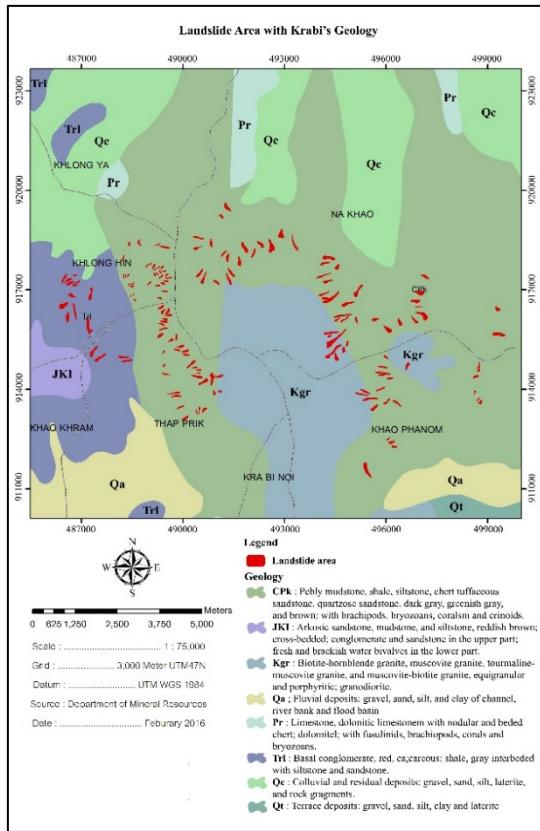


Fig. 5 Geological map of Khao Phanom Benja

### 3. GEOLOGICAL AND ENGINEERING PROPERTIES OF SLOPE MATERIAL

The assessments of geological engineering properties of slope material by field investigations were carried out at various sites. Disturbed and undisturbed samples were collected for laboratory and field tests, including Schmidt hammer, penetration, direct shear, uniaxial compressive strength, index properties and thin section analysis that were conducted to classify slope materials.

Direct shear tests under consolidated undrained condition were conducted for the samples of different grade weathered granite and weathered sedimentary rocks as shown in Table 2. The normal stress was taken as the overburden and its multiples on oven dried, natural water content and saturated conditions.

The uniaxial compressive strength tests and thin section analyses were conducted for samples of moderately weathering grade that is associated with the most rock failures in Khao Phanom Benja. Results of uniaxial compression testing and thin sections analysis are shown in Table 3.

Table 2 Direct shear test results of weathered granite and siltstone samples

Type	Condition	Depth	Cohesion	Friction Angle
Granite Grade VI	Oven dried	0.5 m	32.3 kPa	35.0°
	Natural moist		27.7 kPa	35.3°
	Saturated		20.6 kPa	35.5°
Granite Grade V	Oven dried	3 m	29.0 kPa	34.8°
	Natural moist		26.4 kPa	35.1°
	Saturated		18.0 kPa	35.3°
Siltstone Grade VI	Oven dried	0.5 m	22.7 kPa	32.2°
	Natural moist		18.6 kPa	32.3°
	Saturated		15.5 kPa	32.3°
Siltstone Grade V	Oven dried	3 m	31.8 kPa	33.0°
	Natural moist		29.6 kPa	33.5°
	Saturated		19.7 kPa	32.9°
Siltstone Grade IV	Oven dried	0.5 m	50.2 kPa	42.8°
	Natural moist		49.4 kPa	43.1°
	Saturated		28.1 kPa	24.5°

