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Parametric Evaluation of the Stability of Natural Slopes

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ABSTRACT

A new geotechnical criterion called the Slope Stability Index, SSI, is proposed to be used for the assessment of the relative stability of natural slopes. This criterion involves the calculation of 11 factors in addition to the Rock Mass Rating (RMR). The author has added to the RMR of Bieniawski (1979) two new parameters; namely: the geodurability of the slope material and the geologic setting of the slope. The relative weights of the parameters in the RMR have been adjusted based on experience and judgement. The parameters F1, F2 and F3 related to the joint – slope relationship as well as F4 related to the method of excavation that were introduced by Romana (1996) in his SMR were also adjusted. The new parameters introduced by the author are related to the slope geometry (steepness and shape) and to the environmental factors (rainfall, drainage, climatic and seismic conditions). Zuyu factor E (1995) related to slope height was also introduced with suggested upper and lower values. The new index is believed to give a fair assessment of the relative stability of the slopes under consideration. This would help planners and engineers in their selection of the sites of their engineering projects and in the treatment of slopes that exist in a critical state of stability.

KEYWORDS: Natural slopes, Stability, Parametric evaluation, Slope stability index.

INTRODUCTION

The selection of the proper sites for engineering projects is often considered one of the most critical factors in ensuring their safety and economic feasibility. This is particularly true in the areas characterized by their disturbed past geologic history where potential landslides could result in the destruction of property, loss of life and an inconvenience to the public. Therefore, the development of landside hazard zonation maps is considered of a paramount importance to engineers and planners either for the regional planning of areas selected for their envisaged future development projects or for the selection of the most proper locations for their individual structures. Quantitative assessment of the stability of slopes forms the basis for the development of their hazard zonation maps. This assessment requires careful study of the factors and processes that contribute to the development of the present natural slopes. These primarily include the geologic, hydrodynamic, geotectonic, erosional and environmental processes as well as the human activities that may involve cuts, fills and changes in hydrogeological and drainage conditions.

The author embarked on the study of the reports of 42 landslides that occurred in different parts of Jordan in the period from 1966 till 2008 followed by field visits to the sites of some of them. These landslides ranged in volume from less than 1000m^3 to more than 150,000 m^3. The most common forms of these slides were typical rotational slides in thick homogeneous plastic clays (mainly plastic marls), translational slides (mostly along moderately to steeply dipping bedding planes of thin plastic clay or mudstone layers) and shallow slumps or

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pop – outs along rotational non – circular planes. Most of these slides were accompanied or followed by rockfalls and sometimes by rockslides. Most of the landslides that were studied lie along highway routes and occurred during the construction of these highways or shortly after construction (Parsons Brinckerhoff, 1989; Dames and Moore Int., 1993). Most of them occurred during the seasons that witnessed intense rainfalls or shortly after them.

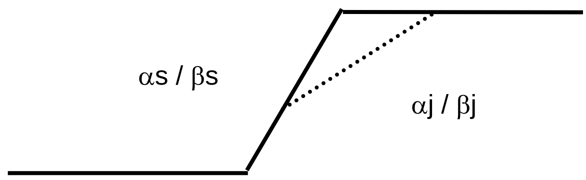
Table 1. Rock mass rating , RMR (adjusted, Bieniawski, 1979)

