Research Article

Effectiveness of Geoelectrical Resistivity Surveys for the Detection of a Debris Flow Causative Water Conducting Zone at KM 9, Gap-Fraser's Hill Road (FT 148), Fraser's Hill, Pahang, Malaysia

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This study reports the findings of resistivity surveys which were conducted at the initiation area of debris flow at KM 9, Fraser's Hill Gap road (FT148). The study involves three slope parallel survey lines and two lines perpendicular to the slope face. The parallel lines are FH01, FH02, and FH03, while the lines FH04 and FH05 are perpendicular. A granite body was detected at the central part of the east line and is nearest to the ground surface along FH02. The existence of low resistivity zones within the granite body is interpreted as highly fractured, water conducting zones. These zones are continuous as they have been detected in both the east-west as well as the north-south lines. The residual soil layer is relatively thin at zones where weathered granite dominates the slope face of the failure mass. The weak layer is relatively thick with an estimated thickness of 80 m and water flow occurs at the base of it. The high water flow recorded from the horizontal drains further supports the possible existence of these highly fractured, water conducting zones located within the granite. The shallow fractured granite is virtually "floating" above the water saturated zone and therefore is considered unstable.

1. Introduction

The study area has experienced at least four debris flow incidents, which are concentrated at an initiation zone. One of the debris flow triggering factors in the mountainous terrain of Peninsular Malaysia is high intensity rainfall during or before the debris flow incident. At the time of occurrence of the debris flows in the study area, the intensity of rainfall recorded was between 0 mm/day to 14 mm/day. This value is not considered high for Malaysian condition. The finding is based on the current larger study on seven other sites in Peninsular Malaysia which showed that heavy rainfall is a major triggering factor. However, a Fraser Hill site, incidents of debris flow occurred during low of rainfall intensity and at

the same time high water flow was observed. Therefore, the source of this water flow needed to be established.

A debris flow is one type of the natural disasters that can be classified as landslides and can cause damage to property and loss of life. The first definition of debris flow was highlighted by Stiny as a flood of mountain torrents, carrying suspended load and transporting quantities of bedload [1]. Sharpe defined debris flow as a rapid flow of saturated or viscous debris in a stream or channel [2]. According to Hungr et al. a debris flow is defined as a very rapid to extremely rapid flow of saturated nonplastic debris in a steep channel [3, 4]. The debris is loose unsorted material of low plasticity such as that produced by mass wasting processes (colluvium), weathering (residual soil), glacial transport

FIGURE 1: Location of the study area on the geological map of Peninsular Malaysia, with Google image of site area [7].

(till or ice contact deposits), explosive volcanism (granular pyroclastic deposits), or human activity (e.g., mine spoil). Meanwhile, Jakob, considered “sources of debris” to include soil blankets and veneers on steep slopes, colluvial gully fills, channel bedload material, zones of weathered or altered rocks, residual soil, headwalls and side slopes of steep gullies, talus deposits, man-made fills, and similar accumulations of unstable or erodible material [5]. Meanwhile, Iverson focuses on widespread Coulomb failure within a sloping soil, rock or sediment mass, pore-fluid pressures, and conversion of landslide translational at debris source zones [6].

Chiessi et al., showed that geoelectrical imaging can be employed to confirm the variability of the characteristics of both the cover material and the substratum, a variability which is also highlighted in seismic surveys by lateral variations in velocity within the same layer [8]. Jongman and Garambois used the geoelectrical resistivity to determine the location of the vertical and lateral boundaries of the slide debris and detection of water within the slide debris [9].

Determination of groundwater flow has been reviewed by Hubbard and Linde by combining Ground Penetration Radar (GPR) with seismic survey and geoelectrical resistivity survey [10]. Results from the application of geophysical methods available, the case studies illustrate the use of hydrogeophysical approaches to quantify subsurface architecture that influence flow (such as hydrostratigraphy and preferential pathways), delineate anomalous subsurface fluid bodies (such as contaminant plumes), monitor hydrological process (such as freshwater-seawater interface dynamics and flow through fractures), and estimate hydrological properties (such as hydraulic conductivity) and state variables (such as water content).

