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# Rock and Debris Slide Risk Maps Applied to Low-Volume Roads in Nepal

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**A discussion is provided of rock and debris slide risk mapping along low-volume road corridors in the foothills of Nepal. First, the results of a data compilation of the main factors leading to the failure of rocky and semi-rocky terrains are described. This research was conducted in Nepal on over 100 rock and debris slides. These data were developed into a rock and debris slide risk mapping method that was experimented with success along 300 km of road corridor sections in Nepal. The method is based on a superimposition of the geological, morphostructural, and slope maps of the road corridor in association with "weights" in percent to the most relevant factors leading to failure. The initial results are of a computerized risk mapping system that was applied to low-volume roads in mountainous developing countries. Because the initial data compilation revealed the structural factor to be a very crucial one, a test of a computerized structural risk map was operated on an already mapped road project section. This test was found to be consistent with the original risk map and revealed, with more accurate limits, similar locations of the risk areas in which slides actually occurred as predicted. Other advantages of the computer map are the systematic aspect of the process and the simulation flexibility of the unique parameters according to the observed field data and the local imposed conditions.**

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A synthesis is presented of geological research concerning techniques for mapping the risks of rock and debris slides along low-volume road corridors in Nepal, and hydrological work in which digitalized elevations were combined with hydric data to yield hydrological balance maps (*1-6*). The goal is to create a computerized system for landslide risk mapping that is geared especially to low-volume roads and other alignments in mountainous developing countries. This work was commissioned by the Swiss National Fund for Scientific Research.

It is well known that careless construction of low-volume roads in mountainous developing countries causes heavy environmental damage and high maintenance costs. This presents constant challenges to the efficiency and liability of the projects themselves. For example, 5 percent of the total surface of landslides in Nepal is created by road construction (*7, 8*). The roads themselves cover a surface of about 15 km$^2$ in the Nepalese foothills, whereas the area sensitive to landslides is about 60,000 km$^2$. In Nepal, the construction of roads therefore creates conditions 200 times more likely to cause land movement than the average of other human activities and the natural tendency of the terrains to slide. The goal of the present work is to contribute to the alleviation of this worrying situation. It is hoped that by implementing a reliable method of accurately identifying alternate, safe alignments and pointing out sections in which specified techniques should be applied for construction and maintenance, significant progress will be made in this direction.

## RESULTS OF THE FIELD-OBSERVED DATA COMPILATION IN THE FOOTHILLS OF NEPAL

The data compilation is concentrated on rock and debris slides of the translational type, which is the dominant form of land movement on slopes and within stream channels in the steep Nepalese foothills. The relatively sparse rotational type of slide is absent from this compilation.

A translational slide consists of a mass that progresses out or down and along a more or less planar, or wedge-shaped, surface. The slide material is either greatly deformed or consists of many semi-independent units. In Nepal, the material that constitutes these slides is usually topsoil mixed with fragments of bedrock that vary in size from gravel to large blocks. In fact, the slide material typically originates in the bedrock, but has been strongly altered by subtropical climatic conditions to the point that, in the upper layer, it constitutes a soil, properly speaking. The majority of these slides can be qualified as debris slides, or sometimes as rock slides.

### Factors That Lead to Debris or Rock Slides: Collection of Data

According to field experience and knowledge of the subject, the following are the most relevant factors of the considered site:

- Relationship between the rock structure and the slope;
- Type of rock;
- State of weathering and crushing of the rock;
- Presence of faults, thrust faults, and folds;
- Hydrology and hydrogeology; and
- Morphology.

This collection of field data was conducted along sections of the Lamosangu-Jiri, Arniko, Muglin-Narajanghat, Raj Path, Prithvi-Rajmarga, and Siddharta road corridors; various rivers; and within various zones of Nepal (Figure 1).

#### *The Structural Pattern of the Bedrock*

The structural pattern of the bedrock is determined by the relation between the different geologic planes or beds within or adjacent to them. The stability of a rocky or sub-rocky slope or cut-slope depends greatly on the relation between the rock pattern and the plane of the slope itself.

An upper equatorial Schmidt projection of the bedrock structure was drawn for each slide. This projection allows the realization of a geotechnical model that enables one to easily determine whether freedom toward a free surface is possible, and, if necessary, to calculate the resulting failure and strength relation.

Freedom of movement on a geologic plane or on two intersecting geologic planes may occur when the plane or the intersection dips in a direction close to the slope of the site, but is less inclined than the slope itself. As stability assessments are made along further cut or eroded slopes, one should consider that freedom of movement also occurs when a geologic plane, or an intersection of two geologic planes, is parallel to the slope of the site. When a geologic plane is parallel to the slope of the site, the latter is called a structural slope. The intersecting geologic planes with freedom of movement result in a so-called wedge pattern (Figure 2). In subsequent angle references in the text, grads are used as angle units (100 grads equal 90°), because their use is more convenient in field practice and structure plotting.

When a wedge shows an intersection parallel or close to the direction of the slope (up to 35 grads on each side of the direction of the slope), it is defined as a central wedge. From 35 to 70 grads, it is defined as a lateral wedge. Beyond this value it is described as a very lateral wedge (Figure 3).

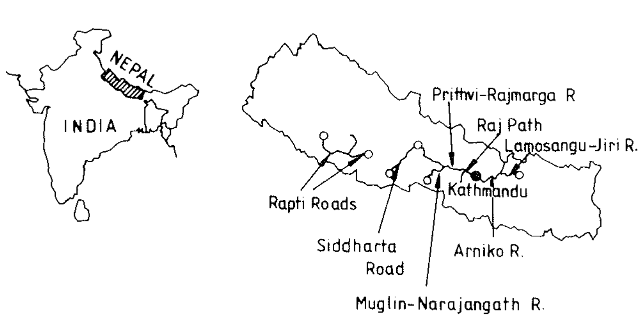



FIGURE 1 Location map.

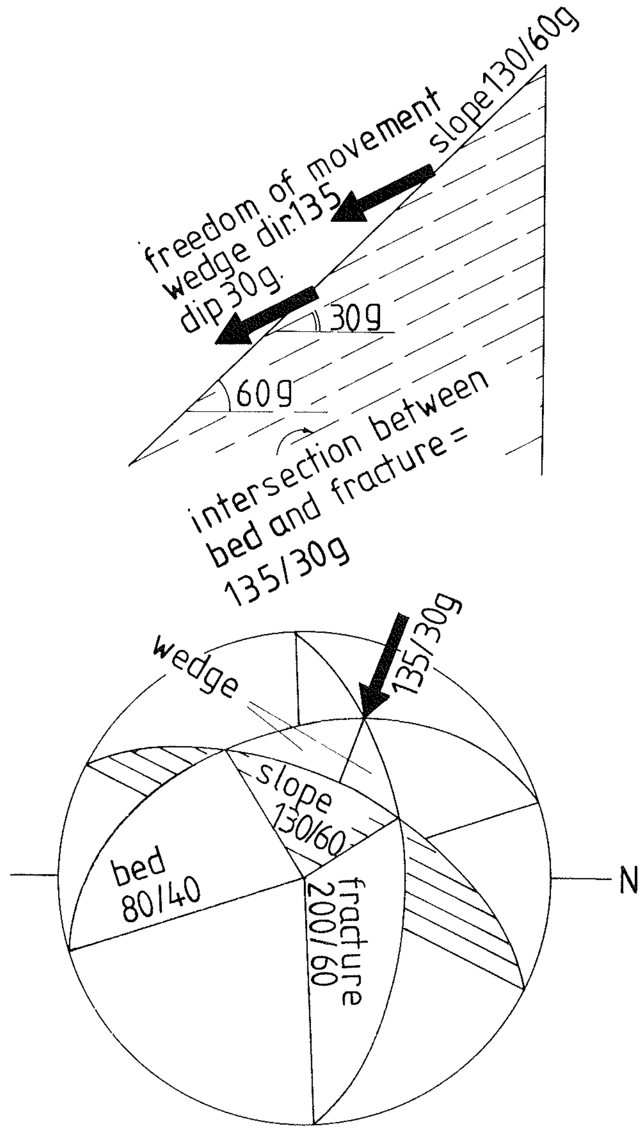



FIGURE 2 Central wedge and freedom of movement. The arrow represents the direction and dip of the structural wedge. The slope, indicated by S = 130/60, is nonstructural.

