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LANDSLIDE PROBLEMS OF SOUTHWESTERN COLORADO

By

Helen D. Varnes

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INTRODUCTION

Landslides of many kinds and of varying magnitude are widespread throughout southwestern Colorado. This discussion is limited to three typical sites, which illustrate some of the more common landslide phenomena and the problems that they pose.

The Cedar Creek, the Ames, and the Knife Edge landslide areas (fig. 1) were selected partly because the slides are recent and erosion has not yet seriously modified their original forms. Equally important reasons for studying these particular slides are that all three have caused serious problems to the maintenance of highways or railroads and that they were caused, in part, by the activities of man. During the 1946 field season, the writer, assisted by Leonard Rolnick, made detailed studies of these slides. In addition to routine geologic observations and measurements, a network of points was established by triangulation within the Cedar Creek landslide and in the stable ground around it; these will serve as a basis for measurement and comparison of future movements in that area.

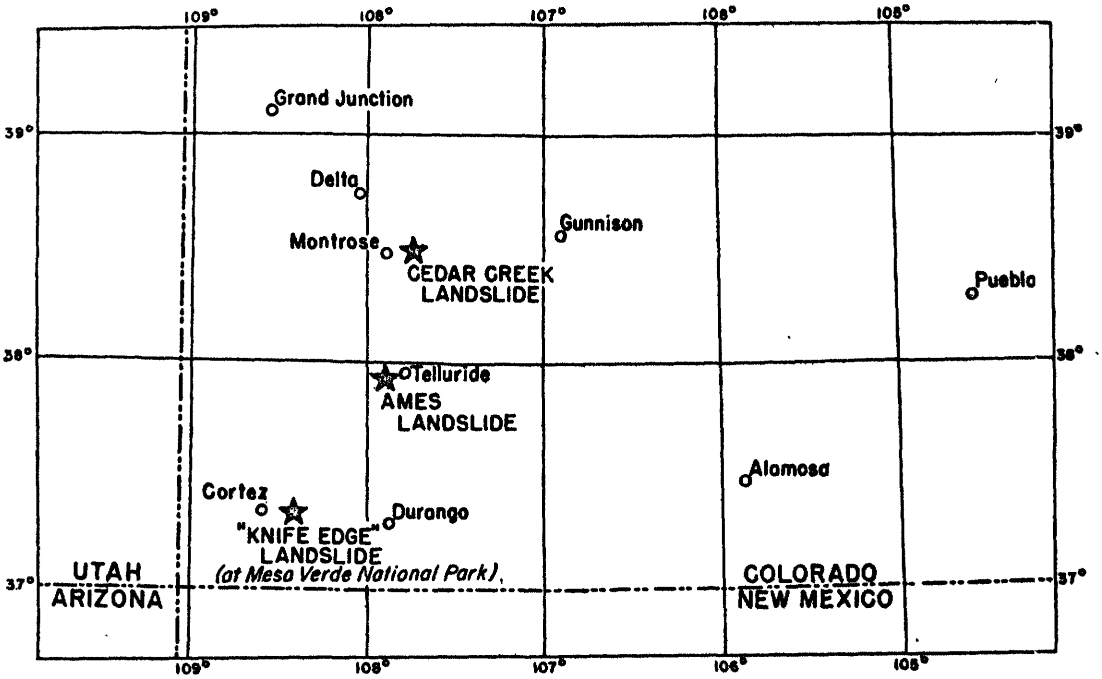

Figure 1.—Index map of southwestern Colorado, showing general location of landslides.

ACKNOWLEDGMENTS

The writer wishes to thank Mr. A.E.Perlman and Mr. K. L. Moriarity of the Denver & Rio Grande Western Railroad for permission to study the Cedar Creek area and for data on recent movement of that slide used in this report. Mr. Fish, section foreman for the Denver & Rio Grande Western at Montrose, supplied most of the information on the history of the Cedar Creek landslide. Mr. McDaniells, Surveyor for Montrose County, furnished data on the irrigation system that supplies water to the mesa south of the slide.