In addition, boreholes could also be used to determine the soil properties and identify type of material and strength of the soil. The combination of these methods is very effective and costly. Unfortunately, boreholes could not to be carried out at the study site because drilling rigs are unable to access the extremely hilly terrain.

The main purpose of this study is to determine the weak layer at the initiation zone using geoelectrical resistivity imaging.

1.1. Objective. Generally the scope of this work is to understand factors associated with debris flow incidents in Peninsular Malaysia. The main objective of this specific study was to determine the main cause of the formation of the debris flow mass within the initiation zone. The existence of a high outflow of water at the toe of the slope suggested the possible existence of weak zones that are water conducting. Therefore geoelectrical resistivity imaging was applied to identify

- (a) zones of soil or weathered rock with high water content,
- (b) groundwater flow,
- (c) weak zones of weathered and highly fractured rocks.

2. Background

The study area is located at km 9, Gap-Fraser's Hill road (FT148), and within the Raub-Bentong Suture zone as shown on the geological map of Peninsular Malaysia (Figure 1). Landslides into the channel at this location occurred repeatedly resulting in debris flow impacts to the Gap-Teranum

TABLE 1: (a) Chronology of landslides at km 9, Fraser's Hill-Gap road (FT148). (b) Chronology of debris flows at km 90, Gap-Tranum road (FT 55).

(a)	
Date	Description
(a) December 16, 2007	A landslide occurred at Kilometre 4-5, FT 148, New Gap road to Fraser's Hill and the road was declared unsafe for all vehicles
(b) January 12, 2009	The collapse of a new embankment occurred within the project site, causing some damage to equipment and machinery and affected work in progress (Figure 18: photograph taken on January 19 2008 and Figure 19: view final landslide before remediation)
(b)	
Date	Description
(a) November 16, 2007	Blockage occurred due to rubble, mud, and rock slide material. Public Work Department (PWD) carried out cleaning work and the road was eventually opened
(b) February 27, 2008	Debris flow occurred again, resulting in the blockage due to mud, rock slides, and rock blocks. Road was closed to all traffic users from 03/03/2008 to 06/06/2008.
(c) March 6, 2008	Clearing work carried out using explosives
(d) March 7, 2008	Route was reopened to all traffic
(e) March 8, 2008	Debris flow occurred again and caused the flow of mud and boulders to cover the road. Cleaning work carried out and the road could be used by light vehicles
(f) March 15, 2008	Debris flow occurred with debris, boulders, and mud. Cleaning work carried out and road was opened to light vehicles only
(g) March 17, 2008	Debris flow occurred. Cleaning work carried out and road was opened to light vehicles only
(h) March 19, 2008	Debris flow occurred resulting in mud and rock slides. The road was closed. Cleaning could not be conducted due to weather conditions that were hazardous to workers at the site
(i) March 22, 2008	Bridge collapsed causing structural breaks of the steel plate beam buckle
(j) March 23, 2008	Debris flow and the cliff road failed and the road surface collapsed for over 60 m (Figure 3 shows this incident)
(k) June 26, 2008	Repairs completed and roads opened to vehicles
(l) July 3, 2008	The collapse of new gabion retaining wall, destroyed by rock slides
(m) July 8, 2008	New debris flow resulting in mudslide. Road was closed
(n) July 15, 2008	Cleaning works carried out. Road reopened to all vehicles

road (FT 55). Repeated failures occurring at km 9, Gap-Fraser's Hill road (FT148), with debris flow were documented on December 16, 2007 and January 12, 2008 and several subsequent incidents which were not recorded. This study location is the source of the debris flow formation down the channel that impacted the Tranum-Gap road at km 90, FT 55 (see Figure 2 for a simplified site location map). The landslides occurred could be classified as regressive landslide of large scale. The chronology of events at both roads is documented in Tables 1(a) and 1(b).

