Pedotechnical Aspects of Terrain Analysis

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Terrain analysis is defined as part of the process through which terrain is evaluated for specific land uses. The example used in this paper concerns the environmental impacts of constructing low-volume roads on steep slopes in forest areas. The basic source of data for the terrain-mapping system described is the standard soil survey, which is already well established in most countries of the world. The paper describes interrelations between principles of pedological mapping and geotechnical analysis of slope stability. A soil survey map and its application to man-created slope failures (shallow translational and rotational failures) in British Columbia is used for illustration of the techniques involved. By analyses carried out in the field, the process of terrain analysis is used to extend and better communicate soil survey data to engineering problems.

Terrain analysis is generally defined as part of the process through which the terrain is evaluated for specific land uses or for solution of specific terrain problems. Because the process is analytical, the particular land use or terrain problem must be defined specifically enough so that the kind and detail of the data needed may be determined. Because the problems usually concern very large areas rather than specific sites, the information base is typically generalized and not site specific. The mapping system used may be any orderly, relevant terrain-mapping system. The mapping may vary from reconnaissance to detailed, depending on the nature of the problem to be solved. The results of the terrain mapping and the terrain analysis may be used along with other data to solve the land use problem.

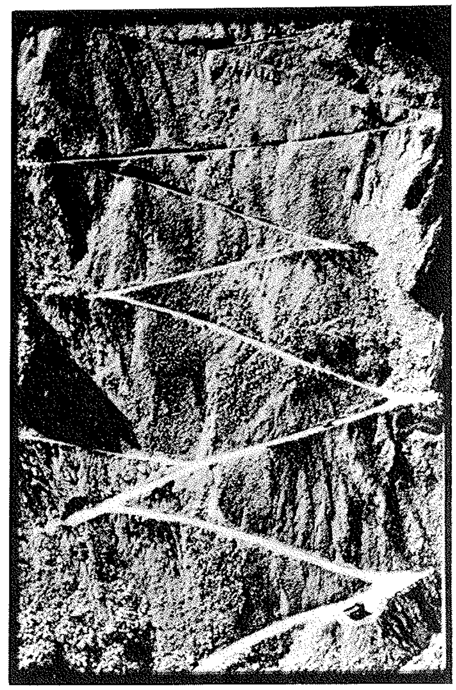
SPECIFIC TERRAIN PROBLEM

The specific terrain problem used here as an example concerns slope stability associated with low-volume roads in mountainous territory. Such roads may include forest or mining-industry access roads that are not necessarily part of any provincial or national system. For this type of road, funds are commonly insufficient for detailed geotechnical investigations, especially considering the complex nature of the problems. The immensity of some of the slope stability problems is illustrated in Figure 1. Many of these roads are not accessible to the general public. The casual visitor may wonder how roads could ever be built on such steep slopes, but engineers have been building them quite successfully for many years. The problem today, however, is that the engineer can no longer assure success by providing an adequate roadbed. The ecological impacts of siltation in mountain streams and other water bodies as a consequence of road construction are well documented (1,2). It is now standard practice to submit environmental impact statements before road construction proceeds.

In many instances, however, ecological disasters due to slope failure precipitated by road construction still occur, despite comprehensive and well-written impact statements. Thus, communication problems must exist. Perhaps their existence is understandable, since quite different interests and different disciplines are involved. In environmental assessment there commonly are engineers, ecologists, the general public, and perhaps even politicians involved.

The viewpoints of two of these groups can be compared by using the analogy of the pendulum. Ecologists, as a group, seem to consider the stability of steep slopes as an inverted pendulum (unstable equilibrium): Any imposed stress may precipitate a catastrophic collapse. The term "inherently unstable" is often used (3). Planning and design engineers in offices remote from the field of activity may be led to think of a very brittle type of stability when they read some ecological reports. In contrast, field engineers actually working at these slopes may use the simple pendulum analogy: Imposed stresses less than the ultimate strength of the soil can be taken up by nature, the result being simply a deflection of which the magnitude and direction are proportional to the imposed stress.

Figure 1. Access roads in mountainous terrain.



Conceptual differences are not only between disciplines, but they are also within disciplines. The term "slope misbehavior" is used by engineers (4,5) who suggest that the engineering technology of slopes has grown exponentially in recent times, but unfortunately the proper use of this knowledge has only grown linearly, if at all. The technology is often available, but the majority of problems result from failure to recognize the need for it or apply it properly.

The objective of the particular type of terrain analysis described in this paper is to provide a framework by which soil surveys can be better and more effectively used--in this particular case, to reduce the ecological impact of access road construction in mountainous areas. It is not to be used to provide a framework for designing the actual control or mitigation of environmental problems but rather to supplement the existing information base (6). It is not to further develop the geotechnics of slopes but rather to better communicate the evidence revealed by completed soil surveys as to whether ecological impacts are likely, where they might occur, what type they might be, and what might be done to reduce them.