The reconnaissance study of the Mesa Verde area was made with the permission of the Director of the National Park Service. Thanks are also due Mr. Peter Nelson, Superintendent of the Public Roads Division at Mesa Verde National Park, and to Mr. W. W. Yaeger, Assistant Superintendent of the Park for their assistance.

Information on the Ames slide was obtained from the section foreman of the Rio Grande Southern Railroad at the Vance Junction station near Telluride.

The terminology in the field of landslide studies is not yet standardized. To simplify the following discussion, C.F.S. Sharpe's 1/ classification is used throughout the paper.

1/ Sharpe, C. F. S., Landslides and related phenomena, a study of mass-movements of soil and rock, 137 pp., New York, Columbia Univ. Press, 1938.

REGIONAL BACKGROUND

Throughout the San Juan and La Plata Mountains and their extensive borderlands of high plateaus and mesas, landslides 2/ are spectacular agents of erosion. Regardless of the types of rock or the local conditions involved in these landslides, a high percentage of them combine the kinds of earth movement defined by Sharpe 3/ as slump and earthflow.

Slump is the failure of a portion of a slope with the resultant downward and outward movement of relatively unified blocks of rock or earth. This is the kind of movement most generally considered as a typical landslide. Both initial failure and subsequent movement occur along one or more well-defined surfaces commonly known as slip planes or slip surfaces. The location and shape of a slip surface depend on several factors: structural and stratigraphic conditions, permeability of beds, pore-water pressures, number and spacing of joints, and the degree to which the slope has been disturbed by excavation or undercutting.

Earthflow is the slow, continuous deformation of an entire mass. Earthflows that are associated with slump masses generally extend below the major slide blocks as buckled and fissured zones bordered by raised rims of debris.

Most of the plateaus of southwestern Colorado are composed, entirely or in part, of soft clay shale, which is notably prone to failure. The Cedar Creek landslide, an almost ideal example of mass movement combining slump and earthflow, is representative of slope failure in these shales. Initial movement at the Cedar Creek site was the downward sliding of large blocks of gravel-capped shale. The sliding was later accompanied by earthflows in the loose weathered and broken shale, which was pushed or fell in front of the moving slide blocks.

In contrast to the Cedar Creek landslide, which affected only weak shale and unconsolidated gravel, some of the landslides involve hard beds, usually sandstone or volcanic rock, which overlie or are interstratified with shale.

In Mesa Verde National Park, landslide movements in the Mancos shale affect and are affected by a cap of thick, relatively hard sandstone of the Mesaverde formation. The shale is weak and easily weathered, but being protected by the more durable caprock, it maintains abnormally high-angle slopes. This oversteepening is favorable to slope failure in the weak shale and prevents the slopes from reaching equilibrium, so that the active life of this slide area has been prolonged far beyond that indicated for either the Cedar Creek or Ames slide areas. Slumping is the most common kind of failure in the shale. Since this process also serves to undermine the sandstone, large rock falls from the caprock are numerous. Earthflows are rare and short-lived because of the steepness of the slopes. Loose material generally moves rapidly as debris slides and falls.

The Ames landslide follows a pattern similar to the Cedar Creek slide. The upper part is composed of several large slump blocks; the remainder is a thick train of jumbled earthflow debris. Unlike the Cedar Creek and Mesa Verde areas, however, movement has been primarily in glacial till rather than in shale. Such slides in unconsolidated till are widespread in the glaciated valleys of the San Juan and La Plata Mountains, although mass movements have also involved almost every kind of consolidated and unconsolidated material present in these areas.

CEDAR CREEK LANDSLIDE NEAR MONTROSE, COLO.

