LANDSLIDES : CASE HISTORIES, LESSONS LEARNED AND MITIGATION MEASURES

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ABSTRACT

A significant portion of the Authors' forensic engineering engagements is related to landslides. Landslides incidents appear to be on the rise in the recent years especially during the monsoon season. Our investigations of 49 cases of landslides over the last 6 years indicate that 60% of the failure are due to design alone, and the rest of the failures are either due to construction errors, a combination of design and construction errors, geological features and maintenance. This paper highlights the common causes of landslides in residual soils, and the lessons learned from this expensive damage and loss. Preventive measures are also proposed to mitigate the occurrence and risk of landslides in residual soils.

Keywords: Landslide; Residual Soils; Slopes; Lessons Learned.

1. INTRODUCTION

Every year during the monsoon seasons, the occurrence of landslides is common in Malaysia. These landslides either cause closure of roads, affect buildings or worse they sometimes cause casualties. The potential economic loss and loss of life could escalate if the causes of landslides in Malaysia are not identified and addressed properly by all parties and stakeholders especially the Government, planners, developers, civil engineers and contractors who are indirectly or directly involved in the design and construction works on slopes, either for development of buildings or roads and highways over hilly or mountainous terrain. Development and construction on slopes are inevitable as a country develops and flat land becomes scarce. This paper presents statistics on the causes of landslides in Malaysia. It is based on 49 cases of landslides investigated by the Authors over the last 6 years. The common causes of landslides in residual soils and, lessons learned from this expensive damage and loss are presented in this paper together with preventive measures to mitigate occurrence and risk of landslides in residual soils. The scope of this paper is limited to landslides on residual soils and does not cover rock falls or rock slope failures.

2. FACTORS ATTRIBUTED TO LANDSLIDES

49 cases of mostly large landslides on residual soil slopes of weathering grade IV to VI were investigated by the Authors over the last six years as part of forensic engineering engagements. Large landslides are landslides which involve more than 5,000 cubic metres. Table 1 shows the percentage of landslides caused by different factors. The results of the investigations indicate that 60% of the failures are due to inadequacy in design alone. The inadequacy in design is generally the result of lack of understanding and appreciation of the subsoil conditions and geotechnical issues. Failures due to construction errors alone either of workmanship, materials and/or lack of supervision contributed to 8% of the total cases of landslides. About 20% of the landslides investigated are caused by a combination of design and

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construction errors. For landslides in residual soil slopes, the landslides caused by geological features only account for 6% which is same as the percentage contributed by lack of maintenance.

Table 1 : Causes of Landslides

Causes of Landslides	**Number of Cases**	**Percentage (%)**
Design Errors	29	60
Construction Errors	4	8
Design and Construction Errors	10	20
Geological Features	3	6
Maintenance	3	6
Total	49	100

The results clearly reveal that the majority of these failures are avoidable if extra care was taken and input from engineers with relevant experience in geotechnical engineering was sought from the planning to construction. Many of the landslides reported above which were caused by design errors were due to following :-

1) The abuse of prescriptive method on the slope gradient (slope angle) to be adopted for cut or fill slopes without proper geotechnical analyses and calculations. It is very common in Malaysia to find many cut slopes that are formed for residual soils that are 1V:1H (which means one vertical: one horizontal = 45 degrees angle). Based on literatures published on residual soils and the authors' own experience of residual soils, it is very unlikely to have an effective angle of friction (ϕ') of the residual soils of 45^o (degrees) or near to this value. The authors' own experiences indicates that the ϕ' values of residual soils generally ranges from 29^o to 36^o and mainly depend on the particle size distribution of the materials. Therefore, if proper analysis of the slopes' stability was carried out with correct soil parameters, most of these slopes of 45^o gradient would not have sufficient Factor of Safety (FOS) recommended against slip failure in the long term even with some effective cohesion. In summary, engineers should not only follow the slope gradients (e.g. 1V: 1H) that have been done previously without proper geotechnical analysis and design.
2) Subsurface investigation (S.I.) and laboratory tests were not carried out to obtain representative soils parameters, subsoil and groundwater profiles for design and analysis of slopes. Therefore, the analysis and design carried out are not representative of the actual site conditions, and thus unsafe.
3) A lack of good understanding of fundamental soil mechanics that the most critical condition of cut slopes is in the long term (in "Drained Condition"). Therefore, it is necessary to adopt effective shear strength parameters for the "Drained Analysis" of the cut slopes in residual soils instead of undrained shear strength (s_u or c_u).

For landslides that were caused by construction errors alone or combined with design, the common construction errors are as follows:-

1) Tipping or dumping of loose fill down the slopes to form a filled platform or filled slopes. This is the most rampant construction error for earthworks construction in Malaysia. Contractors carrying out the filling works on slopes will find it most "convenient" and "easy" to dump or tip soil down the slopes to form the fill. The condition is worsened by not removing the vegetation on the slopes causing the bio-degradable materials to be trapped beneath the dumped fill, forming a potential slip plane with a very low friction angle of the bio-degradable materials (vegetation). The uncompacted fill slopes having a very low Factor of Safety would likely fail in the long term.
2) Errors of the method of construction such as forming cut slopes by excavating slopes from the bottom (undermining) instead of the correct practice of cutting from the top downwards. This wrong practice will trigger landslides or potential shear planes extending beyond the proposed cut slope profile.
3) Over-excavation of cut slopes. Contractors unintentionally over-excavate cut slopes and then try to fill back the excavated materials to reform the slope to the required gradient. The uncompacted loose materials will slip down.

The way to prevent these bad construction practices is to have proper full-time supervision by members of the design consultant and together with reliable and responsible earthworks contractors having clear method statements for construction.

Landslides due to geological features contributed to about 6% of the total failures investigated. However, it should be recognised that these geological features such as discontinuities in residual soils, especially sedimentary formations, are not usually detectable during the design stage even with extensive subsurface investigation (boreholes, geo-physical method), even to an experienced engineering geologist who carries out geological mapping at the site prior to cutting. Most of these geological features can only be detected after exposing the slopes during excavation. In view of this, it is encouraged to carry out confirmatory geological slope mapping of the exposed slopes (after excavation) by an experienced engineering geologist or geotechnical engineer to detect any geological discontinuities that may contribute to potential failure mechanisms, namely planar sliding, anticline sliding, active-passive wedges, etc.

By understanding that geological discontinuities could not be fully addressed during the design stage, design engineers should make moderately conservative assumptions for the soil/rock parameters and also the groundwater profile to ensure adequacy in design and should only carry out adjustments on site if necessary after geological slope re-mapping and re-analysis of the slopes. On the contrary, when optimistic assumptions are made and the results obtained during construction at site are less favourable then expensive options such as retaining walls or slope strengthening using soil nails are required due to space and boundary constraints. Thus the safety of slopes is often compromised.

The common problems of landslides caused by lack of maintenance are blockage of drains for surface run-off, and erosion. Blockage of drains will cause large volumes of water to gush down a slope causing erosion to the slope and the formation of gullies. These gullies will further deteriorate into a big scar on the slope and finally lead to a landslide. The blockage of drains could also be due to debris accumulated on cracked drains, the collapse of drains, etc. If proper maintenance is carried out, then all these small defects would have been rectified and landslides caused by erosion would be-prevented.