TERRAIN-MAPPING SYSTEM

The soil surveys used are based on pedological concepts. The basic concepts of pedology, which originated in the late 1800s in Russia, centered on the notion that it is possible to understand, classify, and map the complex interactions in nature by studying the soil. The soil was viewed as the logical result of natural processes acting on the parent rock over a period of time (7). A basis was established not only for understanding past events that have shaped the land as we see it today but also for speculating about future events, including consequences of human intervention.

Details of soil surveying have evolved over the years to meet current needs; the basic concepts have not been changed. The preparation of soil surveys requires extensive field study to develop a model that depicts the soils on the landscape. The model is a projection or forecast of the nature of the soil, and attendant natural processes, in each part of the landscape. Field observations are made to verify or revise these forecasts and to document the performance of soils. The resulting soil survey is, in effect, a summary of such observations, verifications, and revisions. Detailed soil surveys, mostly at scales of 1:15 840 to 1:24 000, have been completed for only 1 percent of the land in Canada compared with 70 percent of the land in the United States.

The frequency of field observations and the confidence levels or reliability of the information presented should be understood by users of soil surveys (8). Although dominant soils are indicated for all areas, the scale of mapping dictates the minimum size of delineations, and small areas of different or contrasting soils may be included. The occurrence of small bodies of a contrasting soil too small to be delineated may be accurately forecast by recognizing contrasting landforms, vegetation, or other factors. Special spot symbols are sometimes used to show the location of these included soils. The descriptions of soil map units indicate the nature and extent of such inclusions and any unique features, such as landscape positions or vegetation, that would help locate them.

The soil surveys used in the example given are part of a national inventory program and are not necessarily done on behalf of either the forestry or mining industry or exclusively for any of the regulatory bodies. However, their use by these bodies is quite valid, provided that they are supplemented by a minimum amount of additional information. The additional information needed is the terrain analysis information.

TERRAIN ANALYSIS

Pedotechnical Approach

In quantitative pedology, Jenny (7) has indicated that any pedological soil property (s) can be shown to be a function of the soil-forming factors, such as climate (C), organisms (O), relief or topographic position (R), and time (T), which have acted on the parent material (P) to produce that soil; i.e.,

$$s = f(C + O + R + T + P) \tag{1}$$

By quantitatively analyzing each of these factors in turn, a theoretical solution to a soil problem may be identified. Alternatively, by comparing the soil properties of the problem soil with known soils, on which specific soil stability measurements have been documented, an empirical solution may be obtained. The pedological map shows the distribution of these known soils, and the agriculturalist or the engineer has in this map a useful tool. In the pedological concept, whereas the classification scheme embraces collectively all the five soil-forming factors, identical soils may be grouped together and their behavior thus rendered predictable.

The expression given also provides a link with engineering and other earth sciences. In geotechnical engineering, a slope may be analyzed theoretically, assuming homogeneity of materials within a delineated slope or layer by defining theoretical solutions, and then by sampling the soil to determine quantitatively each of the properties and other factors involved in the slope analysis. As the process develops, more and more complex slopes can be analyzed. But when the ground conditions are too complex for analysis, engineers then resort to the empirical method of observation (9). The two disciplines of pedology and engineering can thus be related through the pedological concept and the engineering method of observation. Information provided by the soil survey map can then be interpreted in behavioral engineering terms from observation and the map used to advantage for a variety of purposes.

However, as the purpose changes, so does the relative significance of each of the factors that describe identical soils. From a geotechnical viewpoint, this altered emphasis may be used to define pedotechnique (10). For geotechnical purposes, the consideration and evaluation of soil behavior in soil survey procedures may be far from complete (11). In addition to soil-forming factors, soil behavioral factors should also be considered, and the relation between actual slope failures and unique kinds of soils should be observed and documented. The intent, however, is not to convert pedological maps into geotechnical maps or to revamp established pedological mapping techniques but to show how the information on a pedological map can be used and interpreted. This is quite a different approach from that commonly used in solving engineering problems; the geotechnical approach would probably result in entirely different map units to focus on the central problem. Such a focus is not the intent of the pedotechnical approach at all. The pedotechnical approach aims at full interpretation of information available in the existing pedological map for a multiplicity of potential land uses.

Geotechnical Connection

The first step toward developing a common viewpoint to the question of slopes and their stability (on the basis of strength of soil material) may be to examine the pendulum analogies already stated from the standpoint of the infinite slope concept (12, 13). In this concept, a slope is infinite if the depth to the potential failure plane is very small compared with the length of the slope. Although the soil may be stratified, the slope could be considered infinite if the soil layers or horizons are parallel to the slope and analysis made, assuming that a vertical column of soil is typical of the entire slope.

