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

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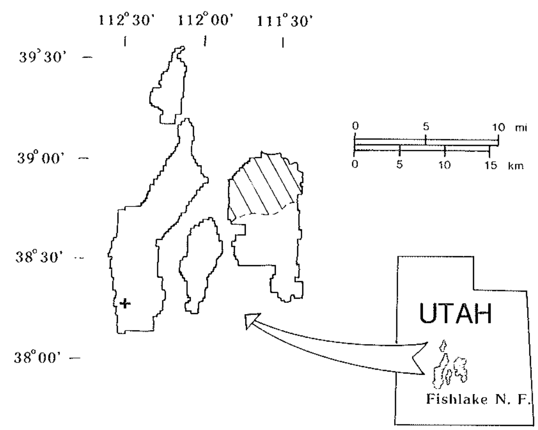
The occurrence of damaging landslides along transportation corridors in the mountainous western United States can be expected to rise with the expansion of the regional transportation network. Because national forests typically encompass major mountain ranges throughout the West, assessing landslide 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-

tions. This facilitates comparison of landslide hazard along a corridor or between corridors.

ASSESSMENT FOR PLANNING

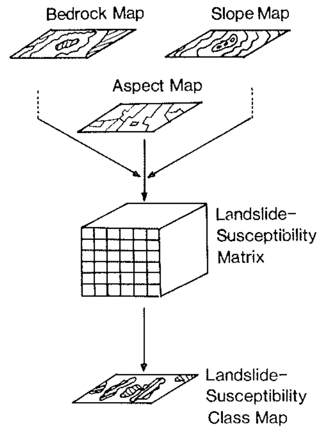
Matrix assessment aids in achieving the planning goal of avoiding reactivation or creation of new landslides along transportation corridors. Matrix assessment is a numerical approach that yields an index of relative landslide risk potential. It employs the key measurable terrain characteristics of bedrock, slope, and aspect. Relative landslide potential for specific locations is defined by discrete combinations of terrain characteristics.

The concept of landslides as threshold phenomena provides the basis for quantitative treatment of landslide potential by using the matrix approach (1). It is possible to numerically define landslide thresholds as the point at which driving forces that promote landslide movement are equal to resisting forces that prevent landslide movement (3). For unfailed slopes, the ratio of driving forces divided by resisting forces is less than the threshold value. The difference between this value and the threshold value is the relative risk of future landslide occurrence. Rather than attempt the difficult task of determining the absolute threshold and the ratio of driving to resisting force values, matrix assessment establishes their relative difference based on past landslide occurrence.

Matrix assessment employs key measurable terrain characteristics. Sharpe (4) categorized basic conditions that favor landsliding as lithologic, stratigraphic, structural, topographic, and organic. Matrix assessment evaluates relative landslide potential in the context of these five condition categories by using bedrock, slope, and aspect as measurable terrain characteristics. Bedrock includes both consolidated and unconsolidated units in an area and is used by formation or mappable member. Differences in physical and chemical factors, including permeability, fractures, and cementation, cause some bedrock units to be more landslide prone than others (4). Landslide potential may be a function of landslide-prone soil derived by weathering of a particular bedrock (5). Slope identifies inclinations of the ground surface susceptible to landsliding (4). It is expressed in percent and grouped in 10 percent classes. Aspect is the compass direction a slope faces, and it is expressed as eight compass direction classes (N, NE, SW, etc.) defined by degrees of azimuth. Aspect is used to include any significant slope orientations that might enhance landsliding by interaction with structural or climatic variables (4,6-10).

Application of matrix assessment begins with an inventory of existing landslides in the area of interest. From this inventory, a matrix of bedrock, slope, and aspect is assembled. The total acres of landslide-disturbed terrain with a given set of bedrock, slope, and aspect characteristics are identified. If all acreage values for every set of bedrock, slope, and aspect are added together, it yields the total acreage of landslides inventoried. A corresponding matrix of all bedrock, slopes, and aspects is developed for the entire study area. The total acreage for all of these combinations equals the total study area acreage. All bedrock, slope, and aspect combinations with no corresponding landslide acreage value define areas with low landslide susceptibility. For all other combinations, the landslide acreage is divided by the corresponding study area acreage to yield the proportion of that combination subject to past landslide disturbance. These proportions are grouped to produce three clusters.