3. PREVENTIVE AND MITIGATIVE MEASURES FOR LANDSLIDES

The best preventive measures for landslides are to have a proper geotechnical/geological input for slopes design, construction and maintenance. The four important stages as follows:-

- Planning
- Analysis and Design
- Construction
- Maintenance

3.1 Planning

The planning of hill-site developments or roads through mountainous terrain can be divided into four major sections:

- Desk Study
- Site Reconnaissance
- Subsurface Investigation
- Planning of Layout for development or Selection of Road Alignment

3.1.1 Desk Study & Site Reconnaissance

Desk study and site reconnaissance are very important to understand the present conditions and history of the site. Desk study includes reviewing geological maps, memoirs, topographic maps and aerial photographs of the site and adjacent areas so that the engineers are aware of the geology of the site, geomorphology features, previous and present land-use, current development, construction activities, and problem areas like previous slope failures etc. Site reconnaissance will confirm the information acquired from the desk study and also will obtain additional information from the site. Some key information such as small streams or water courses that are present or that only appear during rainy season is important for the planning and design of earthworks. Rock outcrops observed from site reconnaissance serve as confirmation of the geological formation and discontinuities on the rocks, and would also be useful for proper understanding of the potential failure plane of the rock (if daylighting, etc). Types of vegetation on site also serve as an indication of surface water and groundwater regimes, and tilting tresses on a slope could also serve as a sign of slope creep movement.

3.1.2 Subsurface Investigation (S.I.)

Subsurface investigations (S.I.) should be properly planned to obtain the representative subsurface conditions of the whole site for a development or along the alignment of a proposed road. The key information from field tests are depth of soft soil, hard stratum, depth of bedrock, geological weak zones, clay seams or layers, and the groundwater regime. The planning of exploratory boreholes shall take into consideration the terrain instead of following a general grid pattern.

General information on subsurface profiles and their properties is very important when planning the cut and fill and formation of the platform or road because the depths of hard stratum and bedrock will have a major influence on the cost and construction time for earthworks. For high cut slopes (e.g. more than 20m), it is encouraged to have two to three boreholes across the proposed cut slopes to obtain a more representative subsoil, rock and groundwater profiles for stability analysis. It is also advisable to have standpipes installed in these boreholes to allow monitoring of the groundwater profile across the proposed cut slope. The information on the groundwater profile is important, especially for high cut slopes as changes of groundwater level will have a significant effect on the Factor of Safety (FOS) of a slope.

Boreholes across a proposed cut slope will also help to detect clay seams (if any) that are often detrimental to the stability of slope due to its lower effective friction angle (ϕ') and potential perched water table above clay seams. In practice, it is quite difficult to detect localised clay seams that could contribute to landslides through boreholes. However, with thorough geological slope mapping of exposed slopes after excavation, clay seams at the exposed surface can be detected and properly addressed.

Depending on the type and size of projects, S.I. could be carried out in stages namely preliminary and detailed. Preliminary S.I. usually consists of boreholes and sometimes also include geophysical survey especially for bigger areas. Preliminary S.I. focuses on obtaining overall general information of a site and detailed S.I. aims to obtain a more detailed information at critical areas and representative parameters for detailed geotechnical analysis and design. For the details on planning of subsurface investigation and interpretation of test results for geotechnical design, reference can be made to Gue & Tan (2000) and Gue (1995).

The two most important parameters needed to analyse and design cut slopes in residual soils are the effective stress strength parameters (c' & ϕ') and the groundwater level. This key information shall be properly obtained when carrying out a subsurface investigation. Groundwater profile can be obtained from standpipes installed in boreholes to allow monitoring of groundwater in the boreholes to be carried out even after S.I. field works and for as long as practically possible. In order to obtain effective stress strength parameters (c' & ϕ') for residual soils, undisturbed soil samples should be collected from boreholes using a Mazier Sampler (Retractable triple-tube Core-barrel) with a sample diameter of about 70mm. Foam drilling can improve the recovery of Mazier sampling. In situations where Mazier sampling recovery is bad/insufficient and foam drilling is not feasible, another method of obtaining "undisturbed" soil samples from stiff residual soils is the use of the Thick Wall sample (sample diameter of 70mm) which is hammered into the hard soil. Although the sampling process using thick walls will cause some disturbance, the effect is not significant for stiff residual soils and the samples collected can still be used for laboratory strength tests. Undisturbed soil samples can also be collected at shallow depth using block sampling which is very useful to collect high quality undisturbed soil samples during excavation of slopes. These undisturbed residual soil samples shall be sent to the laboratory for a series of classification and strength tests.

3.1.3 Planning of the Layout for road networks and platforms

Good planning of platform and road networks for hill-site developments shall be geotechnical engineering-driven with close coordination among developers, planners, architects, civil & structural engineers. With this, a terrain-friendly (less disturbance to existing vegetated slopes), safe, easily constructed and cost effective development can be achieved. The planning of platform layouts for hill-site development shall aim to suit the natural contours and minimise cut and fill. Although retaining walls or soil nailing are generally more costly than normal earthwork solutions, with proper planning, the use of these retaining systems at critical areas will effectively reduce significant earthworks that are often more expensive especially for proposed cut slopes chasing a steep uphill slope as shown in Figure 1.

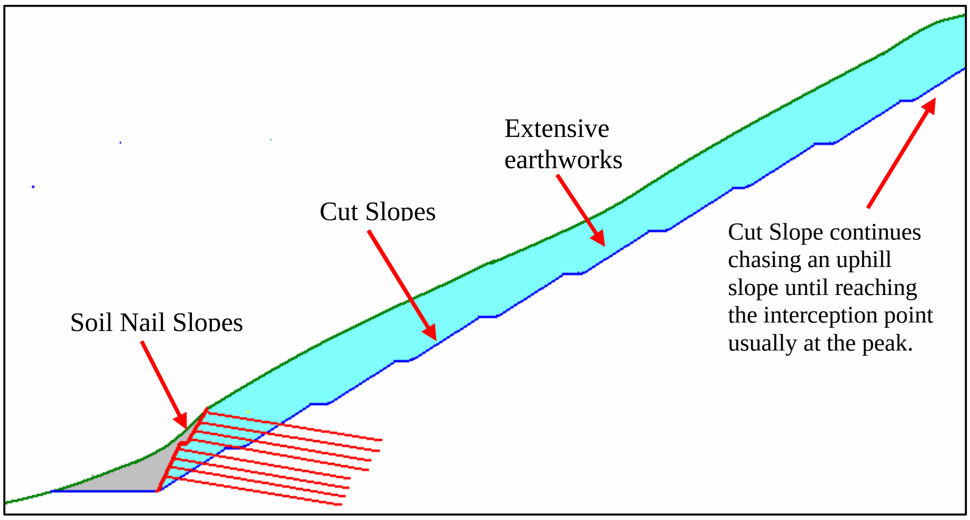

Figure 1 : Comparison of Earthworks Cut Slopes and Soil Nail Slopes

4.0 ANALYSIS AND DESIGN OF SLOPES

4.1.1 Anatomy of a Slope

Figure 2 shows a typical slope consisting of (i) ground profile with some vegetation, (ii) ground water table, (iii) partially saturated soil above ground water table, (iv) saturated soil below ground water table and (v) weathered and/or competent rock.