The infinite slope condition could be assumed to occupy a significant portion of the landscape and, as such, it is mappable in pedologic terms. For the geotechnical approach of starting with a simple model amenable to static analysis, a mine waste dump composed of relatively homogeneous materials could be an ideal starting point. The slopes of the mine waste dump (Figure 2) might resemble those of scree slopes, which are well-known features of mountain landscapes. Some simple questions may be asked with regard to such slopes. As the rock is dumped at the top of the waste pile, what happens? Does the rock run down the slope? Why is it that the slopes are everywhere identical? If a road was constructed across such a slope, what type of ecological consequences could result?

Figure 3 illustrates (in terms of an engineering analysis) that if a structure (A) exerts a stress in the downhill direction, it will begin to cause failure of the slope when the imposed stress (f) plus the active lateral earth stress (a) acting behind the structure equals the passive lateral earth stress (p) acting in front of it. At failure it could be stated that

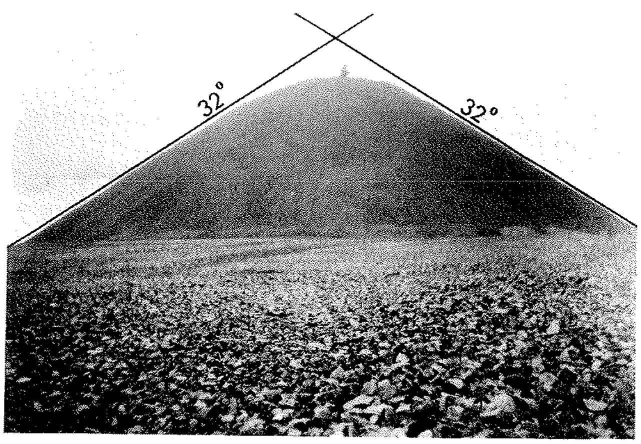
$$f = p - a \quad (2)$$

or, if the imposed stress was zero, the factor of safety (F) of the slope could be considered to be

$$F = p/a \quad (3)$$

The magnitude of the lateral earth stresses on sloping ground for a retaining wall design can be determined by the Mohr diagram (13). The failure envelope (Figure 4), which is defined by the ultimate friction angle, determines the maximum active (Aa) and passive (Ap) stress circles, which meet at the common point defined by the vertical stress (Av) at the depths (A) considered. For horizontal ground, the common point of the circles (Av) is on the abscissa and, since the maximum passive stresses greatly exceed the maximum active stresses, the factor of safety is high. For sloping ground, however, the common point changes, somewhat increasing active stresses and decreasing passive resistance.

Figure 2. Limiting slopes of rock waste pile.



Besides illustrating the ratio of active to passive stresses, the same diagram also gives the direction of the failure plane; this is represented by a line drawn from the maximum stress point to the intersection between the failure envelope and the appropriate circle. The active stress angle is thus steeper than the passive stress angle.

Taylor's original diagram, which was for a retaining wall design, has been extended here to examine slope failure of infinite slopes. At progressively steeper ground-slope angles, an ultimate condition is reached; that is, at a ground slope equal to that of the failure envelope, there is only one lateral stress circle: The active stresses that act downhill are equal to the passive stresses that resist the movement. In addition, the difference in the angles of the failure planes gradually decreases until, at the ultimate condition, the failure planes are all parallel to the ground surface.

The implication of this concept is that, if the factor of safety of the slope is taken as the ratio of the passive to the active stresses, it can never drop below 1 (unity). The ultimate state of the slope, therefore, is one of balance rather than imbalance. The reason why the slope of the mine dump is so regular, despite variations in the size and types of rock on it, and what happens to the load of rock after it is dumped at the top of the slope can also be surmised. The rocks do not tumble down the slope; the whole slope simply readjusts. The slope surface itself is the failure plane, and the angle of the slope is an average inclination of the failure surface for the entire slope--hence its very consistent value.

Because the slope surface is the failure plane, a roadbed built on the surface would not be stable; the standard practice must entail excavation into the slope to obtain a stable roadbed. Failures in the backslope of such excavations would inevitably result. These failures would progress eventually to the top of the slope.

Analyzing Terrain

The rock slope example is for better understanding of certain aspects of the landscape for pedotechnical interpretation purposes. For natural landscapes, the vegetation (O) also contributes to slope

Figure 3. Earth stresses on slopes.

