GEOTECHNICAL CONSIDERATIONS IN THE PLANNING AND DESIGN OF HIGHWAYS IN MOUNTAINOUS TERRAIN

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SUMMARY

Due to the inherent nature of complex topography, geology and environment, design and construction of road system in mountaineous regions demand special considerations. The importance of geological assessment, hydrological study, geotechnical investigation and environmental considerations are highlighted, choice between technical consideration and economy is mentioned. Discussions are focused on the importance of site investigation including hydrogeological information, geological mapping, geotechnical analysis of cut slopes and fill embankment, design of slopes, slope stabilization and remedial measures. Several case records on design and betterment of roads and highways in Southeast Asian countries are referred to in order to illustrate the various problems and approaches. The paper emphasizes the importance of adequate information collection, proper data interpretation and sound engineering judgement.

1. INTRODUCTION

In the Southeast Asian countries, a large proportion of the terrain of the total land area is hilly or mountaineous with steep and rugged topography. The mainly warm, wet climatic conditions have resulted in varying depths of weathering of a wide range of igneous, metamorphic and sedimentary rocks. This has made the Southeast Asian region geologically and physiographically one of the most complex areas in the world. Being in the tropical area, the region experiences high seasonal rainfalls sometimes in excess of 4,500mm per year with intensities sometimes exceeding 150mm per hour. Because of these climatic and geological conditions, landslides or slope instability problems are of appreciable significance in all these countries.

With the rapid economic growth and population increase in recent years, more and more activities and developments are extended to slopelands and mountaineous areas forming many cuts and fills. Road systems are necessarily to be constructed as well in the hilly terrain to provide the vital communication links in the overall economical development of a country. In some cases, national security also requires certain road systems to be constructed in terrains which normally may be bypassed. In the planning and design of highways in mountaineous areas, there are many factors which must be taken into consideration in order to have a most economical but safe road system. The road alignment should be selected with considerations of the topography (which decides the amount of cut and fill), geology, geotechnical characteristics of the soil/rock formation, regional and local hydrology, the environment and economy. Most of these factors are also important in planning and designing of highways in non-mountaineous terrains. However, special attentions are required in the former case in order to avoid disastrous consequences.

Besides cut and fill slopes, a mountaineous highway may have bridges or viaducts, and tunnels. The major considerations for all these structural aspects of a highway system are similar. Since slope instability and landslides play the most significant roles in mountaineous road systems, this paper limits its discussions to this aspect of the problem.

In the past, many of these mountaineous roads were constructed without adequate engineering design and thus suffered numerous landslips and problems of instability. The most notable ones in the Southeast Asian region are the East-West Cross Island Highway in Taiwan and the East-West Highway in Peninsular Malaysia. Hundreds of landslips have occurred since their construction. In his State-of-the-Art report on Landslides in Southeast Asia, BRAND (1984) made a thorough review of several major aspects of the landslip situation of the whole area, and assessed the State-of-the-Art of landslide prevention and control in eight countries covered by his report as shown in Table 1.

Table 1: Landslide Assessment

Country	Area, sq. km	Population, millions	Significance of Landslides	Volume of Relevant	Assessed State-of-the-Art of Landslide Prevention and Control
Singapore	580	3	Low	Low	Low
Thailand	513 517	48	Moderate	Low	Low
Sri Lanka	65 610	15	Moderate	Low	Low
Malaysia	330 669	15	Moderate	Moderate	Moderate
Philippines	299 765	52	Moderate	Very Low	Very Low
Taiwan	35 980	18	High	High	Moderate
Indonesia	1 919 263	157	Very High	Low	Low
Hong Kong	1 050	6	Very High	Very High	Very High

(After BRAND, 1984)

This article presents a summary of some important geotechnical considerations in the design and construction of roads in mountaineous regions. The scope of discussion is confined to slopes of residual soils, gravelly deposits, sandstone-shale formations and some rock formations which are commonly encountered in the Southeast Asian region.

2. FACTORS TO BE CONSIDERED IN DEVELOPMENT OF MOUNTAINEOUS ROADS

2.1 Geological Considerations

The area affected by any highway or road construction stretches for long distances and usually considerable distance laterally. Most mountaineous roads extend into comparatively undeveloped ground. The feasibility, the planning and design, the construction and costs, and the safety of such roads may depend critically on the geological conditions of the area. Geological conditions are often so complicated that they do not permit investigations to be conducted as routine work or they may even not permit detailed site investigations to be carried out due to the extensive variability. The construction site may be endangered by a geological process of a higher order of magnitude than can be recorded by local boring. The value of a detailed study of the potential construction area by an experienced engineering geologist cannot be neglected. The engineering geologist mediates between the engineer and nature. When examining an area, he should endeavour to conceive its general geological processes that led to its development and the geomorphological forms. He should visualize the effect of the engineering work on the natural environment in the sense whether it might cause an unwelcome acceleration of geological processes. It is important that the engineering geologist is adequately acquainted with the project so that he can correctly assess the factors to be considered.

The geological information is usually supplied in the form of engineering geological report and maps. These information are gathered by the engineering geologist from available geological maps and aerial photographs, plus records of field assessment. In areas where they are not accessible during the planning and preliminary design stage, the engineering report can only be made from available information with the assistance of aerial photos. However, these information should be re-evaluated during the detail design as well as construction stages.

The types of information which are required about an area or region include: types of geological formation and its history; descriptions of soil and rock exposures; descriptions of ground masses, primarily the discontinuities traversing or dividing the materials; joint survey of rock formations; slope forms and evaluation of the processes at work, e.g. landsliding, stream action, erosion and weathering; slope angles, lengths and heights of both stable and failed slopes; existence of vegetation and evidence of deforestation, and existence of special topographic features such as benches, cliffs, proximity to the ocean or to a major stream or to a manmade reservoir.

2.2 Hydrological Considerations

Hydrology is another important aspect which must be carefully considered in the planning and design of roads. Many highway slopes failed due to inadequqte drainage to take care of surface runoff and/ or subsurface seepage. For mountaineous roads which cover long stretches of areas, regional hydrology rather than local hydrology must be assessed. The catchment area in mountaineous areas can be quite large and demands detail survey. In evaluating effect of seepage and infiltration, not only the permeability characteristics of the soil/rock formations need to be evaluated, but the intensity and duration of rainfall should be considered. This is particularly important in tropical and semi-tropical countries where the rainfalls are usually concentrated with high intensity and short duration. Use of annual precipitation record alone can be quite misleading. Information required to be collected for hydrological studies includes: annaul precipitation, maximum rainfall and duration; year return period; existence of drainage lines, streams, channels, nullahs, ditches, catchpits and culverts with their locations, sizes and conditions; existence and conditions of vegetation and forest coverages; shapes of valley and ridges, their symmetry or asymmetry.