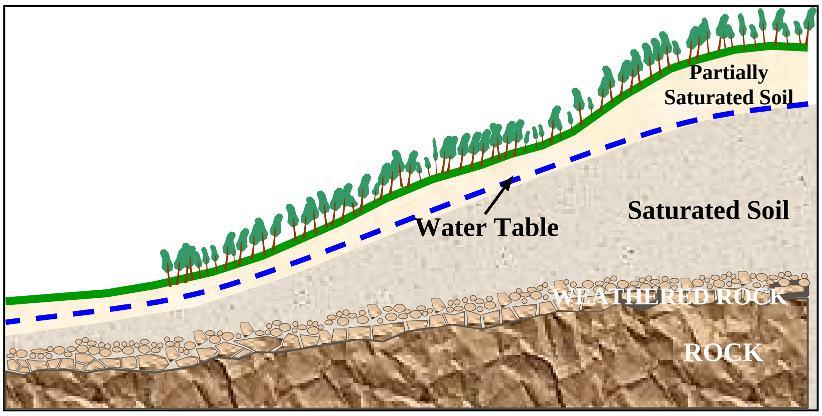

Figure 2 : Anatomy of a Typical Slope

In an analysis of slope stability to determine whether a slope is safe, potential slip surfaces (Figure 3) are postulated on a slope cross-section. These slip surfaces are analysed in terms of total driving forces and total resisting forces. The factor of safety (FOS) is determined from the ratio of resisting forces to driving forces. The lowest FOS is the critical stability of a slope.

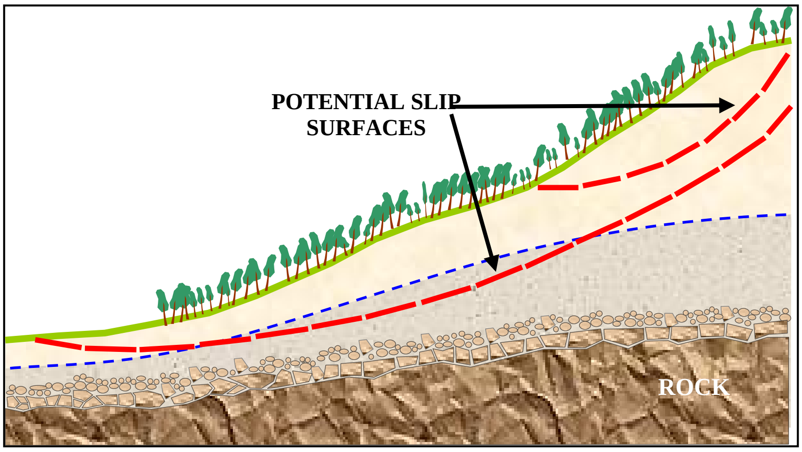

Figure 3 : Potential slip Surfaces for Landslide

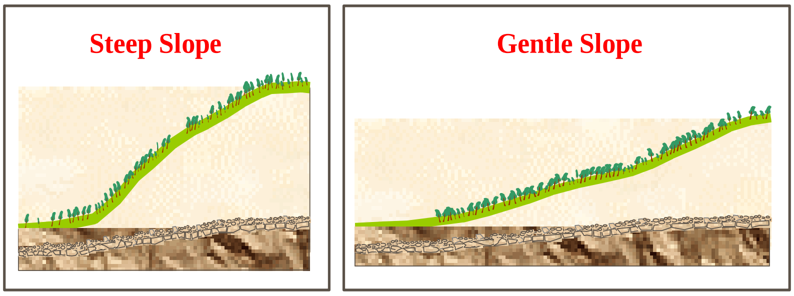

Figure 4 : Slope Geometry

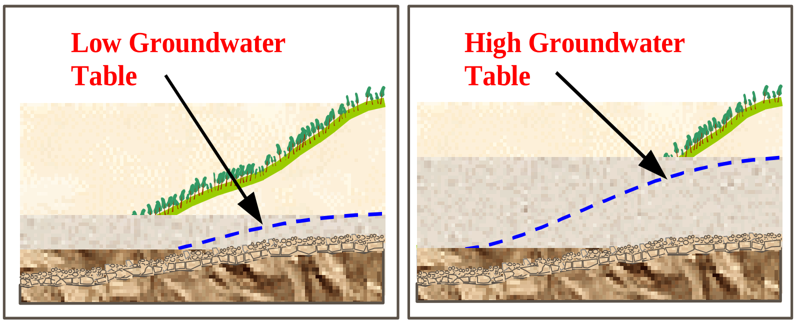

Figure 5 : Effect of Ground Water Table

There are many factors influencing the stability of slopes. Here, only the common important factors are covered and explained. Firstly, the properties of the soil such as effective stress friction angle (ϕ'), apparent cohesion (c') and unit weight are important in slope stability. As an illustration, consider these two extremes:

Secondly, slope geometry is important as illustrated in Figure 4. Low and gentle slopes are safer than high and steep slopes for a similar soil. This is because the latter has more mass on the upslope acting as a driving forces (F) compared to that of a gentle slope. Thirdly, the ground water table profile is an influencing factor in slope stability. Ground water table for hillslopes is generally low and fluctuates with time and rainfall events. Figure 5 shows two general types of ground water table profile which may be found in a slope. A high ground water table increases the risk of failure as the shear resistance in the potential failure plane decreases due to increased water pressure between soil particles. In addition, the ground water table on the upslope acts as an additional driving forces. All these factors decrease the FOS of a slope.

In general, the Geotechnical Manual for Slopes published by Geotechnical Engineering Office (formerly known as Geotechical Control Office) of Hong Kong has been widely used with some modifications to suit local conditions by engineers in Malaysia (Gue & Tan, 2002). Presently it is not advisable to include soil suction (negative pore pressure) in the design of the long term slopes in view of many factors that can cause the loss of suction during prolonged and high intensity rainfall, especially during monsoons that occur at least twice a year.

4.1.2 Information Required for Analysis of Slopes

Detailed information on the topography, geology, shear strength, groundwater conditions and external loadings are required for analysis of slopes.

Topography

The contour of a site is very important for a proposed layout of a development especially in determining areas and amounts of cuts and fills. Positions of subsurface investigation holes along cross-sections of typical and major cuts and fills are required for detailed slope stability analyses.

Geology

Knowledge of the geology of a site will assist engineers to foresee the types of slope failures likely to occur before embarking on investigation and analysis. The geological conditions of a site should also be reviewed during construction to validate the formation and to ensure that irregularities and surprises (if any) are taken into consideration for reassessment, for instance clay seams or layers that can induce a perched water table or reduced slope stability.

Shear Strength

For cut slopes, effective stress conditions (drained or long term condition) are normally more critical than total stress (undrained) conditions. Therefore, the effective stress strength parameters c' and ϕ', determined from testing representative samples of matrix materials, are used in the analysis. In Malaysia, normally Isotropic Consolidated Undrained Triaxial Tests (CIU) are commonly carried out on large diameter undisturbed soil samples (from a Mazier sampler without trimming and side drains). It is important that soil samples are tested at stresses comparable to those in the field, and should be saturated. It is appropriate to measure strength parameters on saturated soil samples because residual soils are usually of high permeability (usually 10^{-4} to 10^{-6} m/sec). Prolonged and high intensity rainfall, especially during the two monsoon periods every year, allows rainwater to infiltrate with ease into it and it is likely that saturation conditions will be approached at shallow depths in the field during the service life of a slope.