Table 3 Results of uniaxial compression tests and thin section analyses

Rock type	Compressive strength and Unit weight	Petrographical Description	Mineral Composition (by Thin Section)
Sandstone	UCS=28.66 MPa UW=26.62 kN/m <sup>3</sup>	Fine-grained Pale-orange color Phaneritic and Porphyritic texture	Q (50%), KF (20%), Plg (20%), Bi (5%), Mu (15%)
Siltstone	UCS 18.70 MPa Unit weight of 27.38 kN/m <sup>3</sup>	Very fine-grained texture	Q (30%), KF (20%), Plg (20%), Bi (35%), Mu (15%)
Granite	UCS 55.13 MPa Unit weight of 26.54 kN/m <sup>3</sup>	Coarse-grained White color, phaneritic and plagioclase porphyritic texture	Q (40%), KF (25%), Plg (15%), Ho (15%) and Bi (5%)

Note: Q: quartz, KF:- Potassium feldspar, Plg: Plagioclase feldspar, Ho: hornblende, Bi: Biotite, Mu-Muscovite

### 4. CORRELATION OF LANDSLIDE WITH RAINFALL

Exceptionally heavy rainfall at the end of March 2011 was one of the most important triggering factors of landslides and debris flows at Khao Phanom Benja. There were no actual data from rain gauges in the areas where the landslides and debris flows occurred. The nearest records of rainfall data for each day located around 50 km from Khao Phanom in Mueang Krabi District recorded by Thai Meteorological Department. The maximum 24-hour rainfall around 160 mm and the cumulative rainfall intensity of more than 550 mm was recorded. Moreover, the unofficial accumulative rainfall data

that continuously poured in 7 days before landslide occurred more than 1,200 mm was recorded by villagers. Attestors recalled that the severe flooding began in the dawn of March 28 followed by landslides and debris flows that occurred at 10.00 AM March 28 after continuously poured rain throughout 7 days.

## 5. CORRELATION OF LANDSLIDE WITH PLANTATION COVER

Plant root system improved the stability of slope because vegetation provides both hydrological and mechanical effects that are generally beneficial to the stability of slopes [4]. However, from field observations in the areas where the landslide occurred, the failures took place on both natural tropical forest and cultivated plant. Almost all landslides at Khao Phanom Benja were covered by very abundant natural tropical forest. Some events of landslides and debris flow such as the disastrous landslides and debris flows on November 1998 in Nakhon Si Thammarat, southern Thailand were caused by extremely rainfall intensity and geological condition, when the slope failures took place on all of the types of vegetation cover. It can be described that the beneficial effect of vegetation cover to increase slope stability could be overridden by prolonged heavy rainfall intensity.

## 6. LANDSLIDE AND DEBRIS FLOWS

Most of the landslides started to occur in granitic rocks in the higher areas and developed into debris flows along stream channels that flowed into sedimentary rocks in lower areas at foothills. The slope failures could be classified into soil slide, surface erosion, curvilinear failure on granitic weak rock and rock slide. It was found that majority of slides on the eastern slopes of the mountain was granitic rock slide modes, while soil slide and surface erosion on the residual soil to completely weathered sedimentary rock were the predominant modes of failure on the western and northern slopes in lower areas at foothills of the mountain.

The most damaged area of 2011 landslides and debris flows is Ban Tonharn. This area was covered up to 3 meters of large boulders, mostly of granitic rocks. Large boulders of granite of up to 10 meters in size could be seen in the stream channel at the outlet while the size of sedimentary rock debris was not larger than 1 meter. The debris flow settlement covered an area of approximately 528,000 m<sup>2</sup> in size. The drainage basin of Ban Tonharn consists of several subchannels. The characteristics of landslides on the eastern slopes of granitic rocks of Khao Phanom Benja are different from those occurring in other areas of the country for which the slope failures commonly involved soil sliding of

weathered zones down to completely to highly weathered rocks. While weathering of granitic rocks had been well developed in the mountain slopes, rock slope failures appeared to be the predominant mode of landslides that occurred on the eastern steep slopes of the Khao Phanom Benja mountain. The major sets of geologic discontinuities that shaped up the north-south trending cliff face of the mountain and the two conjugated sets oriented in a more or less perpendicular direction (i.e., the E-W strike) as shown in Fig. 5 promoted development of deep rock wedges along the stream channels flowing eastward down the east face of the mountain as well as rock wedges on the weathered rock walls of the channels as shown in Fig. 6.

