Slope Failure Risk Mapping for Highways: Methodology and Case History

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Roadway construction along steep slopes in mountainous terrain requires numerous sidehill cuts and fills. Design provisions for stability against slope failures require the engineer to make many difficult judgments. The competency of these judgments depends on the adequacy of geotechnical investigations to define slope conditions and the interpretation of the data available. The observational method provides an approach for evaluating the stability of slopes along transportation corridors. Slope failure risk maps are prepared to present the degree of risk or consequences of slope failures along an entire roadway alignment. The degree of risk is established by evaluation of the degree of the hazard or the potential for slope failures along the roadway. It is formulated from judgments made regarding the form (rotational slides, debris avalanches, etc.) and the magnitude of the potential slope failure to be expected. These judgments are based on assessments of geologic and surface conditions, slope geometry and activity, and weather conditions. Slope treatments for areas designated as having failure risk are determined and presented on slope stabilization maps. Governments with adequate financial resources may choose to provide stabilization treatments for all levels of risk. Alternatively, governments with limited resources can establish priorities regarding necessary treatments, beginning with areas of higher risk levels. A case history is presented in which the methodology was applied for a section of mountain roadway in Brazil.

Roadway construction along steep slopes in mountainous terrain involves numerous sidehill cuts and fills requiring many difficult judgments during design. Two options may be available, depending upon the client's desires and the amount of subsurface information available:

1. Provide complete stability of all cuts and fills. This approach may be prohibitively costly, and it may be inadequate if conditions are misjudged.
2. Accept some failure risk and minimize initial construction costs. Select cut inclinations with the anticipation that some failures may occur and that roadway cleanup and maintenance will be required in the future. Design retaining structures or other stabilization methods only for areas with the potential for failures of serious consequences.

Option 2 is often selected by governments in developing countries with limited financial resources. The objective is that, at worst, failures will be a nuisance requiring periodic cleanup of small portions of the roadway. Large failures resulting in a mass of earth completely covering a stretch of roadway or even the complete loss of the roadway because of failure of a sidehill fill are to be prevented. Even if the roadway is not completely closed, rockfalls and small slides can pose a substantial danger to the public, especially when a roadway is used heavily. At the least, public annoyance will increase as the inconvenience of slope failures continues.

For either option, success depends on the adequacy of the assessment of slope conditions. Even extensive geotechnical investigations with test borings and geophysical surveys may not sufficiently define slope conditions, and in many cases explorations are minimal because of the costs and difficulties caused by terrain. Evaluations based on mathematical analyses may not provide an adequate assessment of stability. The analytical models may not accurately depict slope conditions at failure, and forms such as progressive slides, debris avalanches, and flows are not suitable for mathematical analyses.

The observational method of assessment can efficiently obtain significant information on slope conditions. The methodology requires substantial experience in applying the principles of geology, engineering geology, and geotechnical engineering to slope problems both for existing roadways suffering failures and for the design of new roadways.

RISK MAPPING: BASIS FOR SLOPE STABILITY ASSESSMENT

Slope failure risk mapping provides the basis for predicting where failures are likely to occur and for the formulation of plans for preventive and corrective treatments along an entire roadway alignment. Risk mapping covers a wide corridor extending for some distance upslope and downslope. The methodology proceeds through several phases as follows.

Phase 1

An engineering geology map is prepared as the basis for assessing slope conditions. For new roadways, information mapped includes geologic formations, slope failure scars, erosional features, and drainage pathways. For existing roadways, conditions of cuts, fills, and roadway pavement are also mapped. When slope inclinations and vegetation are plotted, the map is used for runoff evaluations and drainage analyses for culvert designs.

The map is prepared using data obtained from landform analyses, detailed field reconnaissance, and the review of available reports, boring logs, geophysical records, and so forth. For a new roadway, a preliminary map is prepared and used for planning an efficient exploration program. A final engineering geology map is prepared using the data obtained from test borings, geophysical surveys, and other explorations.

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Phase 2

A slope failure risk map is developed for the entire alignment. It depicts where slope failures have occurred or are probable, and includes a rating for each occurrence as to the degree of risk or consequences of failure along the roadway. Ratings may range through a number of levels, from no risk to very high risk. Risk levels are based on the hazard degree, which is formulated from evaluations of the potential failure form expected (fall, slump or planar slide, debris avalanche, or flow) and the failure magnitude. Potential failure forms are determined from assessments of geologic and surface conditions, slope geometry and activity, and weather history.

Phase 3

A stabilization map is prepared giving recommended slope treatments for areas designated as failure risks. Areas requiring detailed exploration and additional study are identified. The agency responsible for the roadway can then establish priorities for necessary treatments, beginning with areas of higher risk levels.

CASE STUDY: HIGHWAY BR 116, BRAZIL

Highway BR 116 connects the cities of Rio de Janeiro and Teresopolis in Brazil. In a distance of 15 km, the roadway climbs from the coastal plain at an elevation of about 100 m above sea level over steep slopes to an elevation of over 1000 m at the crest of the coastal escarpment. Since its construction in the 1950s, this stretch of roadway had suffered numerous slope failures, often resulting in closure to traffic. The failures usually occurred during the periodic heavy rainfalls common to the coastal mountains of Brazil.

