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Rainfall and Slope Failures in the Granitic Bedrock Areas of Peninsular Malaysia

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Abstract

Most slope failures in the granitic bedrock areas of Peninsular Malaysia occur during, or following, short periods (<3 hr) of intense rainfall, or longer periods (>1 day) with somewhat continuous rainfall. These failures usually occur when the total cumulative rainfall exceeds 70 mm and include debris flows that occur at steep (>40°) natural ground slopes and embankments in mountainuous terrain. Slump-flows occur at embankments in undulating to hilly terrain. Earth falls and shallow slips occur at steeply sloping (>60°), low cuts, and upper benches of high cuts (>10 m high), that expose completely weathered bedrock materials (Morphological Zone I). These failures occur long after the end of excavation and are usually preceded by the development of tension, and desiccation, cracks. Where the low cuts intersect groundwater tables in undulating terrain, slumps can sometimes occur. Small to large, slumps and slump-flows, occur at high cuts (>10 m high) excavated at moderate overall angles (usually >45°, though mostly >55°), that expose completely weathered, and highly to moderately weathered, bedrock materials (Morphological Zones I and II). These failures occur towards, as well as some months to several years after, the end of excavation; the slumps only occurring at cuts where unweathered bedrock is found close to the ground surface. The slump-flows occur as a result of several converging factors, including the presence of a triggering factor that can be provided by passing heavy vechicles. Wedge failures, block slides and rock falls can occur at the steep (>60°) lower benches of some high cuts that expose unweathered bedrock (Morphological Zone III)

Hujan dan Kegagalan Cerun Pada Kawasan Batuan Dasar Granit di Semenanjung Malaysia

Abstrak

Kebanyakan kegagalan cerun pada kawasan batuan dasar granit di Semenanjung Malaysia berlaku semasa atau selepas hujan lebat jangka pendek (<3jam) ataupun hujan berterusan dalam jangka lama (>1 hari). Kegagalan ini selalunya terjadi jika jumlah kumulatif air hujan melebihi 70 mm dan meliputi aliran debris pada cerun dan benteng asal yang curam (>40°) di terain pergunungan. Aliran nendatan terjadi di benteng pada terain beralun ke berbukit. Runtuhan tanah dan gelinciran cetek berlaku pada cerun curam (>60°), potongan rendah dan undak atas potongan tinggi (>10m tinggi) yang mendedahkan bahan luluhawa lengkap batuan dasar (Zon Morfologi I). Kegagalan ini berlaku setelah kerja pengorekan tanah telah lama berhenti dan selalunya mengikuti penghasilan rekahan tensi dan pengontangan. Tempat di mana potongan rendah bertemu paras air bawah tanah pada terain beralun, nendatan mungkin berlaku. Nendatan dan aliran nendatan yang bersaiz kecil ke besar berlaku pada potongan tinggi (>10m tinggi), yang keseluruhannya dipotong pada sudut sederhana (biasanya >45° walaupun kebanyakannya >55°) yang mendedahkan bahan terluluhawa lengkap dan terluluhawa tinggi ke sederhana batuan dasar (Zon Morfologi I & II). Kegagalan ini berlaku beberapa bulan ke beberapa tahun selepas kerja pemotongan. Nendatan hanya berlaku pada potongan yang batuan dasarnya yang tidak terluluhawa terdapat berdekatan dengan permukaan. Aliran nendatan berlaku hasil daripada beberapa faktor, termasuklah kehadiran faktor pencetus seperti pergerakan kenderaan berat. Kegagalan baji, gelinciran blok dan jatuhan batuan boleh berlaku pada undak bawah yang berkecerunan >60° di beberapa potongan tinggi yang mendedahkan batuan dasar tak terluluhawa (Zon Morfologi III).

INTRODUCTION

The occurrence of slope failures during rainfall is well documented in published literature and several correlations have been proposed by different authors working in different topographic, geological and climatic settings. Guidicini and Iwasa (1977) for instance, pointed out that landslides in southeast Brazil were generally due to rainfall events with an intensity varying between 12% and 18% of the annual rainfall; catastrophic events resulting when intensities surpassed 20%. da Costa Nunes *et al.* (1979) furthermore, noted that the majority of landslides in Brazil occurred in the coastal mountain ranges that were subject to frequent heavy rains and cloudbursts.