Location and history

The Cedar Creek landslide crosses the Denver & Rio Grande Western Railroad about 9 miles east of Montrose. (See fig.2.) Recently active landslides extend for almost a mile along the north-facing side of the valley. Detailed studies were confined to the area where one of the most recent slides has disrupted the railroad. This landslide (see fig. 3) occupies an area about 1,000 feet square with a maximum height of about 300 feet measured from the railroad grade to the top of the cliff.

The first noticeable activity took place early in 1941, when a slow slump and earthflow down the hillside pushed some soil and shale debris over the track. The largest and only sudden movement noted at any time took place early in the spring of 1942, when several major slide blocks broke away from the cliff and moved down 50 to 75 feet in a few days. These movements buried 1,000 feet of track so deep that the railroad never recovered it. The original alignment of the track in this section was nearly straight, but the large volume of debris that overwhelmed it necessitated relocation of the roadbed, and it now curves around the toe of the slide. The original roadbed is about 150 feet inside the slide at the point of greatest movement. (See fig 3.) Since 1942 there have been some periods of complete quiescence; usually in midwinter, but recurring earthflows and small-scale slumping have kept debris moving over the roadbed most of the time.

General description

The Cedar Creek landslide (fig.3) was formed primarily by the breaking off and downward movement of large masses of Mancos shale along the north end of a mesa. The part of the slide above the 1040-foot contour (fig.3) is composed largely of steplike blocks of shale, which broke off and moved

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2/ Atwood, W. W., and Mather, K. F., Physiography and Quarternary geology of the San Juan Mountains, Colo.: U. S. Geol. Survey Prof. Paper 166, pp. 147-163, 1932.

3/ Sharpe, C. F. S., op. cit., pp. 50-55, 65-74.

down on a slip plane as unified masses. The lower part is made up of unconsolidated earth, clay, and broken shale, which moved as earthflows in front of the slide blocks.

probably of middle Pleistocene age.

Topography of the slide.—The land forms developed by the slide (see fig.3) are of two types, large tilted blocks of shale and gravel in the upper part and ridged and rolling slopes of loose soil, clay and shale in the lower part. The scale and contour interval of figure 3 unfortunately do not permit adequate representation of several small but significant features, such as the small blocks at the head of the slide area, or the ridge and trough structure that characterizes the lower part.

