Landslides Along the Columbia River Valley Northeastern Washington

GEOLOGICAL SURVEY PROFESSIONAL PAPER 367

Landslides Along the Columbia River Valley Northeastern Washington

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With a section on Seismic Surveys

By ROBERT M. HAZLEWOOD

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Descriptions of landslides and statistical analyses of data on some 200 landslides in Pleistocene sediments

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By Fred O. Jones, Daniel R. Embody, and Warren L. Peterson

ABSTRACT

Landslides occur so frequently in the surficial deposits along the upper valley of the Columbia River that they affect greatly engineering developments and land use. Most of the recent landslides took place in the Pleistocene deposits bordering Franklin D. Roosevelt Lake, the Grand Coulee Dam reservoir, which was slowly and intermittently filled during the construction of Grand Coulee Dam (1933 to 1942). Many landslides occurred while the lake was filling; many have occurred since. Downstream from Grand Coulee Dam landsliding has occurred in several places since the beginning of construction. Geologic investigations were made intermittently from 1942 to 1948 and continuously from 1948 to 1955 in an effort to establish criteria for predicting the probable amount of land that will be affected by sliding. The area of study extends along the upper 200 miles of the Columbia River valley in Washington, reaching upstream from Grand Coulee Dam along Franklin D. Roosevelt Lake to Canada and downstream from Grand Coulee Dam along the Columbia River nearly to Chief Joseph Dam. Many fresh landslides in a nearly uniform physical setting presented an unusual opportunity for a study of geologic processes and for a statistical analysis of landslide data.

More than 300 landslides in the Pleistocene terrace deposits were examined. Slides were classified into type groups, so that each type might be analyzed and compared with the others. The geologic environment was subdivided into the classification factors—material, ground-water conditions, terrace height, drainage, original slope, submergence, culture, and material removal. These factors were again subdivided into quantitative or qualitative categories that could be determined by field examinations.

The key measurement of a landslide was taken to be the ratio $HC{:}\,VC$, where HC and VC are, respectively, the horizontal and vertical distances from the foot to the crown of the landslide taken at midsection normal to the slope. The $HC{:}\,VC$ ratio was correlated with the classification units of the geologic environment. The most extensive statistical analysis was done on data from slump-earthflow landslides. Of the eight classification factors analyzed, only material, ground water, original slope, and submergence proved to be significantly related to the $HC{:}\,VC$ ratio. A formula was developed for predicting the $HC{:}\,VC$ ratio of slump-earthflow landslides.

The stability of natural slopes was investigated by comparing data from slopes on which slides have not occurred with data from slopes on which slides have occurred. The analysis included a consideration of material, ground water, terrace height, original slope, and submergence. A formula was developed for predicting the stability of natural slopes.

The glacial geology of selected areas was mapped. The landslides in these areas are described.

To illustrate the practical application of the slope stability and landslide data, detailed landslide-classification studies were made of the lakeshore land in the Ninemile area along Franklin D. Roosevelt Lake and in the Alameda Flat area along Lake Rufus Woods (the Chief Joseph Dam reservoir).

The techniques of geologic classification and statistical analysis described in this report will assist geologists and engineers in judging the stability of natural slopes and in estimating the extent of impending landslide action.

INTRODUCTION

By Fred O. Jones

Landslides occur so frequently in the surficial deposits along the upper valley of the Columbia River that they become an important factor in engineering developments and land use. Geologic investigations of the landslides were made intermittently from 1942 to 1948 and continuously from 1948 to 1955. This report summarizes the results of these investigations. The area included in these studies extends along the upper 200 miles of the Columbia River valley in Washington, reaching upstream from Grand Coulee Dam along Franklin D. Roosevelt Lake to the international boundary, and downstream from Grand Coulee Dam along the Columbia River nearly to Chief Joseph Dam (fig. 1).

Such a large number of fresh landslides in a nearly uniform geologic setting presented an ideal opportunity for study of landslide processes and for a statistical analysis of landslide data. The application of statistical methods is a new approach to the analysis of landslides and the stability of natural slopes.

Most of the recent landslides have been related to the construction of Grand Coulee Dam, especially to the consequent filling of Franklin D. Roosevelt Lake (the Grand Coulee Dam reservoir). Construction of the dam was begun in 1933. The level of the backwater was slowly and intermittently raised as construction proceeded until the dam was completed and full reservoir level was first attained in 1942 thus creating a lake 144 miles long and raising the water level 350 feet at the dam.

Landslides occurred with unusually great and unexpected frequency in the bordering Pleistocene deposits as Franklin D. Roosevelt Lake filled. Because of the damage to property adjacent to the reservoir and the

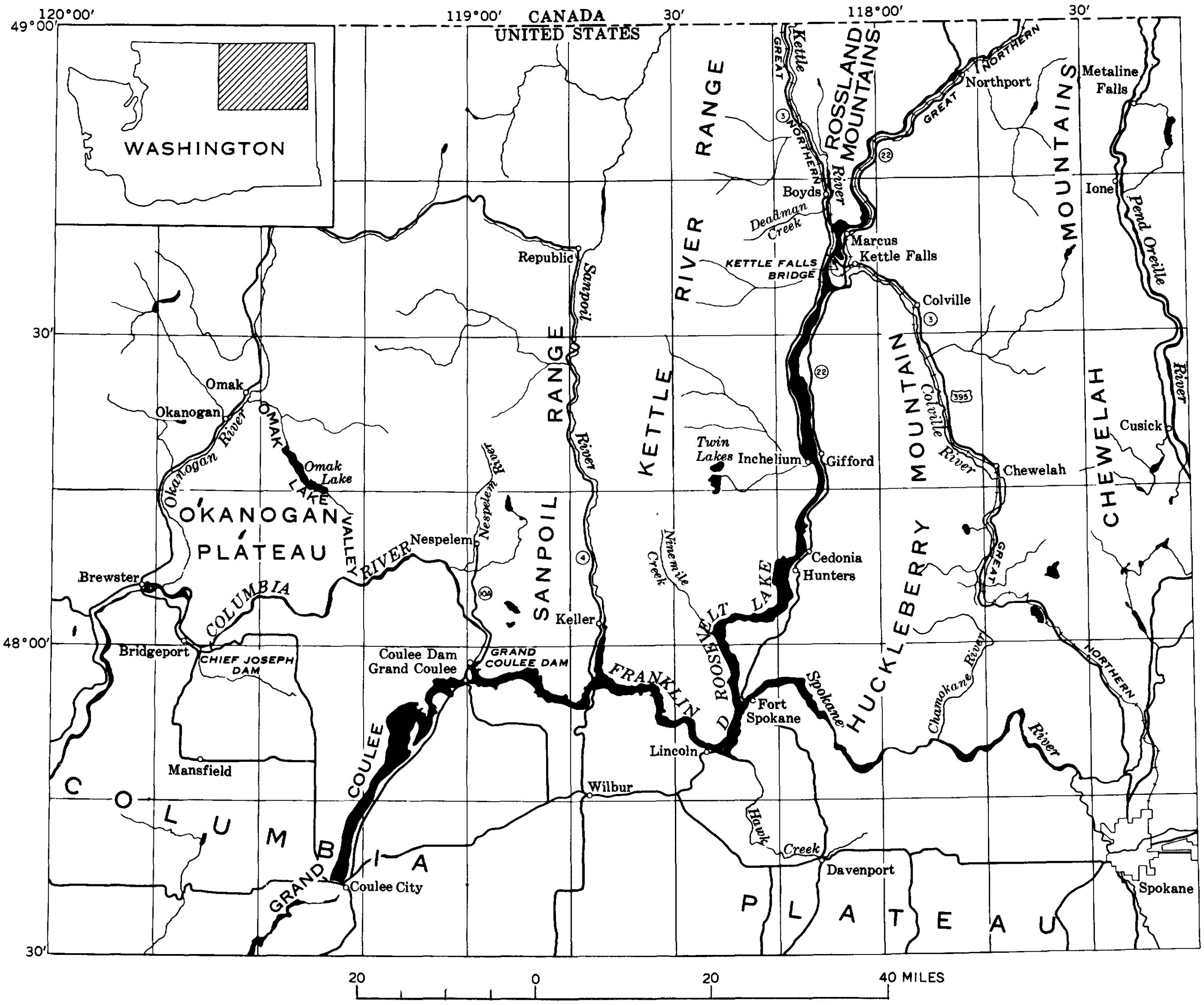

FIGURE 1.—General index map of the Columbia River valley of northeastern Washington.

threat to human lives, a study of the landslides was begun by the senior author in 1942 for the Bureau of Reclamation. The geologic conditions and topographic relations were examined, and the 600 to 700 miles of lakeshore lands were classified generally into five groups: landslides likely, landslides unlikely, slide areas, bedrock, and indeterminate. The indeterminate classification was necessary as data were often insufficient to make a valid determination of the landslide potential. Particular attention was directed to areas where landslides might destroy private property or endanger lives. Where privately owned land was found to be potentially dangerous, the U.S. Government offered to purchase the property.

In 1948 the Geological Survey began research studies on Franklin D. Roosevelt Lake in technical cooperation with the Bureau of Reclamation and the National Park Service, the two Federal agencies most concerned with administrative problems of property adjacent to the lake.

In 1950, in cooperation with the Corps of Engineers, investigations were extended to include a section of the Columbia River valley between Grand Coulee and Chief Joseph Dams. A geologic setting similar to that of Franklin D. Roosevelt Lake exists in the upstream part of the Chief Joseph reservoir (Lake Rufus Woods). Landslides had been frequent along the river in this stretch, and because it was possible to study the valley before flooding by Lake Rufus Woods, investigations were extended to include that part of the reservoir which had similar geologic conditions. The investigations were discontinued in 1955.

The practical purpose of these investigations was to establish criteria for predicting the probable amount of land which will be affected by landslides so that maximum use may be made of lands along the lake. More than 300 landslides have been studied in relation to their geologic environment. Classifications were devised to subdivide the environmental factors so that their separate and combined effects on groups of similar landslides could be analyzed and evaluated.

Statistical methods employed consisted of the analysis of variance and covariance, chi-square tests, multiple regression, and discriminant-function analysis. Each important analysis is presented in brief summary and computational detail is omitted. The section headed "Statistical techniques," page 69 discusses methods used and the purposes which they were intended to accomplish.

The only topographic maps available for studies made along Franklin D. Roosevelt Lake in the years 1942 to 1946 were the river survey sheets, "Plan of Columbia River, International Boundary to Rock Island Rapids (below Wenatchee) Washington, Department of the Interior, U.S. Geological Survey," which were surveyed in 1930. These maps were used though they were limited in extent and accuracy and were inadequate for the work. To provide a basis for detailed geologic and engineering studies, as well as for other uses, the Geological Survey began the topographic mapping of all the 15-minute quadrangles along the Columbia River valley from the Omak Lake valley to latitude 48°30′ N. These new topographic maps became available during the last few years of investigation. The Coast and Geodetic Survey made a hydrographic survey of Franklin D. Roosevelt Lake in 1947 and 1948. This hydrography and the new topography of most of the project area, along with repeated aerial photography, have provided an invaluable basis for the geologic and engineering studies of the landslide features.

REGIONAL PHYSIOGRAPHIC AND GEOLOGIC SETTING

Northeastern Washington is comprised of two strikingly different physiographic subdivisions—the mountainous highlands to the north and the nearly flat Columbia Plateau to the south. The boundary between these subdivisions, with minor exceptions which are outlined later, follows the general east-west trend of the Spokane and Columbia Rivers (fig. 1). The plateau on the south is a part of the vast lava plains which spread over a large part of the Pacific Northwest. The highlands, which lie north of the boundary, are made up of north-south trending valleys between low subparallel mountain ranges. The principal north-south valley is occupied by the Columbia and Kettle Rivers and is a southern extension of the Selkirk Trench.

Of the several minor extensions of the plateau lavas north of the Spokane-Columbia River valley, only two are particularly significant. One of these is the triangular-shaped Okanogan Plateau bounded on the south by the Columbia River, on the northeast by the Omak Lake valley and on the northwest by the Okanogan River valley. Omak Lake valley is an informal name used here for the large valley that contains Omak Lake and extends from the Okanogan River valley to the Columbia River valley. The second significant minor extension is the Spokane Plateau, an irregular group of tongues of the Columbia Plateau which extend north of the Spokane River (Weaver, 1920).

The Columbia River enters the United States at about longitude 117°38′ (fig, 1). It flows southwestward for 40 miles in a moderately broad valley which is between the Rossland Mountains on the northwest and the Chewelah Mountains on the southeast. At the southern tip of the Rossland Mountains the Columbia River is joined by the Kettle River from the north and the Colville River from the southeast. Downstream from these junctures, the Columbia flows southward for 60 miles in a broad valley which lies between the Kettle River Mountains on the west and the Huckleberry Mountains on the east. The rocks exposed in the valley walls along this upper 100 miles are principally limestone, marble, quartzite, schist, gneiss, and granite of Paleozoic and Mesozoic ages (Pardee, 1918; Weaver, 1920).

A few miles below its confluence with the Spokane River, the Columbia turns sharply to the westward and follows a sinuous north-northwest course along the edge of the Columbia Plateau. The sharp change in the course of the river resulted from the creation of the lava plateau in Miocene time. From the mouth of the Spokane River to the Omak Lake valley, bedrock formations on the left bank [1] of the valley are principally lava flows of the plateau and bedrock formations on the right bank are granitic rocks of the Colville batholith.

During the Pleistocene epoch the Cordilleran continental glacier formed one or more times in the intermontane plateau region of British Columbia (Dawson, 1891; Johnston, 1926). The number of ice invasions into the United States area is not known but during the Wisconsin stage ice lobes pushed down southward-trending valleys into eastern Washington, Idaho, and western Montana. Three of these ice lobes entered the area considered here: the Okanogan lobe which occupied the Okanogan River valley, the Sanpoil lobe which occupied the Sanpoil River valley and the Columbia lobe which occupied the part of the Columbia River valley north of the Columbia Plateau. The

[1] Left and right bank refer to the left and right as one is facing downstream.

maximum extent of these lobes has been mapped by Bretz (1923) and Flint (1937).

During the times of ice invasion and recession glaciofluvial and glaciolacustrine sediments were deposited in the Columbia River valley. Deposits in the Columbia River valley upstream from the Nespelem River were first described and named the Nespelem silt by Pardee (1918). These deposits are preserved in terrace remnants the highest of which occur on both sides of the valley at altitudes ranging from 1,720 to 1,900 feet (the Nespelem silt terrace of Flint, 1935). This terrace is found in the Columbia River valley upstream from Omak Lake valley. Pardee concluded that the Nespelem silt was a glaciolacustrine fill deposited in a lake ponded in the Columbia River valley.

The first extensive work on the glacial deposits and erosional features of the Grand Coulee area was done by Bretz (1923, 1932), who concluded that the Nespelem silt was deposited in a lake that was ponded in the Columbia River valley by the Okanogan glacier lobe. The lake drained through the Grand Coulee which had been cut during one or more earlier glaciations.

Subsequent work by Flint (1935), and Flint and Irwin (1939), on the Pleistocene sediments of the Columbia River valley upstream from the mouth of Okanogan River confirmed Bretz's conclusions. Flint and Irwin concluded that all or most of the Pleistocene sediments of the Columbia River valley near Grand Coulee Dam were apparently deposited during a single major advance and recession of the Okanogan glacier lobe, which occurred subsequent to the advance or advances associated with the cutting of the Grand Coulee.

Pardee's definition of the Nespelem silt is based on the interpretation that only one lake stage is involved in the deposition of the Pleistocene sediments. Evidence found this during investigation, shows that more than one lake stage occurred. The name "Nespelem silt" now means little other than Pleistocene lake and stream deposits of the upper Columbia River valley and tributary valleys. The word "silt" in the term "Nespelem silt" is misleading, because, as pointed out by Flint (1936), much of the fill is not composed of silt-sized particles. Probably from 25 to 50 percent of the fill in the Columbia River valley between the Omak Lake valley and Kettle Falls is sand and gravel. The name "Nespelem silt" is not used subsequently in this report.

CULTURAL DEVELOPMENTS

David Thompson, surveyor, geographer, and fur trader, who explored the Columbia River valley of British Columbia beginning in 1800, was the first white man known to record his presence in the upper Columbia River valley of Washington (Elliot, 1918, p. 14). His journal records that on June 19, 1811, he reached the Kettle Falls of the Columbia River. Thompson and his men constructed a canoe at the site of the falls and journeyed downstream to the river's mouth (Fuller, 1931, p. 81).

Many legendary figures of the exploration and fur-trading era followed. The most noteworthy events of the exploration period were the arrival of Lewis and Clark in the Northwest in 1805 (Fuller, 1931, p. 63), and the Canadian Boundary expeditions of 1812 (Fuller, 1931, p. 101). The fur-trading enterprise was punctuated by the rivalry and feuds of the American and Canadian fur companies.

Two of the earliest industries were lumbering and gold mining. Small individual sawmills were operating in the area by 1870 (Durham, 1912, p. 184), and gold placering of gravel deposits began after the gold discoveries of 1852 (Fuller, 1931, p. 304).

The U. S. Army established military Fort Colville in 1859 on the banks of the Columbia River near Kettle Falls. Fort Spokans was established in 1880 on a terrace overlooking the confluence of the Spokane River with the Columbia, and in 1882 Fort Colville was abandoned (Western Hist. Pub. Co., 1904, p. 73–74). Many settlers soon followed. They cultivated benchlands near the river and grazed stock on the uplands along the valley sides. The lower part of the valley had been extensively developed by 1933 when the construction of Grand Coulee Dam was begun. Many of the lower terraces along the Columbia had been irrigated and orchards had been planted on them; 4 sawmills were in operation in the valley between Lincoln, Wash., and the international boundary; and the valley was served by many miles of roads, 2 spur lines of the Great Northern Railway, a bridge at Kettle Falls, and 6 ferries.

With the completion of Grand Coulee Dam in 1942 a reservoir was created which averages about 4,650 feet in width and contains about 9,600,000 acre-feet of water (Hall, 1952). Approximately 70,500 acres of land was flooded, and a lakeshore of more than 600 miles was created. Within the reservoir area were 3,000 people, 2 railroads, 3 primary state highways, about 150 miles of country roads, 14 bridges for rail and vehicular traffic, 11 townsites, 4 sawmills, 4 telegraph and telephone systems, and many powerlines and cemeteries.

Major developments were either purchased or relocated by the U.S. Bureau of Reclamation. The relocated Nelson Branch of the Great Northern Railway (15.3 miles) now follows the left shore of the reservoir from Kettle Falls northward to a point 4 miles southwest of Northport. The relocated Republic Branch (13.1 miles) runs north along the right bank of the reservoir to the Kettle River confluence and then skirts the left bank of the Kettle River to Boyds (fig. 1). Relocated State Highway 22 now follows the left bank of the reservoir from Fort Spokane to Northport, and U.S. Highway 395 follows the right bank of the river from the Kettle Falls bridge to Boyds. A relocated highway follows the right lakeshore generally from Kettle Falls to the mouth of the Spokane River (fig. 1).

Franklin D. Roosevelt Lake, the reservoir created by Grand Coulee Dam, first reached its maximum level in June 1942. There was little human activity along the lakeshore for several years because of the dislocation of roads and industries required by the submergence. However, after a few years, private development and land use increased noticeably near the newly created lakeshore. As many terraces were within easy reach of the reservoir, pumps were installed at many locations to supply sprinkler irrigation systems. Logging operations were accelerated by formation of the lake, and lumber mills were reestablished. The Great Northern Railway constructed a loading dock at Kettle Falls to serve the lumber industry. This loading dock connected lake transportation to the railroad systems. The use of the lake for recreational and industrial developments had hardly begun by 1955.

Chief Joseph Dam at Bridgeport, Wash., was under construction in 1955. Its backwater, Lake Rufus Woods, will extend throughout the area below Grand Coulee Dam included in these investigations. Chief Joseph Dam is a relatively low dam, and the resulting cultural changes should be less pronounced than those caused by the construction of Grand Coulee Dam. On a smaller scale, there will be a movement away from the river and then a movement toward it, as lands adjacent to the reservoir shore are used for agricultural and engineering purposes.

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LANDSLIDES

By Fred O. Jones and Warren L. Peterson

Landslides have been an important factor in the removal of the Pleistocene deposits by the Columbia River during the formation of its present terraced valley. Many terrace slopes are scarred with the vegetation-covered forms of old landslides and some terraces are underlain by landslide debris. Landsliding of surficial deposits apparently began with the first incision by the Columbia River and has continued to the present. The frequency of landslides was increased by the construction of Grand Coulee Dam, which ponded the Columbia River in a 144-mile stretch of the upper Columbia River valley and raised the water level at the dam 350 feet. Many terrace slopes became unstable under saturation by the reservoir waters. Downstream from the dam, fluctuation in river level imposed by the variable demands for power and housing development in old landslide areas have apparently contributed to the reactivation of old landslide areas.

Most of the landslides described in this report have occurred in the Pleistocene and Recent surficial deposits of the upper Columbia River valley. These surficial deposits veneer the bedrock valley and have a terraced surface. They consist of glaciolacustrine sand, silt, and clay, glaciofluvial deposits, fluvial sand and gravel, alluvial-fan deposits, and windblown sand.

TOPOGRAPHY ON THE SURFICIAL DEPOSITS

About 90 percent of the shoreline of Franklin D. Roosevelt Lake is bordered by Pleistocene sediments. On these deposits, there is a topography of terrace remnants separated by stream-cut scarps. The flatness of the terrace surfaces has been modified by deposition of extensive alluvial fans from higher slopes so that a terrace commonly rises gently away from the center of the valley. The terraces and stream-cut scarps have been extensively modified by gullying, landsliding, and creep.

Some important factors that determine the morphology of the interterrace scarps and the gully slopes are: (a) presence or absence of fluvial gravel on the terrace;

(b) type of sediment composing the terrace; (c) degree of saturation of sediment by ground water; (d) age; and (e) erosive processes. Terraces underlain by dry silt and clay tend to have steep scarps. Silt and clay when dry are strong, and resist gravity movements such as creep and landsliding. These scarps are modified primarily by gullying that, in places, has produced spectacular badland topography. Wet silt and clay are weaker, and subject to movement by creep and landsliding. Creep makes a slope more gentle. Landsliding tends to make the lower part of a slope near the foot of a landslide more gentle but the upper part near the crown steeper. Commonly, however, slopes on wet silt and clay are gentle.

Dry sand lacks cohesive strength and runs easily downslope, so that stream-cut scarps underlain by sand become more gentle until the angle of repose of the sand is attained. Sand, being permeable, is commonly dry and is not influenced by mass movements induced by excessive ground water. However, where silt and clay are interbedded with sand to form hydraulic barriers, excessive ground water may accumulate in the sediment and landsliding and related processes may modify the terrace scarp.

Dry silt and clay tend to stand with the steepest slopes and wet silt and clay with the gentlest slopes. Slopes on sand are intermediate.

At the time of initial filling, shorelines along Franklin D. Roosevelt Lake ranged from unembayed along scarps with minor gullies to deeply embayed along severely gullied terraces. Generally, the most intricately embayed shorelines occurred where dry silt and clay had been severely eroded.

TYPES OF LANDSLIDES

Landslides that occurred in the entire area of investigation before and during this investigation were principally of four types: slump-earthflow, slip-off slope, multiple-alcove and mudflow. These types are distinguished by the form of the scars and by the kinds of movement in the sliding. The nomenclature of the parts of a landslide used here is shown on figure 2.

In the data collected for the statistical analyses under the heading "Landslide-type groups" (p. 35), the landslides have been divided into 10 type groups. However, for the purposes of the discussion presented here the fourfold subdivision will suffice.

SLUMP-EARTHFLOW LANDSLIDES

Slump-earthflow landslides combine the processes of sliding and flow. The upper part slides downward in one or more blocks that commonly rotate slightly about axes that are horizontal and parallel to the slope in which the landslide forms; the lower part flows as a viscous liquid. The movement of the upper part is similar to slump, as described by Sharpe (1938, p. 65). The movement of the lower part corresponds to earthflow or lateral-spreading described by Terzaghi (1950) and Varnes (1958). Slides of this type are illustrated on figures 11, 13, and 14. The surface of rupture is commonly concave toward the slip block in horizontal cross section. The shape in vertical cross section varies with the character of the materials. In fine grained, almost horizontally bedded materials, the surface of rupture cuts steeply from the surface to a bedding plane and then follows the bedding plane—similar to the composite surface of sliding described by Terzaghi and Peck (1948, p. 191). In vertical cross section the steep upper part of the surface of rupture in some slides shows curvature; in others it is straight. Figure 3 shows the composite surface of rupture of an ancient slide exhumed by a more recent one. The surface of rupture in coarse-grained, disturbed, and heterogeneous material in vertical cross section commonly takes the form of of a circle, an arc of an ellipse, or a logarithmic spiral.

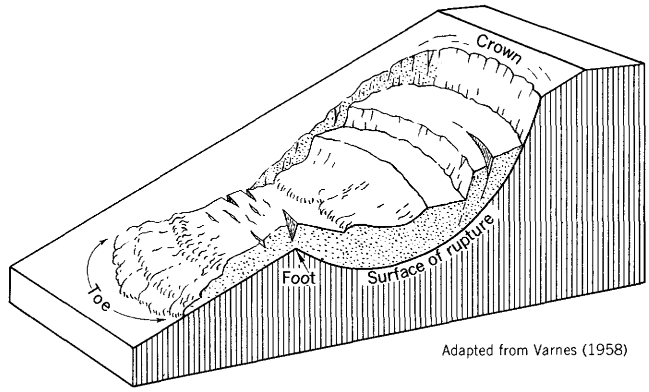

FIGURE 2.—Nomenclature of the parts of a landslide (adapted from Varnes, 1958).

Slump-earthflow landslides have been more frequent and have affected more land in the area of investigation than any other type of landslide.

These slump earthflows are similar to the deep deformational slides described by MacDonald (1947) which plagued the construction of the Panama Canal.

MULTIPLE-ALCOVE LANDSLIDES

Multiple-alcove slides form large, basinlike features by the repeated processes of sliding, flow, and fall. This repeated action commonly results in an interlocking group of landslide alcoves. The movement processes are chiefy those of slump-earthflow slides, but they also include mudflows and headward caving of the main scarp. When the vegetation-covered scars of ancient multiple-alcove slides were first examined, it was believed that their development took place over a period of many years. However, in the spring of 1952,

FIGURE 3.—An ancient slump-earthflow landslide exposed by recent sliding. Note that lower part of the surface of rupture follows a bedding plane. Fort Spokane area, lake mile 42.3 left bank.

the only known recent multiple-alcove slide developed in a few days (figs. 4, 5, Reed terrace landslide 261). The large alcove continued to enlarge slowly for more than a year.

In general multiple-alcove slides form in fine-grained materials where deep channels in the bedrock are filled with deposits of surficial materials. They are similar to the Riviere Blanche slide in Quebec described by Dawson (1899), the Falles on the coast of Zeeland described by Müller (1898), and the landslides in southeastern Norway described by Holmsen (1929).

SLIP-OFF SLOPE LANDSLIDES

Slip-off slope landslides combine in varying proportions the processes of sliding, fall, and flow. They are landslides in which the mass of material shows little backward rotation but slides or rolls forward. Landslides of this type do not cut deeply into terraces. They occur most frequently in materials of medium- and coarse-grain size on slopes that lose support at the toe due to undermining by stream erosion, wave action, saturation, excavation, or similar causes. Unlike most of the slump earthflows, these landslides seldom reach their maximum development in one failure but continue to enlarge by ravelling and caving for a long period. Illustrations of this type are shown on figures 6, 7, 8. They are similar to the slope readjustments and undermined strata defined by Ladd (1935), debris slides and falls defined by Sharpe (1938), and include the sand runs defined by Varnes (1958). Because slip-off slopes have been numerous along Franklin D. Roosevelt Lake in recent times, they form the next to the largest group studied. Although damage and destruction from individual slides are less than from individual slump earthflows, the slip-off slope landslides are an important factor in determining land use.

MUDFLOWS

Mudflows are rapid failures in which the mass of material moves like a thick fluid. Small slumps and

FIGURE 4.—Aerial view of a recent multiple-alcove landslide. See cross section in figure 5.

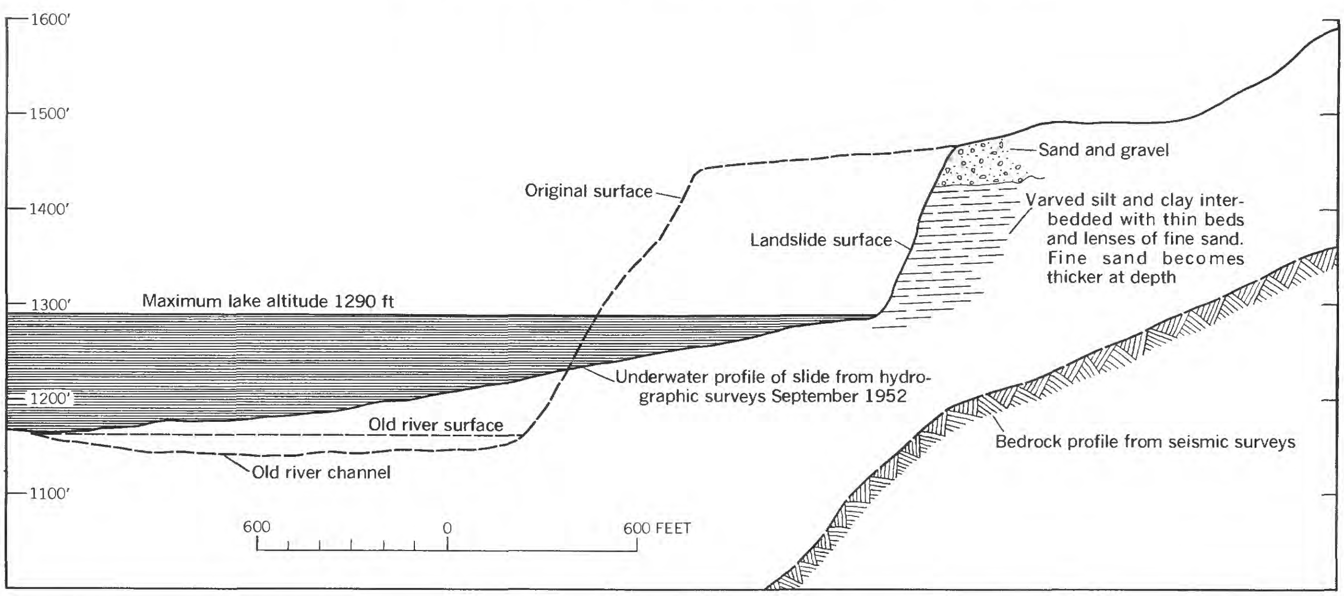

FIGURE 5.—Multiple-alcove landslide and cross section. Another view and details are given in figure 12. Reed terrace area, lake mile 98.65 right bank. Franklin D. Roosevelt Lake in left foreground.

FIGURE 6.—Photograph of a typical slip-off slope landslide. See cross section in figure 7

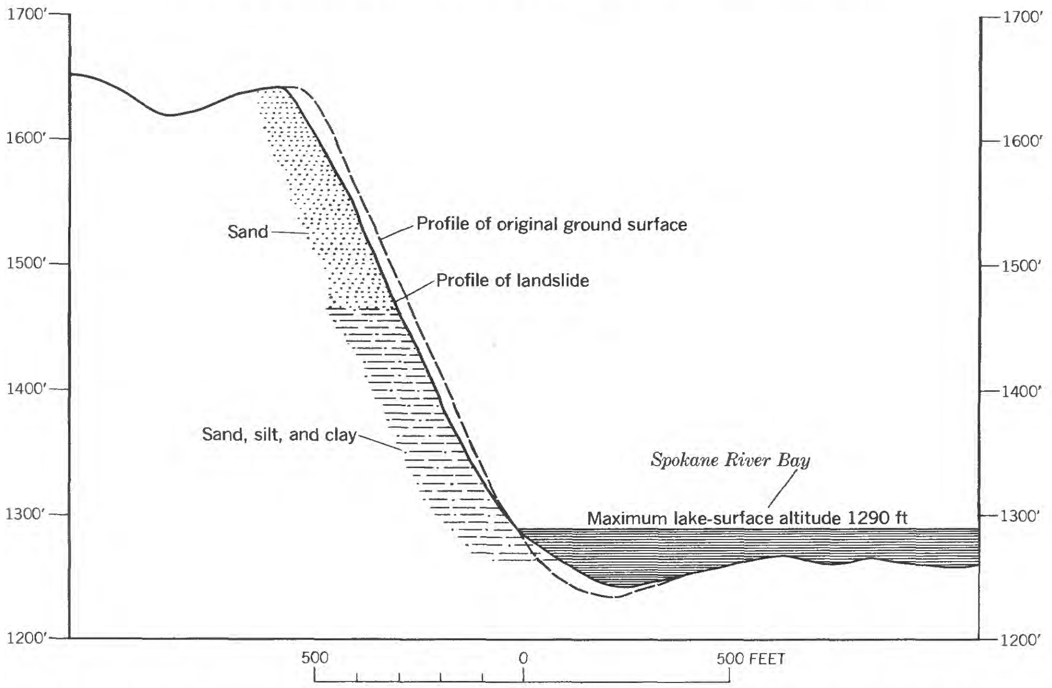

FIGURE 7.—Slip-off slope landslide and cross section. Wave erosion or saturation of sediment by lake water caused a thin skin of material to lose support and ravel off the terrace scarp. Cross section is exaggerated vertically 3 ×. Slide 105, Spokane River arm, mile 22.1 right bank.

FIGURE 8.—Slip-off slope landslide in sand. Slide blocks show little or no backward rotation. Surface of rupture is at shallow depth beneath surface of the slide debris. Slide 268, Kettle Falls area.

falls are common along the sides and upper part of the surface of rupture. Only two mudflows have been recorded in the area in recent years (figs. 9 and 18).

LANDSLIDES ALONG FRANKLIN D. ROOSEVELT LAKE

Many landslides occurred along Franklin D. Roosevelt Lake in terrace scarps that became unstable when the reservoir was filled. Slides occurred in all sediment types. One cause of landslide occurrence has been the fluctuation of the surface of Franklin D. Roosevelt Lake, necessitated by power demands at Grand Coulee Dam. Consequently, the surface of the lake has been lowered different amounts during the winter and spring of each year, the maximum being 85 feet in 1955. The lowering of the reservoir surface left saturated silt and clay above the lake surface without the additional stabilizing effect of the weight of water against the slope. Ground water moved toward the scarp and seepage pressures developed that made the scarps less stable.

The most important type of landslide on Franklin D. Roosevelt Lake has been the slump-earthflow, which has developed in all sediment types. The feet of these slides almost invariably occur well below the surface of the lake, and the crown commonly cuts into the terrace above the lake. A slide that develops in sand commonly consists of one failure that apparently stabilizes the terrace scarp so that repeated sliding does not occur. In contrast, repeated sliding occurs in silt and clay. Slides commonly have cut farther into silt and clay terraces than into sand terraces.

Slip-off slope landslides have developed along much of the shoreline of Franklin D. Roosevelt Lake. This type of landslide has occurred most frequently along sand terraces. During the initial filling of the lake, saturation of terrace materials weakened the sediments and caused failure. Subsequently, undermining by wave erosion has been the principal cause. Along most of the shoreline of the lake, low wave-cut cliffs had formed by 1955, except where shorelines were bordered by bedrock, were composed of Pleistocene sediments with very gentle surface slope, were in protected embayments, or had been recently modified by slump-earthflow land slides.

One multiple-alcove landslide (fig. 4), at the Reed terrace, has formed since the filling of the lake.

Landslides commonly affect only the lowest terrace at a given place on Franklin D. Roosevelt Lake. Most slides occurred in terraces at altitudes of 1,450 feet and below, but a few occcurred in the 1,600-foot terrace.

The deep lake standing against the scarps in which the landslides originate provides an avenue of escape for the slide debris from the site of a slide. Upon descending the slope, the debris enters the water and, mixing with the water, moves as an underwater mudflow or a turbidity current into deeper parts of the lake. This action occurs in all sediment types. Sand, lacking cohesion, forms a mixture of sand grains and water which flows away across the underwater surfaces. Two kinds of mudflow action probably occur with silt and clay debris. Where silt and clay are dry, the chunks of debris probably remain largely intact but are lubricated by water and by some mud, which enables the mass to descend the underwater slopes. Where the silt and clay are saturated, the disturbance causes this sediment to lose its form-retaining strength and in part become a viscous mud. Water is added to the

FIGURE 9.—Mudflow in Hopkins Canyon occurred on February 2, 1953, at about midnight; it lasted an estimated 7 minutes and destroyed a small house. The mudflow originated in the alcove in the background which before the mudflow was an area of seeps. A slump block which settled during or after the mudflow lies to the right of the alcove. This feature is analogous to the slump-earthflow landslide with slump-block above and earthflow at the toe. In this instance, the earthflow was so mobile that a mudflow resulted. Slide 295, Nespelem River-Omak Lake valley area.

mass as it enters the lake and the debris moves downslope as an underwater mudflow. The slide alcoves are completely empty of slide debris along most of the shore of Franklin D. Roosevelt Lake (figs. 12 and 14). Notable exceptions occur in the Sanpoil valley where large masses of slide debris remain in some slide alcoves.

AREAS OF EXTENSIVE LANDSLIDING

Five areas in the Columbia River valley were selected for detailed study and description because they each contain many slides of considerable interest. These are the Reed terrace, Cedonia, and Ninemile areas along Franklin D. Roosevelt Lake, and the Seatons Grove-Koontzville and Nespelem River areas downstream from Grand Coulee Dam (fig. 10).

REED TERRACE AREA

The Reed terrace area is on the right bank of Franklin D. Roosevelt Lake about 3.5 miles south of Kettle Falls bridge (figs. 1 and 10; pl. 1). This area has been one of the most active landslide areas along the upper Columbia River valley in recent years and geologic mapping suggests that landslides also occurred here in the distant past. The area includes the Main terrace at an altitude of about 1,480 feet and 3 smaller terraces. Of these, the Sherman Creek terrace is the highest,

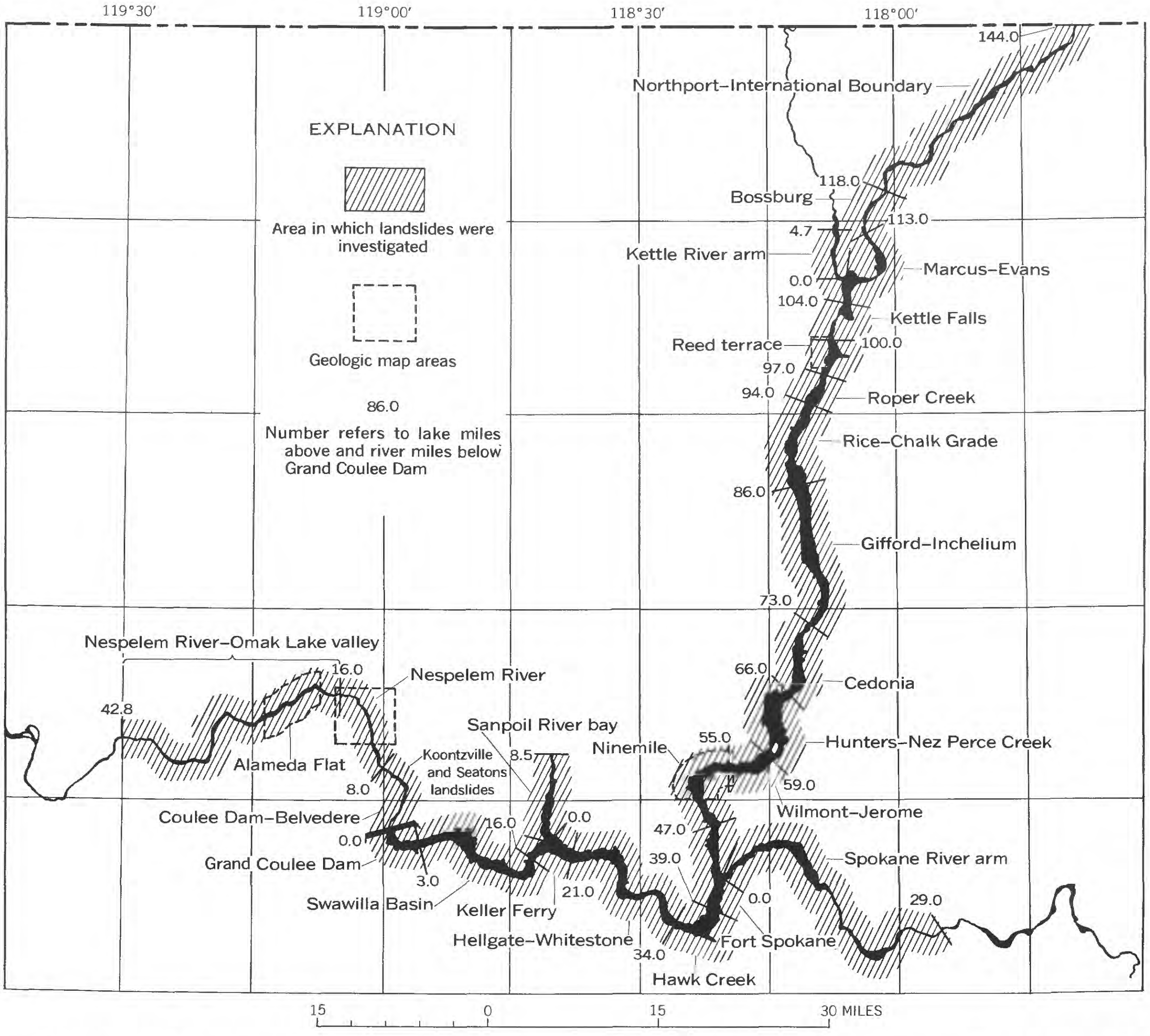

FIGURE 10.—Index map of the Columbia River valley of northeastern Washington. Shows total area of investigation (lined-pattern), the geographic subdivisions referred to in the text, the location of the geologic map areas, and the location of the Seatons and Koontzville landslides. Except for the Alameda Flat area, the geologic map areas have the same names as the geographic subdivisions though they do not cover the same areas. Numbers refer to miles along the centerline of Franklin D. Roosevelt Lake (lake miles in the text) upstream from Grand Coulee Dam at 0.0 and miles along the centerline of the Columbia River (river miles in the text) downstream from Grand Coulee Dam.

lying at about 1,800 feet; the Orchard terrace at about 1,600 feet; and the Farm terrace, at an altitude of about 1,370 feet.

CULTURE

Because of its broad, smooth terraces, good soil, high ground-water conditions, a readily available supply of irrigation water, and strategic location, the Reed terrace area has a history of culture and engineering developments which dates back to the turn of the century. Water for irrigation was first diverted from Sherman Creek in 1905, but it was used farther south and not on the Reed terrace. The Orchard terrace was logged and cleared between 1908 and 1911, and the first irrigation water was put on this terrace in 1911. The Main terrace was logged and cleared for agricultural purposes in 1927 and 1928, and its first irrigation water was put on the terrace in 1929. A logging railroad, built in 1927 and used until 1931, followed close to the edge of the Main terrace and crossed the Farm terrace to a lumber mill located at the mouth of Sherman Creek.

The terraces have been irrigated from April to October each year since irrigation was begun. The volume of water averages between 2 and 2.5 cfs (cubic feet per second). The irrigation system was reconstructed in 1952 by the State Game Commission which now owns and irrigates a large part of the Main terrace.

Extremely high ground-water conditions along the north and east end of the Main terrace and in the southern part of the Farm terrace made the Harrison E. Reed ranch a particularly desirable location. It was possible to raise four crops of alfalfa a year without irrigation.

A network of roads which served the area has been cut in three places by landslides, and the main county highway was severed by the multiple-alcove landslide of 1952.

GEOLOGY

The bedrock of the Reed terrace area is chiefly quartzite, gneiss, and schist which strike slightly east of north and dip eastward. The bedrock is cut by 2 major joint sets, one trending N. 60°- 70° W. and the other N. 5°- 15° W. These joint sets have influenced the growth of a drainage pattern tributary to the Columbia River.

