Slope Failures and Remedial Measures for Strategic Highway Construction in Hilly Terrain

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Introduction

Gravitational forces are always acting on a mass of soil or rock beneath a slope. As long as the strength of the mass is equal to or greater than the gravitational forces, the forces are in balance, the mass is in equilibrium and movement does not occur. An imbalance of forces results in slope failure and movement in the forms of creep, falls, slides, avalanches, or flows. Failure occurs when driving forces exceed resisting forces.

Slope failures are a major issue for the highway safety and stability. Such slope failures as landslides are predominant in warm, humid climates and occur during years of unusually heavy precipitation or during periods of heavy concentration of rainfall or during wet years. However, prediction of landslip failure is often uncertain and slope stability is an important element depending upon slope geometry, inherent soil strength and ground or pore water pressure characteristics.

The paper is related to the slope failure in the mountainous terrain where natural and manmade slope failures such as landslides or landslip usually occur.

A landslide is triggered if the shearing (tangential) stresses appearing in a soil mass exceed the magnitudes that the soil is able to resist. An increase of active shearing force can be due to erection of an engineering structure on the slope, increase in the weight of soil mass, higher gradients etc. A reduction of resisting forces can be due to removal of lateral support, say, when excavating a cut across the slope. In such a case, the prediction of landslide failure is often uncertain and slope stability becomes frequently costly.

Erosion is the natural process of removing soil particles by external agents such as water. This involves rainfall which is responsible for the removal of surface layer, resulting in gullies of about 10-60 cm depth. However, over time the sills and gullies deepen further and cause slope to overstepped, thus precipitating slope instability. The slope protection generally means the engineering feature composed of suitable material constructed as a selectively thin layer on a slope otherwise vulnerable to erosion.

Vegetation is an important slope stabilizer. Planting the slope with thick native vegetation serves to strengthen the shallow soils with root systems, prevents erosion, deters infiltration and increasing seepage pressures. Vegetation also discourages desiccation which causes fissuring. Deep fissures provide channels for rain water to enter the slide mass, increasing seepage pressure within the mass as well as applying hydrostatic pressure against the walls of the fissure or crack.

Seeding can also be used for slope treatment. Asphalt mulch technique can be used in which the slopes are prepared into vast seed beds. Asphalt mulch is then spread by a sprayer. The asphalt film gradually disintegrates, its place being gradually taken up by a carpet of green
vegetation. The carpet of grass, that supplants the asphaltic film, acts as an immediate cover for the slopes till the more deep rooted species of shrubs and trees develop and take root.

Figure 1: The General Methods of slope Stabilization: (a) control of seepage forces and (b) reducing the driving forces and increasing the resisting forces.
Causes of Slope Failure

Slope failures are the result of gravitational forces acting on a mass which can creep slowly, fall freely, slide along some failure surface, or flow as slurry. As stresses are usually highest at the toe of the slope, failure often begins there and progresses upslope. Stability generally depends on the following variables:

- **Topography** - in terms of slope inclination and height
- **Geology** - in terms of material structure and strength
- **Weather** - in terms of seepage forces and run off quantity and velocity
- **Seismic activity** - as it affects inertial and seepage forces

The basic factors that must be considered in the evaluation of slope instability are the type and distribution of geologic materials in the slope, the geologic structure, existing ground water conditions, and the potential for future rise in seepage pressures during rainy periods and the inclination and height of slopes. On these conditions are imposed changes brought about by construction activity, such as the excavation for cuts or the placement of fill. These activities change the natural slope inclination as well as natural drainage conditions. As a general rule, slopes exist naturally at an inclination near to stability and any steepening can be expected to result in failure during critical weather changes. The removal of vegetation also tends to decrease slope stability. Over the geologic long term, slope stability can be decreased naturally by tectonic movements, decomposition of the geologic materials and by earthquake forces.

