CHAPTER 6

SLOPE STABILITY ANALYSIS

CHAPTER 6

SLOPE STABILITY ANALYSIS

6.1 Introduction

There are various approaches to the study of the instability of slopes; the two main ones being the geological approach and the engineering approach. The geological approach, used by a geologist would regard slope instability as a natural process and study the phenomenon to determine the cause of failure, the course it takes and the resulting surface forms. The engineering approach, used by an engineer, would firstly investigate the safety of the slope with regards to the principles of soil mechanics and then create a method to reliably assess its stability and at the same time undertake the necessary steps towards proper monitoring and remedial works. The best approach is a fusion of the two aforementioned approaches to analyse failures of cut slopes caused by movements within the respective slopes, be it a man-made cut, a natural slope or a combination of both. It would take into consideration both the external and internal parameters that control the stability of such slopes and those which cause instability in them. The external parameters emphasized here are the physical features of a cut slope such as its height, width and slope angle while the internal parameters are the shear strength parameters, C (cohesion) and ϕ (angle of internal friction) of the slope forming materials and the groundwater conditions.

CHAPTER 6

SLOPE STABILITY ANALYSIS

6.1 Introduction

There are various approaches to the study of the instability of slopes; the two main ones being the geological approach and the engineering approach. The geological approach, used by a geologist would regard slope instability as a natural process and study the phenomenon to determine the cause of failure, the course it takes and the resulting surface forms. The engineering approach, used by an engineer, would firstly investigate the safety of the slope with regards to the principles of soil mechanics and then create a method to reliably assess its stability and at the same time undertake the necessary steps towards proper monitoring and remedial works. The best approach is a fusion of the two aforementioned approaches to analyse failures of cut slopes caused by movements within the respective slopes, be it a man-made cut, a natural slope or a combination of both. It would take into consideration both the external and internal parameters that control the stability of such slopes and those which cause instability in them. The external parameters emphasized here are the physical features of a cut slope such as its height, width and slope angle while the internal parameters are the shear strength parameters, C (cohesion) and ϕ (angle of internal friction) of the slope forming materials and the groundwater conditions.

6.1.1 Aims of slope stability analysis

Slope analysis enables an understanding of the development of the various forms of natural or man-made slopes as well as the processes responsible for them. It also enables redesigning of failed slopes, and the planning and design of preventive and remedial measures when the need arises. It too allows the study of the effect of exceptional stresses such as earthquake on cut slopes and embankments. Slope stability analysis is an accepted analytical tool in determining the factor of safety for both natural and man-made slopes.

In this study , stability analyses for the above mentioned purposes is more in terms of identifying the factors affecting instability or stability. This has been possible by studying the various failures that have affected existing cuts in quartz-mica schist and identifying the factors affecting failure especially the shear strength parameters, C (cohesion) and ϕ (angle of internal friction). Since the start of a failure or displacement is dependent on conditions and events during the days proceeding it, assessment of the internal shearing resistance of the material involved would help decide how best to prevent and control the change in shearing resistance. This would then help decide on how best to prevent and control the change in shearing stress which may induce instability.

6.1.2 Principles of stability analysis

Many forms of instability progress by sliding along surfaces within the soil or rock mass. After an initial shear failure followed by the sliding phase, the debris or the failure mass separates from the parent mass. This can be analyzed using this simple sliding model:

Factor of Safety (FS) = *destabilising force* : *mobilising strength*

The main force which causes the movement of a mass is principally the resolved component of the weight of the mass acting down the failure plane. The SLOPE/W software by GEO-SLOPE Int. Ltd. (Calgary, Alberta, Canada) has been utilized for the purpose of slope stability analyses in this thesis.