2.3 Geotechnical Considerations

From the geotechnical point of view, it is essential to ascertain the characteristics of soil deposits and rock formation along the proposed road alignment as early as possible. Some of these information should be obtained during the planning and preliminary design stage. Additional ones are acquired for detail design. The information required for geotechnical analyses include: the nature of unconsolidated overburden, whether it is talus, colluvium, alluvium or residual soil; the depth of each type of soil, the depth of weathered rock, and the extent and nature of weathering; the physical and engineering characteristics of the soil and rock, particularly shear strength and permeability; the regional watertable and piezometric pressure distribution.

These above information are usually obtained from borings, sampling, in-situ and laboratory tests. However, it should be pointed out that borings and testing will only provide specific information at limited localities. The selection of locations for boring, and interpretation of test results for application to a regional problem such as design of mountaineous roads must be made in conjunction with engineering geological and hydrological studies.

Geotechnical considerations would depend to a significant extent on the type of development proposed. For instance, some stability, or rather, instability, problems may have to be accepted as a matter of economy in developing roads in mountaineous areas provided that there is no danger to life or property. On the other hand, widening of a hilly road in stretches passing through a highly urbanised area will have to be considered very carefully in order to eliminate any danger to properties, services and even lives. In conventional highway design, the engineer usually adopts the principle of balanced cut and fill for determination of the alignment. With proper consideration of the geological and geotechnical problems, a shift of the alignment could either reduce the risk of slope instability or avoid major cuts or fills and thus result in significant savings in the construction cost.

2.4 Environmental Considerations

When a transportation system, like a highway, is built through a region, there are numerous effects on the existing environment. Some of them take place during the construction or immediately after its completion, and some may take years to occur. The major effects on the environment can be divided into:

(1) Effect on the natural environment including aesthetics, topograph, vegetation, water resources and quality, etc.

(2) Effect on the living environment such as noise, vibration, air and water pollution.

(3) Effect on the social and economic development.

(4) Effect during construction including noise, vibration, pollution, dump of earth materials, settlement, landslide, and soil erosion.

A geotechnical engineer must be aware of effects of developments which are taking place and will take place on the environment due to the planned construction. Some of the effects may not be immediately obvious and may take considerable period of time to be felt. For example, increase in runoff, and also extent of seepage and infiltration, are often the consequences of land clearing and deforestation. This will lead to surface erosion and development of excess porewater pressure. Use of certain form of slope surface protection work will certainly increase the rate of surface runoff.

In short, for a full environmental impact study, a geotechnical engineer must have sufficient vision about the relation between his activity and the environment. The restricted problem-orientated approach adopted by most highway engineers and geotechnical engineers is not sufficient for development of mountaineous roads. Planning and design can be greatly improved by considering the effect of impact which the new construction may have on the environment and the consequences of these impacts on engineering solutions.

2.5 Economical Considerations

In consideration of any project implementation, economy is always one of the important aspects for decision-making. On the other hand, technical soundness and safety cannot be overlooked. It is crucial to reach a realistic balance between the different viewpoints. In development of mountaineous terrain, the question of economy and safety is even more important. It has been accepted by many planners and even engineers that slope failures, especially on cuttings should be "normally expected". A completely no-failure design could be exceedingly costly. In reality, even designs based on detailed site investigations may be liable to unexpected failures due to the inherent variable and unknown nature of the subsurface conditions.

In practical design of mountaineous roads, careful evaluation should be given to the consequences of failures: whether the failures will endanger properties or lives, the effect of traffic disruption and the cost of maintenance and repair. For low-traffic roads in rural areas, it may be cheaper to design the roads with certain amount of risks of failure. On the other hand, for roads of importance, such as expressways with heavy traffic, and vital transportation links for national defence, and roads near urban centers, the adverse effect of disruption to traffic or temporary closure due to slides or failures of the roadway system can be very costly.

As pointed out in an earlier section, proper design of a road system depends greatly on the amount and reliability of information and data collected. In the past, many highway planners and designers had foregone the geological and geotechnical investigations in order to save cost. Due to the lack of information, the engineers either design the project with conservative approach or inadequately. In the latter case, high cost for maintenance and remedial measures would be incurred. This type of "false economy" must be avoided.

The choice between technical consideration and economic consideration must be made by engineers who possess the necessary information, knowledge and experience.

3. FACTORS CONTRIBUTING TO LANDSLIDES OR SLOPE INSTABILITY

In planning and design of mountaineous roads, one of the most important aspects is the stability or instability of slopes along the roadway. In addition to natural slopes, there will be manmade cut slopes and fill slopes. In countries like Malaysia and Taiwan, cut slopes of over hundred meters high are not uncommon. For both natural slopes and manmade slopes, the factors affecting the stability or rather those controlling the instability can be classified into two main categories: the inherent characteristics and the external factors. In order to assess the slope stability it is important to obtain adequate information and to evaluate each of the factors carefully.

3.1 Inherent Characteristics

(a) Topographic condition

(b) Geological formation

(c) Engineering characteristics - strength of soil material, strength along rock joints, permeability, etc

(d) Hydrological regime

(e) Weather

(f) Rainfall - intensity and duration

(g) Presence of reservoir.

3.2 External Factors

(a) Water
- (i) surface runoff
- (ii) infiltration and seepage
- (iii) increase in excess porewater pressure

(b) Change in strength - due to saturation, increase in porewater pressure, lubrication along joints

(c) Seismic activity

(d) Deforestation or devegetation

(e) Improper design and/or construction

(f) Change of groundwater regime

(g) Other manmade activities

(h) Lack of maintenance.

4. GEOTECHNICAL CONSIDERATIONS IN PLANNING, DESIGN AND CONSTRUCTION OF SLOPES

Depending on the type of slope, the amount of time, effort and cost which can be appropriately devoted to site investigation and analysis several different approaches may be used for planning, investigation and design of slopes. The following are three most commonly used approaches. They represent increase in degree of sophistication and rational but also increasing in complexity and cost.

(a) Based on field observations and past experiences alone with no site investigation, testing or slope stability analysis - an empirical approach.

(b) Based on limited amount of data from actual field investigation and testing in combination of field observations, carrying out slope stability calculations by using stability charts (for example, JANBU, 1968; HUNTER and SCHUSTER, 1968) - a semi-empirical approach.

(c) Based on an adequate program of site investigation and testing and carrying out detailed stability analysis - a rational approach.