Ikeya (1989) has pointed out that due to steep slopes, debris flows occur every year somewhere in Japan during torrential downpours, typhoons or the seasonal rain front. In Hong Kong, it has been shown that short-term rainfall intensity is the critical factor for landslides; the 'trigger' value being 70 mm/hr irrespective of antecedent rainfall (Brand, 1991).

Piersen *et al.* (1991) reported that more than 400 landslides were triggered during a 14 hour rainstorm in southeastern Oahu, when total rainfall locally exceeded 600 mm. Most of the failures were mobilized as debris flows; the timing of landsliding correlating closely with periods of peak rainfall intensity (locally in excess of 100mm/hour).

Phien-wej *et al.* (1991) reported several hundreds of slope failures in south Thailand during an unprecedented torrential rainstorm in late November, 1988, when rainfall intensity was as high as 475 mm/day and accumulated to 735 mm in 2 days. DeGraff (1991) noted that the occurrence of these failures was greater under cultivated vegetation than under natural forest.

Kim *et al.* (1991) reported that landslides in the central part of South Korea were mostly dependent upon the 3-day cumulative rainfall prior to failure, whilst those in the southern part were influenced by the intensity of rainfall on the day of failure, and those in the eastern part occurring both as a result of daily, and cummulative, rainfall.

Fukuoka (1980) has pointed out that the causes of landslides with reference to rainfall are i) a decrease in shearing resistance of soils resulting from an increase in moisture content, ii) an increase of pore water pressure in faults or joints, iii) surface erosion, and iv) an increase in unit weight with increase of moisture content. In the case of partially saturated soils furthermore, infiltration of rainwater can lead to a reduction in apparent cohesion through removal of negative pore water (suction) pressures (Lumb, 1962, 1975; Raj, 1998).

There is little doubt that there exist relationships between rainfall and slope failures, though Bhandari *et al.* (1991) have pointed out that there are several pitfalls associated with prediction of landslides through rainfall records. They noted that rainfall could at best be called the triggering factor and that proper weightage needed to be given to all landslide inducing factors.

In this paper, the relationship between rainfall and slope failures in the granitic bedrock areas of Peninsular Malaysia is discussed, based on an examination of the hourly, daily and monthly, rainfall records of rainfall stations located close to the sites of several personally known, or documented, slope failures.

RAINFALL OF PENINSULAR MALAYSIA

The mean annual rainfall of the Peninsula is some 2,540 mm, though rainfall distribution patterns are quite variable and dependent upon local topographic features as well as seasonal wind flow patterns. Although winds are generally light and variable, there are some uniform periodic changes in flow patterns which allows for distinction of four 'seasons', i.e. the southwest monsoon, northeast monsoon and two shorter intermonsoon seasons.

During the southwest monsoon, which is usually established in the later half of May, or early June and ends in September, the prevailing wind flow is generally southwesterly and light (< 15 knots). During the northeast monsoon, which usually commences in early November and ends in March, steady easterly or northeasterly winds (of 10 to 20 knots) prevail, whilst winds during the two intermonsoon seasons are generally light and variable (MMS, 1999).

The seasonal variation of rainfall in the Peninsula is of three main types (MMS, 1999):-

a) Along the East Coast, November, December and January are the months with maximum rainfall, whilst June and July are the driest months in most districts.
b) Over the rest of the Peninsula, with the exception of the southwest coastal area, monthly rainfall patterns shows two maxima and two minima. The primary maximum usually occurs in October-November, whilst the seconday maximum is mostly in April-May. Over the north-western region, the primary minimum is in January-February and the secondary minimum in June-July, though elsewhere, the primary minimum is in June-July and the secondary minimum in February.
c) Over the southwest coastal area, the rainfall pattern is much affected by early morning "Sumatras" from May to August with the result that the double maxima and minima are no longer discernible. October and November are the months with maximum rainfall and February the month with the minimum rainfall, though the April-May maximum and June-July minimum are absent or indistinct.

