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Guidelines to prevention of slope failure related disasters in granitic bedrock areas of Malaysia

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Abstract: A variety of slope failures have occurred in the granitic bedrock areas of Malaysia; the more important of which are slump and debris flows that have sometimes led to considerable economic loss and loss of life. These failures have occurred at cut and fill slopes, as well as at natural ground slopes, having a varied vegetation cover ranging from primary and secondary forest to agricultural crops and grass. The failures have mainly involved weathered materials from morphological Zones I and II of the weathering profiles (or rock mass weathering grades 3 to 6) over granitic bedrock. Several factors are responsible for the failures, though the main cause is saturation and loss of negative pore water pressures within slope materials as the failures have mostly occurred during, or following, short periods (<3 hr) of intense rainfall (when total rainfall >70 mm), or longer periods (>1 day) of continuous rainfall.

In order to prevent slope failure related disasters, it is necessary to evaluate the various factors that give rise to the failures. The regional and local topographic settings of any site or area proposed for development needs to be first evaluated in order to allow recognition of the earth materials present and the earthworks that may be necessary. Evaluation of the local topographic setting is particularly important as the location of buildings and other structures needs to be considered with reference to the surrounding terrain. Surface and subsurface drainage patterns at the proposed site and surrounding area should then be evaluated as they influence variations in moisture contents and pore water pressures within slope materials. Stream channels and valleys also directly control the movement of debris flows in hilly to mountainous terrain. The rainfall at the proposed site and surrounding area also needs to be monitored in order to allow recognition of significant rainfall intensities and/or durations that increase the likelihood of slope failures. The vegetation cover at the proposed site and surrounding area also needs to be monitored as changes in this cover can also give rise to variations in moisture contents and pore water pressures within slope materials. The stability of cut and fill slopes associated with earthworks at the proposed site or area should finally be evaluated. Consideration and evaluation of all these factors will serve as guidelines that can prevent slope failure related disasters in the granitic bedrock areas of Malaysia.

INTRODUCTION

In recent years, there have been slope failures in the granitic bedrock areas of Malaysia that have led to considerable economic loss and loss of life. These disasters include the one at Ulu Kelang on 11-12-1993 when an apartment block was destroyed and some 48 lives lost and the one along the slip road from the Karak Highway to Genting Highlands on 30-06-1995 when a bus and several other vehicles were hit by a debris flow and some 20 lives lost. On Penang Island, periodic rainstorm events have led to several slope failures, the partial closure of major roads and the temporary evacuation of residents from apartment blocks in hilly areas as on 18-09-1995 and on 27-09-1999. In Kuala Lumpur, there has recently been the destruction of a bungalow and 8 deaths during a debris flow at Ulu Kelang on 20-11-2002. Other less prominent, though economically significant, slope failures include those that often occur along the main road from Tapah to Tanah Rata, as in November and December 1999 which caused a decrease in the occupancy rates of leading hotels in Cameron Highlands from the normal 40 to 50% to 20%. On 15-05-1999, several slope failures led to temporary closure of the access road to Bukit Antarabangsa and other residential areas in Ulu Kelang. Several speculative and often conflicting opinions have been expressed on the causes of the failures; these opinions sometimes resulting in unwarranted animosity.

Slope failure related disasters are, however, not unique to Malaysia for similar events have occurred in several other countries as Hong Kong and Brazil where the economic loss and loss of life has often been much greater. In Hong Kong in particular, where several slope failure related disasters occurred in the 1960's and 1970's, there was established the Geotechnical Control Office whose role is the supervision of all development and engineering projects. In Malaysia, several proposals and recommendations on slope failures and the development of hilly to mountainous terrain have been forwarded by various individuals and organizations; some of them even recommending that development not be carried out here.

Notwithstanding the various proposals and recommendations that have been forwarded, this paper discusses the main factors that need to be evaluated in order to prevent slope failure related disasters in the granitic bedrock areas of Malaysia. These factors are those that lead to, or serve as causes of, slope failures and their proper evaluation will therefore, serve as guidelines to prevent the future occurrence of failures. Evaluation of the factors can also allow for the proposal of suitable remedial measures.

It must be pointed out here that slope failures are not an unexpected occurrence, for they have and will continue to occur in different areas of the world as a result of variations in topography.