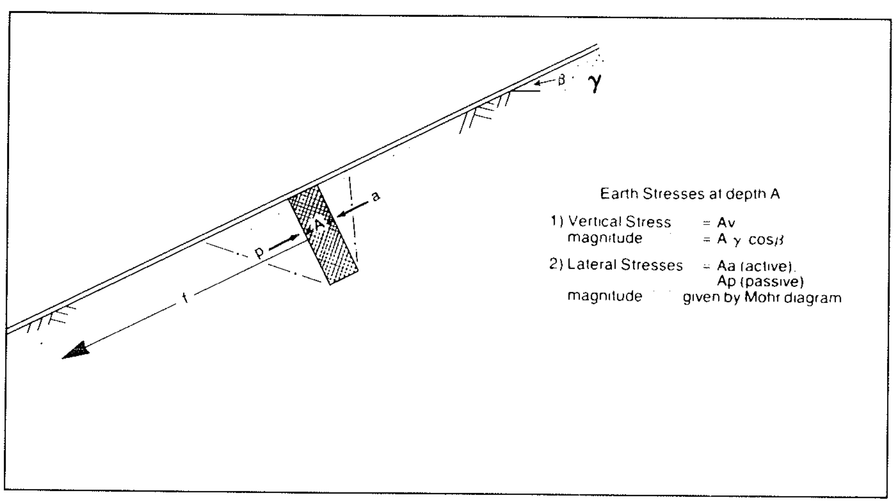
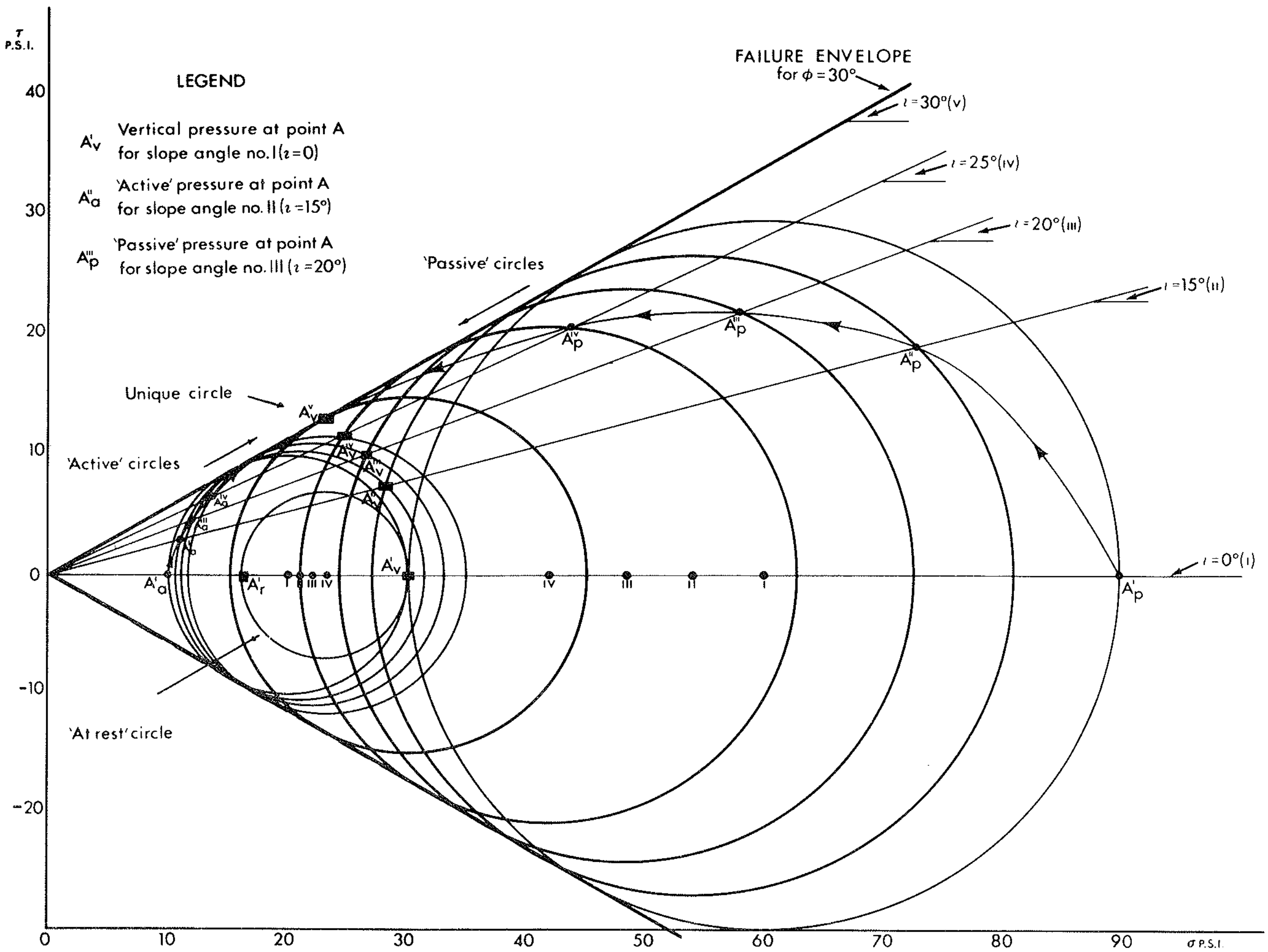


Figure 4. Mohr circles for sloping ground.



development. By combining the pedological concept and the geotechnical method of observation to the development of natural slopes, Equation 1 may be reduced to the following form:

$$LS = f(P + O) \tag{4}$$

where LS refers to the limiting slope of landscapes defined by the soil parent material (P) and the vegetation (O). This would be for given soil age (T), soil climatic conditions (C), and shape of slopes (R).