<table>
<tr><th>Item</th><th>Parameter</th><th colspan="7">Range of Values</th></tr>
<tr><td rowspan="4">1</td><td rowspan="2">q_u (Mpa)</td><td rowspan="2">100 - 250</td><td rowspan="2">25 - 100</td><td rowspan="2">5 - 25</td><td rowspan="2">1 - 5</td><td colspan="3">< 1</td></tr>
<tr><td colspan="3">IP</td></tr>
<tr><td rowspan="2">Rating</td><td rowspan="2">8</td><td rowspan="2">6</td><td rowspan="2">4</td><td rowspan="2">3</td><td>< 12</td><td>12 - 25</td><td>> 25</td></tr>
<tr><td>2</td><td>1</td><td>0</td></tr>
<tr><td rowspan="2">2</td><td>RQD %</td><td>90 - 100</td><td>75 - 90</td><td>50 - 75</td><td>25 - 50</td><td colspan="3">< 25</td></tr>
<tr><td>Rating</td><td>10</td><td>8</td><td>6</td><td>4</td><td colspan="3">2</td></tr>
<tr><td rowspan="2">3</td><td>Spacing of discontinuities</td><td>> 2</td><td>0.6 - 2</td><td>0.2 - 0.6</td><td>0.06 - 0.02</td><td colspan="3">< 0.06</td></tr>
<tr><td>Rating</td><td>8</td><td>6</td><td>4</td><td>3</td><td colspan="3">1</td></tr>
<tr><td rowspan="2">4</td><td>Condition of discontinuities</td><td>Very rough, not continuous, no seperation, unweathered</td><td>Slightly rough, seperation <1mm, slightly weathered</td><td>Slightly rough, separation <1mm, highly weathered</td><td>Slickensided or gouge < 5 mm or seperation 1 - 5 mm continuous</td><td colspan="3">Soft gouge > 5 mm or seperation > 5 mm continuous</td></tr>
<tr><td>Rating</td><td>12</td><td>10</td><td>7</td><td>3</td><td colspan="3">0</td></tr>
<tr><td>5</td><td>Groundwater in joint</td><td>Completely Dry</td><td>Damp</td><td>Wet</td><td>Dripping</td><td colspan="3">Flowing</td></tr>
<tr><td></td><td>Rating</td><td>11</td><td>9</td><td>6</td><td>3</td><td colspan="3">0</td></tr>
<tr><td>6</td><td>Geodurability $\times 10^3$</td><td>Very good > 50</td><td>Good 25 - 50</td><td>Moderate 12 - 24</td><td>Poor 6 - 11</td><td colspan="3">Very Poor <6</td></tr>
<tr><td></td><td>Rating</td><td>6</td><td>5</td><td>3</td><td>1</td><td colspan="3">0</td></tr>
<tr><td>7</td><td>Geologic setting</td><td>Very favourable</td><td>Favourable</td><td>Fair</td><td>Unfavourable</td><td colspan="3">Very unfavourable</td></tr>
<tr><td></td><td>Rating</td><td>5</td><td>4</td><td>2</td><td>1</td><td colspan="3">0</td></tr>
</table>

Table 2. Adjustment rating for joints (adjusted, Romana, 1996)

Case	--	Very favourable	Favourable	Fair	Unfav.	Very unfav.
P	| αj - αs|	> 30°	30° - 20°	20° - 10°	10° - 5°	<5°
T	| αj - αs - 180°|					
P / T	F1	0.15	0.4	0.7	0.85	1.00
P	|βj |	< 20°	20° - 30°	30° - 35°	35° - 45°	> 45°
P	F2	0.15	0.40	0.70	0.85	1.00
T	F2	1	1	1	1	1
P	βj - βs	> 10°	10° - 0°	0°	0° - (-10°)	< - 10°
T	βj + βs	< 110°	110° - 120°	> 120°	--	--
P / T	F3	0	-4	-15	-35	-40

P = Plane failure
T = Toppling failure
αs = Slope dip direction
βs = Slope dip
αj = Joint dip direction
βj = Joint dip



PURPOSE OF THE STUDY

In a past study (1999), the author tried to present a methodology that could help geotechnical engineers in assessing quantitatively the stability of slopes along highway routes in Jordan.

The classification system that was proposed involved the consideration of 7 major parameters with different weights according to their estimated relative importance in affecting the stability of slopes. The present study presents a more comprehensive evaluation of the susceptibility to failure of slopes through the comparative study of the geological, geomorphological, hydrological, seismic and geotechnical conditions of slopes that suffered from instability with those of slopes that exist in a stable state.

The relative stability of a given slope or, in other words, its susceptibility to failure is assessed using a newly proposed criterion called Slope Stability Index, SSI, that includes the consideration of all possible factors that may affect the stability of slopes. Each factor has been subjectively weighted according to its relative contribution to the stability of slopes based on experience and judgement. This index is believed to be an efficient criterion to planners and design engineers in the proper selection, development and management of lands deemed appropriate for the execution of their envisaged development projects.

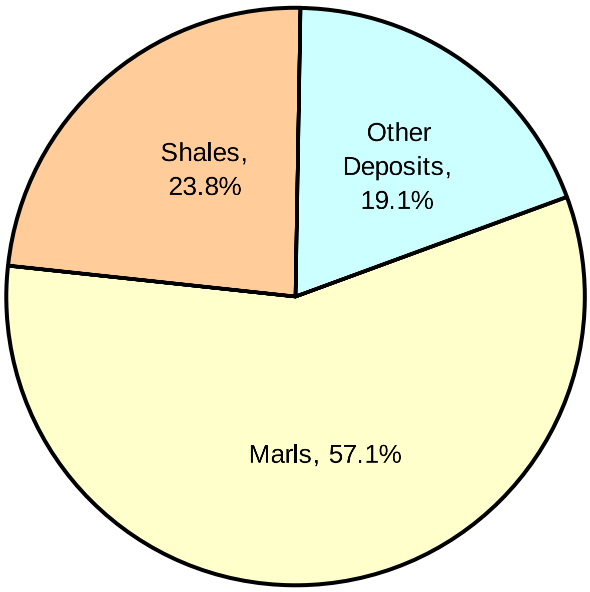


Figure 1: Frequency distribution of the dominating materials in 42 landslide areas

