Landslide Analysis Concepts for Management of Forest Lands on Residual and Colluvial Soils

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A forest land management analysis scheme is discussed for dealing with landslides that occur in residual and colluvial soils. No one geotechnical or statistical model can be expected to apply to all levels of land management where an assessment of the potential for landslide is vital to a rational decision-making process. The U.S. Department of Agriculture Forest Service in cooperation with the University of Idaho is developing a scheme for evaluating soil-mantle landslide potential to provide information at three levels of land management activities: (a) resource planning; i.e., relative landslide hazard evaluation for resource allocation; (b) project planning; i.e., evaluation of management impacts for comparing alternate transportation routes and timber harvest techniques; and (c) road design and landslide stabilization; i.e., evaluation of alternate road stabilization techniques at a specific critical site. Both geotechnical and statistical analysis techniques are advocated so that the information can be in geotechnical form (factor of safety against failure or critical height of slope) or in statistical form (probability of landslide occurrence) with landslide inventories used as a link between the two. A hypothetical example of the three-level analysis is given.

Many forest lands in the West, particularly those on residual and colluvial soils, are classified as unstable and have a high potential for mass failure. Timber-harvesting operations, road construction, and other resource-management activities in these areas can accelerate mass erosion and cause significant degradation of water quality unless carefully planned and executed. Successful management of these lands requires development of a specialized body of knowledge to quantify and integrate those site factors that influence slope stability. Site factors that require special attention are slope, soil depth, soil shear strength, seasonal ground water levels, and the strength derived from vegetation (effective root strength). Geotechnical characterization of these site factors can then be the basis for a landslide hazard analysis tailored to a specific management decision level.

MANAGEMENT COMPLEXITY

The management of lands that have a high potential for landslide is inherently complex, not only because of the nature of the interacting natural processes and management activities but also because of the number of persons of varied disciplines who must possess a degree of understanding of the slope failure processes and be able to contribute to the total stabilization effort. Considerable overlap and interaction between members of key disciplines must be coordinated.

Members of different disciplines must deal with problems of slope stability at several levels of intensity. For example, the resource planner must recognize high-hazard areas, but only on a general scale. The road locator needs to recognize potentially unstable areas along proposed routes and to avoid the problem through adjustment in alignment. The engineer must be able to use soil mechanics in the stability analysis of remedial measures before, during, and after construction to prevent or correct specific road cut or fill slope failures.

FAILURE MODE

Consistent with Varnes (1), landslides may be grouped into two broad categories, depending on the type of slide mass material--either soil (debris or earth) or bedrock. This grouping enables orderly selection of stability analysis techniques and the data required. The concept should apply to soil or bedrock landslides with the proper selection of slope analysis techniques and required data. However, this discussion is directed at landslides where the failure is confined to a soil mantle primarily of colluvial or residual origin.

The usual setting for this type of failure is a relatively loose, cohesionless soil mantle that overlies a less permeable bedrock or denser soil mass. An exception to this is an extremely altered bedrock or residual soil near the surface that overlies a less altered bedrock at some depth. Each of these conditions can result in similar failures and can be analyzed in the same manner. The contact with the underlying, less permeable, material forms a drainage barrier for the normal downward migration of ground water that originates from rainfall, snowmelt, or both. Ground water is concentrated at the drainage barrier and, if sufficient quantities are available, the soil mantle develops within it a perched water table with seepage moving along the barrier. The drainage barrier, phreatic surface (water table), and ground surface are often parallel or nearly so. Seepage of this form is usually considered to be of the infinite slope form because of this parallelism.

Failure of the entire soil mantle can occur naturally due to higher-than-normal ground water concentrations that result from unusually high rainfall or snowmelt. Failure also may result from wildfire, which destroys vegetation and thus the beneficial effects of evapotranspiration and root strength. Failure more often occurs through land management activities such as timber harvest and road construction, which in some manner increase ground water concentration, destroy root strength, or affect the natural parallelism of the ground surface or phreatic surface in relation to the drainage barrier.

Failures are often confined to the soil mantle because the underlying material usually has a higher strength and the critical failure surface is usually at the maximum depth of the soil and water table (tangent to the contact with the drainage barrier). The failure surface may be circular arc or translational in shape, depending on local conditions. Translational failures may begin as a small circular arc and progress into a translational shape or a series of circular arc failures as more of the soil mantle is mobilized.

IDEALIZED LANDSLIDE EVALUATION SYSTEM

A complete system of landslide hazard evaluation is needed that begins early in the resource planning phase, follows through into project development, and provides information back to the planning phase to improve future hazard analyses. The system should be structured on a common scheme but branch early into either soil-mantle landslide analyses or bedrock landslide analyses and use the respective analysis techniques and data. In either case, the complete system should be structured on a common basic analysis form that is simplistic in the resource planning phase and requires primarily available resource inventory data and becomes more complex and

Table 1. Idealized analysis system.