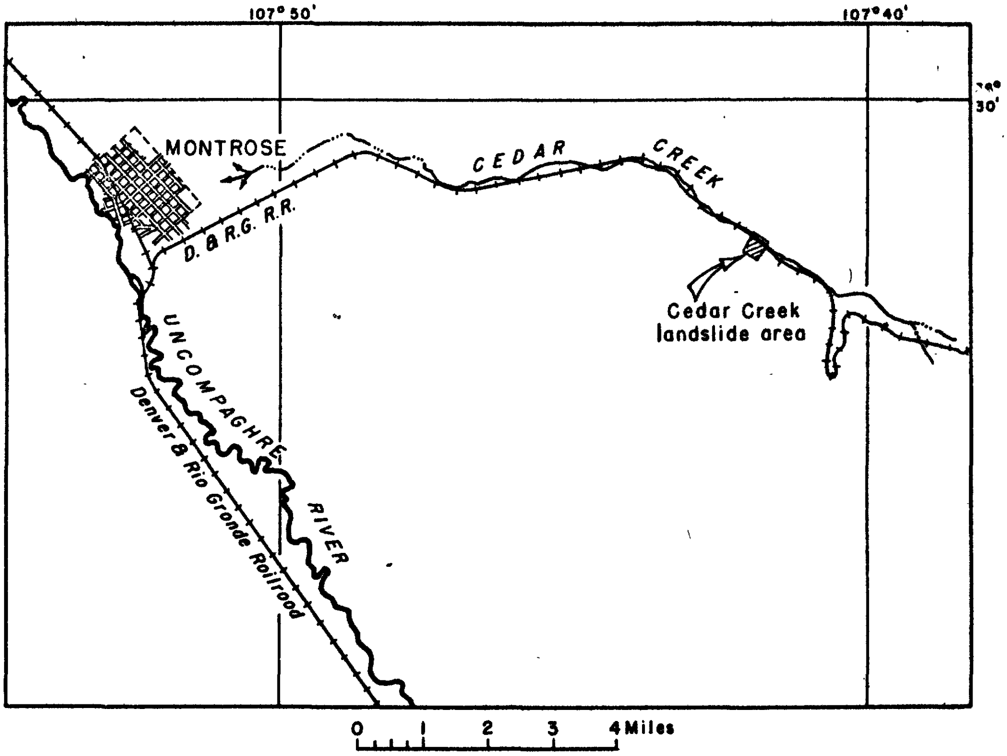

Figure 2.—Index map of the Cedar Creek landslide area.

Geology.—The slide occurred on the north edge of a large undulating mesa composed of shale capped by 15 to 25 feet of coarse boulder gravels.

The Mancos shale is a soft, almost homogeneous, carbonaceous, clay shale. Individual beds range from a fraction of an inch to several feet in thickness. Fresh rock is dark gray to black, but on exposure the shale weathers rapidly to light gray and tan silt and clay. It can be found in place only at the head of the slide, where it is exposed locally along the slide plane. Shale is also exposed in the faces of the large slide blocks, but there it generally shows some weathering.

The gravels are composed largely of well-rounded cobbles and boulders with interstitial silt and clay. Most of the material is more than 4 inches in diameter, and boulders 1 to 3 feet across are common. The gravels, classed by Atwood and Mather 4/ as part of the Florida gravel are widespread periglacial stream deposits around the margins of the San Juan Mountains. They are

The part of the slide above 1,040 feet is composed almost entirely of large blocks, the width of which increases progressively downward from the top of the slide. Just below the cliff that rises from the head of the landslide is a belt of small blocks. Some of these were recently separated from the mesa and still retain intact the complete gravel capping and cover of sage and other low brush. On the older blocks, repeated movements have shattered the gravel cap so that only a few elongated pinnacles of weakly cemented gravel remain. Rotation of these small blocks toward the slide plane is generally greater than 10°; one has a slope of as much as 25°.

Below the belt of small blocks are two major blocks that make up most of the upper part of the slide. The higher block extends