Figure 2: Benching scheme for cut in highly erodable soils in a tropical climate. Low benches permit maximum inclination to reduce the effect of runoff erosion. Cut before
A landslide is triggered if the shearing (tangential) stresses appearing in a soil mass due to one cause or another exceed the magnitude that the soil is able to resist. In the majority of situations, slope failures are caused by water either acting on the surface or through the subsurface. On the surface, heavy flows result in erosion down slope or along the toe of slope, increasing slope angles and instability. A rising ground water table results in increased pore pressures in soil masses and increased water pressure acting along fractures in rock masses.

In rock masses, slope failures will occur along discontinuities representing weakness planes, the major forms which are joints, faults, foliations, bedding planes and slickensided surfaces. Even in highly weathered rock, it is the discontinuities that generally control the strength of the mass.

**Slope Stability Protection Measures**

**General**

Increased stability will result by eliminating or minimizing the effect of any contributing factor for sliding, particularly that of the effect of the force of gravity. Water is also a contributing factor in practically all landslides.
Figure 3: Various types of retaining walls: (a) rock: filled buttress; (b) gabion wall; (c) crib wall; (d) reinforced earth wall; (e) concrete gravity wall; (f) concrete-reinforced semi gravity wall; (g) cantilever wall; (h) counterfort wall; (i) anchored curtain
For a given land slide problem, there can be more than one method of correction and the decision is reduced to a problem of economics. For example, a retaining wall can be designed sufficiently large to withstand any given land slide. However, a wall design that will be successful may be outside a reasonable range of economics for a given landslide.

Correction measures for a landslide can be by elimination or control.

**Elimination**

The elimination method avoids or removes the land slide. The following measures can be taken when the elimination method is used:

1. **Route Relocation.** Geologic conditions often differ from one side of a valley or mountain slope to the other, even where the materials are similar. For example, on one slope dipping beds or foliations may incline downward and out of a cut slope representing an unstable condition, whereas on the opposite side of the valley or mountain the dip of the beds or foliations is into the slope providing stable conditions.

   Where colluvial soils exist they often are thickest and most unstable along the lower slope elevations and at times can be avoided by locating an alignment at higher elevations upslope. Residual soils can also be found with higher strengths and less exposure to changes in seepage conditions upslope.

2. **Removal of the land slide entirely or partially at the toe.** All the slide material should be removed, drains placed to intercept seepage and the area is backfilled with appropriate material.

3. **Bridging,** whereby the landslide area is avoided by a bridge between the two solid extremities of the moving area.

4. **Cementation of loose material.** The material to be cemented should be permeable. Cement grout is injected into the moving area in order to achieve stability. It produces a material that has higher shear resistance. In cohesive soils, vertical columns are obtained and their effect is that of a system of piles. The resisting forces are increased by transferring of load from the moving mass to the underlying stable material.

**Conclusion**

Field studies which include geological and geotechnical investigations are carried out to investigate the causes of landslide. Based on the results of these investigations and stability analysis of slopes, remedial measures have been recommended for the stabilization. Some of the conclusions and recommendations are as given here:

1. It is observed during the field investigations that there are many natural as well as manmade factors, which are mainly responsible for the stability. Rocks present in the area, which are soft, highly jointed, folded, and faulted. These rocks are highly weathered and easily erodible. Steep slopes present in the area again responsible for the instability.

2. The road network without proper design and lack of sufficient drains again is the main cause for the instability.

3. Field investigations indicate heavy inflow of surface and sub surface water from the uphill side to the landslide zone. Improvement in the drainage system with new drains and culverts has been proposed to divert the flow of water from the landslide area.
4. Field density tests and stability analysis of natural slopes of right and left portions of landslide indicated the loose condition and possibility of erosion of slopes. To stabilize the same, gabion walls have been proposed to provide the toe support and surface erosion has been controlled by laying of geogrids on the slopes.

5. Widening of project road has been proposed to be widened by a scheme of three stepped reinforced retaining walls which is provided in the central portion of landslide. Stability analysis of the slope with remedial measure indicated the factor of safety of 2.50.

6. It is also recommended that the landslide awareness program should be arranged for the local people. Therefore, people should be aware of the dos and don’ts. They should not use the slopes as dump yard for the garbage. It should be ensured that the adjoining slopes of landslide should not be used for any activities such as agriculture.