Item	Level 1, Resource Allocation	Level 2, Project Planning	Level 3, Critical Site
Base map	Landslide hazard map on resource inventory scale; 1:24,000; 1 in. = 2,000 ft	Project map of larger scale; 1 in. = 500 ft	Critical site map on even larger scale; 1 in. = 20 ft to 1 in. = 100 ft
Stability analysis	Infinite slope equation requires values for geotechnical variables and their inherent variance	Combination of infinite slope analysis from level 1 but used to model effects of tree removal and critical height analysis of anticipated road cut and fill slopes	Critical failure path analysis by computer program with search routine for circular arc, translation failures, or both; anticipated drained phreatic surfaces generated through computer analysis to predict effects of road with and without various stabilization techniques on infinite-slope-recharged phreatic surface (2,3)
Data display	Resource inventory map overlay of factor of safety against failure or probability of landslide occurrence	Same as level 1 but for more localized project area that has potentially unstable locations of road cut and fill slopes shown on proposed route	Cross-sections of critical site conditions with proposed road and alternate stabilization techniques superimposed
Required data	Available forest resource inventory data, values for geotechnical variables and variance through broad characterization of forest land forms, variables and analysis model tested and refined through association with landslide inventory and subsequent evaluation in levels 2 and 3	Level 1 data, data from timber and route reconnaissance to delineate local areas within project where failures are most likely	Surface and subsurface critical site data; subsurface data from geophysical methods and drilling if severity warrants; soils and ground water hydrologic data from soil sampling and testing and ground water monitoring
Prime use	To delineate areas susceptible to landslides on broad scale to alert land manager to land units where hazard intensity is greatest; through statistical correlation to landslide inventory, to predict number and magnitude of landslides as a result of resource development	To assess severity of instability more accurately as local islands of instability are predicted through reconnaissance; to make decisions to limit development or to continue to level 3 analysis based on improved assessment of probable failure magnitude and intensity; to better evaluate transportation planning, timber harvest techniques, and route locations for project so critical sites can be isolated along selected routes where level 3 analysis will have most benefit	To select and design road stabilization measures through relative stability-probability of failure cost analysis of feasible alternatives

requires more exact data only as the intended use demands greater accuracy.

For soil-mantle landslide analysis the ideal system should be structured to

1. Provide landslide hazard evaluation to guide management decisions on unstable lands at three crucial phases: resource allocation, project planning, and road design;
2. Include soil, vegetation, slope, and ground water hydrologic variables together with their inherent natural variance in a geotechnical analysis (factor of safety against failure or critical height of slope), a statistical analysis (probability of landslide occurrence), or both;
3. Begin with a simplified analysis that requires primarily available resource inventory data and progresses into more complex analyses that require more exact data (the selection of technique should be commensurate with the level of management decision; thus, the user at any level is faced only with the complexity and need for data required at that level); and
4. Facilitate the inventory of new landslides as they occur and slope failures as they are corrected and feed back the data gathered into earlier processes to improve the planning of subsequent projects.

Three levels of analysis complexity and data are visualized for the idealized system in Table 1.

RESTRICTIONS ON USE

Existing Stability Analyses

Current restrictions on the use of an idealized evaluation system for soil-mantle landslides are not due to the lack of slope stability analysis technology. The program recently developed by Simons, Li, and Ward (4) for mapping potential landslides is based on an infinite slope analysis and includes both factor of safety against failure and probability of landslide occurrence options for a level 1 analysis. Stability number charts that have seepage correction factors are being developed for infinite slope seepage conditions (5) and converted to computer programs for the critical height analysis of typical road cut and fill slopes in a level 2 analysis. Numerous programs are available and in use by geotechnical specialists in stability analysis for the correction of existing landslides that have either circular arc and translational failure surfaces. The most widely used methods of slices (primarily the Fellenius, the simplified Bishop, and the Janbu methods) can be integrated into one program to cover a variety of failure surface analyses for level 3. Statistical counterparts for the probability of landslide occurrence option used in level 1 are planned for levels 2 and 3 based on methods currently used in geotechnical engineering (4,6).

Existing Data Base

One current restriction on using the system is the small existing data base for most forests. Many forest managers have (or are in the process of developing) resource inventory maps for soils, bedrock, topography, timber type, and other features. These maps could provide the start of a level 1 data base through proper characterization of geotechnical variables for the inventoried conditions. Statistical analyses used by Simons and Ward (4) and DeGraff (7) will prove invaluable for linking inventoried physical factors such as bedrock, aspect, and slope to inventoried landslides. The accuracy of the values assigned for geotechnical variables, analysis models, and the probability of landslide occurrence

can be tested through association with corresponding physical factors. Currently, only a few forests have landslide inventory data. Geomorphic landtype maps (8), where available, should be the most useful tool for geotechnical variable characterization because the landtype classification includes the major physical factors on which to assign values for the variables.

Existing Variable Definition Methodology

The main restriction to implementing the system is the current state of the art in defining certain geotechnical variables. Techniques for defining slope, soil depth, and soil shear strength have progressed to a state where the values and their variance can be used with some degree of confidence. This is not true for the two most dynamic variables--ground water concentration and tree root strength.

The part of the soil mantle that can be expected to be below the phreatic surface at any point in time is perhaps the most dynamic of the variables. It can fluctuate constantly in response to precipitation. Practical and inexpensive methods are needed to develop local correlations between rainfall and snowmelt and the resulting rise in ground water. Although general knowledge of the time-related effects of tree root strength on forest slope stability has been advanced through research, currently no cost-effective quantitative methods are available for determining the effective tree root strength to use in analysis. To use the system now, it may be necessary to back-calculate to determine values for these two important variables until the state of the art progresses.

ILLUSTRATIVE PROBLEM

The following hypothetical problem illustrates the concept of the three-level analysis system. Where available, actual analysis results are used to demonstrate current progress. All studies within the project should be completed by mid-1985.

Level 1 Analysis for Developed Area

Step 1

Figures 1-3 show drawings of three inventory map overlays for part of the Clearwater National Forest in northern Idaho--the transportation map, landslide

Figure 1. Transportation inventory map of developed part of Clearwater National Forest, Idaho.

