# Regional Concept of Landslide Occurrence

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The report covers the initial phases of a basic study of landslides. The long-range objective is the development or refinement of quantitative methods for analyzing the degree of stability of natural slopes. The underlying principle of the research is that the types of landslides that occur in a given geographic region are relatively limited, and the number of variables present in a given region will be reduced or the range of values limited. Under such an approach a greater possibility exists for the establishment of a comprehensive generalized approach.

The phase of the research reported in the current report covers the basic concepts and the efforts to use physiographic provinces of the United States as the basis for regional considerations. Case histories from the literature, from the files of the authors, and from the questionnaire received by the HRB Committee on Landslide Investigations were the source of data. The landslides were classified in accordance with the new system proposed by the HRB committee, and a summary is included of the types of landslides that occur within the several regions.

Possibilities of immediate use of the results are recognized. If the types of landslides that occur within a region are limited, the highway engineers in a specific area can learn more rapidly and accurately how to analyze and treat the landslides encountered.

● THE DEGREE of importance of the landslide problem is a variable quantity. In some parts of the world, major mass movements represent the ultimate in catastrophe and occur with great frequency. On the other hand, some geographic areas rarely encounter the phenomenon, and are only conscious of the tragic implications through newspaper and periodical accounts. For highway engineers, the economic factors are a glaring reality, but vary also with locale.

From the viewpoint of the soils engineer, "landslides" can and do occur in all areas, regardless of the terrain or material because landslides represent a special type of stability problem (1), that is, a failure of the soil in shear. It is true that in the common conception of landslides, natural slopes are envisioned, and such failures as tunnel cave-ins, trench displacements, and foundation failures are not included. Since the latter types of difficulties occur as a result of man's activity, the locale is a function only to the extent that good soil engineering is a function of the geographic area.

By restricting one's consideration of landslides to failures which involve natural slopes, the indications of an "area-problem" become immediately apparent. Many references and implications in technical literature suggest such an approach. However, past studies of landslides have concentrated upon complete classification, historical aspects, individual case histories, or generalized, over-simplified solutions.

No effort is made in the following discussion to supply a rigorous background on landslides. The reader is referred to a recent publication of the Highway Research Board for a comprehensive treatment (2). The classical theories of soil mechanics applicable to the problem are also omitted, but they are available in the several texts on the subject.

## REVIEW OF THE LANDSLIDE PROBLEM

Landslides have been the target for study for many years, and quite recently an almost forgotten manuscript by Collin (3) shows that good, quantitative efforts were underway in France in the early 1840's. The bibliography published by the Highway Research Board (4) includes 267 articles or texts on the subject prior to 1950.

The analysis of a landslide can be subdivided into (1) classification, (2) recognition, (3) analysis, and (4) treatment. Since classification has no real significance to the engineer except as it aids in the analysis, one could think of the approach as a three-step operation. However, classification is the common tool for grouping similar landslides and will be considered independently.

The geological sciences have been historically, and by definition, interested in major mass movements. Particularly, the field of geomorphology (science of landforms) has been vitally concerned. With reference to the formation of topographic forms, Ladd (5) has said "erosion, alone, should be given less credit for playing the major role." Geologic studies have been of infinite value in establishing classification and historical implications. While many authorities have produced their own system of classifying, the basic form of the system suggested by Sharpe (6) has prevailed. From a historical viewpoint, hypothesizing as to transportation, sedimentation, and loading will continue as a basis for complete understanding, and perhaps, formulation of new theories. As to analysis and treatment, the field of geology has relied upon experience and judgment to provide the solution. Many case histories attest to the contribution of the geologist and the engineer in such endeavors.

With the advent of the theory of soil mechanics (7) efforts were increased to obtain analyses and treatments based upon quantitative techniques. Unfortunately, the classical mechanics theories were developed for idealized materials, and could rarely be directly applied. The resultant status includes a "missing link," or a break, in the orderly progression from the physical and historical description through a rigorous, rational analysis to the treatment.

As applications of theoretical soil mechanics became more common, a basic weakness in the existing landslide classification schemes became evident, and systems similar to the new HRB classification (2) were developed. The major revision consisted of grouping together those landslides with similar behavior relative to stress-strain conditions.

From a quantitative viewpoint, perhaps the most significant weakness in analysis and treatment is the inability to measure accurately the shearing resistance of the material. Of almost equal concern is the problem of predicting and estimating the stress conditions within an earth mass. A theory which will adequately explain landslide phenomena must relate all types and all conditions, regardless of the variables present. Furthermore, an understanding of the existing geologic and mechanics literature, properly interpreted and incorporated, should provide a tremendous impetus to the development of such a theory. It is within this latter comprehensive framework that the current research at Ohio State University is centered.

## PURPOSE AND SCOPE

The current phase of the problem is directed toward a description of the landslide problem in the United States, and the immediate objective is the delineation of the severity of the landslide problem within the several physiographic sections of the country. In addition to focusing attention methodically upon areas established through sound considerations of geography, geology, and climate, landslides will be examined according to the mechanics of failure as represented by the new type of classification system. The advantages of such an approach lie in the ability to (1) obtain maximum utilization of the existing literature, (2) isolate certain variables, and (3) provide immediate educational aid by reducing the problem scope in a given area.

The existing study is preliminary in nature and was intended to serve as an initial or feasibility stage. The data are limited to those available from the questionnaire circulated by the HRB committee (2), case histories from the literature, and files of the authors. Only the continental United States has been considered, and only landslides related to natural slopes. Failures which develop because of man's activities on and around natural slopes are meant to be included.

## CLASSIFICATION OF LANDSLIDES

Landslides will be considered as "downward and outward movements of slope-forming materials—natural rocks, soil, artificial fills, or combinations of these materials." (2) Since the basic intent of the current investigation is related to the development of a quantitative theory for the treatment of landslides, a classification system was desired which would reflect stress-strain considerations. The principles of the method described by the Highway Research Board Committee were therefore adopted for the beginning studies. The method consists of dividing mass movements into one of the three following categories (Fig. 1): (1) falls, (2) slides, and (3) flows. A fourth group, complex, consists of landslides which have the characteristics of more than one of the preceding three. The three factors which reflect engineering properties are the bases for subgroupings: (1) type of material before movement (bedrock or soil), (2) amount of moisture, and (3) relative particle displacement within the moving mass.