The present valley of Sherman Creek upstream from the Orchard terrace follows a course nearly coincident with the trend of the joint set, N. 60°- 70° W., and thus is believed to have resulted from normal headward growth along a zone of less resistant rock. Contours on the bedrock surface (pl. 1) show that at the Orchard terrace, a buried valley, diverges from the present valley of Sherman Creek and continues southeastward beneath the unconsolidated deposits that underlie the Orchard and Main terraces. Evidently the present course of Sherman Creek, which crosses the terraces in a narrow, rock-walled canyon, resulted from superposition from the unconsolidated deposits onto a bedrock spur.

The bedrock surface at the south end of the Reed terrace area is as low as 675 feet, 200 feet lower than the lowest bedrock surface at Grand Coulee Dam, 97 miles downstream. The most likely explanation for this apparent anomalous depth is deep glacial scouring along the axis of the valley.

The highest terrace in the area is the Sherman Creek terrace which occupies a bedrock depression flanking the present valley of Sherman Creek. This terrace is directly underlain by at least 80 feet of sand and gravel, but the nature of the underlying deposits is not known.

The Main terrace is underlain by as much as 60 feet of sand and gravel which rests disconformably upon varved silt and clay (pl. 1 and fig. 32) interbedded with layers and lenses of fine sand, which probably extends to bedrock. The varves range from ½ inch to 3 feet in thickness. Measurement of 50 varves indicates that the silty layer makes up an average of 42 percent of the varve and the clayey layer 58 percent. Where the varves are moist, a color gradation can be observed from the light basal silt to the dark-gray overlying clay. Commonly the contact is sharp between the clayey layer of one varve and the silty layer of the overlying varve, but in places it is gradational. Tiny lenses and minute layers of very fine sand separate some of the varves and in some places are found within a varve. The varves are all sublaminated, and many contain limy concretions. The thickest varves typically are contorted, with the most intense deformation occurring in the silty layer. The entire varve sequence dips gently toward the center of the valley.

Interbedded with the varves are layers of light-colored sand that range from a single layer of sand grains to lenses 4 or 5 feet thick. The sand seems to have been brought into the lake intermittently by tributary streams. Sand beds and lenses are more abundant and thicker in the part of the Main terrace deposits which lie above the former bedrock channel of Sherman Creek, and here there also is a downward increase in the proportion of sand to silt and clay. Exposures in the sides of a landslide alcove (landslide 261, fig. 4) reveal that the sand layers become thicker toward the west.

Although till was not observed within the terrace deposits in the Reed terrace area, its presence on the opposite side of the valley suggests that it may occur below lake level.

The Orchard terrace is probably underlain, beneath fluvial sand and gravel, by a higher part of the lacustrine sequence underlying the Main terrace. Varved silt and clay are exposed to an altitude of 1,500 feet at the east edge of the Orchard terrace.

The Farm terrace is underlain by material generally similar to that of the Main terrace, although its internal structure shows greater deformation. Exposures along the shore of Franklin D. Roosevelt Lake show varved sediments that dip westward at steep angles, suggesting that these beds have been deformed by landsliding. A layer of sand and gravel, which disconformably overlies the deformed varved sediments, indicates that this sliding is not of recent age.

An area of old landslide debris also extends down to lake level at the south end of the Main terrace; this slide area forms a terrace which is submerged when the lake is at its maximum height. Here, too, the slide debris consists chiefly of varved silt and clay.

GEOLOGIC HISTORY

All terrace deposits of the Reed terrace area seem to have been formed during retreat of the last ice sheet that covered northeastern Washington. The highest and therefore probably the oldest deposit is the sand and gravel of the Sherman Creek terrace. This deposit of sand and gravel is outwash that was formed by melt water coming down the valley of Sherman Creek from the west and the northwest. Because of high altitude, the Sherman Creek terrace probably was graded to an ice-marginal melt-water drainage channel along the west side of the Columbia glacier lobe. By the time the glacier uncovered the valley, coarse outwash evidently was no longer being carried by Sherman Creek, for the lacustrine deposits in the Valley show no pronounced coarsening in the vicinity of the Sherman Creek valley. However, an increase in the proportion of sand to silt and clay in this area indicates that Sherman Creek was contributing sand-sized material to the lacustrine deposits.

These lacustrine deposits, represented by the varved silt and clay, were formed after the valley had been cleared of ice in the Reed terrace area, but while the valley was still dammed by the Okanogan glacier lobe at and downstream from Grand Coulee Dam. When this dam of ice melted from the Columbia River valley, the lacustrine deposits upstream were dissected by the Columbia River. Three stages of downcutting are recorded by the successively lower Orchard, Main, and Farm terraces.

SURFACE-WATER AND GROUND-WATER CONDITIONS

Before the formation of Franklin D. Roosevelt Lake, the Columbia River flowed along the east toe of the Main terrace and along the southeast side of the Farm terrace at an altitude of about 1,160 feet. The lake first attained its maximum height of 1,290 feet in June 1942. The lake now extends a short distance into the Sherman Creek valley, and flanks the Farm terrace by water on three sides. At its maximum height, the lake surface stands 130 feet above the former river surface, and the lake submerges 50 percent of the scarp of the Main terrace and 60 percent of the Farm terrace. Measurements by the Washington State Department of Conservation and Development of the only other body of surface water, Sherman Creek, show a range in discharge from 8 to 117 cfs near the mouth of the stream.

Ground-water conditions in the Main terrace and in the south half of the Farm terrace were very high during and for many years before this investigation. Several springs and many seeps issue along the hillside west of the Main terrace. Many large springs, some discharging as much water as a 3-inch pipe could carry, issued from the scarp of the Main terrace before the formation of Franklin D. Roosevelt Lake. Some of these springs were near the base of the terrace scarp; others issued from different zones up to the base of the sand and gravel that overlies the varved sediments. After the lake had risen and sliding occurred, new springs issued from above lake level in the sides of alcoves formed by the landslides.

Wells 25 to 35 feet deep on the Main terrace have generally produced water, and shot holes drilled through the sand and gravel cap reached soupy, saturated silt in many places. Seismic velocity readings on the Main terrace indicated saturation in the fine-grained sediments except in a zone along the north side of the terrace adjacent to Sherman Creek. Seismic velocities showed saturated conditions in the south half of the Farm terrace, but generally dry conditions in the north half. Ground-water conditions in the Orchard terrace were comparable to those in the Main terrace. Velocities of shock waves in the fill underlying the Sherman Creek terrace, however, indicate a dry condition, and suggest that the material beneath the terrace is free draining.

LANDSLIDES

Nineteen landslides and numerous enlargements that occurred in the Reed terrace area are described in chronological order. Some of them are briefly described because little information is available; others, particularly the more recent, are described in detail. All but three of the landslides in this area are of the slump-earthflow type (pl. 1). The information has been assembled during periodic examinations of the area and by discussions with Mr. Harrison E. Reed (formerly a resident of the Reed terrace), Mr. Benjamin Mullenburger, operator of the orchard, Mr. Joseph Aubertine of Kettle Falls, Mr. W. L. Parrott, manager of the Lafferty Transportation Co., and rangers of the National Park Service. Miss Arlene Carson, who lived directly across Franklin D. Roosevelt Lake from the slide area, recorded much of the landslide action as a vountary observer. Figures 11 and 12 show the progressive development of the shoreline of the Reed terrace.

The numbers assigned to the landslides are not necessarily related to the order of occurrence.

Landslide 262.—Location, lake mile 98.67 right bank on the slope between the Main and the Farm terraces at the south end of the Farm terrace (pl. 1). This landslide in 1894 reportedly dammed the Columbia River for about an hour and caused flooding of a large area of orchards and farms. Landslide debris shot across the river and covered part of an orchard on the opposite bank.

Landslide 256.—Location, lake mile 98.35 right bank at the south end of the Main terrace. In the spring of 1929 this landslide also dammed the river and flooded the riverbank areas on the opposite side of the Columbia. Old photographs confirm the report that silt and clay covered parts of an orchard on the left bank and that large areas in the river became islands of slide material. Trees stood upright in midriver for 2 weeks after the slide. It cut a county highway serving the area at that time. A new landslide (No. 257) cut this old slide so that a cross section could be examined from the top of the Main terrace to lake level. The surface of separation is divided into two parts, similar to several other slides in the Reed area. This two-unit feature is illustrated in figures 27 and 28.

Landslides 313 and 314.—Location, Farm terrace. These are the only landslides in the Reed terrace area of the slip-off slope group. They occurred while Franklin D. Roosevelt Lake was filling, before December 1941. The material was principally slope wash of silt, clay, sand, and gravel from the terrace scarp.

Landslide 259.—Location, lake mile 98.5 right bank, Main terrace. This landslide occurred on April 1, 1944, at about 3:00 a.m., and was the first major movement in the Reed terrace area after Franklin D. Roosevelt Lake was formed. The reservoir level at the time of the slide was 1,259.4 feet, or a drawdown of 40.6 feet from maximum. The slide occurred in the two units similar to slide 256. Both units developed concave scarps in the terrace. The upper part of the surface of separation of the lower unit had a general slope of 59°. The sole of the upper unit followed one of the larger sand beds.

Landslide 258.—Location, lake mile 98.4 right bank, Main terrace. This landslide occurred April 8, 1944, at about 6:30 a.m., and its volume was estimated to be between 4 and 5 million cubic yards, the largest of the 1944 landslides. The statistical-data card showing a profile and photograph of this slide is reproduced in figures 27 and 28.

Mr. H. E. Reed witnessed this earth failure from the yard of his ranch. It occurred in two units, as the shape of the profile suggests. The second unit followed the first by a matter of seconds, and waves reaching a maximum height of 30 feet were recorded on the opposite shore of the lake, 5,000 feet away. A tree illustrated on the landslide profile was observed by Mr. Reed to be at about the old shoreline immediately following the slide. During the following week the tree moved directly across the lake, and when the profile was surveyed it was determined that the tree had traveled in an upright position about 2,000 feet during the week. The reservoir was 40.4 feet below maximum pool level at the time of this slide. Afterwards water seeped from the base of the sand and gravel cap near the south end of the scarp.

Landslides 263, 315, 316, 317, 318, 319.—Location, northern end of Main terrace and in slope joining the Farm terrace. This group of six relatively small landslides all formed in late March or April of 1944 within the scarp of the 1894 slide. Ground water in this part of the terrace was very high, as demonstrated by high-level springs. The area is directly over the preglacial channel of Sherman Creek and in the part of the terrace where fine sand beds and lenses are most common. The landslides were all in undisturbed silt and clay. None of them involved much disturbed material related to the old landslide.

Landslide 260.—Location, lake mile 98.6 right bank, Main terrace. Landslide 260 occurred in March of 1951 and was enlarged to half again its original size during the 1952 lake drawdown. The features of this landslide are nearly identical to landslides 258 and 259. Slightly more ground water seeped from the base of the sand and gravel cap than in slide 259 and the northern part of slide 258. The enlargement of the landslide during the 1952 drawdown of the lake extended it back to the right-of-way of the Kettle Falls-Inchelium highway and caused the road to be closed just a day or two before the huge multiple-alcove slide 261 destroyed several hundred feet of the highway.

Figure 11 an aerial oblique photograph of the Reed terrace area, which was taken May 15, 1951, shows the terrace after the initial movement of landslide 260.

Landslide 257.—Location, lake mile 98.37 right bank, Main terrace. This landslide occurred March 12, 1952, at 11:30 a.m. It was enlarged September 12, 1952, at 2:00 p.m., and again October 13, 1952, at 5:00 to 6:00 a.m. This tremendous landslide took out a narrow point of land between slide 256 of 1929 and slide 258 of 1944. It cut much farther back into the terrace than

FIGURE 11.—Aerial oblique photograph of the Reed terrace taken on May 15, 1951, looking southwest. Scars of the two large landslides of 1944 are in the middle left. Vegetation-covered scars of ancient landslides at the lower right. The scar of slide 260 of March 1951, is between. Compare with figure 12. Franklin D. Roosevelt Lake on left.

either of the older slides, included large areas of the older scarps, and cut one of the main farm access roads. Lake waves and surges caused by this landslide broke tugboats and barges loose from their moorings at the docks of the Lafferty Transportation Co. 6 miles up the lake at 11:45 a.m. The stratigraphic sequence, the two-unit failures, and ground-water conditions are similar to those already described in this location.

The October enlargement of landslide 257 caused a wave that reached higher on the opposite lakeshore than any wave caused by other landslides. This happened because the lake was full at the time of the slide. The wave swept logs, driftwood, and chunks of lakeshore sod over a large flat area just above full lake level.

Landslide 261.—Location—lake mile 98.65 right bank, Main terrace. The landslide of April 10 to 13, 1952, was the largest and most spectacular of all the landslides along the upper Columbia River in recent years. The failure was of the multiple-alcove type.

The initial failure took place about 3:00 a.m., Thursday, April 10, 1952. Mr. Reed's house shook and lurched at this time. The landslide is at the north end of the Main terrace, the edge of it being just 2,000 feet from the Reed house. The initial slide occurred in a very narrow throat. Although the throat has been greatly widened by subsequent action, it is still narrow by comparison with the size of the slide (fig. 4). How far back the initial failure cut is not known, but by April 13 repeated sliding had severed the Kettle Falls-Inchelium highway (pl. 1; fig. 12) 2,000 feet from the original lakeshore.

The general sequence of deposits underlying the Main terrace has already been described. The landslide exposures show that beds of fine sand, as much as

FIGURE 12.—Aerial oblique photograph of the Reed terrace looking south on August 1, 1952. The large landslide alcove in the foreground is the multiple-alcove landslide of April 10, 1952 (261). Compare this photograph with figures 4 and 11. The initial landslide slid through a narrow throat on April 10. How far into the terrace the initial failure cut is not known, but by April 13 repeated sliding had severed the middle road of the photograph (the Kettle Falls-Inchelium highway). The scarp advanced along three main lines corresponding to springs that issued high on the scarp until the scalloped form shown here was attained. Mudflows, and water issuing from the springs, built the fans into the slide basin in the later stages of scarp advance. See figure 4 for a more detailed view of this multiple-alcove slide and figure 11 for a view of the terrace before the occurrence of this slide. Franklin D. Roosevelt Lake on left.

5 feet thick, are more common below maximum lake level than above. The rapidity of the slide suggests that there must have been an instantaneous liquefication in the layers of fine sand brought about by extremely high hydrostatic pressures of the ground water.

Conditions conducive to landsliding developed during the previous winter. Unusually heavy snow fell on the terrace and in the large drainage area leading to the terrace; the snowpack on the Orchard terrace measured 39 inches on the level. The snow melted slowly during the early spring, and the water filtered into the terrace deposits. The drainage pattern in the bedrock channeled the snowmelt to the terraces both at and below the surface. During this period Franklin D. Roosevelt Lake was being slowly lowered to 65 feet below full lake level, the minimum altitude since its initial filling. Some triggering effect, such as the slight increase of weight caused by excessive water or exessive pressure in the pores of the sands, started the sands surging from beneath the heavy section of unstable silt and clay. Like other landslides in the Reed terrace area, without warning, there was an instantaneous collapse and the materials flowed with great turbulence into Franklin D. Roosevelt Lake.

Great quantities of water poured out at the base of the sand and gravel cap; however, the greatest quantities came out sporadically at many different locations. A large spring would gush out suddenly in one place and then taper off as another gushed out elsewhere. Mr. Reed said that during the 10 days before the landslide occured the springs along the terrace scarp had dried up, and that for the first time in his memory, his cattle could graze in the spring areas. Perhaps some minor ground movement caused an underground damming of the feeder channels to the springs.

Following the initial failure and much repeated action, a nearly vertical slide scarp was maintained which extended from the top of the terrace to below lake level. Large masses of earth frequently spalled off, particularly with each new outpouring of water along the sand and gravel cap. As the earth fell down the scarp it became fluid enough to flow out through the throat into the lake. This passage was turbulent almost continuously to April 17. Each spall made a little alcove in the terrace, and as the slide grew it worked headward along three general lines corresponding to the position of the ground water and the springs (figs. 4 and 12). By April 22, slide material had piled up above lake level in the central basin below the scarp, the scarp was much less steep, and less ground water issued from the base of the sand and gravel cap. Spalling continued, however, and material was removed by mudflow action.

The Reed family lived on the ranch until April 14, although the house shook and creaked with the landslide action. Mr. Reed reported that activity seemed to be the greatest about 3:00 a.m. each day. While examining the slide on April 30, he found balls of clay the size of a man's head in his field as far as 400 feet from the landslide. The force of chunks of material slapping together apparently threw the clay balls into the air with terrific force.

Many waves were created on Franklin D. Roosevelt Lake during first few days of sliding. The largest wave on the shore directly opposite was 65 feet high. Many waves were noticed at the docks of the Lafferty Transportation Co. 6 miles up the lake.

The landslide was examined frequently between April 1952, and August 1953. The amount of water issuing from the base of the sand and gravel cap gradually decreased until it became neligible by August 1953. With the cessation of waterflow, the retreat of the slide scarp virtually ceased.

The slide took place in the part of the Reed terrace which has been most active since the year 1894. This part overlies the old bedrock valley of Sherman Creek. The landslide occurred because of the configuration of bedrock which directed ground water into the area and because of the beds of sand interbedded in the silt and clay sediments.

Landslide 255.—Location, south end of the Main terrace, Lake mile 98.3 right bank. This slide occurred in the spring of 1952 in the terrace scarp between the south end of the Main terrace area and the submerged terrace to the south.

Landslide 304.—Location, the Main terrace just uplake from landslide 258. This landslide cut back into a large part of the slide scarp of No. 258. The lake had been drawn down 16 feet to an altitude of 1,274 feet.

The initial failure was at 8:15 p.m., February 14, 1953. Blocks of earth caved into the lake intermittently until February 19. Thunderous noises accompanied the initial failure and the subsequent caving. Many large waves were formed on the lake.

Landslide 305.—This landslide is on the Main terrace between slides 304 and 259. It took out all of the remaining original terrace scarp in this area. Wet zones, but no springs, were found in the landslide scarp and at the base of the sand and gravel cap.

February 16, 1953

3:43 a.m. Initial failure. The noises from this slide awakened everyone in the Z. A. Carson household across the lake. Caving and enlarging continued throughout the morning. At least 10 waves crossed the lake and reached the maximum lake-level shoreline, or 16 feet in height. One wave was higher and reached above the high waterline. A block of material was observed as it dropped into the lake and made a mound of white water one-fourth the height of the terrace. Waves crossed the lake. The wave fronts were vertical walls of water; some waves had a dome-shaped surface just behind the vertical wall. On the average the waves crossed the lake in 1½ minutes, or at a rate of 4,000 feet per minute.

10:33 a.m. A major enlargement of the slide, which was photographed about 1:00 p.m., is shown in figure 13. This photograph shows how the large block rotated backward.

3:50 p.m. Large slivers of material peeled off the nearly vertical scarp. The first indication of action was a tremendous thunderlike roar followed by sounds like the crack of a high-powered rifle. The material then dropped from the scarp.

February 18, 1953

10:04 a.m. A block caved off.

12:40 a.m. Another block caved off.

Caving of the scarp continued to about February 22, 1953.

FIGURE 13.—Slump-earthflow landslide. Photograph taken about 2½ hours after landslide. Shows a large block rotated toward the scarp of the landslide which is typical of slump earthflows. Material is varved silt and clay. Slide 305, Reed terrace area.

Landslide 321.—A landslide occurred in about the center of the farm terrace August 19, 1953, about 11:00 a.m. The slide created a small wave at the Kettle Falls beach of the National Park Service and dislocated one of the floating walkways. The part of the slide above the lake was small, but the part beneath the surface of the lake must have been larger to create such a wave.

LAKE FILL IN THE REED TERRACE AREA

A hydrographic survey was made of the lake bottom in the Reed terrace area in September 1952 to determine the amount of material the landslides had deposited in the lake. The new hydrography and cross sections of the fill are shown on plate 2. The maximum fill over the old river channel was 70 feet.

CEDONIA AREA

The Cedonia area (fig. 10) contains more landslides than any other area of comparable size in the upper Columbia River valley in Washington. Although the Cedonia area includes one extensive area of ancient landslides, there is little evidence of recent sliding before formation of Franklin D. Roosevelt Lake. More than 100 slides occurred on the left bank between lake miles 67 and 71 while the lake was filling. Most of these took place before June 1944; subsequent shoreline erosion has been limited to wave and wind erosion. Figure 14 shows a part of the shoreline in the Cedonia area after sliding.

Most of the slides were slump earthflows. The sediment was interbedded glaciolacustrine clay, silt and

FIGURE 14.—Terrace of sand with some interbedded silt and clay. Most of terrace scarp has been cut away by a slump-earthflow landslides. Landslide debris disappeared below the surface of the lake. Cedonia area, lake mile 69 to 70 left bank.

sand and glaciofluvial sand and gravel (figs. 37 and 38), much of which had been folded, faulted, and fractured. The deformation was probably caused by slumping subsequent to the melting of buried glacial ice. The sediment became saturated as the lake was filling and the slides resulted from the consequently decreased shear strength.

NINEMILE AREA

The Ninemile area lies between lake miles 49.3 and 55.3 (fig. 10). It was selected for study because it contains many ancient landslides and a spectacular slide which dammed the Columbia River in 1906. It also serves as a sample area for the illustration of landslide-prediction techniques discussed in this report.

GEOLOGY

Bedrock underlying the Ninemile area on the east side of the lake is granite and that on the west side is metasedimentary rock. The bedrock valley of the Columbia River beneath the valley-fill deposits seems to be steep walled with a broad irregular floor. The two tributary streams entering from the west have not reoccupied their former bedrock channels near their junctions with the Columbia, but form waterfalls and cascades across bedrock spurs. The bedrock channel of Nilemile Creek lies beneath the large landslide in sec. 9, T. 29 N., R. 35 E. (pl. 3) and the channel of Wilmont Creek is in secs. 35 and 36, T. 30 N., R. 35 E.

The surficial deposits of the area that are affected by sliding consist principally of fine-grained lacustrine sediments and glaciofluvial sand and gravel. Along the southeast edge of Ninemile Flat the lacustrine deposits make up 2 distinct sequences separated by a gravelly sand that occurs at an altitude of 1,460 feet. From an altitude of 1,290 to 1,350 feet the lower lacustrine sequence is composed of cycles of lacustrine sand beds, with aggregate thickness of 2 to 5 feet, overlain by silt and clay varves ½ to ⅛ inch thick, with aggregate thickness of 3 to 5 feet. Above an altitude of 1,350 feet the sand disappears from the cycle and the sequence is composed of varves ½ to ⅜ inch thick and single beds of faintly graded silt and clay 3 to 6 inches thick spaced 3 to 5 feet apart. Beds similar to these which form open folds crop out along the lake shores in the SE¼ sec. 16, T. 29 N., R. 35 E., and in the SE¼ sec. 2, T. 29 N., R. 35 E. In some places, as in sec. 2, overturning of these folded beds toward the south suggests deformation by overriding ice. Overlying the lower lacustrine sequence is 3 feet of clean medium-to coarse-grained sand containing scattered pebbles and cobbles. This sand is overlain, in turn, by an upper lacustrine sequence which consists principally of sand and silt with small amounts of silt and clay varves.

Glaciofluvial sand and gravel are exposed in 2 units separated by lacustrine deposits on the south side of the lake in S½ sec. 6, T. 29 N., R. 36 E., where 110 feet of deformed sand, gravel and silt is overlain by 200 feet of silt and clay, and overlain next by 200 feet of sand and gravel. The upper sand and gravel occur south of Corkscrew Canyon and the underlying lacustrine deposits are exposed just south of Tavis Canyon. These deposits are all probably older than the upper lacustrine sequence on the other side of the lake, but their relation to the lower lacustrine sequence there is not known. On the north side of the lake, sand and gravel were deposited on the high terrace by melt water from the valley of Wilmont Creek. At Ninemile Flat, the sand and gravel are overlain by 10 to 20 feet of silt and clay of the upper lacustrine sequence.

LANDSLIDES

An impressive array of topographic forms in the Nilemile area was developed by landsliding before the formation of Franklin D. Roosevelt Lake. The scarps of the 1,900-foot terrace on both sides of the lake are scalloped by landslide scars. Most of these scars have been modified by subsequent erosion and are now covered with trees and shrubs. The low terraces on both sides of the lake are underlain by landslide debris.

Along the east side of the lake, south of Corkscrew Canyon, landslide scars are preserved in the scarp of the high terrace. Most of the landslide debris now lies below present lake level or has been removed by the Columbia River. Slump earthflow landslides formed these scars. On the west bank, the face of the same terrace is sculptured by landslide scars along its entire length. A low terrace just above the lake level from the east edge of the map area to the NE¼ sec. 9, T. 29 N., R. 35 E. is underlain, beneath alluvial fan debris, by landslide debris that came down from the terrace scarp lying to the north. Two types of slides have occurred along this scarp: slump earthflow and multiple alcove.

The largest multiple-alcove landslide on the right bank is recorded by the almost circular scar that indents the southeast edge of Ninemile Flat (pl. 3). This large slide lies above the buried bedrock valley of Ninemile Creek, the floor of which is just west of the slide at an altitude of 1,700 feet. This ancient slide apparently evolved in a manner similar to that of Reed terrace landslide 261. Its history may have been as follows: initial development occurred as numerous small slides that became mudflows as they descended the slopes and moved out of the slide area into water, possibly standing water with a surface altitude of about 1,600 feet. After cessation of the initial activity, erosion by spring water issuing high on the scarp caused headward growth of the scarp surrounding the slide alcove into its present scalloped form. The present floor of the alcove, which is composed of postlandslide mudflow and alluvial deposits, has been partly removed by slides developing on lower slopes. Remnants of the alcove floor occur at an altitude of about 1,600 feet. The original movement did not affect deposits below an altitude of 1,350 feet; undisturbed lacustrine deposits are exposed up to this altitude in the scars of recent landslides in the center of sec. 9, T. 29 N., R. 35 E.

Thin deposits of lacustrine silt and sand on terraces upstream from the Ninemile area and what seem to be wave-built benches at an altitude of about 1,600 feet in the scars of ancient landslides south of the Ninemile area suggest that the Columbia River was temporarily ponded after the valley floor had been eroded below 1,400 feet. It is possible that the large multiple-alcove landslide and other large landslides of the area developed during a temporary damming of the river which raised the water surface to an altitude of about 1,600 feet which is slightly above the present bedrock threshold of the Grand Coulee.

The large indentation into the northeast side of Ninemile Flat was probably also caused by a multiple-alcove landslide.

In 1906, a large slide occurred in sec. 35, T. 30 N., R. 35 E. (The Slide, pl. 3). The slide debris moved swiftly down a narrow gully and extended into the valley, where reportedly it blocked the Columbia River for about 45 minutes. The Slide now is an area of active springs. The entire embayment was not formed during this one slide; evidently sliding had occurred there before 1906. This entire slide embayment is classified as a multiple-alcove landslide.

Additional landslides along the scarp of the high terrace on the right bank were of the slump-earthflow type.

An area of slide topography on the 1,360-foot terrace on the east side of the lake (pl. 3) is characterized by subparallel discontinuous ridges a few feet to 50 feet high oriented west-southwest. Exposures along the shore indicate that the gravel of each ridge is underlain by lacustrine silt and clay with gently to strongly folded bedding. These gravel ridges probably consist of rotated slump blocks that resulted from lateral flowage of the underlying material.

SEATONS GROVE-KOONTZVILLE AREA

SEATONS LANDSLIDE (NO. 7)

The Seatons slide is on the right side of the Columbia River at river mile 5.1 downstream from Grand Coulee Dam. (See figs. 10, 15, and 16.) It is an ancient slump earthflow, limited by bedrock in places. It became active again on November 23, 1948, and minor movements continued each year through 1953.

Topography of the area is one of the granite knobs and river terraces modified by landslides. All of the renewed sliding affects parts of ancient landslides which developed as the river cut through the thick valley fill of silt, clay, sand and gravel.

A small depression formed on the ancient landslide occurs on the side of the slide away from the river. A smooth hill of surficial material is on one side of the depression and granite is on the other. A small earth

FIGURE 15.—Aerial photograph of Seatons landslide. Diagram showing major slide scarps shown in figure 16.

dam was built in 1935 across the outlet of this depression, into which a small stream was diverted by means of a flume and ditch to form Seatons Lake. The dam later was raised about 3 feet and at the time of the 1948 reactivation, the maximum water depth was about 8 feet.

During the building of Grand Coulee Dam this area was developed for home sites, small irrigated tracts, and trailer campsites. At one time a maximum of 55 families had lived on the land which was involved in the 1948 movement, but in 1948 only 18 families were living in houses on the slide. Figure 16 shows the extent of recent slide scarps on April 12, 1949, most of which first appeared in the fall of 1948. The area contained a network of roads, pipelines, and small irrigated tracts. For weeks before November 23, 1948, pipeline operations were impeded; one section broke at every coupling. The practice of joining pipe sections with flexible hose was finally adopted.

On the morning of November 23, 1948, a sudden movement woke most of the people living on the slide. The surface of the ground was cut by a network of deep cracks. The streams and springs ran into these cracks in some places, and the lubrication in new places no doubt aided the movement. Many large basalt erratics which lay on the surface showed upward displacement along the higher side. The toe of the slide moved upward and out into the river horizontally for 5 feet along the downstream edge (fig. 17); the movement in the center of the slide was probably greater. Springs and seeps emerged along the toe of the slide.

The only evidence of recent landslide action before 1948 was a fissure into which irrigation water drained until it was filled with clay. During the slide of November 1948, one of the cracks displaced the flume about 2 feet, and water ran from the severed flume into an open transverse crack.

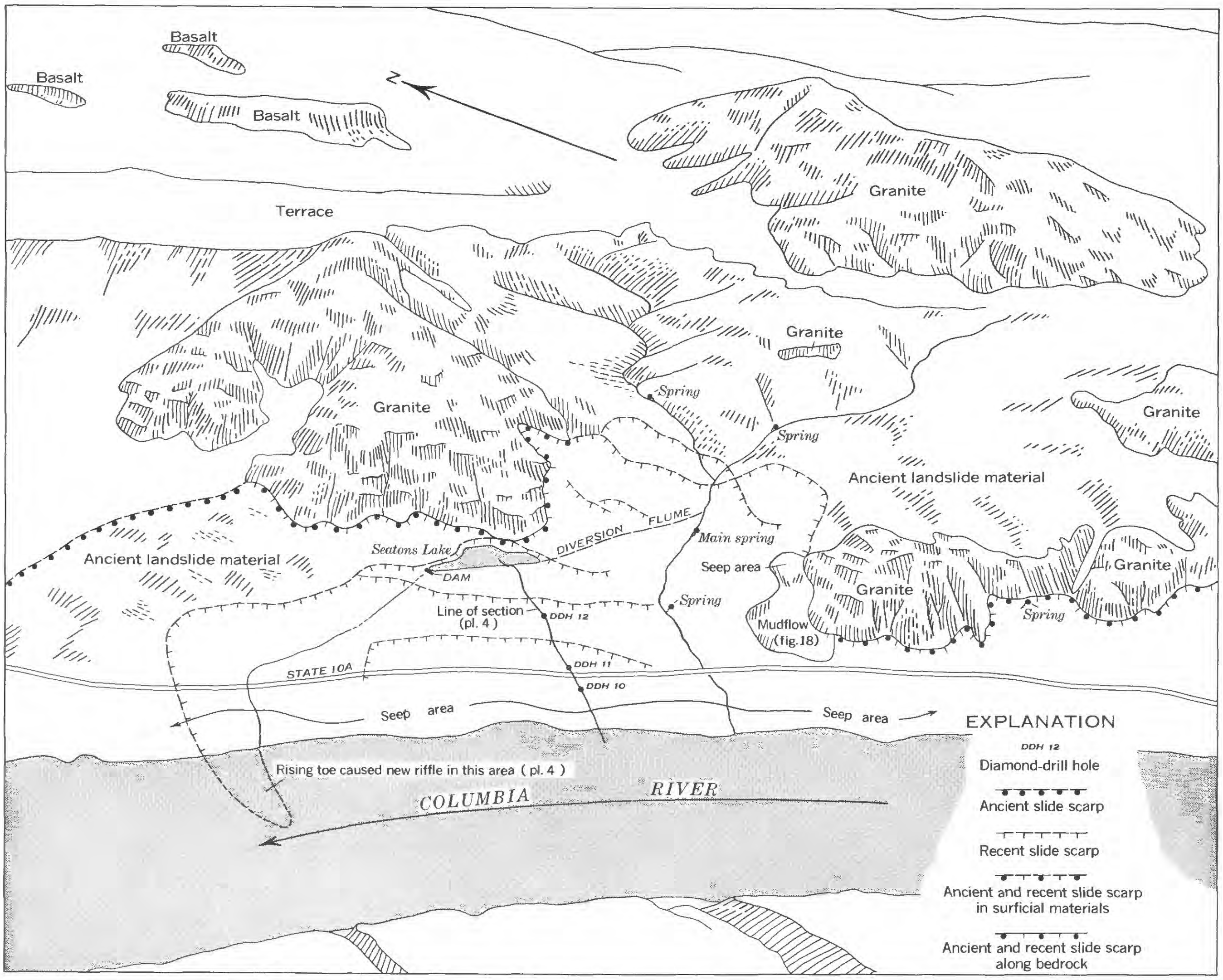

FIGURE 16.—Seatons landslide. An area of ancient landslides that was reactivated in 1948 and moved intermittently through 1953. The diagram shows the major slide scarps as of April 12, 1949, and the position of the cross section plate 4. Grand Coulee Dam-Belvedere area, river mile 5.1 right bank.

Many factors influenced the renewed landslide action in this area, of which the following seem the most important:

1. The unusually heavy rainfall during the spring and summer of 1948.
2. The high water in the Columbia River during the flood of May and June, 1948, undoubtedly resulted in a higher water table throughout the entire slide area.
3. The flood eroded and unloaded the toe of the slide, which is on the outside of a bend in the river where erosion would be greatest.
4. Melt water from the heavy snowfall in the winter of 1948 and 1949 kept the slide lubricated and moving after sliding began.
5. Very deep freezing in the winter of 1948 and 1949 may have had some effect in extending old slide cracks and in damming ground water.
6. Seatons Lake was created in a key position at the head of the ancient slide so that it kept much of the lower part of the ground saturated. Springs on the lower slopes of the hill produced more water when the level of Seatons Lake was higher, and the lake surface was raised purposely at times to make the springs at lower altitudes flow at a greater rate for irrigation.
7. The material at the toe of the slide consisted of silt and clay thinly mantled with sand, gravel, and boulders (fig. 17). Silt and clay could be observed pushing through the gravels at several places along the toe of the slide. Since the construction of Grand Coulee Dam, a replacement supply of sand and gravel to cover and protect the silt and clay from erosion had been largely cut off.
8. The extensive use of this area for homes, gardens, irrigated tracts, and roads had undoubtedly been a factor in encouraging the renewed activity of the slide. Renewed activity might have been postponed if the natural cover of grass and sagebrush had not been removed and if the streams had been kept in their natural channels. The principal spring (fig. 16), which flowed a full stream through a 2½-inch pipe, supplied the entire area with domestic water. The other two springs in the drainage above were about the same size. The small stream, which was seasonally diverted into Seatons Lake, flowed between 0.5 and 0.6 cfs, even in dry years. The stream probably flowed about 1 cfs in the early spring and during unusually wet seasons

The supply of water to the main spring was cut off during the slide of November 1948, but the flow of water was restored to about normal by driving a pipe into a small seep which broke out near the spring. The spring water was milky for several days before it cleared.

In 1953, the Corps of Engineers drilled three test holes in the slide to obtain undisturbed samples of the underlying materials and to install gages to record the pore-water pressures in the soils throughout the year. The material penetrated in the test holes and the ground-water data are shown on plate 4.

The main scarp of much of this slide exposes granite, and the upper part of the surface of rupture follows the contact between surficial deposits and this bedrock. In the initial movement on November 29, 1948, the

FIGURE 17.—Slickensides showing the upward and riverward (right) movement of the downstream side of the Seatons landslide. Striations are on the moved block which is composed of lacustrine silt and clay overlain by river gravel (rock at top of the photograph is a large boulder). Undisturbed material in the foreground. Photograph by H. W. Fuller for U.S. Bureau of Reclamation.

slide sank 12 inches at the scarp. During the winter and spring of 1950–51 the slide sank 9 inches; during the same season in 1951–52, 7 inches; and during 1952–53, 3 inches. No movement was observed or recorded during 1953–54.

SEATONS MUDFLOW (NO. 320)

On March 17, 1949, a mudflow occurred on the edge of the Seatons landslide (fig. 18). The materials of this mudflow were predominantly silt and clay that filled a steep-sided valley in granite. The mudflow was

FIGURE 18.—Mudflow at Seatons Grove, in the foreground, occurred March 17, 1949, at 6:30 p.m. Several observers were almost trapped by the advancing mud. Striations at extreme left were formed as the mudflow crossed undisturbed material. Slide 320, Coulee Dam-Belvedere area, river mile 5.1 right bank.

caused by the lowering of the main unit of the Seatons landslide, which removed support, and by the high ground-water already described. People had been watching the bank for several hours, having been attracted by the noises and small bursts of mud and water. Suddenly, at 6:30 p.m., the whole mass burst and flowed as soft mud over the area. A large quantity of water was released from the materials as they ruptured; simultaneously, a new spring broke out near the top of the main scarp. Several observers were almost trapped by the advancing mud and water. The left foreground of figure 18 shows a mud-slickensided surface over which a part of the mudflow flowed.

KOONTZVILLE LANDSLIDE (NO. 5)

The Koontzville landslide involved the entire village of about 35 houses, one store, and a section of State Highway 10A. The village was built in 1934 and 1935. The general setting is shown on figures 19 and 20. Old landslide materials extend from river level almost to the top of the terrace, or to an altitude of about 1,600 feet. Little or no landslide activity was noticed before the 1948 flood. There may have been some slight highway settlements or minor movements owing to irrigation and river-bank erosion below the highway, but no property damage from landslides was reported. In the fall of 1948 (about the time of the Seatons landslide movement) one resident of the area had trouble with water pipes parting and resorted to flexible hose connections to keep his water system operating. So far as is known, this marked the beginning of reactivation of the ancient slide. The slide has moved many times since. Movements are recorded on the following dates: December 23, 1951; November 10 or 11, 1952; November 27, 1952; and January 10, 1953.

FIGURE 19.—Photograph showing the Koontzville landslide and its relationship to the Seatons landslide (see diagram, fig. 20).

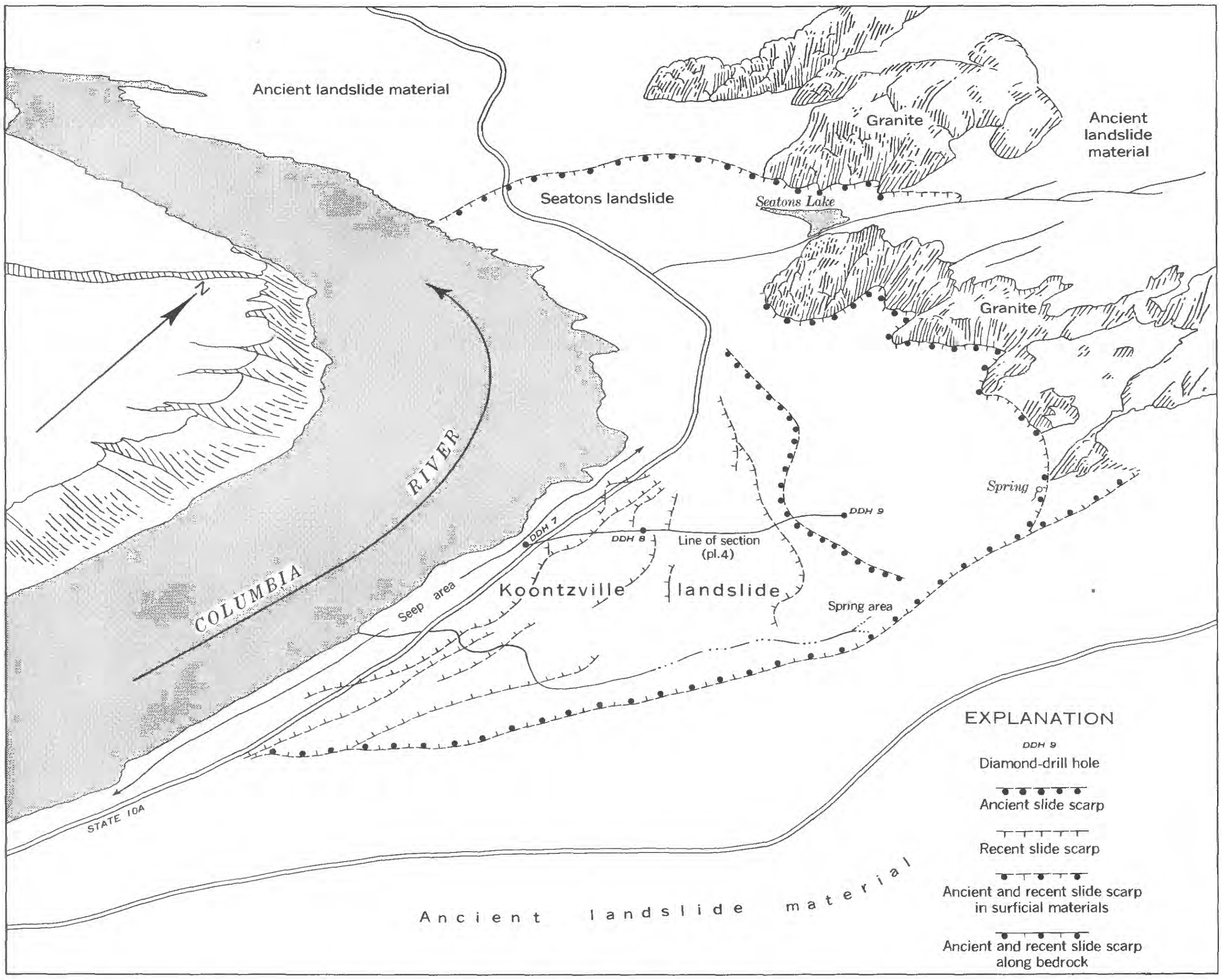

FIGURE 20.—The Koontzville landslide showed signs of reactivation in 1948 and movements occurred in 1951, 1952 and 1953 which damaged many houses and State Highway 10A. Diagram shows the location of cross section plate 4. Coulee Dam-Belvedere area, river mile 4.6 right bank.

In contrast to the diminishing rate of movement observed in the Seaton slide since 1948, the Koontzville slide seemed to move more and at more frequent intervals in successive years to and including the spring of 1953. Local residents have noticed that their houses cracked and moved each weekend during low stages of the Columbia River, which corresponded to drops in river level due to power operations at Grand Coulee Dam. Many houses and the store have been severely damaged, the springs have changed their courses, large fissures have crossed the village area, and each year the slide has worked farther back into the hillside. In 1952, a fissure connected the Koontzville slide with the Seaton slide along the silt-granite contact (fig. 20). The displacement in 1955 extended all along the bedrock outcrops between Seatons Grove and Koontzville. Vertical movement along this bedrock scarp ranges from a few inches to 5 feet. Before the 1948 movement there was a light-colored zone on the granite immediately above the contact with the surficial deposits which ranged in width from 0 to 15 feet. Above this zone, all the granite wall is much darker due to weathering and organic growths. This light-colored zone may represent the amount these slides moved down following an earlier Columbia River flood such as the one in 1896.

Geologically, Koontzville is in a setting where the sequence of Pleistocene deposits is the most favorable for landsliding. A preglacial channel of Peter Dan Creek underlies Koontzville and because of this geologic setting ground-water conditions are very high. Conditions similar to this have been described in the Reed terrace area, and they can be anticipated, almost without exception, where deposits of silt and clay now occupy the area of confluence of preglacial valleys with the main valley.

The causes of the initial reactivation of this ancient landslide seem to parallel those outlined for the Seatons landslide. The causes of the periodic movements, however, are not well understood. In 1953, the Corps of Engineers drilled three test holes in the slide to obtain undisturbed samples of the soil and to install gages to record pore-water pressures throughout the year. The materials found in the test holes and the ground-water data are shown on plate 4.

NESPELEM RIVER AREA

The Nespelem River area (pl. 5; fig. 10) contains large masses of landslide debris and the scarps of many ancient landslides. The area lies about 10 miles downstream from Grand Coulee Dam and is within the area of the Chief Joseph reservoir.