During December 1978, Technosolo SA was engaged by the Departamento Nacional de Estradas and Rodagems (DNER) to perform a geotechnical overview of conditions along the 15 km where the roadway climbs the coastal escarpment. The study was performed under subcontract to Technosolo in order to

1. Determine the causes of instability of natural slopes, cuts, and fills;
2. Identify areas in which failures probably would occur in the future;
3. Recommend various treatments to improve or provide for stabilization; and
4. Establish priorities for stabilization based on the degree of the hazard and risk, thereby enabling the budgeting of treatments over time.

Physical Conditions Along BR 116

Investigation Methodology

A preliminary engineering geology map was prepared to provide the basis for field reconnaissance. Available data included national topographic maps at a scale of 1:50,000 and stereopairs of aerial photographs at a scale of 1:20,000, which were dated 1973. Enlarged to a scale of 1:10,000, the photographs provided base maps of the roadway on which cuts, fills, and retaining structures (as of 1973) were illustrated. Slide, avalanche, and erosion scars; drainage paths; and geologic data (including surface exposures of rock and soil types classified by origin) were plotted on the base maps during stereoscopic interpretation of the photographs. An aerial photograph of a portion of the higher roadway elevations is shown in Figure 1.

Field visits were made, and the significant features delineated on the preliminary map were examined, as were other pertinent conditions. Noted were new slide and erosion scars; geologic conditions exposed in cuts and slide scars, including soil and rock types; slope seepage; the inclinations of apparently stable slopes; and signs of movement, including tension cracks and tilted trees. The pavement was examined both for signs of heave along the toe areas of cut slopes and for cracks and other signs of settlement along sidehill fills. Both cases indicated probable slope movements. Final engineering geology maps were prepared incorporating the field observations. An example for part of the roadway is shown in Figure 2.

Physiography

The study began at roadway Km 104, situated in the lowlands at an elevation of approximately 100 m. After traversing hilly

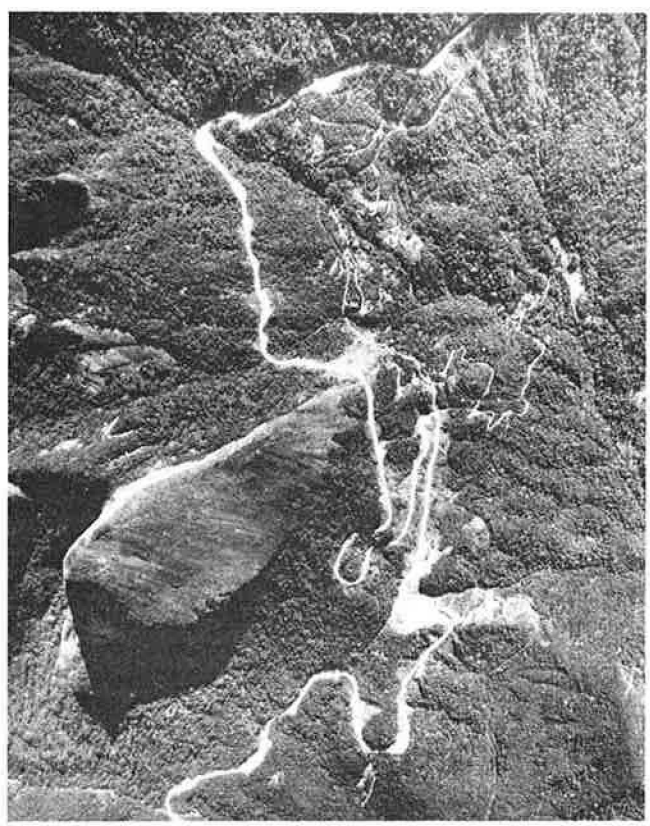

FIGURE 1 Aerial photograph, Km 91–95, BR 116 (scale: 1 cm = 200 m).