Falls can be typified by the rock weathering of exposed bedrock slopes, with the talus at the toe representing the accumulation of many "landslides." In actuality, the size of the moving mass can range from small particles to tremendous blocks. Falls are defined as those landslides which develop because of tension failures in bedrock or soil, followed by free-fall, leaping, bounding, or rolling down the slope until equilibrium is established. The tension failures caused by over-stressing are a result of (1) too steep slopes or undermining, (2) weakening of the mass by the formation of cracks or fissures, or (3) pressure within fissures or cracks. The first is common in sedimentary bedrock deposits in which weak shales underlay more resistant sandstones or limestones. The second effect is prevalent in fissured clays (because of processes such as dessication) or in exfoliated bedrock. Landslides under such conditions are also aggravated by steep slopes. Pressure within cracks or fissures can come from either hydrostatic forces or through ice formation. Although such phenomena may appear to be a compressive-type action with the resultant displacement producing instability due to unbalanced moment, inability to withstand tension will always be a factor although at times insignificant. For the purposes of the current discussion only rockfall and soilfall will be considered. The former consists of bedrock (prior to movement) and the latter is concerned with soil or unconsolidated material.

Slides are landslides caused by a shear failure along warped or plane surfaces. Where the shear-surface is reasonably circular in shape (in two dimensions), the movement is called a slump, while a movement with an essentially planar slip-surface is termed a block glide. "Rock" or "earth" is used as a prefix to differentiate between bedrock and unconsolidated material. Following the initial shear, if the moving mass disintegrates or acts as a group of individual particles rather than as a unit block, the slide is further subdivided into rockslide or debris slide. The former is for bedrock, while the latter is for soil. The latter grouping, as to the behavior after shear, is less significant for preventive purposes than for corrective, historic, or geomorphic considerations.

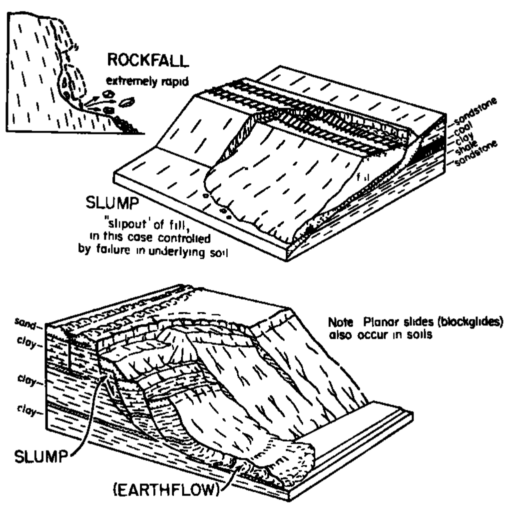


Figure 1. After "Landslides and Engineering Practice." HRB Committee on Landslide Investigations.

Flows are landslides in unconsolidated material, resulting from plastic deformation of an earth mass or from viscous-type flow and caused by insignificant

TABLE 1

PHYSICAL DIVISIONS OF THE UNITED STATES
(After N. M. Fenneman)

I. Laurentian Upland
  1. Superior Upland
II. Atlantic Plain
  2. Continental Shelf
  3. Coastal Plain
    a. Embayed section
    b. Sea Island section
    c. Floridian section
    d. East Gulf Coastal Plain
    e. Mississippi Alluvial Plain
    f. West Gulf Coastal Plain
III. Appalachian Highlands
  4. Piedmont province
    a. Piedmont Upland
    b. Piedmont Lowlands
  5. Blue Ridge province
    a. Northern section
    b. Southern section
  6. Valley and Ridge province
    a. Tennessee section
    b. Middle section
    c. Hudson Valley
  7. St. Lawrence Valley
    a. Champlain section
    b. Northern section
  8. Appalachian Plateaus
    a. Mohawk section
    b. Catskill section
    c. Southern New York section
    d. Allegheny Mountain section
    e. Kanawha section
    f. Cumberland Plateau section
    g. Cumberland Mountain section
  9. New England province
    a. Seaboard Lowland province
    b. New England Upland section
    c. White Mountain section
    d. Green Mountain section
    e. Taconic section
  10. Adirondack province
IV. Interior Plains
  11. Interior Low Plateaus
    a. Highland Rim section
    b. Lexington Plain
    c. Nashville Basin
    d. Possible western section
  12. Central Lowland
    a. Eastern lake section
    b. Western lake section
    c. Wisconsin Driftless section
    d. Till Plains
    e. Dissected Till Plains
    f. Osage Plains
  13. Great Plains province
    a. Missouri Plateau, glaciated
    b. Missouri Plateau, unglaciated
    c. Black Hills
    d. High Plains
    e. Plains Border
    f. Colorado Piedmont
    g. Raton section
    h. Pecos Valley
    i. Edwards Plateau
    k. Central Texas section
V. Interior Highlands
  14. Ozark Plateaus
    a. Springfield-Salem plateaus
    b. Boston "Mountains"
  15. Ouachita province
    a. Arkansas Valley
    b. Ouachita Mountains
VI. Rocky Mountain System
  16. Southern Rocky Mountains
  17. Wyoming Basin
  18. Middle Rocky Mountains
  19. Northern Rocky Mountains
VII. Intermontane Plateaus
  20. Columbia Plateaus
    a. Walla Walla Plateau
    b. Blue Mountain section
    c. Payette section
    d. Snake River Plain
    e. Harney section
  21. Colorado Plateaus
    a. High Plateaus of Utah
    b. Uinta Basin
    c. Canyon Lands
    d. Navajo section
    e. Grand Canyon section
    f. Datil section
  22. Basin and Range province
    a. Great Basin
    b. Sonoran Desert
    c. Salton Trough
    d. Mexican Highland
    e. Sacramento section
VIII. Pacific Mountain System
  23. Cascade-Sierra Mountains
    a. Northern Cascade Mountains
    b. Middle Cascade Mountains
    c. Southern Cascade Mountains
    d. Sierra Nevada
  24. Pacific Border province
    a. Puget Trough
    b. Olympic Mountains
    c. Oregon Coast Range
    d. Klamath Mountains
    e. California Trough
    f. California Coast Ranges
    g. Los Angeles Ranges
  25. Lower California province

shearing resistance along a surface of rupture. Generally, flows will develop in very weak materials only, although if the masses are extensive, slow plastic deformations can occur in relatively strong materials that are stressed beyond their elastic range. While flows are most commonly associated with very wet conditions, dry non-cohesive soils can produce rock fragment flows, sand runs, or loess flows, with the nomenclature expressing the particle size. The fine-grained materials produce earthflows or mudflows, where the principal difference is in the amount of water present. A quantitative delineation has not been established for the preceding two types, but the latter term is intended to designate the most fluid movements. Where a mixture of rock fragments and fine-grained soil is involved, the term "debris" describes the material while the terms "debris avalanche" and "debris flow" are used in a parallel sense to earthflow and mudflow. Since little or no cohesion is available in such materials, once failures have developed movement is relatively rapid.