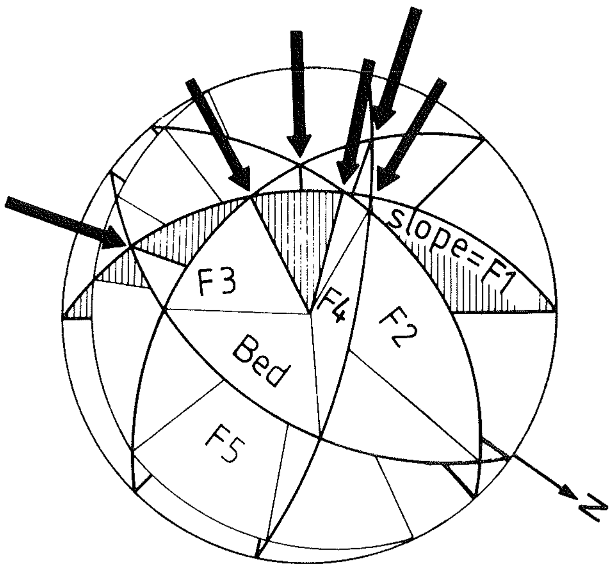



**FIGURE 3 Central, lateral, and very lateral wedges. The arrows represent structural wedges. The slope indicated by S = F1 is controlled by fracture F1 and is therefore structural.**

*Other Factors*

- The incline and direction of the slope are either a) the estimated angles before the slide occurred, or b) angles measured close to the slide within the undisturbed area.
- The density of geologic planes: high, medium, and low. This is an estimation of the number of layers, fractures, or other type of joint, per meter of a rock encountered when crossing a line perpendicular to each geologic plane.
- The type of rock and its state of weathering: highly weathered, fairly weathered, or sound.
- Presence of specific minerals subject to weathering (pyrite and chlorite) or increasing the risk of slide (sericite, micas, and graphite).
- The occurrence of seepages or springs within or adjacent to the slide. The proximity of seasonal or perennial gullies, rivulets, or rivers.
- The presence of faults or thrust faults within or near the slide areas.
- The morphology of the site: concave (coomb and depression) or convex (crest and ridge).
- The size of the slide and a description of its material and slide surface.

## Results of the Field-Observed Data Compilation

*The Structural Pattern*

Particular care was given to the study of the structural pattern. As was stated earlier, experience has shown how important the relation between structure and a natural or cut slope is to stability.

The first working hypothesis was simple. A landslide occurring on a slope with only one central wedge (CW), for instance, a wedge approximately parallel to the direction of the slope and less inclined than the slope (or in a borderline case, equal to the slope), will create two new lateral slopes. But this slide will not create the preconditions necessary for slides to occur on the newly created slopes (Figure 4). A wedge pattern must first exist on the new slopes, after which lateral slides can take place. This cycle could repeat itself several times, provided that wedge patterns exist for each case (Figure 5). Whenever the structural projection of the rock in a site indicates the presence of a fan of wedges, the potential occurrence of a large slide is indicated.

The working hypothesis was confirmed by the compilation of field data in which the results showed that the surface area of a slide tends to increase with the number of wedges (see Figure 6). In fact, the following characteristics can be recapitulated:

- All of the rock slides resulting from the presence of a single wedge had surface areas smaller than 0.25 hectare.
- With 2 to 3 wedges, 70 percent of the slides remained inferior to 0.25 hectare.

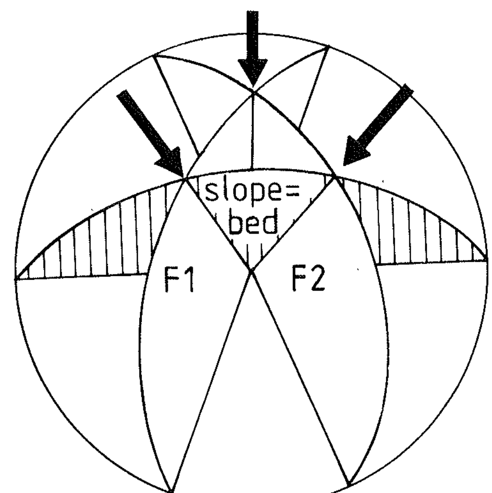



**FIGURE 4 A central wedge acts as a keystone and frees the movement of lateral wedges. The arrows represent structural wedges. The slope S = Bed is controlled by the bed of the rock and is therefore structural.**

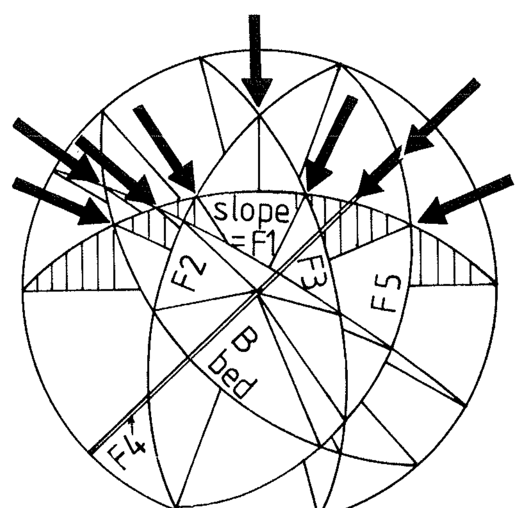



**FIGURE 5 Fan of wedges. The slope S = F1 is controlled by fracture F1 and is therefore structural. The numerous structural wedges, represented by arrows, indicate a potential large rock or debris slide.**