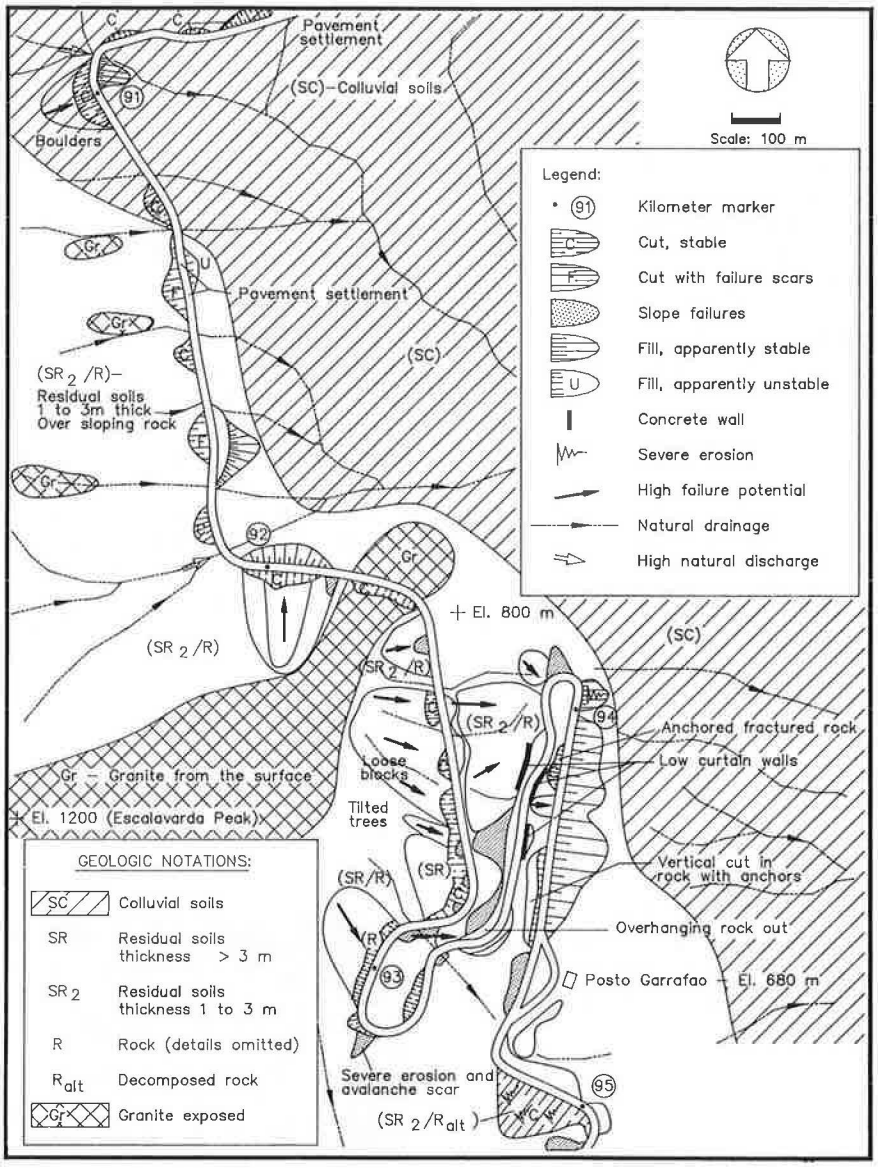

FIGURE 2 Final engineering geology map: existing conditions, cuts, fills, and geology, BR 116, January 1979.

terrain with gentle curves and shallow cuts for about 7 km, the roadway reaches the base of the escarpment formed by the Serra Dos Orgaos Mountains. From here, the land becomes steeper and more irregular, requiring the roadway to take a winding route along the side slopes of hills that rise to an elevation of 900 m or more. The roadway begins to intercept the natural drainage from the mountains and crosses a number of watercourses.

As shown in Figure 2, from Km 95, the roadway doubles back twice to climb from Elevation 680 to 800 m near the base of Escalavarda Peak. It continues on along the slopes of the escarpment to the study terminus at the summit, Elevation 1004 m (Km 89.4), where the roadway branches off to Teresopolis. Along this stretch, the side slopes of the escarpment often range from 45 to 60 degrees. Numerous cuts have been made in soil and rock, and fills were placed. Drainage from mountain runoff is intense.

Geology

For slope stability evaluations, geologic conditions were characterized by three general formations:

1. Colluvial soils (SC), the residue of slope movements, are found on the lower slopes and fill the major valleys, even at higher elevations. Consisting of boulders in a matrix of fine-grained soils, the colluvium blocks the normal slope seepage and tends to contain substantial moisture and to be unstable in cut. It can overlie residuum or bedrock, and is normally found with relatively high piezometric levels in the toe areas of the formation.

2. Residual soils (SR), formed mainly from the decomposition of metamorphic rocks, reach thicknesses of 20 m or more. The thicker deposits, usually clay-silt mixtures of stiff to very stiff consistency, are common at the lower elevations

along the roadway. The formation normally grades to saprolite, and relict joints and other discontinuities remain, representing planes of weakness. Along the higher elevations, a thin cap of residuum commonly overlies a dipping surface of fractured rock. Generally, residuum is relatively dry, with the predominant groundwater movements and seepage forces developing in the underlying fractured rock masses.

3. Bedrock consists of Precambrian igneous and metamorphic rocks. The high peaks, such as Escalavarda Peak, are composed of very resistant granite (Gr). Where exposed in cut, the granite is seen to be very hard, with tight, widely-spaced joints. The metamorphic rocks, primarily gneiss, are found with a wide range of conditions varying from highly fractured masses of intact blocks of rock to highly decomposed masses that are soft and can be dug with a geologic hammer (R_{alt}).

Recent alluvium, present in stream beds in limited deposits, is not significant in the slope stability evaluations.

Roadway Slopes

Slope failure forms usually are classified as falls, slides (rotational and planar), avalanches, and flows (*1,2*). This nomenclature was applied to the slopes along BR 116.

Planar or translational slides, involving masses of residual soils moving along a rock surface dipping downslope, are the dominant form of slope failure along the roadway. The common cause is a cut that extends into rock, exposing a face of overlying soils (see Figure 3). Failure is sudden, occurring during or immediately after heavy rains. Sufficient material is usually displaced to either partially or completely close the roadway. Additional failure will not occur if the slide reaches the crest of the hill, because it is self-corrected. The scar of a planar slide is shown in Figure 4.

Large, deep-seated rotational slides occur infrequently. The only case observed was located at Km 101, at the lower roadway elevations, involving thick colluvium overlying rock. Movement was shown by substantial pavement heave and cracking where the pavement passed over the toe of the failing mass. In most of the study area, soil cover is generally too thin for the development of deep-seated rotational slides. They are common, however, in other areas of the coastal mountains of Brazil.

FIGURE 4 Scar of planar slide that partially closed BR 116.