7. Once a slope was well designed geo-technically with appropriate factors of safety, it behaved that slope protection be properly implemented to ensure long-term stability especially for those high rainfall area and faced with highly-erodible soil materials. One can opt for the soft or green approach which is much less expensive, aesthetically pleasing as well as environment-friendly.

8. The proper channelization and direction of water (surface and sub-surface) flow away from the landslide area was carried out.

## Control Method

The control method produces a static condition of the landslide for a finite period of time. The following measures can be taken when the control method is used:

(i) Retaining devices such as buttresses, retaining wall of masonry stone or concrete, gabion walls and piling can be used.

Rock-filled buttresses are used when good foundation is available at toe in shallow or deep soil. Buttress should extend below the slip plane. The buttresses are constructed with non degradable, equi-dimensional rock fragments with at least 50% between 30 and 100 cm and not more than 10% passing 2 inch sieve. Gradation is important to maintain free-draining characteristics and high friction angle. Retaining walls of masonry stone or concrete are effective for shallow soil where good foundations are available. A wall requires a foundation in bedrock or good soil below the slip surface. Standard practice is to include weep holes in designing the wall. The formula for the safety factor may be used to estimate resistance required to lateral thrust.

Gabion walls are also used as retaining walls. They are wire baskets, about 50 cm each side and filled with broken stone of about 10 – 15 cm across. The baskets are then stacked in rows. They are free draining and retention is obtained from the stone weight and its interlocking. Typical heights are about 5 to 6 meters.

Rock buttresses and retaining walls can be used to correct small slides especially rotational ones, but are not generally speaking effective on large slides. Retaining devices are seldom applicable for correction of falls and flows. Retaining devices placed in the path of a flow slide receive the entire force of the moving mass because of the fact that there is little inherent resistance of the soil involved in the flow. Piling can be used in shallow soil to hold the slide mass temporarily.
For retaining rock slopes rock bolts, wire mesh and shotcreting can be used. Rock bolts can retain exfoliating slabs and other loose blocks. Wire mesh needs periodic removal of blocks. Shotcreting stabilizes local areas of highly fracture rocks. Additional retaining measures are cutting back of the rock slope, sealing fractures and installing drains.

(ii) Control of surface water (infiltration) by providing appropriate drainage and thus creating a direct rebalance of the ratio between resistance and shearing force. Generally, drainage should be designed to intercept water before it enters the slide. Water affects the stability of natural slopes by increasing pressures in the soil or rock interstices, thereby reducing strength and increasing the overburden weight, which result in increased driving force. Prevention or stabilization of slides is often simply a matter of controlling infiltration into the mass and of relieving water pressures within the mass.

(iii) Table 1 Shows the slope values for different slope materials as given below:

<table>
<thead>
<tr>
<th>Table 1: Slope Values for different Slope Materials</th>
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</thead>
<tbody>
<tr>
<td>Type of Slope Material</td>
</tr>
<tr>
<td>Rock</td>
</tr>
<tr>
<td>Hard masses of igneous or metamorphic rocks and hard sedimentary rocks with bedding dipping vertically or dipping into the face of the slope</td>
</tr>
<tr>
<td>Moderately weathered rock</td>
</tr>
<tr>
<td>Highly weathered fractured rocks covered by clayey silty sandy soil mixed with angular gravels and cobbles (based on height of slope)</td>
</tr>
<tr>
<td>Soil</td>
</tr>
<tr>
<td>Residual soils (strong) (based on height of slope)</td>
</tr>
<tr>
<td>Colluvial soils (based on height of slope)</td>
</tr>
<tr>
<td>Terrace Soil (Silt-sand-gravel mixtures with angular cobbles and boulders) (based on height of slope)</td>
</tr>
<tr>
<td>Most other soils (based on height of slope)</td>
</tr>
<tr>
<td>Clay Shales, Black cotton soils</td>
</tr>
</tbody>
</table>

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