GEOLOGY

Bedrock of the Nespelem River area is mostly the granite of the Colville batholith, although in the southwestern part of the area the Columbia River basalt crops out.

A granitic gravel which crops out in the lower part of the valley is probably the oldest unconsolidated deposit in the area (pl. 5). This gravel extended from below present river level to an altitude of at least 1,200 feet. It was largely removed by erosion before the deposition of the overlying sediments. Remnants are composed of stratified angular to rounded fine gravel and angular coarse sand consisting almost entirely of granite and minerals derived therefrom.

The next younger sediment is a lower lacustrine sequence of which 20 feet of fine sand overlain by at least 100 feet of varved silt and clay is exposed in Kaiser Canyon. The top of this exposure is at an altitude of 1,400 feet. About 0.5 mile north of Kaiser Canyon, in the SE1/4SW1/4 sec. 14, T. 30 N., R. 30 E., fine to very fine sand with minor thin beds of silt and clay is exposed between altitudes of 1,400 and 1,520 feet. Still higher beds in the sequence crop out in gullies in the SE1/4 sec. 11, T. 30 N., R. 30 E. Here the following section is exposed.

	Feet (approximate)
Sand, fine to coarse, with lenses of fine gravel (exposed up to altitude of 1,700 ft)	20
Covered interval, probably sand	80
Sand, fine to coarse, contains lenses of fine gravel 2 to 6 in. thick with cut and fill bedding; beds are deformed	10
Very fine to medium sand with minor silt and clay, contains lenses of fine gravel 12 in. thick at an altitude of 1,550 ft	70
Very fine to fine sand containing some silt and clay in beds 1/16 to 1/8 in. thick; base of exposure at an altitude of 1,500 ft	20

Immediately overlying the lower lacustrine sequence is a basalt gravel a few feet to 50 feet thick that is overlain by 3 to 8 feet of silty gray compact till that contains basalt stones.

After deposition of the basalt gravel and till, melt water flowing southward along the wasting glacier formed ice-marginal terraces and channels along the east side of the Columbia River valley between altitudes of 1,760 and 2,400 feet. These terraces are underlain by sand and gravel of undetermined thickness.

Stream erosion occurred after the deposition of the ice-marginal gravels and before the deposition of the next younger deposit, an upper lacustrine sequence.

The upper lacustrine sequence consists of faintly graded silt and clay varves 5 to 15 inches thick with a distinctive yellowish-gray color. Scattered ice-rafted pebbles and calcareous concretions occur in the sequence. Just south of the Nespelem River map area the original thickness of the upper lacustrine sequence must have been between 500 and 700 feet; in the map area, however, the thickness probably does not exceed 50 feet.

Gravel in terraces at and below 1,400 feet in the Columbia River valley was deposited by the river during postglacial dissection of the upper lacustrine sequence. This gravel ranges in thickness from a few feet to at least 70 feet and consists mostly of subrounded pebble gravel. Overlying the fluvial gravel are alluvial fans of sand and silt as much as 50 feet thick which have been built on top of the terraces at the mouths of tributary valleys.

GLACIAL HISTORY

The first glacial event recorded in the Nespelem River area is the deposition of the granitic gravel, which is inferred to be of glaciofluvial origin. A subsequent advance of the Okanogan glacier lobe blocked the Columbia River valley downstream from the Nespelem River area and formed a lake in which the lower lacustrine sequence was deposited. Further advance of the glacier lobe into the area caused overriding of the sequence and deposition of basalt gravel and till. After the lobe retreated, the Columbia River cut down to the profile of the modern flood plain. Later, the Okanogan lobe again blocked the Columbia River valley and formed the lake in which the upper lacustrine sequence was deposited.

LANDSLIDES

An elongated area of ancient landslide topography lies on the east side of the Columbia River valley from the Nespelem River southward to Kaiser Canyon (pl. 5). The southern part of this area is bounded on the west by the Columbia River and the northern part is separated from the Columbia by a terrace at an altitude of about 1,160 feet. The slide topography in the northern part of section 10 consists of narrow northward-trending ridges, suggesting that a series of slices broke away from the scarp of the 1,400-foot terrace and descended westward. Aerial photographs show that the west edge of this higher terrace forms a scarp slightly concave westward. Strongly disturbed lacustrine beds are exposed where the north ends of the ridges are exposed in the Nespelem River valley. These slides in the northern part north of section 10 occurred during the cutting of the 1,160-foot terrace. This inference is based on the interpretation that the west edge of the slide topography is a stream-cut scarp. Apparently the slide material became stable enough to maintain a low scarp while the river still ran at its toe. South of the center of sec. 10, T. 30 N., R. 30 E., the boundaries of the area of slide topography diverge to the east and west. Exposures in the small southwestward-trending stream valley in the NW¼ sec. 14, show that the beds underlying the north-south trending ridges dip steeply eastward. Initial sliding here was probably contemporaneous with the sliding to the north, though the sliding cannot be dated any closer than being younger than the cutting of the 1,400-foot terrace. There has been movement since the cutting of the 1,160-foot terrace.

The slides south of the middle of sec. 10, T. 30 N., R. 30 E., may have been caused largely by the abundant ground water in the sediments that fill the buried bedrock valley of the Nespelem River. Underground water passing southward through the sediments in the Nespelem River valley reaches the surface in springs that issue into gullies in the SE¼ sec. 11, and the NE¼ sec. 14, T. 30 N., R. 30 E., at altitudes of 1,400 to 1,550 feet. This altitude range generally coincides with the transition zone from silt and clay to sand in the lower lacustrine sequence. The high concentration of ground water combined with river erosion at the toes of slopes on silt and clay has provided an ideal setting for landslides. Erosion of the gullies in the SE¼ sec. 11, and the NE¼ sec. 14, T. 30 N., R. 30 E., has been accomplished largely by spring water since the development of the slide topography north of Bailey Basin.

Bailey Basin, landslide 13 (figs. 21 and 22), in the southern part of the map area is a huge ancient slump-earthflow landslide, the finest example of its type in the entire area studied. It is in the right bank of the Columbia River, 11.86 river miles downstream from Grand Coulee Dam in the Chief Joseph Dam reservoir area (pl. 5). The altitude difference from the crown of the slide to the estimated position of its foot is 700 feet, and the horizontal distance between these points is 3,600 feet. The width along the terrace scarp is 3,000 feet.

The Columbia River in this area begins a long sweeping left turn. Bedrock outcrops in the left bank deflects the erosive power of the river into the bank of surficial deposits at the toe of the slide. It seems likely that this erosion, along with very high ground-water conditions, set the stage for failure. Seismic studies of the configuration of the bedrock surface beneath the slide indicated that bedrock in the half of the basin nearest the river is at about the same altitude as the riverbed, 940 feet, and that near the bottom of the main scarp it has an altitude of 880 feet (fig. 21). Bedrock was indicated at an altitude of 1,315 feet in the terrace just behind the crown, and on the terrace east of the crown at altitudes between 1,100 and 1,516 feet. From these data it may be interpreted that the upper part of the surface of rupture has been controlled by a steep slope on the underlying bedrock and that the lower part of the surface of rupture generally follows the contact between bedrock and the overlying silt.

As can be seen from plate 5 and figures 21 and 22, the river channel is now narrowed by landslide debris. As the river erodes the toe, small new landslides develop in the ancient slide material. The channel and shoreline are dotted with large basalt erratics which were carried down by the slide.

LANDSLIDES IN THE COLUMBIA RIVER BASALT

Scars from landslides that occurred during and after Pleistocene time are numerous in the cliffs of the Columbia River basalt which forms the upper part of the Columbia River valley downstream from the confluence of the Spokane River. Examples of landslides that have occurred since the last invasion of glacial ice are to be found at the following localities: (a) east end of the town of Grand Coulee; (b) west side of the Grand Coulee near its intake; (c) secs. 15, 22 and 23, T. 30 N., R. 28 E.; and (d) on the west side of the Omak Lake valley near its junction with the Columbia River in sec. 6, T. 30 N., R. 28 E., sec. 31, T. 31 N., R. 28 E., and sec. 36, T. 31 N., R. 27 E. These landslides definitely postdate the last glaciation, because the debris retains its characteristic form and is not covered with glacial deposits. Examples of landslide scars older than the last glaciation occur at the following localities: in secs. 20, 21, and 22, T. 28 N., R. 31 E.; and in the left Columbia River bluff between 3½ and 6½ miles downstream from the junction of the Omak Lake valley with the Columbia River valley.

The basalt flows lie on a fairly even surface with altitudes ranging from 2,000 to 2,200 feet, in the area from Grand Coulee Dam to the Omak Lake valley. Between and beneath the basalt flows are lacustrine

FIGURE 21.—Aerial photograph showing landslide in Bailey Basin. Columbia River in foreground. Note recent landslides at the river's edge. Landslide 13, Nespelem River area, river mile 11.86 right bank. Cross section shown in figure 22.

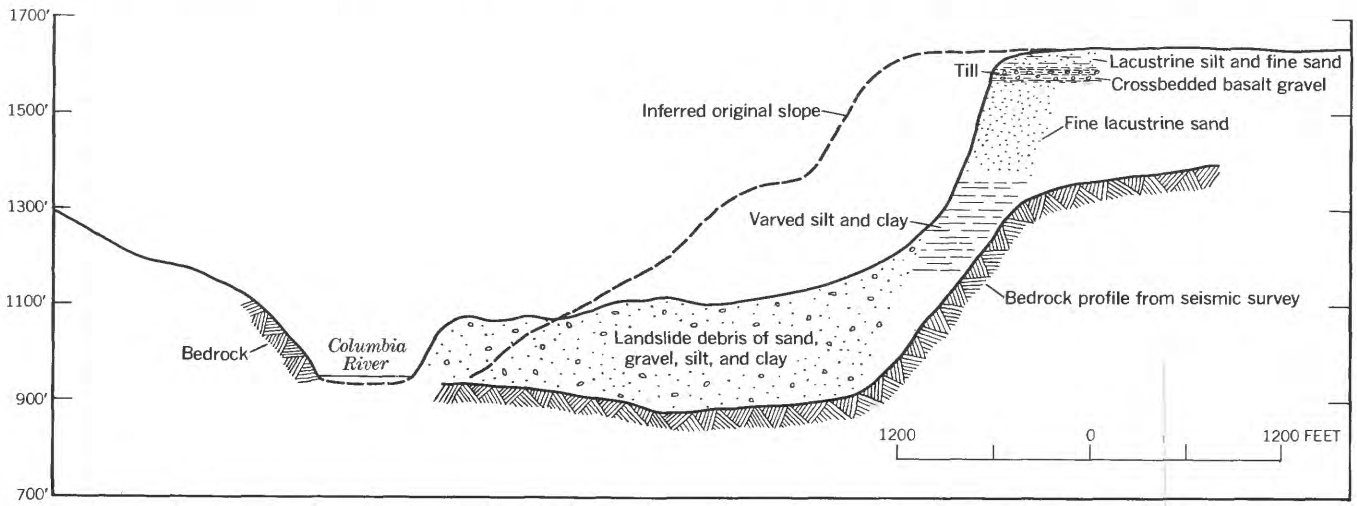

FIGURE 22.—Ancient slump-earthflow landslide and cross section. This well-preserved ancient landslide is designated Bailey Basin on the Nespelem River geologic map (pl. 5). Distance from side to side of the landslide scarp is about 3,000 feet. Several intermittent springs rise in the slide debris. Abundant ground water coupled with river erosion set the stage for sliding.

and fluvial sediments of silt, sand, and fine gravel. These sediments are well exposed in the Grand Coulee and in the Omak Lake valley and probably occur throughout most of the area. They are more than 100 feet thick in the Omak Lake valley in sec. 25, T. 31 N., R. 28 E. The landslides that form huge alcoves in the basalt have apparently failed on these sediments.

A notable feature of the Columbia River valley between the mouth of the Spokane River and Bridgeport is a steplike effect produced by the recession of the basalt cliffs acoss the granite base away from the part of the Columbia River valley incised in the granite. Several explanations are possible but landslide scars and masses of disturbed material suggest that much of the retreat of the basalt cliffs was due to landsliding. The sporadic nature of the widening indicates that some localities were more susceptible to landsliding than others.

SUMMARY OF POSSIBLE CAUSES OF LANDSLIDES

The principal cause of the landslides in the area was the weakening of sediments by ground water. The sediments generally have a lower shear strength when saturated or partly saturated than when dry. During the filling of Franklin D. Roosevelt Lake the sediments bordering the lake became saturated and many landslides occurred. Apparently, buildup of ground water in certain areas downstream from Grand Coulee Dam has been the principal cause of landsliding there.

In an attempt to determine if other factors could have triggered the landslides, the dates of occurrence of 50 landslides that were accurately known were plotted on correlation charts against several possible influencing factors. These landslides occurred between 1941 and 1953. The factors considered were: (a) fluctuations of the level of Franklin D. Roosevelt Lake, (b) riverflow, for slides in the part of the area downstream from Grand Coulee Dam, (c) barometric pressure, (d) maximum and minimum temperatures, (e) precipitation, (f) earth tides and (g) earthquakes. Most of these factors showed no obvious correlation with the times of landsliding. Some relations, however were brought out. Landslides along Franklin D. Roosevelt Lake were most frequent during the filling stage of the reservoir (fig. 23). Since the filling of the reservoir, landslides have been most frequent during periods of drawdowns and during or shortly after periods when the temperature was below freezing. Landslides, along the Columbia River downstream from Grand Coulee Dam were most frequent following and apparently related to a sharp reduction in riverflow and following a 9-month period when precipitation was above the 13-year average.

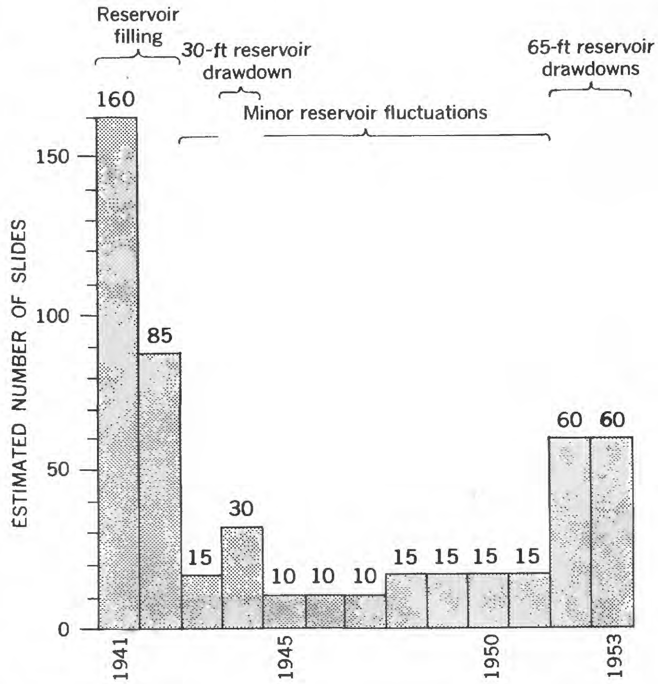

FIGURE 23.—Histogram showing esimated frequency of all landslides along Franklin D. Roosevelt Lake, 1941 to 1954. Number of landslides during this period estimated to be about 500.

ECONOMICS

Landslides cost at least $20 million in the upper Columbia River valley from 1934 to 1955. Most of this cost has been paid by the taxpayers through federal, State, and county agencies engaged in the construction of engineering works. Some of the cost of landslide damage has been borne by private companies and individual property owners. The most skillful geologic and engineering analyses and construction practices could not have saved all of this money, but a large part of it could have been saved had presently known geologic facts been available and had engineers applied them in designing and construction work. This section briefly summarizes the landslides at the site of Grand Coulee Dam and summarizes the cost of remedial measures to correct landslide action for a few locations.

LANDSLIDES AT GRAND COULEE DAM[2]

The construction of Grand Coulee Dam was hindered by a succession of major and minor landslides along both banks of the river (fig. 24). More than 100 separate slide movements were recorded between January 1934 and January 1952, many of which caused damage to structures or other features of the work. In the recent geologic past, erosion and landsliding had reduced

[2] Summarized from memorandum to Chief Engineer, Bureau of Reclamation, Denver, Colo., from B. A. Hall, acting supervising engineer, Grand Coulee Dam, Wash., Historical record of riverbank slides at Grand Coulee Dam, Columbia Basin Project, Wash., 1952: published by permission of Bureau of Reclamation.

FIGURE 24.—Slump-earthflow landslide in lacustrine silt and clay. One of the many landslides that hindered the construction of Grand Coulee Dam. Located in what is now the pumping plant area at the left abutment of the dam. (Photograph by F. B. Pomeroy, Bureau of Reclamation.)

the surficial deposits at the damsite to slopes which were relatively stable to the normal flow and fluctuations of the river. This temporary stability was disturbed by excavation of material at the toe of the slopes, mechanical overloading of existing banks, shifting of the river course, and controlled fluctuations of the river level.

Landslides during the early years of construction (1934–37) were caused primarily by excavation along the toe of riverbank slopes. Many of the later slides may have been due in part to earlier excavation or overloading near spoil banks. To facilitate construction work, the river was often shunted from one side of the channel to the other. Such diversions were accomplished by the use of temporary closure gates which, when lowered into position, sometimes caused rapid drops in the water level below the dam and consequent landsliding. There were very few landslides after the dam had been nearly completed and before the time when the operation of the powerplants required sharp fluctuations of discharge to meet varying powerload demands. There were no slides during 1944 and 1945. As the installed capacity of the powerplants increased, greater regulation of turbine discharge was necessary to meet varying power demands. During this time landslides in the tailrace area of the dam, as well as those in the areas immediately downstream, were closely related to the sharp fluctuations in the river level during periods of low discharge. Excessive river scour due to the 1948 flood was probably also a major cause of increased slide movements in 1948–52.

Frequency of recorded landslides at Grand Coulee Dam and in the area just downstream

Year	Number of slides	Remarks
1934	11	Excavation and construction; many diversions of river from one side of the channel to the other and accompanying fluctuations.
1935	16	
1936	9	
1937	21	
1938	5	Construction, fewer river changes and fluctuations than in 1934–37.
1939	11	
1940	6	
1941	1	Minor sharp river level fluctuations.
1942	4	
1943	2	
1944	0	
1945	0	
1946	2	Period of increasing river fluctuations due to greater installed capacity of Grand Coulee powerplant. Columbia River flood of 1948.
1947	1	
1948	3	
1949	1	
1950	7	
1951	3	
1952	5	
1953	1	

COSTS OF LANDSLIDES

Information on costs of remedial measures to correct landslide activity is available for a few locations.

Left tailrace landslide area, Grand Coulee Dam.[3]—Landsliding of the Pleistocene deposits in the bluff near the left tailrace of Grand Coulee Dam began on March 27, 1934, when as a result of excavation the hillside dropped vertically about 100 feet. The cost of stabilizing this landslide area was more than $6 million. The initial failure required an estimated 1½ million yards of additional excavation. Movements and enlargements of the slide continued to 1950, and although renewed activity is not impossible, engineers of the Bureau of Reclamation consider the area to be stabilized. The stabilization was accomplished by extensive excavation to unload the slope; by installation of a system of underground drainage shafts, drifts, and radiating weep holes; by the construction of a rock-fill plug at the toe of the slope where the slide mass was confined in a narrow bedrock gorge; and by loading and protecting the toe of the slope with a heavy blanket of riprap.

Great Northern Railway slide[4], *No. 272.*—The Great Northern Railway landslide near Marcus, Wash., cost $239,000 for railroad relocation and the excavation of slide material from the highway (fig. 25). This slide of February 23, 1951, destroyed several hundred feet of track of the Nelson branch of the Great Northern Railway, blocked State Highway 22 with slide debris, and narrowly missed a school bus full of children. It was necessary to excavate a bench in bedrock to restore railroad operations—the cost of which was $230,374. Clearing the highway cost $8,719.

Tabulation of costs of landslides at Grand Coulee Dam

[Less engineering supervision and costs]

1934–35	Excavation	$1,500,000
1936–40	Drainage shafts and tunnels	259,000
1936	Rock dam at toe of part of slide	215,000
1936	Gravel blanket above rock dam at toe of part of slide	84,000
1940–41	Unloading and resloping	668,000
1948	Riprap and riverbank protection	363,000
1949–51	do	1,390,000
1951–53	do	1,580,000
		$6,059,000

Deadman Creek slide[5] *No. 271.*—Relocation of Washington State Highway 3 around the Deadman Creek landslide cost $112,000 (fig. 26). This slide is located in the Kettle River valley 5.5 miles north of the Kettle Falls bridge.

Sanpoil valley landslides.[6]—Many landslides damaged or destroyed parts of relocated Washington State Highway 4 along the west side of the Sanpoil River bay of Franklin D. Roosevelt Lake. The Washington State Highway Commission estimates that landslides along these 9 miles have cost $327,000, and that it will cost an additional $500,000 to provide a permanent roadbed in this section.

STATISTICAL STUDIES

During this investigation data were collected on more than 300 landslides. Enough data were collected only on recent slump-earthflow landslides to justify detailed statistical treatment. Two formulas that apply to a geologic environment similar to Franklin D. Roosevelt Lake resulted from the statistical analysis: (a) a formula predicting where slump-earthflow landslides will or will not occur, and (b) a formula predicting how far into a terrace a slump-earthflow landslide will cut.

FIELD OBSERVATIONS AND METHODS

By Fred O. Jones

Studies were made on more than 300 landslides in the Pleistocene deposits along the upper Columbia River valley. Early examinations along Franklin D. Roosevelt Lake revealed a wide range in the size and shape of landslides. These differences seemed to be related to the particular geologic settings of the slides. However,

[3] Published by permission of U.S. Bureau of Reclamation.
[4] Published by permission of Great Northern Railway.
[5] Published by permission of Washington State Highway Commission.
[6] Published by permission of Washington State Highway Commission.

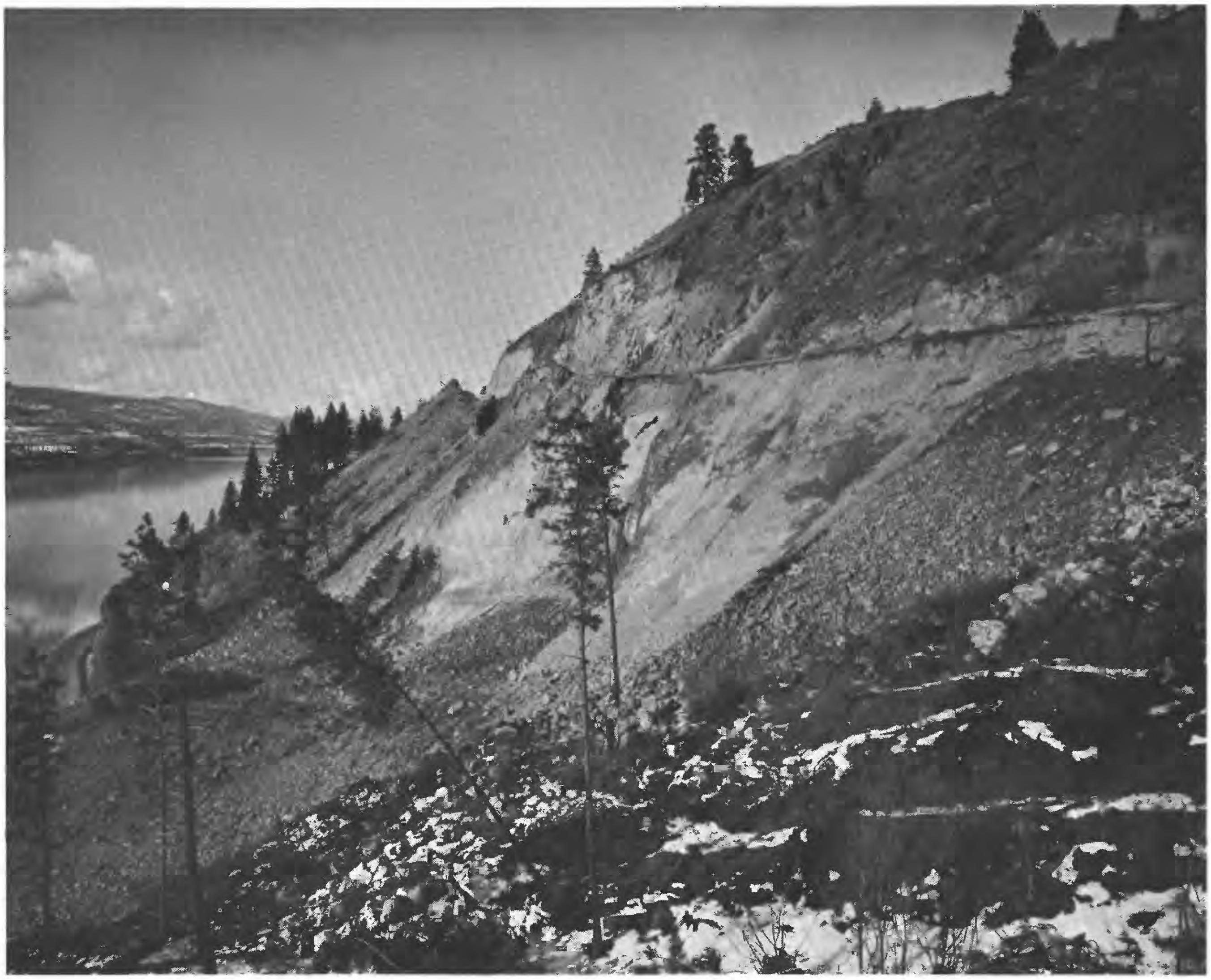

FIGURE 25.—Great Northern Railway slide near Marcus, Wash. This landslide occured from 7 to 9 a.m., on February 23, 1951. It destroyed several hundred feet of railway track (roadbed shown at the crown of the slide). Repair of the roadbed cost $230,374. Cost of removing slide debris from a highway shown at left side of the photograph was $8,719. Photograph by courtesy of the Great Northern Railway Co.

up to 1949, studies were inconclusive as to why slides occurred in one place and not in another, and as to why slides cut deeply into one terrace and shallowly into another. A comprehensive study begun in 1950, attempted to relate the occurrence, magnitude, and location of the slides to the geologic environment.

The first field problem was to differentiate between the various types of landslides. The second field problem was to establish a satisfactory breakdown of the geologic controls.

A data card was devised on which all obtainable information was catalogued. Figures 27 and 28 show both sides of one of these data cards for a typical landslide case. This illustration shows the original classification categories and their subdivisions. As the work of classifying and measuring progressed, it became apparent that some classification subdivisions were unrealistic and some unnecessary. Early statistical analyses indicated that others should be combined or expressed in different forms; for example ground water was originally expressed in four classification categories. Preliminary statistical tests indicated that 3 of these were almost identical for all practical purposes, so the factor, ground water, was divided into only 2 categories. The factors—terrace height, original slope, and submergence—were originally classified into arbitrary categories, but statistical studies indicated that a more precise appraisal of these factors could be made by using the true numerical value. This scheme was adopted.

The definitions of classification categories given in the following sections were revised many times during

FIGURE 26.—Deadman Creek landslide. Slump-earthflow landslide that destroyed several hundred feet of Washington State Highway 3 in the Kettle River valley. Cost of relocation of the highway was $112,000.

the investigations. All landslide data referred to or used in any part of this report are tabulated on tables 1–9 under the heading "Tables of landslide data," p. 74.

Each landslide was located by geographic subdivision, lake, or river mile distance from Grand Coulee Dam and its position on the right or left bank of the river or lake. Figure 10 shows the location and extent of the geographic subdivisions. Theoretical lake mile stationing was established along the center of Franklin D. Roosevelt Lake beginning with zero at the spillway of Grand Coulee Dam. The same system of river mile stationing was adopted downstream from Grand Coulee Dam, again with the spillway as river mile zero. Landslides in bays of the lake were located by distances from the mouths of the bays and whether on the right or left bank. Almost all these bays are at the mouths of tributary streams.

Owing to the large number of landslides, numbers have been assigned to all landslides mentioned in any part of the report. The numbers are not necessarily related to the order of occurrence of the landslides or to the order in which they were studied.

LANDSLIDE TYPE GROUPS

The landslides were classified into 10 type groups, which is an expanded classification of the 4 general types of landslides previously discussed. They conform only in part with the general landslide classifications established by Baltzer (1875), Terzaghi (1925), Ladd (1935), Sharpe (1938), Varnes (1958), and other investigators. The factors which were considered in establishing the type groups were: age, relation to bedrock, and processes of movement (mainly sliding, flow and fall). The term "recent" in type-group classifications and elsewhere in the report refers to landslides whose times of occurrence are recorded or can be recalled by local inhabitants. The term "ancient" in type-group classification refers to landslides whose times of occurrence are not recorded or cannot be recalled by local inhabitants and therefore presumably occurred long ago. All slide scars classified as ancient are now covered with vegetation indicating a great lapse of time since the slide occurred. Almost all of the recent slides since 1940 have been due, either directly or indirectly, to the effects of major engineering projects.

The nomenclature of the parts of the landslide used here is shown on figure 2.

The 10 landslide type groups included in the study; with the number of each are as follows:

		Number of landslides in study
1.	Recent slump earthflows	184
2.	Recent slump earthflows limited by bedrock	4
3.	Ancient slump earthflows	41
4.	Slip-off slopes	51
5.	Multiple alcoves	9
6.	Landslides off bedrock	10
7.	Talus slumps	3
8.	Landslides in artificial slopes, including some natural materials	7
9.	Mudflows	2
10.	Dry earthflows	3
	Unclassified	7
	Total in study	321

Recent slump-earthflow landslides.—Slump-earthflow landslides have been described in a foregoing section of the text under the heading "Types of landslides" p. 6.

This type group includes slope failures in which the surface of rupture intersects the slope at or above its toe, and base failures in which the surface of rupture lies at some depth below the toe of the slope. It has been impossible to determine this difference from field examinations for most of the landslides in this study; consequently, it was necessary to group them together. Landslides of this type have been found in about equal number in all material categories.

Recent slump-earthflow landslides limited by bedrock.—Many slump-earthflow landslides are limited in their extent by bedrock (fig. 29). This group is similar in every respect to the recent slump-earthflow group except that the uppermost part of the surface of rupture follows the contact between surficial deposits and bedrock.

Ancient slump-earthflow landslides.—The terraces of the upper Columbia River valley show the scars of innumerable ancient landslides, most of which apparently date back to a time when river and lake levels

MATERIAL: 1 2 3 4 5 6 7

GROUND WATER CONDITIONS: 21 VERY WET, 22 WET, 23 DRY, 24 VERY DRY
Seeps at sand members

TERRACE HEIGHT OR ELEVATION DIFFERENCE: 31 0'–100', 32 100'–200', 33 OVER 200'
350'

DRAINAGE: 41 GOOD, 42 FAIR, 43 POOR

ORIGINAL SLOPE OF TERRACE SCARP: 51 OVER 1:1, 52 1:1–2:1, 53 2:1–3:1, 54 3:1–4:1, 55 4:1–5:1, 56 UNDER 5:1
2.5 : 1

SLIDE NUMBER: 258

NAME: REED TERRACE AREA

LOCATION: LM 98.4 RB

TYPE: A, B, C, D, E, F, G
Shape

ACTIVATING CAUSES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12

SURFACE WATER RELATIONSHIPS: 60 —
H above lake 61 —
210
H below lake 62 —
140
% submergence 63 —
40% 64 —
37% when slide occurred 65 —

CULTURE: NONE 71 —, MINOR 72 —, MAJOR 73 —

MATERIAL REMOVAL: ALL OR MOST 81 —, INTER-MEDIATE 82 —, VERY LITTLE 83 —

TIME:
Ancient 91 —
Recent: Pre-Reservoir 92 —, Post-Reservoir 93 —
Date-hour is known 94 —
April 18, 1944 6:30 AM

NOTES

PHOTOGRAPH NO. 233

Slide witnessed by Mr. H. E. Reed. It occurred in two units as the shape of the profile suggests. The failure of the first unit was instantaneous and the second followed in just a matter of seconds.

HC/VC 3.8 — 1 2 3 4 5 6 7

VC 350' — 30' 100' 1000'

HC 1320' — 40' 100' 1000' 10,000'

LC 1000' — 100 S 1 2 4 8 16 32 64

FIGURE 27.—Landslide data card (front).

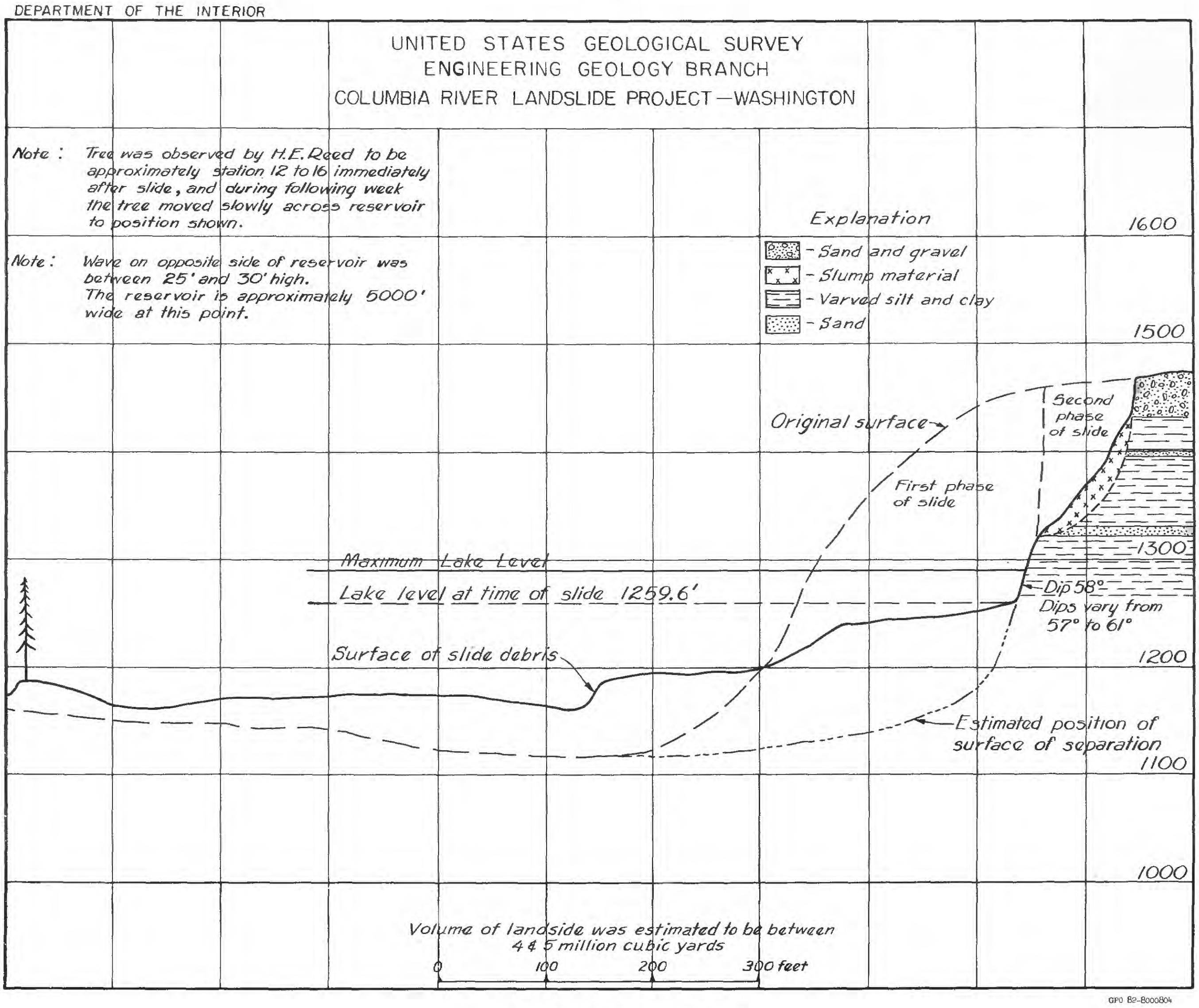

FIGURE 28.—Landslide data card (back).

FIGURE 29.—Slump-earthflow landslide limited by bedrock. Basalt crops out at the crown of the slide. The distance into the slope that this slide cut was apparently limited by the bedrock surface. The slide is in lacustrine silt and clay with some interbedded sand. Initial movement was in August 1941, and minor movements occurred each year through 1953. Slide 63, Hawk Creek area, lake mile 37.2 left bank (Hawk Creek Bay 1,600 feet right bank).

were much different from those of today. Many of the slides are well preserved and can be studied from their topographic form in almost as much detail as some of the recent landslides. The processes involved seem to have been the same as in recent slump-earthflows. The best preserved slides of this type are in the finer sized material categories. Figures 21 and 22 illustrate the ancient slump-earthflow group.

Slip-off slope landslides and multiple-alcove landslides.—Slip-off slope and multiple-alcove landslides have been described in a foregoing section of the text, pages 6–7.

Landslides off bedrock.—In landslides off bedrock, the surface of rupture follows generally the contact between surfical deposits and bedrock. The processes and characteristics of the surficial materials include those described for both the recent slump-earthflow and slip-off slope type groups.

Talus slumps.—Talus slumps sometimes appear to be similar to the slump-earthflow landslides and, at other times, to be similar to the slip-off slope landslides. Talus accumulations in the investigation area are commonly underlain by clay, silt, and sand, which are veneered against steep bedrock cliffs in many places.

Landslides in artificial slopes, including some natural materials.—Artificial-slope landslides consist of failures in cut slopes or in fills where some of the underlying formation also is included in the slide. They are special cases of slump-earthflows because the same movement processes are involved. An illustration is shown on figure 30.

Mudflows.—Mudflows have been described in a foresection of the text, pages 7–8.

Dry earthflows.—Dry earthflows are a combination of fall and flow where there are steep cliffs of silt and clay materials. During prolonged dry seasons, large chunks apparently break off the cliffs and fall. Upon striking, the chunks burst apart and flow like water The flow material is principally a light fluffy powder that contains small fragments of silt and clay. Figure 31 shows a dry earthflow.

CLASSIFICATION UNITS AND MEASUREMENTS OF THE GEOLOGIC ENVIRONMENT

The scheme of classification and analysis used in this landslide study was conceived on the theory that by subdividing the geologic environment into broad units and categories, geologic factors related to groups of landslides could be analyzed by field exmainations and measurements. The classification units and categories are arbitrary. Probably no two investigators would establish identical classifications, even for the same locality.

FIGURE 30.—Failure of an artificial slope. Landslide induced by a roadcut in lacustrine silt and clay (one-fourth mile southwest of Cedonia, Wash.). Toe of landslide was probably removed at intervals as it encroached on the road.

MATERIAL-CLASSIFICATION CATEGORIES

The surficial deposits were classified into six categories which are based primarily on the percentage of lacustrine silt and clay as opposed to the percentage of lacustrine and fluvial sand and gravel in the given sediment and on whether or not the bedding is deformed.

Material category 1.—The materials in category 1 consist predominantly of silts and clays which are in almost their original position of deposition. Terrace deposits of these materials may or may not have a cap of sand or gravel. The silt and clay may be interbedded with lenses or beds of sand, gravel, or till. In general the sand does not exceed 30 percent of the materials lying below the terrace cap. Gravel and till seldom constitute more than 10 percent of the material in this category. They are characteristically poor-draining deposits. Figures 32 and 33 illustrate the materials of this category.

Material category 2.—The materials of category 2 are similar to those in category 1 except that they are in a disturbed or distorted position owing to previous landslide action, slumping, ice shove, or other glacial processes. Figures 34 and 35 illustrate the materials of this category.

Material category 3.—The materials in category 3 consist of alternating beds of silt, clay, and sand in nearly their original position of deposition. Terrace deposits may or may not have a cap of sand and gravel. The silt, clay, and sand may be interbedded with lenses of gravel or till. Gravel does not exceed about 30 percent of the materials lying below the

FIGURE 31.—Dry earthflow. It is believed that one or more blocks of dry lacustrine silt and clay fell at the same time from a high bluff in the background and disintegrated upon striking the base of the bluff, forming a solid-in-air density current which flowed downslope. Common alluvial cones at left of dry earthflow. Nespelem River area, river mile 9.7 right bank.

terrace cap. Till members seldom constitute more than 10 percent of the materials. In general, materials of this category may consist of as much as 60 percent silt and clay or 60 percent sand and gravel. They are partly free-draining and partly poor draining (fig. 36).

Material category 4.—The materials of category 4 are similar to those in category 3 except that they are in a disturbed or distorted position owing to previous landslide action, slumping, and ice shove or other glacial processes (fig. 37).

Material category 5.—The materials in category 5 consist predominantly of sand and gravel. The deposits may be in their original position of deposition, disturbed, or reworked. They may contain cemented zones or sparse layers of silt and clay, but they are free draining. Figure 38 illustrates the materials of this category.

Material category 6.—These materials consist of talus accumulations which may be made up in part of silt, sand, gravel, and boulders. Talus deposits overlie stratified silt, clay, and sand in many places in the area. Material in category 6 is used only in the materials classification of talus slumps—landslide types which are special cases.

FIGURE 32.—Sediments included in material category 1 (silt and clay in, or nearly in, their original position of deposition). This photograph shows varved silt and clay in the Reed terrace area. Ligdt-colored bands are silty, dark-colored bands are clayey. Smooth surfaces of the exposure are vertical joints.

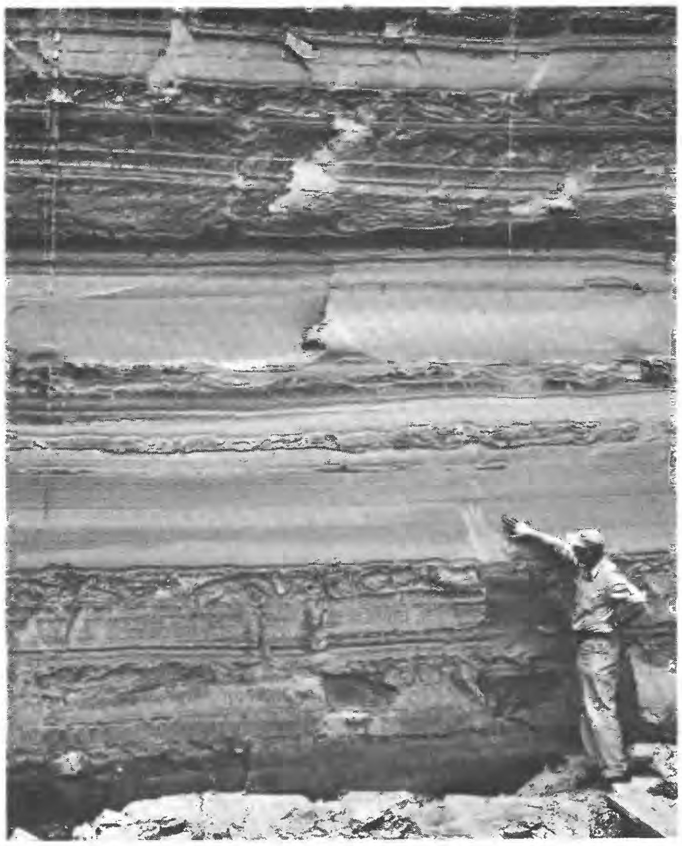

FIGURE 33.—Sediments included in material category 1. This photograph shows thick varves of silt and clay with contortions in the clay zone. These varves are minutely sublaminated as are all varves in the area investigated. Hunters-Nez Perce Creek area.

The material classification for each landslide case was determined from an examination of the exposures opened by the slide and from detailed study of the adjacent area. Individual classifications recorded in the tables of landslide data do not always correspond to the map units on plates 1, 3, 5, and 6 because of local variations in the lithology which are too limited in extent to be depicted on these maps.

GROUND WATER

Ground-water conditions were classified into two categories, high or low, based on observable field criteria. The criteria consisted of the presence or absence of springs, seeps, water-loving vegetation, and high level sources of surface or ground water. The nature and movement of ground water in surficial deposits of the types involved in this study have been adequately described by Terzaghi (1949), Baver (1949), Meinzer (1949), and Meinzer and Wenzel (1949). Ground-water conditions vary from season to season

FIGURE 34.—Sediments included in material category 2 (disturbed or distorted silt and clay beds). This photograph shows varved silt and clay deformed by the thrust of glacial ice. Ninemile area.