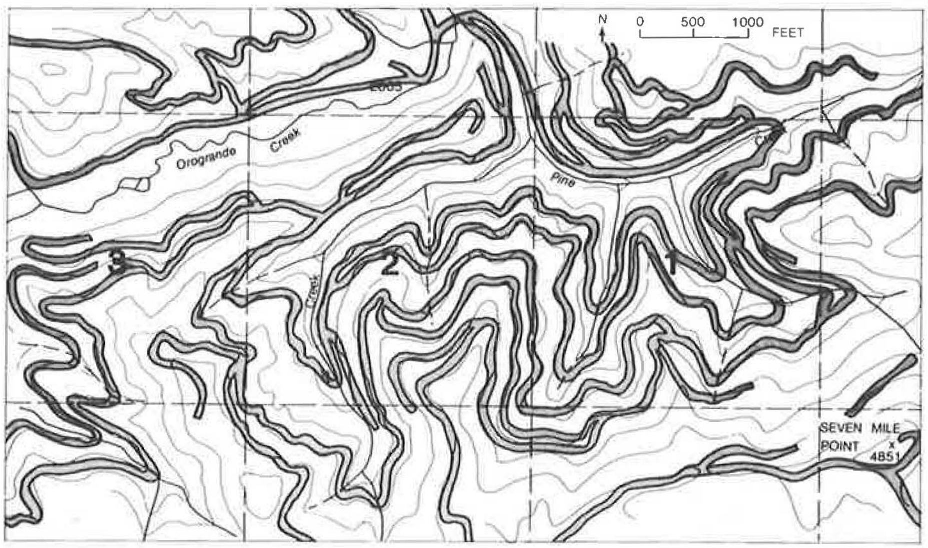


Figure 2. Landslide inventory map of area in Figure 1.

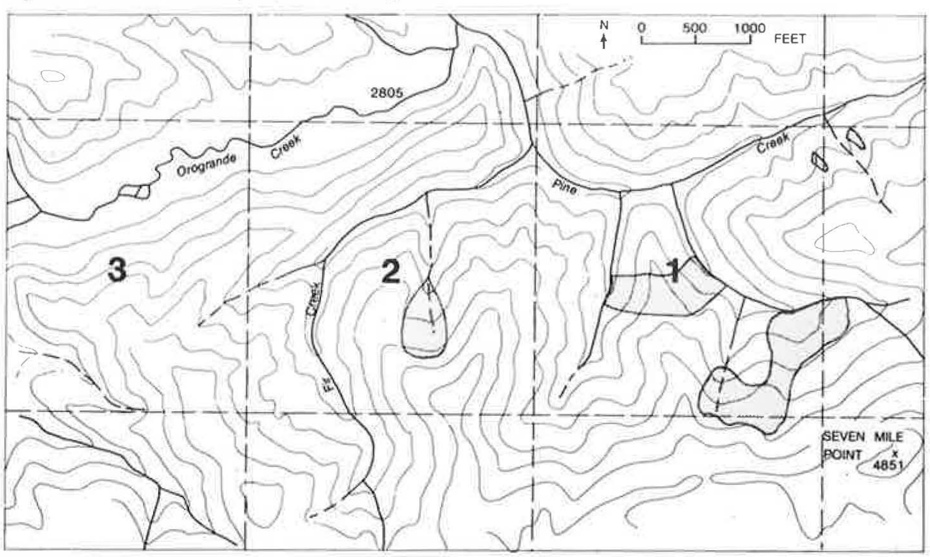


Figure 3. Geomorphic landtype inventory map of area in Figure 1.

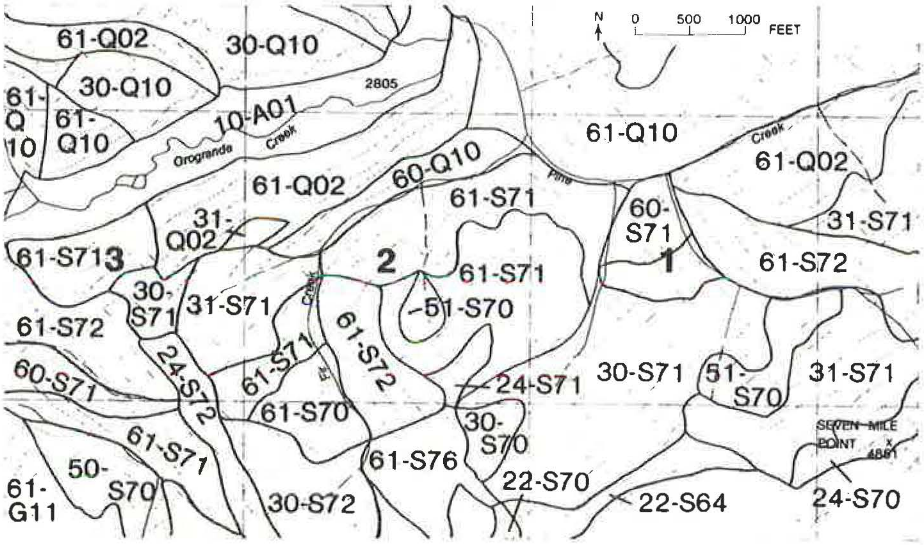
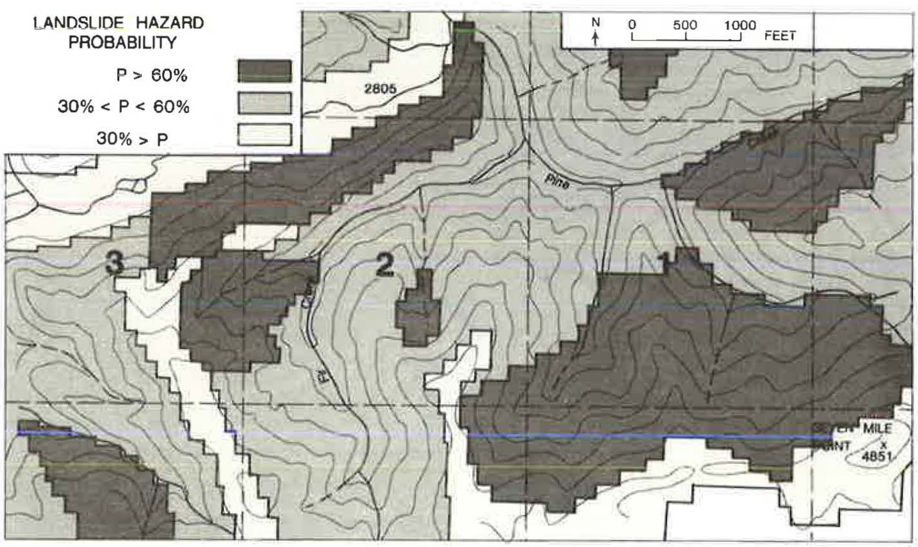


