

Failures at slope cuts in clastic sedimentary bedrock in Malaysia

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Abstract: Interbedded sandstones, siltstones and shales are the dominant clastic sedimentary rocks of Malaysia and are exposed at slope cuts where an upper Zone I (residual soil) of completely weathered bedrock modified by pedological processes is seen. Zone I is up to 6 m thick and overlies the *in situ*, slightly to completely weathered bedrock of Zone II that preserves the minerals, textures and structures of the original strata; the degree of preservation increasing with depth. Low cuts and the top benches of high cuts in undulating to hilly and mountainous terrain expose Zone I and have experienced small earth falls and shallow slips during periods of continuous daily rainfall. Where the cuts intersect unconfined groundwater tables, slumps and compound slides are observed. In hilly to mountainous terrain, the lower benches of high cuts (>10 m high) expose Zone II and have experienced small to large, block and slab slides as well as wedge failures, during periods of continuous daily rainfall. At some very steep benches exposing indurated (hard) bedrock, toppling failures and rock falls have sometimes occurred during rainfall. Design of slope cuts in clastic sedimentary bedrock in Malaysia thus needs to take into consideration their geometry, topographic setting, exposed lithologies and structural discontinuity planes as well as weathering and rainfall patterns.

Abstrak: Batuan sedimen klastik utama di Malaysia adalah batupasir yang saling berlapis dengan batulodak dan syal. Batuan tersebut terdedah di cerun-cerun potongan di mana satu lapisan permukaan terdiri daripada batuan terluuhuhawa sepenuhnya dapat dibezakan (Zon I - tanah baki). Zon I mempunyai ketebalan sampai 6 m dan menindih Zon II yang dicirikan oleh batuan terluluhawa secara *in situ* dengan mineral, tekstur dan struktur batuan asal. Di kawasan beralun sehingga bukit, cerun potongan rendah, dan bench atas cerun tinggi mendedahkan Zone I dan telah mengalami jatuh tanah dan gelinciran cetek semasa tempoh hujan. Di mana cerun potongan merentasi air tanah tak terbatas, nendatan dan luncuran kompleks telah berlaku. Di kawasan berbukit, bench bawah cerun tinggi mendedahkan Zon II dan telah mengalami luncuran blok dan slab yang kecil ke besar dan kegagalan baji semasa tempoh hujan. Di cerun potongan curam yang mendedahkan batuan sedimen keras, kegagalan terbalik dan jatuh tanah batuan telah berlaku semasa hujan. Rekabentuk cerun potongan di kawasan batuan sedimen klastik di Malaysia perlu mengambil kira geometri, keadaan topografi, jenis litologi dan satah ketakselarangan batuan, serta corak peluluhawaan dan hujan.

INTRODUCTION

A variety of clastic sedimentary rocks of different ages, depositional environments and post-depositional histories is found in Malaysia and have mostly given rise to an undulating to hilly terrain, though in East Malaysia, they have also given rise to mountainous terrain. The construction of transport routes through these areas has led to the excavation of slope cuts of variable geometries, though their stability is often a matter for concern in view of the many, small to large failures that have occurred. Several types of failures have occurred; these failures being influenced by not only the geological (lithology and structure) and topographic settings, but also by the geomorphological history. In this paper the failures that have occurred at slope cuts in interbedded sandstones, siltstones and shales; these rocks being the dominant clastic sedimentary rocks of Malaysia are discussed. Conclusions are reached on the various factors that need to be taken into consideration in designing slope cuts in such bedrock.

SEDIMENTARY BEDROCK IN MALAYSIA

Peninsular Malaysia

Sedimentary rocks outcrop over some 40% of Peninsular Malaysia with Lower Palaeozoic rocks confined to its western part where they comprise thick deltaic deposits and shelly limestones in Pulau Langkawi and Perlis, but carbonaceous and siliceous fine grained sediments often interbedded with sandstone and limestone in Kedah and Perak. East of the Main Range, and in Selangor, Negeri Sembilan and Malacca, the Lower Palaeozoic comprises poorly graded and rapidly accumulated sediments associated with contemporaneous volcanic and ophiolitic rocks (Jones, 1973).

