Overview of Slope Stability Problems

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Ir. Neoh Cheng Aik
E-Geo Consultant Sdn Bhd
caneoh@gmail.com

1. Introduction

This paper presents the overview of slope stability problems aimed at providing insights on how a slope can be stabilized or destabilized by various factors. The common stabilization & protection methods for slopes with particular reference to their applications, limitations and engineering basis will also be briefly discussed.

Slopes can be natural or man-made cut or filled slopes, which are invariably prone to erosion and failures when subject to natural weathering process and rainfall unless they are properly engineered by proper slope protection and stabilization methods plus due maintenance.

Generally, slope failure refers to downward and outward movement of soil/rock mass from slopes. Slope failure can be generally classified as debris flow, rock falls, slides, landslips, etc. Large scale or massive slope failure (typically >2,000 m^3) is usually called landslide.

This paper also intends to present and share author's views about important statistics and common causes of slope failures. Slope design practice and usual methods of slope stabilization & slope protection plus their significance to address slope problems are discussed.

2. Overview of Slope Stability Problems & Issues

Slope engineering is a complex subject. Knowing the important statistics and factors/features that can influence the stability of slopes plus the effective mitigations against what can usually go wrong for slopes are of utter importance when designing slope stabilization and slope protection works.

Most of the cut slope failures (>90%) in Malaysia are usually and mainly triggered by excessive infiltration due to intense and prolonged rainfall (Asbi, 1989). Prolong capillary action due to excessive inundation of slope toe also can lead to slope slips. Landslides caused by seismic forces such as blasting, piling, thundering or earthquakes are seldom if not never in Malaysia. The following slope features/factors are the main culprits responsible for excessive infiltration:

- **Presence of large upslope catchments can result in large/extensive infiltration.**
- **Presence of serious localized weakness such as adverse relict geological discontinuities**
- **Inadequate slope drainage can cause more/higher infiltration,**
- **Inadequate or defective slope protection can lead to more infiltration**

The above 4 features/factors can be easily assessed and effectively mitigated based on the current state-of-practice though the presence of geological discontinuities can be treacherous and difficult to be determined by normal soil investigation (SI). **Effective mitigations against infiltration due to these 4 factors are the most effective measures against slope failures**.

Asbi (1989) reports that the instability problems associated with residual soil cut slopes in Malaysia are mainly due to intense and prolonged rainfall. Such slope failures are usually shallow (about 1.0m - 3.0m deep or slip depth to slip length ratio < 10%). In fact, about 90% of slope failures have slided debris of less than 50 m^3. Massive landslide or deep-seated slip surface usually is possible after excessive infiltration and subsequent deep extensive saturation and slope creeping. Extensive saturation is only possible if the slope has massive deep relict geological discontinuities, large upslope catchments especially those with many large connected valleys, poorly protected slope and inadequate slope drainage. Hence, to mitigate massive landslide effectively, efforts to assess the problems caused by these culprits shall at no account be neglected.

Comprehensive slope design shall include RATIONAL ANALYSIS based on engineering principles/codes of practice, realistic parameters from SI results plus past experience or reported case histories/statistics.

Design calculation alone is not everything until and unless it is proven by testing & monitoring to check and to validate the design assumptions/parameters/predictions at site during construction stage. In fact, JB Burland in his NASH lecture (1987) clearly stated ***"It is both arrogant and dangerous to believe that ground engineering can be carried out solely on the basis of numbers (calculations) given from SI coupled with codes of practice. It is necessary to study case histories, learn about local experience, examine the soil and visit the site***." Geotechnical design especially practical slope design is mainly based on empirical methods, which require high degree of engineering judgment, which in turn requires a lot of experiences and reported case histories. Calculations based on some assumptions and SI results are mainly used to justify or to verify the judgment and not otherwise. The main responsibility of geotechnical engineers is to judge soundly, not just to calculate accurately (Terzaghi). The design codes or sample design calculations alone may give inexperienced engineers the undue confidence to produce slope design beyond their competence.

Slope stability is a vast and complex subject involving with many geotechnical principles, some of which are very empirical and required site verification by experienced engineers and geologists during construction. Factors affecting slope stability are numerous and some of which cannot be determined or modeled with high degree of certainty/accuracy due to non-homogenous and anisotropic nature in soil properties which may also be dynamic in nature.

3. Factors/features Influencing Slope Stability

Typical scope/procedures of slope assessment are as follows:

- Desk studies & literature search to get relevant information.
- Field studies to assess conditions about access, site terrains, nearby buildings/structures/utilities, surface drainage, vegetations, any signs of slope distress or pre-existed tension cracks, etc. (walk over-survey/inspection or by Google earth or by drone).
- Geological studies (Site geology, geomorphology, geohydrology, terrain/discontinuities mapping, geophysics, etc.) More applicable for hilly areas with large scale upslope/downslope catchments.
- Ground investigation (Field & lab testing, groundwater monitoring to get subsoil profiles & properties).
- QRA (quantified risk assessment)
- Slope design (scope of design verification & validations to show compliance with CP & local by-laws, Slope maintenance scheme, etc. Scope of slope design verification includes slope geometry, FOS criteria, slope stability analysis, slope stabilization, slope drainage, slope protection, mitigations vs. What can go wrong at site, etc. Refer "Geotechnical Manual for Slopes" published by GEO Hong Kong, 1984.)

Factors that have significant impact on slope stability conditions are discussed as follows:

a) **Slope geometry** (Slope height, inclination, shape, upslope & downslope catchment conditions & topography) can be assessed and determined easily by survey data and aerial photos. Higher and steeper slope inclination normally have lower factor of safety if other features are the same.

b) **Soil density** is typically in the range of about 18 to 21 kN/m^3.

c) **Slope drainage and slope protection are** critical to slope stability, but can be designed satisfactorily based on current state of practice.

d) **Shear strength**

- Shear strength for residual soils are invariably anisotropic, non-homogeneous and dynamic in nature. Effective shear strength (c' and ϕ') may change with time as the result of deterioration and weathering influenced by infiltration, creeping, groundwater movement and seepage and all these are directly or indirectly affected by method of slope protection, slope drainage and upslope catchment conditions, etc.
- It is also difficult to get representative and characteristic shear strength values through normal undisturbed sampling and laboratory tests at distinct layers especially coarse-grained soils. Shear strength envelope can be non-linear at low effective stress. c' values obtained at high normal stress usually overestimate the shear strength.
- Steep cut slopes when subject to excessive infiltration may encounter high strain or creeping and this may lead to reduction of peak to critical or residual shear strength only ($\phi' < 25^o$) for high plastic clayey soil.