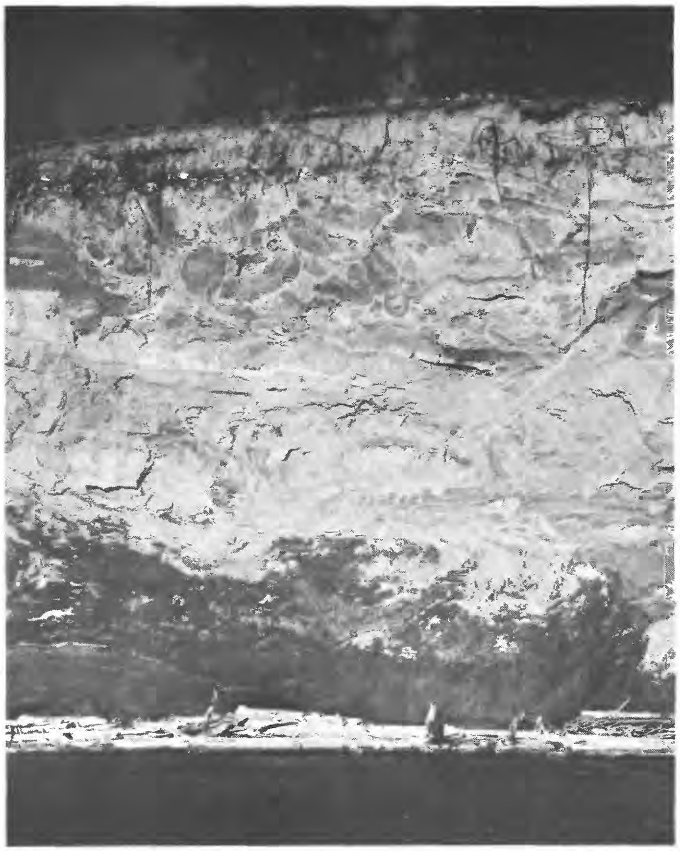

FIGURE 35.—Sediments included in material category 2. This photograph shows lacustrine silt and clay deformed by overriding glacial ice. Wilmont-Jerome area.

and from year to year, but the two classification categories are so distinct that a locality would be classified the same regardless of the season of the year it was examined.

Ground water category 21 (high).—Springs, seeps, and abundant water-loving vegetation above the midpoint of the exposed terrace slope; lakes or springs on the terrace surface or situated at higher altitudes in a position to feed ground water into the terrace deposits.

Ground water category 22 (low).—Springs, seeps, and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; terrace may have a faint line of water-loving vegetation along the base of sand or gravel cap; no springs or lakes on the terrace surface or at higher altitudes to feed ground water into the terrace deposits.

TERRACE HEIGHT

Terrace height is the general altitude difference between the top and bottom of the slope in which the landslide occurred. Commonly it is the altitude difference between two adjacent terraces. Terrace height was originally divided into three categories, and data for many of the slides are tabulated in that form.

Category	*Terrace height (feet)*
31	0–100
32	100–200
33	200 or more

These categories were abandoned as a result of preliminary statistical study and the numerical value of the terrace height was used instead.

DRAINAGE OF TERRACE SURFACE

Drainage category 41.—Drainage lines on the terrace are sufficiently well developed to channel rain and snowmelt rapidly off the area.

Drainage category 42.—Lines of drainage are less well developed and have no significant closed depressions on the terrace surface.

Drainage category 43.—Closed depressions are on the terrace surface; drainage channels are so poorly developed that most of the rain and snowmelt infiltrates the terrace deposits.

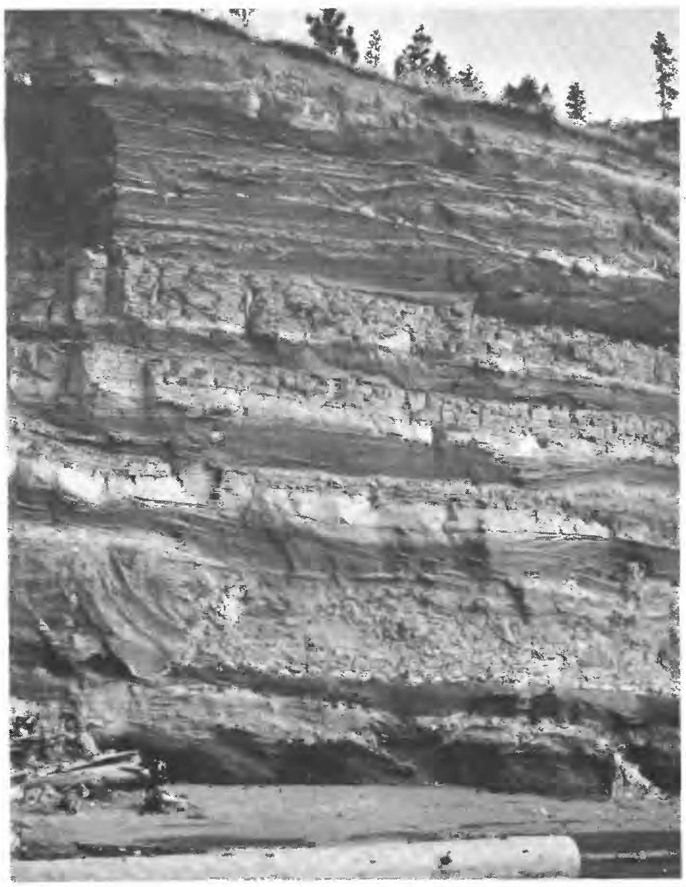

FIGURE 36.—Sediments included in material category 3 (alternating beds of silt, clay, sand and gravel in nearly their original position of deposition). In the central part of the photograph there are megavarves, composed of sand grading upward into silt, which are overlain by many thin silt and clay varves. Hawk Creek area, lake mile 38.0 left bank.

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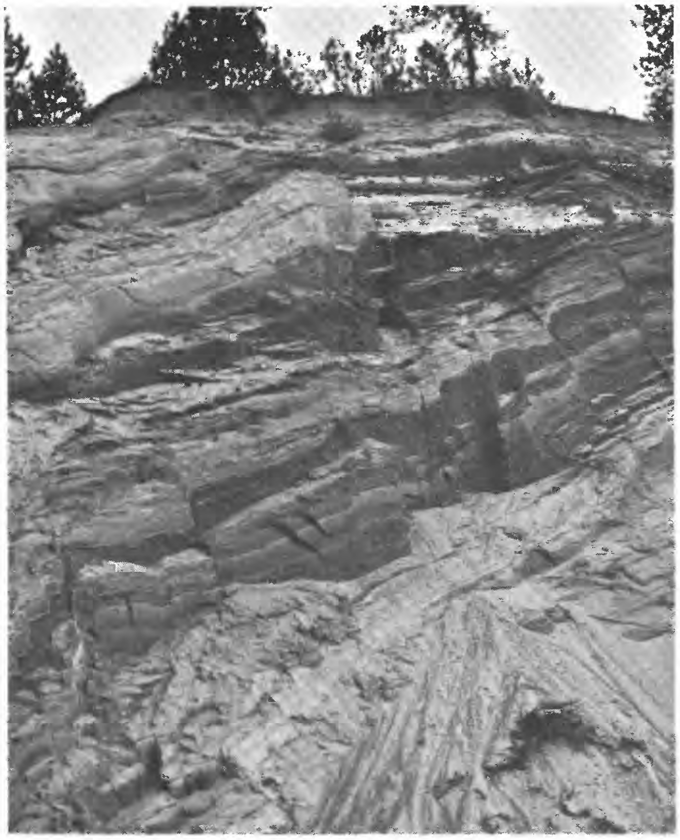

FIGURE 37.—Sediments included in material category 4 (disturbed or distorted alternating beds of silt, clay, sand and gravel). In the photograph, the beds of gravel, sand and silt are tilted, faulted and fractured. Deformation was probably caused by slump over melting glacial ice. Cedonia area.

ORIGINAL SLOPE OF TERRACE SCARP

Six categories were initially defined to study the effect of the original slope on the landslides.

Category	*Slopes*
51	Steeper than 1:1
52	1:1–2:1
53	2:1–3:1
54	3:1–4:1
55	4:1–5:1
56	Flatter than 5:1

These categories were useful in preliminary statistical studies, but it was possible to make a more detailed analysis of this element by using the numerical values expressed as the cotangent of the original slope angle. The measurements were determined for each landslide either from topographic maps made before the slide occurred or by field measurements in the vicinity of the slide.

SUBMERGENCE

Submergence is a measure of the percentage of the mass of the terrace deposit that is submerged and, therefore, subject to the hydrostatic conditions imposed by the lake or river. Six categories of this classification were initially defined.

	Category	*Height (percent)*
60	No relation between lake (or river) level and the terrace or slope in which the slide occurred.	
61	River running at the toe of the slope in which the landslide occurred.	
62	Slope submerged by lake at high-water level	0–25
63	do	25–50
64	do	50–75
65	do	more than 75

Preliminary statistical studies demonstrated no measurable differences between catergories 60 and 61 and the lake submergence percentages established in categories 62, 63, 64, and 65 as they are related to the landslide elements being considered. Consequently, a more accurate evaluation of the submergence factor was made possible by considering river and lake submergence alike and by regarding category 60 as zero percent submergence. The submergence value for each case is the percentage of the terrace height of the slope that is below river or lake surface at high-water level.

CULTURE

This factor was studied to determine the effect of man's cultural and engineering developments on certain landslide elements. The following three categories were established:

Category	*Developments*
71	None.
72	Minor, on or near slide, such as farm buildings, plowed fields, farm access roads, or logging trails.
73	Major, on or near slide, such as deep highway or railroad cuts and fills, irrrigation systems, towns, or storage reservoirs.

MATERIAL REMOVAL

The landslides exhibit wide differences in the amount of movement of the mass of landslide material. In some, particularly those along the lakeshore, practically all of the material slides out, leaving an empty alcove resembling a glacial cirque. In others, the material moves slightly, outlining the shape of the slide. All degrees of movement of the slide material are in between these two extremes. Where several landslides occur side by side and the material is nearly all cleaned out of the scarp, the resulting terrace slope may be steeper than before the landslides. This situation may induce another series of slides cutting farther back into the terrace.

FIGURE 38.—Sediments included in material category 5 (sand and gravel). Cedonia area.

The slides were classified into one of the following three categories:

Category	Removal
81	All or most of the mass of landslide material removed from the scarp.
82	Intermediate.
83	Very little movement of mass of landslide material.

For illustrations of landslides in these categories see figure 12, category 81, and figure 26, category 83.

TIME

To help determine the activating causes of landslides, all data obtainable which related to the age of landslides have been recorded. The following gen eral categories were established, but where exact data were available they also were recorded:

Category	Time
91	Ancient.
92	Recent, before filling of reservoir.
93	Recent, after filling of reservoir.
94	Date of initial sliding or re-movement known.

LANDSLIDE MEASUREMENTS *HC*: *VC* RATIO

The measurements made of each landslide were designated: horizontal component (*HC*), vertical component (*VC*), and length component (*LC*).

HC The horizontal component is the horizontal distance from the foot of the landslide to the crown, taken at midsection of the landslide normal to the slope (figs. 2, and 39).

VC The vertical component is the difference in altitude between the foot and the crown, taken at midsection of the landslide normal to the slope (figs. 2 and 39).

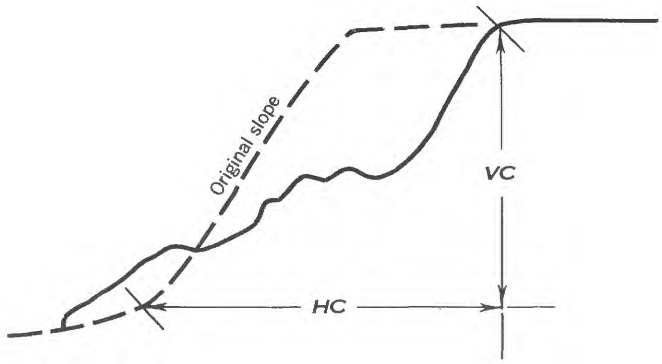

FIGURE 39.—Cross section of a landslide showing *HC* and *VC* measurements, which are respectively the horizontal and vertical distances from foot to crown.

LC The length component is the maximum horizontal distance from side to side of the slide measured parallel to the slope it descends.

The *HC* and *VC* for each landslide were determined either from topographic maps and field measurements or by field measurements alone. Frequently the foot of the landslide was obscured by slide material or by lake water. Its position was arbitrarily placed at the topographic breakpoint (fig. 39) where examinations produced no other criteria for placing it. The *LC* was determined either by map measurements, field measurements, or by estimation.

HC:*VC* is the ratio of the horizontal component to the vertical component of a landslide or the cotangent of the angle of slope of a line between the foot and the crown. Environmental factors have been analyzed with relation to this ratio. For almost every landslide *HC*:*VC* ratio has been determined independently from the original slope value. In the tables of landslide data (p. 74–93) very shallow slides may have a *HC*:*VC* ratio less than the original slope owing to local slope changes and inaccuracies of measurements.

STATISTICAL ANALYSES

By DANIEL R. EMBODY and FRED O. JONES

ANALYSIS AND INTERPRETATION OF LANDSLIDE DATA

Of the 10 landslide type groups, only 5 were represented by sufficient data to warrant statistical study and interpretation. These five type groups were:

Group	
Type 1	Recent slump-earthflow landslides.
Type 3	Ancient slump-earthflow landslides.
Type 4	Slip-off slope landslides.
Type 5	Multiple-alcove landslides.
Type 6	Landslides off bedrock.

For only 3 of the 5 groups were enough data collected to warrant consideration of a statistical analysis. These three type groups were:

Group	
Type 1	Recent slump-earthflow landslides, 160 cases.
Type 3	Ancient slump-earthflow landslides, 37 cases.
Type 4	Slip-off slope landslides, 42 cases.

Statistical methods consisted of the analysis of variance and covariance and multiple regression. Each important analysis is presented in a brief summary with computational detail omitted. For the methods used and the purposes which they were intended to accomplish, the reader is referred to the section headed "Statistical techniques" (p. 69) where an explanation and references to the literature are given.

The analysis of variance method was used to test the significance of the various geologic classifications and to determine whether they could be used as a basis for prediction. Some of the field classifications were found to be significant, others were not; the classifications that were not significant were omitted in arriving at the final analyses and interpretations.

Of the many classifications and measurements made on landslides, the *HC*:*VC* ratio was the only one which described the landslide itself in numerical terms. Consequently, this ratio was defined as the dependent variable. The other factors, both qualitative and quantitative, were defined as independent variables.

The problems considered were:

1. Determining which factors were related to the *HC*:*VC* ratio to a significant degree.
2. The derivation of formulas by which the *HC*:*VC* ratio of an impending landslide could be predicted.

The first analyses were made to determine if any real differences existed in the three larger landslide groups—recent slump earthflow, ancient slump earthflow, or slip-off slope landslides. Preliminary studies revealed that there were large interactions between classifications of geologic materials and the three landslide groups, and between ground-water classifications and the three landslide groups. The interactions indicated that the effects of materials and ground water on the *HC*:*VC* ratio of the landslides were not consistent in the three groups. It was judged, therefore, that each group would have to be analyzed separately. Only the recent slump-earthflow group of 160 landslides contained enough data to justify a detailed statistical treatment. Classifications and measurements of these landslides are tabulated in table 1.

RECENT SLUMP-EARTHFLOW LANDSLIDES

Classifications and measurements were made on eight factors that were initially considered to be of importance in controlling the *HC*:*VC* ratio of landslides. These were as follows:

Qualitative factors
1. Materials
2. Ground water
3. Culture
4. Drainage
5. Material removal

Quantitative factors

6. Terrace height
7. Submergence
8. Original slope

Ideally, the statistical analysis would include simultaneous tests of main effects and interactions of all eight variables. The absence of observations in some of the combinations of factors indicated that such an all-inclusive analysis was not practical since disproportionate subclass methods would be involved.

Preliminary analyses indicated that materials, ground water, and original slope were correlated with the *HC*:*VC* ratio of the landslides. The influence of the above three factors had to be considered in testing the significance of the remaining factors. Each of the remaining factors; namely, culture, drainage, material removal, submergence, and terrace height, were tested individually in a series of analyses that included materials, ground water, and original slope. Had more than one of the remaining factors shown significance in these analyses, it would have been necessary to perform a further analysis to insure that both factors have effects which are independent of each other. The further analysis, however, was not necessary.

QUALITATIVE VARIABLES

The first analysis was made to determine whether culture was associated with the *HC*:*VC* ratio of landslides. Observations of the 160 recent slump-earthflow landslides were arranged in a table which was classified according to material, ground water, and culture. The original slopes and the *HC*:*VC* ratios of the landslides were the independent and dependent variables. Statistical operations were made with logarithms. References to the method of analysis of covariance for three classifications with disproportionate items in the subclasses is given under the heading "Statistical techniques" (p. 69).

Summary of the analysis

Source of variance	Degrees of freedom	Sums of squares	Mean squares	Ratio	Significance
Pooled interactions + residual.	151	1.49058251	0.00987141		
Interactions	13	.16814048	.01293388	1.35	Not significant.
Residual	138	1.32244203	.00958291	------	
Culture + interactions + residual.	153	1.49695583	------------	------	
Culture	2	.00637332	.00318667	.32	Do.

The pooled interactions of materials × ground water, materials × culture, ground water × culture, and materials × ground water × culture were not significant. The main effect for culture was also not significant.

These results were interpreted to mean that within the situation represented by these data, no relation between culture and *HC*:*VC* ratio of the landslides was detected. Cultural developments may be related to ground water or activating causes of landslides, but they could not be judged to relate directly to the *HC*:*VC* ratio of the landslides from these data. The absence of significant interactions supports the conclusion. This may be interpreted to indicate that within each culture classification the effects of materials and ground water on the *HC*:*VC* ratio of landslides may be accounted for by chance variation.

The second analysis was made by the same method to determine whether drainage was associated with the *HC*:*VC* ratio of the landslides. The following table shows a summary of the statistical analysis:

Source of variance	Degrees of freedom	Sums of squares	Mean squares	Ratio	Significance
Pooled interactions + residual.	151	1.44284331	0.00955525	------	
Pooled interactions.	12	.10416158	.00868013	0.90	Not significant.
Residual	139	1.33868173	.00963080	------	
Drainage + interactions + residual.	153	1.49695564	------------	------	
Drainage	2	.05411233	.02705616	2.83	Do.

Neither the pooled interactions nor the main effect for drainage was significant. It was judged, therefore, that the factor, drainage, was not associated with the *HC*:*VC* ratio of the landslides, even though it might be highly correlated with ground water.

The third analysis was made to determine whether the factor material removal was associated with the *HC*:*VC* ratio of the landslides. Data were classified according to material removal, material, and ground water. The original slope was the independent variable. The *HC*:*VC* ratio of the landslide was the dependent variable.

Summary of the analysis

Source of variance	Degrees of freedom	Sums of squares	Mean squares	Ratio	Significance
Pooled interactions + residual.	147	1.43322298	0.00979816	------	
Pooled interactions.	10	.08315798	.00831580	0.84	Not significant.
Residual	137	1.35006500	.00985449	------	
Material removal + interactions + residual.	149	1.46175654	.01051623	------	
Material removal.	2	.02853356	.01426678	1.46	Do.

Neither the pooled interactions nor the main effect for material removal was significant. It was judged, therefore, that material removal was not associated with the *HC*:*VC* ratio of the landslides. The material-removal factor was not expected to be related to the *HC*:*VC* ratio of the landslides. This factor was studied to determine in which geologic setting a series of landslides would tend to load the toe area and contribute to slope stabilization, and in which geologic setting landslides would develop steep scarps and create conditions conducive to additional landslide action.

The 160 observations of material removal which were made on recent slump-earthflow landslides indicated that it was correlated with submergence. Where submergence was high the slide alcove was generally emptied of material which spread over a large area on the bottom of the lake. In places where slides occurred side by side along a terrace, as they have in the Cedonia and Reed terrace areas, this emptying of the slide alcoves resulted in conditions which seemed conducive to a second series of slides cutting deeper into the terrace. This second series has started in the Reed terrace area. The landslide material had a tendency to load the toe area where submergence was lower. Lake and river fluctuations may have caused many re-movements of the material, but new landslides which cut deeper into the terrace have seldom occurred where much of material remains in the slide alcove.

The above analyses completed the simultaneous tests of variables that can be expressed in qualitative terms. Culture, drainage, and material removal were not significant and were consequently judged to be of little importance as they related directly to the *HC*:*VC* ratio of recent slump-earthflow landslides.

QUANTITATIVE VARIABLES

The three quantitative variables, terrace height, submergence percentage, and original slope[7] were next considered. The analysis of covariance method was used and the significance of the quantitative variables was judged from the partial regression coefficients and their standard errors. References to the technique of analysis of covariance and the methods of computation are given under the heading "Statistical Technique" (p. 69.)

The regression equation used was

$$Y=a_{ij}+b_1x_1+b_2x_2+b_3x_3$$

where

$Y=\log HC{:}VC$,

a_{ij} ($i=1, 2; j=1,2,3,4,5$) = constants which represent the 10 sets of material (j) and ground water (i) conditions.

b_1, b_2, b_3, = regression coefficients for the three independent variables

$x_1=\log$ terrace height

$x_2=$ submergence percentage expressed as equivalent angle

$x_3=\log$ of original slope

[7] Original slopes and *HC*:*VC* ratios of landslides are identical geometric measurements, to avoid confusion the term "*HC*:*VC* ratio" has been eliminated in describing original slope.

The value for submergence is a true percentage in that its value cannot be less than 0 percent nor more than 100 percent. The transformation from percentages to equivalent angles is often useful for variables with this characteristic. References describing the equivalent angle transformation and sources of published tables are given under the heading "Statistical Techniques" (p. 69).

In the correlation analysis to be described, the original data were transformed as follows:

Variable	*Transformation*
Terrace height	Logarithm
Submergence percentage	Equivalent angle
Original slope	Logarithm
HC: *VC* ratio slide	Logarithm

Following standard procedures, regression coefficients for the three independent variables were as follows:

Variable	Partial regression coefficient	Standard error	t	Significance
Terrace height	0.051028	0.036416	1.40	Not significant.
Submergence percentage	.302550	.059582	5.08	Highly significant.
Original slope	.407675	.049948	8.16	Do.

Coefficient of determination $R^2=0.389$.

The t-test of significance indicated that the partial regression coefficient for terrace height was not significant, while coefficients for submergence percentage and original slope were highly significant. It was judged, therefore, that in this situation submergence percentage and original slope were important controlling factors with respect to the *HC*:*VC* of slides and that terrace height was not an important factor.

Another important consideration was the consistence of the regression equation under the various combinations of materials and ground water. The covariance method requires that the true relation among the variables be parallel for each set of conditions and that any deviations from parallelism in the data be no greater than might be expected from chance causes.

The test for parallelism among regression coefficients is made by fitting separate regression equations to the data of each of the 10 combinations of materials and ground water. If the total sums of squares accounted for by the individual regression are greater than the total sums of squares accounted for by the combined regression equation to a degree that is significant, then the regressions are judged to be not parallel.

Of the 10 sets of data representing the 10 possible combinations of material and ground water, 1 set contained no slides; 2 other sets contained 1 slide each; and a 4th set contained only 5 slides. The remaining 6 sets contained 17 or more slides. The test for departures from parallelism was made with the latter 6 classes, since including the 4 others would add very little new information and would greatly complicate the calculations.

Test of significance

Source of variance	Degrees of freedom	Sums of squares	Mean square	*f*-test	Significance
Pooled regressions	2	0.677822			
Individual regressions	12	.933487			
Departures from parallelism.	10	.255665	0.0255665	3.52	Highly significant.
Residual	135	.980200	00726074		

A reference to the details for the test for parallelism is given in the section on "Statistical Techniques," (p. 69).

The test for significance showed that the regression equation derived from the combined data of the six classes did not adequately represent the data in the individual classes. It was necessary, therefore, to reexamine the interrelations among the two independent variables (submergence and original slope) and the dependent variable (*HC*:*VC* ratio of slide). Use of a linear function to represent this relation implied that for a given change in the logarithm of the original slope a proportional change would be expected in the logarithm of the *HC*:*VC* ratio of the slide without regard to the level of original slope. It can be easily understood that such a relation is not realistic.

To develop a regression equation which properly represented the data, a quadratic term for logarithm of the original slope was added to the equation. The new regression equation then became

$$Y=a'_{ij}+b_1'x_1+b_2'x_2+b_3'x_3$$

where

$Y=\log HC{:}VC$,

a_1', b_1', b_2', b_3' = intercept and regression coefficients,

x_1 = submergence percentage (equivalent angles),

x_2 = log original slope,

$x_3=\frac{(1+x_2)^2}{10}$ original slope (quadratic).

A new test of parallelism was then made using the new function as follows:

Source of variance	Degrees of freedom	Sums of squares	Mean square	*f*-test	Significance
Combined regressions	3	0.915676			
Individual regressions	18	1.062212			
Departures from parallelism.	15	.146536	0.00976907	1.3	Not significant.
Residual	129	.851475	.00600581		

Using the equation with the quadratic component for original slope, departures from parallelism were not significant. We can assume that the regressions are parallel in the six classes and that a single regression relation is operating with respect to the landslides.

A new covariance analysis was made employing all of the 160 observations of landslides. Estimates of the partial regression coefficients are as follows:

Variable	Partial regression coefficient	Standard error	*t*	Significance
Submergence percentage	0.237621	0.05481	4.34	Highly significant.
Original slope	−1.521044	.3225	4.72	Do.
Original slope (quadratic)	8.067515	1.336	6.04	Do.

Coefficient of determination R^2=0.503.

Submergence percentage and both linear and quadratic terms of original slope were highly significant. Some idea of the overall gain in precision due to adding the quadratic term is seen from the coefficient of determination (square of multiple correlation coefficient), in the previous analysis $R^2=0.389$, while in the last analysis $R^2=0.503$, or an increase of 0.11. The coefficient of determination measured the proportion of total sums of squares accounted for by the independent variables. Adding the quadratic term brought about a sizable increase in precision.

TESTS OF SIGNIFICANCE FOR MATERIALS AND GROUND WATER

The final analysis of *HC*:*VC* ratios devolved about tests of significance for the two qualitative factors, materials and ground water. These tests were made from an extension of the above-described covariance analysis. A summary of the test of significance for the interaction between materials and ground water is as follows:

Source of variance	Degrees of freedom	Sums of squares	Mean square	*f*-test	Significance
Pooled interactions residual.	151	1.015135			
Residual	148	1.000239	0.006758		
Pooled interactions	3	.014896	.004965	0.73	Not significant.

The *f*-test showed that the interaction was not significant. The absence of a significant interaction may be interpreted to mean that the effect of ground water on the *HC*:*VC* ratio of the slide is additive over the entire range of material categories or that within each materials classification the *HC*:*VC* ratio of landslides increases uniformly with increases in ground water.

The summary of tests of significance for main effects is as follows:

Source of variance	Degrees of freedom	Sums of squares	Mean square	*f*-test	Significance
Materials pooled interactions.	155	1.101047			
Pooled interactions residuals.	151	1.015135	0.006723		
Materials	4	.085912	.021478	3.19	Significant.
Ground water pooled interactions residual.	152	1.150310			
Pooled interactions residual.	151	1.015135	.006723		
Ground water	1	.135175	.135175	20.11	Highly significant.

The test of significance showed materials to be significant and ground water to be highly significant. It was judged that both of these factors are very important in controlling the *HC*: *VC* ratio of the landslides.

In the statistical analyses summarized above, 10 independent variables were tested for possible correlation with the *HC*:*VC* ratio. Four factors were highly significant, and one factor was significant. They are as follows:

	f-test	*t*-test	*Significance*
Ground water	20. 11	----	Highly significant
Original slope (linear)	------	4. 72	Do.
Original slope (quadratic)	------	6. 04	Do.
Percentage submergence	------	4. 34	Do.
Materials	3. 19	----	Significant.

All five significant factors exercised important controlling effects on the *HC*: *VC* ratio. Perhaps other factors were related to the *HC*: *VC* ratio, but if relations existed they were too small to be detected and therefore, were not important.

EQUATION FOR THE PREDICTION OF *HC*:*VC* RATIOS OF LANDSLIDES

In the foregoing statistical analyses, the importance of different factors affecting the landslides has been studied. Five factors in particular were important in controlling the *HC*: *VC* ratio. The two qualitative factors ground water and materials showed no interaction. The two quantitative factors original slope and submergence showed no departures from parallelism within the 160 slides studied. It has been established with this information that the *HC*: *VC* ratio is a predictable phenomenon that may be expressed in a single unified equation.

If the predication equation is derived from the analysis of covariance used in making the tests of significance, 10 independent variables are involved and the algebra becomes somewhat unwieldy for field use. Ground water, which contained only 2 levels, was simple to quantify by merely assigning the value of 0.1 to the high level and 0 to the low level. By this device the regression analysis gives an answer identical to that of the analysis of variance.

It would be possible to quantify the five material classifications using the method of least squares as described by Fisher (1946, p. 299–306). The authors were not in a position to conduct such an exhaustive analysis as Fisher's method would require. As an alternative action, numerical values were arbitrarily chosen as follows:

Material designation	*Assignment numerical level*
1	+0. 1
2	0
3	0
4	0
5	−. 1

Using the quantitative values for ground water and materials combined with submergence, and original slope, linear and quadratic, analysis folloeing the multiple regression pattern was made. The computational pattern described by Fisher (1946) was followed. The method of multiple regression is also described by Davies (1954), Youden (1953), Goulden (1952), Mather (1943), Snedecor (1946), and Kempthorne (1953).

Using the redefined variables in a new regression analysis, the reduced prediction equation was developed:

$$Y = 0.6328 + 0.2460X_1 - 1.4121X_2 + 7.5583X_3 + 1.0338X_4 + 0.4015X_5$$

where

Y = Logarithm of predicted *HC*: *VC* ratio of slide
X_1 = Submergence percentage (equivalent angle)
X_2 = Original slope (logarithm)
X_3 = Original slope (quadratic)
X_4 = Ground water (low takes value 0. High takes value 0.1)
X_5 = Materials (1 takes value +0.1; 2, 3, and 4 take value 0; 5 takes value −0.1)

An estimate of the loss in precision which occurred by quantifying the two qualitative variables can be obtained from the analysis of covariance as follows:

Source of variance	Degrees of freedom	Sums of squares	Mean square
Total	159	2. 919848	----------
Reduction due to fitting constants	8	1. 904713	0. 238089
Residual	151	1. 015135	. 006723

From the reduced regression analysis

Source of variance	Degrees of freedom	Sums of squares	Mean square
Total	159	2. 919848	
Reduction due to constants	5	1. 893696	0. 378739
Residual	154	1. 026152	. 00666332

Source of variance	Degrees of freedom	Sums of squares	Mean square	Ratio	Significance
Residual from regression.	154	1. 026152	----------	-----	
Residual from covariance.	151	1. 015135	. 006723	-----	
Loss of precision	3	. 011017	. 003672	0. 546	Not significant.

The analysis showed that the loss of precision brought about in the simplification of the prediction equation was not significant. For prediction purposes, therefore, the reduced equation can be used in place of the complete equation.

Tests of significance were made for the individual regression coefficients as follows:

Variable	Partial regression coefficient	Standard error	*t*-test	Significance
Y intercept	−0. 6328	0. 1209	5. 23	Highly significant.
Submergence	. 2460	. 0538	4. 58	Do.
Original slope (linear)	−1. 4121	. 3036	4. 65	Do.
Original slope (quadratic)	7. 5583	1. 248	6. 05	Do.
Ground water	1. 0338	. 2261	4. 57	Do.
Materials	. 4015	. 1198	3. 35	Do.

The final consideration concerned the precision with which predictions can be made of $HC:VC$ using the reduced equation. The 95-percent confidence limits for the prediction was considered a satisfactory level of precision. Such confidence limits for a six-variable equation, however, require a somewhat involved calculation and would be entirely impractical for field use (see section headed "Statistical techniques", for amplification of this concept). A somewhat less exact measure of precision can be derived from the standard error of estimate of the reduced prediction equation (s_{xy}). The standard error of estimate in the logarithm scale

$$s_{xy}=0.08163$$

This statistic describes the distribution of observed values of $HC:VC$ ratio in logarithms about their respective predicted values. If the data are normally distributed (in this situation it is judged that the data are normally distributed) approximately 95 percent of the observed points will fall within the range described by $\pm(ts_{xy})$.

The 95-percent confidence limits describe a range which brackets the true value with a 95-percent probability. The standard error of estimate describes the variation of the data about an estimated mean. The two kinds of limits will be almost identical within the normal range of the landslide data. The standard error of estimate remains constant over the range of the data, while the 95-percent confidence intervals increase as predictions are made with data which depart from their means.

As an example of the use of the reduced prediction equation and the calculation of limits of variability, consider slide 65. Values of the independent variables for this slide have been estimated as follows:

Variable	Numerical value	Transformed value	Transformation
X_1 Submergence percentage	31	0.338	Equivalent angle.
X_2 Original slope (linear)	1.7	.230	Logarithm.
X_3 Original slope (quadratic)	$\frac{(1+0.230)^2}{10}$	.151	$\frac{(1+\log)^2}{10}$
X_4 Ground water	Low (0)	0	None.
X_5 Materials	1	.1	None.

The above values were substituted into the reduced prediction equation as follows:

Variable	*Regression coefficient*	*Transformed value*	*Product*
Submergence	0.2460	0.338	0.0831
Original slope (linear)	−1.4121	.230	−.3248
Original slope (quadratic)	7.5583	.151	1.1413
Ground water	1.0338	0	0
Materials	.4015	.1	.0402
Intercept (constant term in equations)			−.6328
			0.3070

Estimated value of Y
Antilog $(0.3070)=2.03$

As indicated above, the standard error of estimate was

$$s_{xy}=0.08163$$

as estimated with 154 degrees of freedom. The value of (t) for 154 degrees of freedom representing a 95-percent probability in one direction was

$$t=1.65$$

and

$$ts_{xy}=0.1347$$

In using the equation to predict the $HC:VC$ ratio, interest was centered only on the upper limit, because it was important to know the most probable value of the $HC:VC$ ratio and an upper limit representing the greatest extent to which the slide would cut.

	Logs	*Original values (antilogs)*
Predicted log $HC:VC$ ratio	0.3070	2.03
(1.65) s_{xy}	.1347	
Upper $HC:VC$ ratio limit	.4417	2.76

For slide 65 the predicted $HC:VC$ ratio was 2.03 and the approximate upper 95-percent variability limit was 2.76. The measured $HC:VC$ ratio of the slide was 2.5 and it cut back 1,150 feet into the terrace. The predicted $HC:VC$ ratio of 2.03 estimated that the slide would cut into the terrace only 920 feet. With the confidence interval added, the approximate variability limit for the slide was 2.76. Using this estimated ratio, the slide would have cut into the terrace 1,260 feet, or 110 feet farther than it did.

ANCIENT SLUMP-EARTHFLOW LANDSLIDES

Ancient landslides were studied to determine whether the $HC:VC$ ratio for these slides followed the same general pattern in relation to the classification units as the recent slump-earthflow landslides and to try to evaluate how much $HC:VC$ might increase for the recent landslides during a long period of weathering and erosion.

The classification data of the 37 slides of this type group are tabulated in table 3, page 80. An example of the group is shown in figures 21 and 22. Classification problems were immediately apparent in studying these ancient features. Ground-water conditions at the time of the slides were difficult to appraise. Only two classifications were established, high and low, and these were determined by the general physiographic form of the area behind the landslide. If the shape and trend of the bedrock valleys behind the landslide seemed conducive to channeling an abundant supply of ground water to the landslide area, the ground water was classified as high and, if not, it was classified as low. Only 9 of the ancient landslides were in the low category, and they have a mean *HC*: *VC* ratio of 3.1, as compared to a mean *HC*: *VC* ratio of 3.7 for the 28 classified as having high ground water.

Surface-water relations or the submergence factor of this group were also unknown. The factor, original slope, which was determined to be important in the recent slump-earthflow group, could not be determined for the ancient landslides.

Preliminary statistical tests indicated that the ancient slump-earthflow landslides could not be included with the recent slump-earthflow landslides in a statistical analysis, because this group did not provide adequate data for a detailed statistical analysis. A test was made, however, of the material classifications as they related to the *HC*: *VC* ratio, and the *f*-test was significant, indicating that in the different material classifications represented the mean *HC*: *VC* ratios were significantly different.

The minimum, maximum, and mean *HC*: *VC* ratios of ancient landslides for the material and ground-water groups represented in the data are as follows:

Material	Ground water	Number in group	*HC*:*VC* ratios		
			Minimum	Maximum	Mean
1	High	19	2.4	5.1	3.8
1	Low	5	2.1	5.9	3.2
2	High	4	3.6	6.1	4.8
2	Low	0			
3	High	5	1.7	3.2	2.6
3	Low	4	2.6	3.4	3.0

The following is a comparison of the mean *HC*: *VC* ratios of recent and ancient slump-earthflow landslides for all classes of materials and ground water contained in the ancient type group:

Material	Ground water	Recent slump-earthflow slides (estimated mean of *HC*:*VC* ratio	Ancient land slides (arithmetic mean)
1	High	3.27	3.8
1	Low	2.43	3.2
2	High	2.92	4.8
2	Low	2.16	
3	High	2.87	2.6
3	Low	2.13	3.0

In material category 1 and ground-water categories high and low the general pattern of relation between *HC*: *VC* ratios was similar to that in the recent slump-earthflow landslides. In the other groups, no similar relation was found, but they were represented by such a small number of landslides that conclusions were probably unwarranted. Only the slide group having material category 1 and high ground water contained enough landslides (19) to give any validity to a comparison of the mean value with that of the recent slump-earthflow slides. The mean value of the ancient slides was 3.8 and of recent slides 3.27. This larger mean *HC*: *VC* ratio could be indicative of an increase in time by weathering and erosion, but it could also indicate that only the larger ancient landslides have been preserved in sufficient detail to be recognized in the field and included in the study.

SLIP-OFF SLOPE LANDSLIDES

This group was the second largest included in the study. The classification data of 42 landslides of this group are tabulated in table 2. Figures 6 and 8 illustrate this group. The classifications and measurements made of these landslides were the same as those made for the recent slump-earthflow group.

Preliminary statistical tests indicate that the slip-off slope landslides could not be included with the recent slump-earthflow landslides but would have to be studied independently. The group did not contain data on a sufficient number of landslides to justify detailed statistical treatment. However, a test of significance was made of the material and ground-water classification categories as they related to *HC*: *VC* ratios.

Neither ground water, material classifications, nor their interactions were significantly related to the *HC*: *VC* ratio of the slip-off slope landslides. The *HC*: *VC* ratios for this group ranged from a minimum of 1.0 to a maximum of 2.6 and the mean ratio of the 42 landslides was 1.78. The data showed a high degree of correlation between original slope and the *HC*: *VC* ratio which, as explained in the description of type groups, was an independent determination.

The mean value of the original slope was found to be 1.62, or just 0.16 less than the mean *HC*:*VC* ratio. This type of landslide rarely cuts deeply into a terrace. The causes of these slides can generally be attributed to undermining processes by lake, stream, or excavation.

This type of failure occurs more frequently in coarser grained and dry materials. Of the 42 slides classified, only 4 were in silt and clay, or material category 1, and the remaining 38 were in silt, sand, and gravel categories. Of these remaining 38 slides, 26 were in sand and gravel. All 42 landslides were in the low ground-water classification categories (22, 23, and 24).

Landslides of this type tend to stabilize at the angle of repose of the material involved where a protective wave bench has been built at the toe of the slope and undermining processes are not operating. None of these landslides in the area of investigation could be considered stabilized because of the lack of a protective wave bench in the Franklin D. Roosevelt Lake areas and unusual river fluctuations in the areas below Grand Coulee Dam.

MULTIPLE-ALCOVE LANDSLIDES

Although small in number, this group of nine landslides warrants special attention. The particular geologic setting in which slides of this type are found is described in a foregoing section of the report (p. 7). Perhaps all of these complex slides should be studied individually. More detailed knowledge of them might indicate that they should not be studied together; but because of similarities in the geologic environment they have been grouped in this study. Only one slide of this kind occurred during the investigations (figs. 4, 5, and 12). A detailed description of this slide is given on pages 16–18. The other eight are ancient landslides which have generally a similar physiographic form.

Landslides of the multiple-alcove type are individually the most destructive of the 10 types of slides because of the tremendous area and volume of material involved. The *HC*:*VC* ratio in slide 276 reaches a maximum value of 9.7; however, this measurement may represent much postslide erosion which should not be attributed to the sliding. The mean value of the *HC*:*VC* ratios for these 9 slides is 5.9, and the *HC*:*VC* ratio of the new multiple-alcove slide (No. 261) which occurred in the Reed terrace in 1952 is 6.2. The locations of multiple-alcove slides are limited sharply to deep terrace deposits overlying channels in the bedrock. They are also probably limited to fine-grained materials supersaturated by ground water.

Summary of multiple-alcove slide data

Slide No.	Material	Ground water	*HC*	*VC*	*HC*:*VC*	*LC*
93	3	22	1, 900	400	4. 8	3, 000
103	3	21	1, 600	400	4. 0	1, 500
133	1	21	4, 700	510	9. 2	5, 500
135	1	22	4, 200	850	4. 9	5, 000
145	1	21	2, 600	600	4. 3	2, 000
159	1	21	1, 650	270	6. 1	1, 300
160	1	21	1, 650	400	4. 1	3, 400
261	1	21	2, 100	340	6. 2	1, 400
276	1	21	3, 200	330	9. 7	4, 200

LANDSLIDES OFF BEDROCK

Landslides in which the surface of rupture generally follows bedrock are common in the area. Summarized below are six of the landslides studied:

Slide No.	Material	Ground water	Original slope	*HC*	*VC*	*HC*:*VC*	*LC*
59	5	24	1. 4:1	210	160	1. 3	90
84	2	22	5. 7:1	230	42	5. 5	160
86	1	24	2. 1:1	95	45	2. 1	140
110	2	21	3. 5:1	570	163	3. 5	250
171	1	24	2. 1:1	33	16	2. 1	43
240	1	24	1. 7:1	120	70	1. 7	100

HC:*VC* ratio of these slides is nearly the same as the original slope. The most important fact revealed by this group is that the flattest slopes fail in a setting where superficial deposits are shallowly underlain by bedrock. The flattest slope to slide in all the investigations was in slide 84, where the original slope was 5.7:1. It is interesting to note that ground-water conditions here were dry. The mass of landslide material in landslide 110 flowed around projecting bedrock points which seemingly should have given enough support to resist sliding. The mean *HC*:*VC* ratio of this group was 2.7, but it has little significance in studying the possible occurrence or extent of a landslide of this type at other locations.

UNIFORMITY EXPERIMENT

All the basic data used in the statistical analysis of landslides were collected by Mr. Jones. The question arises, therefore, as to whether these data are conditioned in some manner by his long period of observations and by personal methods of making the measurements. If this is so, other workers might find it difficult or impossible to get similar results. To gain some insight into this problem, a uniformity experiment was conducted to determine whether field observations of independent workers, using the same concept of *HC*:*VC* ratio and the same classification categories of ground water, original slope, material, and percent submergence, would reproduce the results of Mr. Jones' field observations.

The uniformity experiment was planned so that two geologists who were not familiar with the Pleistocene deposits or the landslides in the area were assigned to make a series of measurements. The men were briefed for 2 days before going into the field on the methods used to secure the original data, definitions of the classification categories, and the organization and purpose of the test. Detailed explanations and answers to their questions were given as they requested. All data and results of the author's measurements were withheld until the fieldwork was completed. The first half day in the field was devoted to practice measurements of landslides not included in the experiment and to observations of a few exposures. After this the two geologists, Christopher Erskine and Warren Peterson, used their notes and the definitions which had been established by the author, but no further explanations or guidance were given.

The experiment was conducted on recent slump-earthflow landslides, 160 cases of which were analyzed in the preceding section. Available resources limited the investigation to a sample of 42 slides. The ideal sample would have been 42 slides picked and measured completely at random from the 160 slides available. Under such conditions each of the 160 slides would have had an equal and independent chance of getting into the sample and, as such, it would have been representative of the area as a whole. However, it was impractical to measure 42 of the slides in a random order since some of them were nearly 100 miles apart. Irrespective of the order of measurement, 7 areas were arbitrarily choosen where 6 or more landslides could be measured in 1 day. A random sample of six slides was chosen from each area for inclusion in the test, and the order in which the slides were chosen was the order in which they were measured. The randomization was performed with published tables of random permutations. Landslides were selected for experimental observations for 7 days in the above manner.