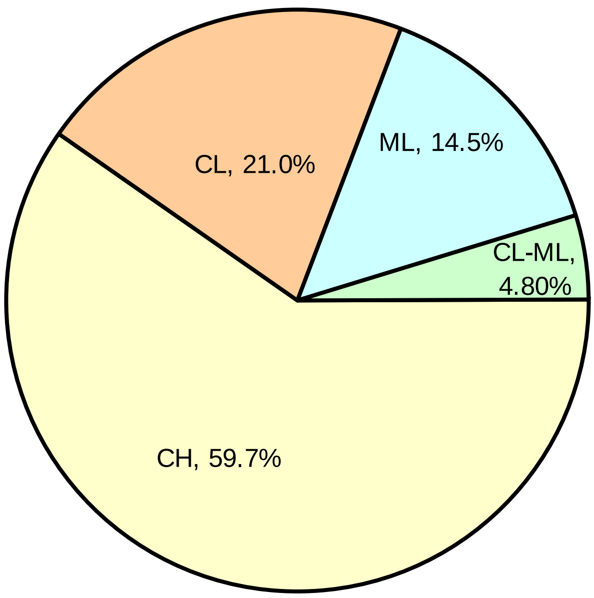


Figure 2: Frequency distribution of 62 samples from the landslide areas according to the unified soil classification system

GEOLOGIC HISTORY

Past geologic history provides a useful indicator to the susceptibility of a given slope to failure due to either natural processes or human activities. This is particularly true in areas that suffered from old landslides where slip planes form potential sliding surfaces, particularly in road construction projects. A decrease in resisting forces due to excavation or an increase in driving forces due to dumping of fill material or blockage of drainage courses will often lead to the reactivation of slope movement along the pre – existing slip planes. These planes are often due to displacement resulting from the composite effect of some or all of the following mechanisms:

1- Over-steepening of slopes by active erosion.
2- Disintegration of air – slaking materials like marls, shales, mudstones, …etc.
3- Rise of piezometric level of perched water, particularly after periods of heavy rain or snow falls.
4- Deep scour erosion at the lower reaches of slopes or hillsides.
5- Tectonic activity causing mass movements, particularly in metastable slopes.
6- Encroachment of unstable slopes over the adjacent metastable slopes.

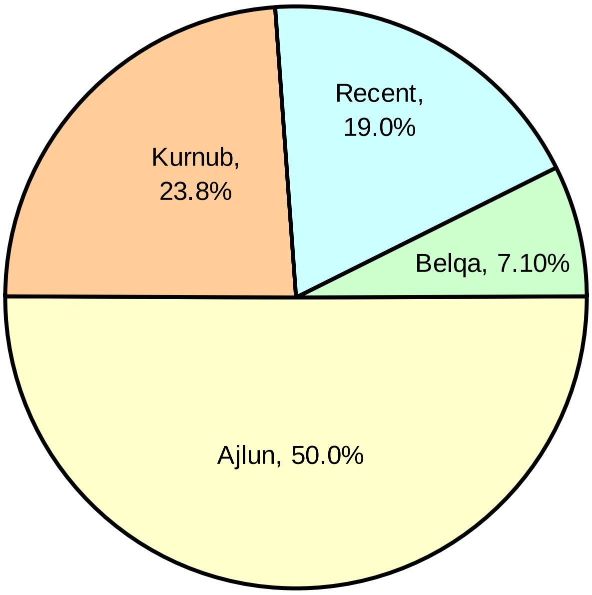


Figure 3: Frequency distribution of the geological formations in 42 landslide areas

Sudden rise in the water content in slopes dominated by clays of moderate plasticity (water content sometimes exceeds the liquid limit) often causes solifluction of slopes. Depending on the local geologic and topographic features, the soliflucted mass may take the form of thin long sheet flows or small lobate flows. Old landslides could be easily recognized by their geomorphological features of hummocky ground, and sometimes by the sudden change in the orientation of the bedding planes as in the case of rotational slides.