Figure 2. Schematic diagram of landslide-susceptibility mapping.



Grouping is achieved by a nonhierarchical clustering method that begins with an initial partition and attempts iterative improvements (11). The initial partition consists of creating three equal divisions for the range of proportion values. The sum of squared deviations about each group mean, called a W function, is calculated. Values are then moved across the group boundaries and the sum of squared deviations about the group means is recalculated until the minimum value is achieved. The group that contains the lowest range of proportional values defines areas with moderate landslide susceptibility. The group that contains the highest range of proportional values defines areas with extreme landslide susceptibility. The intermediate range of values defines areas with high landslide susceptibility. In each group, the combination of bedrock, slope, and aspect within the defined range of proportional values identifies all unfailed areas that have a particular relative landslide susceptibility. Inventoried landslides identified as inactive are assigned a high landslide-susceptibility rating. Inventoried landslides identified as active are assigned an extreme landslide-susceptibility rating.

The relative landslide-susceptibility values generated by matrix assessment are readily locatable. Each susceptibility rating is defined by one or more discrete sets of terrain characteristics. All map locations with the same set of terrain characteristics will have the same relative landslide-susceptibility rating. Map units are constructed from sets of contiguous points with identical landslide-susceptibility ratings (see Figure 2). (Note: Landslide-susceptibility ratings, defined by the matrix, are assigned to bedrock, slope, and aspect map combinations. Contiguous points with the same rating are grouped into mapping units.)

PLANNING EXAMPLE: WASATCH PLATEAU

Transportation corridors have a major impact on management of the Fishlake National Forest near Salina Canyon on the southern Wasatch Plateau (Figure 3). (Note: The cross-hatched section denotes the location of the area shown in Figure 6.) Interstate 70 between Denver and Los Angeles follows the canyon across the forest. This highway serves as a major conduit for trucks that haul coal from regional mines as well as long-distance traffic. Trucks annually haul 1.8 million tons of coal along an access road to I-70 from a mine on the forest. Two 345-kV powerlines follow a corridor parallel to the southern rim of Salina Canyon. Expansion or development of two access roads to I-70, a 69-kV

powerline, and a coal slurry pipeline are all projected additions to the current transportation network near Salina Canyon.

Matrix assessment was initiated with a revised landslide inventory completed in May 1981. The inventory identified, described, and located 72 landslides and 25 landslide zones greater than one acre in size. Individual landslides range in size from 1 to 810 acres. Landslide zones are areas that exhibit complex or multiple movement. Landslide zones range in size from 49 to 1320 acres. Most, but not all, landslide features are currently inactive. A total of 10 625 acres, which amounts to 4 percent of the study area, is subject to landslide disturbance. Data on bedrock, slope, and aspect collected for every landslide feature were assembled into a matrix form (Figure 4). A total of 42 bedrock, slope, and aspect combinations were represented out of a possible 336 combinations within the study area. Computer manipulation of digitized bedrock and topographic data yielded the corresponding acreages for these 42 bedrock, slope, and aspect combinations within the Wasatch Plateau. Proportions generated by dividing corresponding combination acreages range from 0.01 to 1.00 (Table 1). The resultant equal range partition consisted of 0.01 to 0.31, 0.32 to 0.51, and 0.52 to 1.00 with an initial W function of 0.200 676. Final partitioning consisted of 0.01 to 0.15, 0.16 to 0.51, and 0.52 to 1.00 with a final W function of 0.138 630.

Figure 3. Detailed location map of transportation corridors that cross Wasatch Plateau section of Fishlake National Forest.