The empirical approach depends greatly upon the experience of the designer. Slopes are designed based on observations and examinations of existing slopes in the same area and the same types of soil/rock formation. This approach may be applicable in situations where the total cost of remedial measures to failed slopes will likely be appreciably less than the additional cost involved in ensuring that all slopes incorporate an appropriate engineering factor of safety. This approach is also useful in the preliminary planning and design stage for engineering and economic assessment of a project. However, this approach should never be used when a landslide can cause loss of life or significant economic loss or social disruption or high security risk.

The semi-empirical approach of slope stability analysis by use of slope stability charts has commonly been used for the preliminary stage of analysis. Stability charts are useful for preliminary design calculations, to compare alternatives which can be examined more thoroughly subsequently using detailed anlaysis procedures. The use of stability charts, however, should not be indiscriminately, because the charts were developed on the basis of information accumulated from certain particular geographic and geological conditions. It is essential to understand the background and assumptions involved in the stability charts whether these conditions are applicable to a particular project before they are used.

The rational approach incorporates an essential element in a geotechnical analysis, that is, compatibility between data/information available and method of analysis. It offers the most reliable solution to slope design problem. Of course, there are also limitations due to practical constraints on the extent of site investigation and simplified assumptions which are necessary for analytical solutions. Field instrumentations are valuable means for monitoring the performance of slopes. The monitored data can be used to supplement the site investigation study and to check the design assumptions. Data obtained from slope indicators are helpful for determining potential or existing failure zones or the movements of a slope after construction as a check of the design. Long term monitoring of groundwater conditions by piezometers will provide indisputable reliable data for slope stability analysis. Instrumentations are especially useful for sites with very complex soil conditions.

A general design and construction procedure for soil and rock slopes is presented in Fig.1. In analysis and design of slopes in residual and colluvium soil deposits, geotechnical approaches are usually used for assessment of landslip potentials. For rock slopes, engineering geological assessment becomes more important. At the present, there is no conclusive rational method of stability analysis which can be applied to analyze gravel-deposit slopes. Combinations of geotechnical and geological assessments, along with engineering judgement are used (WOO et al, 1981).

4.1 Geological Assessment

For a large and difficult site, it is advisable to carry out surface geological reconnaissance mapping if the area is accessible. The methods used when plotting the data collected are usually based on the Geological Society of London Working Party Report (1972) on the Preparation of Maps and Plans in Terms of Engineering Geology. Figure 2 shows an example of such a survey map for a rock slope along the North-South Freeway in Taiwan (WOO et al, 1981).

The soil and rock exposures are generally indicated on the geological map under generic names. In addition, they should be fully described on field data sheets for subsequent correlation with the results of subsurface exploration. The following features should be recorded:

(a) Color

(b) Grain size

(c) Texture and structure

(d) Weathered state (for rocks)

(e) Lithological characteristics

(f) Estimate of strength and permeability, and

(g) Other engineering characteristics.

1. PLANNING AND PRELIMINARY DESIGN	- project requirement - site selection - preliminary site conditions
↓	
2. INVESTIGATION	- exploration - field and laboratory testing - field measurements
↓	
3. IDEALIZATION	- natural condition - properties of material - potential mechanism
↓	
4. ANALYSIS	- numerical results - sensitivity check - factor of safety
↓	
5. DESIGN	- design criteria - design concept - structure and details
↓	
6. TENDER	
↓	
7. CONSTRUCTION	- fiel. inspection - addit: onal investigation - modification of design
↓	
8. MAINTENANCE AND MONITORING	- instrumentations

Fig. 1: Design-Construction Sequence of Slopes

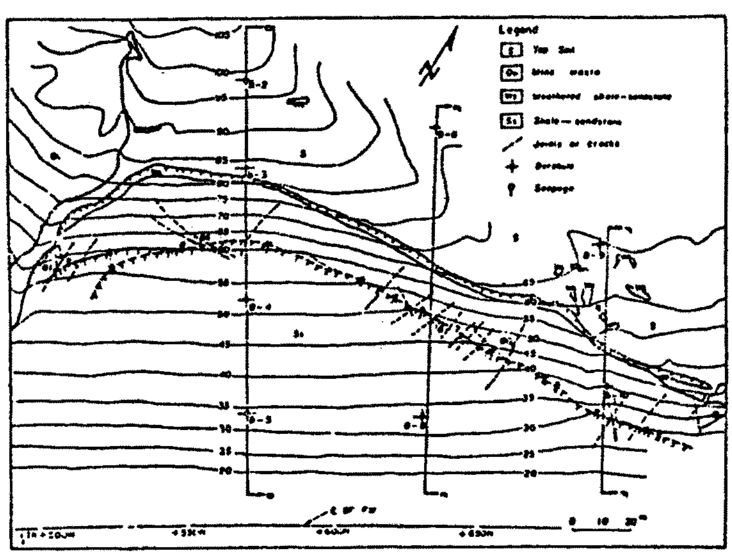


Fig. 2: Example of Engineering Geological Map

Unlike common soil slopes which may fail along any one of infinite number of surfaces, rock slopes tend to fail along well-defined discontinuities, such as faults, joints, fissures and bedding planes. For the purpose of rock slope design, a joint survey should be carried out to collect information on these discontinuities from the natural exposures or from pre-existing manmade slopes. Information pertaining to the discontinuities should include:

(a) dip angle and direction of dip

(b) width, spacing and persistence

(c) roughness of surface

(d) infilling

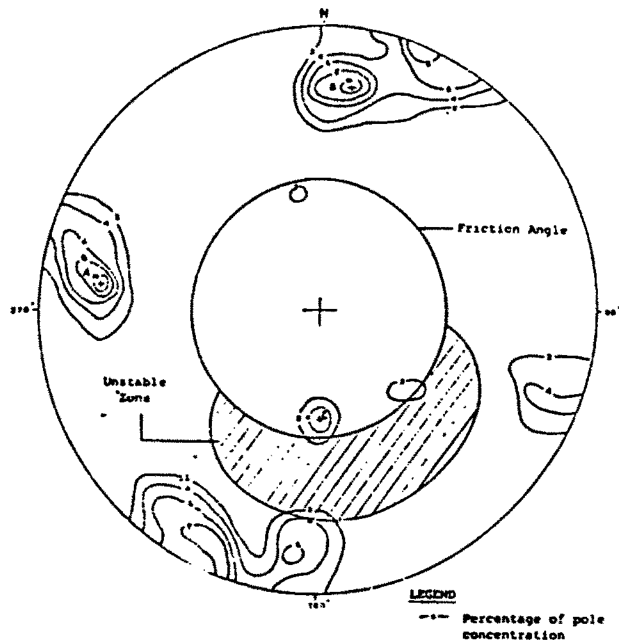
(e) extent and location of seepage.