3. Physiographic and Geologic Setting

The granitic bedrock at Fraser's Hill is a part of the Titiwangsa Mountain Range. The porphyritic granite of the study area is moderate to coarse grain and crossed by the Kuala Lumpur and Bukit Tinggi faults [12]. This area consists of porphyritic granite, biotite granite, and sheared granite (protomylonite, ortomylonite, and ultramylonite) [12]. The distance between the initiation area (km 9, Gap-Fraser's Hill road) of debris flow to the impact area (km 90, Gap-Tranum road) is about 1260 m. Meanwhile, the catchment area at this location is 0.4 km^2 .

FIGURE 2: Simplified site location map.

There are two main streams flowing down to the impact zone of debris flow. The highest peak is Bukit Peninjua with an elevation of 1500 m. Overall the stream bed gradient is 39.3° and the average slope angle of the banks is 40° to 48° . The outcrop of the formation of the debris flow is weathered

TABLE 2: The main coordinates of the resistivity lines.

Name of resistivity line	Location of first electrode (A)	Location of last electrode (B)	Location of center of line (C)
FH01	N3° 42' 58.0"	N3° 42' 58.1"	N3° 42' 58.4"
	E101° 45' 28.5"	E101° 45' 31.8"	E101° 45' 30.3"
FH02	N3° 42' 57.9"	N3° 42' 58.7"	N3° 42' 59.5"
	E101° 45' 31.5"	E101° 45' 28.7"	E101° 45' 30.0"
FH03	N3° 43' 02.3"	N3° 42' 58.6"	N3° 43' 00.2"
	E101° 45' 32.0"	E101° 45' 27.1"	E101° 45' 30.2"
FH04	N3° 43' 02.7"	N3° 42' 58.2"	N3° 43' 00.8"
	E101° 45' 30.7"	E101° 45' 35.4"	E101° 45' 33.3"
FH05	N3° 43' 01.6"	N3° 42' 57.4"	N3° 42' 59.2"
	E101° 45' 26.7"	E101° 45' 29.4"	E101° 45' 27.7"

FIGURE 3: Location of geoelectrical resistivity lines and Mackintosh Probe at initiation area.

granite with weathering grades between IV to V as well as residual soil. There are also blocks of granite boulders loosely suspended within the failure mass.

Figure 3 below shows the location of five 200 meter resistivity lines. Three resistivity lines are named as FH01, FH02, and FH03 which are parallel to each other and spaced 25 m apart. The other two-lines FH04 and FH05 are spaced 100 m a part in north-south direction and are perpendicular to the above FH01, FH02, and FH03 lines (Table 2).

4. Materials and Methodology

4.1. Resistivity Survey. The method employed in this study is the standard method using Wenner array with resistivity line parallel and perpendicular to the slope face. The Wenner array with a total profile length of 200 m was employed with an estimated penetration depth of 20 m to 30 m below the ground surface. Zones of high water content and weak zones could be determined as low resistivity zones by using this

FIGURE 4: The arrangement of electrodes for a 2D electrical survey and the sequence of measurements used to build up a pseudosection [11].

method. Refraction for seismic survey could not be used due to the limited space for seismic lines compared to the estimated target depth.

To determine the true subsurface resistivity, an inversion of the measured apparent resistivity values using a computer program was carried out.

One of the new developments in recent years is the use of 2D geoelectrical resistivity imaging or tomography surveys to map areas with moderately complex geology [11].

Such surveys are usually carried out using a large number of electrodes connected to a multicore cable. A modern resistivity meter together with an electrode selector system is used to automatically select the relevant four electrodes for each measurement.