Moreover, the north-south oriented steep discontinuities created plane failure of rock blocks in some areas of the slope faces as shown in Figs. 7 and 8. Weathering along discontinuities and the opening of apertures in rocks in the vicinity of the stream channels on the mountain slopes increased vulnerability of rock slope failures upon heavy rainfall. The effect of heavy rainfall and stream channel flow on slab block of rock slope erosion along stream bank caused down bank slope failure. The increase in upward water pressure caused the increase in uplift force behind the rock block and rock wedge failure. The second area that was affected by the debris flow located on the stream outlet in the northern side of the mountain at Ban Huynumkeaw. It was covered by up to 1-meter thick of debris flow materials. Large granitic boulders up to 1.5 meters in size were found while the sizes of debris sedimentary rock were not larger than 0.5 meters. The affected area from debris flow was approximately 48,860 m<sup>2</sup>. Most of the landslides in the northern slope were predominantly of soil slope failures. The soil slope failures and debris flow in northern slopes of Khao Phanom Benja in 2011 incident occurred with slope faces of gradient ranging from 10 up to 30 degrees. However, on the northern slope of the mountain, there were some rock slope failures occurred on the rock walls of stream channel flowing northward. Rock slides along the direction of the channel were not common due to lacks of rock joint intersection. As a consequence, the debris flows developed on the northern sides of the mountain at Ban Huynumkeaw was of less significance than that on the eastern side because their movement did not slide into Ban Huynumkeaw directly but it had the potential to slide into the stream channel, and then move to Ban Huynumkeaw.

The characteristics of landslides and debris flows of Khao Phanom Benja were clearly influenced by the discontinuities characteristics of the granitic rocks that make up the mountain. Landslide potentials are different for different sides

of the mountain due to different kinematic instability potential of the rock slopes.



Fig. 6 Deep rock wedge failure along the channel



Fig. 7 Rock plane sliding on the steep slope face



Fig. 8 Rock slope failure near Ban Tonharn

## 7. CORRELATION OF LANDSLIDE WITH SLOPE GRADIENT AND ROCK TYPES

The past landslides in Thailand recorded the potential of landslides with the rock groups and showed that the granitic and sedimentary rocks have the highest frequency potential of landslides [5]. Both of these rocks are dominant at Khao Phanom Benja. Identifications of the spatial relations between landslide occurrences and influencing factors in term of slope gradient and types of rocks were made using Geographical Information Systems (GIS) as shown in Fig. 9.