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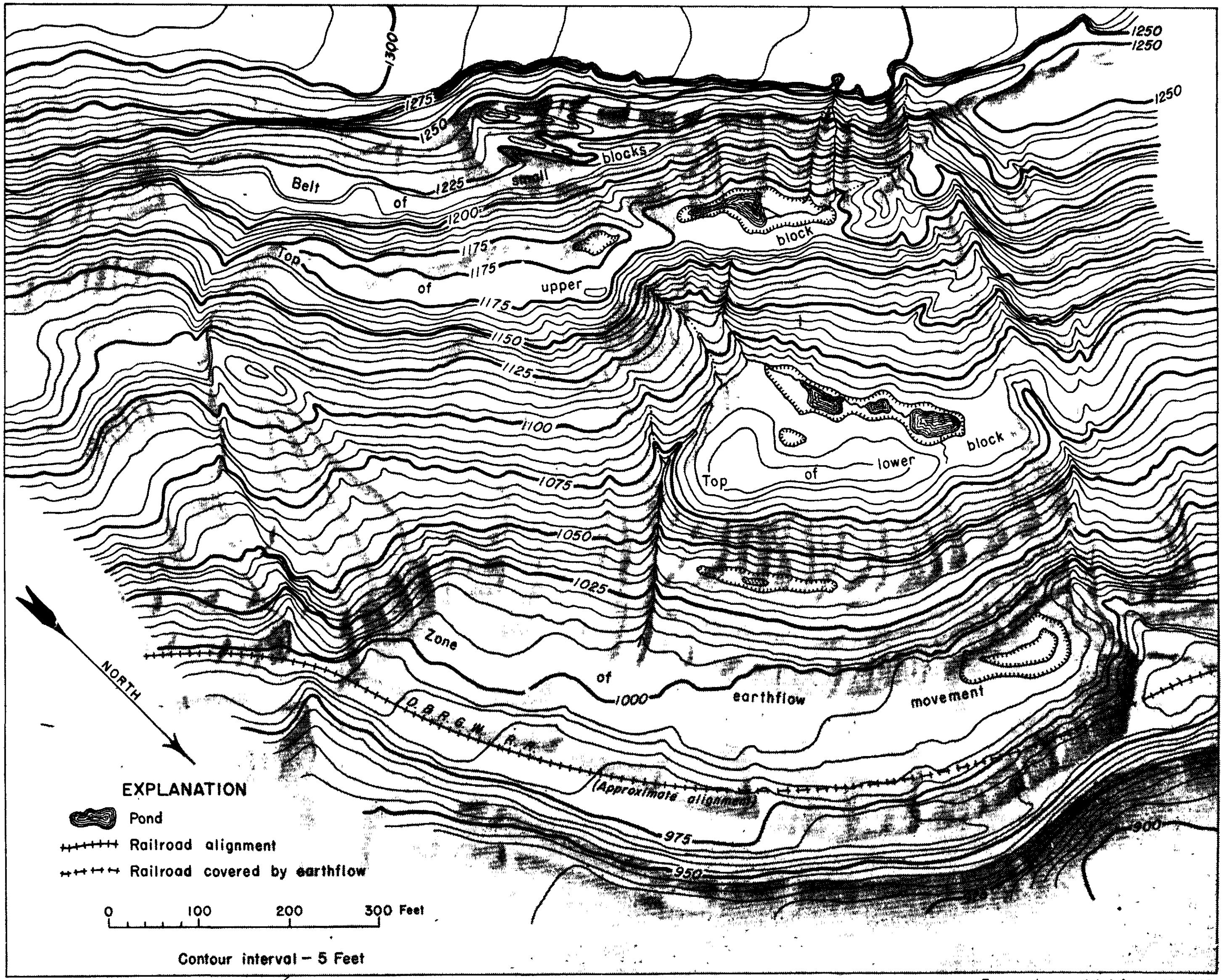
4/ Atwood, W. W., and Mather, K. F., op. cit., 1932.



Assumed datum

FIGURE 3 — CEDAR CREEK LANDSLIDE
NEAR MONTROSE, COLORADO

Topography completed August 14, 1946,
by Helen D. Varnes and Leonard Rolnick

Shaded relief by Eugene Harbart

entirely across the width of the slide and probably represents the largest single mass movement in the history of the slide. It is approximately 850 feet long and has a maximum width of 95 feet. Below it and crossing the western half of the slide is another block about 400 feet long and 140 feet wide. Both blocks show a characteristic backward rotation of 5° to 10° along a horizontal axis parallel to the slide plane. The shale that constitutes the main part of these blocks seems to be only slightly shattered by the downward movement. The gravel that formerly capped them has been disrupted, partly by the downward movement but mostly by rapid weathering of the unconsolidated materials, so that the tops of the blocks are covered by a jumble of boulders, soil, and disintegrating shale. The outer faces of the blocks stand at extremely high angles, but their lower slopes are modified by debris falls and mudflows. Continuous sloughing of material along their outer margins is steadily reducing them in width.