Figure 4 shows the typical setup for a 2D survey with a number of electrodes along a straight line attached to a multicore cable. Normally a constant spacing between adjacent electrodes is used. The multi-core cable is attached to an electronic switching unit which is connected to a resistivity meter or terrameter.

The sequence of measurements to take, the type of array to use, and other survey parameters (such the current to use) are normally entered into a text file which can be read by a built-in computer program in the resistivity meter or terrameter. After reading the control file, the computer program then automatically selects the appropriate electrodes for each measurement.

The terrameter or resistivity meter employed was an ABEM SASI000 and ABEM LUND ES464 electrode selector system. This system is connected to 41 stainless steel electrodes, which are laid out in a straight line with a constant spacing via a multi-core cable (Figures 4 and 22). The resistivity meter selects only four active electrodes to be used for each measurement.

FIGURE 5: Notepad window for correction of data.

4.2. Data Processing. Resistivity data was analyzed using a driven software RES2DINV Ver .3.54 (see Figure 9) with nine usual options at the top of the screen (file, edit, change settings, inversion, display, topography options, print, help, and quit). The input data file must be in a "file. Dat" format. The procedures below were steps followed during the processing of resistivity data using the RES2DINV software.

- Selected data file from read menu.
- Exterminated bad datum points from Edit menu. A negative value or values which were too large were edited using notepad or other text editor (Figure 5). A Function to exterminate bad datum points was used to eliminate further bad data value by clicking the mouse when the cursor at the points of those was not in line (Figure 6).
- Change menu was also used to modify the resistivity data by selecting the number of iterations of required

FIGURE 6: Procedure to remove bad data points. Red circles are data points removed.

FIGURE 7: Blocks datum and datum level rectangular building blocks to produce the geological model.

while the damping factor applications, mesh refinement, convergence limit, and the model resistivity values set values depending on whether the data set have a value that was too high or low.

- (d) Next Inversion menu was selected to initiate data inversion process.
- (e) Adjustment was made by smoothing the resistivity model using the robust inversion procedure from the menu.
- (f) RMS error statistics menu was selected to reduce RMS (Root Mean Square) error that affects the inversion process and the building of the model resistivity data. The resistivity data in the form of rectangular blocks (Figure 7) were modified and recalculated to produce resistivity pseudosection. This process involves a recalculation and observation of resistivity values based on pseudocross-sectional field before generating a pseudocount (calculated pseudosection) that was very similar to the actual field data. The inverse model resistivity sections were produced from pseudocount for the purpose of quantitative interpretation.
- (g) After completing the inversion process, the show display menu was selected to display the actual resistivity model (Figure 8).

FIGURE 8: Actual resistivity model obtained from the inversion process and ready for interpretation process.

FIGURE 9: Block diagram showing fiel data processing techniques using RES2DINV software.

Interpretation of underground mass based on the followings:

- (i) uniform the resistivity values for line survey because the line survey is in the same area;
- (ii) underground mass is an electrical conductor which will produce a low resistivity values;
- (iii) the completely weathered rock mass will produce low resistivity values;
- (iv) water saturated zone will produce low resistivity values.

The data obtained from the resistivity survey profile was used to prepare an illustration model, a three-dimensional subsurface profile using AutoCad (2009) (Figure 16).

The first stage was to build a three-dimensional topography of the initiation area, and the next stage was to build a subsurface profile in three-dimension. Data from the five lines of geoelectrical resistivity survey were combined to produce an illustration three-dimensional model of the study area.

5. Results and Discussion

Based on the resistivity results, a subsurface profile could be divided into four zones as shown in Table 3 below.

TABLE 3: Attribute of various zones based on resistivity values.

Number	Zoning symbol	Description
1	a	Resistivity values above 5000 Ωm , are the fresh granite rock mass
2	b	Resistivity value between 3000 Ωm –5000 Ωm , granite slightly weathering and highly fractured
3	c	Residual soil (IAEG, V-IV) (600 Ωm –3,000 Ωm)
4	d	Water conducting zone or high water content (<600 Ωm)

FIGURE 10: Resistivity results at line FH01.