The phenomenon commonly referred to as creep, would fall into the category of a slow earthflow. Under the current status of knowledge, a separate delineation on the basis of speed of movement is not particularly practical for treatment considerations. The differentiation between flows and slides is more critical and, on occasion, very difficult. Earthflows that produce tension cracks at the top of the slide, but distort under plastic deformation without the development of a continuous surface of shear, may be mistaken for a slump or block glide. Also troublesome are the landslides that develop as a slide, but, after a minimum of displacement, take on the appearances of a flow. For preventive measures, the latter type of failure would be analyzed as a slide, but for corrective purposes, as a flow.

From an engineering viewpoint, the size of the landslide has a special significance, and could logically form a basis for classification. However, for the current study, the volume of the moving mass is considered as a landslide variable, but not as a factor in classification.

## BASIS FOR PHYSIOGRAPHIC CLASSIFICATION

The division of the United States into physiographic areas is a systematic attempt to divide the topography into homogeneous units with respect to certain fundamental concepts established in the field of geomorphology. Briefly, these principles state that three major factors control the evolution of landforms; namely, the initial structure, the erosive processes continually modifying it, and the stage of its destruction. In general, a change in any of these three factors will produce a uniquely different landform. The converse is also true; that is, differences between landforms can be traced to some differences in any of the three factors (8).

The geologic structure is a dominant influence in the landform modification. Included are characteristics such as the nature of the material; physical hardness of the constituent materials and their susceptibility to chemical weathering; the mode of deposition and subsequent stress history; shearing strength; and structural discontinuities and weaknesses such as joints, bedding planes, faults, folds, and others.

Geomorphic processes and corresponding forces consist of the many physical and chemical actions by which the original structure is modified. Most important of these can be associated with stream, wind, wave, glacial, and weathering actions. The effects of these stresses imposed upon the landforms are reflected in the significantly different erosional, residual, and depositional features produced by each of the geologic agents. For instance, the erosional features produced by streams are gullies, valleys, gorges, and canyons; residual features include peaks and monadnocks; and depositional features consist of alluvial fans, flood plains, and deltas.

Modification, and eventual destruction, of the landforms is considered to occur in stages which are generally designated by the geomorphologists as youth, maturity, and old age. Qualifying adjectives, such as early and late, are often used to designate substages. Chronological age is not inferred, but, rather, the degree of destruction as expressed by topographic characteristics is involved. In youth, topography is relatively undissected with only a few streams. Valleys have V-shaped cross-sections and their depths will depend upon the altitude of the region. Mature topography consists

TABLE 2

LIST OF HRB QUESTIONNAIRES AND RELATED CORRESPONDENCE USED IN THE STUDY

| | | |
|---|---|---|
| | I State Highway Departments (30) | |
| Alabama | Maryland | Ohio |
| Arkansas | Massachusetts | Oregon |
| California | Michigan | Pennsylvania |
| Colorado | Minnesota | Rhode Island |
| Delaware | Mississippi | South Carolina |
| Georgia | Missouri | Texas |
| Idaho | Montana | Utah |
| Illinois | New Hampshire | Vermont |
| Kentucky | New Mexico | Washington |
| Maine | North Carolina | West Virginia |
| | II. State Geological Survey (6) | |
| | Florida | |
| | Maryland | |
| | New Jersey | |
| | Oklahoma | |
| | Pennsylvania | |
| | Vermont | |
| | III. Railroad Companies (12) | |
| | IV U S Bureau of Reclamation (6) | |
| | Region III | |
| | Region V | |
| | Region VI | |
| | Region VII | |
| | California | |
| | New Mexico | |
| | V United States Geological Survey (3) | |
| | California | |
| | Colorado | |
| | Washington | |
| | VI. Miscellaneous (9) | |

mostly of slopes of hillsides and valley-sides. Drainage divides are sharp and maximum possible relief exists. Vertical cutting ceases and lateral destruction becomes important. In reacing old age, valleys become extremely broad with gentle slopes. Considerable development of flood plain and stream meandering prevails. For a more complete treatment of the subject of landform evolution see Sharpe (6) or Lobeck (9).

In accordance with the preceding principles, the United States was divided into eight major divisions representing rather extensive areas of strongly characterized constructional forms such as plains, plateaus, highlands, and mountains. These were subdivided into provinces and sections which represent uniquely different landform areas and destructional history. Delineation of the boundaries of most units corresponds closely to strongly characterized geologic features so that the line of demarcation may be exact to within a few feet. In some areas, however, boundaries are vague and may vary up to several miles (Table 1).

The following quotation from Krynine and Judd (12) are of interest with reference to landslides and physiographic areas:

> "Serious consideration should be given to the regional concept of landslide classification. According to this concept the slides within a geomorphic (or physiographic) province may be defined as an area within which the method of deposition of rocks and soils is approximately the same, landforms are similar, and the climate is approximately identical. This regional concept is accepted by some of the workers interested in landslides, but evidence is still needed."

> "The study of slides leads to the conclusion that the slide characteristics within a given region should depend on the geology, topography, and climate of that region. In fact, often certain slide characteristics are reported either from within a large typical area or from two areas that are similar in some respects. For example, the tremendous Colorado landslides often consist primarily of large boulders. In older glaciated zones both rock and soils are often remarkably stable as in some New England regions, and vice versa, in the regions of the so-called "young geology," e. g., in some parts of the San Francisco Bay area, slide scars on natural slopes are so abundant that they really should be considered as characteristic landforms of the region."

From the foregoing discussion on the destructional stages it appears logical to expect some correlations to exist between the various stages of a specific landform and the severity and type of landslides. According to Sharpe (6) and others, landslides are most likely to occur when the valley walls are the steepest during the transitional period from youth to maturity. Primary road construction in such areas will necessitate considerable cut and fill operations. Any disturbance introduced in the form of a cut or fill invites a situation more favorable for landslide occurrence.