6.2 SLOPE/W

6.2.1 Introduction

SLOPE/W is a computer programme that uses limit equilibrium theory to determine the factor of safety (FS) of earth and/or rock slopes. Its comprehensive formulation makes it possible to select a variety of methods for computing the factor of safety and to analyze both simple and complex geometric, stratigraphic and loading conditions. The SLOPE/W programme uses the total and/or effective stress cohesion and friction parameters, C and ϕ, of the slope forming material. In the case of multiple soil types, the C and ϕ of each layer are taken into consideration in determining the critical slip surface. The slip surfaces (circular in this case) are defined by grid of rotation centers and radiie or by data points. The programme computes the factor of safety for each trial slip and displays only the minimum values at the end of the run. The end results are plotted on a 2-dimensional diagram which shows the multiple layers of the slope forming materials differentiated in various colours. The minimum factor of safety computed is shown beside its centre of rotation (highlighted in red) on the grid of rotation centers. The respective critical slip surface is also shown on the diagram. The SLOPE/W programme operates under the Microsoft Windows 3.X graphical interface.

Three main methods of analysis have been used for this study to compute the minimum factor of safety for each slope. They are the Ordinary or Fellenius, and Bishop's Simplified Methods, which determine the factor of safety with respect to moment equilibrium, and Janbu's Simplified Method which determines the factor of safety with respect to force equilibrium.

The existing slopes chosen for the Slope/W analyses were divided into two main types. They are the temporary slopes and the permanent slopes. The temporary slopes refer to slopes where earthworks, still in progress in their vicinity, may cause changes to its existing design. Permanent slopes refer to slopes where earthworks have been completed, where no further change will be made to the general design of the existing slopes.

For the purpose of stability analysis in this study , certain assumptions have had to be made. They are:-

i) a conservative value of more than 1.3 is assumed for the factor of safety of temporary slopes

ii) a conservative value of more than 1.5 is assumed for the factor of safety of permanent slopes

iii) the weight of soil is assumed to be 18 kg per unit (a range of 16→18 for soil→rock)

iv) a standard width of 3.5 meters and a depth of 1.5 meters of fill is assumed for both the Seremban-Mambau-Siliau and Siliau-Rantau roads

v) the groundwater level is assumed to be in the lower part of morphological Zone II (IIB-IIC)

All the characteristics of the existing cut slopes and failures taken into account for the purpose of the stability analyses are the slope height, slope width, slope length, slope angle, the thickness of each morphological zones exposed and their respective C and ϕ values.

6.3 Stability analysis

Each existing cut slope and failed cut slope located in the study area was analysed individually to determine its stability or potential instability. The minimum factor of safety computed using this stability programme is summarised in Table 6.1.

Based on the factor of safety results obtained from the stability analysis, the existing cut slopes and failures are firstly categorized in terms of their stability or failure potential. There are four main categories and they are ranked as I (failed slope), II (soon to fail), III (possibility of failing) and IV (very stable) (Table 6.2). The existing cut slopes and failures are then ranked based on the risk factor which considers the danger or hazard towards road users and premises in the vicinity. It takes into consideration the proximity of these cut slopes and failures to the roads and nearby premises as well as the expected size of failure. This is because the closer a failure is to a road or premise and the larger the failure in question, the greater the danger to the road users and occupants of the premise involved.

6.3.1 Existing cut slopes

A total of seven existing permanent cut slopes have been identified on quartz-mica schists. They are S1, S2, S3, S4 and S5, which are located along the Seremban-Mambau-Siliau road and S6 and S7, which are located along the Siliau-Rantau road.

FEATURES	TOTAL NO. OF SLIP SURFACE	MINIMUM FACTOR OF SAFETY		
		[Moment]		[Force]
		Ordinary	Bishop	Janbu
S1	484	6.28	6.339	6.296
S2	1280	2.186	2.216	2.223
S3	1280	2.36	2.368	2.425
S4	1280	2.36	2.283	2.452
S5	1280	2.167	2.176	2.173
S6	1280	2.553	2.607	2.539
S7	1280	3.627	4.508	5.009
F1	1280	1.055	1.116	1.079
F2	1280	1.706	1.711	1.794
F3	1280	1.322	1.351	1.371

Table 6.1 A summary of the minimum factor of safety obtained for each cut slope (S1-S7) and existing failure (F1-F3) in the study area.