5.1. Resistivity Line FH01. Relatively fresh granite rock that is in “zone a” has a resistivity value greater than 5,000 m Ω . This zone is *in situ* granite in the middle of the profile, at a depth of 15 m to 20 m from the original ground level.

Weathered and highly fractured granite is in “zone b” which encompasses *in situ* granite boulders in the middle of the profile. There are three main locations associated with it; the middle of the profile line at C, between C and A which is at a distance of 60 m from the profile center line, and between C and B, approximately at a distance of 20 m from the center (Figure 10).

The “zone c” is a zone of residual soil with resistivity values between 600 Ωm and 3000 Ωm . This zone is the result of the weathering processes that change the rock into soil. Based on the geoelectrical resistivity value, high water content zone is marked as “zone d”. Resistivity values recorded were less than 600 Ωm . This zone is located between 20 m to 25 m (Figure 10).

5.2. Resistivity Line FH02. A zone of relatively fresh granite is found in the middle of the profile marked as zone a, at a depth of 20 m from the original ground level and with a width of 15 m. In this zone, the resistivity value is between 5,000 Ωm and 45,000 Ωm . The rock mass is surrounded by

FIGURE 11: Resistivity at line FH02.

a layer of weathered rock with a resistivity value between 3,000 Ωm to 5,000 Ωm . There are two rock masses, which could be classified as very large boulders located at a distance of 20 m from the center line of the profile, to the west towards (B), at a depth of 10 m to 20 m, and covered by residual soil (zone c) and the water conducting zone (zone d). The rock masses could also be found at a distance of 60 m to the west as well as at the eastern end of the profile (Figure 11).

The water conducting zone in the middle of the profile below the granite mass and the weathered granite zone with resistivity value of less than 600 Ωm is marked as “zone d” (Figure 11).

The subsurface conditions are relatively heterogeneous; weathered and highly fractured granite with water containing zone was located below it. Therefore the rock mass above this water containing zone is prone to failure (see, e.g., Figure 20).

5.3. Resistivity Line FH03. Zone a, which is a relatively fresh granite rock mass is clearly visible at the center C, and at a distance of 20 m east from center C, at a depth of 10 m. The rock mass is surrounded by layers of zone b weathered rock, and “zone c” residual soil. The rock mass could be classified as *in situ* granite between C and A and is covered with residual soil (zone c), together with weathered and fractured granite (Figure 12).

The zone with high water content detected in lines FH02 and FH01 is at a greater depth at this location and remains undetected because the penetration depth of imaging is insufficient.

5.4. Resistivity Line FH04. Four main zones that are probably water conducting were detected. The “zone d” has a low resistivity value of below 100 Ωm . The water conducting zone is within the residual soil (zone c) and the granite rock which is probably highly fractured and weathered. The weathered granite zone is at a depth of between 0 m to 5 m. Relatively

FIGURE 12: Resistivity result at line FH03.

FIGURE 13: Resistivity line at FH04.

fresh granite rock with resistivity values between 5,000 Ωm to 34,500 Ωm occurs at a depth of 10 m below the original ground level. Granite rock is also found on the surface at the center line of the profile at C (Figure 13).

The whole subsurface at a depth between 0 m to 5 m is composed of weathered granite, residual soil, and a water conducting zone. This layer is very weak because the rock is weathered and highly fractured with soil having high water content. Therefore, this layer is very weak and the complete mass can be considered as highly unstable.

5.5. Resistivity Line FH05. The subsurface is relatively heterogeneous, with layering of residual soil (zone c), and weathered and fractured granite (zone b) as well as fresh granite (zone a). Water conducting zones are detected at the center of the profile at C, between 5 m to 10 m deep.

Furthermore, a water conducting zone is detected below the relatively fresh granite between C and B (Figure 14).