Debris avalanches can completely or partially close the roadway. Occurring during heavy rains, they develop along the hillsides at the higher elevations where residual soils are not thick and overlie a rock surface dipping downslope. Large quantities of runoff move masses of soil and rock fragments downslope at high velocities. Figure 5 shows the scar of a

FIGURE 5 Scar of debris avalanche that partially closed BR 116 near Km 89.

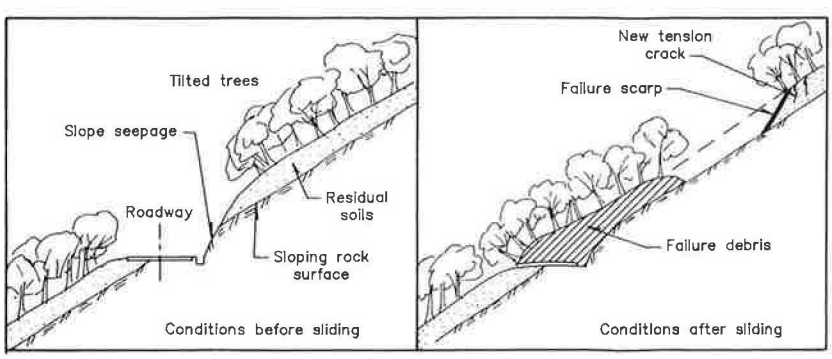

FIGURE 3 Typical planar slide occurring in residual soil cap over sloping rock surface in cuts along BR 116.

debris avalanche that occurred along the upper reaches of the roadway.

Erosion can be severe on natural slopes where the vegetation has been removed or on unprotected cut or fill surfaces. When erosion is uncontrolled, gullies form and slopes are steepened, decreasing stability.

Other forms of slope failures along BR 116 that involve smaller quantities of materials include small rotational slides in shallow colluvium, small wedge failures along relict weakness planes in residuum, and falling blocks of loose rock. In the rock masses, failure normally occurs along joints dipping downslope, and falling single blocks are common. Large failures generally occur only where a group of loose blocks in a vertical to near-vertical cut move together.

Sidehill fill stability is affected by underdrainage, surface drainage, and erosion. Apparent problems associated with sidehill fills along the roadway are the following:

1. Excessive seepage forces develop beneath fills with inadequate underdrainage. Slumping and downslope displacement occur, resulting in pavement deflection and concentric cracking. In extreme cases, complete failure occurs. Lining of drainage ditches along the roadway upslope of fills is generally inadequate to prevent runoff infiltration into embankments.
2. Poor compaction during construction results in consolidation or displacement of the fill mass and generally contributes to instability. However, where fills are constructed of relatively impervious materials, such as the local residual soils, seepage beneath the embankment is the main cause of failure.
3. Uncontrolled erosion of fills eventually removes soil from beneath the pavement, resulting in loss of support and failure along the pavement edge. Such conditions exist at several locations along the roadway.
4. Where fills are placed in stream gullies, if culverts are of inadequate capacity to provide for runoff or become clogged with debris, the fill becomes a dam. Complete roadway failure can occur as the fill slumps and fails, or if it is overtopped and washed out.

Rainfall and Runoff

Rainfall along the roadway and in the surrounding mountains is normally heavy and may reach an annual accumulation of several meters, most of which falls during the summer months of December through March (*3*). Intense storms are common, and in many areas the steep mountain slopes support little to no vegetation along the upper reaches (Figure 1). This condition permits very high quantities of runoff into the brooks that intercept the roadway at numerous locations.

Qualitative Assessment of Hazard

Failure Predictions and Slope Treatments

Slope stabilization along a roadway subjected to failures is normally approached by applying corrective treatments to stabilize existing active slides. This approach is reasonable for deep-seated rotational slides, such as that at Km 101, where movements are relatively slow and occur periodically, sidehill fills are suffering gradual displacements, or erosion is occurring. For the more common case involving the sliding of a cap of residual or colluvial soil over rock, total failure usually occurs suddenly, without much warning. Rockfalls and failure of fills over culverts during heavy rains also occur with little warning. Therefore, to avoid roadway closure in these cases, prediction and prevention of occurrence are required rather than correction.

Corrective or preventive treatment selection depends upon the degree of the failure hazard and the risk to the public should failure occur. "Hazard" refers to the potential slope failure form, magnitude, and probability of occurrence. "Risk" refers to the consequences of failure on human activities.

Rating the hazard and the risk provides the basis for establishing priorities for locations where treatment is required and for evaluating the type of treatment necessary for stabilization. The treatment selected depends on the characteristics of the hazard, that is, the form of failure that may occur and the quantity of material involved.

Qualitative assessment of slopes provides the basis for predicting the failure potential and its form at any given location and for selecting practical treatment methods.

Quantitative assessment, based on mathematical analyses, is not applicable for many forms of slope failures, particularly for most conditions existing along BR 116.

During the planning and design phases for new roadways, there are conditions of high hazard and high public risk that should be avoided, but normally, slope treatment objectives are either to reduce or eliminate the hazard by a change in slope geometry, an improvement in surface and subsurface drainage, or retention. An alternative, often selected by governments with limited financial resources, is to provide minimum treatment and permit failure. Debris is removed periodically, with the hope that, in time, the slope will reach a stable inclination. From the aspect of saving lives during intense storms, the risk can be reduced by temporary closure of the roadway.