As a result of the seasonal variation of rainfall, there occur periods when evaporation rates exceed precipitation rates (Nieuwolt, 1965). Rainfall intensities during single rain storms are furthermore, very variable with distance and area (DID, 1961) and data from nearby rainfall stations is therefore, essential for correlation with slope failures, though such data is often unavailable.

WEATHERING PROFILES OVER GRANITIC BEDROCK

Coarse grained acid igneous rocks are the most prominent lithology of Peninsular Malaysia and outcrop over some 40% of its land surface. These rocks form the bedrock of the main mountain ranges and have been separated into four broad groups on the basis of differences in mineralogy, geochemistry and radiometric ages, i.e. epizonal late Cretaceous granites, epizonal Triassic granites, epizonal Permo-Triassic granites, and mesozonal Permo-Triassic granites (Hutchison, 1977).

Most of the granitic bedrock areas furthermore, are covered by thick weathering profiles that have developed as a result of favourable environmental and tectonic conditions that have facilitated pervasive chemical weathering throughout the Quaternary (Raj, 1982). These weathering profiles can be differentiated into three broad zones and several thinner horizons on the basis of morphological features, particularly differences in the degree of preservation of the minerals, textures and

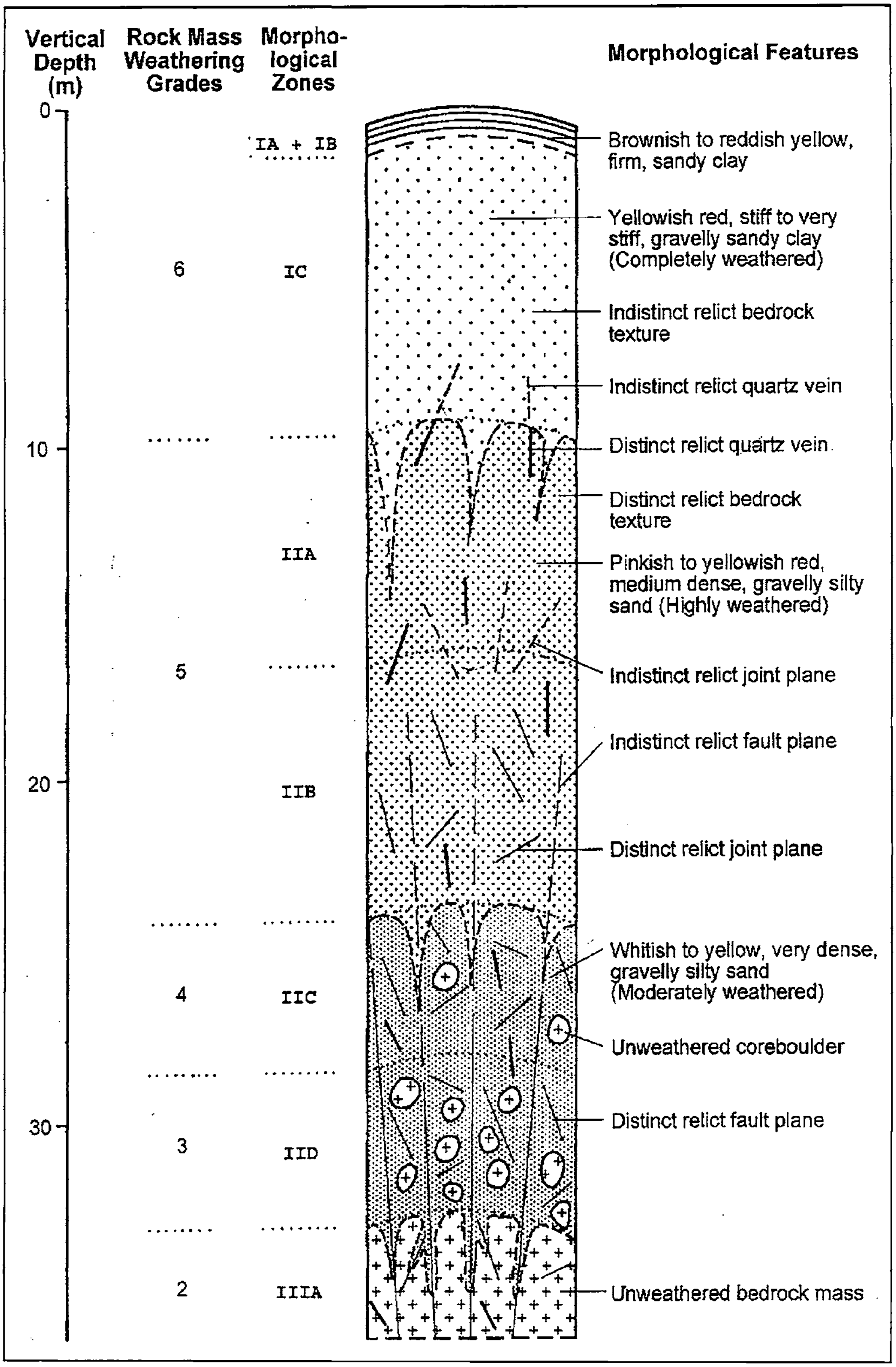

Figure 1: Weathering profile over porphyritic biotite granite.

structures of the original bedrock. These morphological zones and horizons represent different stages of weathering of the bedrock on the scale of the mass and can be correlated with Rock Mass Weathering Grades (Raj, 1985).

In the case of a typical weathering profile developed over a porphyritic biotite granite (Fig. 1), the topmost Zone I (Grade 6) is up to 10 m thick and consists of completely weathered bedrock materials that indistinctly preserve the textures, but not structures, of the original bedrock. The weathered materials have been subject to pedological processes and can be separated into an upper, friable sandy clay IA horizon, an intermediate, firm, sandy clay IB horizon, and a lower, stiff to very stiff, gravelly sandy clay, IC horizon.