GRANITIC BEDROCK IN MALAYSIA

Granitic rocks (i.e. holocrystalline, medium to coarse grained rocks of plutonic aspect with a hypidomorphic-granular texture and composed essentially of quartz, potash feldspar and/or sodic plagioclase and subordinate biotite, muscovite and hornblende) are the most prominent lithology of Peninsular Malaysia and outcrop over some 40% of its' land surface. They form the bedrock of the main mountain ranges and have been differentiated into four groups on the basis of differences in mineralogy, geochemistry and radiometric ages (Hutchison, 1977).

Epizonal Late Cretaceous granites of the Peninsula are only found in Johore State as small plutons of circular to elliptical shapes with pronounced contact aureoles that have mostly intruded Triassic sedimentary rocks and older granites. These granites are commonly pink coloured with medium to coarse grained, equigranular to weakly porphyritic textures. The epizonal Triassic granites also occur as small plutons and are only found in the central part of the Peninsula and on Langkawi Island. These granites are grey coloured with medium to coarse grained, equigranular to weakly porphyritic textures. On Langkawi Island, they intrude folded Palaeozoic rocks with a pronounced contact aureole, though in central Malaya, they intrude folded, Permian to Triassic sedimentary rocks without any pronounced contact aureole.

Epizonal Permo-Triassic granites of the Peninsula are found in its' eastern and northern parts and occur as large, elongated batholiths with pronounced contact aureoles. They are grey to pink in colour with medium to coarse grained, predominantly equigranular to weakly porphyritic textures and intrude strongly deformed, regionally metamorphosed Carbo-Permian sedimentary rocks. Mesozonal Permo-Triassic granites outcrop along the western part of the Peninsula and occur as large, elongated batholiths with unpronounced contact aureoles in their country rocks, which are mostly phyllitic and often isoclinally folded. These granites are grey coloured and commonly show porphyritic, coarse grained textures.

In East Malaysia, granitic rocks are of a very restricted occurrence and mainly found in southwest and central Sarawak, as well as in central and east Sabah. In southwest Sarawak, pre-Triassic granodiorite has given rise to Gunung Jagoi and Gunung Kisam, whilst stock-like intrusions during Jurassic to late Cretaceous times have led to the adamellites at Gunung Pueh, Gunung Gading, Tanjung Datu, Tinteng Bedil and Gunung Buri and the Sebayu granodiorite. During the mid-Miocene, there was widespread intrusion of high-level, hypabyssal igneous rocks throughout West Sarawak, including the large granodiorite stock at Gunung Menuku-Gunung Buri, and the smaller granite stocks at Bukit Garu, Munggu Gran and Bukit Selanjan (Anon, 1993a).

In the Upper Balingan Valley of central Sarawak, there was intrusion of a granitic stock at Piring Hill during the middle Tertiary, whilst in the upper Rejang and Baram Valleys, there were widespread late Tertiary igneous intrusions of hypabyssal character that include the Bukit Kalong tonalite porphyry stock, the tonalite porphyry dykes of the Usun Apau Plateau, and granodiorite and tonalite porphyry dikes in the Linau Balui area (Anon, 1993a).

In east Sabah, granitic rocks are mainly associated with pre-Triassic basement rocks of the Segama Valley and Darvel Bay area where granodiorite, trondhjemite, granite and tonalite were emplaced in Early Triassic time, followed by late-stage pegmatite and aplite intrusions. In central Sabah, the granitic rocks of the Mount Kinabalu intrusion form the most outstanding topographic feature of Sabah and comprise a large adamellite stock that was emplaced during Late Miocene time into tectonically brecciated and faulted Tertiary sedimentary rocks (Anon, 1993b).

WEATHERING PROFILES OVER GRANITIC BEDROCK IN MALAYSIA

Malaysia is located within the humid tropics and has a present-day climate that is characterized by uniform temperatures, high humidity and abundant rainfall. A similar climatic regime is thought to have been operative throughout the Quaternary, though some authors have postulated more seasonal tropical climates. As Peninsular Malaysia is located in a tectonically stable area and has been almost entirely or partially emergent throughout the Quaternary, prolonged and pervasive weathering has given rise to deep weathering profiles (Raj, 1982). In East Malaysia, however, depths of weathering are more variable, with some areas as West Sarawak showing deep profiles as a result of prolonged emergence, while thin profiles are found in other areas due to uplift and active erosion during much of the Tertiary and Quaternary.