The shear strength of soil may be represented graphically on a Mohr diagram. For simplicity of analysis, it is conventional to use a c'-ϕ' soil strength model for saturated and unsaturated soil as expressed in the equations below respectively:

$$\tau_f = c' + \sigma_{nf}'\tan\phi' \text{ (for Saturated Soils)} \qquad \text{- - - - - - - (Eq. 1)}$$

$$\tau_f = c' + (u_a - u_w)\tan\phi^b + (\sigma_{nf}' - u_a)\tan\phi' \text{ (for Unsaturated Soils)} \qquad \text{- - - - - - - (Eq. 2)}$$

where τ_f = shear strength of soil.
σ_{nf}' = effective normal stress at failure.
ϕ' = effective angle of friction (degree).
c' = apparent cohesion (kPa).
u_a = pore-air pressure
u_w = pore-water pressure
ϕ^b = Angle of shear strength change with a change in matric suction.(degree).

The shear strength of the soil for unsaturated soils as in Eq. 2 above has included suction in the calculated soil strength which will give higher shear strength compared to saturated soils. However, to date it is not advisable to include soil suction (negative pore pressure) in the design of the long term slopes in view of many factors that can cause the loss of the suction e.g. prolonged and high intensity rainfall, etc. Most of steep cut slopes not yet collapsed because of the presence of soil suction, but if the suction is lost, these slopes will collapse. The most prominent example is that a slope can stand at a very steep angle (even near vertical) immediately after excavation but with time or after rain, the slope will collapse.

In view of the great uncertainty of relying on the stability of slopes with soil suction, the following section will only concentrate on saturated soil shear strength, which is commonly used in analysing and designing slopes. Figure 6 shows the typical bonding and dilatant characteristics of the residual soil at a low stress range (low confining and consolidation pressure) which exhibits a peak shear strength envelope in terms of effective stress which has a apparent cohesion intercept (c') if the Mohr-Coulomb c'-ϕ' failure line is used. As the consolidation pressure in laboratory tests prior to shearing increases beyond its yield stress, the bonds are destroyed and residual soil will likely behave like normally consolidated or slightly overconsolidated transported soil. The critical state friction angle is represented as ϕ_{cv}.

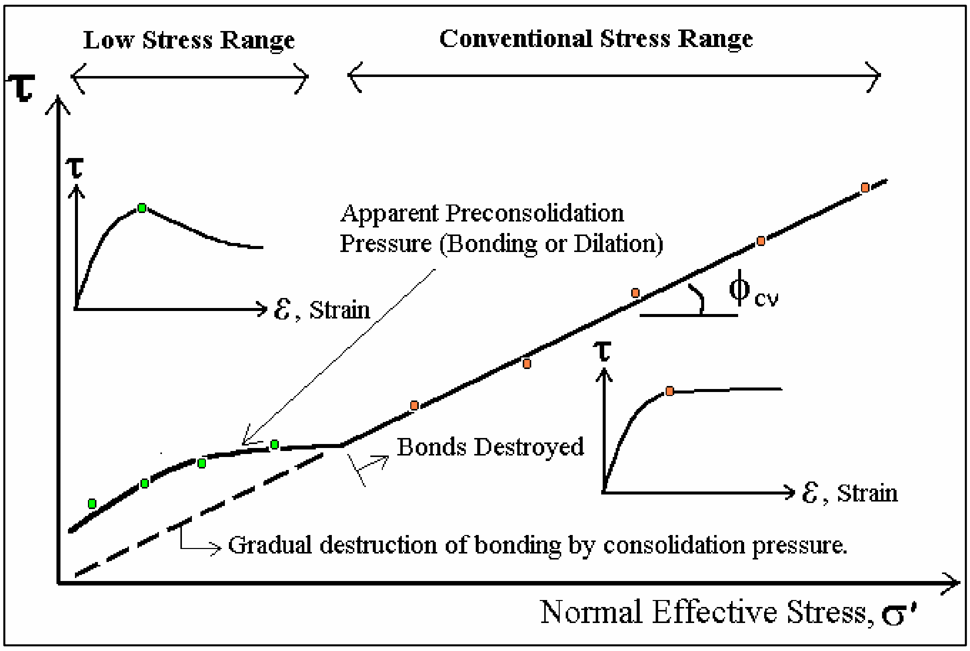

Figure 6 : Effect of Boding on the Apparent Cohesion Intercept of a Drained Strength (Effective Stress) Failure Envelope.

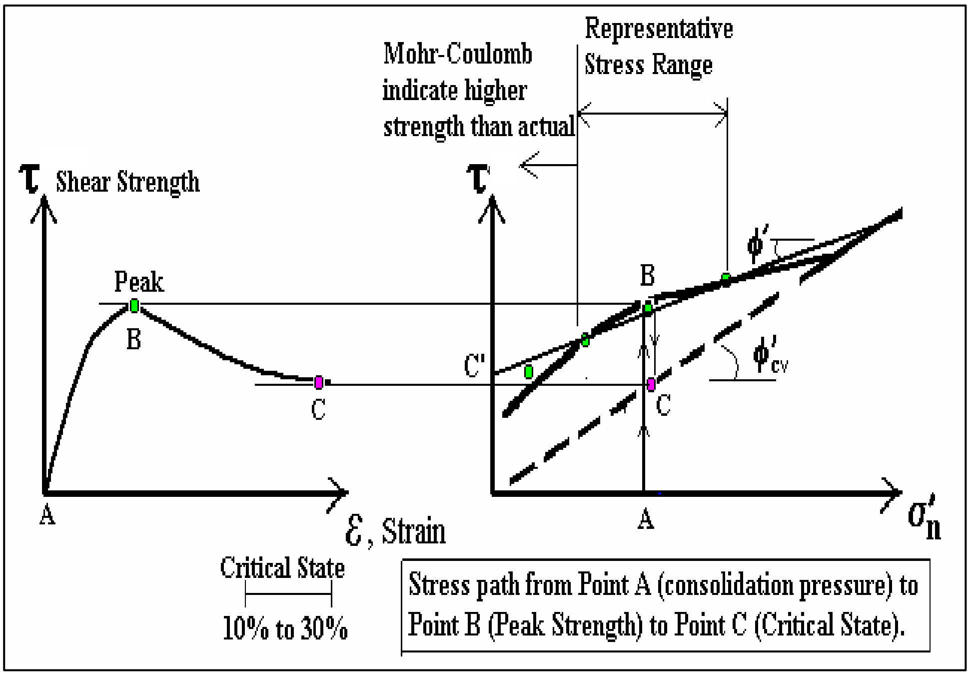

Figure 7 : Typical Shearing Characteristics of Residual Soil and the Tangent Method in Selection of Shear Strength Envelope.

It is important to be aware that c' and ϕ' parameters are not intrinsic soil properties, but are merely coefficients in the simplified design model and should only be assumed to be constant within the range of stresses for which they are evaluated as shown in Figure 6.

Brand (1995) states that most of the critical slip surfaces in residual soil slopes are commonly shallow with effective stress of typically of about 30 to 200kPa. He also reported that there is some evidence suggesting that the strength envelopes for some residual soils are curved at low effective stresses, and that the straight-line projection of strengths measured at high stresses under-estimates the shear strengths in the low stress range. Therefore, for different stress ranges, c' and ϕ' values could be adopted using method shown in Figure 7.