Geotechnical analyses of the type illustrated indicate that, for nonvegetated slopes like the mine dump or for forested slopes on deep frictional soils where the friction angle increases with depth, Equation 4 reduces to

$$LS = f(P) = f(\phi') \tag{5}$$

where ϕ' represents the average effective shearing resistance of the parent material on infinite slopes and the vegetation is no longer a variable.

Observations of the slopes of the mine dump provide an example of the use of Equation 5. The maximum slopes were found to be 32°, and this is the limiting slope (LS) of a landscape so defined. Road excavations into such slopes would result in progressive failure of the backslope, which would have to be retained to mitigate this type of hazard. This slope angle also provides a practical value of the effective shearing resistance of the rockfill at the site conditions that prevail on the natural slope.

For the natural forested landscapes in this area, two different types of LS were generally observed. For example, the well-drained sandy fluvioglacial terraces had characteristic maximum natural slopes of 35°; but the "side-cast" materials, which result from failure of the backslopes of road excavations, had LSs of 32°. Because of this, these forested slopes had often been termed oversteepened, and the additional strength of the tree roots accounted for the steeper 35° slopes. For certain slopes this may be the case, but not for these deep frictional soils. Equation 5 would indicate that 35° is the effective shearing resistance of the well-drained undisturbed parent material, whereas 32° is the value for the same parent material but in the looser disturbed conditions after side casting. As a consequence, it could instead be concluded that deforestation may not necessarily result in generalized mass movement as the tree roots decay. Such decay is said to occur within five years of clearing (14). Ecological impacts of such road construction might only be localized and could possibly be mitigated by providing minimal backslope retention.

The observational method may be extended for pedotechnical purposes even beyond the concepts of infinite slopes. In soils with both friction and cohesion, rotational failures can occur, and these, by nature, depend on the particular geometry of the site. Pedological mapping units are not site-specific entities and normally are not directly applicable to site-specific problems. However, by including the geometrical factors (including LS) within the soil survey interpretation, the method of observation can also apply to rotational slope failures.

LS defines one geometrical boundary of the road section; its other two geometrical boundaries are the width of the roadway and the height of the back-slope. In very steep terrain, the roads have single lanes of standard width excavated into the hillside slope. The normal height of the backslope could thus also be considered, for interpretation purposes, to reach a maximum value at the LS. The observation that, in certain cohesive soils (dense tills), backslopes of single-lane access roads remain stable on very steep slopes without any tendency for shear failure becomes significant. It means that, as long as the road sections are similar, access roads excavated elsewhere in the same soil should, in general, perform likewise (pedological concept); in other words, the average long-term shear strength should, in general, be adequate for vertical back slopes that are approximately the same height as the road width, a fact very difficult to determine with even detailed site investigation techniques.

However, in certain types of cohesive soils, the cohesive strength happens to be decreasing progressively with time due to natural causes. These soils include, for example, highly overconsolidated clays. Slopes in such soils may fail, regardless of road construction. The problem presented by such soils is a separate issue (not considered here) but, by extending the combined theoretical and observational techniques as outlined, useful predictions of the performance of such slopes could also be made.

The method of terrain analysis illustrated is thus, first of all, to observe actual slope failures and determine the limiting natural slopes for the various soil map units. Like large engineering structures, the landscape, as portrayed by these map units, is as stable as its foundations.

The second phase is to tie in the record of any existing construction, and what ecological problems occurred and why. Interdisciplinary cooperation is commonly needed at this phase to identify failures that resulted from avoidable construction mistakes or poor practice; failure could be simply a result of interrupting surface drainage or overloading slopes with side-cast material. Once these spurious failures have been eliminated in the observational process, the actual behavior caused by soil properties of slopes in road construction becomes manifest. Also, these observations may help experienced field engineers determine kinds of mitigation measures to help correct the failure.

Connection with Other Earth Sciences

It has been possible to treat the infinite slope concept and its application to this type of soil survey interpretation only in the briefest way. It is likewise impossible to adequately treat the role of geology, hydrology, geomorphology, or other related disciplines that are required to define all aspects of slopes and their behavior. For this particular application of terrain analysis, only the superficial soils are considered. There is no suggestion of attempts to predict ecological impacts from hydrological or deeper-seated geological causes. A possible exception is the case in which mass movements are already in progress or have occurred in the past. If they are somehow visibly manifest, if their scale is great enough, and if a characteristic soil has developed, such areas are commonly identified on soil surveys. However, for specialists concerned with the total problem of specific slopes in the field, evidence from all of these sources must be considered.

RESULTS AND METHOD OF PRESENTATION

Results

In British Columbia, a field observation program was carried out in an area where a soil survey map existed and where slope stability problems had been associated with access road construction in steep terrain. The objective was to determine whether realistic LS values for the pedological map units could be obtained by applying the terrain analysis reasoning outlined above.