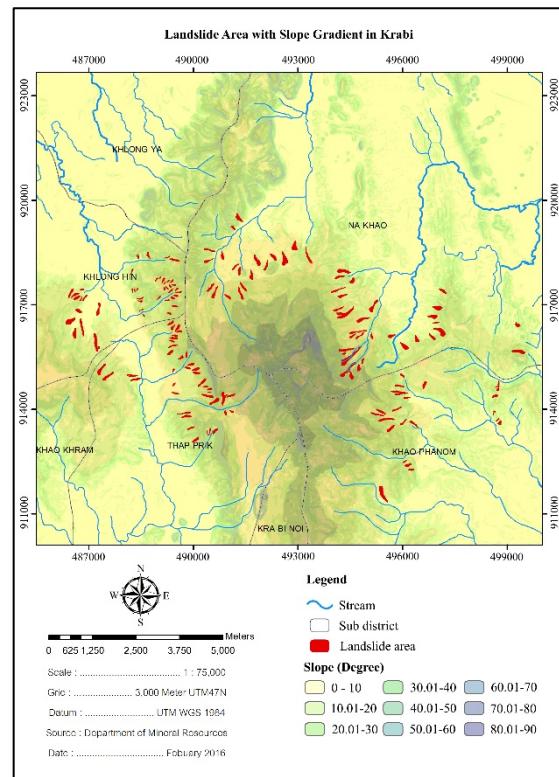


Fig. 9 Relationship between landslides and slope gradient

The overall landslides located on slopes from the gentle slopes up to those of 60-70 degrees. The slope gradient with that most landslides took places ranges between 10-30 degrees. The percentage of landslides per total failure area is plotted against the ranges of slope gradient as shown in Fig. 10, which indicated that more than half of landslides in this area were located on a sedimentary rock with 10-30 degrees. This was largely attributed to the fact that in the area of Khao Phanom sedimentary rocks outstandingly exist more than granite rock. However, when considering the vulnerability of failure per unit area in each rock slope failure, the results in Fig. 11 show that up to 72.53% of the granite rock failures were with slope gradient ranging from 20 to 40 degrees and most of the

sedimentary rock failures are with slope gradient less than 30 degrees. It would be further described that the landslide in sedimentary rock often occurred on lower slope gradient than granite rock because those failures were mostly surface erosion, shallow soil slide or earth flow modes while the predominant slope failure on granite is rock slope failures.

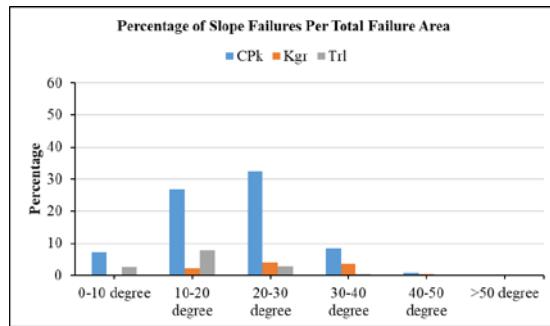


Fig. 10 Distribution of percentage of slope failures per total failure area

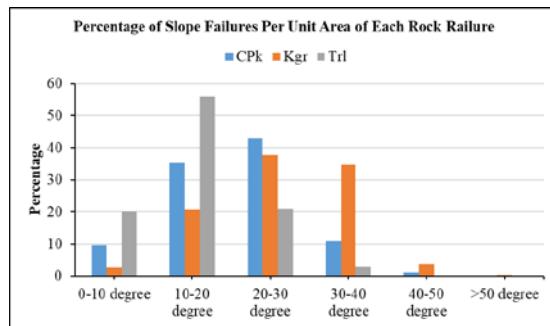


Fig. 11 Distribution of percentage of slope failures per unit area of each rock failure

## 8. EVALUATION OF DEBRIS FLOWS INUNDATION AREAS

The deposition of debris flows at downstream of the watershed at Ban Tonharn and Ban Huynumkeaw was simulated by two-dimensional semi-empirical scaling relations based on an automated code run in MATLAB (i.e., DFLOWZ). Set of input parameters consists of digital elevation model, debris flow volume and possible flow path. DFLOWZ extends an empirical-statistical model (LAHARZ model) originally proposed by [6] to predict the runout distance and the areas affected by lahars to debris flows. Both models are based on the simple observation of the relationship between the volume of flow, cross-sectional flow area, and the inundated planimetric area. The dependence between the volume of flow and cross-sectional

flow area, and that between the volume of flow and the inundate planimetric area, have been documented for different types of flow such as avalanches, lahars, and debris flows and reported [7,8]. The DFLOWZ model is designed to simulate unconfined flow deposition [9]. When the flow exceeds the available channel area, it is assumed that the debris deposits over the ground surface with a constant thickness [10].

As shown in Fig. 12 and 13, the evaluation of debris flow inundated areas by DFLOWZ simulations (Red Line) is in good agreement with the areas detected from satellite image (Yellow Line). The green-shaded polygon shows a good overlapping hazard area by DFLOWZ simulations and satellite image. More comparison details for three inundation areas estimated by these two methods are shown in Table 4.