The margin of relatively stable ground that surrounds these slide blocks is characterized by steep scarps facing the landslide

From the base of the large blocks (1,040 foot-contour on fig. 3) down to the line of the railroad, the slide is composed of rolling slopes and ridged benches. These show the general characteristics of earthflow masses, although the portion immediately above the roadbed has been somewhat altered by roadbed relocations. The outstanding feature of this lower section is the development of pressure ridges and troughs, which closely parallel the toes of the slide blocks above them. As this mass of largely unconsolidated material moved down in front of the slide blocks, it piled up, ridged, and broke because its internal friction was greater than that of the better lubricated clays along the slip surface. The ridges are traversed by two sets of deep cracks. One longitudinal set of tension cracks follows the crests of the ridges; a second set of cracks is almost at right angles to the pressure ridges and forms a radial pattern from the toe behind them. This lower part of the slide is bounded on both sides by the prominent raised rims of shale and clay characteristic of earthflow masses.

The original toe of the slide has been destroyed by reconstruction of the railroad alignment around the base of the slide area. Probably it was similar to that of the small slide to the west, which has a raised and overthrust rim of soil and rock debris at the toe.

The steep bank below the railroad alignment is the result of efforts by the railroad company to maintain the roadbed and is not considered a true part of the slide.

Drainage conditions.—In addition to the annual precipitation of 16 inches, irrigation of the grain fields on the mesa above supplies abundant water to the slide area. The gravel cap is highly porous, and water moves rapidly through it to the underlying impervious shale. Irregularities in the contact of gravel and shale direct the flow of ground water into the western part of the slide and do not permit any significant quantities to reach the eastern part. Thus the slide is effectively divided into a "wet" west half and a "dry" east half.

Because of this abundance of water, the western part shows a greater variety of conditions than the eastern part and is the site of nearly all present slide activity. Each of the large slide blocks holds a pond on its inner margin during the irrigation season. Part of the water that moves along the gravel-shale contact of the mesa seeps down the slip plane; the remainder flows down the face of the slide to form a pond on the higher block. Enough water escapes from this pond and seeps through to feed a pond on the block below. At times of maximum supply, water escapes also along the outer margin of the lower block to appear as small springs farther down its face and to form small ephemeral ponds between the pressure ridges below. Part of the water flows in definite channels as small streams, and part soaks into the loose disintegrated shale that mantles the block.

The finest material from the disintegrated shale is carried along by the water moving through and over the slide until it is deposited as a very sticky plastic clay in the ponds on the slide blocks. This removal of fines leaves a concentration of coarse pebbles and boulders between the ponds and the outer margins of the blocks.

No appreciable quantities of water penetrate the east half of the slide; there lubrication comes only from rain and snowfall. No ponds or springs are present on this side. This dearth of water is reflected in the absence of any movement except settling of small blocks near the top of the slide and minor sloughing of dry material from their margins.

Slide movements and their causes

The mass movements of the Cedar Creek landslide area can be attributed to well-defined conditions and causes. The physical setting of very steep slopes and cliffs at the edge of a mesa, which is underlain largely by weak, easily weathered clay shale, and only indifferently covered by a protective mantle of vegetation, offers the essential passive conditions favorable to slope failure. To touch off actual movement, the excess water from the irrigation of the mesa is the most important factor, for it is the lubricating agent needed to reduce internal friction along joint or shear planes and within loose soil and rock debris, thus permitting sliding or flowing of the material.

The resulting slope failures produced two primary kinds of movement, namely, true sliding or slump, whereby blocks of shale moved suddenly downward as unified masses on a well-defined slip surface, and earthflow, in which the material that was pushed or fell in front of the sliding blocks continued to move throughout the period during which the whole mass was being deformed.

Conditions favoring movement.—The underlying factors that make this area susceptible to landslide movements are the component materials, the vegetation conditions, and the topographic and stratigraphic conditions.

The capping boulder gravels are loose and porous, thus forming a giant sponge, which absorbs an unusually high percentage of any water supplied to the mesa top and feeds it down to the shales below.

The Mancos shale is a very fine-grained consolidated mud that is almost impervious to water. Ground waters percolating through the capping gravels move along the contact of gravel and shale, except where joints or other fractures give admittance into the shale. On contact with water, however, the shale breaks down readily into fine slippery clay and silt. Thus, each fracture or joint that admits water is a potential slip plane, along which the shale can be converted into an efficient mud lubricant. At one point the slip plane of the Cedar Creek slide was found to contain about 6 inches of soft, slick, wet clay.