- Newly compacted fills are usually unsaturated and very stiff with cohesion exceeding 75 kPa (c'>5kPa and ϕ' >35^{o} or more), but when subject to eventual wetting and collapse settlement due to infiltration or capillary action from high water table or inundation, the shear strength may drastically be reduced to about 50 kPa (c'< 3 kPa & ϕ' < 30^{o}) or less, depending on degree of compaction and fill material type used.
- Hence, selection of the shear strength parameters in analysis shall consider these factors carefully as there are extremely diverging expert opinions on how to select long term shear strength parameters in design.
- In practice, shear strength parameters for cut slope stability analysis shall be based on triaxial (CIU) tests from selected representative undisturbed/Mazier samples from distinct layers or block samples or insitu shear box tests or based on correlated values by comparable experiences and also shall be compared with the typical published values to ensure within the realistic and reasonable ranges. Refer Table 8, Geoguide 1 by GEO Hong Kong (1993). The adopted design shear strength parameters should be validated during construction stage.
- It is important to recognize that slip or rupture plane of slope failure is always initiated and formed through weakest zones such as the relict geological discontinuities/seams of kaolinites, which are preferred water path and when infiltrated have low shear strength of c' = 0, ϕ'= 30^{o} or less. Fill slopes with high moisture content zones or localized weak soil are the potential slip/rupture surfaces. Localized weakness can also be formed by soil pipes caused by root holes, animal burrows, cavities by collapse settlement or relict discontinuities especially at depressions where water can concentrate.

e) Pore-water pressure & suction

- Conditions of groundwater, seepage, infiltration & rainfall are dynamic and difficult if not impossible to characterize accurately. It requires instrumentation and longtime monitoring to produce more accurate information. Perched groundwater is common at the interface between colluviums and underlying the compact residual soil. Suction is usually not considered in design because it can be easily destroyed by infiltration unless adequately and reliably protected by good guniting or HDPE geocells with underlying membrane. For granite formation, permanent groundwater is usually found at or near the interface of soil and bedrock or within the IGM (intermediate geomaterial). Though the information about pore water pressure and suction are critical in slope design such information are difficult to be determined with high degree of certainty. More rigorous monitoring or instrumentation especially during the construction stage is only usually carried out to check and verify the assumed values. Groundwater can also be temporarily raised by excessive infiltration or by capillary action when toe is saturated/inundated. Perched water table and seepage account for 30% and 38% of slope failures respectively (Malone & Ken Ho, 1997). Effective mitigations against problems caused by signs of seepage and perched water table are installation of horizontal drains plus mitigations against infiltration such as proper slope protection and adequate slope drainage.
- Groundwater conditions of fine-grained subsoil should be determined by close piezometers.
- Horizontal drains are the most effective method to lower groundwater table and enhance slope stability, especially at strata prone to have perched water table at large upslope catchments. Horizontal drains should be sufficient long to reach the interface of groundwater, if present and located.

f) Treacherous relict geological discontinuities

- Treacherous relict geological discontinuities such as colluviums, interface of different geological formations, faulted planes, day-lightings, foliations, massive relict joints, beddings, etc., are preferred water path and have localized weak or lower shear strength (Irfan & Woods, 1988). These relict unstable geological discontinuities when found in the cut slopes are the usual localized weakness to form potential slip surface/zone. These relict geological discontinuities such as seams of kaolinites can be very thin (<5mm) and normally is missed by usual SI boring and sampling. More practical way to identify these highly treacherous and risky geological discontinuities is to carry out geological discontinuities mapping by experienced geologist/engineers when the slopes are cut & exposed during construction stage. Slope failures are initiated and triggered at weak zones with lowest shear strength, not the average shear strength that counts. That is why even rock slopes such as Bukit Lanjan granite slopes also can fail at weak geological discontinuities though the average shear strength is very high.

4. Statistics about Slope Failures

Some enlightening and significant statistics about slope failures based on "IEM/JKR Lecture Notes for Highway Slope Management" by Malone & Ken Ho (1997) are summarized as follows:

a) Types of slope failures

A survey of 322 slope failures revealed that: 89% are cut slopes (54% soil slopes + 11% rock slopes + 24% soil/rock slopes); 8% are fill slopes; 2% are retaining walls & 1% are natural slopes. Factors affecting the stability of fill slopes can be determined or achieved with a high degree of certainty and accuracy based on current state-of practice as summarized in Fig 4. This explains why fill slopes seldom fail, if they are properly designed, constructed and maintained as outlined by JKR 'Guidelines on Slope Maintenance in Malaysia" (Aug 2006).

b) Volume of slided materials

Results for 225 landslides of all sizes show that about 90% of the landslides involve volumes of debris of less than $50m^3$ and average angle of reach of about 30^o. These findings are useful for assessing zones of hazard or buffer zone for building/structures near the slopes.

c) Causes of slope failures

Findings from another survey of 260 case histories about causes of landslides are:

- infiltration 90%
- seepage 38%
- perched water table 30%
- wash-out/erosion 8%
- rise in main water table 2%
- others (pipe leakage, etc.) 2%

Based on the above statistics, practically almost all the causes for landslides are directly or indirectly due to infiltration. This means that if excessive infiltration for a slope is adequately controlled, landslides can be effectively controlled. **As excessive infiltration is mainly only possible due to large upslope catchments, presence of adverse geological discontinuities, inadequate slope drainage and poor slope protection, effective mitigations against excessive infiltration caused by these features/factors, as elaborated in Fig. 1 and Fig. 3 are the most important parts of slope design provisions to ensure safety of slopes**. Parameters used to derive factor of safety from normal stability analysis can only be realistic and satisfactory, if the parameters are adequately validated during the construction stage and adequate mitigations against infiltration are provided.

d) Factor of Safety (FOS)

Recommended FOS against various types of failures for various geotechnical designs with their respective failure rates as reported by G.G Meyerhof (1970) are:

- Earthworks (slopes): FOS=1.2-1.5 (0.2% failures)
- Retaining walls: FOS=1.5-2.0 (0.07% failures)
- Foundations: FOS=2.0 – 3.0 (0.02% failures)

Failure rate for slopes is reported to be comparatively high among the typical geotechnical designs is mainly due to adopted lower FOS as recommended/accepted by experts/code of practice, mainly based on cost-effective factors, etc.

e) Other statistics about Landslides

Ashaari & Hassandi (2009) has reported that there are about 500 reported landslides and about 500 people were killed by landslides in Malaysia since 1961 (about 10 people/yr killed) with total estimated economic loss of RM 2.5 billion from1973 to 2007 (about RM 73.5 juta/yr). Recent high profile landslides involving with fatalities are Highland Tower Landslide (48 killed,1993), Genting Slip Road Debris Flow (20 killed, 1995), Gua Tempurong Landslide along North-south Expressway near Tapah (1 killed, 1996), Pos Nipang Perak Debris Flow (44 killed, 1996), Keningau Sabah (302 killed, 1996), Taman Hillview landslide (8 killed, 2002), Bukit Antarabangsa landslide (5 killed, Dec 2008), Penang Tanjung Bungah landslide (11 killed, 2017), etc. All these massive landslides have common characteristics of very large upslope catchments which provide large surfaces to excessive infiltration, which is cited for 90% of slope failures. Most of these landslides also have adverse geological discontinuities causing deep saturation.

f) Summary of statistics

The above statistics reinforce the importance of provision of adequate and effective slope protection and drainage for surface runoff and subsoil. Infiltration due to surface runoff from large upslope catchments, extensive relict geological discontinuities or poorly drained and protected slopes can result in an extensive increase of saturation and a subsequent loss of suction and shear strength simultaneously. Effective measures against infiltration are therefore effective methods to avoid landslides.