Upper Palaeozoic rocks are more widespread, with the lower Upper Palaeozoic in the Northwest represented by a clastic sequence that was replaced by a limestone facies in Mid-Permian. In central Perak, limestones with thin shale interbeds form an apparently continuous succession from

Lower Devonian to Mid-Permian, whilst clastic sediments represent the Upper Palaeozoic in Selangor. In central Peninsular Malaysia, Upper Palaeozoic shales and limestones with associated volcanics are found folded together with overlying Triassic rocks. In east Peninsular Malaysia, the Upper Palaeozoic is represented by a sequence of interbedded sandstones, limestones and shales with associated volcanics that have largely been regionally metamorphosed (Gobbett, 1973).

Lower Triassic limestones, shales and volcanics are only found in central Peninsular Malaysia together with Middle and Upper Triassic sandstones, shales and volcanics with minor conglomerate. In the northwest, Middle and Upper Triassic cherts, sandstones, shales and conglomerates with limestone unconformably overlie Palaeozoic rocks. Upper Triassic to Jurassic continental clastic sediments are found in central and east Peninsular Malaysia, whilst similar Upper Jurassic to Lower Cretaceous strata only outcrop in east Peninsular Malaysia.

During the Cenozoic, the Peninsula was largely emergent and Late Cenozoic partly consolidated gravels, sands and soft, often carbonaceous, shales are only found in small isolated basins. During the Quaternary, there was extensive fluvial and coastal deposition resulting in the extensive coastal plains (Stauffer, 1973).

East Malaysia – Sabah

Sedimentary rocks outcrop over about 70% of Sabah; the oldest rocks being Cretaceous to Eocene limestones, cherts, sandstones, conglomerates and argillaceous strata, that are widespread in the east and south-central sectors. Eocene to Oligocene flysch-type sequences of inter-bedded sandstone, siltstone and shale, as well as slate, phyllite, quartzite, limestone, chert and tuff occupy the whole of western and northern Sabah, whilst Oligocene to Early Miocene interbedded shales and sandstones are only found in the southwest (Anon., 1997a).

Miocene to Pliocene rocks are found in east Sabah where the Early Miocene comprises mainly argillaceous materials, pyroclastics and slump breccias. In the Kalabakan Valley, argillaceous sediments are found, whilst similar sediments with tuffs occur in the Binuang area and Kalumpang Valley. Slump deposits in the Sandakan and Dent Peninsulas, and in the upper Kinabatang area, consist of large blocks of older rocks such as chert, limestone and sandstone in a massive grey mud matrix, though tuffs and tuffaceous sediments are also found. Late Miocene sandstones and mudstones with thin coal beds are found in the Kalabakan-Kuamut-Kinabatang Valleys, whilst Late Miocene to Pliocene rocks in the Dent Peninsula comprise a sequence of mainly clastic sediments with minor limestone (Anon., 1997a).

In north Sabah, Miocene strata contain a lower sequence of sandstone and siltstone with minor shale and limestone, and an upper sequence of quartzose sandstones and shales. Miocene sedimentary rocks in southwest Sabah are similar

to those in the Kudat Peninsula and comprise quartzose sandstones with minor shale and limestone.

By Pliocene times, the greater part of Sabah was fully uplifted and sedimentation confined to coastal areas such as the Dent and Semporna Peninsulas, where mainly limestone, sandstone, clay and lignite accumulated. In the Sipitang and Klias Peninsulas, the Pliocene comprises clay, sand, lignitic clay and conglomerate resting unconformably on older formations. Quaternary deposits, consisting mainly of gravels and sands are found along the coast and in several inland plains (Anon., 1997a).

East Malaysia – Sarawak

Sedimentary rocks outcrop over some 80% of Sarawak; the oldest being the Late Carboniferous limestones, cherts and shales of West Sarawak. During the Early Triassic, there was subsidence and deposition of shales, sandstones and conglomerates, followed by widespread volcanic activity during the Late Triassic. In western West Sarawak, a marine sequence of mainly argillaceous rocks was deposited throughout the Jurassic. In Late Jurassic, there was deposition of the Bau Limestone as well as conglomerates and sandstones with minor shale and tuff, whilst in deeper seas, shales, sandstones and limestones accumulated. From the Late Cretaceous to Eocene and possibly Miocene, sandstones and mudstones with conglomerate lenses and shales were deposited in isolated basins. The eastern part of West Sarawak, however, was probably land during much of Jurassic and Cretaceous, though from Late Eocene to probably Miocene, sediments similar to those in western West Sarawak were deposited (Anon., 1997b)

In Central Sarawak, the oldest sedimentary rocks are Lower Cretaceous cherts occurring as tectonic blocks in the Lumar Valley where flysch-type sediments of shale and greywacke with conglomerate were deposited in the Upper Cretaceous. Sedimentation continued throughout the Palaeocene and Eocene; the sediments being mostly greywacke and argillite with some conglomerate and limestone. Late Eocene folding affected all the rocks; the intensity of folding and metamorphism decreasing northeastwards from the Lumar Valley (Anon., 1997b).