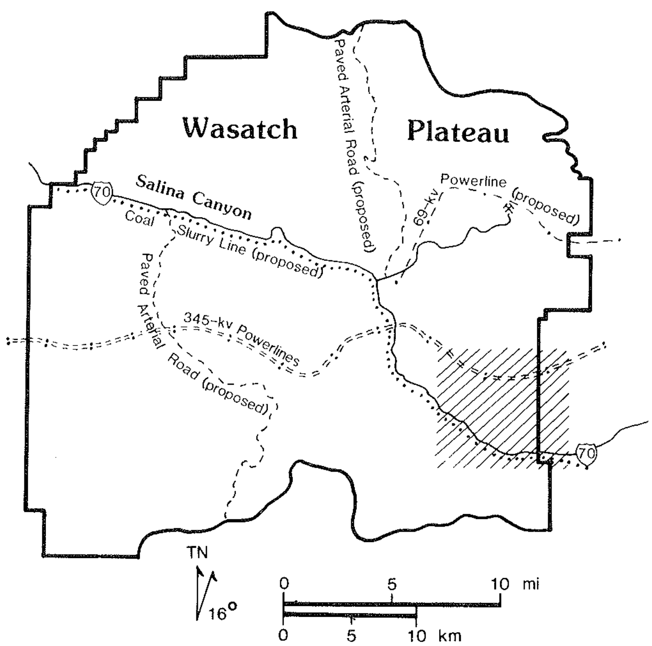


Figure 5 shows a part of the landslide-susceptibility zonation map with I-70, the proposed coal slurry pipeline (heavy dotted line), and the two 345-kV powerlines (dot and dash lines) indicated. [Note: Unshaded areas within the forest boundary (heavy line) have a low susceptibility rating. Light shading shows areas with a moderate susceptibility rating, and heavy shading shows areas with a high susceptibility rating. No areas with an extreme susceptibility rating are present. Accord Lakes 15-min quadrangle is used as the topographic base. Contour level is 250 ft.] Assessment of future route feasibility will include comparing proposed corridors to identify the least landslide-prone corridor and to pinpoint sites that require detailed engineering geology study.

ASSESSMENT FOR MAINTENANCE

A numerical procedure developed by Ogata (2) aids

Figure 4. Sample of matrices that show values for North Horn Formation on Wasatch Plateau.

LANDSLIDE HISTORY MATRIX
MANAGEMENT AREA MATRIX
RATIO

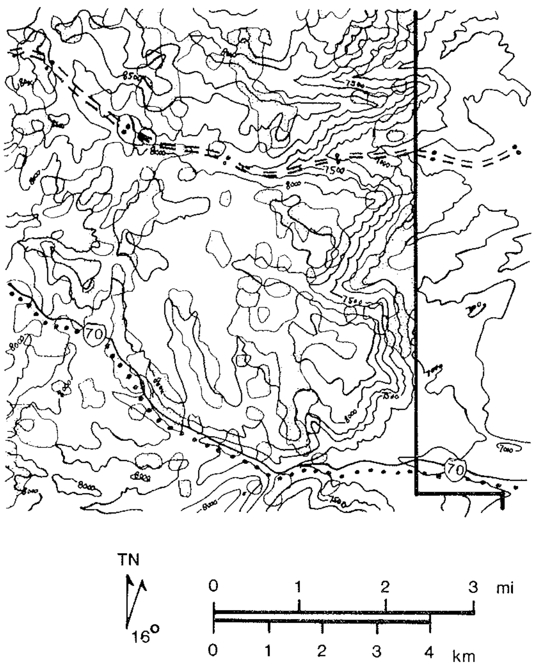
BEDROCK CODED # 5 (North Horn Fm)
(ACRES)

SLOPE	ASPECT NORTH	N-EAST	EAST	S-EAST	SOUTH	S-WEST	WEST	N-WEST	TOTAL BY SLOPE
0-15:	5.0 3718.2 .013	.0 4150.4 .000	238.0 3377.7 .070	.0 4087.9 .000	284.0 2666.9 .106	133.0 2852.4 .047	119.0 2760.1 .043	.0 4037.8 .000	824.0 27651.5
15+-25:	214.0 1431.2 .150	.0 1657.9 .000	214.0 2368.3 .090	134.0 2790.4 .048	1216.0 2574.3 .472	575.0 2275.8 .253	403.0 1936.6 .208	134.0 1720.1 .078	2890.0 16754.7
25+-35:	52.0 761.9 .068	52.0 741.4 .070	111.0 1122.4 .099	143.0 1040.0 .137	10.0 1050.3 .010	96.0 1070.9 .090	137.0 1029.9 .133	48.0 855.1 .056	649.0 7671.9
35+-45:	.0 401.6 .000	38.0 514.8 .074	22.0 638.4 .034	12.0 350.1 .034	12.0 556.0 .022	19.0 638.4 .030	5.0 690.1 .007	12.0 370.8 .032	120.0 4160.2
45+-55:	.0 195.6 .000	.0 298.6 .000	.0 113.3 .000	19.0 205.9 .092	.0 453.0 .000	.0 494.2 .000	4.0 401.8 .010	.0 236.8 .000	23.0 2399.3
55+-65:	.0 103.0 .000	.0 30.9 .000	.0 30.9 .000	.0 92.7 .000	.0 288.3 .000	.0 154.4 .000	.0 61.8 .000	.0 144.2 .000	.0 906.1
65+ :	.0 72.1 .000	.0 10.3 .000	.0 10.3 .000	.0 51.5 .000	.0 61.8 .000	.0 41.2 .000	.0 41.2 .000	.0 20.6 .000	.0 308.9
TOTAL BY ** ASPECT **	316.0 6683.6	90.0 7404.3	585.0 7661.2	308.0 8618.5	1522.0 7650.6	823.0 7527.4	668.0 6921.5	194.0 7385.4	** 43506.0 ** 59852.5