The weathering profiles are characterized by lateral and vertical variations in the degree of preservation of the minerals, textures and structures of the original bedrock; these variations allowing for recognition of several morphological zones and horizons that can be correlated with Rock Mass Weathering Grades (Raj, 1983, 1985).

In the case of a typical weathering profile over a porphyritic biotite granite (Fig. 1), the topmost morphological Zone I (weathering Grade 6) is up to some 12 m thick and consists of completely weathered bedrock that indistinctly preserves 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, sandy clay IA horizon (<1 m thick), an intermediate, sandy clay IB horizon (<2 m thick) and a lower, stiff to very stiff, gravelly sandy clay, IC horizon (up to 10 m thick). Consolidated, drained triaxial tests on undisturbed, and remoulded, samples from the IC horizon, and other similar horizons, yield cohesion (c) intercepts of up to 20.7 kN/m^2 (kPa) and f (angle of internal friction) values of 31° to 38° (Raj, 1983).

Morphological Zone II (comprising weathering Grades 3, 4 and 5) is up to 30 m thick and consists of *in situ* moderately to highly weathered bedrock 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 mainly of loose to medium dense, gravelly silty sands with distinct relict textures and quartz veins, but indistinct relict structural discontinuity planes. The upper IIA horizon is up to 6 m thick and devoid of coreboulders, whilst the lower IIB horizon is about 5 m thick and 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 to very dense, gravelly silty sands showing distinct relict textures and structures. The coreboulders form up to some 50% by area of horizon IIC (about 5 m thick), but constitute more than 70% of the IID horizon. Consolidated, drained triaxial tests on undisturbed, and remoulded, samples of the medium to very dense, gravelly silty sands from Zone II, and from other similar Zone II, mostly only yield f (angle of internal friction) values of between 35° and 38° (Raj, 1983).

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

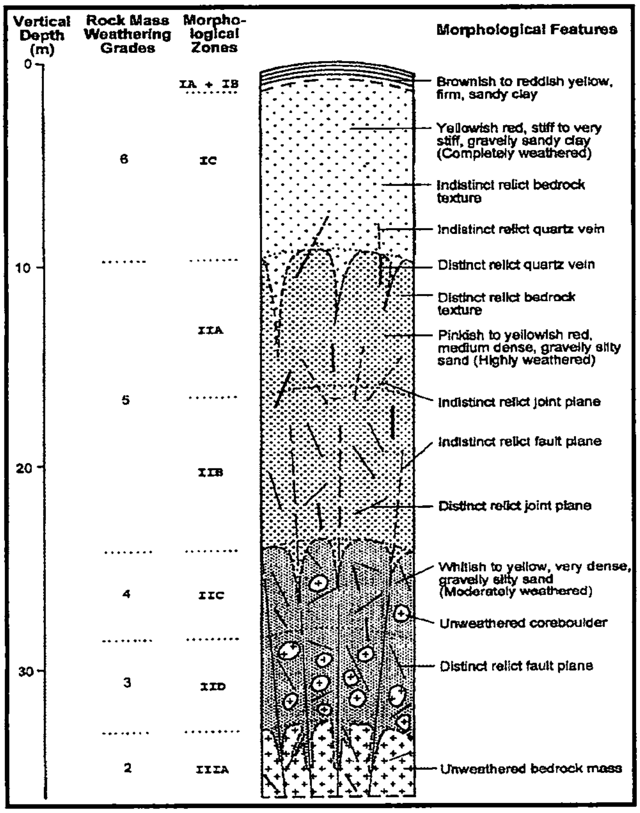

Figure 1. Weathering profile over porphyritic biotite granite.

The morphological zones and horizons are developed approximately parallel to overlying ground surfaces and are thickest below ridge crests and summits, but thin towards valley floors. They show varying 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 site geomorphic history. Over sheared granite for instance, Zone II is very thick and characterized by an absence of large coreboulders, though over more massive bedrock, Zone II is relatively thin and has many coreboulders. Along steep valley slope in mountainous terrain, weathering profiles are also thin with Zone II being up to some 10 m thick, though in undulating terrain over similar bedrock, the same Zone can be over 30 m thick. In hilly to mountainous terrain, granitic bedrock is often found in the valley floors, though in low-lying to undulating terrain, such outcrops are absent.