The collected survey data are usually plotted onto a stereonet as illustrated in Fig.3. From the equal density contours of pole concentrations and geometry of the slope, the possible mode(s) of failure can be rapidly assessed. Details of the method and its application have been described n HOEK and BRAY (1981). However, use of stereoplots for assessing stability of slopes directs attention only to joint concentrations but not to the isolated single joints. Single joints, which may cause insta lity, msut be individually identified on site.

It should be pointed out that not all sites and potential slopes are accessible or exposed for mapping during the planning and design stage. This is particularly true for highways or mountaineous roads crossing virgin lands. The engineering geologist or geotechnical engineer responsible for the work should also visit the site after the analyses are completed and during the construction stage in order to check the possible presence of joint sets which are not identified during the initial survey and any other random joints which could lead to the development of instability.

4.2 Geotechnical Evaluation

For practical reasons, geotechnical evaluations or analyses are usually carried out at certain specially selected locations, particularly at those places where stability or instability is more critical. Therefore the results of evaluation are limited or confined. The selection of locations for detail analyses is usually made on the basis of information obtained from geological assessment, hydrological study, topographic survey, geotechnical investigation and engineering judgement. Since a road project usually stretches over many kilometers, it is practically and economically unfeasible to analyze every slope which will be encountered. The importance of judgement made by experienced geotechnical engineer cannot be overemphasized.



Station : CH 128+850 to 129+300
No. of Joint Survey :
Slope Condition : arameters:
Dip Angle : 65 ° : 23 kN/m³
Dip Direction: 344 ° : 0 kN/m³
Height : m Φ : 38 °

Fig. 3: Stereonet of Rock Joints

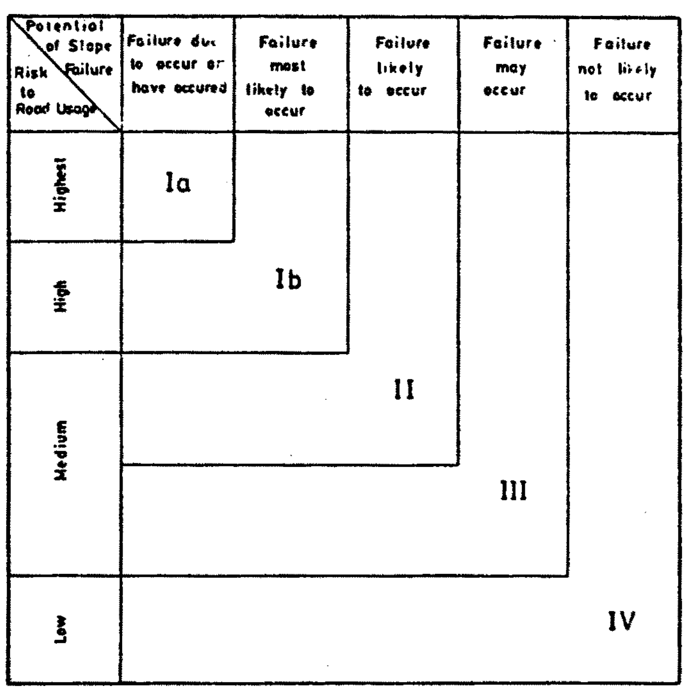


Fig. 4: Slope Categorization

Before carrying out a detail geotechnical analysis or evaluation of a particular slope or terrain, it is necessary to gather sufficient quantitative data from the site. These data are usually obtained by field investigation, in-situ and laboratory testings. MOH (1984) has discussed the various aspects and techniques of subsurface investigation which are adaptable for mountaineous terrains. There are many different methods of subsurface investigation which can be employed. The choice of the method depends upon many factors such as the terrain condition, geological formation, depth of exploration and, of course, the service standard of the roads, etc. The most commonly used method consists of boring and sampling. Standard Penetration Tests are usually carried out to determine the relative consistency of the subsoil strata and piezometers are installed to monitor the variation of subsurface water pressure. At locations where seepage is anticipated to be a major problem, in-situ permeability tests are performed. Laboratory tests are carried out on representative and undisturbed soil samples or rock cores to determine the physical properties, strength and permeability characteristics of the various subsurface strata. In areas where settlement is anticipated to be a problem, consolidation tests are performed. Seismic exploration is often used for estimating the depth of rock formation. In areas where sinkholes or underground channels are expected, other geophysical techniques such as electric resistivity method may be employed.

It should be emphasized that results from few boreholes are inherently limited. Interpretation and application of these limited data should be exercised with caution.

4.3 Slope Categorization

During the planning and preliminary design stage of mountaineous roads, whether for a new road or betterment of an existing road, information obtained from geological assessment can be used to classify the slopes into different categories. Based on the classification, program of more detailed investigation and study can be forumulated. For the slope improvement work for the East-West Highway and the Kuala Lumpur-Karak Toll Highway, such a technique was adopted (MOH and ASSOCIATES, 1983a, 1985).

The categorization of the slopes was based on the potential of failure of the slope (stability) and the risk to road usage if failure occurs.

The degree of potential of slope failure can be categorized as follows:

(a) Failure is imminent or has already occurred

(b) Failure is most likely to occur

(c) Failure is likely to occur

(d) Failure may occur

(e) Failure is not likely to occur.

The degree of risk to the usage of the highway can be classified as follows:

(a) Highest - complete or substantial loss/blockage of access

(b) High - partial loss/blockage of access

(c) Medium - minor blockage of access or damage to appurtenant road structure up to the limit of the carriageway

(d) Low - effect, if any, would be minimal.

Based on these two factors, the slopes can be classified into the following five categories, Fig.4:

Category Ia - Instability of slope is highest and risk to road usage is imminent

Category Ib - Blockage or loss of the road access is impinging

Category II - Danger to road is adherent

Category III - Danger to road is implicit

Category IV - No danger or road blockage.

Geological assessment can also be used advantageously for terrain classification of slopeland for development. Figure 5 illustrates the result of such a classification for the development of a 500 hectare land in the outskirt of Taipei City in Taiwan. (YU et al, 1982).

Terrain evaluation based on terrain classification or land categorization has been used in many countries. Risk maps or hazard maps for landslide areas have been developed in France, Italy, Spain, Australia, the United States and elsewhere. The Geotechnical Control Office of the Hong Kong Government has in the past several years placed considerable effort on its Geotechnical Area Studies Program to provide systematic geotechnical input for land use management and development planning purposes. Geotechnical Land Use Maps are being developed by considering six geotechnical attributes - slope gradient, terrain component, terrain morphology, erosion, slope condition and hydrology (BRAND et al, 1982a, 1982b).