The detection of pre – existing slip planes and the proper evaluation of both the available shear strength and the maximum probable pore pressures along them after heavy rainy seasons are very important in defining the zones that are most susceptible to sliding. This is particularly important along highway routes or at the sites of major engineering projects involving either deep cuts or high fills. Slip planes could also be detected by careful inspection and examination of soil cross – sections in trenches or trial pits or through the study of the orientation of lineations in carefully recovered soil samples from investigation boreholes. The orientation of slickensides on the slip surfaces indicates the direction of displacement. The greater the displacement is, the more these slickensides are developed, the more polished the slip surface becomes and the closer the shear strength parameters become to the residual ones. With continuous sampling and determination of water content, the sharp change in the water content profile (sudden increase in water content with or without sudden increase in fines content or plasticity index) often indicates the location of slip surface. Slip surfaces often form the boundary that separates the remolded zones above them from the undisturbed ones below them.

Table 3. Adjustment rating for slope geometry

Steepness of Slope (degree)	**Very gentle < 10**	**Gentle 10 - 25**	**Moderate 26 - 40**	**Steep 41 - 60**	**Very steep >60**
F4	6	4	2	3	5
Geometry of Slope Surface (d/l)*	-0.08	-0.04	0.00	0.03	0.06
F5	3	1	0	-1	-2

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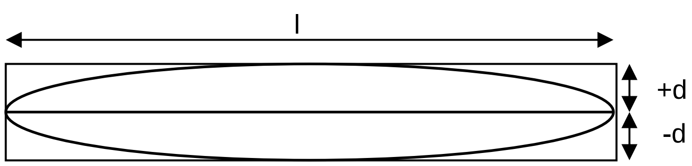

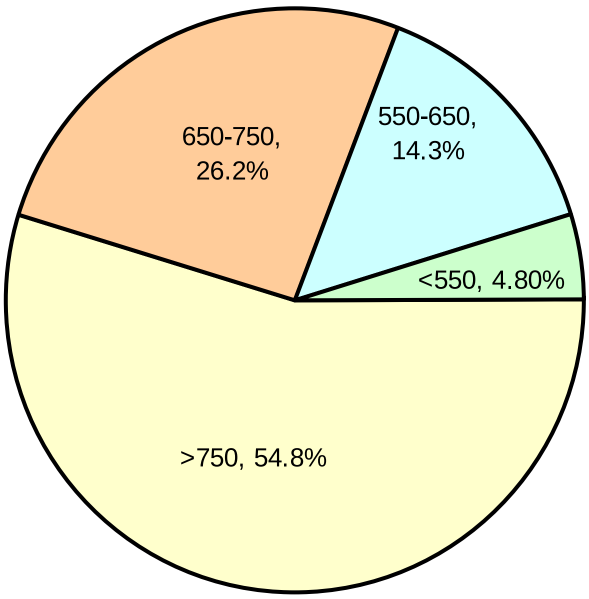

Figure 4: Frequency distribution of 42 landslides according to the total annual rainfall (mm) in the years of their occurrence

Table 4. Adjustment rating for rainfall, drainage, climatic and seismic conditions

Av. Annual Rainfall (mm)	**< 150**	**150 - 350**	**350 - 550**	**550 - 750**	**> 750**
F6	6	5	4	2	0
Drainage Conditions	V. fav.	Fav.	Fair	Unfav.	V. unfav.
F7	6	4	0	-3	-6
Vegetative Cover	Thick	Moderately thick	Fairly thick	Sparse	Barren
F8	5	3	2	-1	-3
Serverity of Climatic Conditions	V. low	Low	Mod.	High	V. high
F9	5	2	0	-3	-6
Susceptibility to Siesmic Hazards	Negligible	Low	Mod.	high	V. high
F10	3	0	-1	-3	-5

Geophysical investigations like electrical resistivity or seismic refraction ones could also be employed to define the location and geometry of pre – existing slip surfaces, particularly those separating loose materials of low plasticity like colluvial deposits from the underlying intact cohesive materials like plastic marls or mudstones.