Main common causes for slope failures and interrelated causes and effects of slope failures are summarized and illustrated in Fig. 1 and Fig. 2 respectively.

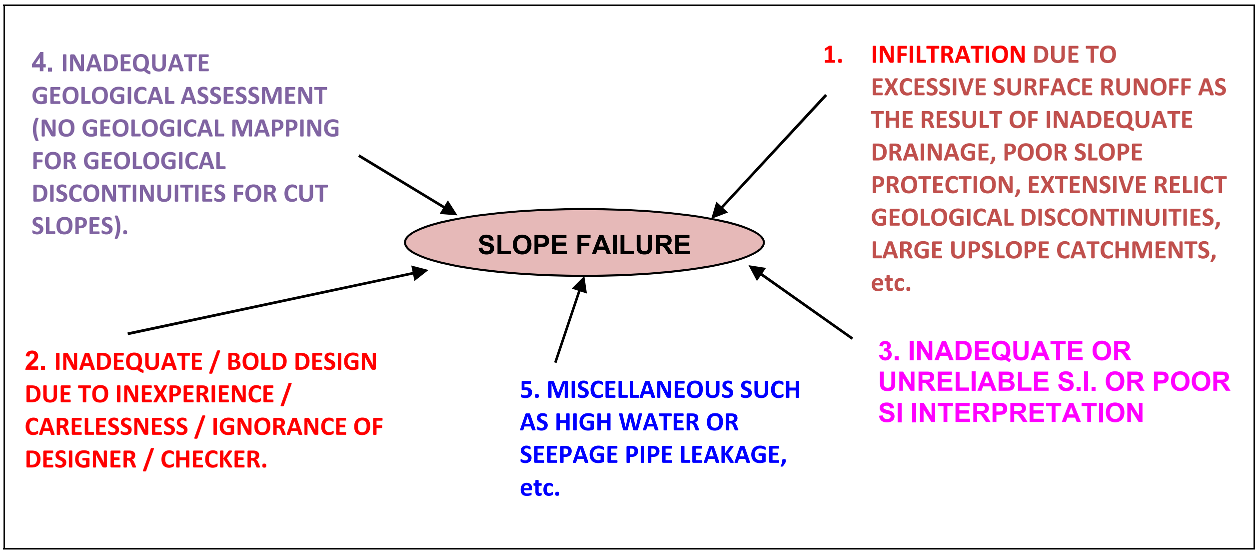
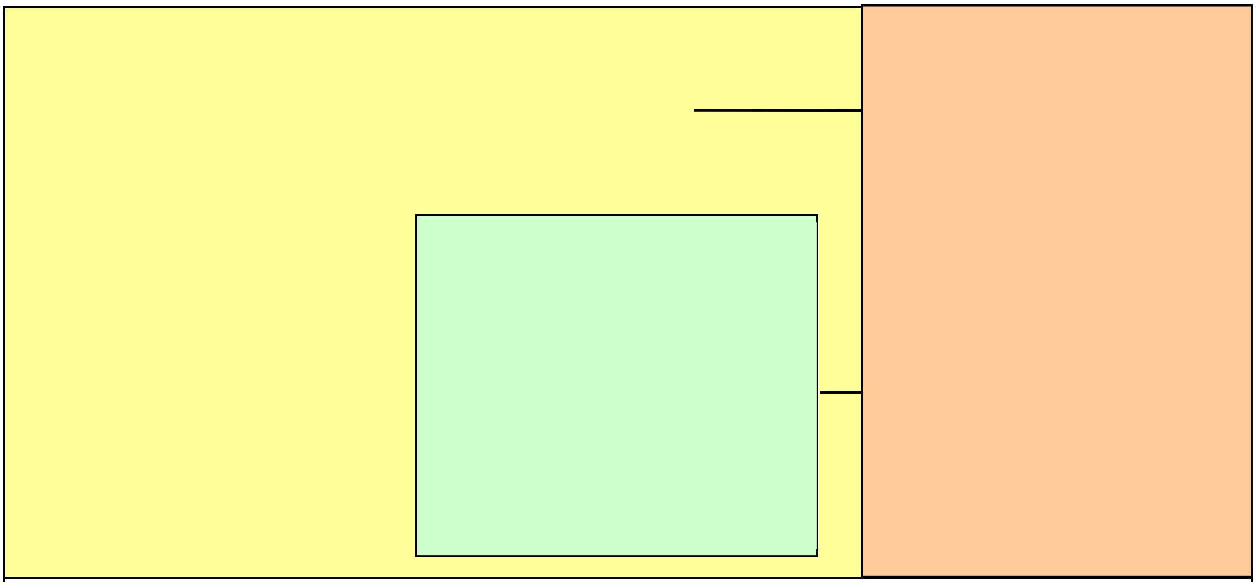


Fig1: Main Common Causes for Slope Failures



This Fig 2 is modified from Mohd Haris Abas (1983)

- Reliable SI refers to SI by CIDB registered SI Contractor using proper equipment, proper test procedure & under supervision by qualified personnel. Adequate SI refers to scope of SI that meets the requirements by established guidelines such as REAM GL6/2004, etc. BEM Circular 4/2005 reminds all Professional Engineers of their responsibility for proper planning & supervision of SI works.
- Refer JKR "Guidelines for Slope Design" (Jan 2010).

Fig 2: Interrelated Causes & Effects for Slope Failures

5. Slope Design Methods

There are many methods and procedures or approaches to assess stability and design of slope stabilization works, but generally and usually the methods can be broadly classified as **analytical method** and **precedent method**.