(The SlopeW software used had utilised the Ordinary, Bishop and Janbu Methods for the purpose of stability analysis)

S = existing cut slopes

F = existing cut slope failures

	CATEGORIES
Stability / Failure Potential	I - Failed II - Soon to fail III - Possibility of failing IV - Very stable
Risk	RI - Very Dangerous RII - Dangerous RIII - Less Dangerous RIV - Not Dangerous

Table 6.2 Ranking of stability or failure potential and risk categories

SLOPE NUMBER	STABILITY/FAILURE POTENTIAL	RISK
S1	IV	RIV
S2	IV	RIV
S3	IV	RIII
S4	IV	RIV
S5	III	RIII
S6	IV	RIV
S7	IV	RIV
F1	II	RIV
F2	III	RIV
F3	IV	RIV

Table 6.3 Summary of stability/failure potential and risk ranking of existing cut slopes and failures

S = existing cut slopes
F = existing cut slope failures

Each cut slope will be analyzed and discussed individually to ascertain its individual stability conditions. It will then be categorized based on the stability or potential instability and risk ranking. Since the cut slopes found along the railway track are not on quartz-mica schists, they will not be included in the following discussion.

The minimum factor of safety computed using the stability programme and the respective stability/failure potential as well as their risk ranking are as shown in Table 6.3. Based on the minimum factor of safety computed, 6.339, and the critical slip surface which involves only the soil zone and not the road (Figure 6.1), S1 is categorized as IV (very stable) with a RIV (not dangerous) risk ranking. With a minimum factor of safety computed is a value of 2.161 and a critical slip surface that involves only the saprolite and not the road (Figure 6.2), S2 is categorized as IV (very stable) with a risk ranking of RIV (not dangerous). Though the critical slip surface for S3 involves all three zones of the weathering profile (Figure 6.3), it does not involve the road. However, should a failure occur, there would definitely be debris spillage on to the road. Since the debris from the failure would only be a minor hindrance to road users, S3 is categorised as IV (very stable) with a risk ranking of RIII (less dangerous). With a minimum factor of safety of 2.283 and no debris spillage on to the road in case of a failure (Figure 6.4), S4 is categorized as IV (very stable) with a risk ranking of RIV (not dangerous). Though S5 has a minimum factor of safety value of 2.176 and its critical slip surface does not involve the road (Fig. 6.5), S5 is categorized as III (possibility of failing) due to its steep slope angle with a risk ranking of RIII (less dangerous) in view of the debris from possible failure which would be of some

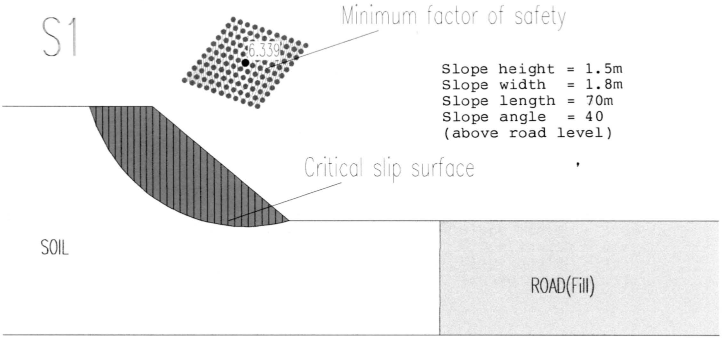


Figure 6.1 Cut slope S1 (2km from Mambau)