4.4 Stability Analysis

Many methods of stability analysis are available for the design of soil and rock slopes. The most commonly used methods are based on limit equilibrium analyses from whch numerical safety factors are obtained. The Geotechnical Manual for Slopes (GCO, 1984) lists the better known methods of analysis which are being used to solve soil/ rock slopes problems with consideration of water pressure. The

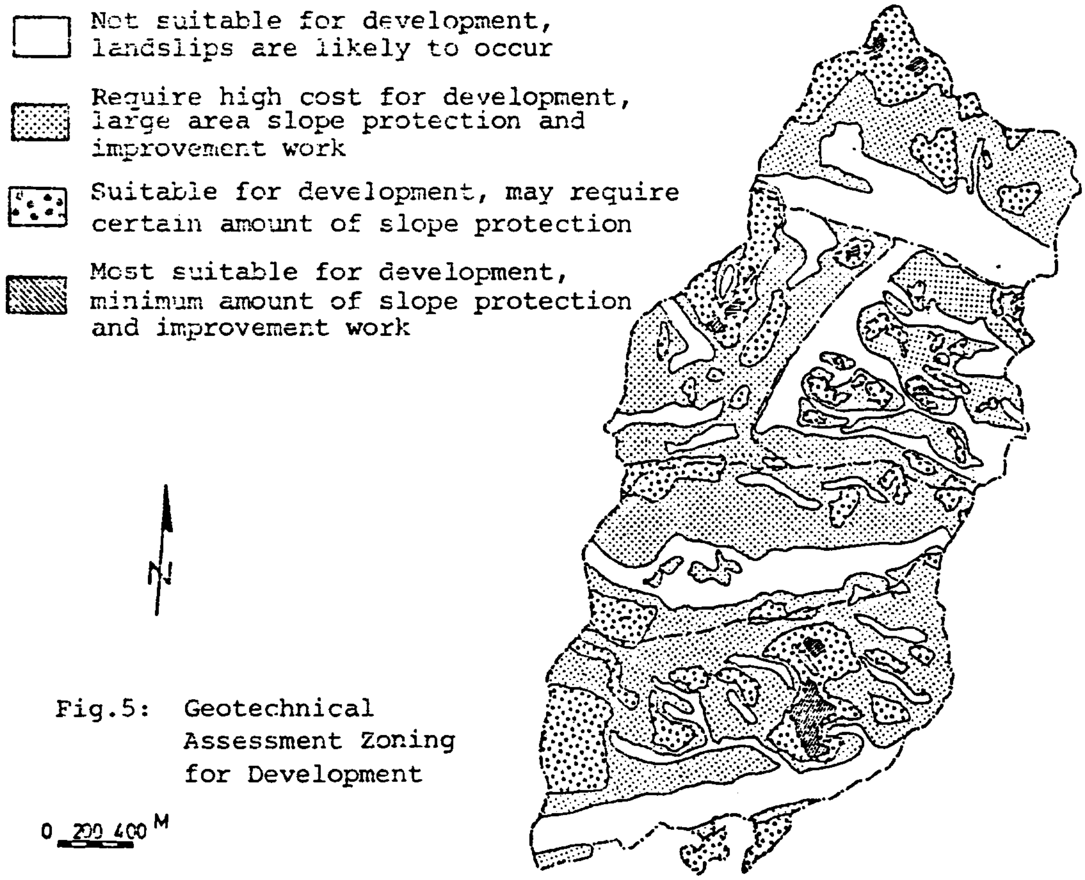


Fig.5: Geotechnical Assessment Zoning for Development

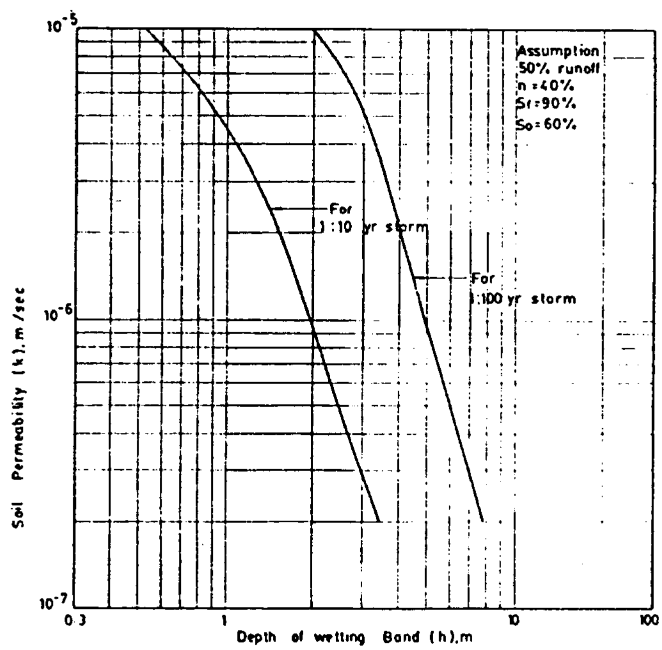


Fig. 6: Effect of Permeability on Wetting Band Thickness

advantages and limitations of these methods are given and recommendations are also made to their application.

4.4.1 Modes of slope failure

For analyses and design of slopes, the probable mode(s) of failure of the slopes should be considered. Broadly speaking from the kinetic point of view, there are four major types of failures, that is, creep, sliding, flow and fall. The exact mode(s) of failure of a slope is different for different materials and geological conditions. They can be classified as:

Earthfill Slope	-	(a) Soil flow
		(b) Circular slip
		(c) Surface erosion
Residual Soil Slope	-	(a) Planar failure
		(b) Shallow non-circular slip
		(c) Surface erosion
Gravelly Soil Slope	-	(a) Toppling
		(b) Circular slip
		(c) Surface erosion
Sandstone-Shale Slope	-	(a) Plane failure
		(b) Wedge failure
		(c) Weathering
Other Rock Slopes	-	(a) Toppling
		(b) Plane failure
		(c) Wedge failure
		(d) Rock fall

In a slope stability analysis, the two most important input parameters are the shear strength of the slope forming material and the groundwater (or more exactly, the porewater pressure) condition.

4.4.2 Shear strength of material

In order to determine the factor of safety of a particular slope against sliding, the strength of materials comprising the slope must be known. Shear strength parameters of the materials are obtained by testing samples of soils and rock joints obtained from the site. The samples should be tested under in-situ stress conditions. In the Southeast Asian countries, the most commonly encountered geological formations are residual soils, sandstone-shale and gravel deposits. For residual soil deposits, because of the high permeability of the material, it is likely that rainwater can infiltrate into the soil and achieve saturated condition at shallow depth. Stability computations should therefore be made in terms of effective stresses. It is generally found that the laboratory measured values of cohesion intercept are quite small and the stability analyses are most frequently carried out with the angle of shearing resistance predominating.