Morphological Zone II (Grades 5, 4 & 3) is up to 25 m thick and consists of *in situ* moderately to highly weathered bedrock materials that indistinctly to distinctly preserve the minerals, textures and structures of the original bedrock; the degree of preservation increasing with depth. This Zone can be separated into four horizons; the top two horizons IIA and IIB consisting mostly of loose to medium dense, gravelly silty sands that show distinct relict bedrock textures and quartz veins, but indistinct relict fracture planes. The upper IIA horizon is devoid of coreboulders, whilst the lower IIB horizon contains a few partly weathered coreboulders. In the lower horizons IIC and IID, unweathered coreboulders are prominent and separated by thin to broad, bands of medium dense to very dense, gravelly silty sands showing distinct relict textures and structures. Unweathered coreboulders form up to some 50% by area of horizon IIC, but constitute more than 70% of the bottom IID horizon.

Morphological Zone III (Grades 2 & 1) consists of continuous bedrock with effects of weathering only along, and between, structural discontinuity planes. An upper IIIA horizon (some 6 m thick) can usually be distinguished where effects of weathering are seen as narrow to broad, strips of very dense, gravelly silty sands showing distinct relict bedrock textures and structures. In the lower IIIB horizon, weathering effects are only seen in thin strips of altered bedrock along discontinuity planes.

The morphological zones and horizons are developed approximately parallel to the over-lying ground surface and are thickest below ridge crests and summits, but thin towards valley floors. They show variable thicknesses that are dependent upon several factors, including the mineralogy and texture of the original bedrock, the regional and local topographic settings as well as the geomorphological history.

TYPES OF SLOPE FAILURES IN GRANITIC BEDROCK AREAS

Low Slope Cuts (<10 m vertical height)

Such cuts usually only expose the completely weathered bedrock materials of Zone I and have been affected by small (<5 m^3 in volume) earth falls and shallow slips when excavated at steep angles (>60°). These failures have occurred during periods of intense, or continuous, daily rainfall; the earth falls occurring at very steep (>80°) cuts and preceded by the development of tension cracks. The shallow slips, however, have mostly occurred at exposed cuts and were preceded by the development of desiccation (or shrinkage) cracks.