Figure 7 illustrates a typical stress-strain curve for residual soil. A sample is isotropically consolidated (Point A) then sheared to reach the peak strength (Point B) at low stress range and continued shearing until the critical state strength (Point C) is reached. Normally the peak strength is obtained at a relatively small strain and after continued shearing, the critical state strength (ϕ_{cv}) is obtained at a larger strain. The critical state usually occurs in the 10% to 30% strain range where a soil sample continues to shear at constant volume and constant effective stress. The critical state strength is also called the ultimate strength (Atkinson & Bransby, 1978) or the fully softened strength (Skempton, 1970). The critical state strength is also different from the residual strength (Skempton, 1964) which is lower and occurs after very large movement on the slip/failure surface. The residual strength is also associated with highly polished slip surfaces in which soil particles have become aligned in a direction parallel with the direction of sliding, and is relevant only after displacements of the order of several meters (Crabb and Atkinson, 1991).

As shown in Figure 7, the critical state strength falls on a straight line through the origin. The conventional interpretation of peak failure strength is the Mohr-Coulomb shear strength envelope (c'-ϕ') at the stress range using the tangent method. It should be noted that ϕ' is different from ϕ_{cr} (critical state); and c' is simply the intercept of the peak failure envelope on the shear stress axis, τ'. It is important to note that c' does not imply that at zero effective stress the strength is of that value. It is just a parameter in the Mohr-Coulomb shear strength envelope. Therefore, at very low effective confining stress (outside the representative stress range), the Mohr-Coulomb failure envelope (c'-ϕ') may overestimate the strength of a soil. On the other hand, if critical state strength is used in the normal stress range of a slope, the strength value will be underestimated giving an unrealistically low Factor of Safety (FOS). Therefore, when the in-situ stress range and the stress path during shearing is correctly determined, the c'-ϕ' peak shear strength envelope will be representative of the field conditions.

For residual soils of grades IV to V that are very stiff, as indicated by indirect values of actual and extrapolated Standard Penetration Tests (SPT) blow counts of high value, these materials usually have bonds between soil particles. These bonds are a component of strength that can be reflected as apparent cohesion, c' and stiffness that is independent of effective stress and void ratio/density. For the strength and stiffness of the soil as a large mass in-situ, the bond actually has a significant influence. The bonding also contributed to 'apparent' overconsolidated behaviour of the soils. Vaughan (1988) highlighted some of the possible causes of the development of bonds as :-

- Cementation through the deposition of carbonates, hydroxides, organic matter, etc.
- Pressure solution and re-precipitation of cementing agents, such as silicates.
- Cold welding at particle contacts subject to high pressure.
- Growth of bonds during chemical alteration of minerals.

Generally, c' is taken at 0 (zero) unless there are sufficient test results to obtain c' values or from back analyses of similar residual soils (in terms of strength, stress range, etc). Sometimes, unrealistically high c' value could be wrongly obtained from laboratory tests due to the rate of strain or time of shearing to failure being too fast. The rate of strain should be estimated from the results during consolidation. Side drains should not be used as this has been shown to produce inconsistency in the sample (Tschebotarioff, 1950 and GCO, 1991). Multistage tests should also not be used as the second test will be significantly affected by the failure surface formed in the first test (GCO, 1991). Further details on the laboratory tests can be obtained from Head (1986).

Groundwater and Pore Water Pressure

Figure 8 shows a possible hydrological effect of rainfall on a permeable slope. Some of the rain water runs off the slope and may cause surface erosion if there is inadequate surface protection. In view of the high soil permeability, the majority of the water will infiltrate the subsoil. This causes the water level in the slope to rise or it may cause the perched water table to be formed at some less permeable boundary e.g. a clay seam. Above water table, infiltration also increases the degree of saturation of the soil thus reduces the soil suction (i.e. negative pore pressure). This is another reason why soil suction should not be included in the selection of strength parameters for slope design.

Failures in residual soil cut slopes may be caused by a 'wetting-up' process which decreases soil suction and hence decreases soil strength contributed by suction. There is also evidence suggesting that transient rises in the groundwater table are responsible for some rain-induced landslides e.g. Premchitt et al, 1985. However in practice, it is very difficult to detect during S.I. and include in the design as they may only be detected during excavation of the slopes through detailed site inspection.

In Malaysia, it is recommended that slopes should be designed for the groundwater conditions that are representatives through observations (e.g. standpipes installed and monitored for a duration, hopefully through monsoon seasons if possible) and estimation for a return period. Slopes in the high risk-to-life category should be checked to determine their sensitivity of the water levels to the stability of these slopes, and this is a required prediction of the worst groundwater conditions.

Sometimes leakage from services, such as sewers, drains or water mains can cause the rising of groundwater levels. These services on hill-sites should be properly protected from leakage to prevent them from contributing to slope failures. Proper maintenance and checking should also be carried out as part of routine maintenance to check for leakages. In some cases, subsurface drainage e.g. horizontal drains, can be used to reduce the groundwater levels thus increasing the Factor of Safety against failure on any potential slip surface which passes below the water table. If the subsurface drainage system is employed, regular maintenance is required to prevent reduction of efficiency caused by siltation, deterioration of seals or growth of vegetation blocking the outlet.

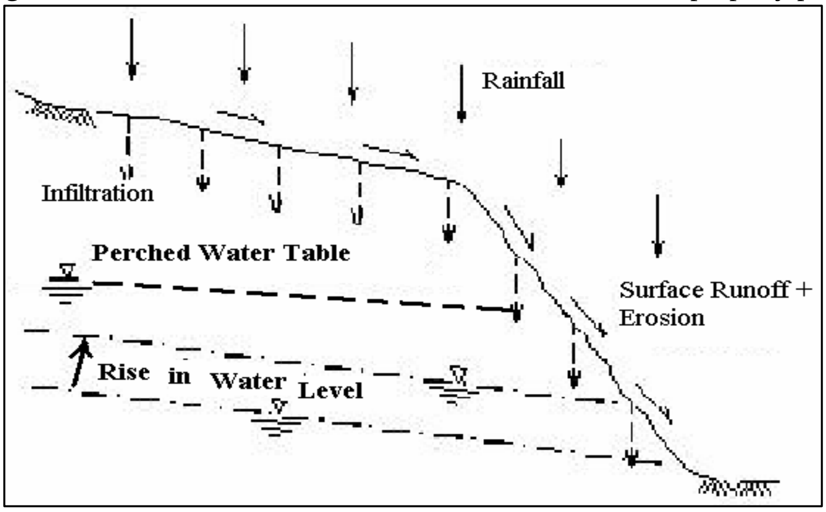

Figure 8 : Effects of rainfall on high permeable slopes (from Brand, 1995

External Loading

Loadings from traffic, building foundations, retaining walls, spoil heaps-, etc. that can influence the stability of the slopes should be correctly determined and included in the analysis. During construction, it is important not to overload slopes with construction spoils even on a temporary basis.

4.1.3 Methods of Stability Analysis

Highly and completely weathered rocks (Grades IV to VI) behave as soil in terms of engineering properties thus stability of the slopes should be assessed for a wide range of potential failure surfaces. Since generally shear strength in a residual soil profile increases with depth, slope failures can be expected to occur on relatively shallow slip surfaces.