Rating the Hazard

The hazard is rated in terms of the potential form, magnitude, and occurrence probability, and these factors influence the type of treatment feasible. Magnitude refers to the volume of material that may fail, the velocity of movement during failure, and the land area that may be affected. It depends on the failure form as related to geology, topography, and weather conditions. For example, the steeper the slope, the thinner the soil cover, and the more intense the rainfall, the greater the likelihood of a debris avalanche rather than a potentially less-destructive, small-volume planar slide. Probability is related to weather and other transient conditions such as slope inclinations (steepened by cut, erosion, or tectonic activity) and, in some areas, seismic activity. Many bases for a hazard rating system are feasible. The following is a suggested approach:

1. No hazard: A slope that is not likely to undergo failure under any foreseeable circumstances.

2. Low hazard: A slope that may undergo total failure (as compared with a partial failure involving relatively small displacements) under extremely adverse conditions that have a low probability of occurrence (such as a 500-year storm or a high-magnitude earthquake in an area of low seismicity) or whose potential failure volume and area affected are small, although the probability of occurrence is high. Potential low-hazard failure forms along BR 116 include rockfalls of single blocks and small rotational or planar slides.

3. Moderate hazard: A slope that will probably fail under severe conditions expected in the future and that involve a relatively large volume of material. Movement will be relatively slow, and the area affected will include the failure zone and a limited zone downslope (moderate displacement), which are characteristic of rotational slide forms similar to the case at Km 101.

4. High Hazard: A slope that is almost certain to undergo total failure in the near future under normal adverse weather and will involve a large to very large volume of material or a slope that may fail under severe conditions (moderate probability) but whose potential volume and area affected are very large and the movement velocity is very high. Characteristic failure forms include planar slides in layered rock masses, debris slides and avalanches, and some forms of flows. Debris slides and avalanches are characteristic of many of the failures along BR 116.

Rating the Risk

A general rating of risk levels may include the following:

1. No risk: Slope failure that will not affect human activities.

2. Low risk: An inconvenience that is easily corrected and does not directly endanger lives or property, such as a single small block of rock falling onto the roadway that is easily avoided and removed.

3. Moderate risk: A more severe inconvenience that is corrected with some effort but usually does not directly endanger lives or structures when it occurs, such as a small debris slide entering one lane of a roadway causing partial closure for a brief period until it is removed.

4. High risk: Complete loss of a roadway or important structure, or complete closure of a roadway for an extended time, that does not necessarily endanger lives by failure.

5. Very high risk: Failure that endangers lives, such as the destruction of inhabited structures or the destruction of the roadway when time is not available to warn traffic.

Assessment Factors

General

Qualitative assessment of the hazard is made from evaluations of geologic conditions, slope geometry, surface conditions, slope activity, and rainfall. The entire stretch of roadway subjected to slope failures is examined, with the objectives of formulating judgments of where failures are to be anticipated, the nature of the hazard, and the degree of the risk. Stabilization treatments that are selected are based on these judgments.

Geologic Conditions

Geologic conditions with a high failure incidence along BR 116 are summarized as follows:

1. Jointed rock masses in steep cuts can result in falls varying from a single block to many blocks of varying sizes.

2. Residual soils on moderate-to-steep slopes may fail progressively where they are relatively thick, usually involving small-to-moderate volumes in rotational slide forms. Where they overlie a downslope-dipping rock surface at shallow depths, large planar slides can occur or, under heavy rainfall, even debris avalanches or flows.

3. Colluvium is generally unstable on any slope in a wet climate, and when cut, it can fail in large volumes, usually in rotational form with progressive slumps.

Slope Geometry

The significant aspects of slope geometry are inclination, form, and height. Soil slopes often rest naturally at a safety factor near unity. When cuts are made along BR 116 where natural inclinations are greater than 30 to 40 degrees, the stability decreases substantially, especially where cuts intercept the contact between the rock surface and the underlying soils. In fractured rock masses where joint conditions are unfavorable, steeply inclined cuts are potentially unstable.

Topographic expression has a strong influence on location of slope failures, because landform provides the natural control over rainfall infiltration and seepage where other factors are constant. Failures are much more likely to occur in swales extending downslope, where runoff and seepage will be relatively high, than on promontories, or "nose-forms," where runoff is directed away from the area. Along BR 116, the highest incidence of failures is along the sides of swales. Where the slope is steep and soil cover is thin, the potential for debris avalanches is high.

Slope height above a cut influences the amount of runoff intercepted. A long slope reaching substantial heights will carry much more runoff than will a cut made a short distance from the crest of a hill. In addition, an area containing a large number of drainage paths upslope of the roadway has a greater susceptibility to failure than does an area with few if any drainage paths.

Surface Conditions

Slope seepage observations during reconnaissance are evaluated by considering the weather conditions prevailing during the weeks preceding the visit, the season of the year, and the regional climatic history. No slope seepage during a rainy period may be considered very favorable, assuming that colluvium or fills are not causing blockage, whereas seepage during a dry period signifies that a substantial increase will occur during wet periods and failures are likely. Toe seepage

in particular indicates a potentially dangerous condition, especially during dry periods.