Geologists Peterson and Erskine made observations on the 42 slides from April 13 to 23, 1953. Measurements and classifications recorded for each slide were the *HC*:*VC* ratio or dependent variable and the four independent variables determined to be important controlling factors from the analysis of the recent slump-earthflow landslides—ground water, original slope, submergence, and material. Table 7 summarizes the data obtained from this test together with duplicate measurements taken from table 1 by the senior author.

SUMMARY OF ANALYSIS OF *HC*: *VC* RATIO OF LANDSLIDES

The problem was to determine whether the means of the *HC*: *VC* ratio in the test differed significantly from the originals. The results showed that the mean values of the *HC*: *VC* ratios did not differ materially; consequently, they were found to be reproducible by other geologists. Because *HC*: *VC* ratios were continuous variables, the statistical analysis followed the standard pattern for the analysis of variance. The computations and tests of significance were made with the logarithmic form of the data. Sample computations, together with references, are given under heading "Statistical Techniques" (p. 69).

Source of variance	*Degrees of freedom*	*Sums of squares*	*Mean squares*	*f-test*	*Significance*
Total	83	1.9038			
Landslides	41	1.3954	0.0340	2.86	Highly significant.
Men	1	.0207	.0207	1.74	Not significant.
Residual	41	.4877	.0119		

Mean HC:VC ratios	*In logarithms*	*In original numbers (antilogs)*
Test	0.2670	1.850
Original measurements	.2986	1.989
Difference	.0316	.139

The tests of significance show that the difference between slides is highly significant, while the difference between men is not significant. It is judged, therefore, that the *HC*: *VC* ratio is a sensitive measurement of a landslide, and the ratio could be reproduced in this situation by at least two other workers. The sensitivity of the *HC*: *VC* measurement is presumably due to significant variations in the four classification factors—material, ground water, original slope, and submergence percentage, which are defined and analyzed in preceding sections. Measurements and classifications were made by Mr. Jones a few years before this test; thus the lack of a significant difference between men leads to the judgment that *HC*: *VC* values are stable over a short span of time.

SUMMARY OF ANALYSIS OF ORIGINAL SLOPE

The problem for original slope was the same as for the *HC*: *VC* ratio—to determine whether the means of original slopes measured in the experiment differed to a significant degree from the originals. It was found that they did not and that this factor was reproducible by the men in the experiment. Original slope, like the *HC*: *VC* ratio, was a continuous variable, so the analysis and computation followed the same pattern.

Source of variance	*Degrees of freedom*	*Sums of squares*	*Mean of squares*	*f-test*	*Significance*
Total	83	1.6618			
Landslides	41	1.3140	0.0321	4.05	Highly significant.
Men	1	.0229	.0229	2.89	Not significant.
Residual	41	.3248	.00792		

Mean original-slope ratios	*In logarithms*	*In original numbers (antilogs)*
Test	0.3476	2.227
Original measurements	.3806	2.402
Difference	.0330	.175

The difference between landslide means is highly significant, whereas the difference between men is not significant. It is judged, therefore, that original slope is a controlling factor in the environment of a landslide and its measurement can be reproduced by other geologists.

SUMMARY OF ANALYSIS OF SUBMERGENCE PERCENTAGE

Since submergence was also a continuous variable, the problem and its solution were the same as in the two previous analyses, except that the percentages were transformed to equivalent angles instead of logarithms.

Source of variance	*Degrees of freedom*	*Sums of squares*	*Mean of squares*	*f-test*	*Significance*
Toatl	83	1.1263			
Landslides	41	1.0274	0.0251	14.2	Highly significant.
Men	1	.0264	.0264	14.9	Do.
Residual	41	.0725	.00177		

Mean submergence values	*In angles*	*In original numbers (antilogs)*
Test	0.4224	45.2
Original measurements	.4579	51.4
Difference	.0355	6.2

Both landslides and men were highly significant. It is judged, therefore, that submergence percentage is also a controlling factor in the geologic setting of a landslide. Statistically, the mean difference of 6.2 in submergence percentage indicates: (a) that submergences were measured differently at the time of the experiment than when they were measured originally, or (b) that the measurement for submergence is not reproducible among geologists. From a practical standpoint this mean difference of 6.2 percent is probably not large enough to be important.

SUMMARY OF GROUND-WATER ANALYSIS

The qualitative variable ground water, with two categories, was reproducible by geologists Erskine and Peterson. Of the 42 landslides classified, only 1 differed from the original. Had the men in the experiment been unable to duplicate the ground-water categories at all, their results would have reflected chance variation. With 2 classifications where chance alone dictated the choice, each classification would have a probability of 1:2 of being correct or erroneous (assuming the original classification to be correct), or it would have been expected that on the average, of the 42 slides, 21 would be classified right and 21 wrong. The results deviated from what would have been expected by chance alone; therefore, it is judged that the men were able to classify ground water in the same way as the author.

Actual and expected results are:

	Expected (by chance alone)	*Actual*
Classifications right	21	41
Classifications wrong	21	1

$\chi^2=38.1$ Degree of freedom = 1 Probability = 0.01

The chi-square of 38.1 is greater than would occur on a chance basis once in 100 times. Chance alone cannot explain these data. Consequently, it is judged that ground-water classifications are reproducible.

SUMMARY OF MATERIAL ANALYSIS

The qualitative variable material, with five categories was not reproducible by the men in the experiment. The method of analyzing the material classifications was the same as for ground water except that material was divided into five categories. Here, if chance alone operates in the classification, the probability of its being correct is one-fifth and of its being incorrect four-fifths.

Actual and expected results are:

	Expected (by chance alone)	*Actual*
Classifications right	8. 4	10
Classifications wrong	33. 6	32

$\chi^2=0.396$ Degrees of freedom = 1 Probability = 0.30

The value of chi-square of 0.396 indicates that the test results are about what would be expected by chance alone; consequently, it must be judged that the men in the experiment were not to classify materials into the five categories. This is not surprising because of the complex nature of Pleistocene deposits in the area and the brief incomplete field review of the deposits given the men in the test before their first attempt at this kind of classification. Classification is one of the most difficult tasks for research workers in any scientific investigation. Geologists Erskine and Peterson could probably have more nearly duplicated the original measurements if the illustrations showing the different types of material (figs. 32–38) had been available to them, and if they had been provided with a working knowledge of all the pertinent material exposures in the investigational area.

SUMMARY AND INTERPRETATION OF UNIFORMITY EXPERIMENT RESULTS

1. The *HC*: *VC* ratio was a precise measurement of a landslide. It was also a measurement reproducible by other geologists unfamiliar with the details of the landslide or the particular geologic setting.
2. The original slope of the terrace scarp was one of the controlling factors in the environment of a landslide. It was also a reproducible measurement.
3. Submergence percentage was also determined to be a controlling factor in the geologic setting of a landslide but was not reproducible by the geologists in the test.
4. Ground-water classifications were reproducible, qualitative measurements.
5. Material classifications were not reproducible in the experiment. The geologists could probably have more nearly duplicated the original classifications if they had been provided with clear-cut definitions, illustrative material, and a working knowledge of the stratigraphy of the Pleistocene deposits.

While the uniformity experiment indicated that material classifications may not be reproduced, the analysis of recent slump-earthflow landslides showed that material classifications were correlated with the *HC*: *VC* ratio of the landslides. Since both of these variables had demonstrated their usefulness in predicting the slide ratio, they were not rejected. Because of the results of the test, definitions of the material-classification categories were painstakingly revised to include many details which were not incorporated at the time of the experiment.

SLOPE-STABILITY INVESTIGATION

In an effort to determine which sections of the banks along Franklin D. Roosevelt Lake were safe from landslides and which were unsafe, a slope-stability investigation was undertaken. The study was designed to combine the data of the 160 recent slump-earthflow landslides with data for 160 representative locations in which there were no landslides. The analysis used the discriminant-function method, in which quantitative and qualitative factors influencing sliding were combined into an equation that provided maximum discrimination between slopes that are likely to fail by landsliding and those that are not. The 320 values of the discriminant function ranged from −0.0019 to +0.0404. The lower values were generally associated with stable slopes, and the higher values with landslides. A value of 0.0106 was found to be the theoretical lower 95 percent confidence limit for slides, and although much overlapping of discriminant values was found between slides and stable slopes, there are clear-cut conditions where nearly all slopes have slides and other conditions where nearly all slopes are free of slides.

For the purpose of this study, a stable slope was defined as a slope on which there was no recent slide. The investigation of stable slopes was made by classifications and measurements in the same manner as the investigation of landslides. Locations were chosen so that the group of 160 stable slopes represented as nearly as possible a random sample of all slopes along Franklin D. Roosevelt Lake which have not been affected by sliding in its first 14-year history. Measurements were made of the slope of the terrace scarp, submergence percentage, and terrace height. Classifications were made of the qualitative variables, ground water and material, following the same definitions and classification categories used for the landslides. The locations of the slopes studied and the classification data are summarized in table 8 (see section headed "Tables of landslide data", p. 74).

SUMMARY OF ANALYSIS FOR THE DISCRIMINANT FUNCTION

The discriminant function employed in this experiment is an equation designed to differentiate slopes that are potential slide areas from slopes that are not potential slide areas. The form is

$$y=b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_5x_5+b_6x_6+b_7x_7+b_8x_8+b_9x_9$$

where

y=the dependent variable or discriminant function

$b_1, b_2 \ldots b_9$=coefficients derived from the analysis of factors influencing sliding in 160 landslides and 160 stable slopes

$x_1, x_2 \ldots x_9$=independent variables determined to be significant factors influencing sliding: original slope, submergence percentage, terrace height, ground water, and materials

The independent variables, original slope, submergence percentage, and terrace height, are quantitative and can be used in their numerical form. To use multiple regression methods, the qualitative variables ground water and materials must be quantified. Ground water is a qualitative variable, and since it has only two levels it presents no problem in quantification. The number 0.1 was arbitrarily assigned to high ground water and the number 0 to low ground water.

Materials were represented by five independent variables, with the following assigned values:

x_5=0.1 for material 1 and 0 for other materials
x_6=0.1 for material 2 and 0 for other materials
x_7=0.1 for material 3 and 0 for other materials
x_8=0.1 for material 4 and 0 for other materials
x_9=0.1 for material 5 and 0 for other materials

Data for orignial-slope and terrace-height variables were transformed to logarithms. Data for submergence percentage were transformed to equivalent angles. For the 160 landslides, the discriminant values are listed in table 1; those for the 160 stable slopes in the experiment are listed in table 8.

Regression coefficients and tests of significance for the discriminant function are as follows:

Symbol	Variable	Coefficient	Standard error	t-test t	Significance
b_1	Original slope	-0.0213	0.0016	13.33	Highly significant.
b_2	Submergence	.0028	.0019	1.44	Not significant.
b_3	Terrace height	.0102	.0013	7.85	Highly significant.
b_4	Ground water	.0616	.0104	5.89	Do.
b_5	Material 1	-.0082	(1)		
b_6	Material 2	.0106	.0066	1.60	Not significant.
b_7	Material 3	.0037	.0070	.53	Do.
b_8	Material 4	.0186	.0076	2.44	Significant.
b_9	Material 5	-.0247	.0071	3.46	Highly significant.

[1] Not estimated.

The variables, original slope, terrace height, ground water, and material 5, showed high significance. Material 4 showed significance at the lower level. Submergence percentage was not significant. The standard error for the coefficient of material 1 could not be readily estimated from the analysis, but since the standard errors for the other materials were approximately equal it was assumed that material 1 was not significant.

The analysis of variance for testing the significance of the discriminant function was as follows:

Source of variance	Degrees of freedom	Sums of squares	Mean square	t-test	Significance
Total	319				
Between groups	9	0.000710936	0.00639842	24.6	Highly significant.
Within groups	310	.00894317	.0000288488		

The high degree of significance between groups may be interpreted to mean that the variables included are related in some manner to the stability of slopes in this area. Nonsignificance of material classifications in categories 1, 2, and 3 is not surprising because these categories contain principally fine grained sediments which when dry stand in clifflike slopes and when wet rest on gentle slopes. When taken together as material groups, both situations are combined. Some different method of quantification based on grain size, amount of compaction, cohesion, or shear strength might provide a way of incorporating them into the slope-stability formula, but this was not within the scope of the investigation. Because of the lack of significance of three of the material categories, it was decided to derive a reduced equation excluding all of the material categories.

The variables, original slope, terrace height, and submergence percentage were all transformed to logarithms. In the case of submergence percentage, preliminary studies indicated that the logarithm transformation would be more highly correlated than the equivalent angle transformation used before. Ground water was defined as 0.1 for high ground water and 0 for low ground water.

The reduced discriminant function and the summary of the analysis of variance is given as follows:

$(y = 0.0216247 \log x_1 + 0.00334811 \log x_2 + 0.00944030 \log x_3 + 0.00673126 x_4)$

where

y = Discriminant function
x_1 = Original slope
x_2 = Submergence percentage
x_3 = Terrace height
x_4 = Ground water (high = 0.1) (low = 0)

SUMMARY OF ANALYSIS OF VARIANCE FOR THE DISCRIMINANT FUNCTION

Analysis of variance

Source of variation	Degrees of freedom	Sums of squares	Mean square	f-test	Significance
Total	319		0.001519		
Between groups	4	0.006076	.0000277	54.90	Highly significant.
Within groups	315	.008715			

Coefficients of the discriminant function and their standard errors

Variable	Coefficient	Standard error	t-test	Significance
Original slope	−0.021625	0.001531	14.12	Highly significant.
Submergence	.003348	.000791	4.23	Do.
Terrace height	.009440	.001234	7.65	Do.
Ground water	.006731	.00988	6.82	Do.

NOTE.—Degrees of freedom=315 t=2.6 for P=0.01

The high degree of significance between groups may be interpreted to mean that the variables taken together are related in some manner to slope stability. The fact that the ratios of the coefficients divided by their standard errors exceed the value of (t) for a 1 percent probability warrants the judgment that each of the 4 variables is related to slope stability in such a way that prediction of potential landslide conditions is possible.

USE OF THE DISCRIMINANT FUNCTION

The discriminant function may be used to differentiate stable from potentially unstable slopes where any combination of values of the four variables exists. Calculations of the discriminant functions for the 320 landslides and stable slopes gave values ranging from −0.0019 to +0.0404.

In general, the lower values of the discriminant function represented stable slopes, and the higher values represented landslides. Less than one percent of the landslides had a discriminant value below a theoretical value of 0.0106; consequently, it will be safe to judge that a slope will not be affected by sliding if its discriminant value is below this level. Less than 5 percent of the landslides had a discriminant value below 0.0142; consequently, it will be relatively safe to judge that a slope will not be affected by landslides if its discriminant value is below 0.0142.

The mean value of the discriminant functions for the two categories was

	y
Landslides	0.02282
Stable slopes	.01411
Midpoint value	0.01846

In theory, when the discriminant function is less than the midpoint 0.01846, the slope will be classified as stable, and when the discriminant function is greater than 0.01846, the slope will be classified as unstable. The difference between either mean and the midpoint is 0.00435. From the analysis of variance the standard deviation is 0.00526. The ratio of the difference to the standard deviation gives a value of

$$t = \frac{.00435}{.00526} = 0.827 \text{ for 315 degrees of freedom}$$

From standard tables of Student's t a value of 0.827 is exceeded about 21 percent of the time. Approximately 21 percent of slides will have discriminant values below the midpoint 0.01846.

Table of actual frequences of landslides and stable slopes for various levels of the discriminant function:

Class limits for discriminant function	*Frequency of slides*	*Frequency of stable slopes*	*Total*
−0.0051–0.0000		5	5
0.0001–0.0050		10	10
0.0051–0.0100		21	21
0.0101–0.0150	2	47	49
0.0151–0.0200	39	51	90
0.0201–0.0250	75	22	97
0.0251–0.0300	41	4	45
0.0301–0.0350	1		1
0.0351–0.0400			0
0.0401–0.0450	2		2
Total	160	160	320

Although there is much overlapping of discriminant values for slides and stable slopes, there are clear-cut levels where nearly all values represent landslides and other levels where nearly all values represent stable slopes.

The use of the midpoint value of the discriminant function 0.01846 as a theoretical dividing line between landslides and stable slopes results in the following misclassification:

Landslides classified as stable slopes	15
Stable slopes classified as landslides	41
Total misclassifications	56

Theoretically the misclassification in either direction should be equal. A chi-square test of significance gives a value of

$\chi^2=15.9$ degrees of freedom=1

According to tables of χ^2 (see references under heading "Statistical techniques," p. 69) a value of 15.9 will occur by chance less than 1 percent of the time. It is judged, therefore, that the discriminant function misclassifies stable slopes as slides more frequently than it misclassifies slides as stable slopes. Since an important use of the function is to identify stable slopes, the discriminant function may err somewhat on the conservative side.

The value of t for 315 degrees of freedom and a probability of $P=0.01$ in one direction is

$$t=2.326$$

Multiplying by the standard deviation

$$st=(0.00526)(2.326)=0.0122$$

The mean value of the discriminant function for slides is

$$\bar{x}=0.0228$$

and

$\bar{x}-st=0.0106$ lower limit of the discriminant function for slides

RESULTS OF EXPERIMENT

Of the 160 slopes selected for stability studies, analysis by the discriminant function method indicated that: 39 were very stable, having discriminant function values of 0.0106 or less; 36 were relatively stable, having discriminant function values between 0.0106 and 0.0142; 85 were likely to be affected by landslides, having discriminant-function values above 0.0142.

Of the 39 locations judged to be very stable because of the low value of the discriminant function, the 5 listed below have the steepest slopes. The data for the locations indicate that low values of submergence percentage, terrace height, and ground water counterbalance the steepness of the slope to such a degree that the slope is stable. The photograph, figure 40, shows a slope judged to be very stable, and the photograph, figure 41, shows a slope judged to be relatively stable.

Five stable slopes with steepest measured slope

[LM, lake mile; RB, right bank; LB, left bank]

Slope No.	Location and area	Original slope	Discriminant value	Submergence (percent)	Terrace height (feet)	Ground water
9	LM 8.2 RB Swawilla Basin	2.8	0.0105	8	65	Low
122	LM 64.7 LB Hunters-Nez Perce	2.8	.0097	10	50	Do.
43	LM 27.5 RB Helgate-Whitestone	3.1	.0106	5	100	Do.
69	LM 43.7 LB Fort Spokane	3.3	.0056	0	60	Do.
38	LM 23.9 RB Hellgate-Whitestone	4.3	.0104	50	90	Do.

Of the 85 locations judged to be susceptible to landsliding due to the high value of the discriminant function, the 5 listed below have the highest values. The photograph, figure 42, shows a slope judged to be susceptible to sliding.

Five stable slopes most likely to be affected by sliding

[LM, lake mile; RB, right bank; LB, left bank]

Slope No.	Location and area	Original slope	Discriminant value	Submergence (percent)	Terrace height (feet)	Ground water
99	LM 51.5 RB Ninemile	2.5	0.0286	58	400	High.
24	LM 19.0 RB Keller Ferry	1.8	.0278	50	220	Low.
17	LM 14.7 LB Swawilla Basin	1.5	.0254	30	370	Do.
64	LM 41.5 RB Fort Spokane	2.9	.0246	30	270	High.
50	LM 34.6 LB Hawk Creek	1.4	.0245	24	275	Low.

APPLICATION OF LANDSLIDE AND SLOPE STABILITY DATA

By Fred O. Jones and Daniel R. Embody

Application of the methods and techniques developed in this research may contribute to the practical usefulness of geologic studies of land stability. The relatively uniform physical setting along the upper Columbia valley not only provided an opportunity to develop new geostatistical techniques for such studies but also presented an ideal opportunity to apply and test the results. This section illustrates the way these data may be used to identify potential landslide areas and estimate the extent of impending landslide action.

The most immediate application of this study should be in land utilization along Franklin D. Roosevelt Lake and Lake Rufus Woods. In future land acquisition programs along these lakes, both the Bureau of Reclamation and the Corps of Engineers may be better able to determine just how much land needs to be withdrawn from public use and just how much is safe for public use. In managing federally owned lands along Franklin D. Roosevelt Lake, the National Park Service may use these methods in its administrative decisions. When

FIGURE 40.—A slope on sand judged to be very stable because of a discriminant function value of 0.0106. The lake is drawn down from its maximum level. Slope no. 43; lake mile 27.5 right bank; Hellgate-Whitestone area. See table 8 for classification data.

FIGURE 41.—A slope on interbedded silt, clay and sand judged to be relatively stable because of a discriminant function value of 0.0138. The lake is drawn down from its maximum level. Slope no. 131; lake mile 71.5 left bank; Cedonia area. See table 8 for classification data.

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FIGURE 42.—A slope on silt and clay judged likely to be affected by landslides because of a discriminant function value of 0.0242. Slope 160; lake mile 107.0 right bank; Marcus-Evans area. See table 8 for classification data.

future landslides sever highways and railroads in the area as they have in the past, these data may be helpful in selecting relocations. Owing to the fact that geologic conditions are so similar the data may be especially useful in the land acquisition and relocation work on the Rocky Reach and Wells projects in Washington and on the Libby project in Montana.

Pleistocene surficial deposits of the types studied are not limited to the area of the present investigations. Similar deposits are found along approximately a thousand miles of river valleys in northern Washington, Idaho, and Montana. They are also found along many thousands of miles of valleys of British Columbia in both the Columbia and Frazier River systems. The Columbia River system alone has a potential hydroelectric generating capacity of about 30 million kilowatts of electricity, of which only 10 million have been developed. The dams, reservoirs, and other engineering works related to this development will encounter deposits similar to those in this investigational area in countless places.

RECOGNITION OF POTENTIAL LANDSLIDE AREAS

The recognition of natural slopes in which landslides may occur is of primary importance in land use. By using measurable data and their own experiences and observations, many geologists and engineers have developed criteria for estimating stability. These stability analyses of natural slopes, for the most part, result from personal judgment of a group of factors; such as, steepness of slope, topography, ground water, spring areas, material, and nearness to recent slides. The discriminant-function method described in this report uses the well-recognized criteria but goes a step further. It provides a numerical value to aid in judging whether or not a slope may slide by classifying the significant factors, transforming them into quantified units, and combining them into a formula. The resulting numerical value cannot be any better than the geologic classification from which it is derived. The discriminant-function method of identifying potential slide areas and stable areas is not intended to replace personal judgment but is offered as a tool to assist the geologist and engineer whose responsibility it is to appraise the stability of natural slopes.

ESTIMATION OF LANDSLIDE EXTENT IN THIS AND SIMILAR GEOLOGIC SETTINGS

An understanding of gelolgic and physiographic relations is fundamental to the estimation of landslide extent and to a practical application of the landslide data assembled in this report. The first step in applying the landslide data should be to determine the different types of landslides which could occur in a particular geologic setting, as in most places more than one type may occur. Examination of the mean and maximum *HC*:*VC* ratios for these groups will provide a basis for judging the average and maximum depths to which a slide of any of the different types will cut. If the slump-earthflow slide is the type having the greatest possible *HC*:*VC* ratio, the formula in the preceding section may be used to estimate how far a landslide might cut back from the toe of the slope. The formula cannot replace competent, experienced judgment, but it should aid in arriving at appraisals which have more basis in fact than a guess.

GENERAL APPLICATION OF METHODS

The system of collecting and assembling field data employed here may be useful in landslide investigations in other geologic settings. The statistical techniques of testing geologic classifications and of combining quantitative and qualitative variables in the development of numerical formulas may prove effective in other landslide areas. Statistical methods similar to those developed in this landslide study should produce worthwhile results in other fields of geologic engineering research.

ILLUSTRATIONS OF APPLICATION OF LANDSLIDE AND SLOPE STABILITY DATA

To illustrate the practical application of the slope stability and landslide data, detailed landslide classification studies were made of lakeshore land in the Ninemile area along Franklin D. Roosevelt Lake and in the Alameda Flat area along the reservoir behind Chief Joseph Dam. The classification of the Ninemile area (pl. 3) is presented according to sections of the lakeshore which have a constant geologic setting. Some of the analyses are based upon only a specifically selected profile location, whereas others are based upon composite data where several hundred feet of the lake banks have similar conditions. The classification data for the Alameda Flat area (pl. 6) is presented in tabular form (table 5).

Research investigations did not provide data to predict when any specific potential slide area will slide, and it seems doubtful they ever could. The following classifications were made on the premise that in land-use problems we are concerned only with areas which may fail in the foreseeable future—which future might be defined as the next 50 to 100 years. From a theoretical standpoint, landsliding may continue until all of the surficial deposits are removed from the rock valley of the Columbia, but consideration of time measured on the geologic scale was not thought to be a practical premise for the landslide classification.

Where landslides are likely to affect the lakeshore land under prevailing conditions, the estimated maximum extent of landslide action is shown on the maps by a line designated *A*. This is an estimate based on the best available data and applies to conditions of maximum submergence by the reservoirs involved. In certain areas the lakeshore land is suitable for developments such as irrigated farming, which could change ground-water conditions from low to high. A study has been made in these areas of the probable extent of landslide action under these postulated changes. This estimate of maximum landslide action is shown by the line designated *B*.

Two mimeographed computation sheets were used in the fieldwork—one for the prediction of slope stability by the discriminant-function method, and one for the prediction of *HC*:*VC* ratio of slump-earthflow landslides where it was applicable. Samples of both sheets are shown below. All computations were made with a slide rule in the field at the time of examination and are considered sufficiently accurate for the use to which they were put.

NINEMILE AREA (FRANKLIN D. ROOSEVELT LAKE)

The following is a detailed description of a landslide classification on the shoreland along Franklin D. Roosevelt Lake in the Ninemile area using the data and guiding formulas developed in the landslide and slope stability research. To aid in following the description, the reader is referred to plate 3. The classification begins at lake mile 49.7 on the left bank and extends uplake along the left bank to lake mile 55.25. It then begins at lake mile 49.7 on the right bank and extends to lake mile 55.25.

Lake mile 49.7 to 50.3 left bank.—The lakeshore land in this section consists of a broad terrace which has a surface altitude of 1,900 feet. The scarp of the terrace has been cut into a series of alternating ridges and alcoves by ancient landslides and subsequent erosion. Materials of the lower part of the terrace are predominantly silt and clay of material category 1; materials of the upper 200 to 400 feet of the terrace are principally sand and gravel. Exposures of bedrock in the area suggest that ancient sliding may have been limited or controlled to some extent by bedrock. The ancient sliding was of the slump-earthflow type, and several small recent slump-earthflow slides have cut into the

Example of slope stability field sheet

Sheet No. **5**
Date **8/18/54**

COLUMBIA RIVER LANDSLIDE PROJECT, WASHINGTON

Computation sheet for predicting slope stability (by the discriminant-function method)

Location. **Ninemile area, lake mile 53.5 right bank**
Formula. $Y=-0.021625 \log X_1+0.003348 \log X_2+0.00944 \log X_3+0.006731\ X_4$
where

Y = the discriminant function
X_1 = original slope
X_2 = submergence percentage
X_3 = terrace height
X_4 = ground water: high = 0.1 low = 0

	Variable	*Numerical value*	*Transformation*	*Transformed value*	*Regression coefficient*	*Product*
X_1	Original slope	**2.0 : 1**	Log	**0.301**	**−0.021625**	**−0.0065**
X_2	Submergence percentage	**85**	Log	**1.930**	**.003348**	**.0065**
X_3	Terrace height	**270**	Log	**2.430**	**.009440**	**.0229**
X_4	Ground water	**low=0**	None	**0**	**.006731**	**0**
						.0229

Should ground water be changed from low to high the discriminant-function value would be **0.0296**
Slopes having discriminant-function values of 0.0106 or less are very stable.
Slopes having discriminant-function values of 0.0106 to 0.0142 are relatively stable.
Slopes having discriminant-function values of above 0.0142 are likely to be affected by landslides.
Types of landslides which could develop in this geologic setting **slump-earthflow**

Remarks: **Terrace surface is smooth and favorable for development.**

Example of HC:VC field sheet

Sheet No. **5**
Date **8/18/54**

COLUMBIA RIVER LANDSLIDE PROJECT, WASHINGTON

Computation sheet for predicting HC:VC ratio of landslides (slump-earthflow type)

Location. **Ninemile area, lake mile 53.5 right bank**
Formula. $Y=-0.6328+0.2460\ X_1-1.4121\ X_2+7.5583\ X_3+1.0338\ X_4+0.4015\ X_5$
where

Y = log *HC*: *VC* ratio of slide
X_1 = submergence percentage (equivalent angle)
X_2 = log of original slope
$X_3 = (X_2+1)_2/10$
X_4 = ground water (takes value of 0.0 for low and 0.1 for high)
X_5 = materials. Takes numerical values as follows:

1 = +0.1
2, 3, & 4 = 0
5 = −0.1

	Variable	*Numerical value*	*Transformation*	*Transformed value*	*Regression coefficient*	*Product*
X_1	Submergence percentage	**85**	Equivalent angle	**0.672**	**0.2460**	**0.165**
X_2	Original slope (linear)	**2.0**	Logarithm	**.301**	**−1.4121**	**−.423**
X_3	Original slope (quadratic)	$\frac{(1+0.301)^2}{10}$	$\frac{(1+\log)^2}{10}$	**.170**	**7.5583**	**1.285**
X_4	Ground water	**Low=0**	None	**0**	**1.0338**	**0**
X_5	Materials	**#2=0**	None	**0**	**.4015**	**0**
	Intercept					**−.6328**
						.394

	Logs	*Original value*
Y = Predicted HC:VC	**0.394**	**2.5**
95% confidence limit constant	**.134**	
Upper limit of HC:VC ratio	**.528**	**3.4**

Should ground water be changed from low to high, upper limit of HC:VC ratio would be **4.3**
Remarks: **Under present ground water conditions it is estimated that slides could cut back 400 feet from lake shore. If ground water conditions were changed to high due to irrigation or other causes, slides may cut back 760 feet from lakeshore.**

banks. Slope-stability studies of the lakeshore land from an altitude of 1,300 to 1,400 feet gave discriminant-function values ranging from 0.0166 to 0.0269, which indicate that all of the lakeshore land is likely to be affected by sliding.

A composite study of slope stability considering the lakeshore land from the lake to the top of the high terrace gave a discriminant-function value of 0.0194. Basic data were: slope, 3.9:1; submergence, 25 percent; terrace height 810 feet; ground water, low. Of the 160 slump-earthflow landslides studied in the statistical work only 2 had original slopes as gentle as 3.9:1, and these were located where water conditions are naturally high. These data and the suggestion that the ancient sliding may have been limited by bedrock lead to the conclusion that future sliding in the area should be considered only insofar as it affects the land at lower altitudes. The broad high-level terrace is favorable for developing irrigation farming. Should ground-water conditions be changed to high because of this or other developments, sliding may extend to about the present front edge of the terrace. Sliding has developed at other places similar to this where terraces have been irrigated, but in no place has it been observed to cut far back into the terrace surface. The *B*–line on the map delineates the possible extent of sliding under such postulated changed conditions.

At lower altitudes on the irregular terrace scarp, the type of landslide expected in this setting is the slump earthflow. A slope-stability study of the area at lake mile 49.7 left bank gave a discriminant-function value of 0.0225, and the *HC*: *VC* prediction formula indicated that slides in this area may cut back as far as 750 feet from the present lakeshore. Basic data were: slope, 2.13:1; submergence, 65 percent; terrace height, 310 feet; ground water, low; material category, 1.

A slope-stability study in the small bay at lake mile 49.8, which has a spring area just above it, gave a discriminant-function value of 0.0269. Basic data were: slope, 2.85:1; submergence, 75 percent; terrace height, 350 feet; ground water, high.

A similar study of the area between lake mile 49.85 and 50.0, left bank, resulted in a discriminant-function value of 0.0204, and the *HC*:*VC* prediction formula indicated that slides may cut back as far as 975 feet from the lakeshore. Basic data were: slope, 2.56:1; submergence, 64 percent; terrace height, 310 feet; ground water, low; material category, 1.

A composite slope-stability study of the area at lake mile 50.15 left bank gave a discriminant-function value of 0.0166, and the prediction formula indicates that slides may cut back as far as 650 feet from the present lakeshore. Basic data were: slope, 2.2:1; submergence, 5 percent; terrace height, 200 feet; ground water, low; material category, 1.

From these data the *A*–line was drawn on the map to outline what is the maximum extent to which landslides are likely to cut into this area under present conditions.

Lake mile 50.3 to 52.5 left bank.—Along this section of lakeshore, slopes are gentle both above and below full lake level. The materials are silt, clay, sand, and gravel disturbed by ancient landslides or glacial processes. Slope-stability studies indicate that landslides are not likely in this section under present conditions. Should ground water be increased from low to high by irrigation of the lakeshore land or other developments, the slopes will probably remain stable.

Summary of four slope-stability studies

Location (lake mile, left bank)	Slope	Submergence (percent)	Terrace height (feet)	Ground water	Discriminant function
50.4	5.7	42	120	Low	0.0087
51.2	7.7	23	130	do	.0121
51.7	3.7	7	75	do	.0082
52.3	4.6	53	150	do	.0120

Wave banks are not present between lake mile 50.3 and 51.3, but they range in height from 2 to 10 feet between lake mile 51.3 and 52.5.

Lake mile 52.5 to 53.55 left bank.—The lakeshore land along this section has a rolling surface which ranges from 20 to 90 feet above lake level. The topography probably reflects ancient landsliding or glacial processes. Exposures along the entire section show distorted and disturbed silt and clay mixed with varying amounts of sand and gravel. For convenience the area will be described in two parts—the lakeshore land paralleling the lake, and that part along the bay at lake mile 53.55.

Nearly all the lakeshore land paralleling the lake has been cut by landslides. Six of the slump-earthflow landslides included in the research study are in this stretch. The following table gives a summary of the slope stability and *HC*: *VC* data of those six slides:

Summary of the slope stabilily and HC:VC *ratio*

Landslides	Material	Ground water	Terrace height	Submergence (percent)	Slope	Discriminant function	Actual *HC*:*VC*	Predicted maximum *HC*:*VC*
52.6	2	Low	100	10	1.8	0.0167	2.4	2.4
52.7	2	Do	140	64	2.1	.0193	2.3	3.2
53.1	2	Do	150	80	1.8	.0214	2.3	3.0
53.2	2	Do	110	82	1.7	.0207	3.3	3.0
53.4	2	Do	80	62	1.8	.0185	2.0	2.8
53.5	2	Do	120	76	2.7	.0166	3.0	3.9

The discriminant-function value of each landslide indicated that the lakeshore land would be affected by sliding. Only one landslide, at lake mile 53.2, has cut back farther than the *HC*: *VC* prediction formula indicated it would.

These slides all occurred soon after the lake was filled. Beach erosion and caving are tending to waste the points of land between them, and the banks are steeper than they were originally. The landslide material tends to flatten out on the bottom of the lake and has little effect of loading the toe area or of creating a more gentle slope. For these reasons it is believed that as the shoreline becomes straightened by erosion and sloughing, conditions conducive for another series of landslides will form. Consequently, the *A*-line on the classification map has been drawn, using the *HC*: *VC* prediction formula and then doubling the computed distance slides may cut into the bank. The tabulation below gives the estimated distances landslides may cut in the foreseeable future. An estimate has also been made of the distance back slides might cut if ground-water conditions were increased from low to high.

Location (lake mile, left bank)	*Distance from present shoreline landslides may extend (A-line)*	*Distance from shore landslides may cut if ground water is increased to high (B-line)*
52.6	300	375
52.7	330	415
53.1	310	380
53.2	100	140
53.4	320	400
53.5	280	380

Small landslides have cut the banks of the bay at lake mile 53.55 from its mouth to points on both banks about 540 feet from the opposite end. Near this end slopes become more gentle and submergence becomes less, so a study was made to determine whether the banks in this area are likely to fail. A composite slope-stability study was made on the right bank 250 feet from the end and on the left bank 300 feet from the end. The discriminant-function value was 0.0107, which indicates that under present conditions the banks are very stable. Should the ground-water conditions be changed to high, the discriminant-function value would be 0.0174, which indicates the likelihood of slides. Basic data: slope, 2.35:1; submergence, 33 percent; terrace height, 30 feet; present ground-water condition, low; material category, 2.

Slope-stability and *HC*: *VC* studies were made on both sides of the bay to determine the probable extent of landslide action in the outer part of the bay. The classification data and results are:

Location	Slope	Submergence (percent)	Terrace height (feet)	Ground water	Material	Discriminant function	*HC*: *VC*	*HC*: *VC* (high ground water)
440 ft from end of bay on right bank	1.8	60	50	Low	2	0.0164	2.8	3.5
700 ft from end of bay on left bank	1.65	44	57	do	2	.0174	2.4	3.1

At the location 440 feet from the end of the bay on the right bank, slides under present conditions may affect the land 90 feet back from shore. If groundwater conditions were changed to high, they could affect the land 125 feet back from shore. At the location 700 feet from the end of the bay on the left bank, slides could cut back 85 feet under present conditions and 125 feet under high ground-water conditions.

Lake mile 53.55 to 54.42 left bank.—Slopes both above and below water along this section are very gentle and studies indicate that they will not be affected by landslides. A measurement at lake mile 53.6 gave a slope value of about 10:1, and no landslides have occurred in the surficial deposits in the area on so gentle a slope. A slope-stability study by the discriminant-function method at lake mile 54.0 gave a value of 0.0127, which indicates a nearly stable condition. Basic data: slope, 2.8:1; submergence, 29 percent; terrace height, 70 feet; ground water, low. A study at lake mile 54.35 gave a discrimimant-function value of 0.0126 with basic data as follows: slope, 3.9:1; submergence, 42 percent; terrace height, 120 feet; ground water, low.

Lake mile 54.42 to 55.25 left bank.—The lakeshore land in this section consists of broad ridges and steep-sided valleys alined normal to the lakeshore. Slope-stability studies indicate that this area is likely to be affected by landslides, and a few minor ones have already occurred. The type of slides most likely to cut these banks is the slump earthflow. At the upstream end of the section they may be limited by bedrock or slides off bedrock may occur.

The following is a summary of three slope-stability studies which have been used as guides in drawing the

Summary of three slope-stability studies

Location	Slope	Submergence (percent)	Terrace height (feet)	Ground water	Material	Discriminant function value	*HC*: *VC* under present ground-water conditions and distance back from shore slides might cut (feet)	*HC*: *VC* under wet ground-water conditions and distance back slides might cut (feet)
Lake mile 54.45–54.55	2.2	30	100	Low	4	0.0164	2.9–180	3.6–250
54.9	3.3	25	200	do	4	.0149	3.9–600	5.0–900
55.05–55.27	3.0	28	320	do	4	.0181	3.6–1,050	4.6–1,400

line on the classification map which delineates the area of potential landslide danger under present conditions and under high ground-water conditions should they be changed by developments in the area.

Lake mile 49.7 to 50.33 right bank.—The bank in this section is a steeply dipping bedrock surface which is covered thinly in places with talus and slope wash. Bedrock gullies contain minor accumulations of sand and gravel mixed with bouldery slope wash. There have been minor talus slides and one small rock slide along this section. Additional slides of this type will occur but they are insignificant in relation to land use.

Lake mile 50.33 to 50.70 right bank.—In this section the lakeshore land with which we are concerned consists of two small areas of surficial deposits resting against steeply dipping bedrock. A slope-stability study of the larger area (lake mile 50.33 to 50.55) gave a discriminant-function value of 0.0200. Basic data: material, category 2; disturbed silt and clay; original slope, 2.85:1; submergence, 61 percent; terrace height, 330 feet; ground water, low. These data indicate that the point is likely to be affected by slides. Three types of slides may develop in this setting—slump earthflow, slump earthflow limited by bedrock, or slides off bedrock. Using the prediction formula for slump-earthflow slides, it was determined that the *HC*: *VC* may be as great as 3.9:1, which would cut back into the terrace 700 feet from shoreline. This is about 100 feet from the bedrock line when measured at the broadest part of the terrace point. It seems more likely that if failures occur, a part of the surface of rupture will follow bedrock; consequently, the entire area of surficial deposits is likely to be affected by slides.

A slope-stability study of the smaller terrace point between lake mile 50.55 and 50.70 gave a discriminant-function value of 0.0171, which indicated that it also may be affected by slides. Slides off bedrock seem most likely here, as they did in the larger terrace point. Thus the entire section is likely to slide into the lake.

Lake mile 50.7 to 51.1 right bank.—The lake bank along this section is steeply dipping bedrock covered thinly in places with talus accumulations. Minor talus-slump landslides may occur, but they would not affect use of the lakeshore land.

Bay at lake mile 51.05 right bank (lake mile 51.1 to 51.25), including Ninemile Bay.—Lake banks along this area are alternating sections of steeply dipping bedrock and thin patches of surficial deposits of silt, clay, and sand resting on bedrock. Landslides have cut the highway in two places. Future landslide action will be of the following types: slides off bedrock, slip-off slopes, and slump earthflows limited by bedrock. All the surficial deposits in this section are expected to be affected by slides from lake level to the *A*–line on the map. Bedrock areas will be free of slides generally, but small areas of silty and clayey slope wash mixed with talus and rubble will fail.

Lake mile 51.25 (silt-bedrock contact on left bank of Ninemile Bay) to 51.8 right bank.—The lakeshore topography in this section contains the finest example of an ancient multiple-alcove slide found in the entire investigation. The slide overlies the deep preglacial channel of Ninemile Creek. Materials are principally silt and clay of material category 1. Ground-water conditions are high. Sections of the surface of rupture of the ancient slide can be observed in new wave banks and minor recent slides along the shore. The high-level position of this part of the surface of rupture suggests that the slide occurred before the Columbia River had cut down to its present level. The probable base of this old slide is at an altitude of 1,360 feet, or 70 feet above maximum lake level. The river channel, which averages 220 feet below maximum lake level, follows close to this bank. Some new sliding of the slump-earthflow and slip-off slope types has already taken place. Slope-stability studies indicated that the entire area is likely to be affected by future sliding. A study of a part of the material within the slide scarp at lake mile 51.5 gave a discriminant-function value of 0.0286. Basic data: material category, 1; ground water, high; slope, 2.5:1; terrace height, 400 feet; submergence, 58 percent.

A slope-stability study of the entire terrace taken through the center of the ancient slide resulted in a discriminant-function value of 0.0217. Basic data: material category, 1; original slope (generalized), 6.2:1; submergence, 29 percent; terrace height, 820 feet; ground water, high.

There may be either slump-earthflow or new multiple-alcove landslides in this setting. On the average, multiple-alcove slides have a much larger *HC*: *VC* ratio than the slump earthflow and, consequently, the prediction formula cannot be used to estimate the extent of landslide action. The average *HC* : *VC* ratio of the 9 multiple-alcove slides measured was 5.9:1 The ancient multiple-alcove slide (133) in the Ninemile terrace has a measured *HC*: *VC* ratio in excess of 9.2:1. (See table 4.) Neither of these ratios seems realistic in estimating how far new slides could cut. It seems likely, however, that new major sliding in which the foot of the slide is lower than the ancient one might tend to rupture along the same general scarp at higher altitudes. Following this reasoning, the *A*–line delineating potential-landslide action was drawn on the map.

Lake mile 51.8 to 52.75 right bank.—An area of ancient landslides which extends to an altitude of 1,925 feet makes up the shoreland topography along this section. The area is thought to be underlain by channels in the bedrock which extend beneath the broad fill in the Ninemile Creek valley. Ancient sliding seems to have been of the slump-earthflow and multiple-alcove types. There is one recent slump earthflow at lake mile 51.8 to 52.0. Surface materials are disturbed silt and clay of material category 2, but at depth and a short distance back in the terrace at an altitude of 1925 feet, materials are regarded to be in about their original position of deposition, or in category 1.

Slopes which have been studied between lake mile 51.8 and 52.1 range from 0.7:1 to 4.3:1. The underwater slope is extremely steep down to the old riverbed, a depth of 220 feet. The slopes are somewhat more gentle between lake mile 52.1 and 52.75, and the water depth is about 110 feet down to a submerged terrace.

A slope-stability study at lake mile 51.95 gave a discriminant-function value of 0.0401. Basic data: material category, 2; ground water, high; original slope, 0.7:1; submergence, 63 percent; terrace height, 350 feet. The predicted value of *HC:VC* ratio of a slump-earthflow landslide at this point would be 3.10:1. Thus a slide would extend 800 feet behind the present shoreline.