TABLE 3

LIST OF MOST TROUBLESOME LANDSLIDE TYPES
(From Questionnaires of the HRB Committee on Landslide Investigations)

| State Highway Department | Rank 1 | 2 | 3 |
|---|---|---|---|
| Arkansas | Slides | -- | -- |
| California | Earth Slump | Earth slump-flow | Debris slide |
| Colorado | Earth flows | -- | -- |
| Delaware | Earth slump | -- | -- |
| Idaho | Earth slump-flow | Earth slump | Debris avalanche |
| Illinois | Earth slump | Earth flow | Debris slide |
| Kentucky | Debris slide | Earth slump | Rock slump |
| Maine | Earth slump | Earth flow | -- |
| Maryland | Not major problem | | |
| Massachusetts | Earth slump-flow | -- | -- |
| Michigan | Soil fall | Lateral spreading | -- |
| Mississippi | Earth slump | -- | -- |
| Missouri | Earth slump | Earth flow | -- |
| Montana | Slides | Rock fall | Solifluction |
| New Hampshire | Debris slide only | | |
| New Mexico | Rock and earth block glides | | |
| North Carolina | Rock slump | Rock fall | Earth slump-flow |
| Ohio | Earth slump | Earth flow | Rock fall |
| Oregon | Earth slump-flow | Earth slump | Debris avalanche |
| Pennsylvania | Slides | Falls | Flows |
| Vermont | Flows | -- | -- |
| Washington | Earth and rock slumps | Earth slump-flow | Mudflow |
| West Virginia | Earth slump | Earth flows | Rock fall |

## PROCESSING DATA

As a preliminary step, the data obtained from the case histories in the questionnaires submitted to the HRB Landslide Investigations Committee (2) were tabulated and analyzed. Information of interest included the total dollars expended by the reporting agency, types of landslides, sizes of the moving masses, and geologic formations associated with slope failures. Additional comments and data on the shape of the slip-surface, type of correction, plan view sketch of the area, causes, etc., were also recorded and used to check landslide classification and areal considerations. The physiographic sections corresponding to specific mass movements were identified from a physiographic map (13). Questionnaires used in the study are listed in Table 2. A total of 24 highway department questionnaires was available, as well as negative statements from six others. The added data from state and federal agencies, railroad companies, and others were also of value.

Table 3 contains a summary of the types of landslides encountered most frequently by the various highway departments. Such information was helpful in determining the landslide types prevalent in the physiographic sections within a state. Furthermore, the preponderance of earth slumps and earth flows throughout the country suggests a degree of similarity as to type of problem encountered.

Tabulations were also made of the type and size of individual landslides reported and the physiographic sections in which they occurred. Tables 4 and 5 are summaries of these data. A total of 527 landslides was studied, with a significantly large group of earth slumps, rock falls, and debris slides. Of the landslides for which sizes were available, more than half were relatively small (less than 50,000 cu yds). The tables also indicate that more case histories were available from the physiographic sections in the eastern part of the country. Whether such a situation developed because of more

TABLE 4

SUMMARY OF NUMBERS OF LANDSLIDES OF VARIOUS MAGNITUDES

| Physiographic Section No. | Total Number of Landslides Reported | Physiographic Section No. | Volume less than 5000 cu yds | Physiographic Section No. | Volume 5000-50,000 cu yds | Physiographic Section No. | Volume 50,000-500,000 cu yds | Physiographic Section No. | Volume more than 500,000 cu yds |
|---|---|---|---|---|---|---|---|---|---|
| 1. 8d | 100 | 1. 12d | 30 | 1. 12d | 27 | 1. 8e | 6 | 1. 14a | 6 |
| 2. 8e | 83 | 2. 8e | 14 | 2. 8e | 21 | 2. 8c, 12a, | 2 | 2. 24g | 5 |
| 3. 24f | 67 | 3. 8d | 8 | 3. 16 | 8 | 12f, 13a, | | 3. 20c | 2 |
| 4. 12d | 64 | 4. 6b | 5 | 4. 9d, 24g | 4 | 13f, 16, | | 4. 13f, 19, | 1 |
| 5. 8c | 62 | 5. 9b, 10, | 3 | 6. 24f | 3 | 20c, 23a | | 23b, 24b, | |
| 6. 6b | 32 | 7. 4a, 6c | 2 | 7. 4a, 11b, | 2 | 10. 3d, 4a, | 1 | 24d, 24f | |
| 7. 19 | 25 | 13f, 14a | | 12a, 20c, | | 9b, 12d, | | | |
| 8. 14a | 19 | 11. 3d, 4b | 1 | 23b, 24a, | | 12e, 13e, | | | |
| 9. 12e | 14 | 8c, 12a, | | 24b | | 14a, 19 | | | |
| 10. 16 | 13 | 12f, 13a, | | 14. 1, 3c, | 1 | 21c, 24b | | | |
| 11. 20c | 12 | 13b, 19, | | 3d, 3e, | | 24c | | | |
| 12. 24g | 10 | 22e, 24c | | 8c, 8d, | | | | | |
| 13. 9b | 8 | 24f | | 9b, 9c, | | | | | |
| 14. 4a, 13f | 6 | | | 11a, 12b, | | | | | |
| 16. 9d, 12a | 5 | | | 12c, 13a, | | | | | |
| 18. 12f, 13a, | 4 | | | 13b, 13f, | | | | | |
| 23b, | | | | 20a, 21b, | | | | | |
| 21. 3d, 6c, 10, | 3 | | | 24d | | | | | |
| 11b, 13b, 24a, | | | | | | | | | |
| 24b | | | | | | | | | |
| 28. 9c, 13d, | 2 | | | | | | | | |
| 21b, 23a, 24c, | | | | | | | | | |
| 24b | | | | | | | | | |
| 34. 1, 3c, 3e, | 1 | | | | | | | | |
| 9b, 7a, 11a, 12b, | | | | | | | | | |
| 12c, 13e, 20a, 21c | | | | | | | | | |
| Total | 587 | | 82 | | 98 | | 33 | | 19 |

landslides or more thorough coverage is not known.