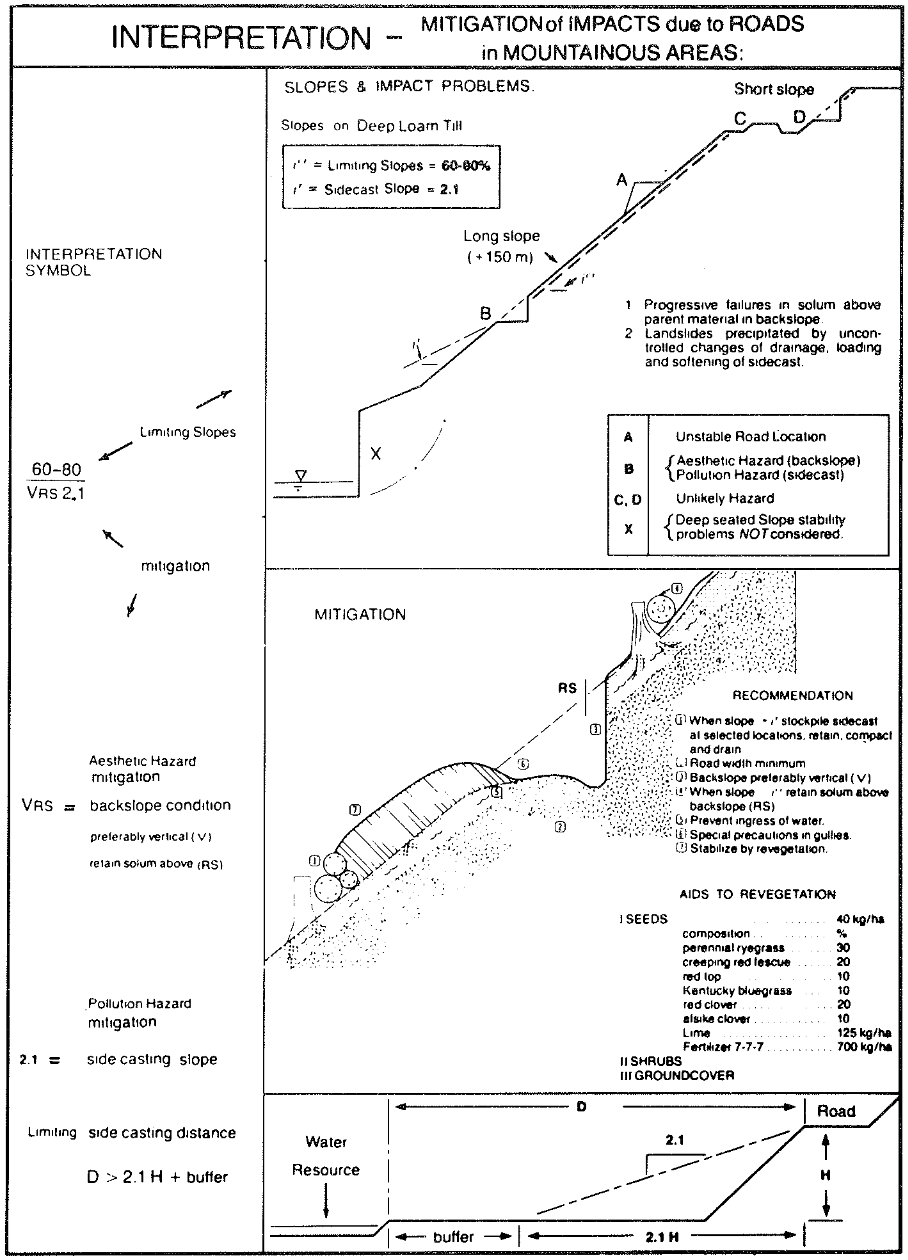
The main problem foreseen was the occurrence of a high percentage of nontypical failures, i.e., failures due to unique local or site-specific variations of the landscape characteristics, and failures due to natural causes such as stream-bank erosion and other types of deep-seated slope failure. Although such failures did occur, they were not found to be dominant, and realistic LS values for the mapping units could be identified. Special attention had to be paid to failures that were due to avoidable construction practices. The most prevalent of these were interruption of the natural drainage and overloading of slopes with side-cast material and other debris. The latter could also be classified as nontypical because the terrain analysis problem is intended to apply to access road construction under modern restrictions and by using the best available practice that is economically feasible. Guidelines that encourage such practices have been prepared (15).

When all such nontypical incidents were eliminated, it was deduced that access roads could be built with minimal impact on slopes much steeper than those usually agreed on by ecologists.