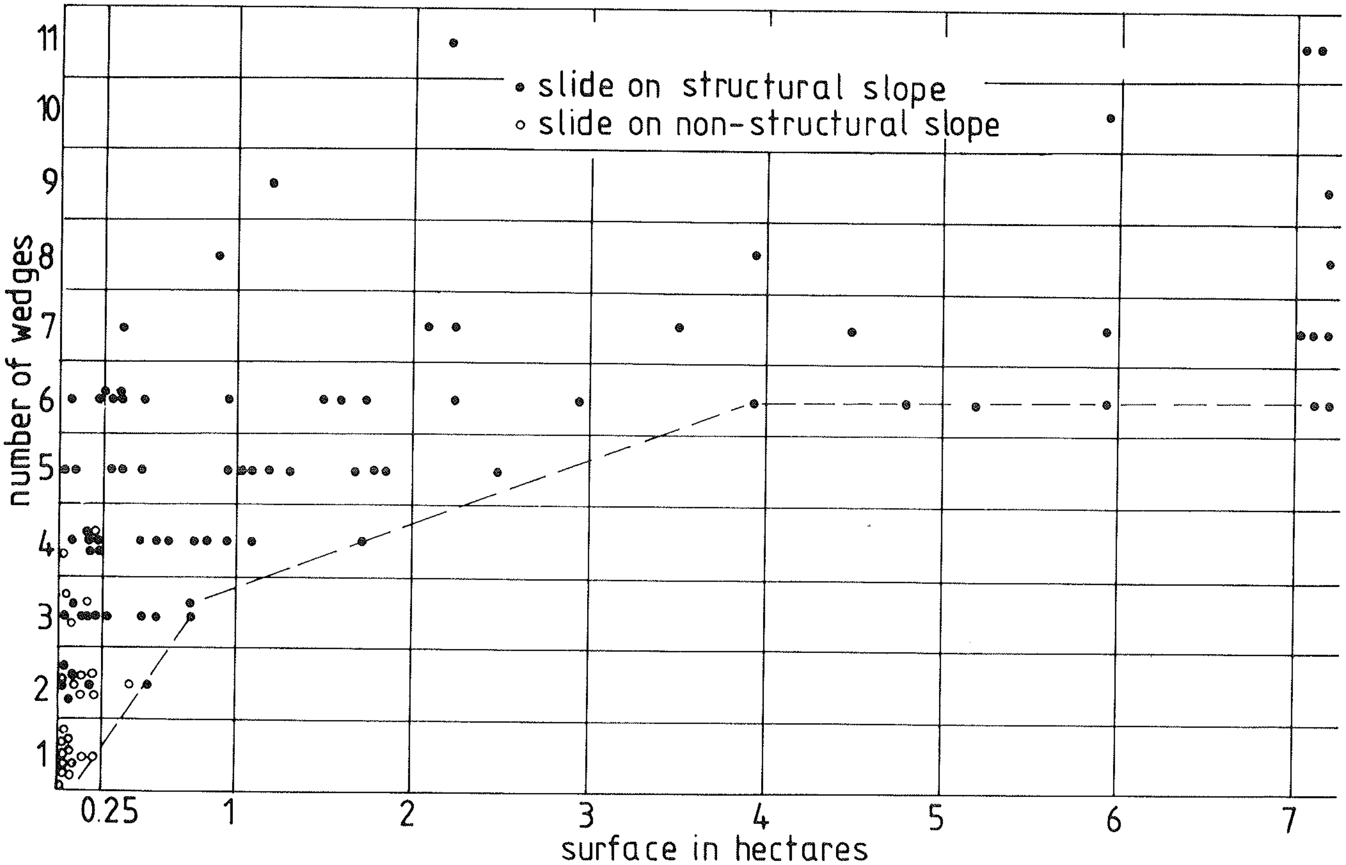



FIGURE 6 Number of structural wedges by surface of rock and debris slides.

- With 4 to 5 wedges, about 70 percent of the slides exceeded 0.25 hectare, provided a structural slope was present.
- With 6 to 7 wedges, 96 percent of the slides exceeded 0.25 hectare, 70 percent exceeded 1.0 hectare, and 42 percent had surface areas greater than 3.0 hectares.

Another working hypothesis was that the surface areas of slides tend to increase with the presence of a structural slope. The statistics fully confirmed this hypothesis, as follows (also see Figure 6):

- The surface area of slides is never very large on non-structural slopes. Fully 75 percent of the slides had surface areas less than 1600 $m^2$, whereas none exceeded 45 ha (one hectare equals 10 000 $m^2$).
- On structural slopes, about 65 percent of the slides exceeded 0.25 ha in surface area. It is shown in Figure 6 that the surface areas of slides on structural slopes clearly tend to increase as the number of wedges increases.
- The statistics also demonstrate that fracture planes are as prone as bedding planes to create slides. In fact, 67 percent of the slides presenting a planar structural component occurred on fracture planes.

*Incline of Slope*

Seventy-seven percent of the slides occurred on slopes with an incline ranging from 40 to 60 grads, whereas only 7 percent took place on slopes with an incline ranging between 35 and 40 grads. Rocks are frequently not present below 30 to 35 grads; the slopes are usually covered with an eluvial or colluvial mantel of varying thickness.

*Density of Geologic Planes*

The density of geologic planes is difficult to estimate. The assignment of numerical values for density becomes even more complex for cases in which several planes exist. Reliable estimations can be made, however, by taking into account the continuity of each of these planes through the space and density of each.

One should also take into account the interval between two geologic planes of the same type. Experience showed that intervals (i.e., density of a fracturation) vary considerably within a given area. Moreover, the study reveals that large slides often take place in areas of moderate density. As a variable for predicting the potential risks of landslides, the density of geologic planes proved insignificant and was therefore abandoned.

The method should nevertheless be used for estimating the stability of given spots that are restricted to areas of limited size. In these cases, the coating and filling between fractures and the quality of their surfaces must also be considered.

*Type of Rock and Its State of Weathering*

Weathering, which is a principal cause of slides, depends mainly on the lithological nature of the mother-rock. Theoretically, the type of rocks least subject to weathering are those constituted by hard minerals that are nonreactive to acids, such as quartzite. Marl, calcschist, and alternating layers of rock of a clay origin mixed with carbonate rock are among those most prone to weathering.

When slide surface area was compared with the type of rock, a statistical analysis along roads of the Kathmandu syncline over sections totaling 110 km allowed the compilation of a lithological coefficient for the potential to slide (see Table 1). Experience showed that the coefficient should have been somewhat lower when the structural slope was created by a fracture system through schists or clay and marly rocks interbedded with hard rocks like quartzite, dolomite quartzite, and gneiss.

### *Minerals*

The lithological coefficient for potential to slide can be increased or decreased according to the presence or absence of minerals subject to weathering. In general, the coefficient should be increased when pyrite, sericite, and graphite are present. The weathering of pyrite, in which sulfuric acid is given off, can considerably weaken rocks, even quartzite. Sericite, graphite, and, in some instances, micas, when oriented according to the slide plane, increase the slippage of rock. Carbonaceous matter, which often contains pyrite, is able to increase the weathering of rock for the reason just mentioned. Chlorite acts through oxidation to also weaken the rock.

### *Water, Springs, and Seepages*

The presence of water, in the form of rivulets adjacent to weathered rock, or springs and seepages within weathered rock, obviously increases the potential occurrence of a slide. The quantifiable role played by water is nevertheless difficult to analyze because springs and seepages are often intermittent as opposed to perennial, and therefore may not be visible at the time of the surveys. Consequently, only 35 percent of the landslides surveyed appeared to be directly connected with rivulets, springs, and seepages, whereas 17 percent appeared indirectly connected.

### *Faults and Thrust Faults*

The presence of faults or thrust faults within or adjacent to a critical area has a significant influence on rock and soil stability, although it is difficult to quantify. In Nepal, the areas adjacent to vertical faults were often found to be connected to slide areas of the translational and rotational type because of their chronic, activity-producing earthquake seismicity. They were also found to induce deep weathering of the rocks. Thrust faults in Nepal, which generally are older and less active than vertical faults, were found to often induce strong gully erosion within the crushed rock of the over-thrusted limb.

### *Morphology of the Site*

The shape of the slope was found to be significant for assessing the influence of water. Because they act as natural collectors, concave slopes were found to be far more subject to slope failure (about 60 percent) than planar slopes. Very few convex slopes appeared to be subject to translational slides.

## LANDSLIDE RISK MAPS

The results outlined earlier enable a quick but relevant assessment of the stability of any rocky or sub-rocky site to be assembled. The assessment system was subsequently standardized and systematically used for a trail bridge survey by the Suspension Bridge Division of Nepal. Slide risk mapping techniques were concurrently utilized along two sections of roads (Prithvi Rajmarga and Muglin-Narajanghat) in Nepal (*1*, *2*). They were then introduced for stability assessments of a

TABLE 1 TENTATIVE LITHOLOGICAL COEFFICIENTS FOR THE POTENTIAL TO SLIDE IN THE KATHMANDU SYNCLINE

| TENTATIVE LITHOLOGICAL COEFFICIENT FOR THE POTENTIAL TO SLIDE (KATHMANDU SYNCLINE) | | |
|---|---|---|
| | Rocks | Coefficients |
| 1) | Slates, phyllites and schists | 10 |
| 2) | Slates, phyllites and schists closely interbedded resp. with metasandstones, quartzite and gneiss* | 10 |
| 3) | Slates, phyllites and schists closely interbedded with calc-slate, calcschists, thin layers of limestone, dolomite and dolomitic quartzite* | 13 |
| 4) | Quartzite | 1 |
| 5) | Massive gneiss | 1,5 |
| 6) | Massive limestone, dolomite | 1 |

section of the Lamosangu-Jiri Road in central Nepal, and ultimately along a 230-km corridor of the Rapti roads project.