Variations in geomorphic history also give rise to differences in thicknesses of the weathering profiles. In coastal areas influenced by the global Holocene rise of sea-level, as Penang Island, granite outcrops are seen at headlands whilst thin weathering profiles are found in their immediate hilly inland areas. Surface erosion post-dating the development of weathering profiles can also lead to truncated profiles, with coreboulders exposed at the ground surface and Zone I being only 2 or 3 m thick as in the Tampin area. Close to the summit of Gunung Kinabalu furthermore, there is an absence of any soil cover due to erosion by glaciers during the late Pleistocene.

SLOPE FAILURES IN GRANITIC BEDROCK AREAS OF MALAYSIA

In view of differences in lithology, regional and local topographic settings as well as geomorphic history, a variety of earth materials can be expected to underlie, or be exposed at, slopes in the granitic bedrock areas of Malaysia. These slopes are found in a variety of environmental settings, though they are more prominent in hilly to mountainous terrain where relative reliefs exceed several tens of meters. Three broad groups of slopes or sloping ground surfaces can be distinguished, i.e. natural ground slopes, cut slopes and fill slopes.

Natural ground slopes

Natural ground slopes (i.e. slopes not modified by man) are found in undulating to hilly and mountainous terrain, in both developed and undeveloped areas. They have a varied vegetation cover, ranging from undisturbed and partially logged, primary forest to secondary forest and agricultural crops, including rubber, oil palm and tea. In undulating terrain (< 100 m elevation), valley slopes show low angles (<10°), though in hilly terrain (between 100 and 1,000 m elevation), they are much steeper (<20°). In mountainous terrain (above 1,000 m elevation), valley slopes show moderate to steep angles (15° to 35°) and can sometimes be very steep (up to 45°) as at sites where undercutting by rivers occurs.

Slope failures at natural ground slopes in different environmental settings have mostly occurred close to the valley floors of the small and large streams draining these areas. Along stream channels, where there is active fluvial erosion, small (<10 m^3 in volume), earth falls and slumps are found, whilst small, shallow slips have sometimes occurred along the valley slopes.

Large slope failures (involving up to a few thousand m^3 in volume) have also occurred at natural ground slopes in hilly to mountainous terrain with a very varied vegetation cover, including primary and secondary forest and agricultural crops. These failures are best classified as 'debris flows' and have occurred along, or close to, the valley floors of small streams where shallow unconfined groundwater tables and a thin layer of weathered materials over bedrock is found (Raj, 2000a). These failures occurred during, or following, periods of exceptionally, intense, or continuous daily, rainfall, when over-saturation of the weathered materials resulted. These failures also sometimes resulted from accumulation of several smaller, valley side slips that occurred at about the same time within a single drainage basin (Chow *et al.*, 1996).

Examples of debris flows occurring at natural ground slopes with a primary forest cover during periods of exceptional rainfall include those at Bukit Berkelah in the Kuantan area between 22-12-1926 and 30-12-1926, and the one along the slip road from the Karak Highway to Genting Highlands on 30-06-1995 (Raj, 2000a). Debris flows occurring at natural ground slopes with a secondary forest cover include several in the Ulu Kelang area, as the ones along the access road to Bukit Antarabangsa on 18-09-1995 and 15-05-1999, and more recently, the one at Taman Hillview on 20-11-2002.

Cut slopes

Such slopes are mainly found along transport routes and developed areas in hilly to mountainous terrain (above 100 m elevation) and have a varied vegetation cover ranging from grass to ferns and other plants. In view of inherent differences in topographic settings and geomorphic history, these cuts are excavated in, and expose, a variety of earth materials ranging from completely weathered to fresh, unaltered granitic bedrock. This variability in earth materials has been considered to make difficult the prediction of the stability of the cuts on the basis of field or laboratory tests, as well as prevent realistic applications of mathematical stability analyses (Bulman, 1968; Broms, 1978; da Costa Nunes *et al*, 1979; Brand, 1984).