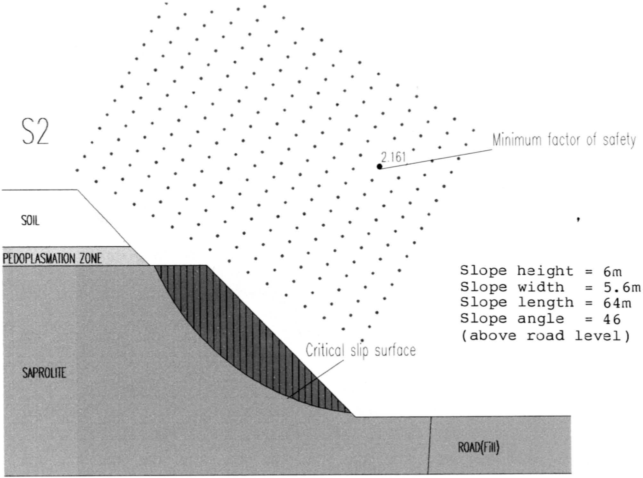


Figure 6.2 Cut slope S2 (4.5km from Mambau)

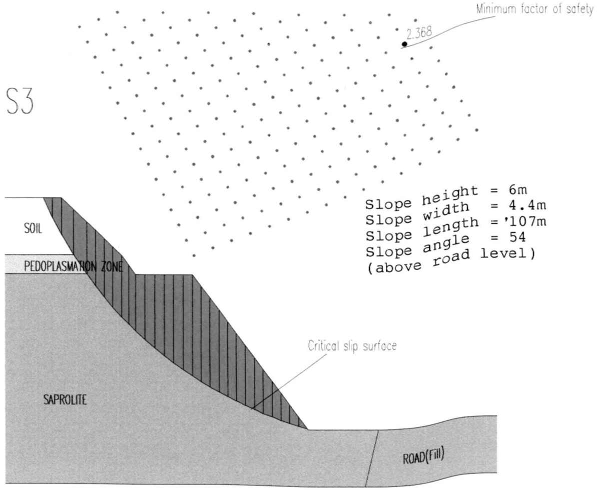


Figure 6.3 Cut slope S3 (7km from Mambau)

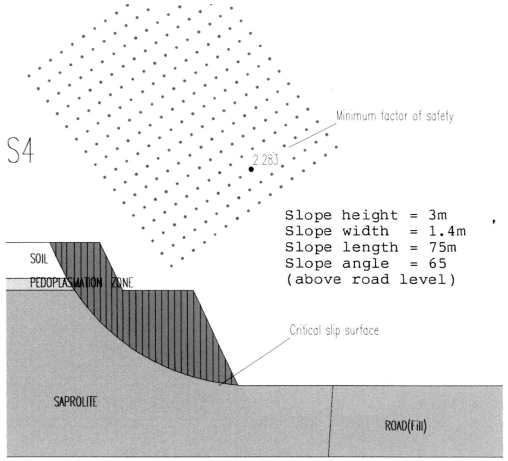


Figure 6.4 Cut slope S4 (100m from S3)

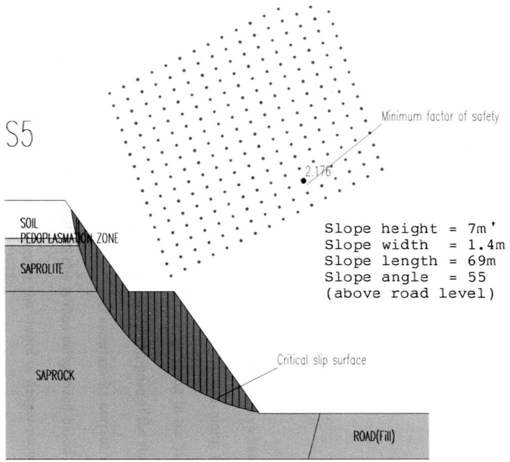
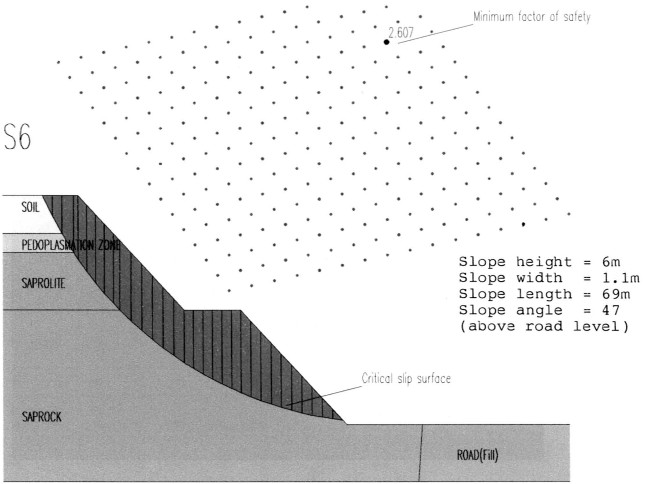