The system of slide risk mapping is based on a combination of three basic maps: a slope map, a geological map, and a morphostructural map. The superimposition of these three maps yields a landslide risk map. The landslide risk map is completed by notes on specific and questionable areas of the proposed road alignment.

The final goal of these documents and the accompanying report is to give the civil engineers documents and recommendations to enable them to undertake the correct steps to stabilize existing failures, avoid incorrect design in risky areas, and select optimal alignments for roads and other constructions. The risk mapping technique is further illustrated on a map of a section of the Lamosangu-Jiri Road corridor from km 101 to km 103 (see Figure 7).

## The Geological Map

The geological map in Figure 7 depicts the nature of the various rocks according to their lithological potential to slide. The dip of each rock is indicated as is its state of weathering or crushing. Tectonic features such as faults, thrust faults, and folds are also depicted. These are carefully surveyed in the field and are supplemented by aerial photographs. Morphological features, including eroded streams and gullies, other eroded or sliding areas, scarps, cliffs, terraces, and landslides close to or within the corridor, are mapped from the field and by a survey of aerial photographs. The location and behavior of springs and seepages are surveyed with particular care to enable general hydrogeological characteristics to be recorded whenever possible. Soils are also represented and are divided into three categories: colluvial, eluvial, and alluvial.

## The Slope Map

The slope map, which is expressed in grads (see Figure 7), is derived directly from the topographical map by counting the number of intervals between contour lines contained in a standard unit, the size of which depends on the scale of the topographical map and its accuracy. For inaccurate topographical maps, a systematic measurement of the upward and downward side-slopes of the alignment permits the results to be adjusted to some extent.

Shown in the slope map are preliminary views of potential instabilities in the area because rock and debris slides preferentially occur on predilected inclines ranging from 35 to 55 grads. The map is also used to superimpose slope values on structural projections for given structural areas of the morphostructural map.

## The Morphostructural Map

The morphostructural map (see Figure 7) shows the division of the road corridor into slope units. The directions of the slopes are indicated. Broader units, called structural areas, are also outlined.

Experience revealed that it was possible to divide the rocky and sub-rocky terrains into structural areas in which the rock contained similar structural patterns. The structural areas were delimited by overlaying the results of a regular interval field sampling of rock structures onto Schmidt pole nets. The pole nets allowed the design of the representative structural projections of the various structural areas (Figure 8).

As these statistics demonstrate, a systematic measurement of the rock's planar discontinuities (i.e., bedding and fractures) is essential to assess the stability of rocky and sub-rocky slopes. The structural pattern of the rock determines the structural risk, which is a highly important factor for predicting potential rock slides and most debris slides.

Slope units were distinguished from so-called structural slope units, which are potentially controlled by a bedding or a fracture along which a broad planar failure can be set in motion.

The superimposition of the structural system of a given structural area onto the slope map allows structural slopes to be distinguished from nonstrucural slopes. If the natural slope is equal to or steeper than a planar discontinuity (i.e., bedding or fracture given by the Schmidt projection) and dipping in the same direction, the slope is structural. The mean structural projection of the structural area also gives the wedge's direction and the wedge dips. Finally, this superimposition enables the so-called structural risks for plane and wedge failure to be assigned probabilities from the statistical study.

## Rock and Debris Slides Risk Maps

The risk for these types of slides is obtained by superimposing the three maps described earlier (see Figure 7). Tentative proportional weights are attributed to the different lithological groups, hydrological factors, state of weathering and crushing of rock, and tectonics (see Table 2).

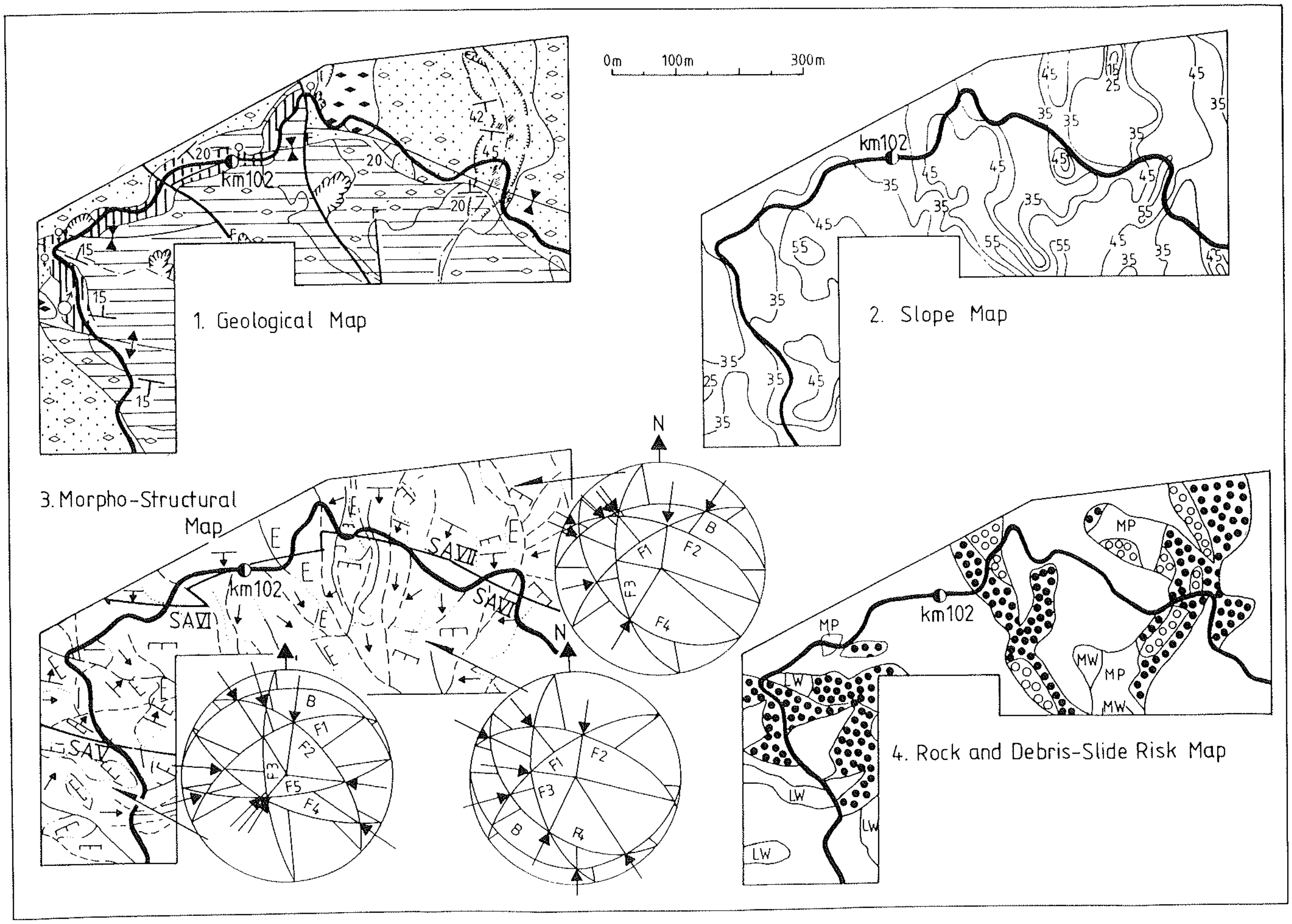
The compilation of field observations, corroborated by further experience, showed that the weight of the structural factor is an important determinant of the site's degree of susceptibility to and the potential size of a rock failure. Wedge failures were found to not exceed 0.25 hectare in size, whereas planar failures in combination with wedge patterns were sometimes found to reach very large proportions.