Where low cuts in undulating terrain have intersected groundwater tables, there have sometimes occurred slumps, during, or following, extended periods of continuous daily rainfall. These slumps, of various sizes (of up to 10 m^3 in volume), have occurred some 3 months to 2 years after the end of excavation at cuts of moderate slope angles (>40°) and were preceded by the development of desiccation cracks.

High Slope Cuts (>10 m vertical height)

In hilly to mountainous terrain, high cuts can expose a variety of earth materials ranging from completely weathered bedrock at the ground surface to fresh and unweathered bedrock at depth. In general, however, the top one or two benches expose the completely weathered bedrock materials of Zone I, whilst the middle and lower benches expose the *in situ* moderately to highly weathered bedrock materials of Zone II that often contains coreboulders. The bottom benches in some very high cuts furthermore, sometimes expose the continuous bedrock of Zone III and also intersect unconfined groundwater tables.

Top Benches of High Cuts

Where these benches have been excavated at steep face angles (>60°), there have sometimes occurred small (<5 m^3 in volume) earth falls and shallow slips; these failures showing similar features as those occurring at the low cuts.

Middle and Lower Benches of High Cuts

Where these benches have been excavated at steep face angles (>55°), there have sometimes occurred small to large (<10 m^3 in volume) wedge failures during periods of intense, or continuous daily, rainfall These failures have occurred within some 6 months of the end of excavation, at benches where steeply dipping (>45°) relict discontinuity planes show day-lighting lines of intersection.

At some high cuts of moderate to steep overall slope angles (>45°, but usually >55°), there have occurred small to large failures (of up to a few thousand m^3 in volume) towards, as well as several months to years after, the end of excavation. These failures have involved materials from both Zones I and II and have all occurred during, or following, periods of intense, or continuous daily, rainfall. Three different varieties may be distinguished, i.e. slump, slump-flow and debris flow (after Varnes, 1978), though they are somewhat gradational into one another.

'Slumps' are not common and have only occurred at cuts where the bedrock of Zone III is located close to the ground surface. At the lower benches of these cuts, slumping of Zone II materials has sometimes occurred along apparently deep seated, cylindrical sliding surfaces.

The 'slump flows' have involved weathered materials from both Zones I and II with the lower parts of the failure mass showing features of flow, whilst the upper parts appear to have just slumped down. The failure surfaces have been approximately cylindrical in shape, though they have also been located along relict structural discontinuity planes (Raj, 1998).

The 'debris flows' have only occurred along the sides of some high cuts during, or following, periods of exceptionally intense rainfall. These failures have mostly involved weathered materials from Zone II, with the failure mass, although consisting of silty sands and some coreboulders, behaving as flows.

Bottom Benches Of High Cuts

Where these benches have been excavated at steep face angles (>60°), there have sometimes occurred failures controlled by structural discontinuity planes present in the bedrock. The failures have been of various sizes (<10 m^3 in volume) and have occurred during periods of intense, or continuous daily, rainfall, some 6 months to several years after the end of excavation.

Where broad, planar discontinuity planes (particularly exfoliation) have day-lighted with steep dips (>45°), block slides and more rarely slab slides, have sometimes occurred; their sides being defined by other discontinuity planes. Where two planar discontinuity planes of steep dips with day-lighting lines of intersection are found, wedge failures have sometimes occurred. In some cases, where the discontinuity planes dip steeply (>70°) into the cut, toppling failures have occurred. At some benches with steep face angles and closely spaced fractures of variable orientations furthermore, rock falls have occurred.

Natural Slopes

Natural slopes in hilly to mountainuous terrain, covered with primary or secondary forests, have been affected by failures that are best classified as 'debris flows' (after Varnes, 1978). These failures, which are of various sizes (of up to a few thousand m^3 in volume), originate along, or close to, the valley floors of small streams where shallow unconfined groundwater tables are present and where a thin layer of weathered materials overlies bedrock. These failures have occured during, or following, periods of exceptionally, intense, or continuous daily, rainfall, when over-saturation of the weathered materials results in their down-slope movement as flows.

Embankment Slopes

Embankments over steep (>30°) natural ground slopes in mountainuous terrain have been affected by debris flows that have occurred during, or following, periods of intense, or continuous daily, rainfall. Embankments in undulating to hilly terrain, however, have been affected by slump-flows that have occurred during periods of continuous daily rainfall.