If one assumes that the amount of money expended is a measure of severity, the results of the questionnaires are of interest. Of the 24 state highway departments reporting, only four indicated that landslide costs exceeded $500,000 per year. Five additional states estimated that between $100,000 and $500,000 were expended annually, while 10 showed an annual cost of less than $100,000. Of the ten railroad companies reporting, only two indicated annual costs in excess of $100,000. Assuming that the 24 states not submitting questionnaires expended less than $25,000 per year, an estimate of the annual expenditure for landslides on highways in the continental United States would approach $10,000,000.

In order to rate the physiographic sections as to the degree of severity, a base was needed for the judgment. Frequency of occurrence as a highway or engineering problem would be different from frequency as a problem in a specific area; that is, landslides may occur in a locale where few highways or other engineering structures are located and could go unreported in an engineering study. Other bases for severity could be size of the moving mass, dollars expended by a company or agency, or number of landslides per unit of area or per mile of highway. For the first attempt, the frequency of occurrence, size of the moving mass, and dollars expended per year were combined in an arbitrary, qualitative manner to arrive at a rating using only the questionnaire data. Another factor in the evaluation was the negative effect of the authors' not having a report from a given state. In effect, it assumes that the problem could not be severe or a questionnaire would have been submitted. Obviously, other reasons could have accounted for the absence of the questionnaire.

Several discrepancies were immediately apparent, and attempts to amplify and to further delineate the areas were made. Such adjustments were partially based upon published records and case histories. The work of Ladd (5), the Highway Research Bibliography (4), and Ta Liang (10) were of significant value in this respect. In many cases, the preliminary classification as to severity was verified. However, the following changes were considered justified, although direct verifications with geologists and engineers were not completed:

1. Sections 16, 19, 20a, and 23a were changed to major severity.
2. Sections 12d, 18, and 20d were changed to intermediate severity.
3. Sections 3a, 13c, 21a, 21d, 21e, 22a, 22e, and 24e were changed to minor severity.

The final results are shown in Table 6 with the preceding list of modifications and are shown graphically in Figure 2.

While the degree of severity as shown in Figure 2 is felt by the authors to be both reasonable and sound, several cautionary statements are in order. First, the delineation between the groups is open to question, although it is probable that even after more study the major severity group will remain as classed. Three groups could be reasonably anticipated for the intermediate and minor groups. It is also probable that the "few to none" class will remain as such.

Secondly, the results tend to indicate the problem severity from an engineering viewpoint of the past and present. As the more remote areas are attacked, some of the areas may become more troublesome. A study and severity analysis from a pure landslide basis is highly desirable.

TABLE 5

SUMMARY OF NUMBERS OF LANDSLIDES OF VARIOUS TYPES REPORTED

| Physiographic Section No. | Rock Fall | Physiographic Section No. | Soil Fall | Physiographic Section No. | Rock Slump | Physiographic Section No. | Block Glide | Physiographic Section No. | Soil Slump |
|---|---|---|---|---|---|---|---|---|---|
| 8d | 56 | 12a | 1 | 24g | 4 | 24g | 5 | 12d | 50 |
| 8e | 33 | 8e | 1 | 13d | 2 | 13b | 1 | 8c | 40 |
| 6b | 16 | | | 4a | 2 | | | 8d | 30 |
| 19 | 7 | | | 9 with | 1 | | | 8e | 25 |
| 8c | 4 | | | | | | | 19 | 12 |
| 9 with | 1 | | | | | | | 12e | 12 |
| | | | | | | | | 14a | 10 |
| | | | | | | | | 9b | 5 |
| | | | | | | | | 6b | 5 |
| | | | | | | | | 12f | 4 |
| | | | | | | | | 3 with | 3 |
| | | | | | | | | 10 with | 1 |
| Total | 125 | | 2 | | 17 | | 6 | | 212 |

| Physiographic Section No. | Rock Slide | Physiographic Section No. | Debris Slide | Physiographic Section No. | Dry Flows | Physiographic Section No. | Earth Flows |
|---|---|---|---|---|---|---|---|
| 6b | 8 | 19 | 19 | 16 | 8 | 8c | 8 |
| 8d | 2 | 8e | 16 | 9b | 1 | 8e | 5 |
| 13f | 2 | 8d | 12 | 9d | 1 | 19 | 3 |
| 19 | 1 | 12d | 8 | | | 23b | 2 |
| 24b | 1 | 8c | 5 | | | 24a | |
| | | 6b | 3 | | | 8 with | 1 |
| | | 9b, 9d, 21b | 2 | | | | |
| | | 7 with | | | | | |
| Total | 14 | | 76 | | 10 | | 28 |

Thirdly, the failure of the physiographic sections to relate perfectly to the severity of the landslide problem was noted in a number of cases. For example, section 12e which covers most of the glaciated areas of Ohio, Indiana, and Illinois was interpreted as a major problem in western Illinois, but is certainly not so reported for the same physiographic section in Ohio and Indiana. The eastern portion of West Virginia (section 8e), the western edge of section 3d, northern part of section 12f, and the western edge of section 13f all typify areas that appear to differ from the major portion of the physiographic section.

Finally, the results thus far are quite general, and major differences, particularly in highly localized areas, are to be anticipated. The values of the work thus far completed are highly restrictive, and are of more interest as a guide to further endeavors than for immediate utility.

## FUTURE RESEARCH

The immediate goal for the future will be the bolstering of data for the areas where the information available was most sparse. By continuation of the literature study, correspondence with engineers and geologists, and field evaluation, the results shown in Figure 2 can be stated more accurately. Subsequent steps will also include, (1) a closer scrutiny of the magnitude of the mass and the types of landslides which occur in the various areas, (2) development of more data as to the geological formations associated with mass movement, (3) a search for a better basis than pure physiography for regional classification purposes, and (4) evolving a guide for landslide considerations within specific regions.