Two main categories of structural risk were consequently determined, to which were added the other factors mentioned earlier for rock and debris failure. The first category is the risk of plane failure; the second is the risk of wedge failure. According to the type of potential slide plane (bedding or fracture), its dip, the wedge pattern accompanying it, and the other slide factors, three degrees of potential plane failure were determined: low, medium, and high. Three degrees of potential wedge failure were determined in the same manner for wedge patterns in the absence of slide planes.

The probabilities of potential rock and debris slides given on the map approximate the degree of risk existing within the natural slopes. The units represented on the map show general areas of risk. Specific spots within these units, instead of the whole unit, can be affected by the specified risk.

Cut-slopes can create plane or wedge failures when they cross low- or medium-risk areas. Such cases especially occur in 30- to 35-grad slopes, which tend to retain water and consequently lead to deeper weathering of rock. Nevertheless, large failures along cut-slopes usually appear within naturally high-risk areas.

Structures within intensely folded areas are atypical. Statements on risk within these areas are given both on the map and in the accompanying notes. Tectonized areas are also indicated




1. Geological Map

- Thick eluvial or colluvial soil
- Rather thin eluvial or colluvial soil; In general sparse outcrops of rock
- Calcareous quartzite with laminae of phyllite; lithological susceptibility of sliding very high
- Carbonaceous, micaceous, and garnet phyllite; lithological susceptibility of sliding very high to high
- Fault
- Anticline and syncline axis
- Dip of the rock
- Crushed rock
- Spring and seepage
- Landslide
- Groundwater level
- Unstable area

2. Slope Map

- Slope contour line (grads)

3. Morphostructural Map

- Ridge or crest
- Sharp ridge or crest
- Rivulet
- Limit of slope unit
- Nonstructural slope unit
- Possible structural slope unit (bed of rock)
- Possible structural slope unit (fracture)

4. Rock and Debris Slide Risk Map

Risk of large failures

- High risk of planar failure
- MP Medium risk of planar failure
- LP Low risk of planar failure

Risk of medium and small failures

- High risk of wedge failure
- MW Medium risk of wedge failure
- LW Low risk of wedge failure
- Very low risk of rock and debris slides; possible soil failure within wet areas

**FIGURE 7 Examples of geological, morphostructural, and slope maps, and resulting risk map from km 101 to 103 in the Lamosangu-Jiri road corridor.**

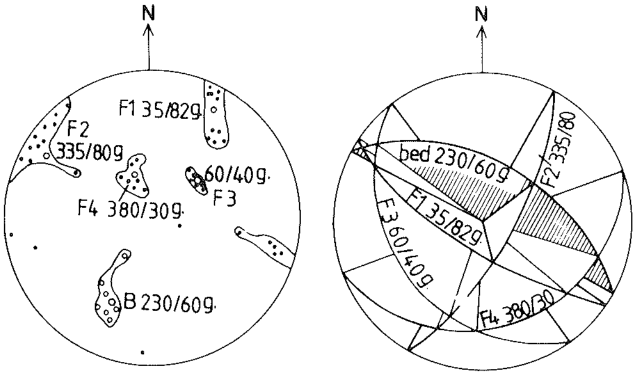



**FIGURE 8 Pole net of a structural area and its corresponding structure. The structure at the right is a mean structure that represents a structural area obtained from the pole net. The poles are reported from structures measured in different locations of the structural area.**

directly on the landslide risk map. Except along ridges or within rather flat areas, the risk of rock failure in tectonized areas is in principle rather high, even if the structural risk is low.

From Table 2 one can point out the following tentative degrees of specific risks:

- Up to 65 percent there is a low risk of wedge or planar failure,
- From 65 percent to 85 percent there is a moderate risk of wedge or planar failure, and
- Above 85 percent there is a high risk of wedge or planar failure.

### Evaluation of the Results

The three high-risk areas visible on the rock and debris slide risk map (Figure 7) were found to be the scene of major slides in 1983 and 1984 after completion of the road. When the first geological reconnaissance was made in 1982, no visible signs were observed, except that the convex morphological aspect of those particular areas and their hydrological and lithological components were found to be prone to slides.

## LANDSLIDE RISK MAPPING BY COMPUTER

Few prior examples of computerized landslide risk mapping exist. Those that do exist are based exclusively on the dip of the rock beds or on rain density and earthquake frequency (*9-11*). One interesting method, developed in Italy, is based on the collection of the 20 main attributes of terrain, including lithology, vegetation, elevation, slope, vertical and horizontal slope convexity, and stream rate (*12, 13*). Mathematical models were created from the combination of these attributes. This system nevertheless requires more data and documentation than are generally available in developing countries.

The computerized landslide risk mapping system described in this paper is based on the results, statements, and methods described in the preceding sections. An important concern is to create a system that can be adapted to the needs of civil engineering projects in developing countries. This requires that the system operate with data collected in remote areas with portable instruments, large-scale topographical maps, and

**TABLE 2 TENTATIVE WEIGHTS FOR FACTORS THAT LEAD TO ROCK AND DEBRIS SLIDES**

| TENTATIVE WEIGHTS FOR FACTORS LEADING TO ROCK AND DEBRIS-SLIDES (IN %) | |
|---|---|
| 1a. Structural Risk of Planar Failure ("Plane Risk") | |
| | Percentage of total weight |
| Condition A1: The potential plane failure is controlled by the beds of the rock. The slope is therefore structural. Three or more wedges are present, at least one of which is central or centro-lateral. Other are not very lateral. If the dip of the potential bed plane failure is less than 20 grads, the percentage weight is reduced to 20%. | 35% |
| Condition A2: Same as A1, but the slope is controlled by two geologic planes with orientation and dip values approximatel/ those of the slope. Reduced to 20% when the dips of the plane are less than 20 grads. | 40% |
| Condition A3: Same as A1, but the slope is controlled by a fracture. Reduced to 20% when the plane dip is less than 20 grads. | 30% |
| Condition A4: Same as A1, but the slope is controlled by a fracture cutting a more or less thick layer of sandstone, quartzite, gneiss, limestone or dolomite interbedded with rock of clay origin. Reduced to 15% when the plane dip is less than 20 grads. | 25% |
| Condition B: The potential plane failure is controlled by the bed or a fracture of the rock as in condition A, but only one wedge is central or centro-lateral and a total of only two wedges are present within the ce ral and lateral sector. Reduced to 12% when the plane dip is less than 20 grads. | 20% |
| Condition C: The potential plane failure is controlled by the bed or a fracture of the rock as in condition, A and B but there are no central or lateral wedges. Only very lateral wedges are present. Reduced to 6% when the plane dip is less than 20 grads. | 12% |
| 1b. Structural Risk of Wedge Failure ("Wedge Risk") | |
| 15% of the total is added for each central or lateral wedge (up to 40 grads from the direction of the slope). When the dip of wedge line is less than 15 grads, the wedge risk is nil. | 15% per wedge |
| 2. Lithological Risk | |
| Lithological Risk should be established for each specific region according to the visible rock failures within given types of rock or group of rocks. The following scale was established for the landslide risk map of the Rapti Road Assessment Project, a 230 km long road Project in Western Nepal. The scale has been simplified for adaptation to other situations. | |
| a. Fissile green-light brown phyllitic slate with fine laminae and marl beds. Black shales. | 20% |
| b. Sandstone with green and red shale. Black shales with ferruginous quartzite and silty limestone. Light brown laminated slate with calcareous slate. Green phyllite with fine laminae. | 15% |
| c. Gray clay slate with quartzite. White pink quartzite and red purple shale. The percentage is raised 15% when the slope is structural with the bed of rock. | 10% |
| d. Dolomite and limestone. Quartzite. | 5% |
| 3. Hydrogeological and Hydrological Risk | |
| Areas with perennial spring(s) or seepage(s), or areas close to stream(s). | 25% |
| Areas with seasonal spring(s) or seepage(s), or close to stream(s). | 20% |
| Areas with only seasonal rain. | 15% |
| 4. Tectonic and Weathering Risk | |
| Crushed or folded rock, rock with open joints, strongly weathered rock adjacent to faults areas. | 20% |
| Slightly weathered to moderately weathered rock. Not tectonized rock. | 10% |