RAINFALL AND SLOPE FAILURES

Newspaper Reports

Reports in local newspapers of slope failures in the granitic bedrock areas of the Peninsula for the period 1981-1998 show a disproportionate pattern with some years having considerably more reports than others (Fig. 2a). When this pattern is compared with the total annual rainfall of selected stations for the same period, there is a distinct correlation with the years having a large number of reports coinciding with the years having relatively high annual rainfalls.

When the number of reports per month for the same period (Figs. 2b & 2c) is examined, a distinct monthly pattern is seen with few reports between January and April, and in July. Most reports of the East Coast are found in November and December (i.e. during the Northeast Monsoon), whilst those of the West Coast are mostly between October and December, and in May (i.e. during the two periods with maximum rainfall). Slope failures are therefore, to be associated with the months having relatively high rainfalls.

Individual Rainfall Events

1. The association of slope failures with rainfall has long been recognized in Peninsular Malaysia beginning with Scrivenor (1931, p.138) who reported that in "*December, 1911, big landslides caused by very heavy rain, carried away large sections of the Pahang road between the Gap and Tras*". These landslides, which can be classified as debris flows, occurred during the Northeast Monsoon, though the lack of detailed rainfall data prevents further inferences.
2. Fitch (1951, p.7) reported that many landslides at Bukit Berkelah and Gunong Serundom in the Kuantan area "*were started or deepened by the unusually heavy rains of the monsoon season in 1926-27, when the sound of falling rock and debris was audible in Gambang about 10 miles away*". These landslides, which can be classified as debris flows, occurred at natural slopes that were then most likely covered with primary forest. The monsoon season of 1926-27 was an exceptional one for the rainfall in December, 1926 was 1,961.9 mm; a value that is more than 3 times the mean December rainfall of 594.2 mm for the period 1898-1997. Winstedt (1927) furthermore, reported that in the Kuantan area, "*heavy rain commenced on the evening of 22nd December and continued incessantly till the 30th. The average rainfall for these nine days, was something over 9 inches* (228.6 mm) *in each 24 hours; the heaviest fall in 24 hours occurring on 27.12.26 when Jeram Kuantan Estate recorded 24.85 inches* (631.2 mm)". The occurrence of the landslides