A slope-stability study in the small bay at lake mile 52.2 showed the discriminant-function value to be 0.0149. The *HC:VC* prediction formula here indicated that a slide could cut back on a slope of 4.6:1, or 100 feet from the back of the bay. Basic data: original slope, 2.5:1; submergence, 72 percent; terrace height, 70 feet; ground water, low; material category, 2.

A composite slope-stability study was made of the section between lake mile 52.3 to 52.65. The discriminant-function value was 0.0154. The predicted *HC:VC* ratio was 4.75:1, which indicates that landslides could cut back 420 feet from the shore. Basic data: material category 2; ground water, low; submergence, 71 percent; original slope, 3.4:1; terrace height, 155 feet. A study was also made of *HC:VC* ratio should ground water be changed from low to high, and it was 5.9:1. In plotting these data to determine the distance back from shore the slide could cut, it was found that this slope did not intersect the upper surface of the lower terrace made up of landslide debris, but passed into the upper terrace at an altitude of 1,925 feet before intersecting the surface. At this point a study was made of the stability of the high terrace, using a generalized slope, from altitude 1,925 to the toe of the scarp at the bottom of the lake. Using an original slope of 4.3:1, submergence, 15 percent, terrace height, 740 feet, and low ground water, the discriminant-function value was 0.0162, or 0.0020 above the mathematical dividing line between relatively stable slopes and slopes which are likely to be affected by slides. Should ground-water conditions be changed to high, the discriminant-function value would be 0.0229.

Slides will not affect the upper terrace under present ground-water conditions; consequently, the *A*–line delineating the anticipated extent of landslides in this area was drawn from the three studies of land at lower altitudes. It seems entirely possible, however, that development of the broad Ninemile terrace behind this potential-slide area could change ground-water conditions to high and induce sliding which would extend from the lake to the terrace surface.

A study of the probable *HC:VC* ratio of slump-earthflow slides showed that they might extend back from the present lakeshore as much as 4,500 feet, or on a ratio of 6.6:1. This is an even larger ratio than the average for multiple-alcove slides of 5.9. Both types have occurred here, and it seems likely that under high ground-water conditions and new submergence conditions they could recur. The *B*–line delineating the possible extent of slides under these conditions was drawn from these data and reasoning.

Lake mile 52.75 to 53.6 right bank.—Lakeshore land here consists of a gentle sloping terrace just above maximum lake level. Its surface ranges from an altitude of 1,290 feet at shoreline to 1,400 feet at a distance of 1,000 to 1,500 feet back from the shore. The shoreline is indented by several small bays which extend back from the main shoreline 200 to 350 feet. Materials comprising the terrace are principally silt and clay which are distorted and disturbed due to ancient landslide action or glacial processes or both (category 2). Slopes of the terrace scarp which are mostly submerged range generally from 2.0:1 to 3.5:1. Between lake mile 53.25 and 53.60 the terrace scarp slopes generally to the old river channel or to a depth of 200 feet. Between lake mile 52.75 and 53.25 the terrace scarp slopes evenly to a depth of 140 feet, the depth of an underwater terrace.

A composite slope-stability study of the section between lake mile 52.7 and 52.85 showed original slope, 2.32:1; submergence, 81 percent; terrace height, 155 feet; ground water, low. The discriminant-function value was 0.0191, which indicates that the terrace may be affected by landslides. The type of slide in this setting which would have the maximum *HC:VC* ratio is a slump earthflow. The prediction formula indicates that the *HC:VC* ratio here would likely not exceed 3.56:1 or cut back more than 290 feet from shore. A study at lake mile 53.1 resulted in a discriminant-function value of 0.0167. Predicted *HC:VC* ratio of a possible slide was 4.75:1. Thus a slide would cut back 350 feet from shore. Basic data: material category, 2; ground water, low; submergence, 97 percent; original slope, 3.1:1; terrace height, 155 feet. A study at lake mile 53.5 resulted in a discriminant-function value of 0.0229 and a predicted *HC*:*VC* ratio of 3.4:1, which indicates that slides could cut back as far as 400 feet from shore. The *A*–line delineating the probable extent of slide action was plotted on the map from these three studies.

This terrace has a desirable lakeshore location. Its smooth surface and nearness to a supply of water make it seem favorable for an irrigated farm development; consequently, the slide potential was studied, assuming that such a development was made and that ground-water conditions were to be changed from low to high. The discriminant-function value at lake mile 52.75 to 52.85 would rise from 0.0191 to 0.0258; at 53.1 it would rise from 0.0167 to 0.0234; at 53.5 it would rise from 0.0229 to 0.0296, which suggest a much greater likelihood of landslide action with high ground water.

The *HC*:*VC* ratios and the distance slides would likely cut back from the lakeshore are:

	Predicted HC: VC	*Distance slides could cut back from shore (feet)*
Lake mile 52.7–52.85	4.51	480
53.1	6.0	750
53.5	4.3	760

Using these data, the *B*–line was drawn on the map to indicate the probable limit of potential slides if for any reason ground-water conditions were changed from low to high.

Lake mile 53.6 to 53.85 right bank.—In this section a narrow strip of surficial material rests on a steeply dipping bedrock surface. Minor sliding of the slump-earthflow and slip-off slope type has already taken place. Its extent has been limited in places by bedrock. The principal materials are disturbed and distorted silt and clay, although above high-water sand, gravel, and slope wash predominate. For slope-stability studies materials were classified as category 2.

A composite slope-stability study was made of the bank between lake mile 53.6 and 53.7. The original slope was 2.40:1; submergence, 83 percent; terrace height, 205 feet; ground water, low. The discriminant-function value was 0.0191. A second composite study was made from lake mile 53.7 to 53.85, with the following basic data: original slope, 2.06:1; submergence, 87 percent; terrace height, 240 feet; ground water, low. The value of the discriminant function was 0.0289. Both parts of the section are likely to be affected by future landsliding. The types of slides most likely in this setting are slides off bedrock or slump earthflows limited by bedrock. It was judged from these data that the line delineating the extent of probable landslide sction should follow the contact between surficial deposits and bedrock.

Lake mile 53.6 (altitude 1,600 feet) to lake mile 54.9 right bank.—Landslides have already cut into about two-thirds of the shoreland between lake miles 53.6 and 55.0 and will likely affect the remainder. Slide types in this section are multiple-alcove, slump-earthflow, slump-earthflow limited by bedrock, slides off bedrock, and slip-off slopes. These slides cut into a terrace which averages 1,900 feet in altitude. Only the multiple-alcove slide at lake mile 53.6 to 54.0 cuts into terrace surface. This slide (145) enlarged in 1906 following the San Francisco earthquake, and slide material partly dammed the flow of the river for about 45 minutes. This multiple-alcove feature is shown on the geologic map (pl. 3) and on the Wilmont Creek quadrangle map as "The Slide." Surficial materials of the high terrace are silt and clay interbedded with sand and gravel (material category 1). Openwork gravel just above an altitude of 1,290 feet shows cracking and crushing which suggest that a part of the terrace has been overridden by ice. The terrace scarp between lake mile 54.5 and 54.9 becomes less steep and joins a lower terrace which has an altitude of 1,300 to 1,400 feet. The materials in this transition zone and in the lower terrace are predominantly disturbed silt and clay of material category 2. Bedrock projects through the surficial deposits at several places but neither in sufficient amount nor in a position to limit future landsliding. The slope of the terrace scarp ranges from 1.3:1 to 2.9:1. The old channel of the Columbia River followed the toe of the terrace scarp at an altitude of 1,900 feet between lake mile 53.6 and 54.6 where the water is about 225 feet deep. Water depths along the terrace scarp lessen to 80 feet between lake mile 54.6 and 54.9. Ground water is high in the multiple-alcove slide area where there are many springs and seeps. There are seeps and wet areas as high as 30 feet above maximum lake altitude between the upstream edge of the multiple-alcove slide between lake mile 54.0 and 54.4. Above this, on the terrace scarp, are patches of water-loving vegetation.

Slope-stability studies indicated that all of this section may be affected by future sliding. A slope-stability computation at lake mile 54.3, where original slope is 1.5:1, submergence, 30 percent, terrace height, 755 feet, and ground water is high, gave a discriminant-function value of 0.0350. A computation at lake mile 54.84, where the slope is 2.9:1, submergence, 61 percent, terrace height, 130 feet, and ground water is low, gave a discriminant-function value of 0.0159.

This entire section of surficial deposits overlies an area of preglacial channels in the bedrock. One of these channels leads directly to the multiple-alcove slide at lake mile 53.6 to 54.0. The remaining part of the section is probably underlain by the preglacial channel of Wilmont Creek. In this geologic setting, any of the following types of slides may occur in the future, and some form of all of them is presently recognizable—multiple alcove, slump earthflow, slump earthflow limited by bedrock, slides off bedrock, or slip-off slopes.

The type of slide which has the maximum *HC*:*VC* ratio that may cut into this lakeshore land is the multiple alcove, so for this type the formula for predicting the *HC*:*VC* ratio of slump-earthflow landslides is of no assistance in judging how far back future slides will cut.

Examination of table 8 showed that the average *HC*:*VC* ratio for multiple-alcove slides was 5.9:1 and that the only recent slide of this type had a ratio of 6.2:1. Using this as a guide, it was judged that slides in this area may cut back as far as 6.0:1 from the toe of the terrace scarp. At lake mile 53.8 the distance is 3,200 feet from the shoreline; at lake mile 54.2 it is 3,000 feet; at lake mile 54.3 it is 3,300 feet. The line delineating the area of potential landslides in this section was drawn on the map from the above data.

Lake mile 54.9 to 55.25 right bank.—Slopes along this section are generally similar both above and below lake level. One small bay indents the shoreline. The terrace, which averages about 70 feet in height, is submerged 86 percent at full lake level. The terrace scarp has an average slope of 5.7:1 except in the small bay at lake mile 55.0 where slopes are more gentle. Present ground-water conditions are low. Materials in this section are not exposed at full lake level, but exposures examined during stages of lake drawdown revealed that they are principally disturbed silt and clay of category 2. A composite slope-stability study resulted in a discriminant-function value of 0.0071 which indicates that the terrace is very stable. This section of lakeshore terrace is favorable for developing irrigation farming.

A study was made to determine whether this section would remain stable if ground-water conditions were changed from low to high. This composite slope-stability study resulted in a discriminant function value of 0.0138, which indicates that the terrace would be relatively stable. Wave-cut banks along the lake front range from 3 to 8 feet in height. Wave-cut banks in the small bay are minor.

GEOLOGY AND LANDSLIDE CLASSIFICATION OF THE ALAMEDA FLAT AREA (LAKE RUFUS WOODS)

The Alameda Flat area of Lake Rufus Woods was also selected to illustrate the practical usefulness of the landslide and slope-stability research. The landslide-classification data are summarized on table 5. The results of the classification studies are shown on plate 6 and the geology of the area is discussed below.

Bedrock of the Alameda Flat area is chiefly the granite of the Colville batholith.

Interbedded till and angular basalt gravel are exposed in secs. 7, 17, and 18, T. 30 N., R. 29 E. The till has a matrix of sandy silt and is dark gray; stones in it are predominantly basalt. Relations between the deposit and the other map units are not known but it is probably older, at least in part, than the fluvial sand and gravel unit discussed below.

A fluvial sand and gravel is exposed in the bluffs above the Columbia River between altitudes of 910 and 970 feet at the west end of the Alameda Flat area. The gravel is composed of rounded pebbles and cobbles in beds 2 to 4 feet thick that are foreset downstream. The stones are predominantly granite; although a small percentage of basalt is present. They are conspicuously fractured and crushed though generally unweathered. Coarse-grained to very coarse-grained sand is interbedded in layers 6 inches to 10 feet thick; it is composed of unweathered fragments of granite minerals. A few feet of undifferentiated lacustrine silt overlies the fluvial deposit and immediately underlies the gravel surface on the 1,000-foot terrace on the north bank at Mah-kin Rapids (pl. 6).

Lacustrine silt and clay is exposed in the bluffs above the Columbia River and in the numerous tributary gullies from river level to an altitude of 1,200 feet throughout most of the Alameda Flat area. Its lower contact was not observed. The unit is composed primarily of silt and clay in finely laminated beds ½ to 2 inches thick. Varve structure generally is not well developed though some grading is faintly discernible. Between altitudes of 1,000 and 1,200 feet, fine and very fine sand is interbedded with the silt and clay. The sand almost invariably occurs in graded beds; those measured range in thickness from 3 to 27 inches. In bulk, these graded sand beds probably make up less than 20 percent of the deposit. Ice-rafted pebbles are scattered throughout the unit.

In parts of the lacustrine deposit the bedding is greatly contorted. The contortion is commonly confined to layers several feet thick that are overlain and underlain with sharp contact by undisturbed beds. This deformation was probably caused by slump or flowage on a lake bottom when the distorted material formed the lake bottom.

A lacustrine sand that occurs between altitudes of 1,200 and 1,300 feet overlies the lacustrine silt and clay unit with abrupt contact. The sand is composed almost entirely of fine- and medium-grained sand in beds 1 to 4 inches thick although thin beds and lenses of coarse-grained sand are present in the deposit between altitudes 1,280 and 1,300 feet in the extreme northwest corner of sec. 4, T. 30 N., R. 29 E. In contrast to the underlying sequence, the beds are undisturbed. The lacustrine sand is overlain, with erosional contact, by the gravel of the 1,320- to 1,360-foot terrace deposit. The upper surface of the sand deposit probably was never much higher than at present; only minor erosion occurred during the deposition of the overlying gravel.

Other surficial deposits in the Alameda Flat area include channel gravel, alluvial-fan deposits, and windblown sand. These deposits are included in one map unit because contacts between them are not well exposed. Channel gravel forms terraces at and below 1,400 feet and was deposited by the Columbia River during postglacial dissection of the valley-fill deposits. The gravel is a few feet to at least 70 feet thick and is mostly of pebble size. Large areas of the terraces are overlain by alluvial fans of sand and silt as much as 50 feet thick. Windblown sand that forms small dunes and thin sheets also veneers the terrace deposits.

Some time after the cutting of the 1,120-foot terrace in secs. 3 and 4, T. 30 N., R. 29 E. landslides occurred along the scarp at the back of the terrace; the debris of these slides forms long narrow ridges on the surface of the 1,120-foot terrace.

STATISTICAL TECHNIQUES

By Daniel R. Embody

In this investigation a particular group of landslides was selected for study. Modern statistical methods were used to solve the problems of indentification and prediction. As far as the writers are aware, this investigation is one of the first attempts to study landslides by statistical methods. Very little recorded experience has been available for guidance.

During this work many intuitive judgments were made to obtain some of the answers. Only as later investigators test these judgments in other situations will their overall usefulness be appraised. This section of the report discusses the overall experimental logic, the statistical concepts employed, the assumptions implied, and the interpretations drawn.

Statistical work was not begun until all the measurements of the slides had been made and recorded. The first attempts to analyze the data consisted of averaging the *HC*: *VC* ratios for the various classifications. From preliminary analysis it appeared that a number of the factors under study might affect the slides, and a series of more comprehensive analyses were made. Gradually the data were examined in greater detail until the final analyses presented in the report were made.

The analysis of slides and stable slopes indicated that both the occurrence of slides and their resultant *HC*: *VC* ratio could be predicted. In drawing conclusions from the data an important factor is the reproducibility of the field measurements. The uniformity experiment was planned and executed to evaluate this reproducibility.

ASSUMPTIONS MADE IN THE ANALYSIS OF VARIANCE

The assumptions, logic, and numerical details of the commonly used statistical methods are described by Davies (1954), Fisher (1946), Fisher (1947), Goulden (1952), Kempthorne (1953), Mather (1943), Snedecor (1946), Youden (1953). No attempt will be made in this section to give numerical details.

Generally the statistical methods used in the landslide inquiry were specific applications of the general technique of analysis of variance originated by R. A. Fisher in the late 1920's. Briefly, this technique provides a uniform pattern for designing experiments, analyzing data, and making statements of probability regarding certain hypotheses. Scientists in nearly all fields have accepted the analysis of variance as a proper basis for constructing the various judgments which are the products of their inquiry.

For data to be analyzed properly by the analysis of variance, a number of requirements must be fulfilled. Complete statements of these requirements and the consequences to be expected if they are violated are given by Cochran (1938), Cochran (1947), and Eisenhart (1947).

In the landslide investigations careful attention was given to the data so that the requirements for analysis could be met. In this section a brief summary of requirements will be given so that the landslide data and the validity of the analyses made may be discussed.

The three major requirements for experimental observations are as follows:

1. Experimental errors must be distributed normally.
2. Experimental errors must be uncorrelated.
3. Experimental errors must form a homogeneous distribution with a single variance.

For detailed definitions of the term "experimental errors," see Cochran (1938), Cochran (1947), and Eisenhart (1947).

A fourth requirement is generally mentioned at this point; namely, that the effects of the classifications ground water and materials must be additive over the range of the data. This factor is extremely important and was the subject of a detailed test with each of the landslide analyses. As will be noted, with each of the analyses for the *HC*: *VC* ratio, a test for interaction was made which indicated whether the treatments and conditions were additive.

It is generally argeed that the requirement for normality of the experimental errors is the least important of the three. Except where departure from normality is very large, the consequences can be ignored.

Correlation among experimental errors is a more serious requirement. It can be seen that if the errors for a particular treatment tend to be in one direction (postively correlated) then part of the error will become entangled with the treatment effect. As such, the estimate of the treatment effect may be biased on the high side, whereas estimate of experimental error may be biased on the low side. The exact opposite would be true if errors were negatively correlated; that is, if one error in a series is associated with an error in the opposite direction.

The requirement that the errors must form a single homogeneous distribution with a single variance is also a critical requirement. For the tests of significance to be valid, this requirement must be fulfilled.

RECONCILIATION OF PROPERTIES OF FIELD DATA AND THEORETICAL REQUIREMENTS FOR VALIDITY

Of the 12 combinations of ground water and material, 6 contained observations on 17 or more slides. The table below shows the number of slides, the mean *HC*:*VC* ratio, the standard deviation, and the low-high extreme values.

Number of slides	*Mean* HC:VC *ratio*	*Standard deviation*	*Lower extreme observation*	*Upper extreme observation*
17	3. 35	0. 869	2. 0	5. 3
22	2. 55	. 764	1. 5	3. 8
21	2. 22	. 753	1. 1	4. 3
39	2. 22	. 592	1. 5	3. 8
33	2. 05	. 470	1. 2	3. 3
21	1. 84	. 344	1. 3	2. 5

The method by which the means and standard deviations were calculated is described by Snedecor (1946, p. 17–20).

Means are slightly but consistently nearer the lower extreme in each of the six groups, indicating that the data are not normally distributed. Standard deviations are obviously correlated with means so that the larger means have the larger standard deviations. Thus, these rather primitive tests indicate that experimental errors violate 2 of the 4 requirements listed and statistical analyses made would not necessarily yield valid results.

The question as to whether errors are correlated cannot be examined simply. Correlation among errors might arise from two causes: first, the observations may not have been obtained in a random order and slow changes in measurement techniques may have brought about similar errors in adjacent slides; second, several slides with almost identical measurements may frequently occur side by side. Such slides may not be independent, and the experimental errors may tend to be correlated.

No formal randomizing was performed (except in the uniformity experiment) in measuring the slides. However, some slides were measured and remeasured many times. It is believed that by these repetitions in many different orders, the methods of measurement were applied without significant trends. The question of the independence of adjacent slides must be left for later investigations. It was judged, however, that the effect was not serious.

The problem of heterogeneous errors was solved by transforming the *HC*:*VC* observations to base-10 logarithms. The logarithm transformation and the kinds of situations where it is useful are thoroughly described by Bartlett (1947) and Cochran (1938). Data for the 6 groups with 17 or more slides are converted to logarithms as follows:

Number of slides	*Mean log* HC:VC *ratio*	*Standard deviation*	*Standard error of estimate*
17	0. 512	0. 113	0. 1040
22	. 388	. 132	. 0844
21	. 323	. 146	. 0956
39	. 333	. 111	. 0662
33	. 300	. 099	. 0884
21	. 258	. 081	. 0534

The method by which the standard errors of estimates were calculated is described by Snedecor (1946, p. 274–285).

The observations in logarithms showed no apparent correlations between means and standard deviations. To further examine the situation, the independent effects of original slope, both linear and quadratic, and submergence percentage were removed by regression methods to give standard errors of estimate for each of the six groups. No correlation between means and standard deviations was apparent. It was judged that the variances of the transformed data were substantially equal.

Deviations from the upper and lower extremes of the data converted to logarithms are shown for the six groups:

Deviation to lower extreme	*Mean log* HC:VC *ratio*	*Deviation to upper extreme*
0. 211	0. 512	0. 212
0. 212	. 388	. 192
0. 287	. 323	. 306
0. 144	. 258	. 140
0. 221	. 300	. 162
0. 157	. 300	. 247

The means appear to be approximately at the centers of the ranges. Of the 6 groups, 3 show larger deviations on the high side and 3 show larger deviations on the low side. The distributions of errors are substantially symmetrical.

Since no previous experience with landslide data was available upon which to draw, it was arbitrarily judged that the experimental errors of the landslide data when converted to logarithms were approximately normally distributed with equal variances. It was further judged that the data transformed to logarithms could be properly analyzed and interpreted by the method of analysis of variance.

In forecasting the *HC*:*VC* ratio the regression equation gives the logarithm of the *HC*:*VC* ratio. The antilogarithm gives the geometric mean of the estimate rather than the arithmetic mean. The writers made no effort to convert to arithmetic means but recognize that such a step might be desirable. Finney (1941) discusses this problem for those who wish to study it in further detail.

EXPERIMENTAL LOGIC, TESTS OF SIGNIFICANCE AND PRECISION

Attention will now be directed toward the logical patterns which were followed. In general, the experimental logic as set forth by R. A. Fisher (1947) was followed. In each analysis the problem at issue was developed in specific terms to fit the pattern for the analysis of variance. The null hypothesis became the possible solution and the *f*-test provided the test of significance. For a discussion of the concept of the null hypothesis, the test of significance, and the basic principles of inquiry, reference is made to the paper of C. M. Mottley and Daniel R. Embody (1942).

The test of significance evaluates the probability that our result (correlation, differences among means, and other factors) could occur because of chance causes alone. As a result of experiences by many scientists in many fields it is customary to attach the term "significant" to a result if it could occur by chance with a probability of 1 to 20 or less. The term "highly significant" is attached to results where the explanation in terms of chance causes is 1 to 100 or less. It is recognized that these specifications are arbitrary conventions.

The test of significance is the evidence upon which the scientific judgment is constructed. If the *f*-test shows high significance, it becomes apparent that chance cannot reasonably explain the results. If all other considerations appear to be in proper form, then the scientist makes the judgment that a real effect has in fact been demonstrated. The judgment is based upon the test of significance, but the scientist in charge must make the judgment.

When significance but not high significance occurs in the test then the judgment can be made, but the data do not give as strong support. If no significance is indicated, chance may then provide a satisfactory explanation. The effect may be real, but the experimental observations do not have the capacity to demonstrate its existence.

Further study can be made in these tests to determine the power of the test of significance; that is, possible to estimate the smallest difference that could be detected with a specified probability. If this smallest difference appears to be of no economic consequence, inquiry may be terminated. If economic importance could be attached to the smallest difference, then further inquiry may be indicated. A detailed discussion of the subject of the power of tests with tables and references is given by Kempthorne (1953).

The desirable precision of *HC*:*VC* ratio predictions is a 95-percent confidence limit. In designed experiments where the correlations among independent variables are zero, the 95-percent confidence limits are relatively simple to calculate. In the landslide investigation, however, the independent variables were all highly correlated and the calculation of 95-percent confidence limits for a predicted value would be tedious. For a complete discussion of the subject see Schultz (1930.)

In the landslide study the standard error of estimate was used to describe the precision of predictions. This measure, although crude, would have immediate practical use in the field. A discussion of the standard error of estimate is given in Snedecor (1946).

It should be strongly emphasized that the results of the research in this investigation have not proved that landslides are predictable by statistics. The statistical analyses merely were used as tools to obtain probability statements. The conclusions and judgments made in the statistical parts of this report were made by the writers and responsibility must rest on them. These judgments can be considered as true and proper only if the community of scientists tests and accepts them. Other workers who plan to use the results of the inquiries must test and retest the various concepts presented.

SPECIFIC METHODS AND SOURCES

The various statistical methods employed in the landslide investigation are listed as follows:

1. Simple analysis of variance.
   The uniformity experiment was patterned after simple analysis of variance. Davies (1954), Fisher (1946), (1947), Goulden (1952), Snedecor (1946), and Youden (1953) describe this method.
2. Analysis of covariance with disproportionate numbers in the subclasses.
   This technique was used in the analyses with the *HC*:*VC* ratio. Patterns were obtained from Kempthorne (1953), Snedecor and Cox (1935), Tsao (1945)[1], (1942), (1946), and Yates (1933).

[1] Tsao, Fei, 1945, General solution of the analysis of variance and covariance in the case of unequal or disproportionate numbers of observations in the subclasses: Unpub. thesis, Univ. Minnesota, 115 p.

3. Multiple regression analysis.
   Final prediction equations were developed by this method.
   Techniques were obtained from Fisher (1946), Kempthorne (1953), and Snedecor (1946).
4. Discriminant functions.
   References for this method are Durand (1941), Fisher (1936; 1946), Goulden (1952), Mather (1943), Park and Day (1942).
5. Transformations.
   References, Bartlett (1947), Cochran (1938; 1947), Snedecor (1946).
6. Tests for parallelism.
   Reference Snedecor (1946).

SUMMARY OF RECONNAISSANCE SEISMIC SURVEYS

By Robert M. Hazlewood

Refraction seismic surveys of four small areas in the upper Columbia River valley were made to determine the position of the bedrock surface underlying the Pleistocene terrace deposits because landsliding in the terrace deposits may be influenced by the position and the configuration of that surface.

The terrace deposits are composed of clay, silt, sand, and gravel which range in thickness from a few feet to 700 feet or more. Paleozoic and Mesozoic metamorphic and igneous rocks form the bedrock. They consist principally of quartzite, schist, gneiss, and granite. The seismic-refraction method was applicable here because of the contrast in velocities between the metamorphic and igneous rocks and the surficial deposits composed of clay, silt, sand, and gravel deposits.

Reconnaissance seismic measurements were made along the shores of the northern part of Franklin D. Roosevelt Lake in the Reed terrace and Ninemile areas and also along the Columbia River in the Nespelem River area, which is 12 miles downstream from Grand Coulee Dam (figs. 1, 10). Fieldwork was done from July 15 to August 28, 1952, and additional work in the Reed terrace area was done from June 8 to 26, 1953. Fred O. Jones, who was in charge of the geologic studies, selected the areas for investigation and furnished the necessary maps and geologic information.

FIELD MEASUREMENTS

The survey was made with a portable 12-trace refraction seismograph unit, and the reversed profile method of shooting was used for bedrock depth determinations. In this method the geophones are arranged in a straight line and dynamite is detonated alternately in shotholes at the ends of the line. Because the depth to bedrock ranged from less than 50 to more than 750 feet, profiles were 500 to 2,400 feet in length to obtain the necessary depth of penetration. Geophones were spaced at 100-foot intervals along the 1,200-foot profiles and at 200 feet along the 2,400-foot profiles. The geophones were placed in shallow holes 4 to 6 inches in depth to reduce background noise caused by wind. Because the material lying near the surface of the ground was extremely dry, large charges of ex-

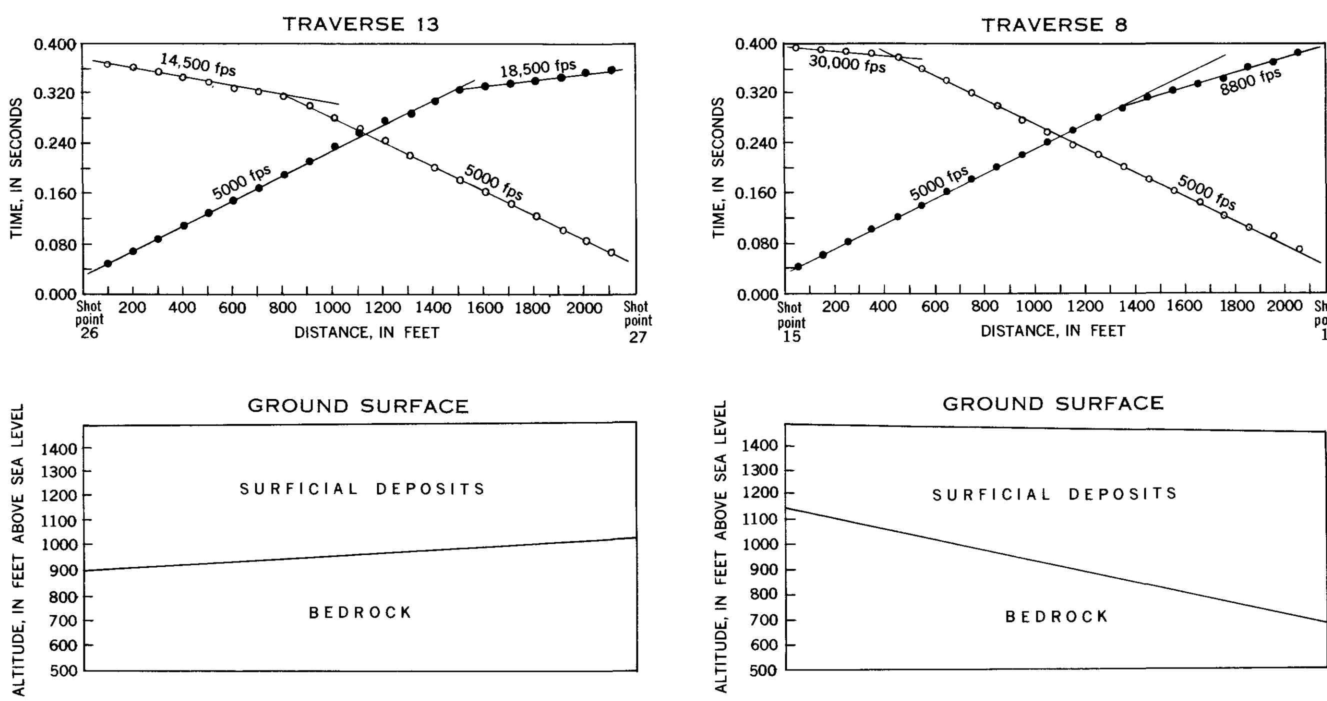

Figure 43.—Sample time-distance curves and bedrock profiles for Reed terrace area, Franklin D. Roosevelt Lake, Wash.

plosives were needed to send seismic impulses to distant geophones. From 10 to 50 pounds of 60 percent dynamite was used per shothole. Electric seismic blasting caps were used to detonate the explosive. A power auger mounted on a jeep was used where possible to drill shotholes to depths from 10 to 25 feet. Where it was not possible to use the power auger, shotholes 4 to 6 feet deep were dug by hand.

A total of 50 profiles were shot: 37 in the Reed terrace area, 9 in the Ninemile area, and 4 in the Nespelem River area.

Depths were computed by a critical-distance formula, assuming a single dipping layer, and were checked by means of the time-intercept method. The measurements were made over even ground and few altitude corrections were necessary. A sample of travel-time curves for Reed terrace area is shown on figure 43.

RESULTS

The terrace deposits varied greatly in their moisture content. Where the deposits were dry or nearly so, the velocity ranged from 1,500 to 3,500 feet per second. Where the terrace materials were water soaked, the velocity was uniformly 5,000 feet per second. The velocities in the individual beds within the terraces were so similar that lithologic changes were not evident. The velocity in the bedrock ranged from 15,000 to 19,000 feet per second.

A bedrock contour map was prepared for the Reed terrace area. In the Ninemile and Nespelem River areas sufficient data were not available to prepare contour maps, and only the location of the shotpoints and the depths to bedrock are given.

REED TERRACE AREA

The Reed terrace area includes one large terrace and several smaller terraces at higher and lower levels. The surficial deposits are composed of clay, silt, sand, and gravel (pl. 1). The bedrock is quartzite, gneiss, and schist.

Depths to bedrock are shown in the table below. Shotpoints and bedrock contours are shown on plate 1. Measurements in the uppermost terrace in the northwestern part of the Reed terrace area (the Sherman Creek terrace) show an old valley in the bedrock surface draining southeast into the sediments underlying the largest terrace (Main terrace). The velocity in the material underlying the Sherman Creek terrace is is 1,500 to 3,000 feet per second. This velocity is lower than that in water-soaked material, and it suggests that there is little or no movement of water in the channel from the upper terrace to the lower main terrace. The possibility of seasonal movement of water is not excluded. In the other parts of the

Seismic results Reed terrace area

Shotpoint	Depth to bedrock	Shotpoint altitude	Bedrock altitude
1	90	1,490	1,400
2	150	1,490	1,340
3	422	1,490	1,068
4	410	1,490	1,080
5	597	1,470	873
6	47	1,493	1,446
7	53	1,496	1,444
8	328	1,496	1,168
9	439	1,491	1,052
10	441	1,482	1,041
11	215	1,585	1,370
12	204	1,535	1,331
13	220	1,601	1,381
14	220	1,584	1,364
15	333	1,490	1,157
16	765	1,450	685
17	560	1,310	750
18	144	1,310	1,166
19	240	1,450	1,210
20	237	1,450	1,213
21	459	1,479	1,020
22	553	1,470	917
23	541	1,458	917
24	520	1,470	950
25	385	1,490	1,105
26	576	1,478	902
27	455	1,490	1,035
28	175	1,515	1,340
29	401	1,491	1,090
30	170	1,455	1,285
31	225	1,455	1,230
32	245	1,795	1,550
33	230	1,805	1,575
34	66	1,780	1,714
35	126	1,790	1,664
36	155	1,700	1,545
37	91	1,660	1,569
38	91	1,650	1,559
39	45	1,590	1,545
40	525	1,340	815
41	102	1,325	1,223
42	226	1,438	1,212
43	252	1,490	1,238
44	37	1,622	1,585
45	115	1,515	1,400
46	220	1,470	1,250
47	190	1,510	1,320
48	185	1,475	1,290
49	265	1,475	1,210
50	632	1,299	667
51	305	1,290	985
52	110	1,800	1,690
53	221	1,790	1,569
54	148	1,785	1,637
55	218	1,802	1,584
56	535	1,450	915
57	241	1,500	1,259
58	390	1,490	1,100
59	469	1,485	1,016
60	425	1,485	1,060
61	550	1,479	929
62	385	1,490	1,105
63	504	1,470	966
64	170	1,500	1,330
65	320	1,490	1,170
66	90	1,490	1,400
67	221	1,455	1,234
68	256	1,500	1,244
69	539	1,470	931
70	118	1,775	1,657
71	255	1,798	1,543
72	120	1,800	1,680
73	88	1,841	1,753
74	220	1,800	1,580
75	220	1,790	1,570

Reed terrace area, a uniform velocity of about 5,000 feet per second was observed in the surficial deposits, indicating water-soaked material; and, in fact, the silt and sand were saturated with water where holes were drilled through the overlying dry surface. The average velocity in bedrock throughout the area was 17,000 feet per second.

NINEMILE AREA

The seismic investigations were done on Ninemile Flat (pl. 3) and in the ancient multiple-alcove landslide to the south. Pleistocene deposits, chiefly silt and clay with some sand and gravel, overlie Paleozoic and Mesozoic metamorphic rocks in this area.

Depths to bedrock are shown in the table below; the locations of the shotpoints are shown on plate 3. The depths to bedrock indicate that there is an old valley in the bedrock beneath Ninemile Flat. The line shot west to east (shotpoints 3, 5, 6 and 7) shows the bedrock surface to be dipping to the west into the valley. The velocity of 3,500 to 4,000 feet per second in the overburden along this line indicates that these materials were not water soaked. The velocity of 5,000 feet per second in the overburden in the buried valley, however, indicates water-soaked conditions and suggests that the subsurface drainage probably follows the old valley.

Seismic results, Ninemile area

Shotpoint	Depth to bedrock	Shotpoint altitude	Bedrock altitude
1	599	1, 885	1, 286
2	630	1, 860	1, 230
3	477	1, 890	1, 413
4	475	1, 900	1, 425
5	275	1, 900	1, 625
6	278	1, 920	1, 642
7	265	1, 940	1, 675
8	361	1, 860	1, 499
9	315	1, 460	1, 145
10	406	1, 440	1, 034
11 [1]	385+	1, 390	1, 005−

[1] Incomplete, at least 385+.

NESPELEM RIVER AREA

In the Nespelem River area, seismic profiles were run across Bailey Basin (pl. 5). The overburden is composed of clay, silt, sand and gravel. The bedrock is granite. The east end of Bailey Basin is formed by a landslide scarp; the floor is landslide debris. The surface material was exceedingly dry sand with a large amount of very coarse gravel, making it almost impossible to dig shotholes.

Depths to bedrock are shown in the table below; the locations of the shotpoints are shown on plate 5. On the floor of Bailey Basin velocities of 5,000 feet per second indicated that the overburden was water soaked. On the terrace above and to the east of the landslide scarp, velocities of 2,700 to 4,000 feet per second indicated that the overburden was dry.

Seismic results, Nespelem River area

Shotpoint	Depth to bedrock	Shotpoint altitude	Bedrock altitude
1	140	1, 040	900
2	210	1, 120	910
3	74	1, 244	1, 170
4	285	1, 600	1, 315
5	164	1, 680	1, 516
6	300	1, 560	1, 260
7	440	1, 540	1, 100

CONCLUSIONS

The results of this investigation indicate that the seismic-refraction method can be used successfully over terrace deposits to determine depths to bedrock. This method was ideally suited to the area because of the large contrast between the velocity of the overlying material and the velocity of the bedrock. From the observed velocities it was possible to determine whether the terrace materials were dry, relatively dry, or water soaked. The velocities in the individual beds of the terrace were so similar that lithologic changes were not evident.

TABLES OF LANDSLIDE DATA

All landslide and slope-stability data used or referred to in any part of the study are tabulated in the following tables (tables 1–9, inclusive). More complete definitions of classification categories are given in the section on statistical studies under heading "Field observation and methods" on page 33.

TABLE 1.—*One hundred sixty recent slump-earthflow landslides used in statistical analysis*

Landslide No.	Area [1] [2]	Location [2]			Classification and landslide data: Material category [3]	Ground water [4]	Terrace height [5] (feet)	Drainage [6]	Original slope of terrace scarp [7]	Submergence [8] (percent)	Culture [9]	Material removal [10]	Relative age [11]	Time of slide	*LC* [12]	*HC* [13]	*VC* [14]	*HC*: *VC* [15]	Discriminant function values [16]
Columbia River downstream from Grand Coulee Dam																			
10	Nespelem River	River mile	(RB)	11.5	2	High	560	43	4.7:1	25	71	83	92	Following 1948 flood	300	245	52	4.7	0.0228
11				11.6	2	do	100	43	2.7:1	5	71	81	92		400	270	100	2.7	.0186
14				11.9	2	Low	100	43	1.1:1	5	71	81	92		200	110	100	1.1	.0203
17	Nespelem River (Nespelem River, 6,800 ft RB).			14.2	1	High	400	43	2.7:1	0	73	81	92	Initial movement 1940, renewed movement 1945.	400	660	210	3.1	.0220
20	Nespelem River			13.5	1	do	130	43	2.7:1	15	73	82	92	Following 1948 flood	1,000+	570	130	4.4	.0213
21				14.9	1	do	180	43	1.9:1	15	72	82	92	Prior to 1942	1,500	630	160	3.9	.0259
Franklin D. Roosevelt Lake																			
24	Sanpoil River bay	Mile	(RB)	0.1	3	Low	340	43	3.1:1	82	73	81	93	Prior to June 1944	500	790	210	3.8	0.0197
25			(LB)	.1	1	do	390	42	1.8:1	74	71	83	93		100	520	250	2.1	.0252
26				.4	5	do	150	42	2.4:1	33	71	81	93		300	210	95	2.2	.0174
27				.8	5	do	360	42	2.6:1	69	71	81	93		300	660	325	2.0	.0213
28				1.3	3	do	360	43	1.8:1	67	72	81	93	Prior to June 1944	700	830	310	2.7	.0247
29				1.6	3	do	330	43	2.1:1	68	72	81	93	do	800	610	285	2.1	.0229
30				1.8	3	do	310	43	2.4:1	74	72	81	93	do	500	700	280	2.5	.0216
31				2.05	3	do	330	43	2.2:1	66	72	82	93	Between June 29 and July 24, 1944.	300	680	285	2.4	.0225
32				2.3	3	do	150	43	2.9:1	33	72	83	93	do	175	330	110	3.0	.0156
33				2.4	3	do	315	43	3.0:1	68	72	81	93	Prior to June 1944	250	860	270	3.2	.0194
34			(RB)	2.5	1	do	290	43	2.4:1	69	72	81	93	Prior to June 1944, enlargement Apr. 13, 1953.	2,000	720	280	2.6	.0212
35				3.1	1	do	310	43	2.6:1	61	72	81	93	1952 lake drawdown	350	1,080	310	3.5	.0205
36			(LB)	3.2	1	do	240	42	3.7:1	71	72	83	93	Main movement 1952 lake drawdown—enlargement Apr. 13, 1953.		720	190	3.8	.0164
37				3.7	1	do	240	42	2.8:1	62	72	83	93	do		600	190	3.2	.0188
38	Sanpoil River bay (lower Manilla Bay).		(RB)	3.8	2	do	85	43	2.4:1	59	71	81	93		70	180	85	2.1	.0159
39	Sanpoil River bay (upper Manilla Bay).			3.8	2	do	90	43	2.9:1	56	71	81	93		200	250	85	2.9	.0143
40	Sanpoil River bay		(LB)	4.1	1	do	240	42	2.8:1	62	72	83	93	1952 lake drawdown		650	190	3.4	.0188
41			(RB)	4.3	1	do	220	41	2.3:1	82	71	83	93	do		400	125	3.2	.0207
42			(LB)	6.05	1	High	245	43	3.0:1	45	72	82	93	Nov. 8, 1942	1,875	1,200	225	5.3	.0245
43				6.7	1	Low	180	43	2.9:1	33	72	82	93		125	310	85	3.6	.0164
44			(RB)	6.8	2	High	90	43	3.9:1	22	73	83	93		225	240	60	4.0	.0169
45				7.1	1	do	165	43	3.5:1	15	73	83	93		700	500	155	3.2	.0198
46				8.0	2	Low	105	43	3.5:1	14	71	82	93		75	100	40	2.5	.0112
49	Whitestone-Hellgate	Lake mile	(LB)	22.6	5	do	230	43	2.1:1	44	71	81	93		175	300	125	2.4	.0208
50				22.95	5	do	340	43	3.6:1	65	72	81	93		500	700	340	2.1	.0180
51				23.2	5	do	190	43	1.7:1	37	72	81	93		250	280	160	1.8	.0218
56				30.3	5	do	500	43	1.6:1	62	71	81	93	Prior to June 1944	1,500	960	465	2.1	.0271
57				30.8	5	do	480	43	1.5:1	61	71	81	93	do	1,300	900	390	2.31	.0275
58			(RB)	32.5	5	do	170	42	2.1:1	47	71	81	93		350	250	125	2.0	.0197
60	Hawk Creek			35.4	5	do	730	41	1.9:1	41	71	81	93		250	460	260	1.8	.0264
61				35.8	3	do	670	42	1.5:1	36	71	81	93		180	360	220	1.6	.0281
64	Hawk Creek (Hawk Creek bay, 4,200 ft RB).		(LB)	37.2	1	do	340	43	1.8:1	38	71	81	93	July 26, 1949	500	800	340	2.4	.0237
65	Hawk Creek (Hawk Creek bay, 5,000 ft RB).			37.2	1	do	460	43	1.7:1	31	71	81	93	July 27, 1949	1,300	1,150	460	2.5	.0252
71	Fort Spokane		(LB)	39.1	5	do	125	43	1.4:1	44	71	82	93		70	48	34	1.41	.0221
74	Spokane River arm	Mile		.7	5	do	540	43	1.3:1	41	72	81	93		300	500	350	1.4	.0287
77				2.7	3	do	330	43	2.4:1	57	71	82	93		1,000	780	300	2.6	.0214
78				2.8	3	do	330	43	2.5:1	57	71	82	93	Renewed movement during 1953 drawdown.	500	600	240	2.5	.0210
79				6.3	3	do	340	41	1.6:1	29	72	82	93	Prior to June 1944	250	530	310	1.7	.0244
82			(RB)	9.0	1	do	260	43	2.1:1	50	71	81	93	1952 lake drawdown	700	700	185	3.8	.0215
83			(LB)	9.6	5	do	120	41	2.3:1	50	71	83	93		75	210	85	2.5	.0175
88				12.1	4	do	200	43	2.4:1	70	72	82	93		600	450	180	2.5	.0197

See footnotes at end of table.