Table 4 Comparisons of three potentially inundated areas by DFLOWZ and satellite images

Village	$A_{\text{satellite}}$ (m <sup>2</sup> )	$A_{\text{simulate}}$ (m <sup>2</sup> )	$A_{\text{overlap}}$ (m <sup>2</sup> )	%Diff. area (%)	%Diff. overlap (%)
Ban Tonharn	528,000	472,800	369,445	10.6	30.03
Ban Huynumkeaw	48,860	47,710	39,122	2.35	19.93

Remark:

$$\% \text{ difference area} = \left| \frac{A_{\text{satellite}} - A_{\text{simulate}}}{A_{\text{satellite}}} \right| \times 100$$

$$\% \text{ difference overlap} = \left| \frac{A_{\text{satellite}} - A_{\text{overlap}}}{A_{\text{satellite}}} \right| \times 100$$

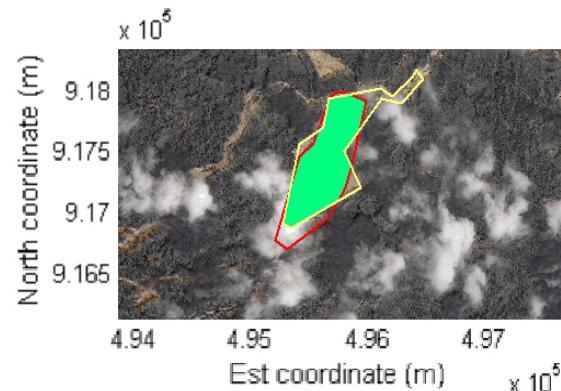


Fig. 12 The comparison between the deposition areas at Ban Tonharn by 2011 landslides and the hazard zone delineation areas calculated by DFLOWZ

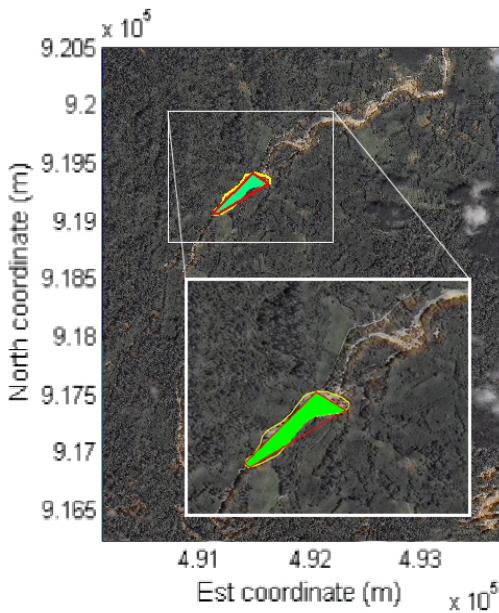


Fig. 13 The comparison between the deposition areas at Ban Huynumkeaw by 2011 landslides and the hazard zone delineation areas calculated by DFLOWZ

## 9. PREDICTION OF DEBRIS FLOWS INUNDATION AREAS USING DFLOWZ

The first step of prediction of debris flows settlement areas at Khao Phanom Benja starts with the estimation of debris flow volume and the corresponding probability of occurrence (magnitude-frequency relationship). In this study, maximum debris flows volume was assumed to be 125, 150 and 200% of the debris flow event in 2011. Fig. 14 and 15 show the evaluation of debris flow inundated areas of DFLOWZ simulations (Red Line) and hazard zone delineation areas with 125% (Green line), 150% (blue line) and 200% (violet line). The comparison between the deposition areas of two study areas shows that the debris flows starts to spread on deposition area at the same location and spreading wider. DFLOWZ cannot indicate the depth of inundation. We compared the areas of inundation with those in the previous case to identify the possible location of debris flow settlement. The percentage of inundation areas are lower than the percentage of the design volume of debris flow. In other words, the major factors affecting the large debris flow volume at Ban Tonharn and Ban Huynumkeaw are the larger thickness of the deposition area. Moreover, the results indicated that the deposition areas of debris flows are not significantly different from previous landslide and debris flow.