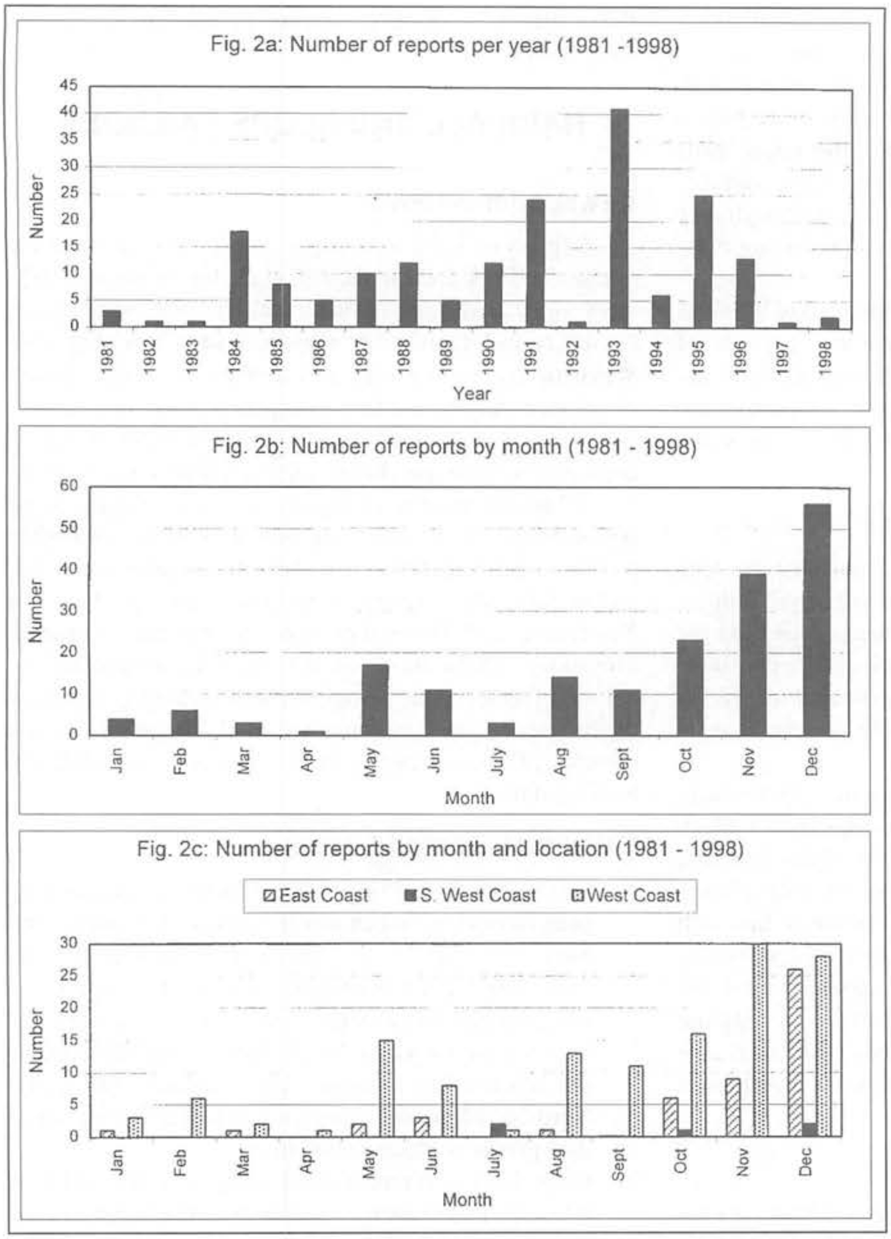

Figure 2: Local newspaper reports on slope failures in the granitic bedrock areas of Peninsular Malaysia (1981-1998).

can definitely be attributed to rainfall, in particular to the cumulative effect of continuous daily rainfall, though the effects of short-term high intensity rainfall cannot now be evaluated.

3. On 24th September, 1981, there occurred a slump-flow at a slope cut into the weathering profile over a porphyritic biotite granite at Km 24.5 of the Kuala Lumpur - Karak Highway. The failure occurred some 5.7 years after the end of excavation and involved the down-slope movement of about 2,000 m^3 of gravelly silty sands and a few coreboulders. The failure was considered to result from several converging factors; the triggering factor being ground vibrations set-up at the time of passing of three large trucks. Conditions of instability, however, were already present through infiltration of rainwater that led to saturation and loss of apparent cohesion within the slope materials. Infiltration of rainwater was encouraged by the clearing of surface vegetation, as well as rainfall patterns for failure occurred after some 29 days with almost continuous rainfall; this wet period being preceded by a dry period of 27 days (Raj, 1998). Infiltration of cumulative daily rainfall is therefore, considered to have given rise to conditions of instability within the slope materials.

The role of passing heavy vehicles as a triggering factor can also be cited for the large slump-flow that occurred on 6th December, 1996 at Km 303.8 of the North-South Expressway when a large container truck was swept down-slope by the failure mass. The failure occurred at a time of no rain, though there were several, preceding days of rainfall in the general area. Infiltration of cumulative daily rainwater is therefore, likely to have contributed to the development of conditions of instability within the slope materials.