TABLE 1.—*One hundred sixty recent slump-earthflow landslides used in statistical analysis*—Continued

Landslide No.	Area [1,2]	Location [2]			Classification and landslide data														
					Material category [3]	Ground water [4]	Terrace height [5] (feet)	Drainage [6]	Original slope of terrace scarp [7]	Submergence [8] (percent)	Culture [9]	Material removal [10]	Relative age [11]	Time of slide	*LC* [12]	*HC* [13]	*VC* [14]	*HC*:*VC* [15]	Discriminant function values [16]
	Franklin D. Roosevelt Lake—Continued																		
90	Spokane River arm	Mile	(RB)	12.6	3	Low	320	42	2.6:1	34	71	83	93		100	220	97	2.3	0.0198
91				12.8	3	do	240	42	1.5:1	50	71	83	93	Renewed movement during 1952 lake drawdown.	300	390	230	1.7	.0244
94			(LB)	16.5	3	High	400	43	1.9:1	3	71	81	92		100	370	190	1.9	.0269
95				17.1	3	Low	360	43	1.5:1	19	71	81	93		100	340	220	1.5	.0246
98				18.1	4	do	95	43	2.4:1	65	71	81	93		125	250	95	2.6	.0165
100				18.6	4	do	350	42	1.4:1	23	71	82	93	Renewed movement during 1952 lake drawdown.	300	260	160	1.6	.0254
101				18.7	4	do	155	42	1.3:1	42	71	82	93		300	260	150	1.7	.0236
107				28.8	3	do	550	43	1.3:1	4	73	81	93		150	260	135	1.9	.0254
108				28.9	5	do	520	43	1.3:1	4	73	81	93		100	200	120	1.7	.0252
109				29.05	5	do	520	43	1.3:1	4	73	81	92		100	200	120	1.7	.0252
111	Fort Spokane	Lake mile		42.3	3	do	155	42	1.7:1	45	71	82	93		300	120	78	1.5	.0212
114	Fort Spokane (Abraham Cove—outer).			43.5	1	High	120	43	1.6:1	66	72	83	93		220	320	120	2.7	.0280
115	Fort Spokane (Abraham Cove—inner).			43.5	1	do	85	43	1.6:1	18	72	83	93		100	100	50	2.0	.0247
116	Fort Spokane (Fox Canyon—outer).			46.9	1	Low	170	41	3.6:1	53	71	82	93	1952 lake drawdown	100	390	130	3.0	.0151
117	Fort Spokane (Fox Canyon—inner).			46.9	1	do	170	41	2.1:1	53	71	82	93	Renewed movement during 1952 lake drawdown.	300	440	175	2.5	.0199
120	Nine mile			47.9	4	High	250	43	2.4:1	40	71	83	93		200	190	70	2.7	.0265
125				49.0	4	Low	270	42	1.6:1	73	72	81	93	1952 lake drawdown	250	500	270	1.9	.0248
129				49.9	1	do	410	41	2.1:1	63	72	83	93		100	140	75	1.9	.0237
131			(RB)	51.4	1	do	300	41	1.8:1	16	73	82	93	July 3, 1949	200	280	120	2.3	.0219
134				51.95	2	High	350	43	.7:1	63	71	82	92–93	Prior to June 1944	800	300	160	1.9	.0401
136			(LB)	52.6	2	Low	100	43	1.8:1	10	71	82	93		90	300	125	2.4	.0167
137				52.7	2	do	140	43	2.1:1	64	71	81	93		120	200	100	2.3	.0193
140				53.1	2	do	150	43	1.8:1	80	71	81	93		100	210	90	2.3	.0214
141				53.2	2	do	110	43	1.7:1	82	71	81	93		400	300	90	3.3	.0207
142				53.4	2	do	80	43	1.8:1	62	71	81	93		400	200	100	2.0	.0185
143				53.5	2	do	120	43	2.7:1	76	71	81	93		150	300	100	3.0	.0166
146			(RB)	53.9	3	do	155	41	1.7:1	35	71	83	93	1952 lake drawdown	150	320	160	2.0	.0209
149	Wilmont-Gerome (Wilmont Bay off point).			56.5	2	do	175	41	2.1:1	80	71	81	93		350	380	175	2.2	.0206
150	Wilmont-Gerome (Wilmont Bay 1,750 ft RB).			56.5	1	do	230	41	1.8:1	43	71	81	93	1952 lake drawdown	250	430	210	2.0	.0223
151	Wilmont-Gerome (Wilmont Bay 2,100 ft RB).			56.5	1	do	270	41	1.6:1	33	71	82	93	do	300	310	180	1.7	.0236
152	Wilmont-Gerome (Wilmont Bay 3,700 ft RB).			56.5	1	do	240	41	1.8:1	25	71	82	93		500	280	140	2.0	.0216
153	Wilmont-Gerome (Gerome Bay 200 ft LB).		(LB)	57.8	4	do	160	41	2.0:1	37	72	81	93	Prior to June 1944	500	350	175	2.0	.0196
154	Wilmont-Gerome (Gerome Bay 800 ft LB).			57.8	5	do	210	41	1.2:1	42	71	81	93		120	145	110	1.3	.0256
155	Wilmont-Gerome (Gerome Bay 1,500 ft LB).			57.8	3	do	250	41	2.1:1	40	71	81	93		120	330	120	2.8	.0210
156	Wilmont-Gerome		(RB)	58.3	3	do	250	42	2.2:1	64	71	81	93		550	420	205	2.1	.0213
157				58.4	3	do	250	43	.3:1	84	71	81	93	Prior to June 30, 1951	1,000	600	210	2.9	.0404
158				59.0	3	do	220	43	1.0:1	91	71	81	93	July 30, 1940	1,550	720	225	3.2	.0287
161	Hunters-Nez Perce Creek.		(RB)	62.4	2	do	330	41	2.8:1	31	71	83	93		100	420	160	2.6	.0191
165			(LB)	62.7	1	High	100	42	3.3:1	20	73	83		About 1926 after filling of Hunters Creek reservoir.	900–1,000	280	80	3.5	.0188
172	Hunters-Nez Perce Creek (Nez Perce Creek 0.6 mile LB).		(RB)	64.7	1	Low	260	41	1.7:1	27	71	81	93		150	200	130	1.5	.0226

173	Hunters-Nez Perce Creek (Nez Perce Creek 0.7 mile RB).			64.7	1	do	170	41	1.3:1	41	71	81	93		130	160	105	1.5	.0240
179	Cedonia		(LB)	67.5	3	do	380	42	3.2:1	47	71	81	93		400	1,050	330	3.2	.0190
180				67.55	3	do	190	42	1.8:1	22	71	82	93		125	370	190	1.9	.0205
181				67.6	3	do	270	42	2.1:1	56	71	81	93		300	600	280	2.1	.0218
182				67.65	3	do	450	42	2.1:1	38	71	81	93	Prior to June 1944	350	900	430	2.1	.0234
183				67.75	3	do	500	43	1.8:1	30	71	81	93	do	250	850	460	1.8	.0249
184				67.8	3	do	640	43	1.4:1	30	71	81	93	do	400	800	490	1.6	.0283
186				67.9	4	do	580	43	1.3:1	33	71	81	93	do	275	1.050	530	2.0	.0287
187				68.0	4	do	630	43	1.4:1	33	71	81	93	do	200	930	520	1.8	.0284
188				68.1	5	do	540	43	1.7:1	33	71	81	93	do	350	750	370	2.0	.0259
190	Cedonia (Bay 800 ft RB).			68.2	2	do	110	41	1.8:1	27	71	82	93		250	100	85	1.2	.0185
193	Cedonia (Bay 360 ft LB).			68.2	2	do	95	43	1.5:1	53	71	81	93		150	100	54	1.9	.0206
195	Cedonia			68.3	4	do	360	41	2.7:1	73	71	81	93	Prior to June 1944	240	850	260	3.3	.0197
198				68.5	4	do	280	43	2.0:1	59	71	81	93	do	450	460	370	1.2	.0225
200				68.7	4	do	260	43	2.5:1	56	71	81	93	do	500	780	290	2.7	.0214
201				68.8	4	do	120	43	2.1:1	35	71	81	93		100	200	100	2.0	.0178
202				69.0	5	do	340	43	1.7:1	54	71	81	93	Prior to June 1944	450	530	320	1.7	.0247
211	Cedonia (Bay 600 ft LB).			69.2	4	do	70	42	1.3:1	14	71	81	93		130	115	68	1.7	.0188
212	Cedonia			69.3	4	do	270	41	.7:1	55	71	81	93	Prior to June 1944	600	460	290	1.6	.0321
213				69.4	4	do	340	43	1.3:1	59	71	81	93	do	450	850	290	2.9	.0274
214				69.5	4	do	340	43	1.3:1	59	71	81	93	do	400	680	260	2.6	.0274
215				69.6	4	do	340	43	1.3:1	59	71	81	93	do	250	500	300	1.7	.0274
216				69.7	5	do	330	43	1.3:1	48	71	82	93		300	460	280	1.6	.0269
217				69.9	4	do	380	43	1.6:1	43	71	81	93	Prior to June 1944	300	680	345	2.0	.0254
219	Cedonia (mouth of Bay LB).			70.0	4	do	135	43	1.7:1	19	71	82	93		150	160	90	1.8	.0194
220	Cedonia (mouth of Bay RB).			70.0	2	do	170	43	1.7:1	24	71	81	93		120	165	105	1.6	.0207
221	Cedonia (Bay 500 ft LB).			70.0	4	do	170	43	2.1:1	29	71	81	93		250	290	160	1.8	.0190
222	Cedonia			70.1	2	do	300	43	1.4:1	60	71	81	93	Prior to June 1944	150	410	290	1.4	.0262
223				70.15	4	do	350	43	1.8:1	56	71	81	93	do	200	630	300	2.1	.0244
224				70.2	4	do	340	43	2.1:1	56	72	81	93	do	500	640	330	1.9	.0228
225				70.25	4	do	350	43	1.3:1	49	72	81	93	do	270	680	380	1.8	.0272
226				70.3	4	do	370	43	1.8:1	49	72	81	93	do	420	730	380	1.9	.0244
227				70.45	4	do	400	43	1.5:1	47	71	81	93	do	225	740	400	1.9	.0264
228				70.47	5	do	120	42	1.4:1	50	71	81	93		110	130	85	1.5	.0222
229				70.5	4	do	360	43	1.8:1	56	71	81	93	Prior to June 1944	200	630	340	1.9	.0245
230				70.55	4	do	330	43	1.3:1	66	71	81	93	do	250	700	310	2.3	.0274
231				70.6	4	do	330	43	1.3:1	66	71	81	93	do	275	840	320	2.6	.0274
232				70.65	4	do	320	43	1.3:1	63	71	81	93	do	175	710	300	2.4	.0272
233				70.7	4	do	320	43	1.3:1	63	71	81	93	do	350	690	280	2.5	.0272
235	Gifford-Inchelium		(RB)	74.8	2	do	220	41	1.6:1	23	71	81	93		200	350	195	1.8	.0223
236			(LB)	78.3	1	do	170	43	.9:1	83	72	81	93	Prior to July 19, 1941	1,000	260	160	1.6	.0285
241	Rice-Chalk grade			87.8	3	do	360	43	2.0:1	42	72	81	93	do	800	450	265	1.7	.0231
242				88.3	3	do	355	43	2.9:1	42	71	81	93	Prior to June 1944	500	810	261	3.1	.0195
243				88.4	3	do	280	43	1.9:1	61	71	81	93	do	250	660	260	2.5	.0230
244				88.45	3	do	290	43	1.7:1	61	71	81	93	Prior to July 19, 1941	250	650	270	2.4	.0242
248	Roper Creek		(RB)	95.0	3	do	280	43	1.5:1	40	71	81	93	Prior to June 1944	200	340	230	1.5	.0247
249				95.1	3	do	280	43	2.5:1	40	71	81	93	do	900	440	210	2.1	.0199
250	Roper Creek (Bay 800 ft RB).			95.2	2	do	160	43	2.2:1	37	71	83	93		250	340	140	2.4	.0187
251	Roper Creek (Bay 900 ft LB).			95.2	2	High	235	43	3.7:1	28	71	83	93		200	380	100	3.8	.0217
252	Roper Creek (Bay 1,300 ft RB).			95.2	2	Low	160	43	1.7:1	25	71	81	93		300	270	200	1.4	.0205
255	Reed terrace			98.3	2	do	305	42	2.1:1	49	71	81	93	1952 lake drawdown	400	530	275	1.9	.0221
256				98.35	1	High	340	43	2.5:1	4	73	82	92	1926 or 1927	1,400	800	350	2.3	.0240
257				98.37	1	do	350	43	2.5:1	50	73	81	93	Mar. 12, 1952; Sept. 12 and Oct. 13, 1952.	800	1,560	350	4.5	.0278
258				98.4	1	do	350	43	2.5:1	40	73	81	93	Apr. 8, 1944	1,000	1,320	350	3.8	.0275
259				98.5	1	do	340	43	2.3:1	38	73	81	93	Apr. 1, 1944	920	990	340	2.9	.0281
260				98.6	1	do	340	43	2.3:1	50	72	81	93	Mar. 1951	350	1,140	320	3.6	.0285
262				98.67	1	do	320	43	2.3:1	4	73	81	92	About 1898	1,530	1,100	320	3.4	.0246
263				98.7	1	do	320	43	2.5:1	45	73	81	93	Prior to June 1944	250	450	130	3.5	.0273
265	Kettle Falls		(LB)	103.0	3	Low	195	43	1.4:1	45	71	81	93		200	240	165	1.5	.0240
266				103.1	3	do	190	43	1.4:1	47	71	81	93		400	400	190	2.1	.0240
267				103.2	3	do	190	43	1.4:1	45	71	81	93		250	180	110	1.6	.0239
271	Kettle River arm	Mile	(RB)	2.0	2	do	255	43	3.5:1	18	73	83	93	Apr. 26 and 30, 1952; continued to move through July.	1,400	1,130	260	4.3	.0152
273	Marcus-Evans	Lake Mile		105.0	1	do	240	43	2.2:1	70	73	82	93	Enlarged during drawdown 1952.	150	370	175	2.1	.0213
274				105.7	1	High	150	43	2.3:1	55	73	82	93		75	250	100	2.5	.0253
277				106.75	1	do	115	43	2.4:1	13	71	82	93		150	260	110	2.4	.0217

See footnotes at end of table.

TABLE 1.—*One hundred sixty recent slump-earthflow landslides used in statistical analysis*—Continued

Landslide No.	Area [1] [2]	Location [2]	Classification and landslide data														
			Material category [3]	Ground water [4]	Terrace height [5] (feet)	Drainage [6]	Original slope of terrace scarp [7]	Submergence [8] (percent)	Culture [9]	Material removal [10]	Relative age [11]	Time of slide	LC [12]	HC [13]	VC [14]	$HC:VC$ [15]	Discriminant function values [16]
Franklin D. Roosevelt Lake—Continued																	
282	Bossburg	(LB) 114.4	3	Low	170	43	1.0:1	41	72	81	93	Prior to June 1944	1,000	300	170	1.8	0.0265
283		(RB) 117.0	4	do	150	43	1.8:1	13	71	81	93		175	330	160	2.1	.0188
284		117.5	4	do	165	43	1.3:1	39	71	81	93		1,000	220	165	1.3	.0238
287	Northport-international boundary.	122.2	5	do	230	42	1.5:1	56	71	81	93	Prior to June 1944	250	400	230	1.7	.0243
288		(LB) 123.9	5	do	160	43	1.2:1	37	71	82	93		150	240	165	1.5	.0244
289		124.8	3	do	160	43	1.5:1	37	73	81	93		200	320	160	2.0	.0223
292		126.2	4	do	140	43	1.5:1	43	73	81	93		125	195	135	1.4	.0219
293		(RB) 126.8	3	do	170	43	1.5:1	53	72	81	93		200	260	155	1.7	.0230

[1] See figure 10.
[2] River mile, miles along centerline of Columbia River downstream from Grand Coulee Dam; Lake mile, miles along the centerline of Franklin D. Roosevelt Lake upstream from Grand Coulee Dam; Mile, miles from the mouth of a bay on Franklin D. Roosevelt Lake (bays commonly occur at the mouths of tributary streams); RB, right bank as one is facing downstream; LB, left bank as one is facing downstream; a description such as "(Bay 600 ft RB) Lake mile (LB) 69.2" means that 69.2 miles upstream from Grand Coulee Dam, there is a bay on the left bank of Franklin D. Roosevelt Lake and the site of the landslide is on the right bank of the bay 600 ft from the mouth.
[3] (1) Predominantly lacustrine silt and clay in its original position of deposition; (2) predominantly lacustrine silt and clay with bedding disturbed by landsliding, glacial processes; (3) alternating beds of clay, silt and sand in nearly their original position of deposition; (4) alternating beds of clay, silt and sand disturbed by landsliding, glacial processes, etc.; (5) predominantly sand and gravel.
[4] High springs, seeps and abundant water-loving vegetation above the midpoint of the exposed terrace slope; lakes or springs on the terrace surface or situated at higher altitudes in a position to feed water into the terrace deposits; low springs, seeps and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; no springs or lakes on the terrace surface or at higher altitudes to feed water into the terrace deposits.
[5] The altitude difference in feet from the top to the bottom of the slope in which the landslide occurred, commonly the vertical distance between two terraces.
[6] (41), drainage lines on the terrace sufficiently well developed to channel rain and snowmelt rapidly off the area; (42), lines of drainage less well developed with no significant closed depressions on the terrace surface; (43), closed depressions on terrace surface; drainage channels so poorly developed that most of the rain and snowmelt infiltrates the terrace deposits.
[7] The ratio of the horizontal distance from the top to the bottom of the slope to the vertical distance from the top to the bottom.
[8] Percentage of the distance from the bottom to the top of a slope that is under water.
[9] (71), no cultural or engineering developments on or near slide; (72), minor developments on or near slide such as farm buildings, plowed fields, farm access roads, or logging trails; (73), major developments on or near slide, such as deep highway or railroad cuts or fills, irrigation systems, towns or storage reservoirs.
[10] (81), all or most of the landslide material removed from the scarp; (82), part of the landslide material removed from the scarp; (83), very little movement of the landslide material.
[11] (92), Recent prereservoir landslides; (93), recent postreservoir landslides.
[12] The length component (LC), is the maximum horizontal distance from side to side of the slide measured parallel to the slope it descends.
[13] The horizontal component (HC), is the horizontal distance from the foot of the landslide to the crown.
[14] The vertical component (VC), is the difference in altitude between the foot and the crown of a landslide.
[15] The ratio of the horizontal component to the vertical component.
[16] Value of the discriminant function for the original terrace scarp.

TABLE 2.—*Forty-two slip-off slope landslides used in statistical analysis*

Landslide No.	Area [1,2]	Location [2]	Classification and landslide data: Material category [3]	Ground water [4]	Terrace height [5] (feet)	Drainage [6]	Original slope of terrace scarp [7]	Submergence [8] (percent)	Culture [9]	Material removal [10]	Time of slide [11]	*LC* [12]	*HC* [13]	*VC* [14]	*HC:VC* [15]
	Columbia River downstream from Grand Coulee Dam														
12	Nespelem River	River mile (RB) 11.77	2	Low	135	43	1.2:1	5	71	81	92	200	70	60	1.2
22		(LB) 15.3	1	do	335	43	1.6:1	3	71	81	92	200	400	300	1.3
	Franklin D. Roosevelt Lake														
23	Keller Ferry	Lake mile (RB) 16.2	5	Low	500	41	1.5:1	28	71	81	93	400	360	250	1.4
52	Hellgate-Whitestone	(LB) 23.4	5	do	420	43	1.5:1	72	72	81	93	1,200	450	210	2.1
53		24.1	5	do	420	43	1.4:1	73	72	81	93	2,000	740	360	2.1
54		(RB) 25.3	5	do	785	43	1.5:1	35	71	81	93	500	1,000	560	1.8
67	Hawk Creek	(LB) 37.5	3	do	440	42	1.1:1	20	71	82	93	250	70	47	1.5
68		37.55	3	do	510	42	1.8:1	31	71	81	93	300	130	80	1.6
69		37.9	3	do	480	43	1.7:1	52	71	81	93	200	200	110	1.8
70		38.1	3	do	170	43	2.1:1	53	71	81	93	200	100	40	2.5
72	Spokane River arm	Mile (RB) .2	5	do	115	43	2.8:1	48	71	81	93	250	90	35	2.6
73		(LB) .5	5	do	480	42	1.2:1	46	71	81	93	200	70	55	1.3
75		.8	5	do	400	42	1.8:1	52	71	82	93	150	90	60	1.5
76		.9	5	do	230	42	1.7:1	35	71	81	93	200	100	70	1.4
85		10.8	5	do	190	42	1.7:1	63	71	81	93	350	290	165	1.8
89		(RB) 12.5	3	do	300	42	1.2:1	17	71	81	93	300	130	105	1.2
92		(LB) 13.2	5	do	210	43	1.4:1	55	72	81	93	800	120	80	1.5
105		(RB) 22.1	3	do	380	43	1.5:1	12	71	81	93	1,500	630	380	1.7
106		28.2	5	do	140	43	1.3:1	14	71	81	93	150	200	120	1.7
138	Ninemile	Lake mile (LB) 52.9	2	do	180	43	1.5:1	67	71	81	93	140	400	170	2.4
139		53.0	2	do	170	43	1.5:1	71	71	81	93	200	450	170	2.6
169	Hunters-Nez Perce Creek	(RB) 64.45	1	do	360	41	1.0:1	53	71	81	93	900	350	350	[16] 1.0
174		65.1	1	do	290	41	2.0:1	62	71	81	93	1,650	740	290	2.6
189	Cedonia	(LB) 68.2	5	do	290	43	1.6:1	62	71	81	93	200	600	280	2.1
192	Cedonia (Bay 840 ft RB)	68.2	5	do	130	41	1.7:1	38	71	82	93	220	260	130	2.0
203	Cedonia	69.1	5	do	340	43	.9:1	56	71	81	93	150	400	275	1.5
204	Cedonia (Bay 100 ft LB)	69.2	5	do	190	42	1.7:1	45	71	81	93	150	250	170	1.5
206	Cedonia (Bay 200 ft LB)	69.2	5	do	180	42	1.7:1	39	71	81	92	75	260	170	1.5
207	Cedonia (Bay 300 ft LB)	69.2	5	do	180	42	1.7:1	39	71	81	93	180	290	165	1.8
208	Cedonia (Bay 400 ft RB)	69.2	5	do	170	42	1.7:1	12	71	82	93	110	160	75	2.1
209	Cedonia (Bay 500 ft LB)	69.2	5	do	180	42	1.7:1	33	71	81	93	150	255	135	1.9
210	Cedonia (Bay 600 ft RB)	69.2	5	do	125	42	1.7:1	8	71	82	93	300	165	85	1.9
218	Cedonia (Bay 400 ft LB)	70.0	2	do	155	43	1.5:1	17	71	82	93	75	70	68	1.0
234	Cedonia	70.9	5	do	300	43	1.5:1	60	71	81	93	750	550	270	2.0
239	Gifford-Inchelium	(RB) 84.8	1	do	110	43	2.6:1	55	71	81	93	1,000	110	50	2.2
245	Rice-Chalk grade	(LB) 88.6	5	do	280	43	1.8:1	68	71	81	93	700	220	105	2.1
247		(RB) 90.3	5	do	210	43	1.6:1	52	73	81	93	100	150	85	1.8
254	Roper Creek	96.9	5	do	160	43	1.7:1	28	71	81	93	700	210	124	1.7
268	Kettle Falls (200 ft east of U.S. Coast and Geodetic Survey control station "EAT" in Marcus Bay).	(LB) 103.7	5	do	300	43	1.6:1	13	71	82	93	100	270	160	1.7
270	Kettle Falls (1,200 ft west of "EAT" in Marcus Bay).	103.7	3	do	170	42	1.5:1	35	71	81	93	300	150	100	1.5
290	Northport-International boundary.	124.8	3	do	160	43	1.5:1	43	73	81	93	80	160	85	1.9
291		125.6	5	do	165	43	1.4:1	55	73	81	93	300	170	90	1.9

[1] See figure 10.

[2] River mile, miles along centerline of Columbia River downstream from Grand Coulee Dam; Lake mile, miles along the centerline of Franklin D. Roosevelt Lake upstream from Grand Coulee Dam; Mile, miles from the mouth of a bay on Franklin D. Roosevelt Lake (bays commonly occur at the mouths of tributary streams); RB, right bank as one is facing dowstream; LB, left bank as one is facing downstream; a description such as "(Bay 600 ft RB) Lake mile (LB) 69.2" means that 69.2 miles upstream from Grand Coulee Dam, there is a bay on the left bank of Franklin D. Roosevelt Lake and the site of the landslide is on the right bank of the bay 600 ft from the mouth.

[3] (1), Predominantly lacustrine silt and clay in its original position of deposition; (2), predominantly lacustrine silt and clay with bedding disturbed by landsliding, glacial processes; (3), alternating beds of clay, silt and sand in nearly their original position of deposition; (5), predominantly sand and gravel.

[4] High—springs, seeps and abundant water-loving vegetation above the midpoint of the exposed terrace slope; lakes or springs on the terrace surface or situated at higher altitudes in a position to feed water into the terrace deposits. Low—springs, seeps and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; no springs or lakes on the terrace surface or at higher altitudes to feed water into the terrace deposits.

[5] The altitude difference in feet from the top to the bottom of the slope in which the landslide occurred, commonly the vertical distance between two terraces.

[6] (41), Drainage lines on the terrace sufficiently well developed to channel rain and snowmelt rapidly off the area; (42), lines of drainage less well developed with no significant closed depressions on the terraced surface; (43), closed depressions on terrace surface; drainage channels so poorly developed that most of the rain and snowmelt infiltrates the terrace deposits.

[7] The ratio of the horizontal distance from the top to the bottom of the slope to the vertical distance from the top to the bottom.

[8] Percentage of the distance from the bottom to the top of a slope that is under water.

[9] (71), No cultural or engineering developments on or near slide; (72), minor developments on or near slide such as farm buildings, plowed fields, farm access roads, or logging trails; (73), major developments on or near slide, such as deep highway or railroad cuts or fills, irrigation systems, towns or storage reservoirs.

[10] (81), All or most of the landslide material removed from the scarp; (82), part of the landslide material removed from the scarp.

[11] (92), Recent prereservoir landslides; (93), recent postreservoir landslides.

[12] The length component (*LC*) is the maximum horizontal distance from side to side of the slide measured parallel to the slope it descends.

[13] The horizontal component (*HC*) is the horizontal distance from the foot of the landslide to the crown.

[14] The vertical component (*VC*) is the difference in altitude between the foot and the crown of a landslide.

[15] The ratio of the horizontal component to the vertical component.

[16] Major enlargement May 11, 1953, on slide 169.

TABLE 3.—*Thirty-seven ancient slump-earthflow landslides used in statistical analysis*

Landslide No.	Area [1,2]	Location [2]	Classification and landslide data									Remarks and re-movement data
			Material category [3]	Ground water [4]	Terrace height [5] (feet)	Present drainage [6]	Material removal [7]	*LC* [8]	*HC* [9]	*VC* [10]	*HC*:*VC* [11]	
	Columbia River downstream from Grand Coulee Dam											
1	Grand Coulee Dam-Belvedere.	River mile (RB) 4.2	1	High	790	43	82	3,500	3,350	790	4.2	Some renewed activity of material near river level since 1948 flood.
3	Grand Coulee Dam-Belvedere (Peter Dan Creek, 5,000 ft RB).	4.3	1	do	400	43	82	1,800	1,220	400	3.0	
4	Grand Coulee Dam-Belvedere (Peter Dan Creek, 5,000 ft LB).	4.3	1	do	260	43	82	400	560	230	2.4	Landslide 5, minor movements Dec. 23, 1951; Nov. 10 or 11, 1952; Nov. 27, 1952; and weekend of Jan. 10, 1953.
5	Grand Coulee Dam-Belvedere.	4.6	2	do	250	43	82	2,700	1,400	230	6.1	Renewed activity following community development, irrigation, and 1948 flood. Major enlargement Nov. 23, 1948.
6		4.4	1	do	820	43	82	2,100	3,900	790	4.9	Landslide 5 is situated in landslide material of the toe of this slide.
7		5.1	2	do	380	43	82	2,000	1,800	380	4.7	Renewed activity following community development, irrigation, and 1948 flood; Dec. 23, 1951; Nov. 10 or 11, 1952; Nov. 27, 1952; and weekend of Jan. 10, 1953. Major movement on slide 7, Nov. 23, 1948.
8	Nespelem River	11.2	2	do	550	43	83	500	1,270	260	4.9	
9		11.4	1	do	550	43	82	3,000	2,570	530	4.8	
13		11.86	1	do	735	43	82	3,000	3,600	700	5.1	
15		12.1	2	do	150	43	82	900	430	120	3.6	
18	Nespelem River (Nespelem Creek, 7,900 ft LB).	14.2	1	do	230	43	82	900	600	230	2.6	
19	Nespelem River	13.2	1	do	210	43	82	600	680	200	3.4	
	Franklin D. Roosevelt Lake											
47	Sanpoil River bay	Mile (RB) 8.15	1	High	125	43	82	500	450	125	3.6	Renewed activity following lake filling and highway construction.
66	Hawk Creek (Hawk Creek bay, 6,300 ft RB).	Lake mile (LB) 37.2	1	Low	470	43	81	850	1,270	380	3.3	
81	Spokane River arm	Mile 7.1	3	do	280	43	82	1,200	920	270	3.4	
96		17.15	3	High	360	43	81	200	570	330	1.7	
97		17.2	3	do	360	43	81	300	600	340	1.8	
99		18.4	3	do	380	43	82	1,200	1,200	370	3.2	
102		19.3	3	Low	470	43	82	1,000	960	370	2.6	
112	Fort Spokane	Lake mile 42.6	1	High	670	42	81	1,400	1,940	670	2.9	
123	Ninemile	48.3	1	do	670	43	82	1,300	2,600	670	3.9	
124		48.8	1	do	800	43	81	700	2,450	580	4.2	
126		49.2	1	do	800	43	82	1,500	2,250	540	4.2	
127		49.6	1	do	800	43	82	1,200	1,650	540	3.1	
128		49.8	1	do	800	43	81	700	2,500	670	3.7	
162	Hunters-Nez Perce Creek	62.5	1	do	410	43	81	850	1,270	410	3.1	Renewed activity following irrigation of terrace in 1920's; additional re-movement when lake was filled, and in years through 1953.
163	Hunters-Nez Perce Creek (Hunters bay, 1,000 ft LB).	64.8	1	do	280	43	81	780	900	210	4.3	Renewed activity following irrigation of terrace in 1920's.
164	Hunters-Nez Perce Creek (Hunters bay, 1,600 ft LB).	64.8	1	do	270	43	81	720	850	180	4.7	Do.
185	Cedonia	(RB) 67.9	3	Low	400	42	81	500	960	320	3.0	
194		68.3	3	do	400	42	81	300	820	280	2.9	
196		68.4	3	High	500	42	81	500	1,200	370	3.2	
197		68.5	3	do	540	42	81	500	1,180	410	2.9	

See footnotes at end of table.

TABLE 3.—*Thirty-seven ancient slump-earthflow landslides used in statistical analysis*—Continued

Land-slide No.	Area [1] [2]	Location [2]	Classification and landslide data									Remarks and re-movement data
			Material category [3]	Ground water [4]	Terrace height [5] (feet)	Present drainage [6]	Material removal [7]	*LC* [8]	*HC* [9]	*VC* [10]	*HC*:*VC* [11]	
Franklin D. Roosevelt Lake—Continued												
237	Gifford-Inchelium (Hall Creek bay, 1,000 RB).	Lake mile (RB) 79.4	1	Low	300	43	81	700	620	300	2.1	Renewed activity following irrigation of terrace before Franklin D. Roosevelt Lake and minor activity from the lake.
253	Roper Creek (Roper Creek bay, 1,800 ft LB).	95.2	1	do	150	43	82	700	890	150	5.9	Renewed activity of slide material following partial inundation by Franklin D. Roosevelt Lake.
275	Marcus-Evans	106.0	1	do	140	43	82	200	360	140	2.6	Do.
278		106.8	1	High	320	43	82	1,670	1,130	320	3.5	Do.
294	Hawk Creek (Hawk Creek bay, 4,500 ft RB).	(LB) 37.2	1	Low	470	43	81	1,100	840	380	2.2	

[1] See figure 10.

[2] River mile, miles along centerline of Columbia River downstream from Grand Coulee Dam; Lake mile, miles along the centerline of Franklin D. Roosevelt Lake upstream from Grand Coulee Dam; Mile, miles from the mouth of a bay on Franklin D. Roosevelt Lake (bays commonly occur at the mouths of tributary streams); RB, right bank as one is facing downstream; LB, left bank as one is facing downstream; a description such as "(Bay 600 ft RB) Lake mile (LB) 69.2" means that 69.2 miles upstream from Grand Coulee Dam, there is a bay on the left bank of Franklin D. Roosevelt Lake and the site of the landslide is on the right bank of the bay 600 ft from the mouth.

[3] (1), Predominantly lacustrine silt and clay in its original position of deposition; (2), predominantly lacustrine silt and clay with bedding disturbed by landsliding, glacial processes; (3), alternating beds of clay, silt and sand in nearly their original position of deposition.

[4] High—springs, seeps and abundant water-loving vegetation above the midpoint of the exposed terrace slope; lakes or springs on the terrace surface or situated at higher altitudes in a position to feed water into the terrace deposits. Low—springs, seeps and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; no springs or lakes on the terrace surface or at higher altitudes to feed water into the terrace deposits.

[5] The altitude difference in feet from the top to the bottom of the slope in which the landslide occurred, commonly the vertical distance between two terraces.

[6] (42), Lines of drainage less well developed with no significant closed depressions on the terrace surface; (43), closed depressions on terrace surface; drainage channel so poorly developed that most of the rain and snowmelt infiltrates the terrace deposits.

[7] (81), All or most of the landslide material removed from the scarp; (82), part of the landslide material removed from the scarp; (83), very little movement of the landslide material.

[8] The length component (*LC*) is the maximum horizontal distance from side to side of the slide measured parallel to the slope it descends.

[9] The horizontal component (*HC*) is the horizontal distance from the foot of the landslide to the crown.

[10] The vertical component (*VC*) is the difference in altitude between the foot and the crown of a landslide.

[11] The ratio of the horizontal component to the vertical component.

TABLE 4.—*Classification and landslide data*

Landslide No.	Area [1,2]	Location [2]	Material category [3]	Ground water [4]	Terrace height (ft) [5]	Drainage [6]	Original slope of terrace scarp [7]	Submergence (percent) [8]	Culture [9]	Material removal [10]	LC [11]	HC [12]	VC [13]	HC:VC [14]	Time of slide, and remarks
	Type group 2—Recent slump-earthflow landslides														
2	Columbia River downstream from Grand Coulee Dam: Grand Coulee Dam-Belvedere (Peter Dan Creek 3,000 ft LB).	River mile (RB) 4.3	2	High	130	42	2.7:1	0	73	83	700	352	132	2.7	Broken pipeline and watering ditch in area of landslide crown were principal factors contributing to activation of slide.
	Franklin D. Roosevelt Lake:														
63	Hakw Creek (Hawk Creek Bay 1,500 ft RB).	Lake mile (LB) 37.2	1	Low	270	42	3.2:1	35	72	82	1,000	1,550	490	3.2	Initial movement in August 1941. Minor re-movements each year through 1953. (Submergence in August 1941 was 23 percent.)
130	Ninemile (Ninemile Bay).	(RB) 51.2	2	do	----	41	1.8:1	74	73	83	400	570	260	2.2	In early spring of 1952, completely severed Ferry County highway.
170	Hunters-Nez Perce Creek.	64.5	1	do	450	41	1.5:1	40	71	81	1,100	990	475	2.1	During filling of Franklin D. Roosevelt Lake prior to June 1944.
	Type group 5—Multiple alcove landslides														
	Franklin D. Roosevelt Lake:														
93	Spokane River arm	Mile (LB) 16.3	3	Low	400	43	----	----	71	81	3,000	1,900	400	4.8	Ancient.
103	do	19.9	3	High	400	43	----	----	71	81	1,500	1,600	400	4.0	Do.
133	Ninemile	Lake Mile (RB) 51.7	1	do	850	43	----	----	71	82	5,500	4,700	510	9.2	Do.
135	do	52.2	1	Low	850	43	----	----	71	82	5,000	4,200	850	4.9	Do.
145	do	53.8	1	High	820	43	----	----	71	82	2,000	2,600	600	4.3	Ancient—part of this slide occurred about 2 weeks after the San Francisco earthquake of 1906 and partly dammed the flow of the Columbia River for about an hour.
159	Hunters-Nez Perce Creek.	(LB) 61.52	1	do	500	42	----	----	71	81	1,300	1,650	270	6.1	Ancient—renewed activity in two alcoves following irrigation of terrace in 1926.
160	do	61.75	1	do	450	42	----	----	71	81	3,400	1,650	400	4.1	Ancient—renewed activity at many places following irrigation of terrace in 1926—some minor slide activity following filling of Franklin D. Roosevelt Lake.
261	Reed terrace	(RB) 98.65	1	do	----	43	2.3:1	55	73	81	1,400	2,100	340	6.2	Apr. 10, 1952 to May 1952.
276	Marcus-Evans	106.1	1	do	330	43	----	----	71	82	4,200	3,200	330	9.7	Ancient.
	Type group 6—Landslides off bedrock														
	Franklin D. Roosevelt Lake:														
59	Hawk Creek	Lake mile (RB) 35.35	5	Low	650	41	1.4:1	40	71	81	90	210	160	1.3	
84	Spokane River arm	Mile (RB) 10.2	2	do	----	41	5.7:1	33	71	83	160	230	42	5.5	
86	do	11.3	1	do	----	41	2.1:1	33	71	83	140	95	45	2.1	Submergence percentage is of slide not terrace.
110	Fort Spokane	Lake mile (RB) 42.1	2	High	235	42	3.5:1	42	71	83	250	570	163	3.5	Materials below high-water level flowed around projecting rock points.
171	Hunters-Nez Perce Creek (Nez Perce Creek Bay 1,000 ft RB).	64.8	1	Low	----	41	2.1:1	44	71	81	43	33	16	2.1	Submergence percentage is of slide not terrace.
240	Rice-Chalk Grade	86.6	1	do	110	42	1.7:1	36	71	81	100	120	70	1.7	

See footnotes at end of table.

Type group 7—Talus slump landslides

	Franklin D. Roosevelt Lake:														
62	Hawk Creek	Lake Mile (LB) 37.2	6	High	---------	41	1.7:1	36	71	81	400	530	280	1.9	Shortly before Sept. 22, 1941. Submergence percentage is of talus slope not terrace.
104	Spokane River arm	Mile (LB) 21.2	6	Low	---------	41	1.7:1	10	71	83	1,000	500	290	1.7	Submergence percentage is of talus slope not terrace.
167	Hunters-Nez Perce Creek.	Lake Mile (RB) 63.7	6	do	---------	41	2.1:1	13	71	83	165	184	150	1.2	Do.

Type group 8—Failures of artificial slopes involving natural materials

	Franklin D. Roosevelt Lake:														
168	Hunters-Nez Perce Creek.	Lake Mile (RB) 64.4	1	High	---------	41	---------	58	73	82	200	175	150	1.2	In spring of 1951 severed Ferry County highway. Submergence percentage is figured to highway elevation.
177	Cedonia (0.5 mile southwest of Cedonia Post Office, NW¼ sec. 32).	---------	1	do	---------	41	5.1:1	0	73	83	106	158	31	5.1	Slide material pushed onto State Highway 22.
272	Marcus-Evans	(LB) 104.0	6	do	---------	42	---------	0	73	81	500	250	280	.9	Feb. 23, 1951, 7:00-9:00 a.m. Great Northern Railway line severed and State Highway 22 blocked.
279	do	108.6	5	Low	340	42	1.6:1	23	73	81	750	630	270	2.3	Slide action originally started by Great Northern Railway construction and aggravated by impounding of Franklin D. Roosevelt Lake.
280	do	108.8	5	do	380	42	2.4:1	21	73	81	750	900	300	3.0	Do.
281	do	109.1	5	do	230	42	1.1:1	43	73	81	800	500	210	2.4	Do.
286	Northport-international boundary.	119.1	2	do	370	43	---------	---------	73	82	800	900	340	2.6	Great Northern Railway has experienced landslide trouble at this point for many years.

[1] See figure 10.

[2] River mile, miles along centerline of Columbia River downstream from Grand Coulee Dam; Lake mile, miles along the centerline of Franklin D. Roosevelt Lake upstream from Grand Coulee Dam; Mile, miles from the mouth of a bay on Franklin D. Roosevelt Lake (bays commonly occur at the mouths of tributary streams); RB, right bank as one is facing downstream; LB, left bank as one is facing downstream; a description such as "(Bay 600 ft RB) Lake mile (LB) 69.2" means that 69.2 miles upstream from Grand Coulee Dam, there is a bay on the left bank of Franklin D. Roosevelt Lake and the site of the landslide is on the right bank of the bay 600 ft from the mouth.

[3] (1), Predominantly lacustrine silt and clay in its original position of deposition; (2), predominantly lacustrine silt and clay with bedding disturbed by landsliding, glacial processes; (3), alternating beds of clay, silt, and sand in nearly their original position of deposition; (5), predominantly sand and gravel; (6), talus accumulations.

[4] High—springs, seeps, and abundant water-loving vegetation above the midpoint of the exposed terrace slope; lakes or springs on the terrace surface or situated at higher altitudes in a position to feed water into the terrace deposits. Low—springs, seeps, and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; no springs or lakes on the terrace surface or at higher altitudes to feed water into the terrace deposits.

[5] The altitude difference in feet from the top to the bottom of the slope in which the landslide occurred, commonly the vertical distance between two terraces.

[6] (41), Drainage lines on the terrace sufficiently well developed to channel rain and snowmelt rapidly off the area; (42), lines of drainage less well developed with no significant closed depressions on the terrace surface; (43), closed depressions on terrace surface; drainage channels so poorly developed that most of the rain and snowmelt infiltrates the terrace deposits.

[7] The ratio of the horizontal distance from the top to the bottom of the slope to the vertical distance from the top to the bottom.

[8] Percentage of the distance from the bottom to the top of a slope that is under water.

[9] (71), No cultural or engineering developments on or near slide; (72), minor developments on or near slide such as farm buildings, plowed fields, farm access roads, or logging trails; (73), major developments on or near slide, such as deep highway or railroad cuts or fills, irrigation systems, towns, or storage reservoirs.

[10] (81), All or most of the landslide material removed from the scarp; (82), part of the landslide material removed from the scarp; (83), very little movement of the landslide material.

[11] The length component (*LC*) is the maximum horizontal distance from side to side of the slide measured parallel to the slope it descends.

[12] The horizontal component (*HC*) is the horizontal distance from the foot of the landslide to the crown.

[13] The vertical component (*VC*) is the difference in altitude between the foot and the crown of a landslide.

[14] The ratio of the horizontal component to the vertical component.