Table 1. Landslide susceptibility partitioning and related W function values that lead to final partition of proportional values.

	Landslide Susceptibility			
Partition	Moderate	High	Extreme	W Value
Initial	0.01 to 0.31	0.31+ to 0.51	0.51+ to 1.00	0.200 676
Left	0.01 to 0.25	0.25+ to 0.51	0.51+ to 1.00	0.168 319
Left	0.01 to 0.21	0.21+ to 0.51	0.51+ to 1.00	0.142 149
Left	0.01 to 0.15	0.15+ to 0.51	0.51+ to 1.00	0.138 630
Left	0.01 to 0.14	0.14+ to 0.51	0.51+ to 1.00	0.159 149
Initial	0.01 to 0.15	0.15+ to 0.51	0.51+ to 1.00	0.138 630
Left	0.01 to 0.15	0.15+ to 0.47	0.47+ to 1.00	0.261 244
Right	0.01 to 0.15	0.15+ to 1.00	1.00+ to 1.00	0.805 297
Final	0.01 to 0.15	0.15+ to 0.51	0.51+ to 1.00	0.138 630

Figure 5. Landslide-susceptibility zonation for part of Wasatch Plateau.



assessment of landslide problems in maintenance situations. Specifically, it applies to landslide activity induced by construction of highways, railways, and powerlines in mountainous terrain. The procedure assumes that initiation of new landslides and natural stabilization of existing landslides on a slope follows a stochastic process. Rather than examine landslide activity in terms of exogenous and endogenous factors or mechanical analysis, Ogata considers change in activity over time to forecast future landslide conditions. Assuming a stochastic process introduces the element of uncertainty into the analysis (12). This incorporates the variability of both basic and initiating conditions that contribute to landslide activity for a given slope (2,4). Ogata's analysis approach is not carried through to a model that yields probabilities. Rather, the approach identifies whether the disturbed slope is tending toward stability or instability over time, the expected number of landslides per unit area, and the projected time for an active landslide to assume a stable configuration. This information is excellent guidance in prioritizing areas that need artificial stabilization and projecting future maintenance work load. Ogata notes that a separate analysis is needed on slopes underlain by different bedrock types. This need is clearly illustrated by examples that apply the analysis approach at two dam and reservoir sites (2).

To apply this procedure, an initial survey locates all landslides within the area of interest. This inventory would likely occur after construction when landslide problems attributable to the project develop. After several years pass, this inventory is repeated. Careful note is made of the number of landslides from the initial survey that are now inactive or stable. This number is divided by the number of years between initial and subsequent inventories. Ogata (2) calls this value the decrement value (K). The number of new landslides that developed since the initial survey is also noted in the subsequent inventory. This number is divided by the number of years between the initial and subsequent inventories. This value is called the increment value (U). If the increment value is divided by the decrement value, i.e., U/K, it yields the equilibrium number. The equilibrium number represents the net change, over time, between occurrence of new landslides and termination of old ones. Comparing U/K with the initial number of landslides present (N_O) indicates whether the slopes are tending toward a more stable or unstable condition: (a) $N_O > U/K$, increasing stability; (b) $N_O < U/K$, increasing instability; and (c) $N_O = U/K$, no change from initial stability conditions.

The equilibrium number (U/K) can be used to provide an index of potential landsliding for a slope. This is accomplished by dividing the equilibrium number by the area being evaluated. The computed value is the potential number of landslides, per unit area, based on the current trend of landslide activity. It is termed "slidability" by Ogata. Slidability enables direct comparison of relative landslide problems between areas of differing size.