In addition to indicating realistic LS values, the terrain analysis indicated other aspects of the ecological problem in the area. The effects of excavating into long, very steep vegetated slopes have already been mentioned. Even with comprehensive soil mechanics testing, it is often quite difficult to predict the long-term effects of such excavations, especially in deep loam till soils. The difficulties are due to imperfections in sampling; presence of thin, weak layers; and the variability of natural materials. The observational record showed that these soils actually failed by a raveling process in the solum rather than by a shearing in the parent material. Such a record gives useful information otherwise difficult to obtain. With this information, it was possible to discuss with contractors methods by which the raveling process could be controlled before it would become a more serious environmental problem, and the ecologist, engineer, and contractor were thus able to communicate. The results of such a discussion are summarized on the pedotechnical interpretation sheet (Figure 5).

In the whole area covered by the survey, the majority of ecological situations fitted into only four well-defined slope categories. Thus, four interpretation sheets, of which Figure 5 is but one example, could adequately define the ecological problem for this survey.

Figure 5. Pedotechnical interpretation sheet.



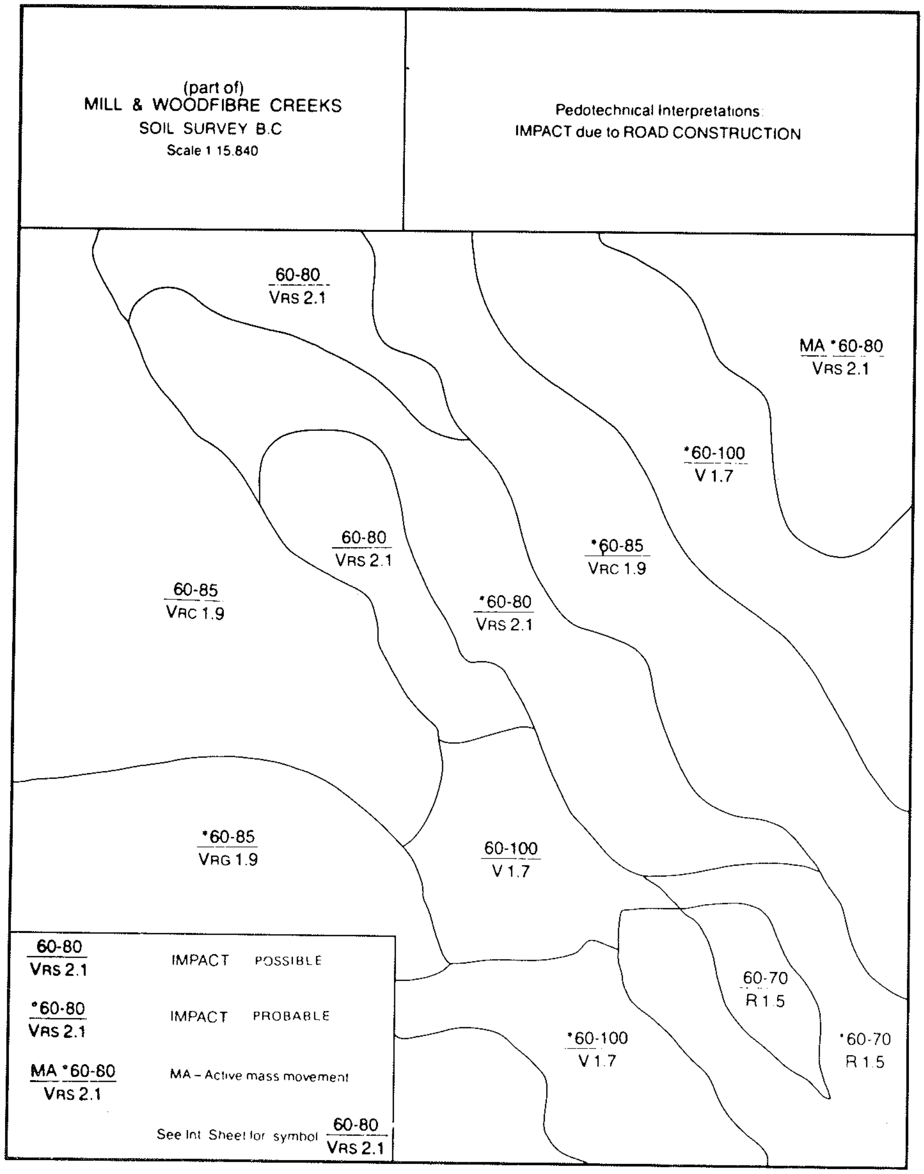
<u>Method of Presentation</u>

The objective of a soil survey is neither to solve road construction problems such as this one nor to administer slope regulations; instead it attempts to inventory the land resource. It is therefore most important to exhibit the information as clearly and briefly as possible for those concerned with the problems (16).

All the predictive information available from the soil survey relevant to this particular problem is given on a map and an interpretative legend. Some modern soil survey maps contain so much information that they may be cumbersome for specific uses. This problem is solved with a derived map that contains only the information relative to the specific purpose.