The conditions in West Virginia can be used to illustrate the degree of detail which will be needed for the various areal groupings, because of the authors' familiarity with

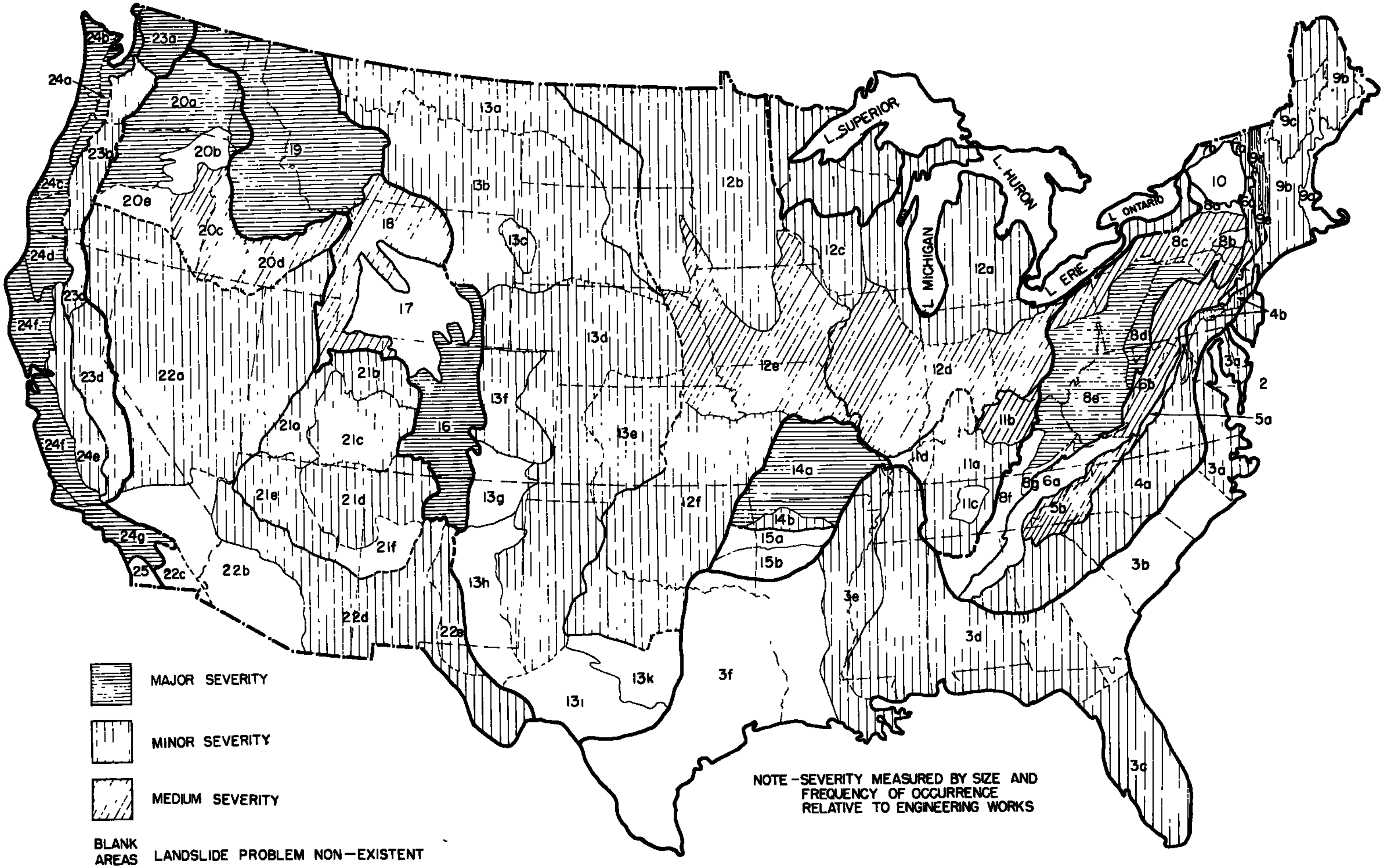


Figure 2. Landslide severity of the United States. Based upon "Physical Divisions of the United States." N. M. Fenneman.

TABLE 6

RATING OF LANDSLIDE SEVERITY
(Based upon HRB Questionnaires and partial literature search)

| | | |
|---|---|---|
| I. | Major Severity | |
| | 8d. | Allegheny Mountain section |
| | 8e. | Kanawha section |
| | 14a. | Springfield-Salem Plateaus |
| | 16. | Southern Rocky Mountains |
| | 19. | Northern Rocky Mountains |
| | 20a. | Walla Walla Plateau |
| | 23a. | Northern Cascade Mountains |
| | 24a. | Puget Trough |
| | 24b. | Olympic Mountains |
| | 24c. | Oregon Coast Range |
| | 24d. | Klamath Mountains |
| | 24f. | California Coast Ranges |
| | 24g. | Los Angeles Ranges |
| II. | Medium Severity | |
| | 5b. | Southern section of Blue Ridge province |
| | 6b. | Middle section of Valley and Ridge province |
| | 8c. | Southern New York section |
| | 11b. | Lexington Plain |
| | 12d. | Till Plains of the Central Lowland province |
| | 12e. | Dissected Till Plains of the Central Lowland province |
| | 18. | Middle Rocky Mountains |
| | 20c. | Payette section |
| | 20d. | Snake River Plain |
| III. | Minor Severity | |
| | 1. | Superior Upland |
| | 3a. | Embayed section |
| | 3c. | Floridian section |
| | 3d. | East Gulf Coastal Plain |
| | 3e. | Mississippi Alluvial Plain |
| | 4a. | Piedmont Upland |
| | 4b. | Piedmont Lowlands |
| | 6c. | Hudson Valley |
| | 7a. | Champlain section |
| | 9b. | New England Upland section |
| | 9c. | White Mountain section |
| | 9d. | Green Mountain section |
| | 9e. | Taconic section |
| | 11a. | Highland Rim section |
| | 12a. | Eastern Lake section |
| | 12b. | Western Lake section |
| | 12c. | Wisconsin Driftless section |
| | 12f. | Osage Plains |
| | 13a. | Glaciated Missouri Plateau |
| | 13b. | Unglaciated Missouri Plateau |
| | 13c. | Black Hills |
| | 13d. | High Plains |
| | 13e. | Plains Border |
| | 13f. | Colorado Piedmont |
| | 14b. | Boston "Mountains" |
| | 21a. | High Plateaus of Utah |
| | 21b. | Uinta Basin |
| | 21c. | Canyon Lands |
| | 21d. | Navajo section |
| | 21e. | Grand Canyon section |
| | 22a. | Great Basin |
| | 22d. | Mexican Highland |
| | 22e. | Sacramento section |
| | 23b. | Middle Cascade Mountains |
| | 23c. | Southern Cascade Mountains |
| | 23d. | Sierra Nevada |
| | 24e. | California Trough |
| IV. | Non-Existent Problem | |
| | 2. | Continental Shelf |
| | 3b. | Sea Island section |
| | 3f. | West Gulf Coastal Plain |
| | 5a. | Northern section of Blue Ridge province |
| | 6a. | Tennessee section |
| | 7b. | Northern section of the St. Lawrence Valley province |
| | 8a. | Mohawk section |
| | 8b. | Catskill section |
| | 8f. | Cumberland Plateau |
| | 8g. | Cumberland Mountains |
| | 9a. | Seaboard Lowland section |
| | 10. | Adirondack province |
| | 11c. | Nashville Basin |
| | 11d. | Western section of the Interior Low Plateaus |
| | 13g. | Raton section |
| | 13h. | Pecos Valley |
| | 13i. | Edwards Plateau |
| | 13k. | Central Texas section |
| | 15a. | Arkansas Valley |
| | 15b. | Ouachita Mountains |
| | 17. | Wyoming Basin |
| | 20b. | Blue Mountain |
| | 20e. | Harney section |
| | 21f. | Datil section |
| | 22b. | Sonoran Desert |
| | 22c. | Salton Trough |
| | 25. | Lower California province |