Figure 6.5 Cut slope S5 (7.5km from Mambau)

hindrance to road users. The minimum factor of safety computed for S6 is 2.607 (Figure 6.6). In the event of a failure, its debris will not affect road users since it will not spill over on to the road. Therefore, S6 is categorized as IV (very stable) with a risk ranking of RIV (not dangerous). S7 has a minimum factor of safety of 4.508 (Figure 6.7) with a critical slip surface that involves the soil, pedoplasmation zone and the upper saprolite only with the exclusion of the road. In case of a failure, the resulting debris will not pose any danger to road users and therefore, S7 is categorized as IV (very stable) and ranked as RIV (not dangerous). The stability and risk categories for all these cut slopes are summarised in Table 6.3.

6.3.2 Existing Failures

A total of three existing failures on quartz-mica schists have been identified in the study area and they are F1, F2 and F3 which are found along the Seremban-Mambau-Siliau road. Since excavation work is still on-going in the vicinity of these failures, they are regarded as temporary slopes for the purpose of the stability analysis. Each existing failure is analyzed individually to ascertain its current stability or the possibility any subsequent failure. Each one is then categorized based on its stability or potential subsequent failure and ranked on the hazard or danger posed to road users or adjacent premises.



Slope height = 6m
Slope width = 1.1m
Slope length = 69m
Slope angle = 47
(above road level)

Figure 6.6 Cut slope S6 (4.5km from Siliau)

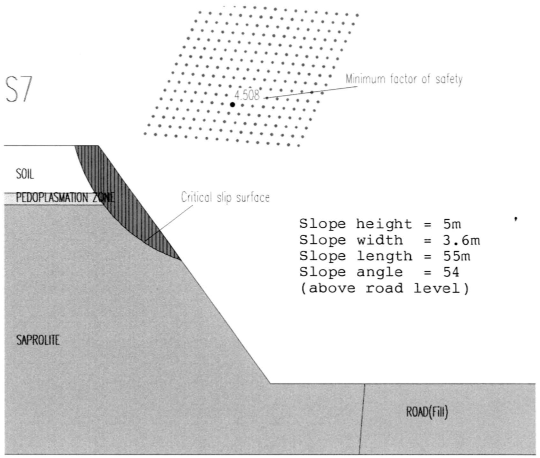


Figure 6.7 Cut slope S7 (4km from Siliau)