Deltaic sedimentation during the Oligocene migrated northwards from central Sarawak and by Late Miocene had encroached upon the shelf seas of North Sarawak before spreading northeastwards into Sabah. Deposition ceased in Late Miocene, except around Balingan, where a thick sequence of Upper Miocene and Pliocene sediments were deposited. Pliocene and Pleistocene folding phases brought practically the whole of Sarawak above sea level with peneplanation of large areas during the early Pleistocene, followed by uplift and warping. The older Quaternary sediments consist of semi-consolidated gravel, sand and clay and are succeeded by younger and less consolidated clay, sand and minor gravel (Anon., 1997b).

Table 1: Morphological features of a generalized weathering profile over interbedded sandstones, shales and siltstones (after Raj, 1983).

| Thickness | Zone/Horizon | Morphological Features |
|-----------|-----------------|---|
| 0.5 m | IA | Brownish to reddish yellow, firm clay with many roots. |
| 1.0 m | IB ₁ | Yellowish red, firm to stiff clay with reddish yellow mottles. |
| 1.5 m | IB ₁ | Red, stiff clay with many gravel sized lateritic concretions. |
| 1.5 m | IC ₁ | Red, stiff clay with some reddish yellow mottles & gravel sized lateritic concretions. |
| 2.0 m | IC ₂ | Indistinct bands of red, mottled brownish yellow, stiff, silty clay, sandy clay & clay with indistinct relict quartz veins & pods. Indistinct relict bedding shown by inclined stone lines of gravel sized lateritic concretions and lateritized corestones. |
| 3.0 m | IIA | Thick bands of red, mottled brownish yellow, stiff, silty clay, sandy clay & clay (completely weathered bedrock) with indistinct relict textures alternating with thin bands of red to yellow, firm to stiff, silty clays & clays (highly weathered siltstones & shales) and pink to red, loose sands (highly weathered sandstones) with distinct textures, quartz veins & bedding planes, but indistinct relict fracture planes. Some platy secondary iron oxide/hydroxide concretions along bedding planes. |
| > 5 m | IIB | Thick bands of red to yellow, firm to stiff, silty clays & clays (highly weathered siltstones & shales) & pink to red, loose sands (highly weathered sandstones) alternating with thin bands of pink to yellow, stiff silts & dark grey, stiff to hard, clays (moderately weathered siltstones & shales) & pink to yellow, dense sands (moderately weathered sandstones). Distinct bedrock textures, quartz veins, bedding and fracture planes. |

WEATHERING OF CLASTIC SEDIMENTARY BEDROCK

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 climate is thought to have been operative throughout the Quaternary, though some authors have postulated more seasonal climates. As the Peninsula is located in a tectonically stable area and has been entirely or partially emergent throughout the Quaternary, there has been prolonged exposure giving rise to deep weathering profiles (Raj, 1982). In East Malaysia, however, some areas such as West Sarawak have deep weathering profiles again as a result of prolonged exposure, though other areas have thin profiles as a result of uplift and active erosion during much of the Tertiary and Quaternary.

In areas of interbedded sandstones, siltstones and shales, weathering profiles show an upper morphological Zone I (or residual soil) of completely weathered bedrock modified by pedological processes. This Zone, which is up to about 6 m thick, can be separated into the agricultural A, B and C soil horizons and usually contains lateritic concretions and lateritized corestones (Table 1).