State-of-the art for slope stability analysis remarked by Brand (1985) are as follows:

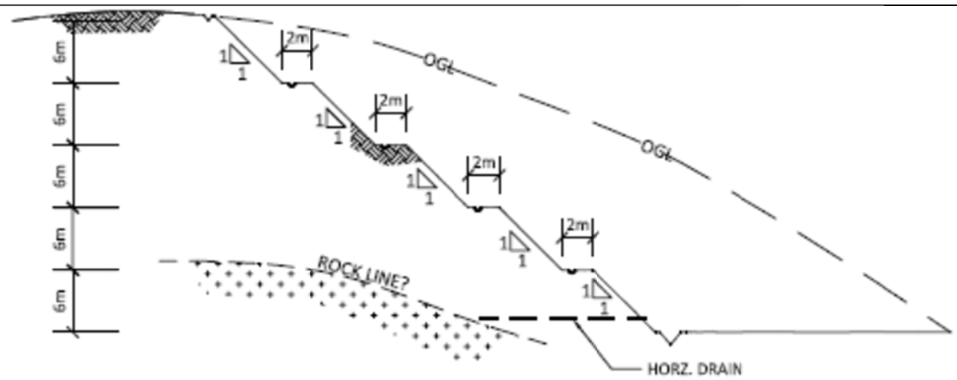
- **Modeling & mechanism: very good – good**
- **Shear stress (soil density, H, WT, etc.): very good – good**
- **Shear strength (c', ϕ'): fair – good**
- **Shear strength (suction/ pore pressure): poor – very poor**

Peak shear strength can be high when unsaturated or dry, but can be reduced to critical or residual strength when the slope suffers creeping (high strain) after excessive infiltration and saturation, especially when cut slope is steep & there are extensive relict geological discontinuities or large upslope catchments. Fill slope with excessive subsoil seepage or toe inundation or excessive infiltration also can cause extensive saturation, collapse settlement & creeping, especially when compaction is inadequate and the fill has collapsible minerals.

a) Analytical method refers to rigorous and time-consuming method based on detail site survey, site investigation and laboratory tests. This rigorous method is normally justified for high risk to life and high economic risk structures such as high slopes near high-rise buildings, deep excavation near buildings, or important structures. Detail design validation including geological mapping and monitoring of slope performance are also parts of analytical method. This method shall only be carried out by experienced geotechnical engineers and independently checked by BEM accredited checkers or experts. The most challenging/difficult part (time-consuming and costly/expensive) for the success of this method is to get adequate quality undisturbed samples at distinct strata for CIU tests and determination of realistic groundwater conditions especially the perched water table.

b) Precedent method generally based on precedent experience and some limited SI & surveys during the design stage but extensive design validation and design review during the construction stage, after more specific and detail information are available. This method is simple and faster but is more applicable and practical for urgent projects involving with many slopes such as highway projects. This precedent method should have scope of design validation including geological mapping, block samples for CIU tests at distinct layers for stability analysis review, etc., especially for cut slope height exceeding 12m. This method is summarized in Fig. 3. Fill slope design scope is given in Fig 4.

This method is very popular among designers because it is practical and fast. Success for this method requires a lot of comparable local experiences and reported case histories to justify the design. Stability analysis can be based on deduced or correlated shear strength parameters from some SI or reported typical values (Refer Table 8 of Geoguide 1, GEO Hong Kong). Precedent method can be as reliable as that of analytical method if the design verification scheme and mitigations as stated in Fig. 3 are truly carried out. The main difficulty and problem of this method is to identify the WT, seepage, upslope catchment conditions and the unstable geological discontinuities/settings during the construction stage and provide due effective mitigative measures against infiltration. The success of this method requires the committed site engineer to ensure the necessary design validation and review are truly and duly carried out during the construction stage. This method is soundly based on statistical study/comparable experiences and provision of adequate and effective mitigations against infiltration, which is cited at major cause for slope failures.

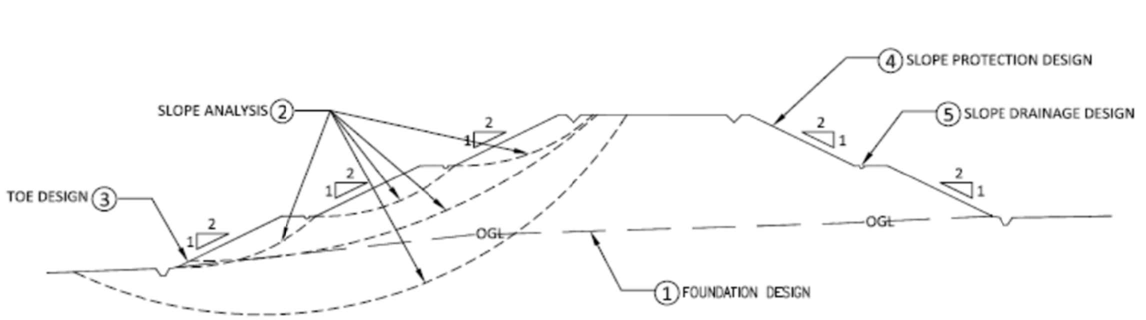


1. Based on statistical survey of cut slopes along KL-Karak Highway, generally 1:1 cut slopes with minimum 1.5m to 2.0m berms cut of max 6m vertical intervals shall be statistically stable (FOS>1.2) provided the following assessments & design validations are carried out by qualified geotechnical engineers.
   a) Adequate & effective cast-insitu surface drains & slope protection works (refer Fig 5) shall be provided
   b) Provide horizontal drains at strata underlain by comparatively impermeable strata or if seepage is observed at site.
   c) If adverse relict geo discontinuities are present, provide impermeable slope protection such as guniting or HDPE geocell with underlying membrane plus horizontal drains, etc.
   d) In case of large upslope catchment is encountered, it should be engineered by qualified engineers to ensure compliance with the basic requirements recommended by "Geotechnical Manual for Slopes" (GEO Hong Kong, 1984). Mitigations to reduce infiltration such as more interceptor drains, horizontal drains, provision of impermeable surface, etc., should be provided.
   e) Earthwork practice shall comply with the requirements of Nota Teknik (J) 20/98.
2. Adequate scope of SI for cut slope design as per REAM GL6/2004 shall be carried out to assess slope stability (prelim design). Water table shall be monitored by piezometers especially at potential perched water table.
3. In case of inadequate FOS, proper methods of slope stabilization as discussed in Para. 7 shall be considered.
4. Unless design review by BEM accredited checker & adequate design validation during construction stage are carried out by suitably qualified P Eng, this precedent method is not recommended for
   a) Cut slopes exceeding 18m high and/or slopes with high risk to life or high economic risk structures
   b) Cut slopes with large upslope catchments and slopes with extensive relict geological discontinuities.
5. Shear strength for stability analysis shall be validated by insitu shear box tests for gravelly soils or block/Mazier samples taken at representative distinct strata and at relict discontinuities (if any) for CIU tests during the construction stage.
6. Flexible Debris Flow Barriers shall be constructed for large and long connected valleys at upslope catchments to reduce the risk of debris flow (Asbi, et, al, 2008).