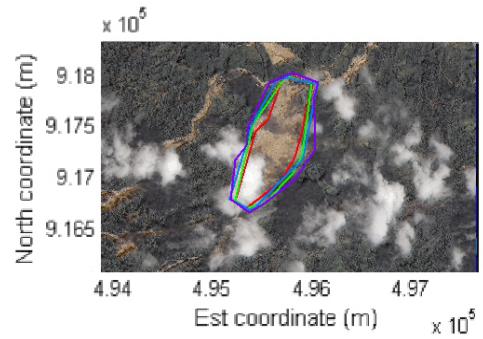


Fig. 14 The comparison between the deposition areas of 2011 DFLOWZ simulation and hazard zone delineation areas at Ban Tonharn

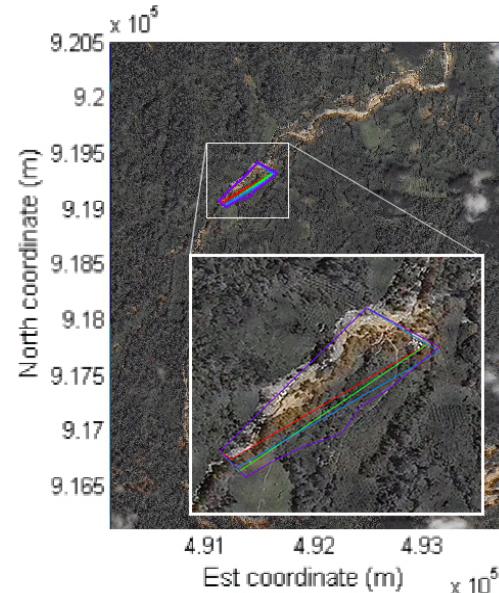


Fig. 15 The comparison between the deposition areas of 2011 DFLOWZ simulation and hazard zone delineation areas at Ban Huynumkeaw

## 10. CONCLUSIONS

Investigation of the characteristics of the 2011 catastrophic landslides and debris flows at Khao Phanom Benja led to the following conclusions.

The geomorphological and geological features of Khao Phanom Benja are important factors influencing the rock slopes failures. Moreover, weathering and joint opening in the areas of slopes and stream channels increase the vulnerability of rock slides in an event of prolonged heavy rainfall such as that occurred in 2011.

Landslides and debris flow at Khao Phanom Benja were not controlled by deforestation and plantation cover. Rainfall triggering landslides contributed rock slope failures in causing the active force of water and reduction of mechanical resistance of the sliding surface. This might be the reason why the landslide and debris flow at Khao

Phanom Benja usually occurred during a period of prolonged extremely rainfall.

The unfavorable orientations of four major joint sets of the mountain created high kinematic instability potential of rock wedge slides along the stream channel direction as well as rock wedge formation on the channel walls on the eastern side of the mountain. The characteristics of landslides on the eastern slopes of granitic rocks of Khao Phanom Benja are different from those occurring in other areas of the country for which the slope failures commonly involved soil sliding of weathered zones down to completely to highly weathered rocks.

Khao Phanom Benja can be considered a dynamic landslide area. Based on field investigation, there are evidence suggesting that the historical landslide and/or debris flows have frequently occurred.

The modes of failure were found to be dependent on the degree weathering, rock type, joint orientation, slope gradient, and especially rainfall duration and intensity.

Evaluating the inundation of debris flows may help the relevant public agencies to prevent severe landslides and debris flows of Khao Phanom Benja in the future. Although the DEFLOWZ model is based on empirical scaling relationships without describing the complex dynamic of debris flows, it can perform a sensitivity analysis of influencing parameters such as debris flows volume, the starting point of debris flows deposition and specific the flow channel path in order to predict hazard zone delineation and plan of landslide disaster management policies.

## 11. ACKNOWLEDGMENTS

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