Figure 4. Results of level 1 analysis for Figure 1 area by using probability of landslide occurrence option.



inventory map, and geomorphic landtype map, respectively. The association of these inventories is the most useful for this forest as an initial level 1 data base. The transportation and landslide maps show the location of all existing roads and landslides. The landtype map shows the boundaries of distinctive geomorphic landforms. The coded landtype classification includes the major geomorphic physical factors that make this mapping unit distinctive (8). Physical factors such as parent rock type, aspect, slope, and timber type are used in the classification and corresponding values for geotechnical variables such as soil shear strength, soil depth, slope, and ground water concentration, and are characterized and stored into an initial level 1 data base. This data base will be updated by using new data from levels 2 and 3.

Step 2

The level 1 (infinite slope) analysis is completed. The results will be either in ranges of factor of safety against failure or probability of landslide occurrence. Figure 4 shows the printout of the Simons, Li, and Ward program by using the option of ranges of probability of landslide occurrence for the data from step 1. This analysis for developed areas can be repeated as necessary to test and refine the model and variable values until the planner is satisfied that the results correlate realistically to the landslide inventory. In this procedure, the planner must remember that the values are to be used in conjunction with the infinite slope equation. This model is selected for this level of analysis because of its simplicity but not

necessarily because of its accuracy. Accuracy depends largely on how well the model fits the ground water concentration mechanism and whether translational failures develop; even then the model will probably be applicable only to parts of any landtype (where the worst conditions exist).

Level 1 Analysis for Undeveloped Area

Step 3

Step 3 is similar to steps 1 and 2 for adjacent undeveloped areas with similar landtypes. Figure 5 shows the transportation map of the undeveloped area. Figure 6 is the level 1 analysis printout of landslide hazard probability. By beginning the analysis in this manner, the planner can calibrate the analysis by using the developed areas for predictions about the undeveloped areas to aid the land manager in resource planning decisions on whether or not to develop, how intensely to develop, and the landslide risk involved as a result of development. In addition, the following advantages are available through a level 1 analysis:

1. The land manager can be given a comparison of landslide magnitude and consequences by relating to experiences in the developed areas.
2. The accuracy of at least some of the level 1 data base can be improved through the feedback loop from levels 2 and 3, which follows.
3. The intensity and location of the level 2 analysis can be planned commensurate with the anticipated landslide hazard.

Level 2 Analysis

Step 4

Figures 5 and 7 show the area selected for level 2 analysis on levels 1 and 2 scales. In this case, the level 2 analysis is used to evaluate two possible routes to a proposed log landing site. Reconnaissance data are gathered at selected cross-sections along each route for better assessment of the extent of the anticipated problem areas and estimation of values for geotechnical variables.

Figure 5. Transportation resource inventory map of undeveloped part of Clearwater National Forest, Idaho, showing existing road terminal.

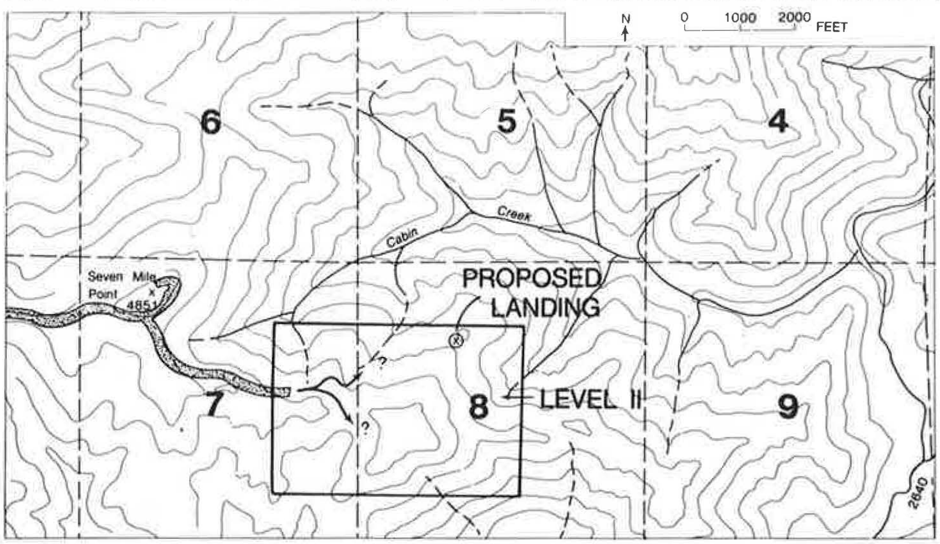
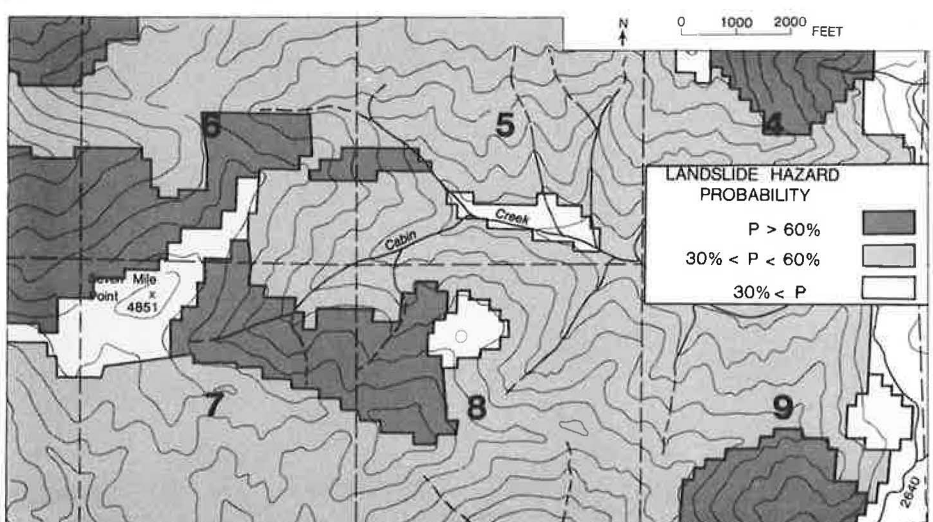