Fig 3: **Cut Slope Design (Precedent Method)**

Fig 3A: **This cut slope has no large upslope catchments for excessive infiltration**. No sign of seepage, no severe geological discontinuities except some localized boulders. Hence, with proper slope protection & slope drainage the risk of excessive infiltration is practically negligible or the slope is bound to be safe and stable. Some block sample samples from distinct layers should be taken for CIU tests for quantitative stability analysis to ascertain the local & global stability. With regular routine inspection and maintenance by suitably qualified personnel as per recommendations by JKR Guidelines on Slope Maintenance in Malaysia (Aug 2006) and some simple instrumentation monitoring, the slope should be reliably able to ensure long safety and stability.

Fig 3B: **This cut slope at the road level has very large upslope catchments** which are prone to excessive infiltration. Adequate mitigations against signs of excessive infiltration plus instrumentation should be provided to mitigate against landslide.



Scope of design to ensure compliance with design criteria (Refer JKR Nota Teknik (J) 20/98):

1. **Foundation Stability:** Check FOS_b vs. bearing failure & post construction settlement
2. **Slope Stability Analysis:** Check FOSs vs. slope slip. If FOS_b <2 (long term) &/or FOS_s< 1.2, design the necessary ground treatment & slope stabilization.
3. **Toe Stability Design:** Design/provide toe stabilization (rock toe/reinforced toe) for the toe likely to be inundated or high capillary action, etc., or high fill slopes (>18m).
4. **Slope Protection Design:** Check slope geometry & soil type & select suitable slope protection method (refer Fig 5).
5. **Slope Drainage Design**: Refer REAM Guidelines for slope drainage design.

Fig 4: **Design of Fill Slope/Embankment**

JKR "Guidelines for Slope Design" (Jan 2010) provides some useful design guidelines for rock, cut and fill slopes with particular reference to slope design requirements for site investigation, geological mapping, independent check for slope stabilization, design criteria plus typical details of soil slope stabilization methods, etc.

6. Slope Protection Methods

Proper slope protection not only can prevent slope surface erosion due to surface runoff, etc., but also can reduce infiltration, which is the main culprit for slope failures. Proper slope protection also can enhance slope appearance to ensure pleasing and aesthetic environment. It has been reported that bare or poorly vegetated slopes have 3 to 5 times more infiltration rate than the properly vegetated slopes.

Factors that can affect selection of suitable slope protection methods are given in Fig. 5 & 6.
Various types of slope protection and the applications/limitations are briefly discussed as follows:

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Methods * / Conditions	Close Turfing	Hydro-Seeding	Hydro-Seeding with Biomat	Vetiver Grass	HDPE Geocell	Gabion Mattress	Stone Pitching	Gunite	RC Skin Wall
1.0 SOIL TYPE									
1.1 Silty/Sandy CLAY	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓	✓	✓
1.2 Sandy SILT	✓	?	✓	✓	✓✓	✓	✓	✓	✓
1.3 Silty SAND	✓	x	?	?	✓✓	✓✓	✓	✓	✓
1.4 Fractured/Rocky/Boulderly	x	x	?	x	✓	✓	✓	✓	✓
1.5 Very stiff/hard	?	?	✓	?	✓	✓	✓	✓	✓
1.6 Acidic	?	x	x	?	✓	?	✓	✓	✓
2.0 SLOPE GEOMETRY									
2.1 Gentle slope, $B < 35^0$	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓	✓	✓
2.2 Medium slope	?	✓	✓	✓	✓	?	✓	✓	✓
2.3 Steep slope, $B > 42^0$	x	?	✓	?	✓	x	✓	✓	✓
2.4 Down-slope length, L > 10m	✓	✓	✓	✓	✓	✓	✓	✓	✓
3.0 MISCELLANEOUS									
3.1 Aesthetic	✓	✓	✓	?	✓	?	✓	✓	✓
3.2 "Green" requirement	✓	✓	✓	✓	✓	x	x	x	x
3.3 High water table	✓	✓	✓	✓	✓	✓	?	x	x
3.4 Poor slope surface drainage	?	?	?	✓	✓	✓	✓	✓	✓
3.5 Shady area	?	?	?	x	?	✓	✓	✓	✓
3.6 Unit cost (RM/m^2)	< 8	< 3	< 5	< 5	< 50	< 70	< 70	< 90	< 100