The majority of the methods of stability analysis for soil slopes are based on limit equilibrium. For cut slopes, usually circular slips would only take place when the there is a deep layer of residual soils without structural features (e.g. relict discontinuities) or the presence of an intermediate hard layer. For circular slip surfaces, the Simplified Bishop Method (1955) can be employed. However, failures frequently occur along surfaces dictated largely by relict joints or by boundaries between weathering zones where clear boundaries exist. This is more so when subsoils are weathered from highly fractured rocks. Spencer (1967) or Morgenstern & Price (1965) methods are recommended for the check on non-circular and wedge failure modes. In practice, it is advisable to check for both circular and non-circular failure modes.

4.1.4 Factor of Safety

For hill-site developments in Malaysia, normally the Factor of Safety (FOS) against slope failure recommended by the Geotechnical Manual for Slopes (GCO, 1991) of Hong Kong is adopted. When selecting an FOS to be adopted in stability analysis, the two main factors to be considered are :

(a) Risk-to-life or Consequence to life (e.g. casualties)
(b) Economic Risk or Consequence (e.g. damage to property or services)

There are three levels of risk in each factor (negligible, low and high) as defined in detail by GCO (1991). Engineers have to use their judgment when selecting the seriousness of the consequences for both loss of life and economic loss. Generally slopes are divided into three categories namely:

- New Slopes
- Existing Slopes
- Natural Slopes

Table 2 : Modified Recommended Factors of Safety for New Slopes (modified from GCO, 1991)

Economic Risk	**Risk-to-Life**		
	Negligible	**Low**	**High**
Negligible	>1.0	1.2	1.4
Low	1.2	1.2	1.4
High	1.4	1.4	1.4

Note :
1. The FOS above is based on Representative Groundwater Conditions.
2. A slope in the high risk-to-life category should have an FOS of 1.1 for the predicted worst groundwater conditions.
3. The FOS values listed are recommended values. Higher or lower FOS must be warranted in particular situations in respect to both risk-to-life and economic risk.

Table 3 : Modified Recommended FOS for Existing Slopes (modified from GCO, 1991)

FOS against Loss of Life for a Representative Groundwater Conditions		
Negligible	**Low**	**High**
>1.0	1.1	1.2

Note :
1. These FOS values are minimum values recommended where rigorous geological and geotechnical studies have been carried out, where the slope has been standing for a considerable time, and where the loading conditions, remain substantially the same as those of the existing slope.
2. Should the back-analysis approach be adopted for the design of remedial or preventive works, it may be assumed that the existing slope has a minimum FOS of 1.0 for the worst known loading and groundwater conditions.
3. For a failed or distressed slope, the causes of the failure or distress must be specifically identified and taken into account in the design of the remedial works.

For new slopes, the recommended FOS for slopes with representative groundwater conditions as recommended by GCO (1991) are listed in Table 2 for different levels of risk. In addition, slopes of high risk-to-life category should have an FOS of 1.1 for the predicted worst groundwater conditions using moderately conservative strength parameters (characteristic values). If characteristic values are not available due to insufficient statistical data then conservative strength parameters should be used. These values can also be back-analysed from failed slopes.

Existing slopes should be analysed to check for its stability and to determine the extent of any remedial or preventive works required. If an engineer has the opportunity to examine geology and subsoil conditions of the slope closely and can obtain more realistic information on groundwater, the FOS for existing slopes recommended FOS in Table 3 may be used. Otherwise strengthening or modification to the existing slopes should comply to the recommended FOS in Table 2.

It is very important to be aware that **not all natural slopes are safe**. It is very common for natural slopes to fail during a monsoon even there is no activity like clearing of trees or development around it. Therefore stability of the natural slopes in or adjacent to the site of interest should be evaluated. Usually it is not advisable to disturb the natural slopes and vegetation just to achieve marginal improvement in stability unless the slope is unsafe.

4.1.5 Design of Cut Slopes

The vertical interval of slopes between intermediate berm is usually about 5m to 6m in Malaysia. GCO (1991) recommends that the vertical interval of slopes should not be more than 7.5m. The typical stable gradient for cut slopes in residual soils is 1V:1.75H to 1V:1.5H depending on the types of soil and groundwater regime. The berms should be at least 1.5m wide for easy maintenance. The purpose of berms with drains is to reduce the volume and velocity of runoff on the slope surface to reduce erosion and infiltration. Cut slope should be designed to the recommended FOS indicated in Tables 2 and 3.

Prescriptive design should only be used for slopes with low risk to life and low economic risk. These slopes should be of low height of not more than 6m. For a typical cut slope in residual soils of not more than 6m high, a slope gradient of 1V:1.25H will likely yield a Factor of Safety (FOS) of about 1.2.

4.1.6 Design of Fill Slopes

Similar to cut slopes, berms of 1.5m wide at about 5m to 6m vertical slope interval are commonly used for fill slopes in Malaysia. Usually a fill slope is at one vertical to two horizontal angles 1:1.5V to 1:1.75V depending on the subsoil conditions and the materials used as fills.

Before the placing of fill, vegetation, topsoil and any other unsuitable materials should be properly removed. Removal of vegetation of slopes prior to filling is very important to prevent slip failure along the plane of degraded vegetation having very low friction organic materials. Original ground should also be benched to key fill materials into an existing slope. Sometimes a free-draining layer conforming to a filter criterion may be required between the fill and natural ground to eliminate the possibility of high pore water pressures from developing and causing slope instability especially when there is an existing surface stream or creek. For high fill slopes of more than 5 berms, the placing of free-draining layers or subsoil drains (e.g. French drains) in the fill itself after a few berms (every 2 to 3 berms) is also encouraged. Sufficient numbers of discharge drains should be placed to collect the water in filter layers and to discharge it outside the limits of the fill and away from slopes.

4.1.7 Surface Protection and Drainage

Surface drainage and protection are necessary to maintain the stability of designed slopes through reduction of infiltration and erosion caused by heavy rain especially during monsoon seasons. Runoff from both slopes and their upslope catchment areas should be cut-off, collected and led to convenient points of discharge away from slopes.

When designing surface drainage on steep slopes, it is important to make sure the drains have sufficient capacity to carry the runoff. A general guideline for the design of permanent surface drainage is based upon a hundred-year return period rainfall and temporary drainage is based upon a ten-year return period. Over-sizing slightly for drains despite some extra cost can help to cater for extra-ordinarily heavy rain.

For proper slope drainage, runoff should be channelled by the most direct route away from vulnerable areas of slopes, particularly runoff from behind the top of slopes. Cast-in-situ reinforced concrete berm drains instead of precast drains should be constructed at all berms. Berm drains should be suitably reinforced to prevent them from cracking. Cracked berm drains will induce water seeping into slopes, thus could reduce their factors of safety of slopes against slip failures.

For large slopes, several stepped channels (e.g. cascading drains) should be employed instead of concentrating into one or two channels only. Since the flow in stepped channels is turbulent, sufficient freeboard must be allowed for splashing and for some cases, energy breaker should be provided. Special attention should also be given to the design of junctions (e.g. catchpits or sumps) of channels due to inevitable turbulence, splashing and vulnerability to blockage by debris.