Vegetation density is an important stability factor. Cut slopes where upslope vegetation has been cleared are much more likely to fail during severe weather conditions than if vegetation remains undisturbed. Removal of vegetation permits erosion to increase, reduction in the shallow portions of the slope from loss of root structure, increased infiltration during rainy periods, as well as an increase in evaporation during dry spells. The latter condition results in surface desiccation and cracking, and provides entrances for runoff into a potential slide area. These factors pertain also to unprotected cut and fill slopes.

Vegetation type may be an indicator of areas with a relatively high failure potential. It appears that in tropical climates, banana plants favor less stable colluvium over the stronger residuum, probably because of the higher moisture content of the colluvium.

Indicators of slope movements and existing instability include tilted or bending tree trunks and tilted poles and fenceposts, tension cracks along the slope and behind the crest, slump and hummocky topography, and failure scars. Straight but tilted tree trunks indicate recent slope movements, whereas trunks curving near the bottom and then growing vertically indicate old and progressive movement. Tension cracks are a well-known failure indicator, but for many of the forms along BR 116, such as the planar slides and debris avalanches that occur suddenly during heavy rains, tension cracks may develop only immediately preceding failure.

Slope Activity

Slopes are characterized by various levels of activity, ranging through the following stages:

- Stage 1 is a stable slope with no apparent movement.
- Stage 2 is the early failure stage, in which shallow slumping, creeping, and formation of tension cracks associated with small movements have occurred.
- Stage 3 is the intermediate failure stage. Significant movement has occurred. Progressive slumps and scarps have formed during rotational slides, blocks have separated during planar slides, and tension cracks have grown in width and depth. Movement velocities may have been in the range of about 2 to 5 cm/day, accelerating during rainy seasons and storms and decelerating during dry periods.
- Stage 4 is partial failure of the slope, with the total movement of a major block or portion of its volume to its final location.
- Stage 5 is the final failure stage. The slope has failed completely, with a final total movement having occurred characteristically during the wet season and after heavy rains.

For predicting slope failures, Stages 2 through 4 are primarily significant because they indicate that the slope is residing at a factor of safety near unity. Slopes can remain stable in these conditions for many years and then fail completely (Stage 5) as the result of either unusually heavy rains with a high level of ground saturation, the long-term decrease in material strength caused by weathering processes, or an unfavorable change in slope geometry.

Where slopes are undergoing progressive movements (such as occur in deep-seated rotational slides or large planar slides in rock masses where complete failure has not occurred), movement velocity and acceleration are important assessment factors. Such sliding masses require monitoring with instrumentation. In Brazil, experience generally shows that if velocities are relatively high—on the order of 2 to 5 cm/day and accelerating during the rainy season—complete failure can be expected in the near future.

Sidehill fill activity assessment is based on the occurrence of pavement settlements and cracking, bulging at the embankment toe, and movement velocities. Slopes where movements are judged to be excessive should be monitored.

Rainfall

Ground saturation and rainfall are major factors in slope failures and affect their incidence, form, and magnitude. Several aspects are important in slope stability assessment for a given location:

1. Climatic cycles over a period of years (whether the current cycle is one of high or low annual average precipitation);
2. Rainfall accumulation in the current year as compared with normal precipitation (i.e., higher, lower, normal);
3. The current season (wet or dry); and
4. Storm intensities (in centimeters per hour).

Evaluations of rainfall records have two important applications:

1. A basis for judging the future stability of cut slopes that have remained stable for some time interval under a particular weather history, and
2. Establishment of the criteria for early warning of impending slope failures.

An early warning system based on "danger charts" has been suggested by Guidicini and Iwasa (*4*). Such a system has been used to forecast slope failures and even to temporarily close roadways to traffic in Brazil. In the evaluation of the potential stability of an existing cut slope and the development of early warning systems, it is necessary to use records that cover as long a time interval as possible, because weather is cyclic. To judge that a particular cut slope is stable because it has remained so for a long time, its weather history and the possible weather conditions that could occur must be considered. The occurrence of the severest long-term historical conditions represents the true test of a slope's stability.

Slope Failure Risk Map

The slopes along the roadway were evaluated on the basis of the assessment factors, and judgments were made regarding the hazard degree and the failure risk. Slope failure risk maps were prepared for five levels of risk incorporating the hazard

rating; an example of one section of roadway is shown in Figure 6. The levels of risk were defined as follows:

1. Very High Risk: High slopes where relatively large failures will close the roadway are considered Level 1. Natural drainage permits substantial water to enter the area, and failures have already occurred. Conditions include steeply inclined cut or uncut slopes, generally greater than 30 degrees, with a layer of SR or SC over a rock surface inclined downslope or SC intercepted in the cut; fills subjected to severe erosion with danger of pavement undercutting causing loss of support; and culverts beneath fills in locations with potentially very high runoff.

2. High Risk: Relatively large failure probably will close the roadway. Conditions are similar to those for very high risk except that the slope is generally less steeply inclined and natural drainage is more favorable. The risk is judged to be only somewhat less than that in Level 1, and in many cases it is difficult to differentiate between these two levels. Failures have not necessarily occurred in areas assigned Level 2. Fills have consolidated or displaced, or both, causing pavement settlement and cracking.

3. Moderate Risk: Slope heights are moderate. Failures are likely to be small in volume and not likely to close the roadway or severely affect its performance. Conditions include shallow cuts in steep slopes of SR or moderate slopes with SC, very steep cuts in fractured rock with a risk of falling blocks, slopes and fills with erosion, and areas with a layer of soil overlying rock that has already been subjected to sliding, which removed most of the overburden.