The shear strength values of shale formations depend on the clay content, the degree of cementation and the degree of saturation. For this type of formation, the bedding planes or joint surfaces are usually the weak planes where most of the slope failures occur. It is extremely difficult to accurately determine the strength characteristics along these planes. A conservative approach is to determine the residual angle of shearing resistance of samples by direct shear tests along artificially cut surfaces of intact rock specimens to similate bedding planes. Samples soaked with water before testing can represent the actual site conditions better if the potential slip surface were below the groundwater table. In some cases, large scale in-situ direct shear tests have been carried out. But this method is rather costly and sometimes very difficult. If joint-fill materials were found existing in an interbedded rock formation, the shear strength of these joint-fill materials should be determined and used in analysis.

For unsupported slopes, the residual strength parameters should be used, whereas for slopes which incorporate restraining measures, e.g. when the stability of slope is enhanced by prestressed anchors, the peak parameters may be used in the design.

In most rock masses where rock joints are not smooth or planar, the roughness of the surfaces contribute additional shearing resistance, (PATTON, 1966; BARTON, 1971).

4.4.3 Groundwater

The stability of slopes is seriously affected by the groundwater pressure. For all types of slopes, the groundwater conditions should be monitored for periods as long as possible, at least during the site investigation and afterwards by means of piezometers. The groundwater pressures measured within a short period of time may not represent the highest or critical groundwater pressures in the slope for long term stability. The groundwater condition in a particular slope is dependent on the rainfall intensity and duration, the infiltration capacity of the slope forming material, slope topography, extent of vegetation cover, and environment.

For design of residual soil slopes in Hong Kong, estimate of rise in water table after a rainstorm is determined by the wetting band as suggested by LUMB (1962). The wetting band or zone of saturation caused by a rainstorm will extend downwards from the ground surface under the effect of gravity. Based on the calculated wetting band thickness determined from rainstorms of different return periods (for example, Fig.6) together with records of groundwater level, estimation on the probable rise in groundwater level can be made.

In sandstone-shale slopes, perched water table normally exists because of the different permeability of the sandstone and shale layers. Figure 7 illustrates the probable water tables of an inclined sandstone-shale formation. To determine the groundwater pressure in this type of slope, piezometers should be installed in every layer of the rock formation at a number of locations.

There are many cases showing that the groundwater table in a slope can change due to environment changes. For example, on the banks of a reservoir, the groundwater level rises after storing of water and fluctuates with the water level in the reservoir. Phenomenon is shown in Fig.8. Another example is seen in Fig.9 for a highway embankment crossing a valley. If the drainage capacity of the culvert becomes insufficient because of blockage, or other reasons, a temporary pond will be formed at the intake of the culvert. The ponding water may create seepage through the embankment which may be originally designed without any consideration of excessive water seepage.

4.4.4 Factor of safety

The minimum factor of safety against failure which can be accepted for a slope will depend on the factors such as risk to life, cost of consequence associated with failure of that slope. The choice of an appropriate factor of safety in the slope design is subjected to the judgement of the designer. Table 2 presents some suggested values of safety factor for slope design. In the application of a factor of safety to slope stability, the possible change in groundwater pressure and influence of external loading should be considered. In design of a slope, it is a good practice to check the sensitivity of the factor of safety of a slope against each parameter. For example, the factor of safety of a slope may increase 100 per cent between saturated and drained condition, this indicates that the use of drainage would be effective to control the instability of that slope.

The stability of a slope is also affected by dynamic loading like earth quake and blasting. The response of a slope to an acceleration amy be simplified to a horizontal force acting on the center of gravity of the potential sliding mass towards the free face of the slope. Since the dynamic force occurs only in a short duration, a lower factor of safety under dynamic condition is acceptable (HOEK, 1976).

4.4.5 Other factors to be considered in design

Besides those discussed in the previous section, there are several other important considerations which deserve attention in practical design work.

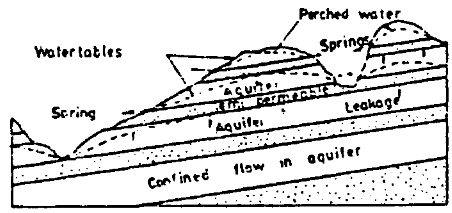


Fig. 7: Groundwater Condition in a Sandstone-Shale Formation

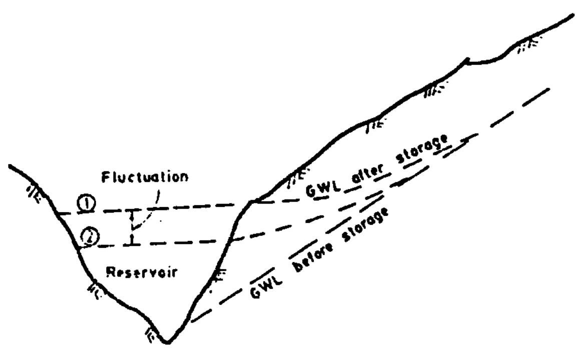


Fig. 8: Effect of a Reservoir on Groundwater Level

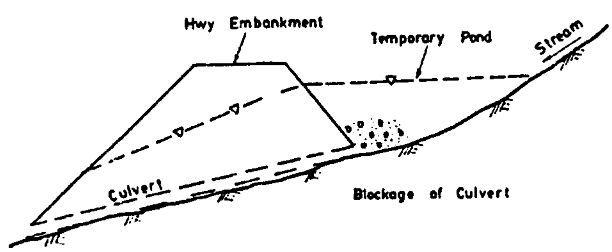


Fig. 9: Effect of a Temporary Pond on Groundwater Level in an Embankment

Table 2: Suggested Values of Factor of Safety for Slopes

Factor of Safety	Remarks	Source
1.2	Slope with low risk	GCO (1984)
1.4	Slope with high risk	
1.2	Temporary slope	Hoek and Bray (1981)
1.5	Important slope	

Table 3: Rock Slope Stabilization Measures

Failure Type	Stabilization Measures																				
	Excavation			Structural Support									Drainage				Rockfall Control				
	Flatten Slope	Bench	Local Excavation	Gunite Facing	Permeable (mansonry) Facing	Local Structural Dentition	Buttress	Anchored Wall	Strap	Dowel	Bolt	Anchor	Drainage Ditch	Screeded (paved) Surface	Short Drainholes	Long Drainholes	Move Structure/Highway	Rock Trap Ditch	Rock Trap Fence/Wall	Netting	Scaling of Loose Blocks
Plane Failure	✓	✓					✓	✓			✓	✓	✓	✓	✓		✓	✓	✓		
Wedge Failure	✓						✓	✓		✓	✓	✓	✓	✓		✓	✓				
Topping	✓										✓	✓	✓	✓		✓		✓			
Rock or debris fall & general Degradation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓

(Modified from Fookes and Sweeney, 1976)

These important considerations are:

(1) In soil cuttings if the bedrocks dip steeply into the cuttings, sliding of the entire overburden above the cuttings alc g the bedrock surface may occur.