Surface protection should be applied to slopes formed in materials susceptible to rapid surface erosion or susceptible to weakening by infiltration. The most common surface protection method used in Malaysia is closed turfing or hydro-seeding (slope vegetation). Establishment of vegetation on a slope is governed by several factors such as steepness and material composition of slopes. The steeper a slope, the greater the effort required to establish vegetation. Generally cut slopes can be regarded as relatively infertile and appropriate fertilisers should be added at the time of planting. If turfing is carried out in the dry season, frequent watering is required to enable the growth of turf.

When importing soil for back filling, the engineer is encouraged to include in the tender for contractors to protect borrow pits from further erosion with turfing after excavating the required soils to the proposed profile. This will also directly contribute to the protection of the environment.

If slope vegetation cannot be carried out or is unsuitable for a slope, other options such as the use of geosynthetics (e.g. geocells, fibre-mats, etc) or rigid protection measures would be required. The most common rigid protection measures used in Malaysia are sprayed concrete (shotcrete and gunite) reinforced with BRC with proper drainage weepholes. Despite their effectiveness in protecting against surface erosion, this option is not aesthetically pleasing.

5.0 CONSTRUCTION CONTROL

It is very important for a Consultant to properly supervise the construction of a hill-site development. The personnel supervising hill-site developments, especially on the formation of cut and fill slopes, should have sufficient knowledge and experience in geotechnical engineering and geology to identify any irregularities of the subsurface conditions (e.g. soil types, surface drainage, groundwater, weak planes, etc.) that might be different from those envisaged and adopted in the design. Close coordination and communication between design engineer(s) in the office and supervising engineer(s) are necessary so that modification of the design to suit the change of site conditions can be carried out.

This should be carried out effectively during construction to prevent failure and unnecessary remedial works in the future. Site staff should keep detailed records of the progress and the conditions encountered when carrying out the work in particular if irregularities like clay seams and-, significant seepage of groundwater are observed. Sufficient photographs of the site before, during and after construction should be taken. These photographs should be supplemented by information like dates, weather conditions or irregularities of the subsoil conditions observed during excavation.

Whenever possible, construction programmes should be arranged such that fill is placed during the dry season, when the moisture content of fill can be controlled more easily. When filling, tipping should not be allowed and all fill should be placed in layers not exceeding 300mm to 450mm thick (unless compaction trials prove that higher loose thickness is achievable) in loose form per layer and uniformly compacted in near-horizontal layers to achieve the required degree of compaction before the next layer is applied. The degree of compaction for fill to be placed on slopes is usually at 90% to 95% of British

Standard maximum dry density (Standard Proctor) depending on the height of the slope and the strength required. Figure 9 shows a good procedure to carry out filling on slopes.

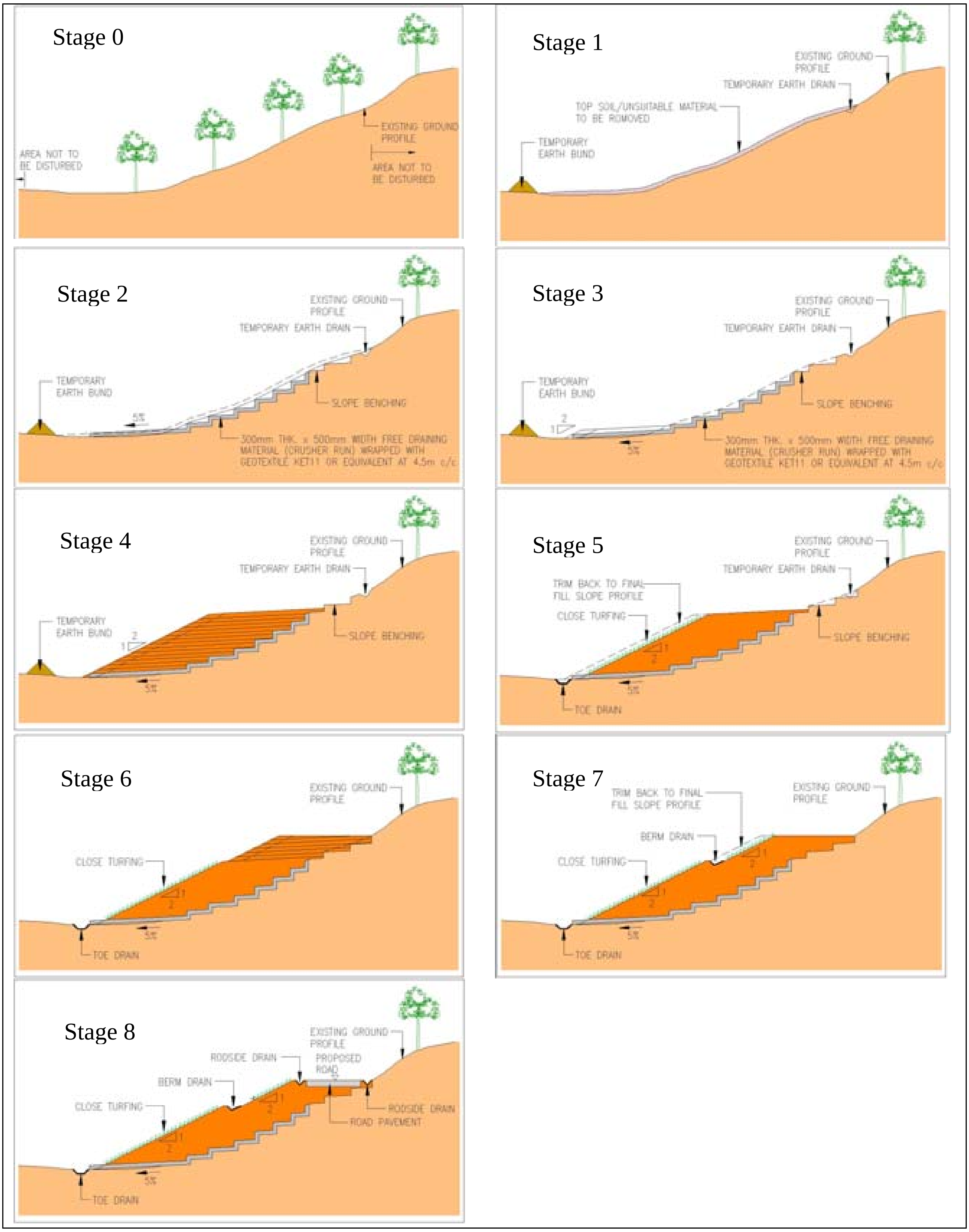

Figure 9 : Typical Good Practice for Engineering Fill

Cutting of slopes should be carried out from top-down followed by works like drains and turfing. When carrying out excavation on cut slopes, care must be taken to avoid overcutting and loosening of the finished surface which may lead to severe surface erosion. Minor trimming should be carried out either with light machinery or by hand as appropriate. It is also a good practice to construct interceptor drains or berm drains with proper permanent or temporary outlets and suitable dissipators before bulk excavation is carried out or before continuing to excavate the next bench.