Figure 6. Results of level 1 analysis for undeveloped area in Figure 5.



Step 5

Typical road template sections are superimposed on the selected cross-sections and cut slope height, fill slope height, and the relation of cut and fill to the ground water level, root zone, and drainage barrier contact are determined by computer analysis. Figure 8 shows a self-balance road template commonly used on forest roads (cut volume balances fill volume with appropriate compaction factor). The critical heights of the cut and fill slopes are then determined and compared with the anticipated slope heights. Figure 9 shows the prototype program printout from a programmable calculator for a combined levels 1 and 2 analysis of the cross-section of Figure 8. The compaction factor can also be evaluated by this analysis. A full-bench road template may also be used on steep slopes where a fill slope will not catch or would be too high.

Step 6

A program similar to that used for Figure 9 will be developed as a subroutine for a computer analysis that represents the results as either S for stable or U for unstable on a project map. In addition, a statistical subroutine will be developed similar to that in level 1 for an optional output in terms of probability of slope failure. Figure 10 is a hypothetical drawing of the anticipated display.

Step 7

To assess the impact of timber harvest (tree removal) on the stability of the natural slopes, the level 1 analysis will be repeated at level 2 with changes made in tree-root strength, tree surcharge, and ground water concentration to reflect the impact

Figure 7. Level 2 analysis area showing location of alternate routes to proposed landing and selected cross-section locations on each route.

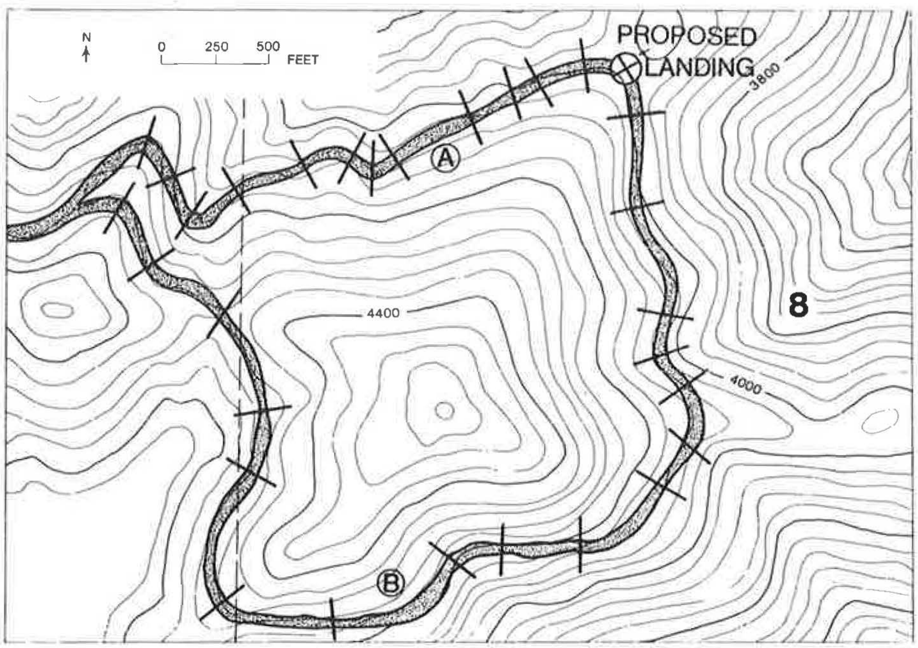


Figure 8. Self-balancing road template cross-section from level 2 analysis summarized on Figure 9.