Legends:
✓✓ = Very suitable ✓ = suitable ? = Doubtful x = Not suitable

Figure 5: Slope Protection Selection Chart

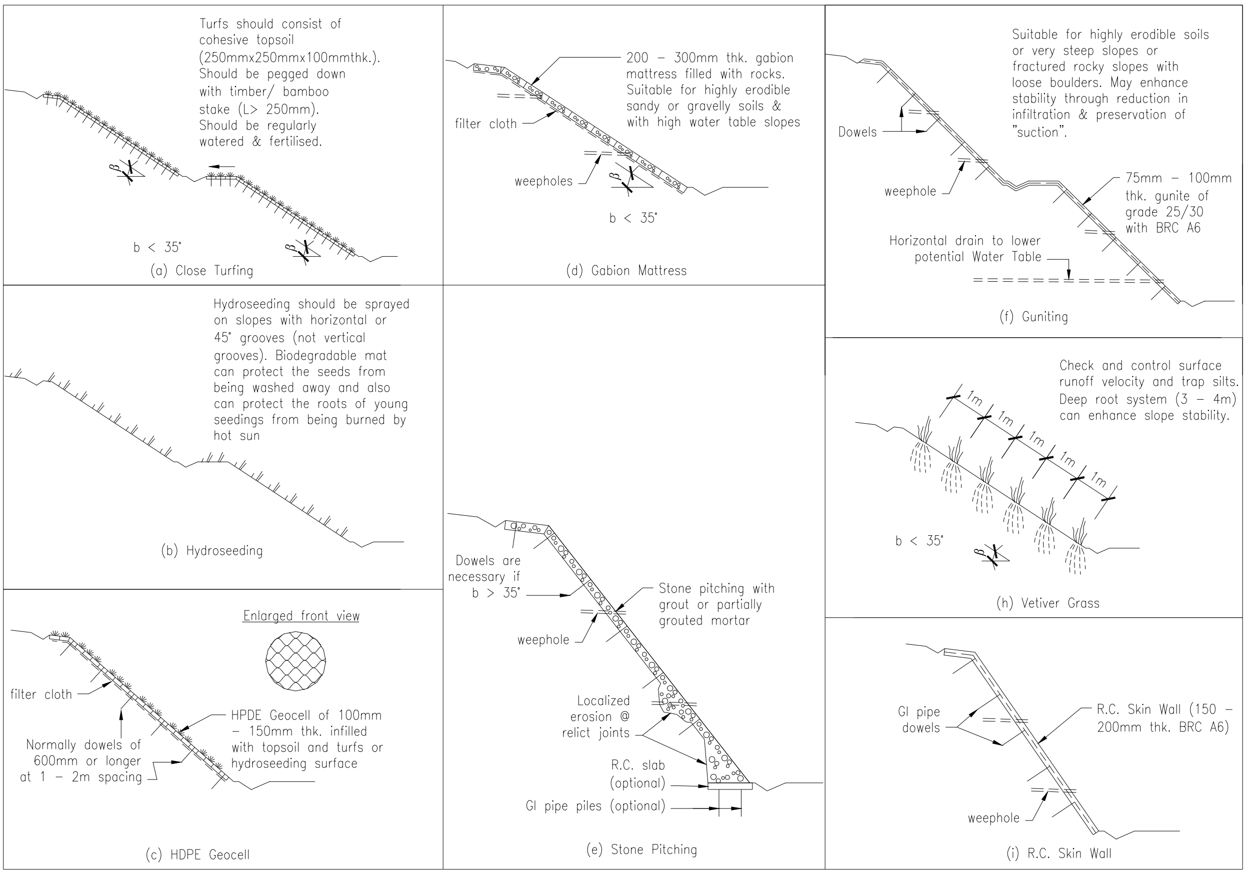


Fig 6: **Slope Protection Methods & Details**

7. Slope Stabilization Methods

Generally, slope stabilization methods can be classified as preventive methods for existing slopes of low FOS and remedial methods for failed/slipped slopes. The fundamental principle for slope stabilization is just to improve the resisting forces or to reduce the destabilizing forces or both. The most difficult issues are to show the proposed slope stabilization method has met the Client requirements and adequate mitigations are provided to ensure FOS is not deteriorated during the process of remediation and in service.
For fill slopes, normal cost-effective slope stabilization methods include mechanical stabilized slope/wall or RE walls or geosynthetic reinforced walls/slopes with flexible wrap-back or gabion facing or RC panels, RC anchored wall, bored pile wall, etc. For cut slopes, the common slope stabilization methods are soil nailing, gunting and HPDE geocell with underlying membrane, etc. These methods can be applied as preventive and remedial measures.

a) Soil Nailing

Soil nailing is a well proven and widely used method by engineers in Malaysia since early 80' to reinforce or stabilize new cut soil slopes or enhance slope stability of existing or natural slopes with low or unsatisfactory factor of safety.

Soil nailing technique to reinforce slope was introduced to Malaysia in early 1980 and one of the early slopes reinforced by soil nailing was Bukit Jugra Army Camp slope in Banting in 1983. Pos Betau-Ringlet Highway, a new JKR R3 hilly road of about 85km long, is estimated to have successfully about 55,000 soil nails with gunite area of about 180,000m^2 to stabilize and protect very steep and high cut slopes up to about 70m or more.

The basic design concept of soil nailing is to reinforce and strengthen the slopes insitu by installing grouted steel bars or driven pipes, called "nails", into progressively excavated slope/wall by the "top down" process. This process can create a reinforced mass that is internally stable and able to retain the ground mass against active pressure, sliding, bearing and overturning forces. To ensure the soil nailed mass is adequate to resist overturning due to lateral active forces, the following important conditions shall be fulfilled. Soil nailing generally is not applicable or not cost-effective to stabilize slopes with soft/loose soils and/or aggressive/organic soils.

The nail-soil interaction consists of transferring the resisting tensile forces generated in the inclusions of "non-extensible" rebars into the slope/wall through friction or bond or adhesion mobilized at the nail-soil interface. Normally, lateral displacement due to stress-relief of excavated slope is about 0.1%H to 0.3%H, where H is the total excavated depth. Soil nails work predominantly in tension but may develop some bending/shear in certain circumstances when internal strain or deformation is too large. When the lateral displacement exceeds 0.5%H, excessive bending and shear in soil nails may happen and develop excessive creeping and tension cracks in the upslope, resulting in excessive infiltration and eventual failure. The existence of tension cracks is likely to decrease stability fatalistically because the length of potential slip surface over which the shear strength can be mobilized is reduced and also when the tension cracks are filled with water, the additional driving force will keep on increasing until failure takes place. Hence, it is very important to assess the possible causes and mitigations against excessive deformation, which are mainly caused by poor construction practice resulting in low bond strength, presence of unstable geological discontinuities and excessive infiltration from large upslope catchments, if any. It is also a good practice to install some simple surface markers on the crest of nailed slope to monitor the deformation and the upslope conditions so that early mitigative or preventive measures such as sealing the upslope with some membrane or gunite and additional large interceptor drains, etc., can be taken.

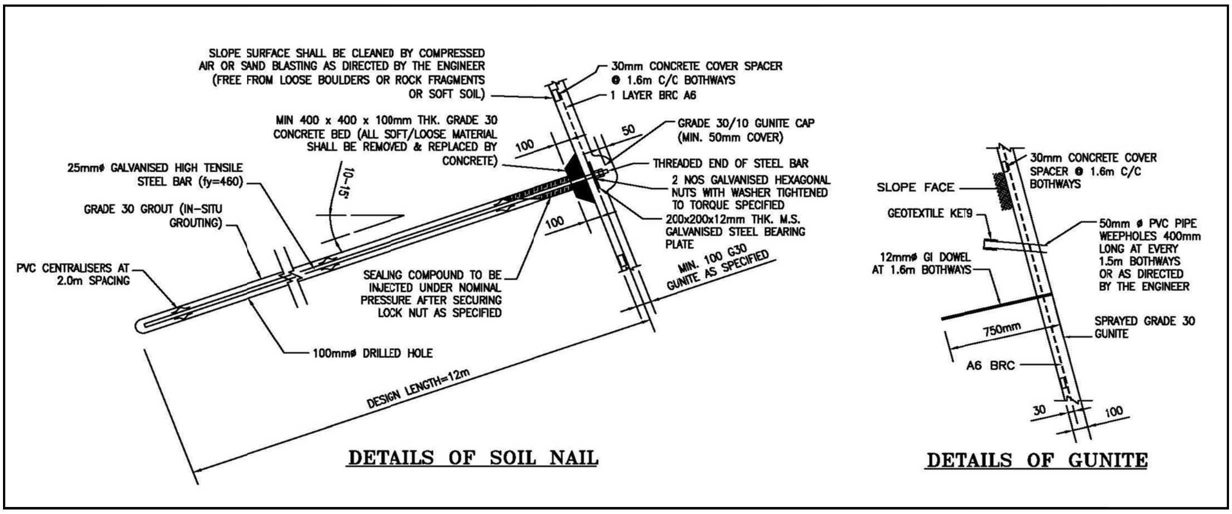
The resisting tensile forces mobilized in the grouted rebars can induce an apparent increase of normal stresses along the potential slip surfaces to increase the overall shearing resistance of insitu soil. The effect of the rebars is thus to improve stability by increasing the normal force and hence, the soil shear resistance along the potential slip surfaces in frictional soils; and reducing the driving force along potential slip surfaces in both frictional and cohesive soils.