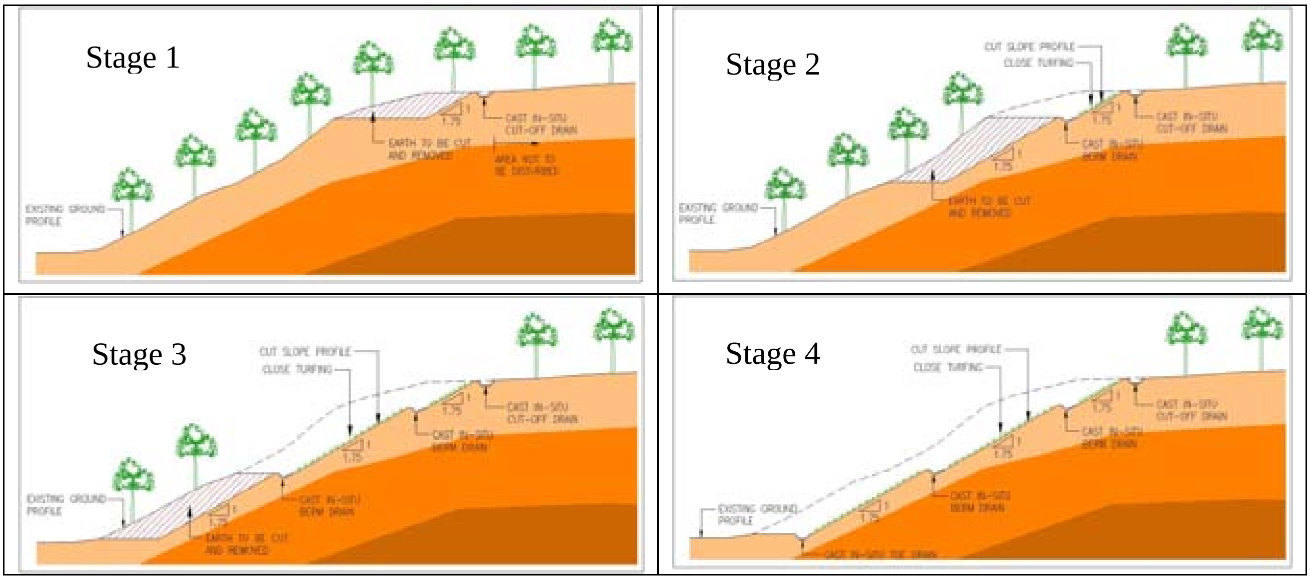

Figure 10 : Typical Good Practice for Engineering Fill

For hill-site earthworks, it is very important that platform or formed slopes are not left open for long (more than 1 week) without any surface protection (e.g. turfing) to prevent erosion that could in time lead to slope failure. Therefore it is a good practice to specify in the specifications and construction drawings that close turfing or hydroseeding shall be carried out within **one (1) week** (practical) after reaching the final formation of any cut and fill (for any exposed permanent slope surface) instead of waiting for completion of all other berms/slopes. All cut & fill slopes should be graded to form suitable horizontal groves (not vertical groves) using a suitable motor grader before hydroseeding. This is to prevent gullies from forming on slopes by running water before the full growth of vegetation and also to enhance the growth of vegetation.

The contract should also impose a penalty on contractors who fail to implement turfing in a timely fashion, or who fail to implement other surface protection measures. This includes allowing the Consultant to instruct another contractor to carry out the turfing works immediately. All newly excavated temporary slopes should also be temporarily protected using plastic sheeting if it is to be left exposed for **more than one (1) week**. It is also very important to regularly monitor, inspect and maintain slopes and drainage systems.

At borrow source (even not on the project site), provision of turfing and hydroseeding should also be applied to the final excavated surface to prevent erosion. Temporary drainage and silt traps should also be constructed and maintained throughout the excavation works. All these items must be included in the specifications and drawings by the consultant and reflected in the method statement by the contractor.

6.0 MAINTENANCE OF SLOPES

A lack of maintenance of slopes and retaining walls is not often a direct cause of a failure. However, failure to maintain slopes, particularly after erosion, may propagate and trigger a landslide. Therefore regular inspection and maintenance of slopes are necessary.

Awareness alone is not sufficient. Engineers and personnel involved in slope maintenance should also know how to properly carry out the work, and, they need a set of standards of good practice for slope maintenance. Good guidelines from the GEO of Hong Kong such as "Geoguide 5 – Guide to Slope Maintenance" (1995) for engineers should be referred to as well as the "Layman's Guide to Slope Maintenance" which is suitable for laymen.

Geoguide-5 (1995) recommends maintenance inspections be sub-divided into three categories:

(A) Routine Maintenance Inspections, which can be carried out adequately by any responsible person with no professional geotechnical knowledge (layman).

(B) Engineer Inspections for Maintenance, which should be carried out by a professionally-qualified and experienced geotechnical engineer.

(C) Regular Monitoring of Special Measures, which should be carried out by a firm with special expertise in the particular type of monitoring service required. Such monitoring is only necessary where the long term stability of the slope or retaining wall relies on specific measures which are liable to become less effective or deteriorate with time.

Malaysia has at least two monsoon seasons. For this reason, Routine Maintenance Inspections (RTI) by a layman should be carried out a minimum of twice a year for slopes with negligible or low risk-to-life. For slopes with high risk-to-life, more frequent RTI such as once a month is required. In addition, it is a good practice to inspect all the drainage channels to clear any blockage caused by siltation or vegetation growth and to repair all cracked drains before the monsoon. Inspection should also be carried out after every heavy rainstorm.

The Category B, Engineer Inspection for Maintenance should be undertaken to prevent slope failure when the Routine Maintenance Inspection by laymen has observed something unusual or abnormal, such as occurrence of cracks, ground settling, bulging or distorting walls or settlement of the crest platform. Geoguide-5 (1995) recommends as an absolute minimum, that an Engineer Inspection for Maintenance should be conducted once every five years or more as requested by those who carry out the Routine Maintenance Inspections. More frequent inspections may be desirable for slopes and retaining walls in the high risk-to-life category.

Slope maintenance is also an important factor. Poorly maintained slopes can lead to slope failure. These may include, amongst others, damaged/cracked drains, inadequate surface erosion control and clogged drains. Eventually, erosion of the slopes allow the formation of gullies (Figure 11a) or cause localised landslips (Figure 11b) which will propagate with time into bigger landslides if erosion control is ignored.

Figure 11: (a) Gullies on Slopes (b) Localised Erosion on Slopes

Excavation or unengineered activities at the toe of a slope can also cause slope instability. These activities disturb the stabilising soil mass at the toe of a hill and hence reducing the FOS of the slope. In addition, activities such as stockpiling earth which imposes surcharge loads at the top/crest of a slope also decreases the FOS of the slope as this surcharge increases the driving forces.

7.0 CONCLUSION

Geotechnical engineering inputs for hill-site development are very important to achieve a safe and cost-effective hill-site development. The inputs should be obtained during the preparation of layout for roads and platforms. The four key engineering processes involved are planning, design, construction and maintenance.

Desk study, site reconnaissance and site investigation are essential to obtain the necessary information for the planning of layout and design of geotechnical works for hill-site developments. Proper design of cut and fill slopes are imperative to prevent slopes failures. It is important for the Consultant to send personnel with knowledge on geotechnical engineering to supervise hill-site constructions so that any irregularities of the subsoil conditions different from those adopted in the design can be identified and rectified. Close coordination and communication between design engineer(s) in the office and supervising engineer(s) are necessary so that modification of the design to suit the site condition can be carried out effectively during construction to prevent failure and unnecessarily high-cost remedial works in the future.

Finally, even with correct design and proper construction, a lack of maintenance of slopes and retaining walls can also trigger landslides. Owners and engineers should regularly inspect and maintain their slopes.

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