(2) The surface of cut slopes will be subjected to weathering and erosion.

(3) When empirical approach is adopted for design cut slopes, the potential of "insignificant" or "uncritical" slides may be allowed. In those cases, wider right of way should be provided for catching debris from slips.

(4) In design of embankment fills, it is important that the fill materials are properly keyed in with the original ground. It is particularly critical in cases of half cut-half fill sections. Benching may be necessary.

(5) The toe area of an embankment fill is an inherently weak zone and requires special attention for strengthening.

(6) In designing drainage facilities for both cut and fill slopes, the drains should be designed in such a way that they will be self-cleaning and require minimum amount of maintenance.

(7) It is important to recognize that design of slopes for mountaineous roads needs to be "flexible". In other words, it is more often than exceptional that revision of design will be necessary during construction. The degree of this need depends upon the amount of geological and technical information available during the design stage. Additional site investigation should always be considered during the construction stage and therefore should be included in the design tender document.

4.5 Construction of Slopes

4.5.1 Formation of soil slopes

As pointed out in an earlier section, it is a common practice for highway planners to adopt the principle of balanced cut and fill. Theoretically, this approach may be more economical. However, from the engineering point of view, this approach may not be desirable particularly in areas where the slope formations will be partly in cut and partly in fill. These slopes are potentially unstable and difficult to construct. It is more preferable wherever possible to form the slope either entirely in cut or entirely in fill. Realignment of the roadway may prove to be more stable, trouble free, and easy to construct. Economy in the long run should be taken into consideration when designing roads in mountaineous areas.

The construction of slopes, whether cut or fill, should be strictly under engineer's control. The fill materials should consist of well-graded soils and free from organic matters. The fill is normally placed in layers of 30 to 50cm in thickness and compacted to at least 95 per cent of the maximum dry density determined by standard proctor test. To ensure that the surface of the slope is also compacted to the required degree of compaction, the slope is normally slightly over-built by about 1m, and then trimmed back after compaction to the required profile. For cut slopes, it is important that control be exercised to avoid over cutting. For both cut and fill slopes, it is very useful to provide intermediate berms of sufficient width between flights normally of 8 to 10m high.

4.5.2 Surface and subsurface drainage

It is of prime importance to install adequate surface drainage system to collect and safely convey the run-offs from catchment areas above and adjacent to the slope and from the slope itself to an appropriate point of discharge. For this reason, concrete surface drainage channels should be provided along the top, the toe and along each berm of the slope. Herringbone drainage system consisting of chevron drains and stepped channel is constructed along the slope surface to reduce the flow velocity of surface run-off, thus minimizing soil erosion.

In areas where the subsurface porewater pressures are high or where the potential of seepage and infiltration of water is great, subsurface drains should be installed. The subsurface drains are usually constructed of perforated PVC pipes installed at an inclination to the slope surface. In order to maintain proper functioning of the subsurface drains, the drain pipes must be adequately protected with filter material to prevent clogging up the holes by the surrounding soil particles.

4.5.3 Surface protection of slopes

In order to prevent soil erosion and to minimize infiltration of water into the slopes, the slopes should be protected with grassing or covered with impermeable layers as soon as possible after formation. Grassing can be placed by means of turfing or hydroseeding together with fertilizers on the slope surface. When hydroseeding is to be carried out in wet seasons, it is suggested that the seeding be applied together with erosion control fabrics or straw mats. Apart from reduction of erosion on slopes during the wet seasons, other advantages of using fabrics are the discouraging of birds from eating the germinating seeds, retention of moisture during droughts and prevention of dislodging seeds due to careless watering.

Other types of surface protective measures include chunaming, guniting, stone-pitching, and concrete revetment. Chunaming, which is very commonly used in Hong Kong is the placement, usually by hand, of a plaster of cement-lime stabilized soils available locally in layers to a thickness of 5 to 8cm on the slope surface. Being more durable and less susceptible to cracking problem, guniting is the spraying of cement-sand mixture in mortar form. onto the slope. The thickness of guniting layer is commonly 5cm but sometimes is increased to 7 to 10cm when reinforcements are incorporated. The concrete revetment consists of precast or cast-in-place interlocking grids filled with a layer of no-fine concrete, onto which top soil and turf are placed.

4.6 Slope Improvement and Stabilization

4.6.1 Slope improvement

Sometimes it is impossible to design stable cut slopes which will meet the development requirement of a particular site, especially in steep urban terrains where the economic use of land is of major importance, or in rural areas where it is considered to be more economical to accept a higher probability of failure in cut slopes and to rectify failures when they occur, rather than to design stable slopes at the outset. The latter case is particularly justified for low cost roads which accommodate small traffic volumes. Slope imporvement or rectification measures are therefore necessary for many instances:

(1) Flattening of side slope - This is the most effective means to increase the stability of slopes, if geometric constraints allow. The principle is simply to reduce the weight of the soil/rock mass which has a sliding potential.

(2) Subsurface drainage - The long-term stability of steep slopes in areas with shallow GWL can be enhanced by modifying the seepage pattern in the slope, thus suppressing the development of unfavorable seepage force and diminishing the pore pressure acting on the potential slip surface. This can be achieved by installing inclined drain pipes, drainage blankets and galleries with sandwiched filter materials into the slope to intercept the ground or perched water in subsoils and discharge it out from the slope thereby relieving any potential of hydraulic pressure build-up. It is normally required to place a drainage blanket between the original ground and fill in embankment construction (for example, MOH AND ASSOCIATES, 1978, 1983b).

(3) Stabilizing piles/caissons - Another means to increase the stability of the slopes is to construct a series of stabilizing piles/caissons on the slope to provide additional resistance against sliding through pull-out and dowel actions. It is preferred to have the piles/caissons keyed into hard soil stratum and spaced at least one diameter apart to avoid any damming effect on the upslope areas (for example, HSIUNG 1986).

(4) Retaining structures - Due to aerial constraint, structures are sometimes needed to support the slopes and these take the forms of conventional reinforced concrete cantilevered wall, contiguous bore-piled wall, either cantilevered or supported by ground anchors, crib walls, gabbion walls and buttress wall (for example, MOH et al, 1979).

4.6.2 Stabilization measures for rock slopes

Rock cuts are usually made at 60 to 75 degrees to the horizontal, depending on the nature of rock mass, with 1m wide benches at every 15m height of slope. Excavation is normally carried out by blasting in unrestricted remote areas and by pneumatic drills in restricted urban areas. The design of blasting should be aimed at achieving a good production of well fragmented rocks with least damage to the rock slope left behind. Blasting, if not properly controlled, will cause back-break, reducing the strength of joints and thus causing rock falls, and instability of the finished slope surface. In order to eliminate unnecessary remedial works caused by overblasting, controlled blasting technique using presplitting should be commonly employed for the final face of the rock cut slope, and the primary blasting is carried out to a distance of about 5m from the final face. Presplitting blast holes are loaded with light, well distributed charges completely stemmed and fired simultaneously before any adjoining main excavation area is blasted. Delay blasting technique is strongly recommended.