Below Zone I is found Zone II with *in situ* moderately to completely weathered bedrock that indistinctly to distinctly preserves the minerals, textures and structures of the original strata; the degree of preservation increasing with depth. There can usually be distinguished an upper IIA horizon (up to 4 m thick) that consists of thick bands of completely weathered bedrock with distinct relict textures but indistinct relict structures (Table 1). It is to be noted that it is very difficult to quantify weathering of sedimentary bedrock in terms of changes in mineral composition as the

original minerals are relatively stable. Weathering, however, is reflected by changes in colour, textures and physical properties, especially in terms of 'softening' or loss of induration (hardness), of the original strata due to their exposure and unloading. Differences in colour are mainly due to dissolution, and later precipitation, of secondary iron oxides and hydroxides by water seeping through the strata. Morphological features thus allow for distinction of various stages of weathering of the original clastic bedrock considered on the scale of the mass (Raj, 1983).

Due to the interbedded nature of the strata, below horizon IIA are found thick bands of highly to moderately weathered sandstones, siltstones and shales (with distinct relict textures and structures) alternating with thin bands of completely weathered strata that show distinct textures but indistinct relict structures. With depth, there is a gradual increase in the amount of moderately to slightly weathered strata, though effects of weathering, especially staining, can extend to depths of over 30 m. Extremely variable lateral patterns of weathering can also develop due to the interbedded nature of the strata and the presence of inherent structural discontinuities such as bedding, joints and fault planes. Depths of weathering furthermore, are dependent upon the regional and local topographic setting, though maximum depths occur below ridge crests and hill summits and thin towards valley sides. The site geomorphology also plays an important role in determining weathering patterns and depths. In Peninsular Malaysia for instance, Zone I is usually thin (<3 m thick) in hilly terrain, but much thicker (>5 m thick) in undulating terrain over similar clastic sedimentary bedrock. In undulating terrain close to the coast furthermore, fluctuations of groundwater tables in response to sea-level changes have also led to 'softening' and a very thick upper Zone II of completely weathered bedrock.

FAILURES OF SLOPE CUTS IN AREAS OF SEDIMENTARY BEDROCK

Slope cuts in undulating terrain

In undulating terrain, low cuts (<5 m high) in undulating terrain only expose morphological Zone I, whilst high cuts expose Zone I in the top benches and *in situ* moderately to completely weathered bedrock (Zone II) in the lower benches. Field surveys of these cuts and benches show that where they have been excavated at steep angles ($>60^\circ$), there have sometimes occurred small (<5 m³ in volume) earth falls and shallow slips during periods of continuous daily rainfall. The slips, with approximately cylindrical failure surfaces, mostly occurred at non-vegetation covered cuts and were preceded by the development of desiccation cracks, whilst the earth falls occurred at very steep ($>80^\circ$) cuts and were preceded by the development of tension cracks. These failures mainly involved firm to stiff, silty to sandy clays whose cohesive strength was reduced through development of the desiccation and tension cracks which also allowed for infiltration of rainfall. Saturation of the slope materials during periods of continuous daily rainfall, thus led to the earth falls and shallow slips.

In low-lying, undulating terrain, where low to high cuts intersected unconfined groundwater tables, there sometimes occurred small (<5 m³ in volume) rotational slides (slumps) within 6 months of the end of excavation. These slumps involved saturated Zone I and /or upper Zone II materials and are considered to be undrained failures that are partly due to the non-dissipation of high pore water pressures as a result of low permeabilities. In some cases, similar slumps are due to the presence of swelling clay minerals, as the Paloh Formation in Johore (Raj, 1987). In the case of the slump deposits of Sabah furthermore, as the Garinono Formation, similar slumps occur during periods of heavy rainfall even when excavated at low angles (about 30°) (Collenette, 1966).

In a few cases, where high cuts intersected unconfined groundwater tables in low-lying, undulating terrain, compound slides occurred some 8 months to several years after the end of excavation. These small to large failures (up to 300 m³ in volume) occurred during or following, long periods of continuous daily rainfall; the failure surfaces being located in part along day-lighting, bedding planes. These slides resulted in part from a decrease in shear strength along the bedding planes with time as well as transient high pore water pressures caused by a rise in groundwater tables. Compound slides that involved Tertiary strata at Batu Arang are also due to increased pore water pressures as a result of the rise in the groundwater table, though this rise was caused by the cessation of pumping of subsurface water.

Slope cuts in hilly to mountainous terrain

Low cuts (<5 m high) in hilly to mountainous terrain only expose Zone I, whilst high cuts expose Zone I in the

top benches and *in situ* completely to moderately and slightly weathered bedrock (Zone II) in the lower benches. Field surveys of such cuts and benches, show that where they have been excavated at steep angles ($>60^\circ$), there have sometimes occurred small (<5 m³ in volume) earth falls and shallow slips; these failures showing similar features as those occurring at cuts in undulating terrain.