In undulating terrain (<100 m elevation), low cuts (<10 m vertical height) usually only expose the completely weathered bedrock of morphological Zone I, whilst high cuts expose Zone I and the moderately weathered bedrock of upper Zone II. In hilly to mountainous terrain (>100 m elevation), low cuts also only expose the completely weathered bedrock of Zone I, whilst high cuts (>10 m vertical height) can expose a variety of earth materials ranging from completely weathered to fresh, unaltered bedrock. The top one to two benches, however, expose morphological Zone I, whilst the middle and lower benches expose the *in situ* moderately to highly weathered bedrock of Zone II. At some very high cuts, the bottom benches can expose the continuous bedrock of Zone III.

Low cuts (<10 m vertical height)

At low cuts in undulating to hilly and mountainous terrain, excavated with steep face angles (>60°), there have sometimes occurred small (<5 m^3 in volume), earth falls and shallow slips, during periods of intense, or continuous, daily rainfall. The earth falls were preceded by development of tension cracks and occurred at very steep (>80°) cuts, whilst the shallow slips were preceded by development of desiccation cracks and mainly occurred at cuts devoid of a vegetation cover. The occurrence of these failures has been attributed to saturation during rainfall and a decrease of shear strength with time (due to the cracks) (Raj, 2000b).

High cuts (>10 m vertical height)

Along the upper benches of high cuts in undulating to hilly and mountainous terrain, 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 to those occurring at the low cuts.

Along the middle and lower benches of a few high cuts, excavated at steep face angles (>55 °), there have sometimes occurred small (<10 m^3) wedge failures during periods of intense, or continuous, daily rainfall. These failures occurred within some 6 months of the end of excavation at benches where steeply dipping (>45°), day-lighting relict discontinuity planes were present. These failures have been attributed to rainwater induced saturation and low shear strengths along the day-lighting relict discontinuity planes (Raj, 2000a).

In undulating terrain, where high cuts intersected unconfined groundwater tables, there have sometimes occurred slumps of variable size (<10 m^3 in volume), during, or following, extended periods of continuous daily rainfall. These slumps occurred some 3 months to 2 years after the end of excavation at cuts of moderate overall slope angles (>40°) and were preceded by development of desiccation cracks. Their occurrence is attributed to a decrease in strength with time of the slope materials and an increase in pore water pressure due to a temporary rise in the groundwater table. Examples of such slumps are seen along several Highways where they cross undulating terrain such as the New Klang Valley Expressway.

In hilly to mountainous terrain, at high cuts of steep overall slope angles (>45°, but usually >55°), there have sometimes occurred large failures (up to a few thousand m^3 in volume) that have taken place towards, as well as several months to years after, the end of excavation. These failures can be classified as slumps, slump-flows and debris flows, though they are gradational into one another (Varnes, 1978). As these failures all occurred during, or following, periods of intense, or continuous daily, rainfall, they have been considered to result from rainwater induced saturation that led a decrease in shear strength through loss of negative pore pressures within the slope materials (Raj, 1983, 2000a).

'Slumps' are not common and have only occurred at cuts where the Zone III bedrock is found close to the ground surface. At the lower benches of these cuts, slumps of Zone II materials have sometimes occurred along apparently deep seated, cylindrical sliding surfaces. Examples of such slumps have been seen along the Kuala Lumpur-Karak Highway.

The 'slump flows' involved weathered materials from both morphological Zones I and II with the failure surfaces having been approximately cylindrical in shape, though sometimes located along relict structural discontinuity planes. Examples of such slump flows have been seen along several Highways, as the Kuala Lumpur-Karak Highway where a slump-flow at km 24.5 on 24-09-1981 occurred in part as a result of the clearing of surface vegetation and a prolonged dry period; the failure triggered at the time of passing of three large trucks (Raj, 1998). The triggering role of passing heavy vehicles can also be cited for the large slump flow that occurred on 06-12-1996 at km 303.8 of the North-South Highway when a large container truck was swept down-slope by the failed materials.

The 'debris flows' have only occurred along the sides of some high cuts, as those along the Kuala Lumpur-Karak Highway, during or following periods of very intense rainfall. They are similar to those that have occurred at natural ground slopes and have mostly involved weathered materials from morphological Zone II.