COMMON CONDITIONS OF LANDSLIDE AREAS

The dominating material that was encountered in the 42 landslide areas studied by the author was marl, followed by laminated shales (Figure 1). The characteristics of marl were comprehensively studied by the author (Masannat, 1988). They range from being of low plasticity classified as ML and CL – ML according to the Unified Soil Classification (USC) system to being of high plasticity classified as CH according to the same system. The shales are generally of lower plasticity than the marls. Most of the samples recovered from the landslide areas are of high plasticity (Figure 2). Most of the marls and shales in the landslide areas are highly overconsolidated. The highly plastic clayey marls mostly belong to the Lower Ajlun Group of Upper Cretaceous, while the shales mostly belong to Kurnub Sandstone Formation of Lower Cretaceous (Figure 3).

According to the Geodurability Classification of Olivier (1979), the shales are generally of poor to very poor quality, while the plastic clayey marls are generally of poor to moderately poor quality. According to Gamble's Slake Durability classification (1971), most of the shales and clayey marls are classified as materials of very low to moderate durability. The highly overconsolidated clayey marls have residual angles of shear resistance, $\grave{\Phi}r$, generally ranging between 7° and 9.5° with residual cohesion, ćr, ranging between 6 and 12 kN/m^2. The overconsolidated clayey marls have high affinity to water. Most of the slope failures in case of deep cuts in plastic marls took the form of slumps or pop – outs or the form of mudflows in the case of access to abundant amounts of water. Differential weathering of shales and marls underlying fractured beds of competent rocks like limestone or dolomite often resulted in rockslides or rockfalls. Daylighting of dipping strata of wet plastic clayey marls or shales underlying beds of limestone, marlstone or dolomite often resulted in translational slides if the dip angle toward the face of cut exceeded 8° to 10°. These slides generally commence with a slow creep displacement that accelerates gradually until they culminate in a relatively rapid catastrophic shear failure.

The Kurnub Sandstone Formation (KSF) is dominated by weak to moderately weak cemented sandstones and shaly sandstones. Solution cavities and channels are common in this formation. Shaly sandstones and shales demonstrate well pronounced slaking properties and readily disintegrate upon exposure to cycles of wetting and drying. This is particularly true in shales with fissile structure. Daylighting of shales and mudstones due to deep excavation often leads to their desiccation and the breakdown of their inter - crystalline bonds. High water content (30% to > 40%) in clayey shales often indicates the presence of pre – existing slip planes or potential slip planes with high pore pressure.

Colluvial deposits often exist in a metastable condition. They become susceptible to failure upon saturation or if subjected to overloading, dynamic stresses or undercutting during excavation. Frequent failures of colluvial deposits occurred during the construction of Amman – Jerash – Irbid highway in Jordan in 1993/1994 and during the excavation works for Wadi Es-Sir Sewage Treatment Plant in Jordan in 1994-1997.

Most of the landslides occurred in the years of high rainfall (Figure 4), particularly in the year 1991/1992, where the annual rainfall exceeded 850 mm in the west and northwest of Jordan (Salt, Ajloun and Irbid Governorates).

PARAMETERS OF SLOPE SUSCEPTIBILITY TO FAILURE

Bieniawski (1974, 1989) introduced the concept of Rock Mass Rating (RMR) to assess the stability of the rock mass in tunnels and mines in terms of average stand – up time for different span widths (Table 1).

Romana (1996) introduced the concept of Slope Mass Rating, SMR, by considering the RMR of Bieniawski in addition to four adjusted factors related to the joints – slope relationship and the method of excavation (Tables 2 and 5). The author has reconsidered Bieniawski rock mass rating parameters by introducing two additional parameters (Table 1); namely: the geodurability of the slope rock mass and its geologic setting and by assigning different weighing factors to the listed parameters based on experience and judgement.

The geodurability as defined by Olivier (1979) is equal to q_u / ϵ_D, where:

q_u = uniaxial compressive strength of an intact rock sample (MPA).

ϵ_D = free swelling percentage of an intact rock sample from an oven – dried state to 24 hour saturation state.

The geologic setting refers to the past geologic history of the study area and its implication on its stratigraphic, structural and hydrogeologic conditions that may or may not exacerbate the instability of slopes.

The steepness of the slope and its geometry also affect the susceptibility of slope failure (Table 3). It has been noticed that most failures occurred on slopes ranging between 26° and 40°, particularly after periods of intense rainfall or melting of snow and where the top soil is underlain by fractured and weathered rock. Most of the areas that suffered from old landslides fall within this slope range. No failures were observed on slopes less than 10° and very few failures were observed on steep slopes greater than 60°. Most of these steep slopes consist of competent rocks with high shear strength and with no shallow soil cover. These observations are in conformity with the findings of Maharaj (1993) who conducted a landslide susceptibility analysis as a case study form St. Andrew, Jamaica.