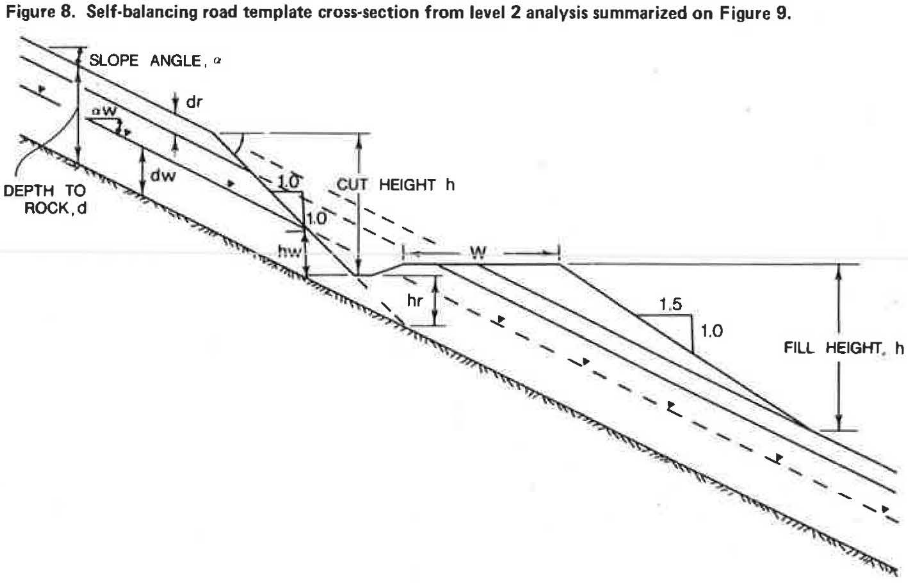


Figure 9. Printout of level 2 analysis of Figure 8 cross-section data.

```
STA.134+50

SOIL DATA
 DEN.1 DEN.2  PHI  COH.
 120.0 130.0 32.0 40.0

ROOT DATA
 5 YRS. AFTER HARVEST
ROOT COH.= 20.0PSF/FT.

SITE DATA
ALPHA= 50.0%= 26.6DEG.
AL.W= 50.0%= 26.6DEG.
  d   dw   dr
 10.0 5.0 2.0
   INF. SLOPE F.S.= 1.02
            STABLE

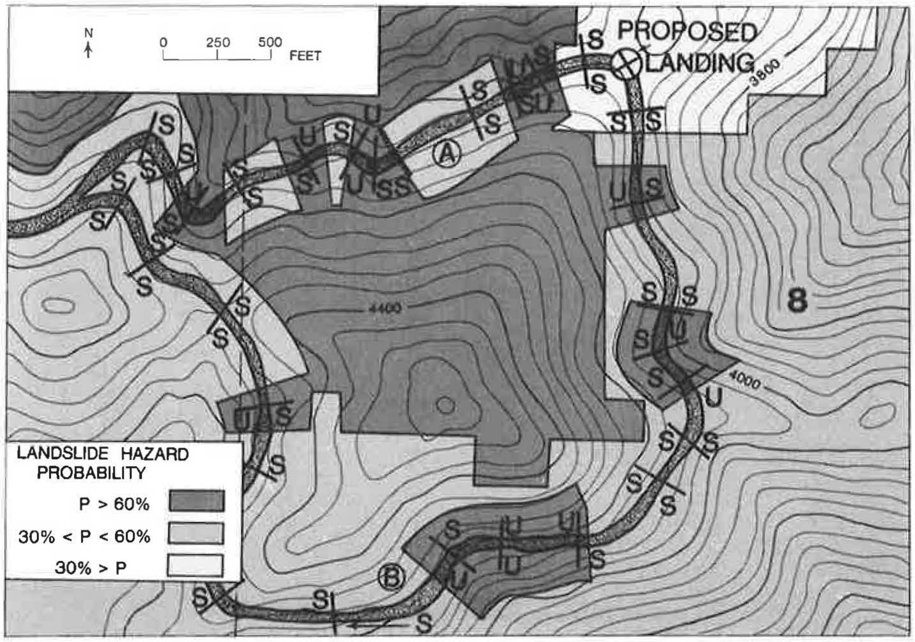
ROAD DATA
       CUT SLOPE= 1.00:1
DITCH
 SLOPE  DEPTH  BOT.W
 3.0:1    1.0   2.0
     ROAD WIDTH= 16.0FT.
      FILL SLOPE= 1.50:1
       COMP. FACT.= 25.%
FOR 50.% LOSS IN dr,
        COMP. FACT.=22.%

SELF-BALANCE SECTION

CUT
 h    hw    hr
 14.4  4.4 -5.6
 H    S    Hc
 42.8 0.52 14.7
           STABLE

FILL
 DEN.  PHI  COH
 130.0 34.0 40.0
  h   hw   hr
 17.3 -1.4 -17.3
  H    S   Hc
 151.8 0.73 34.0
           STABLE
```

Figure 10. Hypothetical drawing of the probability of landslide occurrence for level 2 analysis.



(9). The uses of the level 2 analysis are then as follows:

1. To facilitate management decisions on development through evaluation of alternate transportation routes and alternate timber harvest techniques and
2. To locate the critical sites where level 3 analyses are necessary on the selected routes.

Level 3 Analysis

Step 8

Figures 11 and 12 show one critical site selected for level 3 analysis on levels 2 and 3 scales. A critical site investigation (both surface and subsurface) is made for each site selected. The extent of this investigation and the subsequent analysis are planned by the geotechnical specialist in the same manner as a landslide correction project is planned.

Step 9

The antipipated road section is superimposed on cross-sections of the critical site and the stability of the anticipated cut and fill slopes are analyzed for circular arc, translational failure, or both. This step differs from step 5 in that the mode of failure is analyzed to determine the failure surface that has the least factor of safety and the anticipated extent of the slide mass. Many stability analysis programs are in use that would serve as a level 3 analysis for either shape of failure surface. Plans are to formulate the most functional of these as subroutines for one master program. Figure 13 shows possible translational and circular arc failure surfaces for the cut slope on the cross-section of the critical site. Figure 14 shows a programmable calculator printout for a program that combines the Fellenius (ordinary method of slices), simplified Bishop, and Janbu methods of slices solution for failure along these surfaces. The master computer program will combine analyses such as these, which can be preselected by the designer in conjunction with failure surface predicting, slice generating, and optional search for minimum factor of safety subroutines. Subroutines for predicting the steady-state drained phreatic surface to be expected from an infinite slope seepage source will also be programmed to evaluate the various drainage conditions in steps 9 and 10.