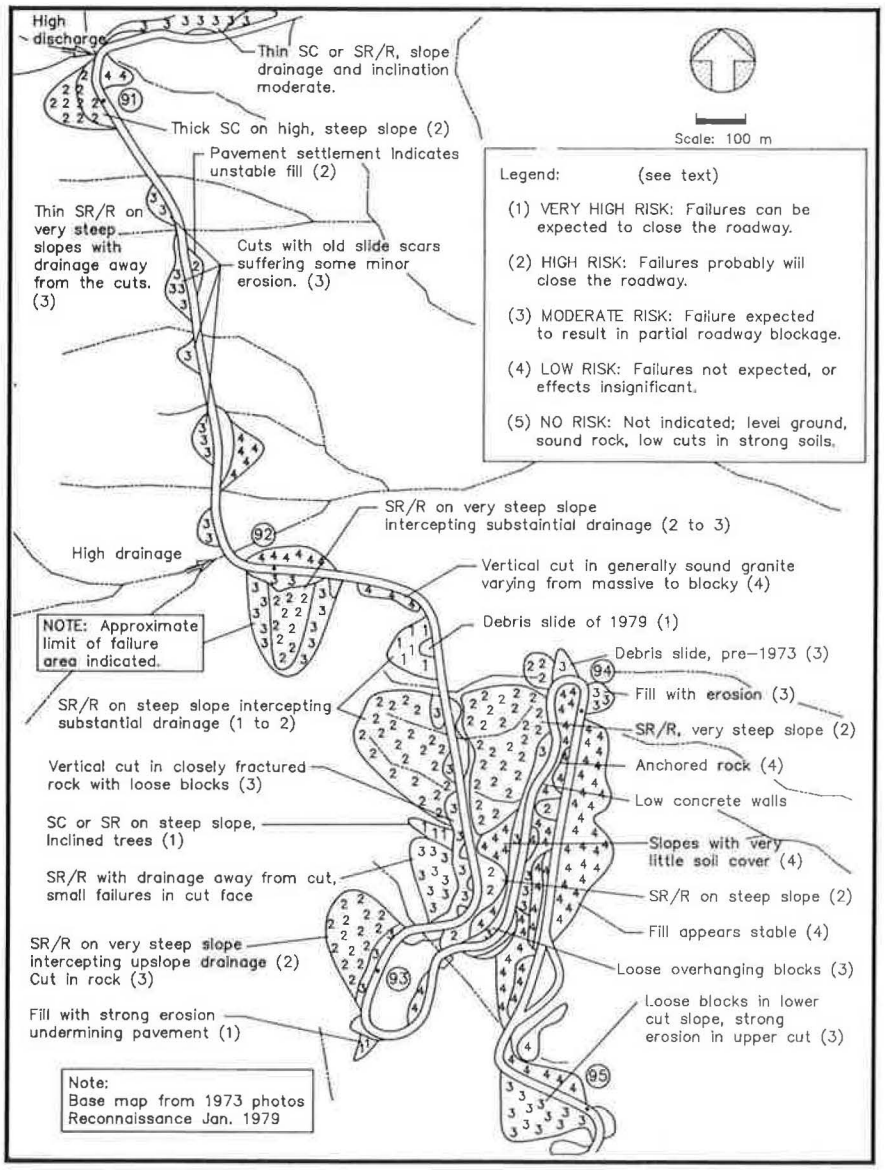

FIGURE 6 Slope failure risk map, BR 116, Km 91–95.

4. Low Risk: Slope failures are unlikely. Conditions include shallow cuts in strong soils or rock and areas in which failures have removed the overburden. Some minor erosion may occur on cut slopes. Fills appear stable and not subject to erosion or consolidation.

5. No Risk: Level ground, no cuts, or shallow cuts in very strong soils or massive hard rock present no risk.

Slope Stabilization Along BR 116

General

The risk maps provided the basis for recommending slope treatments. To establish budget priorities, immediate treatments were recommended for areas with high or very high risk, since these conditions were expected to close the roadway to traffic. High priorities were given also to unstable rock cuts and erosional features, but the large rotational slide at Km 101 was assigned a lower priority. A section of roadway with suggested treatments is shown in Figure 7. Stabilization work should be performed during the dry season, beginning in April or May.

Soil Slopes

For the dominant case of a soil cap over a rock surface, retention with an anchored curtain wall (*5*) was recommended. For other soil slopes, recommended treatments