generally poor supporting documentation. The system can currently be run on a portable, IBM PC-compatible microcomputer. Its purpose is to integrate more and more terrain instability factors onto a grid after having attributed weights to them.

The project will last 3 years and is financed by the Swiss National Fund for Scientific Research, a government agency. The project will integrate data collected in Nepal during low-volume road projects and in Switzerland. It will also test a method for soil slide risk mapping based mainly on field sample soil tests and measurements of soil anisotropy by pocket seismographs. The first results of the project concern only rock and debris slide risk mapping, in particular the structural risk within the same zone of the Lamosangu-Jiri road corridor that was previously described.

## Structural Risk

### *Slope of the Terrain*

The slope mapping of the terrain enables the eluvial, colluvial, and morainic terrains to be roughly distinguished from the rocky or sub-rocky areas. Eluvial soils, produced by weathering of rock within equatorial, tropical, and subtropical regions, are mostly present on slopes with an incline of less than 30 grads in which water penetrates deeply. Colluvial and morainic soils also occur on smooth slopes rarely exceeding 30 grads. All these terrains are strongly influenced by the laws of soil mechanics. The terrain above 30 grads is generally rocky, sometimes with a thin eluvial or colluvial mantel. Stability is mostly determined by the laws of rock mechanics. Detailed field and aerial photographic surveys give more information on the limits of the different terrains. A structural risk is theoretically present on slopes steeper than 30 grads.

### *Computer Inputs for Slope*

The following variables must be assigned values for each point on the terrain grid:

X = horizontal coordinate (meters),
Y = vertical coordinate (meters), and
Z = elevation (meters).

After these topographical values are digitalized on the grid, a special program gives the following variables:

D = incline of the slope (grads),
O = orientation of the slope (from 0 to 400 grads),
A = structural area code, and
G = lithogeological code.

See Figure 9.

### *Structural Areas*

Structural areas are areas in which the rock structure remains roughly similar throughout. They are generally outlined by field measurements, aerial photographs, and pole net plottings.

For a slope with a given incline and orientation, values for the following variables must be entered into the program for each structural area:

NP = number of geologic planes (i.e., bed, schistosity, planes, and fractures);
ID = identification of geologic plane (bed, fracture, or plane of schistosity);
OP = orientation of plane (North = 0 grad);
DP = dip of the plane;
NW = number of structural wedges;
OW = orientation of structural wedges (North = 0 grad); and
DW = dip of the wedge.

For example, a structure with five geologic planes is depicted in Figure 10. At this point on the grid, the slope is structural because it coincides with fracture F1. Seven structural wedges characterize the structure at this point on the grid.

NP = 5.

Identification of a plane (Figure 10), example for fracture 1:

ID1 = fracture 1 (220/60 grads) coincides with the slope incline and orientation of the node.
OP1 = 220 grads.
DP1 = 60 grads.
NW = 7.

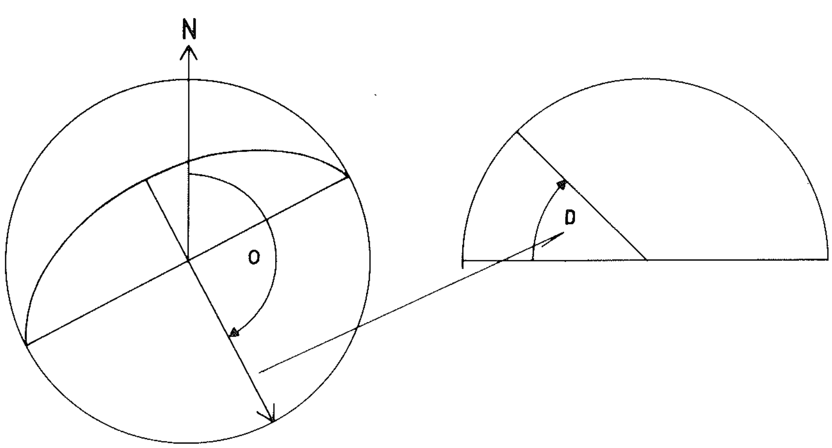



**FIGURE 9 Orientation O and dip D of a geologic plane.**

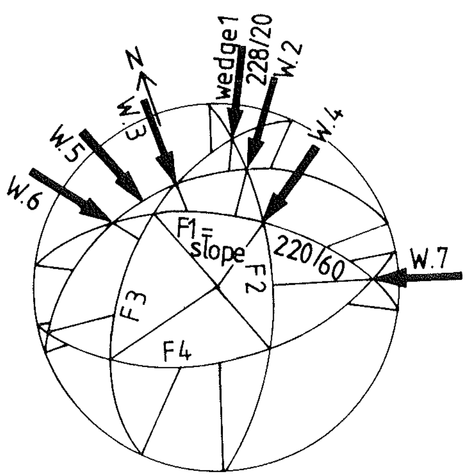



FIGURE 10 Plane and wedge identification.

Identification of a wedge (Figure 10), example for wedge 1:

OW1 = 228 grads.
DW1 = 20 grads.

*Parameters Unique to the Method*

Values have been attributed to several parameters listed in the following paragraphs by utilizing the results of the statistical study. Several parameters need to be refined through experimentation or research; others are specific for given terrains.

The slope threshold is denoted as RM and is a threshold above which the laws of rock mechanics can be applied to the terrain. The angle has been set to 30 grads for humid and hot climates. Below this value, stability is frequently ruled by the laws of soil mechanics.

The permitted angle, which is denoted as TOP, exists between the slope orientation and the orientation of a given geologic plane, within which the orientation of the plane can be considered equal to that of the slope at the node. This angle depends on the gap values that have been observed within the corresponding structural area. In general, the permitted angle can be set at 30 grads (Figure 11).

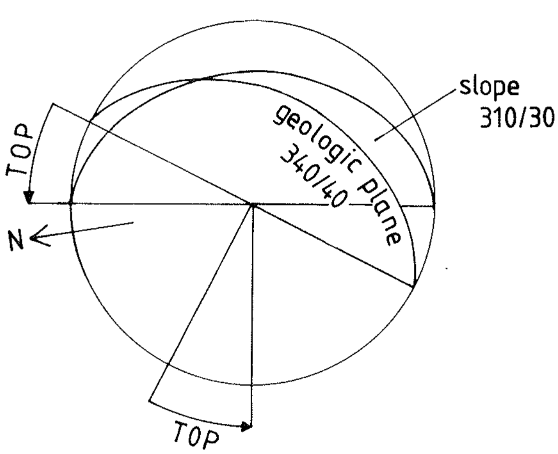



FIGURE 11 Permitted angle TOP between the orientation of a geologic plane and the orientation of a slope.