Step 10

The analysis of the unstabilized case in step 9 serves as a standard of comparison for the relative stabilization technique analysis that begins with step 10. In step 10 all feasible stabilization alternatives are analyzed to determine the relative increase in factor of safety over the unstabilized case.

Step 11

Decision analysis components (6) are determined for each alternative:

1. Probability of failure,
2. Construction and maintenance costs,
3. Consequences of failure (cost of failure).

Level 3 analysis provides the design engineer a decision analysis through which to select the optimum stabilization alternative for the current constraints.

Feedback to Level 1

Step 12

The data gathered for levels 2 and 3 are fed back into the level 1 data base to improve future analy-

Figure 11. Level 2 base map showing one area selected for level 3 analysis.

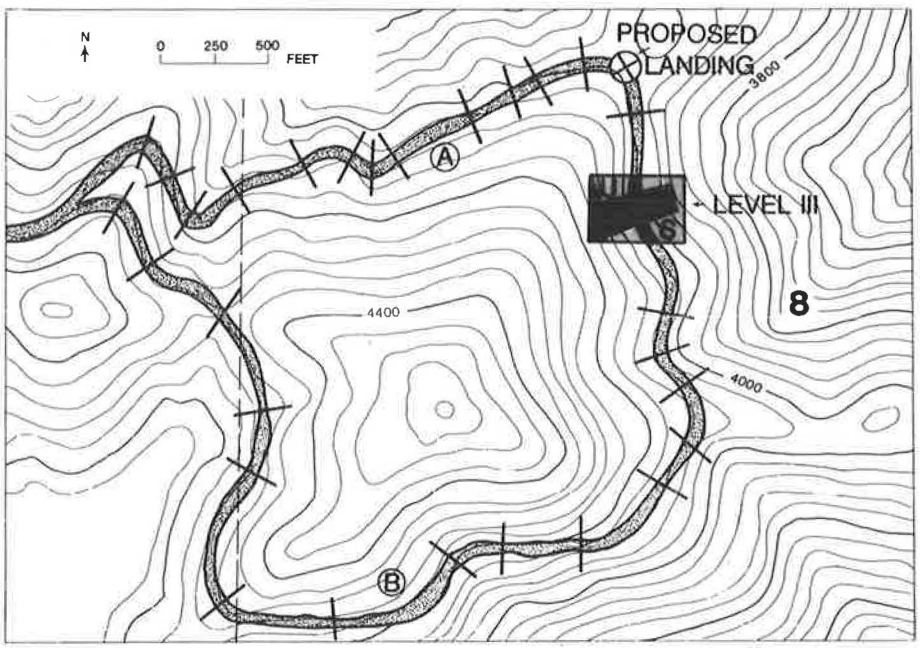


Figure 12. Level 3 analysis area showing proposed road.

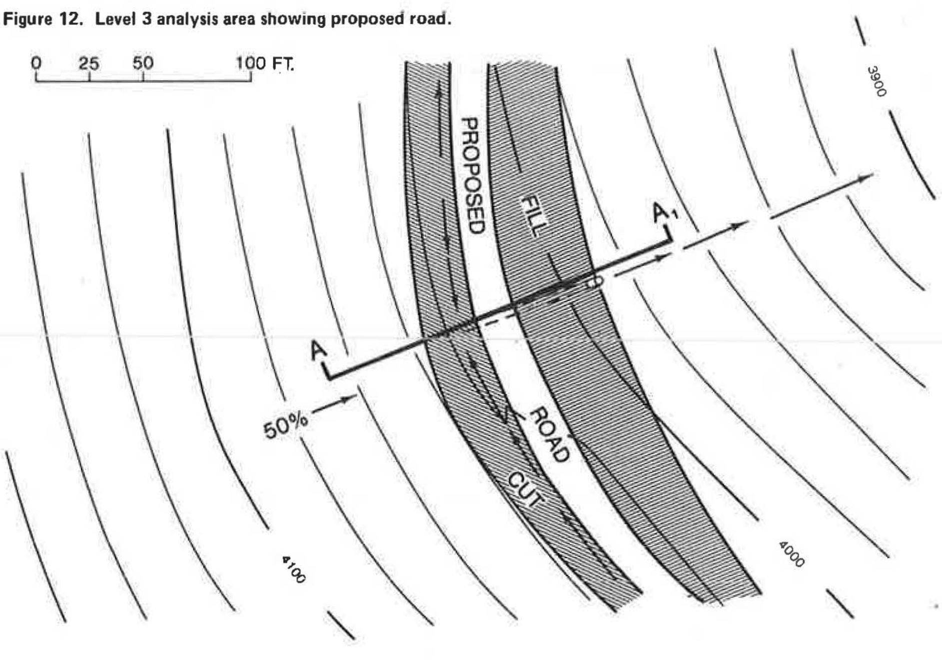


Figure 13. Cut slope portion of cross-section A-A' from Figure 12 showing possible circular arc and translational failures analyzed in Figure 14.