After the formation of rock cut slopes, an engineering geological survey should be carried out to determine the overall stability of the cut slope, the stability or instability of localized zones, joints and rock surfaces. If potential instability were found, remedial measures will be necessary. The following lists some of the most commonly used methods for stabilizing rock slopes:

(1) Joint plane stabilization - After the final cut face is formed, if daylighting joint planes which can form a potential failure wedge are identified, the potential sliding rock mass can be arrested by the use of dowel and shear bars, rock bolts and anchors.

(2) Surface strengthening - For highly fractured and uneven rock faces, either inherent or as a result of overblasting, it is sometimes necessary to cover the slope surface with gunite or shotcrete, preferably with reinforcement, to prevent further weathering and to arrest fall of rock debris.

(3) Fencing and/or netting - In areas where it may not be economically practical to eliminate rock falls from a cut face, protective fence or netting can be erected to keep the rock fragments from falling onto the site.

FOOKES and SWEENEY (1976) summarized some appropriate stabilization measures for different rock slope failure patterns, as shown in Table 3. Among the various techniques, the control of water and drainage is normally most effective and economical.

5. CONCLUDING REMARKS

This paper describes some of the important geotechnical considerations for designing roads in mountaineous regions. Due to the very nature of the complex topographic and geological conditions of mountaineous areas, the engineer responsible for planning and design of mountain roads should not lose his vision by considering the engineering aspect alone. Geological, hydrological, geotechnical, environmental as well as economical considerations all play important roles. In the practical design and construction work for mountain roads, adequate data collection, proper evaluation and interpretation of data with sound engineering judgement are essential elements for a safe but economical construction project.

6. REFERENCES

Barton, N. (1971), A Relationship between Joint Roughness and Joint Shear Strength, Proc., International Symposium on Rock Fracture, Nancy, France, pp.1-8.

Brand, E.W. (1984), Landslides in Southeast Asia, A State-of-the-Art Report, Proc., 4th International Symposium on Landslides, Toronto, pp.1-43.

Brand, E.W., Burnett, A.D. and Styles, K.A. (1982a), The Geotechnical Area Studies Programme in Hong Kong, Proc., 7th Southeast Asian Geotechnical Conf., Hong Kong, Vol.1, pp.107-123.

Brand, E.W., Styles, K.A. and Burnett, A.D. (1982b), Geotechnical Land-use Maps for Planning in Hong Kong, Proc., 4th Congress IAEG, New Delhi, Vol.1, pp.145-153.

Fookes, P.G. and Sweeney, M. (1976), Stabilization and Control of Local Falls and Degrading Rock Slopes. Quart. Journal of Engrg Geology, Vol.9, pp.37-55.

Geological Society of London (1972), The Preparation of Maps and Plans in Terms of Engineering Geology, Geological Society Working Party Report, Quart. Journal of Engrg. Geology, Vol.5, pp.295-382.

Geotechnical Control Office (1984), Geotechnical Manual for Slopes, 2nd Ed., Public Works Dept., Hong Kong.

Hoek, E. (1976), Rock Slopes, Proc., Specialty Conf. on Rock Engineering for Foundations and Slopes, ASCE, Colorado, Vol.2, pp.157-171.

Hoek, E. and Bray, W.J. (1981), Rock Slope Engineering, Institution of Mining and Metallurgy, Revised 3rd Ed., Asian Ed., MAA Publishing Co. Ltd.

Hsiung, K.I. (1986), Slope Stabilization with Retaining Caissons, a paper presented at a seminar organized by Sino-Geotechnics, Taipei, April (in Chinese).

Hunter, J.H. and Schuster, R.L. (1968), Stability of Simple Cuttings in Normally Consolidated Clays, Geotechnique, Vol.13, No.3, pp.372-378.

Janbu, N. (1968), Slope Stability Computations, Soil Mechanics and Foundation Engineering Report, The Technical University of Norway, Trondheim.

Lumb, P. (1962), Effect of Rainstorm on Slope Stability, Proc., Symposium on Hong Kong Soils, Hong Kong Institution of Engineers, Hong Kong, pp.73-78.

Moh, Z.C. (1984), Site Investigation, a paper presented at Seminar on Design and Construction of Roads in Mountaineous Terrain in Malaysia, Jabatan Kerja Raya, Peninsula Malaysia.

Moh, Z.C., Chiang, Y.C. and Ou, C.D. (1979), Design and Construction of a High Retaining Scheme, Proc., 6th Asian Regional Conf. on SMFE, Vol.1, pp.233-236.

Moh and Associates (1978), Report on Study and Design for Slope Stabilization at 14k and 16k of the Taiwan N-S Freeway, Report submitted to the Taiwan Area Freeway Bureau, Taipei (in Chinese).

Moh and Associates (1983a), Preliminary Stability Assessment of Slopes along Grik-Jeli Section of East-West Highway, West Malaysia unpublished report submitted to Malaysian-Thai Development Sdn Bhd

Moh and Associates (1983b), Report on Geotechnical Study for an Existing Cut Slope at Mile 21, Jeli Side, East-West Highway, West Malaysia, Report submitted to Malaysian-Thai Development Sdn Bhd.

Moh and Associates (1985), Geotechnical Investigation for the Kuala Lumpur-Karak Toll Highway, unpublished report submitted to the Malaysian-Thai Development Sdn Bhd.

Patton, F.O. (1966), Multiple Modes of Shear Failure in Rock, Proc., 1st Congress of ISRM, Lisbon, Vol.1, pp.509-513.

Woo, S.M., Moh, Z.C., Yu, K. and Guo, W.S. (1981), A Study on the Causes of Some Rock Slope Failures Along Highways in Taiwan, Proc., 3rd Conf. Road Engineering Assoc. Asia and Australasia, Taipei, pp.761-777.

Woo, S.M., Guo, W.S., Yu, K. and Moh, Z.C. (1982), Engineering Problems of Gravel Deposits in Taiwan, Proc., Specialty Conf. on Engineering and Construction in Tropical and Residual Soils, ASCE, Honolulu, Hawaii, pp.500-518.

Yu, K., Guo, W.S. and Chou, C.K. (1982), Site Investigation and Design for Slopeland Development - A Case Study, Proc., Annual Meeting of the Chinese Institute of Civil and Hydraulic Engineering, Taipei (in Chinese).