Finally, the average life span of a landslide can be computed. This is based on the half-life of existing landslides (2). It uses the decrement value (K) in the following formula:

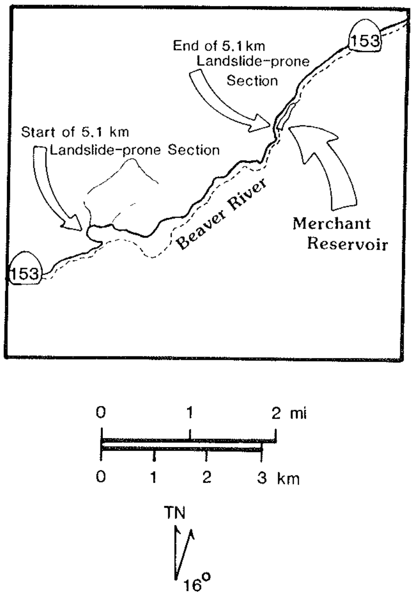
$$\tau = 0.693\,(1/K) \qquad (1)$$

where τ is the average time (in years) that a landslide will be active.

MAINTENANCE EXAMPLE: BEAVER CANYON

A number of roads on the Fishlake National Forest require periodic maintenance due to landslide activity. UT-153, which provides access to the Tushar Mountains via Beaver Canyon, chronically requires maintenance due to landslide activity (Figure 6). (Note: Stipled area is the Big Cove landslide, an old, natural landslide. Beaver Canyon widens significantly above Merchant Reservoir.) The Utah Department of Transportation maintains this highway. However, the national forest is obliged to provide disposal sites to stockpile landslide debris removed from the highway. This limits the amount of sediment that would otherwise enter the Beaver River. Most of the landslide activity occurs along an 8.2-mile section, which was widened and paved in 1962. In this section, the highway was constructed along a natural slope break that corresponds to the contact between basaltic lava flows overlain by ash-flow tuffs (13). An initial survey identified 22 landslides along the road section in 1978. This survey involved ground observation, but an aerial photograph survey may be appropriate in other situations. In 1981, 10 landslides were identified. The basic data on the area and landslides along UT-153 are as follows: observation period, 3 years; road length, 8.2 miles; and number of landslides: N_O = 22, inactive = 13, and new = 1. The computed values for

Figure 6. Generalized location map of landslide-prone section of UT-153, which crosses Fishlake National Forest.



landslide activity along UT-153 for the three-year observation period are as follows: increment value (U) = 0.3; decrement value (K) = 4.3; equilibrium number (U/K) = 1; slidability (per mile) = 0.6; and average life span = 1 year.

The following generalizations about landslide activity can be derived from these computed values. The equilibrium number (U/K) of 1 is considerably less than the original landslide total (N_O) of 22. This is an apparent sharp decrease in landslide activity and an increase in slope stability over the past three years. It is unclear if this reflects a long-term trend. Landsliding has occurred for 19 years along this road section. Annual fluctuation in landslide activity has varied greatly: 1978, 22 landslides; 1979, 12 landslides; 1980, 26 landslides, and 1981, 10 landslides. In this particular situation, a three-year observation period is minimal with a five- or seven-year period being preferred. This would ensure the long-term validity of the computed trend. Slidability is calculated as 0.6 landslide/mile. The average life span of a landslide is computed as a year or less. Slidability and life span indicate a reduced need for landslide debris disposal areas. Maintenance needs can be expected to decrease over the next few years. Comparison of these values with other road sections subject to continuing landslide problems would prioritize remedial work to the most troublesome sections.

CONCLUSIONS

As transportation corridors proliferate in the mountainous West, so too will the occurrence of damaging landslides. To avoid the costly impact of landslide activity, more effective assessment of landslide hazard is needed. Quantitative approaches minimize subjective interpretations and quantify results for comparison of alternatives. These approaches are especially effective when based on measurable terrain characteristics related to basic conditions that influence landslide activity. To facilitate comparison of landslide hazard, the approaches must assign results to geographic locations. Assessment of landslide hazard achieves the best results in the planning of transportation corridors. Quantitative assessment of landslide hazard along existing corridors can maximize the return on limited remedial funds.

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