Estimation of pull-out resistance of soil nails is the most important part in soil nail design. In practice, the pull-out resistance is mainly based on bond strength or adhesion at the interface of nail-soil by empirical formula or some assumed or correlated values based on SI results and then verified by pull-out tests during the construction stage. The soil nails should be long enough and extended a minimum distance beyond the back of the critical slip surface to achieve the minimum targeted FOS. Generally, Morgenstern & Price or Janbu's stability analysis method is preferred to Bishop's Modified Method because the former method is less sensitive to the assumed location of applied load in soil nails.

Prediction of displacement and axial forces along the soil nail can be carried out by LEM (limit equilibrium method) or FEM (finite element method). Generally, FEM gives lower values or lower factor of safety.

In Malaysia, soil nails, typically and invariably, consist of 16mm to 32mm diameters high yield steel reinforcement bars of 6m to 24m long at centre to centre spacing of about 1.0m to 2.0m with design working load of 50 to 180 kN per nail, depending mainly on the geotechnical capacity. The nails are typically inclined slightly downwards (10-20^0) and grouted in pre-drilled holes having diameters in the range of 100mm to 150mm.

Several publications are available for the design methods for soil nails and reference may be made to GEO HK Geoguide 7 (2008) or Neoh CA (2004 & 2008) for design details as examples.



Notes:

1. ***The Method Statement as specified shall be prepared & submitted for approval before commencement of works.***
2. ***All soil nails, gunite & horizontal drains shall be constructed as specified & shown.***
3. ***Unless otherwise proven that the drilled hole is stable & no collapse, duplex drilling, casing or equivalent shall be used for soil nailing. Grouting shall be carried out within 2 hr after completion of drilling.***
4. ***Cement grout shall be thoroughly mixed by high speed colloidal mixer (>1000rpm) and its quality shall be checked as specified or at least daily for bleeding test, flow cone afflux time test & crushing strength (BS1881).***
5. ***Soil nail head shall be constructed as specified & shown. All soft or loose material at nail head shall be removed & replaced by grade 30 concrete/mortar to ensure proper contact.***
6. ***BRC wire-mesh, spacers, pvc weepholes & dowels shall be properly fixed and guniting shall be commenced from top slope portion first and the nozzle shall be directed perpendicular to the surface at about 0.5m to 1.8m away. Workers carrying out guniting shall stand on staging & shall not step on BRC during guniting. At least one core per 500 sq m or per slope at locations selected by the Engineer shall be carried out to check quality, thickness and crushing strength as specified.***
7. ***Pull-out test according to GEO HK Geoguide 7 or REAM Spec shall be carried out to verify design bond strength.***

Fig 7: Typical Details for Soil Nail & Gunite

b) Horizontal Drains

Presence of groundwater reduces the stability of slopes through reduction of shear resistance of the soil, decrease in cohesion, subsurface erosion, lateral pressure in fractures and joints, and excess pore pressure. Horizontal drains are effective to reduce these undesirable effects of groundwater on slope stability as had been reported by Ir. Dr. Ahmad Nadzri (1989) in several case histories in Malaysia (East-West Highway and Seremban Highway).

The effectiveness depends on the spacing, diameter of the drains and on the location relative to the critical slip zone or zones of pervious, water bearing material, which is usually located near Grade 3 or 4 weathering profile or the interface of soil and bedrock.

For more details about design, construction and maintenance of horizontal drains - please refer 'Review of horizontal drainage systems for slopes on Malaysian Highway, 1989' by Ir. Dr. Ahmad Nadzri Hussein, JKR and 'Groundwater Lowering by Horizontal Drains' by DJ Craig and Gray, GEO Hong Kong, 1985.

c) Geosynthetic Reinforced Slope

Use of soil reinforcement principles to apply geosynthetic products in fill slope stabilization works in Malaysia has been increasing over the past decade. Inclusion of geosynthetic products in the form of geotextile, geogrid, geocells, etc., in compacted fill soil structures can reliably prevent excessive localized shear deformation of localized weakness due to rain or soil property variations or seepage that may trigger shear failure. Principles of shear reinforcement or enhancement in soil structures by geotextile have been clearly explained by BS 8006-1 (2010).

The requirement of high factor of safety against local and global slip failure as specified in JKR Nota Teknik (J) 20/98 (FOS >1.5) or GEO, Hong Kong (FOS >1.4) in slope stabilization works near important structures has made normal compacted earth structures difficult to be achieved economically and reliably unless some reinforcements such as geotextiles, geogrids or geocells are included.

To avoid failures due to localized weakness as the results of subsoil variation, slopes could be reinforced by using geotextiles or geogrids or other methods. Function of geotextiles or geogrids is to transfer excessive shear stress in soil in localized weak soil mass into tension within the geotextiles or geogrids. This will significantly reduce the risk of slope movement or failures. Geotextiles or geogrids will also enable fill slopes to be constructed with steeper slopes to save space/ land or increase FOS to more than 1.4.

Subsoil conditions especially shear strength may change or deteriorate with time due to weathering and infiltration or seepage resulting in loss of fines or migration of fines (piping problems). This leads to localized void and weakness. This also explains why some slopes, which do not fail after many years of service and after many heavy rainstorms, can suddenly fail during or after a less severe rainstorm. Inclusion of geotextiles or geogrids can greatly help to prevent such failure.
Inclusion of geogrid in compacted fill can ensure reliable shear strength to prevent almost unavoidable excessive localized shear deformation or failure due to possible localized weakness resulted from localized wet spots saturated by rain or poor site drainage.

Application of reinforced earth principles by geotextile in steep slopes or behind walls also can help to reduce lateral load and lateral deformation significantly as illustrated in Figure 8. Second case history in Figure 9 has illustrated how this principle is applied successfully in the design of construction of RC anchored wall to stabilize failed slope in difficult site conditions with space constraints and stringent design criteria.