Field surveys of existing high cuts also show that a variety of other, small to large failures (up to several hundred m³ in volume) have occurred in their lower benches; these failures being due to structural discontinuities such as bedding, joints and fault planes, inherent in the *in situ* highly to slightly weathered bedrock of Zone II. These failures, which can be classified as block and slab slides, wedge and toppling failures and rock falls, have all occurred a few months to several years after the end of excavation, during, or following, periods of continuous daily rainfall. All these failures are due to favourably oriented, structural discontinuity planes, though their occurrence during periods of rainfall also indicates the presence of transient high pore water pressures. 'Stress relief' or 'unloading' with time has also been a factor of significance, for several slabs and blocks, although located along favourably oriented discontinuity planes, only failed some 6 months and more after the end of excavation. Shear strengths along bedding and other discontinuity planes in clastic sedimentary bedrock are also variable, though generally low (Table 2).

The block and slab slides have occurred at steep ($>60^\circ$) cuts and benches where moderately to steeply dipping ($>40^\circ$) bedding planes day-lighted; the sides of the blocks and slabs being demarcated by joint planes. In geologically young rock formations such as the Pliocene Sandakan Formation, slab slides have occurred along very gently sloping (15°) bedding planes during heavy rainfall (Lee, 1970). The wedge failures have also occurred at steep ($>60^\circ$) cuts and benches, though they have involved two steeply dipping ($>45^\circ$) discontinuity planes that had day-lighting lines of intersection.

The rock falls and toppling failures have only occurred at very steep ($>70^\circ$) cuts and benches where slightly weathered and indurated sandstones and shales were exposed. The falls occurred where the bedrock was very closely fractured, whilst the toppling occurred where the major discontinuity planes dipped steeply ($>75^\circ$) into the slope.

CONCLUSION

From the preceding discussions, it can be concluded that the failures at slope cuts in clastic sedimentary bedrock in Malaysia are influenced by several internal and external factors, including the geometry of the cuts, their topographic setting, the lithologies or strata involved, the types and orientations of their inherent structural discontinuity planes, the depths and patterns of weathering, daily rainfall and time. The design of slope cuts in the clastic sedimentary bedrock areas of Malaysia thus needs to take into

FAILURES AT SLOPE CUTS IN CLASTIC SEDIMENTARY BEDROCK IN MALAYSIA

Table 2: Shear strength along discontinuity planes in clastic sedimentary bedrock (after Raj, 2000).

| Bedrock | Discontinuity plane | Method of test | Peak strength | Residual strength |
|---------------------|---------------------------------|---------------------------------|---|---|
| Semanggol formation | Mudstone - Smooth bedding plane | Multi-stage, field direct shear | - | $\phi = 18^\circ$ |
| Sandstone | Diamond sawn plane. Tested dry. | Compression in bevelled dies | - | $\phi = 25^\circ$ |
| Sandstone | Diamond sawn plane. Tested dry. | Compression in bevelled dies | - | $\phi = 27^\circ$ |
| Sandstone | Bedding & joint planes | Back analysis - wedge failure | - | $\phi = 20^\circ$ |
| Jurong formation | Bedding planes - smooth & wavy | Tilt test | - | $\phi = 44^\circ$ |
| Jurong formation | Diamond sawn plane. | Field shear box | - | $\phi = 32^\circ$ |
| Jurong formation | Highly weathered bedding plane | Shear box | $c = 1 \text{ kN/m}^2$ $\phi = 30^\circ$ | $c = 0.5 \text{ kN/m}^2$ $\phi = 26.5^\circ$ |
| Gemas formation | Bedding & joint planes | Back analysis - wedge failure | - | $\phi = 45^\circ$ |
| Gemas formation | Bedding & joint planes | Back analysis - wedge failure | - | $\phi = 45^\circ$ |
| Karak formation | Siltstone/shale bedding plane | Back analysis - wedge failure | - | $\phi = 26^\circ$ |
| Karak formation | Siltstone/shale bedding plane | Back analysis - wedge failure | - | $\phi = 19^\circ$ |

consideration all these factors in order to ensure their stability.

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