Rockfalls mostly occur in steep slopes due to the differential weathering of weak strata like shales, mudstones or marls that underlie stronger beds of fractured or jointed rocks like dolomite, massive limestone, chert, …etc.

Table 5. Adjustment rating for methods of excavation of slopes (Adjusted, Romana, 1996)

Method	Natural Slope	Presplitting	Smooth Blasting	Blasting or Mechanical	Deficient Blasting
F11	10	7	5	0	-5

Slope Stability Index (SSI)
= E RMR + (F1*F2*F3)+ F4 + F5 + F6 + F7 + F8 + F9 + F10 + F11 , where:
$E = 0.57 + 0.43 \times 80 / H$
H= height of slope in meters, and $0.7 \leq E \leq 1.2$.

Table 6. Relative stability of slope as determined from SSI

SSI Rating	**100 - 81**	**80 - 61**	**60 - 41**	**40 - 21**	**≤ 20**
Class	I	II	III	IV	V
Description of Stability	High	Good	Fair	Critical	Unstable

Concave slopes are analytically more stable than convex or straight ones (Table 3). However, it is worth noting that concave slopes often occur in areas that suffered from old landslides. This observation should be carefully considered when assessing the overall stability of such slopes. Concave slopes allow more concentration and deeper percolation of surface water. This enhances the process of weathering and the softening of slope material, and thus increases its susceptibility to failure. Thus, the combined effects of these factors should be considered when assessing the short – term and the long – term stability of a given slope.

Most landslides occur in areas characterized by their high annual rainfall and poor drainage conditions. This is due to the softening of slope materials at high degrees of saturation and the build – up of pore water pressures in addition to the seepage forces that cause a rapid drop in the factor of safety as well as the erosion of slope materials that have low cohesion like silts and silty sands.

Thick vegetative cover adds cohesion to the soil cover of slopes and decreases the rate of water infiltration into the slope material. However, the deep roots of trees may act as wedges that contribute to the further jointing of rock masses. Both factors should be carefully considered when assessing the stability of a given slope.

Slopes in areas characterized by intense change in climatic conditions from, for example, hot dry summer to cold wet winter are more susceptible to landslides than areas characterized by mild changes in their climatic conditions.

Failures often result from deep scour erosion at the toes of slopes during floods resulting from rainstorms preceded by long dry climatic conditions. This is particularly true in slopes dominated by soils of low plasticity like silts and silty sands or soils that exist in a metastable state like colluvial deposits.

Slopes are also more susceptible to failure in areas characterized by their noticeable seismic activity or those subjected to strong ground vibrations resulting, for example, from explosions, heavy traffic or any artificial source.

The relative contributions of the above environmental factors to the stability of a given slope are summed up in Table 4.

In cut slopes, the method of excavation greatly affects the susceptibility of slope to failure. As outlined by Romana (1996) (Table 5), deficient blasting has the greatest adverse impact on the stability of a given slope as compared with, for example, presplitting.

The overall stability of a given slope is then estimated from the proposed Slope Stability Index, SSI, where:

$$SSI = RMR + (F1\times F2 \times F3) + F4 + F5 + F6 + F7 + F8 + F9 + F10 + F11$$

This index is applicable to slopes of low to medium heights (less than 80 m) which is often the case in highway construction works and most civil engineering projects. Zuyu (1995) introduced the correction factor E to the RMR to account for the effect of slope height on the stability of slopes, where:

$$E = 0.57 + 0.43 \times 80 / H \quad \text{(H in meters).}$$

According to Romana (1996), this new factor is useful to be applied for high slopes (up to 250m) as in the case of high dams. However, it is the opinion of the author that E be applied to slope heights exceeding 80m with a lower value not less than 0.7 and with an upper value not more than 1.2 for low slopes to reasonably assess their long – term stability.

Thus, the SSI could be calculated as:

$$SSI = E.RMR + (F1\times F2\times F3) + F4 + F5 + F6 + F7 + F8 + F9 + F10 + F11$$

with E ranging between 0.7 and 1.2.

Table 6 shows the relative stability of a given slope as determined from its calculated SSI.

This classification would help planners and design engineers in selecting the best routes for their highways and the best sites for their engineering projects. It also helps the geotechnical engineers in selecting the most economic and technically feasible alternatives for minimizing the risks of slope failures in sites with critical stability. These generally include strengthening methods, supporting methods, changing the design features of slopes by cut and/or fill or by the abandonment or shifting of the developed site.

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