TABLE 7

SUMMARY OF TYPE AND SIZE FOR GROUP OF CENTRAL WEST VIRGINIA LANDSLIDES

| Landslide Type | Less than 5000 | 5000-25,000 | 25,000-50,000 | Greater than 50,000 | Total |
|---|---|---|---|---|---|
| Earthflow | 1 | 4 | 1 | 1 | 7 |
| Slump | 4 | 4 | 3 | 4 | 15 |
| Earth Block Glide | 0 | 0 | 3 | 0 | 3 |
| Total | 5 | 8 | 7 | 5 | 24 |

TABLE 8

SUMMARY OF 742 VIRGINIA LANDSLIDES[1]

| Geologic Formation | Percent of Total Landslides Studied | Approximate Outcrop Area (sq mi) |
|---|---|---|
| Alluvium | 7 | |
| Dunkard | 21 | 2500 |
| Monongahela | 20 | 1500 |
| Conemaugh | 33 | 1500 |
| Allegheny | 2 | 1500 |
| Pottsville | 9 | 4000 |
| Miscellaneous | 8 | 13000[2] |
| Total | 100 | 24000 |

[1] Conducted by John L. Wray, former geologist, West Virginia State Road Commission.
[2] Includes Alluvium.

the region. The state of West Virginia contains approximately one-third of the Kanawha Section (8e), one of the areas of major severity. Much has been written specifically about the landslide problem in the region (14, 15, 16, 17, 18). Other studies not previously reported in the literature have also been conducted. A survey completed in November, 1952, indicated more than 750 known landslides in the state. Unfortunately, complete information on all of these landslides is not available. A partial analysis from the viewpoint of geologic formations was conducted in 1953 by John L. Wray, a geologist formerly with the Department of Soil Mechanics of the West Virginia State Road Commission. The results are shown in Table 7.

All but a small area of eastern West Virginia lies in the Kanawha Section. A map of the location of the many landslides was submitted to the HRB Landslide Committee along with the questionnaire. Practically no landslides were reported northwest of the line that extends southwesterly from the southwest tip of Maryland to Williamson, in southwest West Virginia. The line is considerably west of the eastern boundary of the Allegheny Section. Thus, physiographic sections in themselves are not sufficient to describe landslide susceptibility. In a map which accompanies a Civil Aeronautics Administration report (11), soil boundaries are drawn which come much closer to properly delineating the landslide area of the Kanawha Section.

Also available to the authors were the data from a special study of certain landslides in Braxton and Gilmer counties in central West Virginia. These landslides (Table 8) illustrate the range of sizes and types of mass movement which are most common in West Virginia. It will be noted that the vast majority are relatively small (less than 50,000 cu yds) and more than half involve less than 25,000 cu yds. It is also evident that slumps (soil) and earthflows are most frequently encountered.

Reports by Ladd (5), Baker (19), and others have indicated the presence of numerous rock falls in West Virginia. While very little general data as to size and frequency are available, the problem can be described as general throughout the landslide-susceptible area. With notable exceptions, the masses involved are not great since the falls consist principally of fine-grained weathering products, but they do include individual boulders as large as 25 cu yds. The failures usually develop as the result of differential weathering; that is, a weak, less resistant layer underlies a blocky, exfoliated or jointed strata.

The additional data from West Virginia indicates that the Conemaugh, Dunkard, and Monongahela formations of the Pennsylvanian System are related to 74 percent of the landslides studied. Furthermore, earth slumps, earth block glides, earthflows, and rockfall represent the greatest problem in terms of frequency of occurrence. Most of the landslides involve mass movements of quantities less than 50,000 cu yds. It is also known that the present physiographic boundary is not exact in defining landslide susceptibility. Much more is known and much more is needed concerning West Virginia and the remainder of the Kanawha Section, but the restrictive nature of the problem in the area is evident.

With reference to developing data as to the geologic formations associated with landslides, Table 9 lists the principal offenders as shown by the questionnaire. As in the preceding example for the Kanawha Section, it appears certain that relatively few geologic formations are associated with the landslides in a specific region. The availability of such information should aid in the development of a comprehensive theory.

Landslide types within a state or physiographic section are listed in Table 2, and the range of sizes of the moving masses is given in Table 3. Systematic evaluation of these data will simplify the landslide problem in a specific area and will permit a better understanding by highway engineers. The absence of a clear concept of the limited nature of landslide occurrence in a locale currently requires a complete understanding of all types of mass movements. The result is a hopeless jumble of terminology and