Exposure of the shale to air results in rapid decrepitation, which produces an abundant surface cover of loose material. The addition of water readily converts this material into moving masses.

The natural vegetation cover is generally a sparse growth of scrub oak, sage, and other low brush that is not very effective in stopping a sliding or flowing mass.

The youthful profile of Cedar Creek valley increases the danger of landsliding. The steep valley walls cut in potentially weak gravel and shale will fail much more readily than would the moderate slopes of a more mature topography.

Other conditions that favor earth movements are present on the south side of Cedar Creek Valley, where the slide occurred. Moisture contributed by irrigation or precipitation evaporates less readily than on the north side and hence has greater opportunity to penetrate the underlying material. The contact of gravel and shale and the bedding of the shale have an apparent dip of less than 2° to the north. On the south side of the valley, this slight dip tends to lead ground waters to the cliff face, where the slides develop. On the north side of the valley water follows the dip away from the valley slopes. Old landslide scars and more recently active slides extending for at least a mile on both sides of the Cedar Creek slide indicate that such movements have long been a characteristic of the slopes on the south side of the valley, whereas the north slopes show no good evidence of recent landslides.

Activating or initiating causes.—Actual movement in the Cedar Creek landslide can be attributed almost entirely to the relatively large amount of water supplied to that area. About 300 acre-feet of water is used each season in a 12-acre area immediately south of the active landslide. The porous boulder gravels take up all water not held by the top soil and transmit it along the gravel-shale contact. For a long period some of that surplus water contributed towards the establishment of the slip plane by working into the hairline joints characteristic of the more massive phases of the Mancos. The initial quantity able to penetrate such joints below the gravel-shale contact would have been almost negligible. Over a sufficient period of time, however, continued action of the water along these minute joints would thoroughly wet the shale and reduce its shearing strength. Failure would take place and the slip surface would develop wherever the shearing stresses due to gravity had become equal to the shearing resistance of the shale. Once initial failure had occurred, water moving along the slip plane would alter the shale to a greasy, slippery clay on which the newly developed slide blocks could readily move.

The remainder of the surplus water flowed over the surface of the slide itself. The water thus supplied to the overburden of clay, silt, and boulders was often sufficient to start this debris in motion by the double process of lubricating the unstable mass and by adding weight to it at the same time.

The width of the slide coincides almost exactly with the zone that originally received water escaping from the irrigated land on the mesa. When re-routing of the irrigation ditches channeled the water into a narrower zone, the active part of the landslide decreased in width. The east half, which received no irrigation water after 1944, has become dormant. Recent activity is confined to the west half of the slide area, where water is still abundant.

While the moisture provided by rain and snow might have produced the Cedar Creek slide, just as this moisture has been the activating agent for the older slides in the vicinity, it is doubtful whether the slide would have attained its present size so quickly or would show such prolonged activity without the aid of the large quantities of water supplied since irrigation was begun in 1927.

A secondary factor aiding the activity of the landslide has been the unavoidable work performed in railroad maintenance. In the past few years, clearing away the debris that overwhelmed the tracks has removed the toe of the slide, which acted as partial support to the material above, thus leaving a considerable weight of material resting insecurely on its base of wet, slippery clay. Construction during the spring of 1947 avoided this difficulty by leaving the toe intact and laying the track on a fill built out around the landslide area.