FIGURE 14: Resistivity result at line FH05.

FIGURE 15: A hypothetical cross-section at the main scarp.

Hence, the granite is virtually “floating” above the water conducting zone and therefore could be considered unstable.

5.6. Discussion. The subsurface conditions are visualized in Figure 17. At the surface, exposed boulders could be found, and, by observing the surface of the main failure mass found at the location, highly weathered granitic rock is determined. The residual layer is relatively thin at this zone where weathered granite dominates the slope face of failure mass. Below this *in situ* granite mass, a water conducting zone with an approximate thickness of 20 m is detected.

This water flows out at the lower part of the slope (Figures 15 and 17) at a rate of 43 cc/sec and is a main causative factor for this debris flow. An illustration subsurface model view of the subsurface conditions is shown in Figure 17. A hypothetical cross-section of the failed slope is shown in Figure 15 and the interpretative geological profile and seepage within that slope. The underground water flow and seepage through the fractured and highly weathered granite mass are the main causative factor for this debris flow. Figure 23 shows

FIGURE 16: Conceptual sketch showing the subsurface profile at the initiation area of the debris flow.

FIGURE 17: Postulated subsurface conditions at initiation zone of debris flow.

the water seepage along the boundary of the two different geological materials and a close view of the main failure scarp, exposing the unconformable contact between the overlying residual soil and the underlying weathered granite. Figure 24 is an on-site view of initiation zone of the study area (see Figure 21 for a general view). A combination of surface and subsurface geological data (geoelectrical resistivity) were used to produce illustration in three-dimensional model as shown in Figure 12.

Thirteen (13) Mackintosh Probe tests were conducted in the initiation debris flow zones and flow paths zones. Mackintosh Probe resulted in that the residual soil was between 1.20 meters to 3.00 meters thick with value of 100 blows (Table 4). That location of Mackintosh probe tests is shown in Figure 3.

This method is suitable to determine the flow of the groundwater in the initiation zone by the characteristics as shown below:

- (i) initiation of a steep slope,
- (ii) seepage at the slope surface and toe of the slope,
- (iii) low intensity of rainfall before and during debris flow incident,
- (iv) material consisting of residual soils and weathered rock.

6. Conclusion

This rock mass within the initiation zone of the debris flow is a heterogeneous mass of fresh, moderately weathered, and

FIGURE 18: The first landslide, photo taken on Jan 19, 2008, at Fraser's Hill Gap road (FT 148).

FIGURE 19: View of the final landslide before strengthening of slope was carried out.

FIGURE 20: The view of conditions at FT 055, Trnum-Gap road, near a Bailey Bridge on March 28, 2008.

FIGURE 21: General view of initiation zone during geoelectrical resistivity survey.

FIGURE 22: The ABEM SAS1000 resistivity meter and ABEM LUND ES464 electrode selector system.

FIGURE 23: Boundary of residual soil and weathered granite at the main scarp.

FIGURE 24: View of main failure scarp or initiation area of debris flow at Fraser's Hill.

highly fractured granite with residual soil together with a water conducting zone at a depth below the *in situ* granite. The geoelectrical resistivity profiling revealed that the granite rock mass is virtually “floating” above the water conducting zone and is therefore highly unstable. In conclusion, the groundwater flow is identified as a weak zone or a plane of weakness. Determination of the position of the groundwater flow and subsurface profile is very important in designing slope strengthening and reinforcement works in this area.

TABLE 4: Mackintosh Probe result.

MP number	Depth with 100 blows	Remarks
5	2.10	Flow path
6	2.10	Flow path
7	3.00	Initiation zone
8	3.00	Initiation zone
9	2.10	Initiation zone
10	1.20	Initiation zone
11	2.70	Initiation zone
12	3.00	Initiation zone
13	2.10	Flow path
14	2.40	Flow path
15	2.70	Flow path
16	3.30	Flow path
17	0.60	Flow path

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