In the lower benches of a few high cuts excavated with steep face angles (>60°) that expose the continuous bedrock of Zone III, there have sometimes occurred failures controlled by inherent structural discontinuity planes. These failures have been of various sizes (<10 m^3 in volume) and occurred during periods of intense, or continuous daily, rainfall, some 6 months to several years after the end of excavation. Wedge failures have occurred at benches where two planar, day-lighting discontinuity planes with steep dips (>45°) were present, whilst toppling failures sometimes occurred at benches where the discontinuity planes dipped steeply (>70°) into the cut. At benches, where closely spaced joints of variable strikes and dips were present, rock falls have sometimes occurred. Examples of such failures have been seen in the bottom benches of some high cuts along Highways, as the Kuala Lumpur-Karak Highway, and at abandoned quarries, as in the Paya Terubong area of Penang Island on 27-08-1999.

Fill slopes

Fills are found in a variety of environmental settings with slopes that have been created through dumping and compaction of weathered granitic bedrock materials. These fills (that can serve as embankments) have thus been constructed of varying proportions of sands, silts and clays and more rarely coreboulders derived from the weathered bedrock. Fills are found in undulating to hilly and mountainous terrain, especially along transport routes and in developed areas. They are of variable heights, but usually constructed with moderate overall slope angles (<30°).

Failures at fill slopes have occurred several months to years after the end of construction, during, or following, periods of intense, or continuous daily, rainfall. These failures, which can be classified as slumps or slump-flows, have been considered to result from rainwater induced saturation that led a decrease in shear strength within the slope materials (Raj, 2000b). Examples of slumps and slump flows at fills have been seen along several transport routes as on Penang Island during a rainstorm on 18-09-1995 (Goh and Yeap, 1997) and in developed areas as the Cameron Highlands during any rainstorm. Some failures that occurred in the Ulu Kelang area during a rainstorm on 15-05-1999 also involved fill slopes.

GUIDELINES TO PREVENTION OF SLOPE FAILURE RELATED DISASTERS

Although a variety of failures have occurred in the granitic bedrock areas of Malaysia, the more important ones are the debris and slump flows that have been of sufficiently large volumes to have had a significant impact on human activities. Four main factors are associated with the occurrence of these failures, i.e. rainfall, topography, drainage and vegetation cover and their evaluation prior to the development of any site or area can thus help prevent any slope failure related disaster.

Rainfall

Rainfall is undoubtedly the most significant factor that needs evaluation for most slope failures have occurred during, or following, short periods (<3 hr) of intense rainfall (when total rainfall >70 mm), or longer periods (>1 day) with somewhat continuous rainfall (Raj, 2000a). Rainfall, however, is a natural phenomena whose intensity and duration is highly variable both in space and time. Given such variability, it is difficult to predict the likelihood of slope failures during any particular rainstorm. As the intensity and duration of rainfall can be correlated with slope failures, however, it is possible to have 'threshold' values that would indicate the increased likelihood or risk of slope failures.

Monitoring of rainfall can thus help prevent slope failure related disasters especially in situations where transport routes, buildings and other structures are located at the foots of slopes, or hilly to mountainous terrain, covered with primary or secondary forest (Chow *et al.*, 1995). When rainfall in the relatively inaccessible forested area exceeds a specified intensity or duration indicating an increased risk or possibility of slope failure, then warning signs or notices for evacuation can be quickly issued and perhaps even have temporary closure of the transport routes.

Topographic setting

The topographic setting, both regional and local, is the next most important factor that needs evaluation, for it influences the earth materials as well as surface and subsurface drainage patterns present at any site or area. The topography also influences the earthworks that are necessary, especially cut and fill slopes.

The regional topographic setting reflects the geomorphic history of the site and controls the earth materials that will be exposed at slope cuts, or used for fills. In undulating terrain for instance, deep weathering profiles are anticipated and low cuts will expose the relatively stable, cohesive clayey sand to sandy clay of Zone I, though shallow groundwater tables may influence their stability. Along steep valley sides in mountainous terrain furthermore, thin weathering profiles are anticipated and high cuts may expose the continuous bedrock of morphological Zone III.