The permitted angle between the dip of a given geologic plane at the node and the associated slope of the node is denoted as TP. When the dip of the geologic plane is higher than the associated slope of the node (Figure 12), no freedom of movement exists, and, consequently, there is no possibility of a planar slide. Nevertheless, a permitted angle TP is attributed following examination of the variability of the given geologic plane dip within the given structural area. When the dip of the geological plane is less than or equal to the incline of the associated slope, freedom of movement and risk of planar slides exist.

The limit orientation angle of a central sector is denoted as ±OT1. A given sector can be defined as central in regard to the geologic plane under consideration. A central sector therefore contains central wedges (see plane risk A, Figure 13). Such central wedges act as the keystones of a structure. When one central wedge is set in motion, the lateral wedges follow. The risk is considered to be at plane risk A when a central wedge exists.

The statistics presented earlier in this paper indicate that the plane risk decreases when the orientation of the wedges is outside the central sector (i.e., ±OT1 = ±35 grads); the risk in such a case is referred to as plane risk B or C (see Figure 13).

The permitted angle between the slope orientation of a node and the slope orientation of the wedges under consideration is denoted as ±TOW.

When a plane risk A, B, or C is absent, a possible wedge risk still exists. A wedge risk is the risk of a slide along the intersection of intersecting planes. Slides that originate in wedge patterns are comparatively smaller than slides that originate from plane risk A, B, or possibly C. The sector wedge risk is possible at ±40 grads (±TOW) in regard to the direction of the slope at the node. The intensity of the wedge risk depends on the number of wedges and the dip of each (Figure 14).

The number of structural areas is denoted as NAS. A number is attributed to each structural area. Each structural area is defined by a typical structure.

The minimum dip of a geologic plane is denoted as DL. This dip is associated with the nature of the rock. As was stated earlier, any geologic plane, the dip and orientation of which are

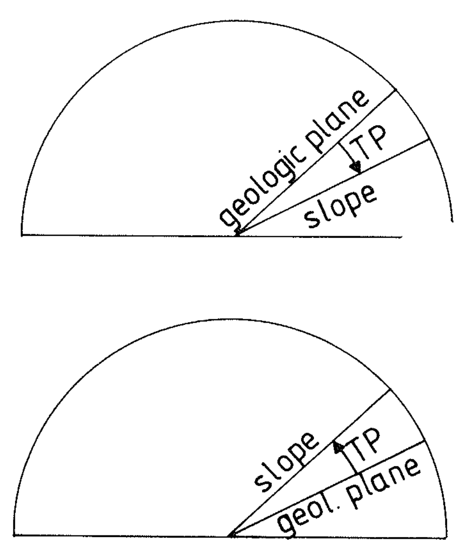
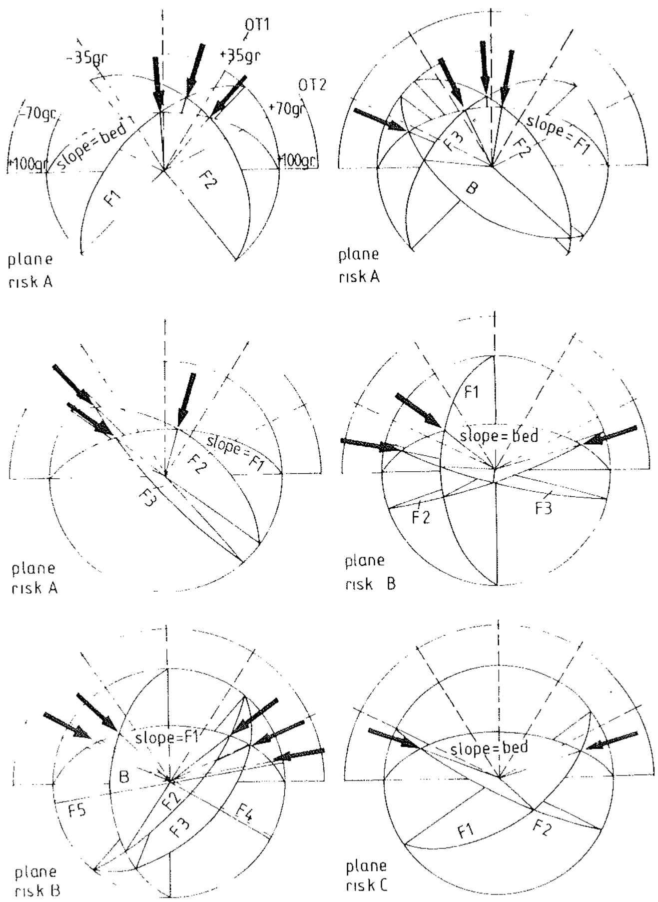



FIGURE 12 Permitted angle TP between a geologic plane and a slope.




From left to right and up to down:

Plane risk A—The risk is high because there are two central wedges and one lateral wedge, and the structural slope is controlled by the beds of the rock.
Plane risk A—A similar situation with four wedges.
Because the slope is controlled by a fracture, the risk is a little less great.
Plane risk A—There is at least one central wedge with two lateral ones; there is also a structural slope controlled by a fracture, but the risk is lower than before.
Plane risk B—There are three wedges and a structural slope controlled by the beds, and three wedges of which none is central.
Plane risk B—Similar to previous one, with five wedges of which none is central. Because the slope is controlled by a fracture and not by the beds, the risk is lower than before.
Plane risk C—Although the slope is controlled by the bed, there are neither central nor lateral wedges. Only very lateral wedges are present.

**FIGURE 13 Plane risks A, B, and C.**

within the permitted angles TOP and TP, has to be considered a plane of potential failure if the dip is less than or equal to the incline of the slope. In such a case, freedom of movement exists. However, a minimum angle DL exists below which no motion is possible. This angle depends on the friction angle of the rock. The angle is therefore higher for quartzite and limestone than for a clay rock. The minimum angle is also higher along fracture planes than along the beds of a rock.

In addition to the minimum angle DL, local conditions such as intensity of weathering, gaps in joints and fractures, hydrogeology, and tectonics should also be taken into consideration. All data inputs for slope and structural areas are registered on appropriate files on floppy disks.

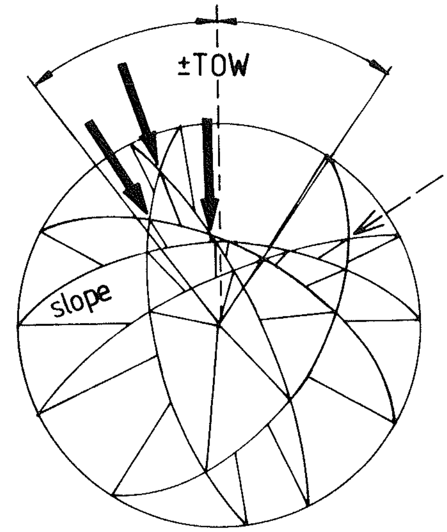



**FIGURE 14 Permitted angle TOW between the orientation of a wedge and the orientation of a slope.**

### Flow Chart of the Computer Processing of Structural Risk

Each node of the grid is considered independently in i rows by j columns.

Step A: For the current node the variables X, Y, Z, D, O, A, and G are read on disk file.
If $D < RM$, the rock mechanics treatment is feasible; if not, the process will consider a new node and return to step A.
Otherwise, it will search on disk file the specific structural area data corresponding to the considered node ij: NP, ID, OP, DP, NW, and so forth as described earlier.