Computerized cartographic facilities now exist, and the Canadian Soils Information System (CanSIS) has two main data-storage systems in operation (17). The cartographic facility permits the boundaries of soil map units to be digitized. A turnaround document system permits derived maps to be generated by automated symbol conversion from the original detailed soil map. The turnaround document is generated from the digitizing process and lists every map unit symbol on the original soil map. By use of the pedotechnical interpretation sheet (Figure 5), the original map unit symbol is transposed to an interpretation symbol that relates to the specific terrain analysis application. The turnaround document then generates a new map (see Figure 6). The interpretation sheets become the legend for the new derived map. The derived map thus shows, independent from all the other inventory information, the application of the survey to the particular terrain problem of immediate interest.

Figure 6. Derived terrain analysis map.



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Publication of this paper sponsored by Committee on Exploration and Classification of Earth Materials.

Quantitative Approach to Assessing Landslide Hazard to Transportation Corridors on a National Forest

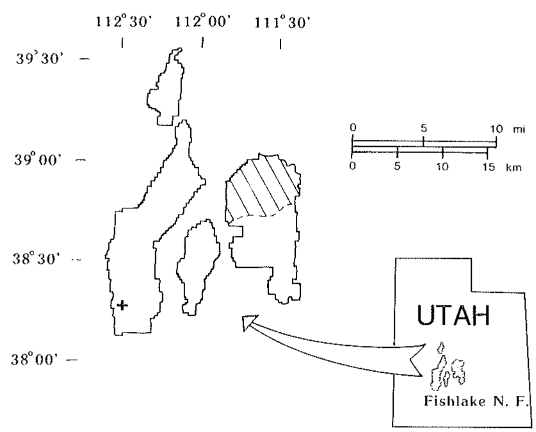
JEROME V. DeGRAFF

The occurrence of damaging landslides along transportation corridors in the mountainous western United States can be expected to rise with the expansion of the regional transportation network. Because national forests typically encompass major mountain ranges throughout the West, assessing landslide hazard is of special concern to forest management. The Fishlake National Forest in central Utah employs quantitative methods to assess this hazard. The matrix-assessment approach forecasts landslide hazard for planning purposes. It seeks to avoid reactivation of existing landslides or creation of new ones. The other method is applied to maintenance concerns. It emphasizes the frequency and areal extent of landsliding over time. Both methods have the following common characteristics: (a) each employs a numerical procedure, (b) each employs measurable terrain characteristics, and (c) procedure results can be assigned to specific geographic locations. The matrix assessment for transportation corridor planning is illustrated by application to the Wasatch Plateau section of the Fishlake National Forest. The method used in maintenance problems is illustrated by application to an 8.2-mile section of UT-153 along Beaver Canyon in the Tushar Mountains.

On February 27, 1981, a landslide developed along a paved county road that crosses the Fishlake National Forest in central Utah. The failure occurred in natural slope materials where the road is cut along a steep valley slope. This rotational landslide destroyed half the width of the outside lane for a distance of 100 ft. This road is the only access to a major coal mine within the forest. All traffic was restricted to a single lane for one month. This included empty incoming and loaded outgoing double-trailer coal trucks, which averaged one truck/10 min. As the party charged with road maintenance, the coal company spent approximately $150 000 stabilizing and restoring the road. Prior to this occurrence, a similar amount was programmed for improvement to the existing mine facilities. Restoration of the access road failure caused a delay in efforts to increase mine productivity. This example clearly illustrates the importance of assessing landslide hazards to transportation corridors.

Shifting population growth and a developing energy industry are creating an increased demand on transportation networks in the West. Corridors capable of satisfying transportation needs are limited by mountainous terrain common to this region. Landslide hazard can be acute along these corridors due to steep slopes, climatic extremes, and landslide-prone bedrock. Assessing landslide hazard potential for expanding or developing corridors is of special concern to national forests. Forest land typically encompasses major mountain ranges throughout the West.

Figure 1. Location map of Fishlake National Forest.



The Fishlake National Forest assesses landslide hazard for both planning and maintaining transportation corridors. Assessment for planning focuses on avoiding reactivation of existing landslides or creation of new ones. For planning purposes, potential landslide hazard is forecast by using the matrix-assessment approach (1). Application to the Wasatch Plateau within the forest provides an example of the method (see Figure 1). (Note: Cross-hatched area delineates the southern Wasatch Plateau section of the national forest, and the cross denotes the location of a landslide-prone road segment in Beaver Canyon.) Assessment for maintenance emphasizes the frequency and areal distribution of landsliding. An approach developed by Ogata (2) defines existing landslide hazard for maintenance situations. Landslide activity along UT-153, which crosses the forest in Beaver Canyon, is used to illustrate this technique (Figure 1).

Both matrix assessment and Ogata's technique are terrain analysis methods that share some common characteristics. First, each method follows a numerical procedure. This minimizes subjective interpretations and quantifies results for comparison. Second, basic data are measurable terrain characteristics. This ties evaluation to basic conditions that contribute to landslide activity. Third, assessment results can be assigned to specific loca-