The local or site topographic setting is a more important factor that needs evaluation and refers to the location of any site relative to its surrounding terrain. Local topographic settings can thus involve the top of a hill or ridge, the upper, middle or lower, slopes of a large valley, the valley floors and so on. The local topographic setting not only influences the earth materials that are involved, but also the surface and subsurface drainage patterns. The surface drainage patterns are particularly important for sites at, or close to, the outlets of streams draining hilly to mountainous terrain can be swamped by debris flows as the disaster at Pos Dipang on 29-08-1996. Sites located close to, or along, surface drainage lines or depressions, in hilly to mountainous terrain thus need to be carefully evaluated. Zoning of sites for different purposes can be taken into account during evaluation of the topographic setting with unsuitable sites forming buffer zones or green belts.

Drainage

Surface and subsurface drainage patterns also need evaluation as they influence the stability of slopes in granitic bedrock areas through their control on variations in moisture content (as saturation and loss of apparent strength) and pore water pressures (as rise of ground water table). Existing surface drainage lines and stream channels furthermore, are conduits along which debris flows can move, especially in hilly to mountainous terrain.

The surface drainage of cut and fill slopes is also an extremely important factor for evaluation as their failures mostly result from saturation during rainfall. Proper surface drainage will reduce infiltration and thus prevent saturation of the slope materials, and in the case of slope cuts, maintain negative pore pressures within the earth materials.

Vegetation cover

The vegetation cover has a variable effect on slope failures for debris flows have occurred at natural ground slopes with an undisturbed primary forest cover as well as with a secondary forest cover. In the case of slope cuts, however, the clearing of surface vegetation has been considered to enhance infiltration and the development of conditions of instability (Raj, 1998). This is to be expected, as exposure of the ground surface will allow for increased infiltration, particularly where desiccation and tension cracks develop within the slope materials. Changes in vegetation cover at the proposed site for development and in the general area surrounding the site, thus need to be monitored and evaluated in order to recognize any increased infiltration and likelihood of slope failures. Such monitoring would especially be needed in areas, where existing vegetation covers, including primary forest and agricultural crops, are cleared for replanting.

Slope type

This is an indirect factor that needs evaluation and results from the earthworks needed for the development of any site or area. In the case of cut slopes, it is perhaps better to design them based on precedence rather than analytical analyses for such analyses using laboratory determined strength parameters often give low factors of safety. In Peninsular Malaysia, however, there are several high cuts (>40 m vertical height) with steep, overall slope angles (45° to 60°) excavated in the weathered granitic bedrock of Zones I and II, where failures have not occurred for several decades (>50 years). These weathered materials thus appear to possess an inherent strength (apparent strength) that is likely due to negative pore water (or suction) pressures (Lumb, 1975; Brand, 1984, Raj, 1983, 1998, 2000a).

It is also necessary to evaluate the stability of individual benches in view of some failures having only involved specific zones of weathering profiles over granitic bedrock. For instance, where the continuous bedrock of morphological Zone III is exposed in the bottom benches of high cuts, evaluation will be needed of the orientations, extents and spacings of the structural discontinuity planes inherent in the bedrock and indistinctly to distinctly preserved (as relict structures) in morphological Zone II. Arising from this evaluation, stabilisation measures as rock bolts, concrete buttresses and the like may be proposed to enhance the stability of the cuts.

In the case of fill slopes, proper laboratory tests on representative samples are needed to ensure their proper compaction and hence stability. As these fill slopes involve reworked earth materials, there is better control on their subsequent behaviour.

CONCLUSION

In conclusion, it can be said that an evaluation of the factors that give rise to slope failures can prevent slope failure related disasters in the granitic bedrock areas of Malaysia. The regional and local topographic settings of any site or area proposed for development needs to be first evaluated in order to allow recognition of the earth materials present and the earthworks that may be necessary. Evaluation of the local topographic setting is particularly important as the location of buildings and other structures needs to be considered with reference to the surrounding terrain. Surface and subsurface drainage patterns at the proposed site and surrounding area should then be evaluated as they influence variations in moisture contents and pore water pressures within slope materials. Stream channels and valleys also directly control the movement of debris flows in hilly to mountainous terrain. The rainfall at the proposed site and surrounding area also needs to be monitored in order to allow recognition of significant rainfall intensities and/or durations that increase the likelihood of slope failures. The vegetation cover at the proposed site and surrounding area also needs to be monitored as changes in this cover can also give rise to variations in moisture contents and pore water pressures within slope materials. The stability of cut and fill slopes associated with earthworks at the proposed site or area should finally be evaluated. Consideration and evaluation of all these factors will serve as guidelines that can prevent slope failure related disasters in the granitic bedrock areas of Malaysia.