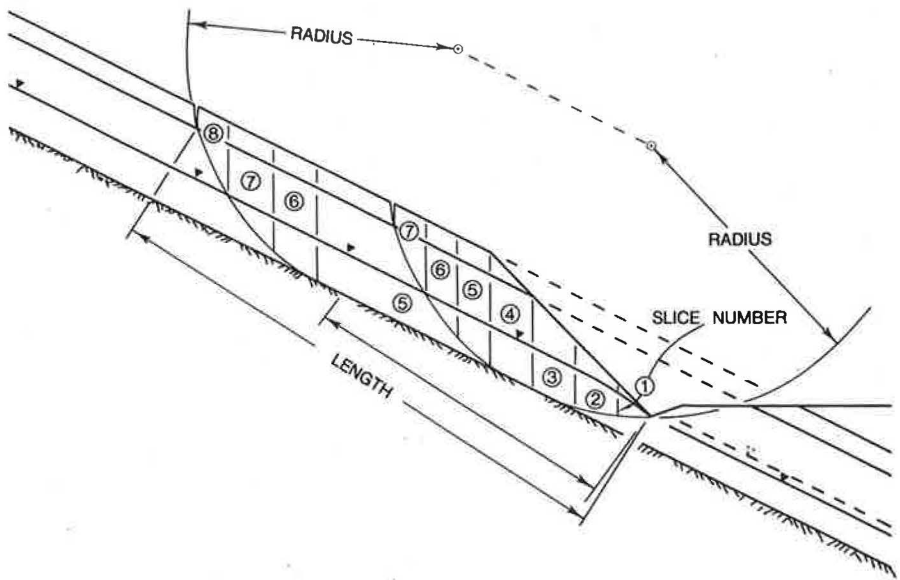


Figure 14. Printout of the level 3 analysis of Figure 13 cross-section data.

```
I.D.: CIRCULAR ARC

OMS BISHOP JANBU
          chord d= 4.9
          chord l= 29.5
TENSION CRACK
               Zw= 2.0
                a= 6.6
                R= 25.0
MIN FS= 0.70
MAX FS= 0.90

SLICE 1
NEW SOIL
 DEN.1 DEN.2 PHI  COH.
 110.0 125.0 32.0 0.0
THETA  d1  dW  X  AL.W
 4.0 0.5 1.0 3.0 33.5

SLICE 2
THETA  dl  dW  X  AL.W
 11.5 1.7 2.8 4.0 28.0

SLICE 3
THETA  dl  dW  X  AL.W
 20.9 3.6 3.8 4.0 26.6

SLICE 4
NEW SOIL
 DEN.1 DEN.2 PHI  COH.
 106.0 125.0 32.0 0.0
THETA  d1  dW  X  AL.W
 31.0 5.5 3.6 4.0 26.6

SLICE 5
NEW SOIL
 DEN.1 DEN.2 PHI  COH.
 103.0 125.0 32.0 0.0
THETA  d1  dW  X  AL.W
 41.5 6.8 2.1 3.0 26.6

SLICE 6
THETA  d1  dW  X  AL.W
 51.5 6.8 1.1 3.0 26.6

SLICE 7
NEW SOIL
 DEN.1 DEN.2 PHI  COH.
 101.0 125.0 32.0 60.0
THETA  dl  dW  X  AL.W
 65.0 4.6 0.0 3.0 0.0

  OMS FS=0.78

  BMS FS=0.87

  JMS FS=0.87

I.D.: TRANSLATIONAL

OMS BISHOP JANBU
          chord d= 6.1
          chord l= 49.5
TENSION CRACK
               Zw= 2.0
                a= 6.6
                R= 25.0
MIN FS= 0.80
MAX FS= 1.00

SLICE 1
NEW SOIL
 DEN.1 DEN.2 PHI  COH.
 110.0 125.0 32.0 0.0
THETA  dl' dW  X  AL.W
 4.0 0.5 1.0 3.0 33.5

SLICE 2
THETA  dl  dW  X  AL.W
 11.5 1.7 2.8 4.0 28.0

SLICE 3
THETA  d1  dW  X  AL.W
 20.9 3.6 3.8 4.0 26.6

SLICE 4
NEW SOIL
 DEN.1 DEN.2 PHI  COH.
 106.0 125.0 32.0 0.0
THETA  dl  dW  X  AL.W
 26.6 5.5 4.0 4.0 26.6

SLICE 5
NEW SOIL
 DEN.1 DEN.2 PHI  COH.
 103.0 125.0 32.0 0.0
THETA  d1  dW  X  AL.W
 26.6 6.8 4.0 16.0 26.6

SLICE 6
THETA  dl  dW  X  AL.W
 36.2 6.8 3.5 4.0 26.6

SLICE 7
THETA  dl  dW  X  AL.W
 49.5 6.8 1.7 4.0 26.6

SLICE 8
NEW SOIL
 DEN.1 DEN.2 PHI  COH.
 101.0 125.0 32.0 60.0
THETA  dl  dW  X  AL.W
 65.0 4.6 0.0 3.0 0.0

  OMS FS=0.88

  BMS FS=0.92

  JMS FS=0.94
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ses. Techniques for data storage and analysis that upgrade the values for geotechnical variables for each landtype as the sample size is expanded (10) will be used.

SUMMARY AND CONCLUSIONS

The concept for a three-level landslide analysis system has been outlined. Important points regarding the system are as follows:

1. Each level of analysis is designed to require its own data base and to provide guidance for land management decisions at that level only. The level of analysis complexity, data required, and accuracy must be commensurate with the type of management decision they are intended to support.
2. A loop that channels levels 2 and 3 data back into the level 1 data base will upgrade the accuracy for future analyses.
3. Although the system described is for soil-mantle failures common in residual and colluvial soils, the concept is a series of building blocks that may be made applicable to rock slope failures by the proper substitutions.
4. Current restrictions on use of this system are not in the analysis techniques that are either in existence or at least feasible for development. The current restrictions are (a) the general lack of a dynamic and easily upgraded storage system and (b) the present state of the art for determining the values for certain geotechnical variables such as ground water concentration and effective tree root strength.

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