TABLE 9

LANDSLIDE SUSCEPTIBLE FORMATIONS

| Formation or Stratigraphic Sequence | Location | Reference[1] |
|---|---|---|
| Pierre, Carlile, Graneros Shales, Dakota Sandstone, Denver and Araphoe | Colorado | 1 |
| Pierre Shale and Fort Union overlain by till | North Dakota | 1 |
| Gaconade and Cherokee | Missouri | 1 |
| Morrison and Sundance Clays and Shales | Gros Ventre River Valley-Middle Rocky Mountains Section-Wyoming | 2 |
| Chinle Shales | Vermillion and Echo Cliffs-Grand Canyon Section-Arizona | 2 |
| Cox Shales | Diablo Plateau-Mexican Highland Section-Texas | 2 |
| Kaibab overlying weak shales and gypsum beds | Unikaret Plateau-Arizona | 2 |
| Fruitland Shale | LaPlata County-Navajo Section-Colorado | 2 |
| Columbia Lava overlying soft lacustrine beds | Northern Cascade Mountains-Washington | 2 |
| Navajo Sandstone overlying extensive fractured and jointed formation | Zion Canyon-High Plateau of Utah Section-Utah | 2 |
| Eagle Ck. volcanic breccia underlying Columbia lava | Columbia River Gorge-Oregon | 1 |
| Eden shales and limestones | Harrison County, Kentucky | 3 |
| Quaternary alluvium (37%), Franciscan sandstone (34%), serpentine (7%) and Franciscan greenstone (6%) | San Francisco North Quadrangle, California Coast Ranges Section-California | 1 |
| Nespelem silts, Astoria siltstone and Eocene shales | Washington | 1 |
| Hawthorne clays | Florida | 1 |
| Massive basalt underlain by weaker layers | Columbia Plateaus Province | 3 |
| Bearpaw shale and bentonite seams | Fort Peck Dam-Montana | 3 |
| Payette | Payette section-Idaho | 1 |
| Merchantville and Woodbury clays, Woodbridge | New Jersey | 1 |
| Tablot-Wicomica, Wissahickon | Delaware | 1 |
| Rincon Shale, Serpentine | California Coast Ranges-California | 1 |
| Jackson Clays | Natchez Trace Parkway-Jackon-East Gulf Coastal Plain Mississippi | 3 |
| Mancos Shales overlying: | | |
| a. competent Mesaverde sandstone | Montezuma County-Canyon Lands Section-Colorado | 3 |
| b. glacial till | Telluride area-Southern Rocky Mountain Section-Colorado | 3 |
| Pottsville, Allegheny, Conemaugh, Monongahela, Dunkard | Pennsylvania | 1 |
| Eden shales and limestones, Conemaugh and Dunkard shales | Ohio | 1 |
| Conemaugh and Dunkard shales | Kanawha section-West Virginia | 1 |

[1] 1. Highway Research Board Questionnaire submitted to Committee on Landslide Investigations.
2. Tompkin, J. M., and Britt, S. B., "Landslides—A Selected Bibliography," Bibliography No. 10, HRB (1951).
3. Liang, Ta, "Landslides—An Aerial Photographic Study." Unpublished Tesis for Degree of Doctor of Philosophy, Cornell University (1952).

empirical relationships for the engineer with insufficient time to develop a comprehensive background.

Perhaps the most significant indication from the preliminary studies reported here is the fact that physiographic section boundaries are not sufficient in themselves for delineating landslide severity. The most striking example is the Dissected Till Plains Section of the Central Lowland (12e) where landslides appear to be heavily concentrated along the Mississippi River, within a relatively small percentage of the total section area. Part of this discrepancy may be because of improper location of boundaries, or of the difficulties inherent in attempting to group the highly variable components of the earth's surface. The fact that unexplained differences exist means that either the physiographic regional bases are not sound for relating landslide susceptibility or the areas are too large and a further subdivision is needed.

An interesting observation relative to apparent physiographic discrepancies is the presence of landslides near major water courses. The Pacific Coast, the Great Lakes, the Mississippi River, and the Ohio River and its tributaries are all prime examples. Ta Liang (10) and others have also noted the relationship between rivers and landslides. The basic tenent of areal erosion and the attendant landslide influence suggests such a relation. However, the difference in severity is not completely explained by the presence or absence of a major water course. Perhaps some combination of physiography, surface drainage system, pedology (11), or other dominant factors will provide the ultimate basis for classification.

## CONCLUSIONS

Based upon the Highway Research Board questionnaires submitted by various state and federal agencies, companies, and consultants, and upon a limited literature search the following conclusions are offered:

1. Efforts to relate degree of severity of landslides to standard physiographic sections produced encouraging results, although several deviations were noted. The degree of severity was defined as a function of the effect on engineering works as opposed to general landslide susceptibility. Both magnitude of moving mass and frequency of occurence were considered in assigning the measure of severity.
2. Unquestionably, the most severe landslide problems exist in the following physiographic sections: Allegheny Mountain section (8d), Kanawha section (8e), Springfield-Salem Plateaus (14a), Southern Rocky Mountains (16), Northern Rocky Mountains (19), Walla Walla Plateau (20a), Northern Cascade Mountains (23a), Puget Trough (24a), Olympic Mountains (24b), Oregon Coast Range (24c), Klamath Mountains (24d), California Coast Ranges (24f) and Los Angeles Ranges (24g).
3. Equally evident is the fact that landslide problems in the following sections are practically non-existent: Continental Shelf (2), Sea Island section (3b), West Gulf Coastal Plain (3f), Northern section of the Blue Ridge Province (5a), Tennessee section (6a), Northern section of the St. Lawrence Valley province (7b), Mohawk section (8a), Catskill section (8b), Cumberland Plateau (8f), Cumberland Mountains (8g), Seaboard Lowland section (9a), Adirondack province (10), Nashville basin (11c), Western section of the Interior Low Plateaus (11d), Raton section (13g), Pecos Valley (13h), Edwards Plateau (13i), Central Texas section (13k), Arkansas Valley (15a), Ouachita Mountains (15b), Wyoming Basin (17), Blue Mountains (20b), Harney section (20e), Datil section (21f), Sonoran Desert (22b), Salton Trough (22c), and Lower California province (25).
4. The remaining physiographic sections showed a range between the preceding two, and a precise delineation is somewhat open to question.
5. Continued research in the establishment of landslide-susceptible areas is recommended, with the following major objectives:

   a. Continued literature search in order to incoporate all existing knowledge into the framework, and to lend impetus to the study;

   b. A detailed examination of the several physiographic sections in order to better establish the degree of severity, the types of landslides that occur, the range in magnitude of the landslides, and the geologic formations which are associated with mass movements;

c. Examination of possible modifications and subgroupings which will better define a region's susceptibility to landslide problems;

d. Development of a comprehensive description of the landslide problem on a regional basis in order to provide breadth of knowledge and to simplify landslide treatment within a specific area;

e. With the better understanding that will result from such a systematic delineation it will be possible to study the development of a rational theory for landslide treatment. The existing practice of applying an adjusted theory to the problem is leading to its own form of empiricism because of the absence of a clear concept of the basic components.

## ACKNOWLEDGMENTS

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