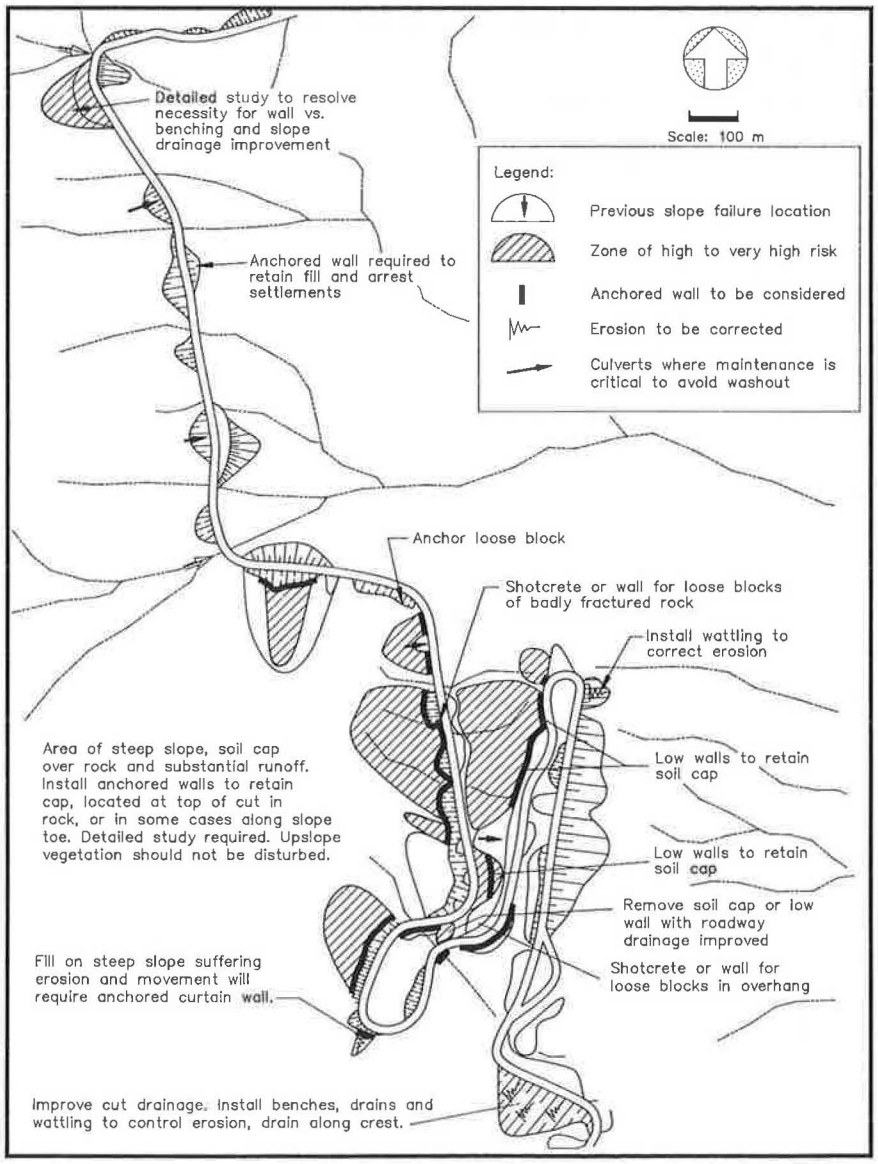

FIGURE 7 Preliminary consideration of slope stabilization schemes for high-risk areas along BR 116, Km 91–95.

included improvements of surface drainage within the cut area and erosion protection, or regrading and the installation of subhorizontal drains.

Improvements to upslope drainage were not recommended since installations would be difficult and costly on the steeply inclined and heavily vegetated slopes and the necessity of removing vegetation would decrease stability.

Rock Cuts

It was recommended that large masses of small blocks (fractured to crushed zones) in vertical cuts be reinforced by shotcreting or retained by lightly anchored walls. In either case, rock drainage must be maintained. Individual blocks judged to be free and unstable should be removed by scaling or reinforced with bolts or anchors. A group of large, unstable blocks will require anchored concrete straps or wire mesh and shotcrete. Blasting for any purpose should be strictly controlled to avoid reducing rock quality.

Sidehill Fills

Stability of sidehill fills is more critical than most cuts, since a complete failure would result in the loss of the roadway, necessitating reconstruction. Recommendations for correction of erosion included regrading the fill slope and planting heavy vegetation, and improving roadway and slope drainage. In severe cases where the sidehill fill was in danger of failing, retention with an anchored curtain wall was recommended.

Culverts

Recommendations emphasized the importance of careful maintenance of culverts and other drainage systems to prevent failures.

CONCLUSIONS

Qualitative Assessment of Slopes

By application of the techniques of landform analyses, geologic conditions along a stretch of roadway subjected to slope failures can be determined efficiently. Conditions are assessed and judgments made to identify areas with various risk levels of future instability. Recommended stabilization treatments depend on the risk level and the predicted nature of the potential failure. As an interim solution to completion of a stabilization program, early warning systems and roadway closure provide some temporary public protection, although they are an inconvenience.

Study Limitations

The evaluations of the failure risks and the determination of solutions along BR 116 were based entirely on interpretations of stereo-pairs of aerial photographs and field reconnaissance. In some areas of potentially high risk, additional detailed geotechnical studies with explorations were recommended to accurately establish geologic sections for detailed evaluations.

Postscript

In the years following the study, as budgets permitted, DNER began to install the recommended stabilization treatments. During December 1981, over 28 cm of rain fell during a 2-week period, most of it in storms of 1 or 2 days' duration. Many slope failures occurred causing loss of roadway sections, and the roadway was closed for about 2 weeks. A major failure near Km 92 resulted in a number of deaths when a bus was pushed from the roadway into a deep ravine. The location had been mapped as having a high risk. In 1982 DNER began to close mountain roadways to traffic when pluviameter measurements of rainfall reached 10 cc in 15 min (about 10 cm/hr).

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Publication of this paper sponsored by Committee on Soils and Rock Instrumentation.