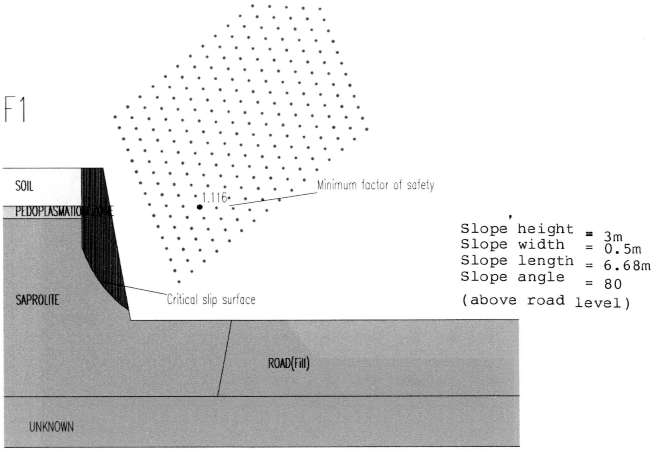
6.3.2.1 F1

The minimum factor of safety computed for F1 is 1.116 (Fig 6.8) which is less than the assumed acceptable conservative value of 1.3 for temporary slopes. F1 is expected to experience subsequent failure before attaining a naturally suitable stable condition. The subsequent failure will involve the soil, pedoplasmation zone and saprolite zones. However, the resulting debris will not hinder road users as the computed failure mass is of small quantity. Therefore, F1 is categorized as III (soon to fail) with a risk ranking of RIV (not dangerous).

The reason for the initial failure of F1 is due to a high groundwater table caused by heavy rainfall in the area. The failure mechanism is triggered by rainfall that infiltrates into the slope (especially through its exposed slope face), causing an increase in the load bearing down the slope which induces "softening" i.e. desication cracks. When this downward force exceeds the shear resistance of the slope forming material, failure occurs.

6.3.2.2 F2

The minimum factor of safety computed is 1.711 (Fig 6.9) which is above the assumed conservative value of 1.3 for temporary slopes. The critical slip surface



Slope height = 3m
Slope width = 0.5m
Slope length = 6.68m
Slope angle = 80
(above road level)

Figure 6.8 Failed cut slope F1 (4.1 km from S1)

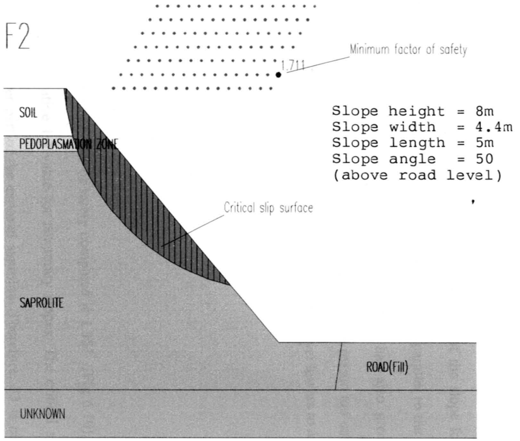


Figure 6.9 Failed cut slope F2 (3.35km from S1)

involves the soil, the pedoplasmation zone and the upper three-quarters of the saprolite exposed. Should a failure occur, the resulting debris will not pose any danger or hindrance to road users. F2 is categorized as III (possibility of failing) due to its high degree of weathering. However, it is ranked as RIV (not dangerous) because though the failed mass may spill over on to the road, it will not hinder or endanger road users.

The initial failure of F2 was due to its steep dip angle, existing foliation as well as jointing and highly weathered characteristics of the slope forming material with low shear resistance along weak schistosity planes parallel to the slope face. The increase in groundwater table due to heavy rainfall has also greatly contributed towards it. Any failure in the future will be due the same reason too until the surface is rid of all loose weathered material and the groundwater level lowers to a level that is not exposed on this temporary cut slope.

6.3.2.3 F3

The minimum factor of safety computed is 1.351 (Fig 6.10) which is higher than the conservative 1.3 value for temporary slopes. The critical slip surface only involves the lower part of the exposed saprolite. Therefore, F3 is categorized as IV (very stable) and RIV (not dangerous). Should a failure occur i.e due to increase in groundwater table, the computed critical slip surface shows a failure which will not affect an adjacent road and that the failure mass will not hinder road users.