Step B: Each geologic plane is considered as follows:
If OP is within O ±TOP, the plane is selected; if not, the next plane is considered.
*Test for the lithogeology*
If $DP < DL$ (G), no slide risk exists; return to step B.
*Test for the dipping*
If $DP > D + TP$, no slide risk exists; return to step B.
*Test of the number of wedges*
The NW wedges of the selected structural area are then considered (see Figure 13).
If OW is within OP ± TO1, NBW (1) is incremented.
If OW is within OP ± TO2, NBW (2) is incremented.
If OW is without OP ± TO2, NBW (3) is incremented.

Terminate step B.
When each geologic plane has been considered, the plane risks RP are established. If no plane has been selected, the process will continue to step C.
If $\Sigma\ NBW = 0$, then $RP_C = 0$.
If $\Sigma\ NBW > 0$, then

1. $NBW(1) + NBW(2) = 0$; $RP_C = 1$.
2. $NBW(1) = 0$; $RP_B = \Sigma\ NBW$.
3. $NBW(1) > 0$; $RP_A = \Sigma\ NBW$.

At this stage, plane risks A, B, and C are registered for the node ij.

Return to step A.

Step C: The wedge risk can be established as follows. The number of wedges $NS$ is calculated among all the wedges of the selected structural area if they are within the domain TOW in regard to O and if DW > TDW, after initialization of $RP$ and $RW = 0$.

Also, if NS ≥ NW, then RW = 1.

Terminate step C.

Terminate step A, after recording the risk value on a disk file.

When the process has gone through the grid, the computer can map each different risk category (plane risks A, B, and C, and wedge risk) at the proper scale.

### The Computer Structural Risk Map

The map shown in Figure 15 is a concatenation of the structural risk (plane risks A, B, C, and wedge risk) in which the black zone corresponds to the major risk (plane risk A). This zone delineates the most dangerous areas for road construction. The dotted areas correspond to minor risks of large failures. The striped areas correspond to wedge risk, or the danger of small to medium failures.

## COMPARISON BETWEEN STANDARD RISK MAPPING SYSTEMS AND THE COMPUTER MAPPING SYSTEM

It can first be seen that there is an excellent correlation between both methods. Although the standard map (Figure 7) includes more factors for sliding such as hydrological, hydrogeological, tectonical, and weathering factors, the comparison shows how crucial the structural risk is.

The process that has been developed is therefore appropriate, at least in that geographical area.

The zoning of the computer map shows more accurate limits. In addition, the computer process is able to disclose the risk areas systematically whereas only a general trend can be shown in the standard process.

However, the most relevant improvement of this new method is the usefulness of the systematic aspect of the process, which represents a savings in time in the end. Another significant characteristic of this computer method is the simulation flexibility of the unique parameters according to the observed field data and features, and the local imposed conditions.

This first approach in the computer map allows more confidence to implement the other risk factors and their corresponding weights, provided there is constant control through field experience.

Finally, the implementation of such a simple, facile system will aid the conservation of the road corridor environment in sensitive mountainous subtropical and tropical areas, in regard to both landslides and erosion. It will also help diminish the high maintenance costs of low-volume roads in these regions.

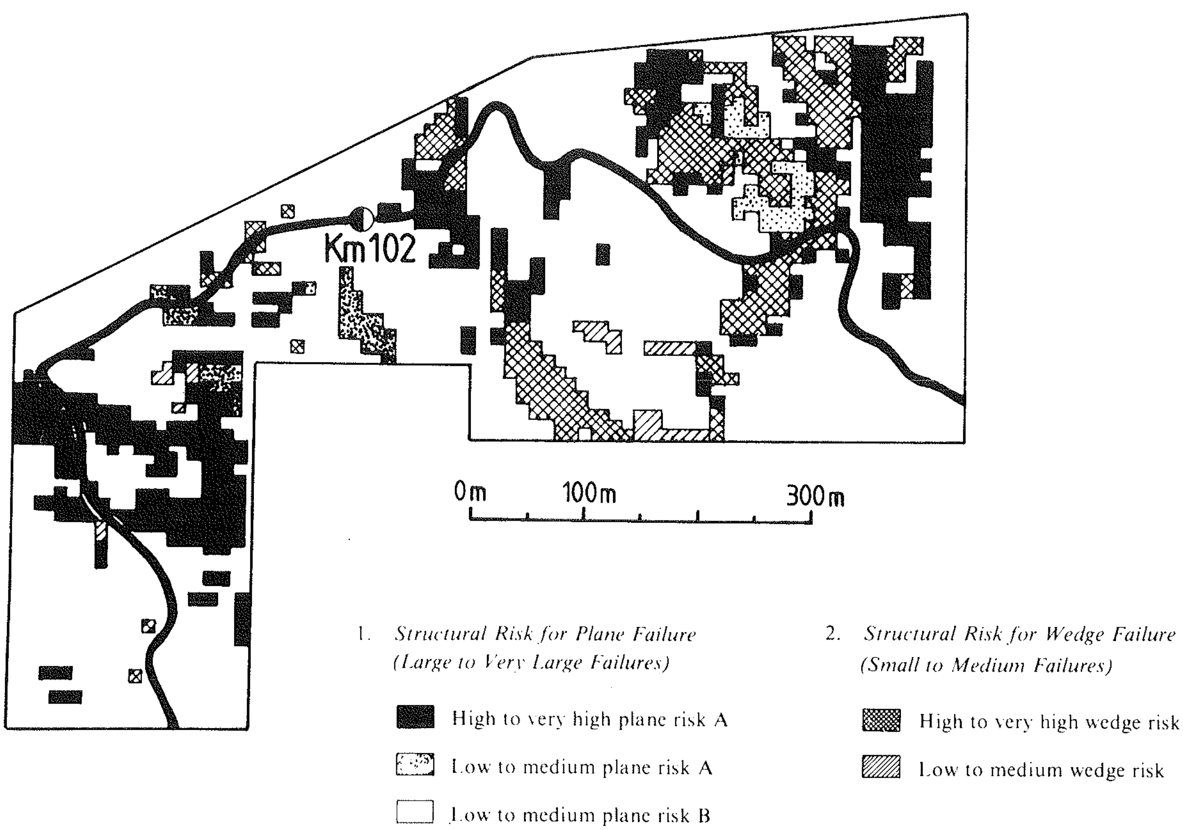



**FIGURE 15 Computer structural risk map.**

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# Efforts To Reduce Construction Costs of Logging Roads in Muskeg and Wet Soils in Southeast Alaska

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**A description is provided of the efforts of the U.S. Department of Agriculture, Forest Service, to reduce the costs of low-volume logging roads constructed in the muskeg terrain of southeast Alaska. Muskeg and its characteristics as a road supporting material are described. Techniques to more accurately design and build roads across muskeg and wet soils are discussed. The methods used by the Forest Service to reduce construction costs are analyzed empirically to determine their effectiveness.**

An old axiom known to most road engineers is that a requirement for good road construction is "to build and maintain it with a tight roof and a dry basement." That is impossible in southeast Alaska, especially for low-volume and relatively low-cost roads. Roads in this region must be built in the mud and the muskeg, because frequent rainfall prevents the attainment of optimum soil moisture content.

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## DEFINITION OF SOUTHEAST ALASKA MUSKEG

Muskeg is defined as terrain composed of a living organic mat of mosses, sedges, or grasses, with or without tree and shrub growth, and underlain by a highly compressible mixture of partially decomposed and disintegrated organic material commonly known as peat or muck (*1*). It is variable in its composition as well as its depth. It may consist of as much as 3,000 percent water; water contents of 900 percent are common in southeast Alaska (*1, 2*). Because summer temperatures are cool (55° F average) and annual rainfalls are high (60 to over 200 in), vegetation in southeast Alaskan muskegs decomposes very