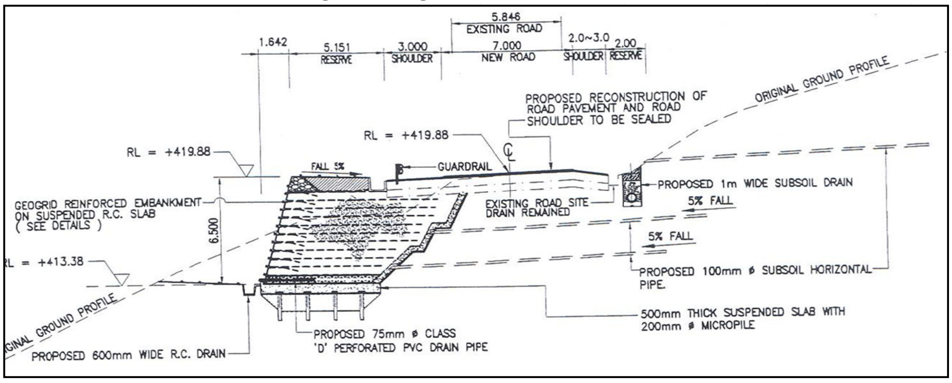


Fig 8: Geosynthetic Reinforced Wall for Unstable/creeped/seepage Slopes. The 500 mm RC slab & micropiles are aimed to transfer load deep into competent layer without surcharging the slope, which is frequently saturated by capillary action of the stream at the toe of the slope. The 1m wide subsoil drain and long horizontal drains are to minimize the adverse effects of excessive infiltration due to presence of very large upslope catchments. The steep geogrid reinforced embankment is to achieve high FOS (>1.5) and to create adequate formation.

d) RC Anchored Wall

This method of slope stabilization is particular applicable for existing very steep eroded/failed slope or when some formation widening is required where site constraint is the main problem. It consists of the RC vertical wall panel held by soil nails or anchors which are designed to resist active forces and also used to stabilize the slopes. Small sized and flexible micropiles of 125mm to 150 mm diameter or vertical nails are also used to support and hold the RC panel. The lateral load on RC wall is reduced by the inclusion of geotextile reinforced fill (sand). Adequate subsoil drainage including horizontal drains, free drainage backfill materials and weepholes are included to prevent the risk of building-up of pore water pressure. This method has been successfully used for more than 30 slope locations for roads around Cameron Highlands. This method is not suitable or not cost-effective for creeping ground or soft or saturated slopes. The advantages of this proposal are summarized as follows:-

- Easy construction (bottom-up construction technique, no disruption or inconvenience to road-users), only light and portable machines are necessary & only small and light staging for working platform is necessary;
- Geotextiles can be included to reduce lateral load and lateral deflection of wall significantly.
- The design is based on simple multiple tie-back engineering principle. Important design assumptions and acceptance performance criteria can be reliably and cheaply monitored, checked and verified by pull-out tests (as for soil nails & micropiles) and surface markers (for wall deformations). Horizontal drains shall be added if perched water table is suspected.
- Construction is fast and neat. Minimum or no jungle clearing is necessary. Almost no earthwork is necessary except some sand filling. Hence, the problems of siltation of drains or waterway will not arise.

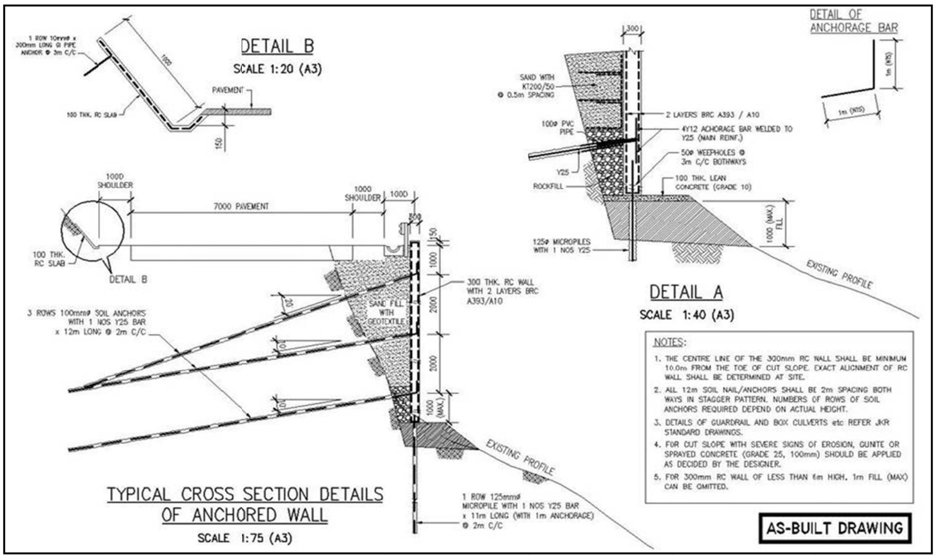


Fig 9: **RC Anchor Wall.** This method is applicable to stabilized formation effectively for slopes that have very steep and high downslopes.

e) Bored Pile Wall

This method is slow and expensive but suitable and applicable for creeping massive slop poor soil. Heavy duty staging may be needed for heavy & large machines if there are site constraint problems. Usually large diameter bored piles of 1m to 1.5m socketed in stable/hard soil or the bedrock with or without tie-back anchors are necessary and effective mitigations against slope creeping.

8. Concluding Remarks

This paper has presented overview of slope problems with particular reference to slope instability and effective mitigations against the common adverse features/factors for slope problems.

In tropical countries like Malaysia, generally and invariably the slope instability problems and landslides are mainly due to excessive infiltration as the results of intense and prolonged rainfall. 90% of slope failure is due to excessive infiltration with subsequent excessive saturation as the results of excessive surface runoff. Excessive infiltration for a slope is invariably caused by inadequate slope drainage, poor slope protection, presence of unengineered large upslope catchments and adverse geological discontinuities. Hence, effective slope design shall be based on sound engineering principles and design concepts to mitigate these adverse features/factors that can lead to excessive infiltration, which is the main cause (>90%) for landslides as illustrated in Fig. 1 to Fig. 3.

Important design parameters especially the groundwater level and effective shear strength plus geological discontinuities used for stability analysis and slope design should always be validated during construction stage. It should be recognized that calculation alone to determine FOS is not everything until and unless it is proven by instrumentation and testing/design validation. Routine maintenance inspection by suitably qualified personnel as recommended by JKR Guidelines on Slope Maintenance (Aug 2006) is also crucial to ensure long-term slope stability. For important and high-risk slopes near buildings/structures and important infrastructures, instrumentation (piezometers, inclinometers, etc.) to monitor the slope movement and groundwater fluctuations should be carried out by suitably qualified personnel. Slopes that have large upslope catchments should be assessed and engineered by qualified engineers to ensure adequate mitigations against the risks of excessive infiltration are provided.

Awareness and understanding the important factors that can influence the stability of slopes and knowing the effective mitigations against what can usually go wrong for slopes are of utter importance when designing slopes. What can go wrong will go wrong unless proper effective mitigations are in place.

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