REFERENCES

ANON, 1993a. Regional Geology — Sarawak. *Ann. Rept. 1993, Geol. Survey Dept. Malaysia.* Percetakan Zainon Kassim Sdn. Bhd., Ipoh, 67-82.

ANON, 1993b. Regional Geology — Sabah. *Ann. Rept. 1993, Geol. Survey Dept. Malaysia.* Percetakan Zainon Kassim Sdn. Bhd., Ipoh, 83-90.

BRAND, E.W., 1984. Landslides in South-East Asia: A State of the Art Report. *Proc., 4th Int. Symp. On Landslides, Toronto, Canada, 1*, 17-59.

BROMS, B.B., 1975. Landslides. *In:* Winterkorn, H.F. and H.Y. Fang (Eds.), *Foundation Engineering Handbook*, van Nostrand Reinhold Co., 373-401.

BULMAN, J.N., 1968. A survey of road cuttings in Western Malaysia. *Proc. 1st S.E. Asian Conf. Soil Eng., Bangkok*, April 1967, 219-300.

CHOW, W.S., MIOR SALLEHHUDDIN, M.J. AND SAZALI, Y, 1996. Geological and geo-morphological investigations of debris flow at Genting Sempah, Selangor. *Proc. Geol. Soc. Malaysia, Forum "Geohazards: Landslide & Subsidence"*. 22 Oct. 1996, Kuala Lumpur, 5.1-5.15.

DA COSTA NUNES, A.J, COUTO FONSECA, A.M.M. AND HUNT, R.E., 1979. Landslides of Brazil. *In:* Voight, B. (Ed.), *Rockslides and Avalanches, Dev. In Geotech. Eng. 2.* Elsevier, Amsterdam. V.2, 419-446.

GOH, S.H. AND YEAP, E.B., 1977. The analysis on the cause of the slope failures and debris fluid flows in Penang Island which happened on 18th September 1995. *Abstracts, Ann. Geol. Conf. 1997, 31 May & 1 June, 1997, Geol. Soc. Malaysia*, 21-30.

HUTCHISON, C.S., 1977. Granite emplacement and tectonic subdivision of Peninsular Malaysia. *Bull. Geol. Soc. Malaysia, 9*, 187-207.

LUMB, P., 1975. Slope failures in Hong Long. *Quat. J. Eng. Geol., 8*, 31-36.

RAJ, J.K., 1982. A note on the age of the weathering profiles of Peninsular Malaysia. *Newsletter, Geol. Soc. Malaysia, 8(4)*, 135-137.

RAJ, J.K., 1983. *A study of residual soils and the stability of their slope cuts.* Unpubl. Ph.D. Thesis, Univ. Malaya, 462p.

RAJ, J.K., 1985. Characterisation of the weathering profile developed over a porphyritic biotite granite bedrock in Peninsular Malaysia. *Bull. Int. Assoc. Eng. Geol., 32*, 121-128.

RAJ, J.K., 1998. The failure of a slope cut into the weathering profile developed over a porphyritic biottie granite. *J. Asian Earth Sc., 16(4)*, 419-427.

RAJ, J.K., 2000a. Rainfall and slope failures in the granitic bedrock areas of peninsular Malaysia. *Proc. Ann. Conf., Geol. Soc. Malaysia, Sept. 8 & 9, 2000, Penang*, 275-282.

RAJ, J.K., 2000b. Landslides In Malaysia — Types, Causes and Prevention. *Inaugural Lecture*, Dept. Geology, Univ. Malaya. Nov. 2000.

VARNES, D.J., 1978. Slope movement types and processes. In: R.L. Schuster and R.J. Kriek (Eds.), Landslides — Analysis and Control. *Spec. Rept. 176, Nat. Acad. Sciences, Washington*, 11-33.

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