4. In early September, 1988, there were several days with flash floods in Kuala Lumpur and Petaling Jaya during some 3 weeks of almost continuous daily rainfall. Several slope failures, including shallow slips, slumps and slump-flows, were observed at cuts in granitic, and sedimentary, bedrock areas. Failures in the granitic bedrock areas mainly occurred on 1st September, whilst those in the sedimentary bedrock areas occurred later. When daily rainfall records for August and September, 1988 at nearby rainfall stations were examined, it was seen that the failures on 1st September occurred after some 5 days of continuous rainfall with a cumulative total exceeding 140 mm. Infiltration of cumulative daily rainfall is thus considered to have given rise to the slope failures in the granitic bedrock areas.
5. In the Cameron Highlands area, there occurred a rainstorm in early December, 1994, which caused flash floods as well as over 90 slope failures. Debris flows, shallow slips and slump-flows were the main types of failures and mostly occurred during the evening of 6th December. Rainfall records show that a 3-day cumulative rainfall of 157.8 mm, and 134.6 mm, were recorded between 4th and 6th December, 1994 at the Cameron Highlands Meteorological Station, and Tanah Rata Climatological Station, respectively. Individual daily total rainfalls, however, did not exceed 87 mm at the Meteorological Station, where the 1-day maximum rainfall is 123.2 mm, and the 2-day maximum, 159.5 mm. Hourly rainfall records for the period 4th to 6th December, 1994, furthermore, show that most of the failures occurred at about the time of maximum rainfall intensity (32 mm/hr).

   When daily rainfall records for the months of November and December, 1994 are compared with similar records for 1993, 1995 and 1996 when there were no reports of slope failures, an interesting correlation arises for the failures on 6th December, 1994 occurred after a 2-day, cumulative total rainfall of some 70 mm; a total not seen in the same months for the other years. Infiltration of cumulative daily rainfall is thus likely to have given rise to the slope failures. A similar pattern of cumulative daily rainfall leading to slope failures in the Cameron Highlands area is also shown by the daily rainfall records for the months of September and October, 1995 and 1996, when flash floods and slope failures were reported on 24th October 1995 and 15th October 1996.
6. On Penang Island, there occurred a rain storm between 17th and 18th September, 1995, when some 250 mm of rain was received in most places over a period of 37 hours. Some areas, however, received more than 400 mm of rain, as Bt. Bendara (Penang Hill) where a total of 405.8 mm was received; this value surpassing the previous 2-day rainfall maximum of 298.9 mm. At a station further north (Kolam Bersih), 349.8 mm of rain were recorded during the rain storm, whilst the previous 2-day rainfall maximum was 318.5 mm. During the rain storm, some 312 slope failures were reported from different places on the island, particularly in the northern coastal stretch (59 failures), the Teluk Bahang - Balik Pulau road (85 failures), the Penang Hill jeep track (111 failures) and Jalan Tun Sardon (50 failures). Various types of failures occurred, though the main ones were debris flows, earth falls, shallow slips and slump-flows (Goh, 1997). An analysis on the progress and distribution of the rain storm using a 1-hour moving, 4-hour cumulative rainfall, indicated that the areas most affected by failures were spatially and temporaly related to the most intense part of the 100-year return period storm (Goh & Yeap, 1997). The exact timing of the failures is, however, unknown and it is likely that some of them resulted from the infiltration of cumulative rainfall, particularly those in the southern part of the island, where rainfall intensities were low.
7. On 30th June 1995, there occurred a large debris-flow along the slip road leading from the Kuala Lumpur - Karak Highway to Genting Highlands (Chow et al., 1996). The failure occurred at 6.00 pm and was preceded by a series of smaller landslides between 5.30 and 6.00 pm. The occurrence of the large failure can be correlated with rainfall, for a freak storm between 4.00 and 6.00 pm, led to some 96.5 mm of rain in 2 hours. This extraordinary amount of rainfall is especially significant for the previous 1-day total rainfall for the area is 131.9 mm. During the period of the freak storm, more than 200 other landslides (mostly earth falls, shallow slips and slump-flows) were also reported in a 3 km radius of the tragedy. There is little doubt that it was the intense rainfall during the storm that led to the failures. As the smaller landslides started at 5.30 pm, it is likely that landsliding was initiated after some 70 mm of rain.

CONCLUSION

Arising from the preceding discussions, it is concluded that slope failures in the granitic bedrock areas of Peninsular Malaysia are associated with rainfall; most failures occurring during, or following, short periods (<3 hr) of intense rainfall, or longer periods (>1 day) with somewhat continuous rainfall. The failures have often occurred when the total daily rainfall exceeds 70 mm and include earth falls, shallow slips, slumps, slump-flows and debris flows, as well as wedge failures, block slides and rock falls..

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