TABLE 5.—*Landslide-classification data, Alameda Flat area*

Location (miles)	Basic data					Slope stability data				Types of landslides likely in this geologic setting	*HC:VC* data [6]				Remarks
						Present ground-water conditions		If ground-water conditions are changed from low to high			Present ground-water conditions		If ground-water conditions are changed from low to high		
	Material category [1]	Ground water [2]	Original slope of terrace scarp [3]	Submergence to 940-ft altitude (percent)	Terrace height [4] (feet)	Discriminant function value [5]	Stability	Discriminant function value [5]	Stability		Predicted *HC:VC* ratio	Predicted distance back from 946-ft [7] contour that slides may cut, using a 95 percent probability limit (feet)	Predicted *HC:VC* ratio	Predicted distance back from 946-ft [7] contour that slides may cut, using a 95 percent probability limit (feet)	
Right bank															
18.85	1	Low	2.7:1	35	185	0.0173	Slides likely	0.0240	Slides likely	Slump earthflow and slip-off slopes.	3.7	550	4.7	750	
19.05			4.6:1				Stable		Stable						Judged to be stable due to gentleness of slope.
19.14			4.2:1				do.		do.						Do.
19.51			5.5:1				do.		do.						Do.
19.77			5.0:1				do.		do.						Do.
20.03	1	Low	2.8:1	64	110	.0156	Slides likely	.0223	Slides likely	Slump earthflow and slump earthflow limited by bedrock.	4.2	400	5.3	525	Do.
20.36	1	do.	2.8:1	59	135	.0163	do.	.0230	do.	do.	4.5	400	5.2	725	Do.
20.68			5.4:1				Stable		Stable						Do.
21.03			5.0:1				do.		do.						Do.
21.21			4.3:1				do.		do.						Do.
21.42			5.5:1				do.		do.						Do.
21.85			8.0:1				do.		do.						Do.
22.21			8.1:1				do.		do.						Do.
22.36	2	Low	3.3:1	20	500	.0183	Slides likely	.0250	Slides likely	Slump earthflow and multiple alcove.	3.8	1300	4.8	1700	Formula-predicted distance slides may cut back reduced due to unusually low natural ground-water conditions.
22.46	2	do.	3.4:1	16	500	.0179	do.	.0246	do.	do.	3.9	1625	4.9	2100	Do.
22.59	2	do.	3.6:1	8	450	.0160	do.	.0227	do.	Slump earthflow	3.9	1475	4.9	1925	
23.05	2	do.	2.6:1	18	460	.0204	do.	.0271	do.	Slump earthflow and slump earthflow limited by bedrock.	3.1	1000	3.9	1200	Do.
23.10	2	Low	2.0:1	44	170	.0200	do.	.0267	do.	Slump earthflow	2.9	350	3.7	425	
23.31	2	do.	1.5:1	43	105	.0208	do.	.0275	do.	do.	2.5	200	3.2	300	
23.65	2	do.	2.4:1	29	85	.0148	do.	.0215	do.	do.	3.0	180	3.8	240	
24.13	2	do.	2.0:1	57	140	.0195	do.	.0263	do.	do.	3.0	280	3.8	400	
Left bank															
18.72	1	Low	2.0:1	43	150	0.0195	Slides likely	0.0262	Slides likely	Slump earthflow and slip-off slopes.	3.4	330	4.0	470	
19.01	1	do.	1.8:1	50	100	.0191	do.	.0258	do.	do.	3.0	260	3.7	360	
19.19	1	do.	1.6:1	50	150	.0218	do.	.0285	do.	do.	2.9	300	3.7	440	
19.45	1	do.	1.7:1	41	295	.0238	do.	.0305	do.	do.	2.9	750	3.6	980	
19.68	1	do.	1.7:1	23	285	.0229	do.	.0332	do.	do.	2.7	625	3.4	860	
19.85	1	do.	1.5:1	31	180	.0225	do.	.0292	do.	do.	2.5	400	3.1	570	
20.03	1	do.	2.0:1	41	160	.0197	do.	.0262	do.	do.	3.2	350	4.0	540	
20.20	1	do.	1.5:1	38	170	.0226	do.	.0293	do.	do.	2.7	350	3.4	460	
20.49	1	do.	1.8:1	38	170	.0209	do.	.0274	do.	do.	2.8	340	3.6	480	
20.76	1	do.	2.0:1	72	90	.0181	do.	.0248	do.	do.	3.2	160	4.0	260	
21.03	2	do.	2.7:1	81	80	.0150	do.	.0217	do.	do.	4.0	100	5.1	210	
21.25	2	do.	1.6:1	52	190	.0228	do.	.0295	do.	do.	2.7	340	3.4	650	Formula-predicted distance slides may cut back increased due to topographic shape.
21.39	2	do.	1.5:1	17	270	.0233	do.	.0300	do.	do.	2.3	520	2.9	700	
21.51	2	do.	3.2:1	15	260	.0158	do.	.0224	do.	do.	3.6	750	4.5	1100	
21.75	2	do.	1.8:1	20	220	.0200	do.	.0267	do.	do.	2.4	430	3.0	600	
21.92	2	do.	1.5:1	22	225	.0229	do.	.0296	do.	do.	2.3	400	2.9	450	
22.17	2	do.	2.4:1	34	160	.0177	do.	.0244	do.	do.	3.1	350	3.9	490	
22.50	2	do.	1.9:1	12	120	.0172	do.	.0239	do.	do.	2.6	270	3.3	400	

22.80	2	do	2.0:1	17	115	.0171	do	.0238	do	do	2.6	290	3.3	410	
23.08	2	do	2.0:1	21	170	.0190	do	.0257	do	do	2.7	440	3.4	600	
23.35	2	do	1.8:1	79	95	.0196	do	.0263	do	do	3.0	240	3.8	500	Formula-predicted distance slides may cut back decreased due to topographic shape
23.65	2	do	2.7:1	81	80	.0151	do	.0218	do	do	4.1	150	5.3	270	
23.91			5.4:1												Judged to be stable due to gentleness of slope.
24.10			10.0:1												Do.

[1] (1), Predominantly lacustrine silt and clay in its original position of deposition; (2), predominantly lacustrine silt and clay with bedding disturbed by landsliding, glacial processes.

[2] Low—springs, seeps and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; no springs or lakes on the terrace surface or at higher altitudes to feed water into the terrace deposits.

[3] The ratio of the horizontal distance from the top to the bottom of the slope to the vertical distance from the top to the bottom.

[4] Percentage of the distance from the bottom to the top of a slope that is under water.

[5] Value of the discriminant function of the terrace scarp.

[6] The ratio of the horizontal component to the vertical component.

[7] Maximum operating level of Chief Joseph Dam pool, altitude 946 ft.

TABLE 6.—*Miscellaneous landslides—data recorded for special studies, including landslides for which data were not sufficiently complete for type group analyses or summaries*

Landslide No.	Landslide type group [a]	Area [12]	Location [2]	Classification and landslide data: Material category [3]	Groundwater [4]	Terrace height (feet) [5]	Drainage [6]	Original slope of terrace scarp [7]	Submergence (percent) [8]	Culture [9]	Material removal [10]	*LC* [11]	*HC* [12]	*VC* [13]	*HC*: *VC* [14]	Time of slide, and remarks
16	1	Nespelem River (Nespelem River 6,200 ft (LB)).	River mile (RB) 14.2	1	High	280	43			71	82	1,000	1,000	270	3.7	About 1875.
48	3	Hellgate-Whitestone	Lake mile (LB) 22.6	5	Low	300	43			71	82	1,200	850	260	3.3	Ancient.
55	6		29.7	5	do		41			71	81	150	210	140	1.5	Recent, after filling of reservoir.
80	6	Spokane River arm	Mile (RB) 7.0	6	do		41	2.7:1		71	83	75	250	90	2.8	Do.
87	1		11.5	1	High		43	1.7:1	39	71	81	300	275	195	1.4	Do.
113	4	Fort Spokane	Lake mile (LB) 43.1	3	Low		43			72	81	250				Do.
118	1	Ninemile (Sixmile Bay)	(RB) 47.3	2	do	75	43		87	71	81	50	220	75	2.9	Do.
119	3	Ninemile	(LB) 47.8	3	do		43			71	83	600	800	230	3.5	Ancient.
121			(RB) 48.1	4	do	150	43	1.5:1	87	71	83	100	210	120	1.8	Recent, after filling of reservoir.
122	1		(LB) 48.2	4	High	125	41		48	72	81	140	330	110	3.0	Do.
132			(RB) 51.6	1	Low	350	41		66	71	81	300	330	160	2.1	Do.
144	6		53.7	5	do		41	1.6:1		71	81		330	210	1.6	Do.
147			54.2	1	do		43	2.1:1		71			1.620	560	2.9	Ancient.
148	4		54.3	5	do		42	1.2:1	31	71	81	300	250	210	1.2	Recent, after filling of reservoir.
166		Hunters-Nez Perce Creek	63.1	6												Do.
175	4		65.3	1	Low		41	.9:1		71	81	400				Do.
176	4		65.5	1	do		41			71	81	300				Do.
178	4	Cedonia	(LB) 66.3	5	do		42			71	81	1,500	100	110	.9	Do.
191		Cedonia (in bay)	68.2													Do.
199	3	Cedonia	(RB) 68.6	3	Low		42	2.3:1		71	81	240	510	250	2.0	Ancient, limited by bedrock.
205	4	Cedonia (Bay 200 ft RB)	(LB) 69.2	1	do		41			71	81		200	80	2.5	Recent, after filling of reservoir.
238		Gifford-Inchelium (Hall Creek Bay 3,700 ft RB).	(RB) 79.4	1	do		43	1.4:1	19	72	81	95	200	100	2.0	Do.
246	6	Rice-Chalk Grade	90.2	1	High		43	1.4:1	43	73	81	200	180	130	1.4	Do.
264	1	Kettle Falls	(LB) 102.7	5	Low		43		33	73	81		200	190	1.1	Do.
269	4	Kettle Falls (Marcus Bay) (900 ft south of U.S. Coast and Geodetic Survey control station).	103.7	2	do		43			73	83	100	120	45	2.7	Do.
285	3	Northport, international boundary.	118.6													Ancient.
295	9	Nespelem River-Omak Lake valley.	Hopkins Canyon	1	High		43			71	81	250	500	170	2.9	Feb. 2, 1953, about midnight; lasted about 7 minutes.
296	1	Grand Coulee Dam	Lake mile (LB) 2.05													June 3, 1952, 9:30–10:00 a.m.—muddied Columbia River discharge over Grand Coulee Dam for 10 hours.
297	1	Grand Coulee Dam-Belvedere (tail tower east bank).	River mile (RB) 0.27													Sept. 6, 1949.
298	1	Grand Coulee Dam-Belvedere (tailrace east bank).	.2													Aug. 25, 1943 (re-movement). Aug. 31, 1943 (re-movement). Sept. 8, 1950 (re-movement).
299	1	Grand Coulee Dam-Belvedere (Elmer City).	3.8	2	High											Sept. 8. 1950 (re-movement). Sept. 26, 1950 (re-movement). Aug. 11, 1952 (midnight to daylight) (re-movement). Sept. 1, 1952 (re-movement).
300	1	Grand Coulee Dam (Washington Flats)	(LB) 2.9		Low											Sept. 8, 1950.

See footnotes at end of table.

TABLE 6.—*Miscellaneous landslides—data recorded for special studies, including landslides for which data were not sufficiently complete for type group analyses or summaries*—Continued

Landslide No.	Landslide type group[a]	Area [1, 2]	Location [2]	Classification and landslide data: Material category [3]	Groundwater [4]	Terrace height (feet) [5]	Drainage [6]	Original slope of terrace scarp [7]	Submergence (percent) [8]	Culture [9]	Material removal [10]	LC [11]	HC [12]	VC [13]	HC:VC [14]	Time of slide, and remarks
301	1	Grand Coulee Dam (Main west slide).	River mile (LB) 0.3	2	--	--	--	--	--	--	--	--	--	--	--	Oct. 16, 1941, Oct. 8, 1942, Sept. 8, 1950 (re-movements).
302	1	Grand Coulee Dam (Lone Pine).	(RB) 1.6	2	--	--	--	--	--	--	--	--	--	--	--	Nov. 20, 1946 (initial.) Oct. 7, 1950, 3:00-6:00 a.m. (re-movement). Nov. 10, 1952 (re-movement).
303	1	Grand Coulee Dam (Downstream launching ramp—east bank).	.9	2	--	--	--	--	--	--	--	--	--	--	--	Feb. 5, 1951. Dec. 17, 1951 (re-movement).
304	1	Reed terrace (Main terrace)	--	1	High	--	--	--	--	--	--	--	--	--	--	Feb. 14, 1953, 8:15 p.m. Feb. 15, 1953. 12:00-7:00 p.m., (enlargement) Feb. 16, 1953, 2:08 p.m., (enlargement).
305	1		--	1	do	--	--	--	--	--	--	--	--	--	--	Feb. 16, 1953, 3:43 a.m. Feb. 17, 1953, 10:33 a.m., (major enlargement).
306	1	Spokane River arm	Mile (RB) 9.1	1	Low	--	--	--	--	--	--	--	--	--	--	Mar. 30, 1953.
307	1	Grand Coulee Dam-Belvedere (dry dock-tailrace area).	--	2	--	--	--	--	--	--	--	--	--	--	--	Mar. 10, 1942 (re-movement). Nov. 24, 1947 (re-movement).
308	1	Grand Coulee Dam-Belvedere (CBI machine shop, tailrace area).	--	--	--	--	--	--	--	--	--	--	--	--	--	Apr. 27, 1942 (re-movement).
309	10	Nespelem River	River mile (RB) 9.7	--	--	--	--	--	--	--	--	--	--	--	--	Dry earthflow in fall of 1952 following an extremely dry period.
310	10		9.8	--	--	--	--	--	--	--	--	--	--	--	--	Do.
311	10		9.9	--	--	--	--	--	--	--	--	--	--	--	--	Do.
312	1	Hunters-Nez Perce Creek (Ferry County highway slide).	Lake mile (RB) 64.3	2	Low	--	--	--	--	--	--	--	--	--	--	May 13, 1953 (re-movement).
313	4	Reed terrace (Farm terrace)	--	--	--	--	--	--	--	--	--	--	--	--	--	During filling of Franklin D. Roosevelt Lake prior to December 1941.
314	4		--	--	--	--	--	--	--	--	--	--	--	--	--	Do.
315	1	Reed terrace (in scarp of slide 262 of 1894 between Farm and Main terraces).	--	--	--	--	--	--	--	--	--	--	--	--	--	April 1944.
316	1		--	--	--	--	--	--	--	--	--	--	--	--	--	Do.
317	1		--	--	--	--	--	--	--	--	--	--	--	--	--	Do.
318	1		--	--	--	--	--	--	--	--	--	--	--	--	--	Do.
319	1		--	--	--	--	--	--	--	--	--	--	--	--	--	Do.
320	9	Grand Coulee Dam-Belvedere (Seatons mudflow).	River mile (RB) 5.1	--	--	--	--	--	--	--	--	--	--	--	--	Mar. 17, 1949, 6:30 p.m.
321	--	Reed terrace (center of Farm terrace).	--	--	--	--	--	--	--	--	--	--	--	--	--	Aug. 19, 1953, 11:00 a.m.

[a] (1) recent slump earthflow, (3) ancient slump earthflow, (4) slip-off slope, (6) landslide off bedrock, (9) mudflow, (10) dry earthflow, (..) unclassified.

[1] See figure 10.

[2] River mile, miles along centerline of Columbia River downstream from Grand Coulee Dam; Lake mile, miles along the centerline of Franklin D. Roosevelt Lake upstream from Grand Coulee Dam; Mile, miles from the mouth of a bay on Franklin D. Roosevelt Lake (bays commonly occur at the mouths of tributary streams); RB, right bank as one is facing downstream; LB, left bank as one is facing downstream; a description such as "(Bay 600 ft RB) Lake mile (LB) 69.2" means that 69.2 miles upstream from Grand Coulee Dam, there is a bay on the left bank of Franklin D. Roosevelt Lake and the site of the landslide is on the right bank of the bay 600 ft from the mouth.

[3] (1) Predominantly lacustrine silt and clay in its original position of deposition; (2), predominantly lacustrine silt and clay with bedding disturbed by landsliding, glacial processes; (3), alternating beds of clay, silt, and sand in nearly their original position of deposition; (4), alternating beds of clay, silt and sand disturbed by landsliding, glacial processes, etc., (5), predominantly sand and gravel; (6), talus accumulations.

[4] High—springs, seeps and abundant water-loving vegetation above the midpoint of the exposed terrace slope; lakes or springs on the terrace surface or situated at higher altitudes in a position to feed water into the terrace deposits. Low—springs, seeps, and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; no springs or lakes on the terrace surface or at higher altitudes to feed water into the terrace deposits.

[5] The altitude difference in feet from the top to the bottom of the slope in which the landslide occurred, commonly the vertical distance between two terraces.

[6] (41), drainage lines on the terrace sufficiently well developed to channel rain and snowmelt rapidly off the area; (42), lines of drainage less well developed with no significant closed depressions on the terrace surface; (43), closed depressions on terrace surface; drainage channels so poorly developed that most of the rain and snowmelt infiltrates the terrace deposits.

[7] The ratio of the horizontal distance from the top to the bottom of the slope to the vertical distance from the top to the bottom.

[8] Percentage of the distance from the bottom to the top of a slope that is under water.

[9] (71), No cultural or engineering developments on or near slide; (72), minor developments on or near slide such as farm buildings, plowed fields, farm access roads, or logging trails; (73), major developments on or near slide, such as deep highway or railroad cuts or fills, irrigation systems, towns, or storage reservoirs.

[10] (81), All or most of the landslide material removed from the scarp; (82), part of the landslide material removed from the scarp; (83), very little movement of the landslide material.

[11] The length component (LC) is the maximum horizontal distance from side to side of the slide measured parallel to the slope it descends.

[12] The horizontal component (HC) is the horizontal distance from the foot of the landslide to the crown.

[13] The vertical component (VC) is the difference in altitude between the foot and the crown of a landslide.

[14] The ratio of the horizontal component to the vertical component.

TABLE 7.—*Uniformity experiment—recent slump-earthflow landslides*

[Landslides classified by Peterson and Erskine (P&E) and Jones (J)]

Landslide group and landslide No.	Location [1]			Classified by—	*HC*:*VC* [2] ratio	Material category [3]	Ground water [4]	Original slope of terrace scarp [5]	Submergence [6] (percent)
Sanpoil River bay area									
Group 1:									
31	Mile	(LB)	2.05	P&E	3.4	3	Low	3.6	68
				J	2.4	3	do	2.2	66
30			1.8	P&E	2.7	3	do	2.1	66
				J	2.5	3	do	2.4	74
35		(RB)	3.1	P&E	2.5	1	do	3.0	65
				J	3.5	1	do	2.6	61
27		(LB)	.8	P&E	2.8	5	do	2.4	74
				J	2.0	5	do	2.6	69
33			2.4	P&E	1.6	1	do	1.3	40
				J	3.2	3	do	3.0	68
29			1.6	P&E	1.6	1	do	1.3	40
				J	2.1	3	do	2.1	68
Group 2:									
42			6.05	P&E	4.2	1	do	2.6	21
				J	5.3	1	High	3.0	45
36			3.2	P&E	3.2	3	Low	3.0	65
				J	3.8	1	do	3.7	71
40			3.8	P&E	2.7	1	do	2.2	54
				J	3.4	1	do	2.8	62
43			6.7	P&E	2.8	2	do	3.1	17
				J	3.6	1	do	2.9	33
41		(RB)	4.3	P&E	2.9	3	do	2.5	76
				J	3.2	1	do	2.3	82
44			6.8	P&E	3.7	1	High	3.7	13
				J	4.0	2	do	3.9	22
Ninemile area									
Group 3:									
143	Lake mile	(LB)	53.5	P&E	2.4	5	Low	1.7	71
				J	3.0	2	do	2.7	76
125			49.0	P&E	1.9	3	do	1.7	73
				J	1.9	4	do	1.6	73
131		(RB)	51.4	P&E	2.2	5	do	1.6	15
				J	2.3	1	do	1.8	16
150	Wilmont Bay	(RB)	1,750 ft	P&E	2.5	3	do	1.7	45
				J	2.0	1	do	1.8	43
152			3,700	P&E	2.0	3	do	1.2	24
				J	2.0	1	do	1.8	25
141	Lake mile	(LB)	53.2	P&E	2.7	5	do	1.4	64
				J	1.7	2	do	3.3	82
Cedonia area									
Group 4:									
193	Lake mile	(LB)	68.2	P&E	1.4	3	Low	1.6	42
	(Bay 360 ft LB)			J	1.9	2	do	1.5	53
195		(LB)	68.3	P&E	2.0	5	do	2.0	71
				J	3.3	4	do	2.7	73
183			67.75	P&E	1.7	5	do	1.7	35
				J	1.8	3	do	1.8	30
187			68.0	P&E	1.6	5	do	1.6	33
				J	1.8	4	do	1.4	33
190			68.2	P&E	1.6	5	do	1.5	33
	(Bay 800 ft RB)			J	1.2	2	do	1.8	27
186	Lake mile	(LB)	67.9	P&E	1.9	5	do	1.6	19
				J	2.0	4	do	1.3	33

See footnotes at end of table.

TABLE 7.—*Uniformity experiment—recent slump-earthflow landslides*—Continued

[Landslides classified by Peterson and Erskine (P&E) and Jones (J)]

Landslide group and landslide No.	Location [1]			Classified by—	*HC*: *VC* [2] ratio	Material category [3]	Ground water [4]	Original slope of terrace scarp [5]	Submergence [6] (percent)
Cedonia area—Continued									
Group 5:									
217	Lake mile	(LB)	69.9	P&E	1.7	5	Low	1.3	53
				J	2.0	4	do	1.6	43
212			69.3	P&E	1.5	5	do	1.5	50
				J	1.6	4	do	0.7	55
202			69.0	P&E	1.7	5	do	1.9	56
				J	1.7	5	do	1.7	54
213			69.4	P&E	1.5	5	do	1.5	50
				J	2.9	4	do	1.3	59
215			69.6	P&E	1.7	4	do	1.4	53
				J	1.7	4	do	1.3	59
222			70.1	P&E	3.0	4	do	1.6	67
				J	1.4	2	do	1.4	60
Group 6:									
227			70.45	P&E	2.2	5	do	1.4	50
				J	1.9	4	do	1.5	47
231			70.6	P&E	1.9	5	do	1.6	52
				J	2.6	4	do	1.3	66
232			70.65	P&E	2.0	5	do	1.6	52
				J	2.4	4	do	1.3	63
229			70.5	P&E	1.6	5	do	1.5	56
				J	1.9	4	do	1.8	56
230			70.55	P&E	1.8	5	do	1.5	57
				J	2.3	4	do	1.3	66
225			70.25	P&E	2.0	5	do	1.4	49
				J	1.8	4	do	1.3	49
Roper Creek—Reed Terrace area									
Group 7:									
252	Lake mile	(RB)	95.2	P&E	1.8	4	Low	1.7	27
	(Bay 1,300 ft RB)			J	1.4	2	do	1.7	25
250	Lake mile	(RB)	95.2	P&E	2.6	4	do	1.9	10
	(Bay 800 ft RB)			J	2.4	2	do	2.2	37
251	Lake mile	(RB)	95.2	P&E	3.5	4	High	3.5	22
	(Bay 900 ft LB)			J	3.8	2	do	3.7	28
259	Lake mile	(RB)	98.5	P&E	3.1	1	do	3.0	41
				J	2.9	1	do	2.3	38
271	Mile	(RB)	2.0	P&E	2.3	4	Low	1.2	11
				J	4.3	2	do	3.5	18
257	Lake mile	(RB)	98.37	P&E	3.8	1	High	2.3	45
				J	4.5	1	do	2.5	50

[1] Lake mile, miles along the centerline of Franklin D. Roosevelt Lake upstream from Grand Coulee Dam. Mile, miles from the mouth of a bay on Franklin D. Roosevelt Lake (bays commonly occur at the mouths of tributary streams); RB, right bank as one is facing downstream; LB, left bank as one is facing downstream; a description such as "(Bay 600 ft RB) Lake mile (LB) 69.2" means that 69.2 miles upstream from Grand Coulee Dam there is a bay on the left bank of Franklin D. Roosevelt Lake and the site of the landslide is on the right bank of the bay 600 ft from the mouth.

[2] The horizontal component *HC*, is the horizontal distance from the foot of the landslide to the crown; the vertical component *VC*, is the difference in altitude between the foot and the crown of a landslide; *HC*: *VC*, the ratio of the horizontal component to the vertical component.

[3] (1), Predominantly lacustrine silt and clay in its original position of deposition; (2), predominantly lacustrine silt and clay with bedding disturbed by landsliding, glacial processes; (3), alternating beds of clay, silt and sand in nearly their original position of deposition; (4), alternating beds of clay, silt and sand disturbed by landsliding and glacial processes; (5), predominantly sand and gravel.

[4] High—springs, seeps and abundant water-loving vegetation above the midpoint of the exposed terrace slope; lakes or springs on the terrace surface or situated at higher altitudes in a position to feed water into the terrace deposits. Low—springs, seeps and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; no springs or lakes on the terrace surface or at higher altitudes to feed water into the terrace deposits.

[5] The ratio of the horizontal distance from the top to the bottom of the slope to the vertical distance from the top to the bottom.

[6] Percentage of the distance from the bottom to the top of a slope that is under water.

TABLE 8.—*Slope-stability investigation, Franklin D. Roosevelt Lake*

Slope No.	Location [1]			Classification and measurement data: Material category [2]	Ground water [3]	Terrace height [4] (feet)	Original slope of terrace scarp [5]	Submergence [6] (percent)	Discriminant function values [7]
Grand Coulee Dam									
1	Lake mile	(RB)	0. 5	5	Low	130	8. 8:1	85	0. 0060
2		(LB)	2. 5	2	do	120	11. 6:1	50	. 0023
Swawilla Basin									
3	Lake mile	(LB)	4. 5	1	Low	155	3. 4:1	6	0. 0118
4			5. 5	1	do	150	2. 3:1	7	. 0155
5			6. 3	2	do	110	15. 3:1	73	—. 0001
6			7. 5	2	do	110	2. 6:1	55	. 0161
7		(RB)	7. 5	1	do	330	4. 7:1	3	. 0108
8			8. 0	1	do	80	1. 8:1	0	. 0125
9			8. 2	1	do	65	2. 8:1	8	. 0105
10			8. 6	1	do	85	6. 0:1	13	. 0051
11		(LB)	9. 6	1	do	290	5. 2:1	66	. 0139
12		(RB)	10. 1	1	do	155	5. 7:1	73	. 0106
13		(LB)	11. 3	2	do	45	12. 4:1	67	—. 0019
14		(RB)	11. 9	5	do	285	2. 7:1	70	. 0200
15			12. 8	1	do	235	2. 8:1	83	. 0191
16			14. 1	5	do	30	5. 1:1	50	. 0043
17		(LB)	14. 7	5	do	370	1. 5:1	30	. 0254
18			15. 0	3	do	200	1. 8:1	75	. 0225
19			15. 8	1	do	25	5. 7:1	20	. 0012
Keller Ferry									
20	Lake mile	(LB)	16. 8	2	Low	25	6. 8:1	52	0. 0010
21			17. 5	2	do	40	3. 5:1	20	. 0077
22			17. 8	2	do	230	3. 4:1	83	. 0172
23		(RB)	18. 3	5	do	350	2. 6:1	14	. 0189
24			19. 0	3	do	220	1. 8:1	50	. 0278
25			20. 0	3	do	130	2. 5:1	31	. 0163
26			20. 3	3	do	270	3. 5:1	67	. 0173
27		(LB)	20. 8	4	High	150	8. 3:1	43	. 0129
Sanpoil River bay									
28	Mile	(RB)	0. 9	3	Low	80	2. 0:1	0	0. 0163
29			1. 0	3	do	92	2. 0:1	13	. 0206
30			1. 1	3	do	130	1. 5:1	31	. 0211
31			4. 5	1	do	170	2. 7:1	82	. 0181
32		(LB)	5. 2	2	do	240	5. 0:1	50	. 0130
33		(RB)	7. 5	1	do	40	4. 5:1	20	. 0054
Hellgate—Whitestone									
34	Lake mile	(LB)	21. 0	4	High	300	9. 3:1	57	0. 0151
35			21. 3	4	Low	260	2. 4:1	13	. 0183
36			21. 6	4	do	320	2. 7:1	16	. 0184
37			22. 3	5	do	190	3. 0:1	95	. 0178
38		(RB)	23. 9	5	do	90	4. 3:1	50	. 0104
39			24. 3	5	do	100	2. 1:1	10	. 0153
40			24. 4	5	do	100	1. 4:1	10	. 0191
41		(LB)	24. 8	5	do	300	3. 4:1	77	. 0182
42			25. 1	5	do	340	6. 5:1	65	. 0124
43		(RB)	27. 5	5	do	100	3. 1:1	5	. 0106
44			28. 0	5	do	90	2. 6:1	11	. 0130
45			28. 7	5	do	125	3. 2:1	28	. 0137
46			29. 0	5	do	90	3. 3:1	22	. 0117
47			31. 7	5	do	220	3. 8:1	27	. 0144
48			32. 7	5	do	110	6. 1:1	9	. 0055

See footnotes at end of table.

TABLE 8.—*Slope-stability investigation, Franklin D. Roosevelt Lake*—Continued

Slope No.	Location [1]	Classification and measurement data					Discriminant function values [7]
		Material category [2]	Ground water [3]	Terrace height [4] (feet)	Original slope of terrace scarp [5]	Submergence [6] (percent)	
Hawk Creek							
49	Lake mile (LB) 34.0	5	Low	270	1.4:1	41	0.0252
50	34.6	5	do	275	1.4:1	24	.0245
51	35.1	5	do	260	2.5:1	35	.0194
52	35.4	5	do	280	1.8:1	40	.0230
53	35.5	5	do	280	2.5:1	65	.0206
54	(RB) 37.0	3	do	190	1.7:1	21	.0210
55	38.0	5	do	230	5.5:1	26	.0110
56	(LB) 38.8	3	do	280	2.8:1	75	.0197
57	38.9	3	do	200	2.4:1	60	.0195
58	(RB) 38.9	3	do	210	3.8:1	5	.0117
Fort Spokane							
59	Lake mile (RB) 39.6	3	Low	60	2.8:1	17	0.0112
60	40.5	3	High	40	12.0:1	25	.0032
61	(LB) 40.8	3	Low	170	2.2:1	53	.0194
62	(RB) 41.1	1	High	170	2.5:1	0	.0192
63	(LB) 41.3	3	Low	170	2.1:1	53	.0199
64	(RB) 41.5	1	High	270	2.9:1	30	.0246
65	(LB) 42.3	1	Low	220	2.3:1	68	.0204
66	(RB) 42.9	5	do	100	5.7:1	80	.0089
67	43.2	5	do	210	8.2:1	91	.0087
68	(LB) 43.4	1	do	270	3.6:1	78	.0173
69	43.7	1	do	60	3.3:1	0	.0056
70	(RB) 43.8	5	do	250	2.0:1	68	.0223
71	(LB) 44.0	1	do	70	1.8:1	14	.0157
72	44.5	1	do	210	3.5:1	5	.0125
73	44.8	2	High	120	10.7:1	50	.0098
74	(RB) 44.8	2	Low	250	4.6:1	60	.0143
75	45.3	2	do	160	3.7:1	82	.0146
76	45.9	2	do	50	2.9:1	30	.0110
77	46.9	2	do	120	6.7:1	92	.0083
Spokane River arm							
78	Mile (RB) 0.5	1	Low	105	2.7:1	38	0.0151
79	(LB) 1.1	3	do	240	2.9:1	42	.0179
80	(RB) 5.8	5	do	80	4.3:1	25	.0089
81	6.7	5	High	40	6.4:1	0	.0044
82	(LB) 7.1	4	Low	220	3.1:1	23	.0161
83	(RB) 7.6	5	do	365	1.7:1	4	.0212
84	(LB) 7.7	4	do	210	2.7:1	5	.0149
85	(RB) 7.8	4	High	70	5.4:1	29	.0132
86	(LB) 9.7	3	Low	160	1.8:1	43	.0208
87	(RB) 10.2	3	do	460	3.4:1	30	.0186
88	(LB) 10.9	5	do	80	2.6:1	75	.0153
89	11.8	1	do	160	3.8:1	75	.0145
90	(RB) 11.9	1	do	140	2.3:1	14	.0163
91	(LB) 12.8	5	do	105	2.4:1	28	.0157
92	(RB) 13.5	5	do	130	2.1:1	85	.0195
93	(LB) 13.9	5	do	210	1.8:1	62	.0224
94	16.7	3	do	320	1.8:1	12	.0217
95	(RB) 17.8	5	do	170	10.5:1	41	.0044

See footnotes at end of table.

TABLE 8.—*Slope-stability investigation, Franklin D. Roosevelt Lake*—Continued

Slope No.	Location [1]			Classification and measurement data: Material category [2]	Ground water [3]	Terrace height [4] (feet)	Original slope of terrace scarp [5]	Submergence [6] (percent)	Discriminant function values [7]
				Ninemile area					
96	Lake mile	(LB)	48. 0	2	Low	165	4. 4:1	64	0. 0131
97		(RB)	48. 4	2	High	150	5. 7:1	87	. 0174
98		(LB)	51. 2	2	do	130	7. 7:1	23	. 0121
99		(RB)	51. 5	1	do	400	2. 5:1	58	. 0286
100		(LB)	51. 6	2	Low	75	1. 7:1	7	. 0156
101		(RB)	51. 7	2	High	125	3. 0:1	44	. 0217
102		(LB)	52. 3	2	Low	150	4. 6:1	53	. 0120
103		(RB)	52. 6	2	do	450	5. 1:1	49	. 0154
104			53. 1	2	do	155	3. 1:1	97	. 0167
105			53. 5	2	do	270	2. 0:1	85	. 0229
106		(LB)	54. 0	2	do	70	2. 8:1	29	. 0127
107			54. 45	2	do	130	2. 2:1	54	. 0184
108		(RB)	54. 84	2	do	130	2. 9:1	61	. 0159
				Wilmont-Gerome					
109	Lake mile	(RB)	55. 5	2	Low	100	4. 4:1	60	0. 0109
110			56. 0	2	do	90	4. 2:1	56	. 0108
111			56. 4	2	do	95	3. 4:1	95	. 0138
112			56. 5	2	do	140	6. 0:1	86	. 0099
113			57. 0	2	do	130	3. 8:1	46	. 0130
114		(LB)	57. 5	4	do	90	1. 6:1	33	. 0191
115			57. 9	4	do	210	3. 0:1	95	. 0182
116			58. 3	4	do	140	3. 5:1	21	. 0129
				Hunters-Nez Perce					
117	Lake mile	(LB)	59. 0	4	Low	470	3. 0:1	38	0. 0202
118		(RB)	59. 9	5	do	60	10. 7:1	33	. 0004
119			62. 8	2	do	80	3. 6:1	62	. 0119
120			63. 6	1	do	230	2. 9:1	52	. 0181
121		(LB)	64. 1	1	do	190	2. 4:1	79	. 0197
122			64. 7	1	do	50	2. 8:1	10	. 0097
123		(RB)	64. 9	1	do	155	3. 2:1	29	. 0147
				Cedonia					
124	Lake mile	(RB)	66. 2	3	Low	80	3. 6:1	50	0. 0116
125		(LB)	66. 9	1	do	500	2. 5:1	40	. 0222
126		(RB)	67. 0	3	do	100	2. 1:1	50	. 0176
127			67. 8	1	do	130	4. 0:1	77	. 0133
128			68. 3	1	do	170	6. 0:1	35	. 0094
129			68. 45	1	do	120	2. 7:1	50	. 0160
130			68. 6	1	do	120	4. 7:1	66	. 0112
131		(LB)	71. 5	4	do	110	2. 8:1	18	. 0138
132		(RB)	72. 4	2	do	250	8. 5:1	24	. 0072
133		(LB)	72. 5	4	do	95	9. 5:1	84	. 0040
134		(RB)	72. 6	2	do	135	8. 4:1	41	. 0055
135		(LB)	72. 7	4	do	75	10. 4:1	80	. 0021

See footnotes at end of table.

TABLE 8.—*Slope-stability investigation, Franklin D. Roosevelt Lake*—Continued

Slope No.	Location [1]	Classification and measurement data: Material category [2]	Ground water [3]	Terrace height [4] (feet)	Original slope of terrace scarp [5]	Submergence [6] (percent)	Discriminant function values [7]
				Gifford—Inchelium			
136	Lake mile (RB) 73. 0	2	Low	170	6. 7:1	41	0. 0086
137	73. 3	2	do	190	7. 8:1	53	. 0080
138	73. 6	2	do	200	4. 5:1	35	. 0128
139	73. 8	2	do	90	5. 1:1	55	. 0090
140	74. 2	2	do	370	3. 4:1	62	. 0187
141	74. 4	2	do	150	2. 3:1	13	. 0164
142	75. 7	2	do	90	3. 0:1	78	. 0145
143	76. 4	2	do	200	2. 8:1	95	. 0187
144	(LB) 76. 8	2	do	110	14. 5:1	54	—. 0003
145	(RB) 77. 0	2	do	60	12. 0:1	67	—. 0004
146	77. 5	2	do	50	4. 6:1	60	. 0077
147	(LB) 77. 5	2	do	210	11. 6:1	43	. 0044
148	77. 9	2	do	85	6. 0:1	35	. 0066
149	(RB) 78. 3	2	do	210	3. 3:1	0	. 0107
150	78. 8	1	do	270	1. 9:1	19	. 0212
151	79. 2	1	do	85	4. 2:1	59	. 0107
152	81. 2	1	do	95	2. 1:1	95	. 0183
153	81. 4	1	do	95	3. 2:1	95	. 0144
154	82. 3	1	do	100	3. 2:1	60	. 0139
155	82. 7	1	do	120	1. 9:1	92	. 0202
				Rice—Chalk Grade			
156	Lake mile (RB) 86. 0	1	Low	100	1. 7:1	50	0. 0196
157	(LB) 89. 6	5	do	185	2. 5:1	19	. 0171
158	(RB) 94. 6	2	do	70	1. 9:1	86	. 0179
				Reed terrace			
159	Lake mile (RB) 99. 4	1	Low	70	2. 8:1	86	0. 0142
				Marcus—Evans			
160	Lake mile (RB) 107. 0	1	High	·130	2. 3:1	38	0. 0242

[1] River mile, miles along centerline of Columbia River downstream from Grand Coulee Dam; Lake mile, miles along the centerline of Franklin D. Roosevelt Lake upstream from Grand Coulee Dam; Mile, miles from the mouth of a bay on Franklin D. Roosevelt Lake (bays commonly occur at the mouths of tributary streams); RB, right bank as one is facing downstream; LB, left bank as one is facing downstream; a description such as "(Bay 600 ft RB) Lake mile (LB) 69.2" means that 69.2 miles upstream from Grand Coulee Dam, there is a bay on the left bank of Franklin D. Roosevelt Lake and the site of the landslide is on the right bank of the bay 600 ft from the mouth.

[2] (1), Predominantly lacustrine silt and clay in its original position of deposition; (2), predominantly lacustrine silt and clay with bedding disturbed by landsliding, glacial processes; (3), alternating beds of clay, silt and sand in nearly their original position of deposition; (4), alternating beds of clay, silt and sand disturbed by landsliding, glacial processes, etc.; (5), predominantly sand and gravel; (6), talus accumulations.

[3] High—springs, seeps and abundant water-loving vegetation above the midpoint of the exposed terrace slope; lakes or springs on the terrace surface or situated at higher altitudes ina position to feed water into the terrace deposits. Low—springs, seeps and abundant water-loving vegetation absent or limited to zones below the midpoint of the exposed terrace slope; no springs or lakes on the terrace surface or at higher altitudes to feed water into the terrace deposits.

[4] The altitude difference in feet from the top to the bottom of the slope in which the landslide occurred, commonly the vertical distance between two terraces.

[5] The ratio of the horizontal distance from the top to the bottom of the slope to the vertical distance from the top to the bottom.

[6] Percentage of the distance from the bottom to the top of a slope that is under water.

[7] Value of the discriminant function for the terrace scarp.

TABLE 9.—*Landslide date and time data*

Landslide No.	Area	Location or name [1]	Date and hour: Major landslides [2]	Time of slides and remarks: Minor landslides and re-movements [3]
		Columbia River downstream from Grand Coulee Dam		
5	Grand Coulee Dam-Belvedere.	Koontzville slide		Dec. 23, 1951 (initial).
		do		Nov. 10 or 11(?), 1952.
		do		Nov. 27, 1952.
		do		Weekend, Jan. 10, 1953.
7		Seatons slide	Nov. 23, 1948	
295	Nespelem River-Omak Lake valley.	Hopkins Canyon mudflow	Feb. 2, 1953, 12 p.m	

See footnotes at end of table.

TABLE 9.—*Landslide date and time data*—Continued

Land-slide No.	Area	Location or name [1]	Date and hour — Major landslides [2]	Time of slides and remarks — Minor landslides and re-movements [3]
		Columbia River downstream from Grand Coulee Dam—Continued		
297	Grand Coulee Dam-Belvedere.	Tail Tower slide	Sept. 6, 1949	
298		East tailrace slide		Aug. 25, 1943.
		do		Aug. 31, 1943.
		do		Sept. 8, 1950.
299		Elmer City slide		Do.
		do		Sept. 26, 1950.
		do		Aug. 11, 1952 (midnight to daylight).
		do		Sept. 1, 1952.
300		Washington Flats slide	Sept. 8, 1950	
301		Main west slide		Oct. 16, 1941.
		do		Oct. 8, 1942.
		do		Sept. 8, 1950.
302		Lone Pine slide	Nov. 20, 1946 (initial)	
		do		Oct. 7, 1950, 3, 6 a.m.
		do		Nov. 10, 1952.
303		Downstream launching ramp	Feb. 5, 1951	
		do		Dec. 17, 1951.
307		Drydock		Mar. 10, 1942 (re-movement).
		do		Nov. 24, 1947 (re-movement).
308		CBI machine shop		Apr. 27, 1942 (re-movement).
320		Seatons mudflow	Mar. 17, 1949, 6:30 p.m.	
		Franklin D. Roosevelt Lake		
34	Sanpoil River bay	Sorimpt slide	Apr. 13, 1953 (major enlargement).	
36		Mile (LB) 3.2		Apr. 13, 1953 (re-movement).
37		3.7		Do.
42		Hughes slide	Nov. 8, 1942, 5, 7 a.m.	
64	Hawk Creek	Lake mile (LB) 37.2 (Hawk Creek bay 4,200 ft RB).	July 26, 1949, 5:30 p.m.	
65		Lake mile (LB) 37.2 (Hawk Creek bay 5,000 ft RB).	July 27, 1949, 10:00 a.m.	
131	Ninemile	Lake mile (RB) 51.4	July 3, 1949, 2, 4 p.m.	
169	Hunters-Nez Perce Creek	64.45		May 11, 1953 (enlargement).
257	Reed terrace	98.37	Mar. 12, 1952, 11:30 a.m.	
		98.37	Sept. 12, 1952, 2:00 p.m.	
		98.37		Oct. 13, 1952, 5, 6 a.m.
258		98.4	Apr. 8, 1944	
259		98.5	Apr. 1, 1944	
261		Multiple-alcove slide	Apr. 10, 1952, 3:00 a.m. (particularly active first 4 days).	
272	Marcus-Evans	Great Northern Railway slide.	Feb. 23, 1951, 7, 9 a.m.	
296	Coulee Dam	Lake mile (LB) 2.05	June 3, 1952, 9:30, 10:00 a.m.	
304	Reed terrace	Main terrace	Feb. 14, 1953, 8:15 p.m.	
305		do	Feb. 16, 1953, 3:43 a.m.	
306	Spokane River arm	Mile (RB) 9.1	Mar. 30, 1953	
312	Hunters-Nez Perce Creek	Lake mile (RB) 64.3		May 13, 1953 (re-movement).
321	Reed terrace	Center of Farm terrace		Aug. 19, 1953, 11:00 a.m.

[1] Lake mile, miles along the centerline of Franklin D. Roosevelt Lake upstream from Grand Coulee Dam; Mile, miles from the mouth of a bay on Franklin D. Roosevelt Lake (bays commonly occur at the mouths of tributary streams); RB, right bank as one is facing downstream; LB, left bank as one is facing downstream; a description such as "(Bay 600 ft RB) Lake mile (LB) 69.2" means that 69.2 miles upstream from Grand Coulee Dam, there is a bay on the left bank of Franklin D. Roosevelt Lake and the site of the landslide is on the right bank of the bay 600 ft from the mouth.

[2] New landslides in areas which have been stable in the known past or major enlargements of recent landslides; in general, both of above involve more than 5,000 cu yds of material.

[3] Slight movements and displacements of a few feet in large masses of material; or small enlargements involving less than 5,000 cu yds of material.

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