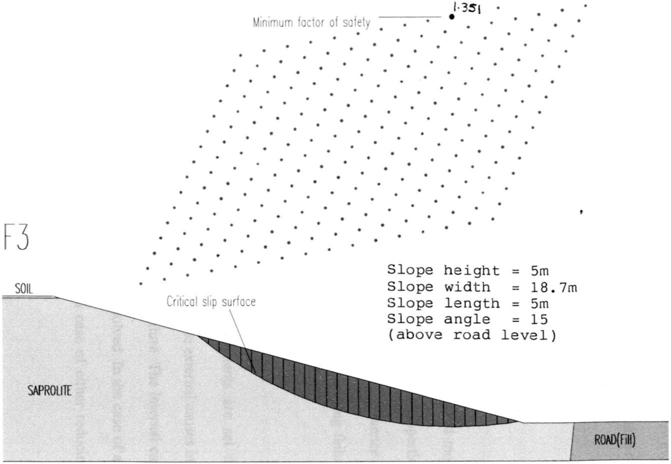


Figure 6.10 Failed cut slope F3 (3km from Seremban)

The initial failure of F3 was due to the seasonal heavy rainfall which had caused an increase in the groundwater table on this temporary cut slope. The high degree of weathering had contributed too, where it had created weak zones of low shear resistance along schistosity planes and joints. Opening of these schistosity planes joint, leave the material on the surface exposed and prone to downward movement, especially due to gravity. Any future failure would be due to the same reason too.

6.4 Factors affecting stability

A simple cut slope with no structural loading on it would most probably fail mainly due to unsuitable slope geometry, low shear strength properties of weathered material, morphology of weathered zones and of course the presence of groundwater (Sweeney & Robertson, 1984). This is the case with the existing failures in the study area.

In general, the instabilities or mass movements are set in motion by a combination of both external and internal causes. The external causes increase shearing stress along the surface of failure at the time of failure. The internal causes meanwhile reduce the shearing resistance of the material involved. In the case of a combination of both external and internal causes, it may be a case of either reducing or increasing shear stress.

External causes which in reality are external changes experienced in this case are the geometrical and water regime changes. The geometrical change which is due to undercutting, erosion and excavation cause a change in height, length or slope angle. Similarly is the effect of the change in rainfall regimes especially due to the monsoon where the increase in rainfall causes an increase in weight, pore pressure as well as groundwater level. Instabilities of cut slopes especially in quartz-mica schist are mainly due to their vertical horizonation of slope material (morphological horizoning) in the course of weathering and the preservation of various structural feature of the original bedrock. These horizoning leads to the development of unconfined groundwater at the lower part of a weathering profile. The unconfined groundwater zones vary from one area to another as it is dependent on the topographic feature of the area in question and amount of rainfall experienced. However, only slopes where the zones of unconfined groundwater are exposed or are close to the base of the slopes are affected.

The internal factors causing internal changes are factors such as progressive failure, weathering and seepage (Terzhagi, 1950 & Brunsden, 1979). Progressive failures occur following lateral expansion or fissuring as well as extensive erosion due to the reduction in the cohesive (C) value, an increase in cementing and erosion. Effects such as solation and piping due to seepage too trigger off failures.

6.5 Recommendations

Generally the reduction of potential instability of cut slope or stabilization involves some or all of the following measures: -

i) reducing pore pressure in the slope

ii) reducing de-stabilizing forces

iii) increasing stabilizing forces

iv) supporting unstable areas

The reduction of pore pressure is achieved by means of groundwater control involving drainage systems. The reduction in de-stabilizing forces or the increase in stabilization forces is achieved by altering the slope geometry. Support for unstable areas is achieved by means of constructing structural support. The choice of the stabilization method will be based on whether the cost is commensurable with the damages incurred in case of a failure.

6.5.1 Reduction of pore pressure

The aim of surface and sub-surface discharge is to acquire a water pressure reduction in an acceptable length of time. This is because the decrease in groundwater pressure or pore pressure will result in an increased shear strength and therefore an increase in the factor of safety. The drainage system will promote vertically downward flow in a slope resulting in a decrease in pore pressures which effectively increase stability and at the same time not necessarily lowering the water table appreciably since it is not necessary to dry the soil above the slip surface (Nonveiller, 1970). Of the many methods of drainage control are trench drains, horizontal drains, vertical drains and vegetation cover.

Another approach to groundwater pressure is by decreasing infiltration of surface water. This can be achieved by intercepting rainfall and reducing the infiltration characteristics of the surface of the slope by means of soil treatment or impermeable membrane. Infiltration can also be reduced by increasing surface drainage efficiency of the slope in order to promote surface run off. Surface cover vegetation too can reduce infiltration of rainwater by absorbing as much moist as possible with its roots. Vegetation suitable for this purpose should have massive and deep particle binding root system e.g. *Vetiver zizanioides*, a grass with massive and deep particle binding root systems.

Since the existing failures in the study area are all with exposed surface and increased groundwater table, the above methods are practical and of minimal cost. These methods of stabilization are only applicable if these temporary cut slopes are to be made permanent cut slopes.

6.5.2 Reduction of de-stabilizing forces

A bigger part of de-stabilizing forces on a slope is contributed by the mass above the critical slip surface. It is the load or the weight of this unsuitable mass acts in a downward direction of the slip surface, causing an increase on de-stabilizing forces. Therefore by removing the slide material or unstable material from the upper part of the slide, the load on the failure surface is reduced. This will in turn cause a considerable reduction in de-stabilizing forces and an increase in the factor of safety. The removing of unstable mass also changes the slope geometry from a less stable to a more stable profile.

The above methods are however not practical and too expensive for the cut slopes in the study area with small computed failure mass or debris.

6.5.3 Increase of stabilizing forces

Stabilizing forces are increased by adding weight to the toe of an unstable area or by increasing the shear strength along the failure surface. The added weight at the toe will add more resistance against destabilizing forces acting down the critical slip surface. The adding of weight to the toe can be achieved by means of a toe fill, designed to provide a satisfactory factor of safety on a pre-existing critical slip surface.

The shear strength along a failure surface can be increased, among other methods, by covering the surface with a thin skin of free draining material e.g. 40mm granular beach shingle, especially for a slope with thin unstable surface layer. This form of surface cover will significantly increase the effective stress and subsequently the shear strength on the shallow failure surface and prevent sliding.

The above method is applicable to the cut slopes in the study area provided this stabilization measures are economical and practical.

6.5.4 Support for unstable areas

Stabilization of unstable areas can be achieved by means of constructing structural support. This structural support may be in the form of retaining walls such as reinforced concrete gravity walls, crib-block walls, gabion walls, reinforced earth walls or geotextile reinforced walls to name a few. The design of these structural supports will take into consideration bearing pressure under the base of the wall; overturning, about the base of the wall and sliding. The purpose is to achieve a suitable factor of safety for the overall slope (original slope and support).

The above methods are expensive and only practical for cut slopes with huge failure mass and close to a road or premise. Therefore, since the existing cut slopes are a distance from roads and premises as well as of small to average failure mass, these methods are not advisable.

6.6 Summary

Of the seven existing cut slopes (S1-S7) and three existing failures (F1-F3), F1 is expected to fail again soon is F1 while S5 and F2 are of high possibility of failing in the near future. The very stable existing cut slopes are S1, S2, S3, S4, S6 and S7. The only stable existing failure is F3. On the risk factor, the existing cut slopes and failures can be ranked into two main categories: the less dangerous and the not dangerous. The less dangerous slopes are S3 and S5. The not dangerous slopes are S1, S2, S4, S6, S7, F1, F2 and F3.

The factors affecting the instability of these existing cut slopes and failures in the area are unsuitable slope geometry, seasonal fluctuation of groundwater table, presence of foliated and jointed slope surfaces and exposed slope surfaces. The recommended stabilization methods are pore-pressure reduction methods i.e. vertical and horizontal drains, increase of stabilization forces method using economical toe support at the critical slip failure and support for unstable area method especially surface cover using vegetation ,geotextile or shotcrete or concrete dentures.