Types of movement.—Slump and earthflow (see p.3) are the two primary types of movement in the Cedar Creek landslide. Slump is probably first in importance, especially in the early stages of movement. The original slip plane probably remains as a kind of sole over which the lower part of the slide moves. The position of the upper part of the slip plane, which forms the head of the slide, has continually migrated back into the mesa as new blocks break off and slide down. It seems probable that the lower end of the slip plane came to the surface at or a little above the level of the railroad alignment, for there is no record that the track was ever buckled or broken by the landslide. Rather, it seems to have been overwhelmed from above. Earthflow ranks almost equally in importance with slump. The buckled ridges and broad rolling benches that make up the lower part of the landslide were shaped almost entirely by this type of mass movement.

Although there was no visible movement of the large blocks during the time the landslide was under close observation, evidence of some movement was supplied by the doming of a large mud deposit on the top of the lower block, owing to the settling of the upper block. In the lower half of the landslide, the ridge-and-trough structure became increasingly prominent, and new cracks appeared and deepened from day to day. Maximum activity during August 1946 occurred on the toe at the northwest corner of the landslide, where the first bench above the old railroad alignment moved 7 feet in one week; a total horizontal movement of 49 feet was recorded for this section from June 5 to August 20.

Movements other than slump and earthflow are of secondary importance in that they merely modify and do not essentially change the characteristic features of the slide. Of these, debris falls are most common. Generally, debris falls come from boulder gravels that have been undermined by water seeping out at the contact of gravel and shale, or from which the loose silt and clay that bind the large rocks have been removed.

Along the outer edges of the major blocks, narrow wedgelike blocks break off, producing miniature slump movement. After a short descent, these small blocks break up into debris falls.

True mudflows and sheet flows of fluid mud are fairly common in the west half of the Cedar Creek landslide.

KNIFE EDGE LANDSLIDE AREA IN MESA VERDE NATIONAL PARK

General description

The Mesa Verde is the westernmost part of a dissected plateau composed largely of Mancos shale and capped by sandstone of the Mesaverde formation. Steep escarpments extend almost unbroken around the east, north, and west sides of the mesa. The southern escarpment has been breached by several deep canyons, which extend almost to the north end of the mesa.

Along the canyons and marginal escarpments, earth mass movements of various types have been important destructive processes. Rockfalls from the capping sandstone are present along all the escarpments. Scars of the slump type of landslide movement are especially numerous and prominent in the shale on the north and east margins of the mesa. Some are evidently of very recent origin; others are older and their characteristic features are largely obscured by erosion. Large-scale slumping in the shale is commonly followed by collapse of the overlying sandstone.

Southward from the Park entrance the road, which leads to the Indian ruins at the south end of the mesa, climbs about 6 miles along the north and northeast faces of the mesa on sidehill cuts and fill in the shale. Minor slumping, washing, and sloughing of the shale is prevalent along most of the road. In a few places, large-scale slumping, debris slides, and subsidence of the grade have caused serious trouble ever since the road was built. One of the most troublesome parts is a section about 1½ miles long generally called "Knife Edge." (See fig. 4.) This area was the focal point of reconnaissance studies in Mesa Verde National Park during the 1946 field season, because it represents a kind of slope failure that is common to the Mancos formation of the southwestern Colorado plateaus but is different in several respects from the Cedar Creek landslide.

Landforms and types of movement

The Knife Edge area can be divided into two parts on the basis of steepness of slope and type of movement most prevalent in each.

The eastern part (B in fig. 4) has natural slopes of 2:1 to 1:1, although the man-made slopes of the road cut are locally steeper. Movement in this part of the Knife Edge area is mostly of the slump type. The blocks are composed largely of weathered shale and are usually less than 15 feet wide and from a few feet to 100 or 200 feet in length. Each block occupies only a small part of the total slide area, which is more than 1,400 feet wide. The steepness of the slopes, together with the highly weathered nature of the shale in the slide blocks, probably contributes to the tendency of the blocks to disintegrate into debris slides, and, in wet weather, into small mudflows as they move down the slope.

The location of the slip surface appears to be determined, at least in part, by the boundary between fresh shale and weathered shale. Only small amounts of unaltered shale are found, even in the larger blocks.

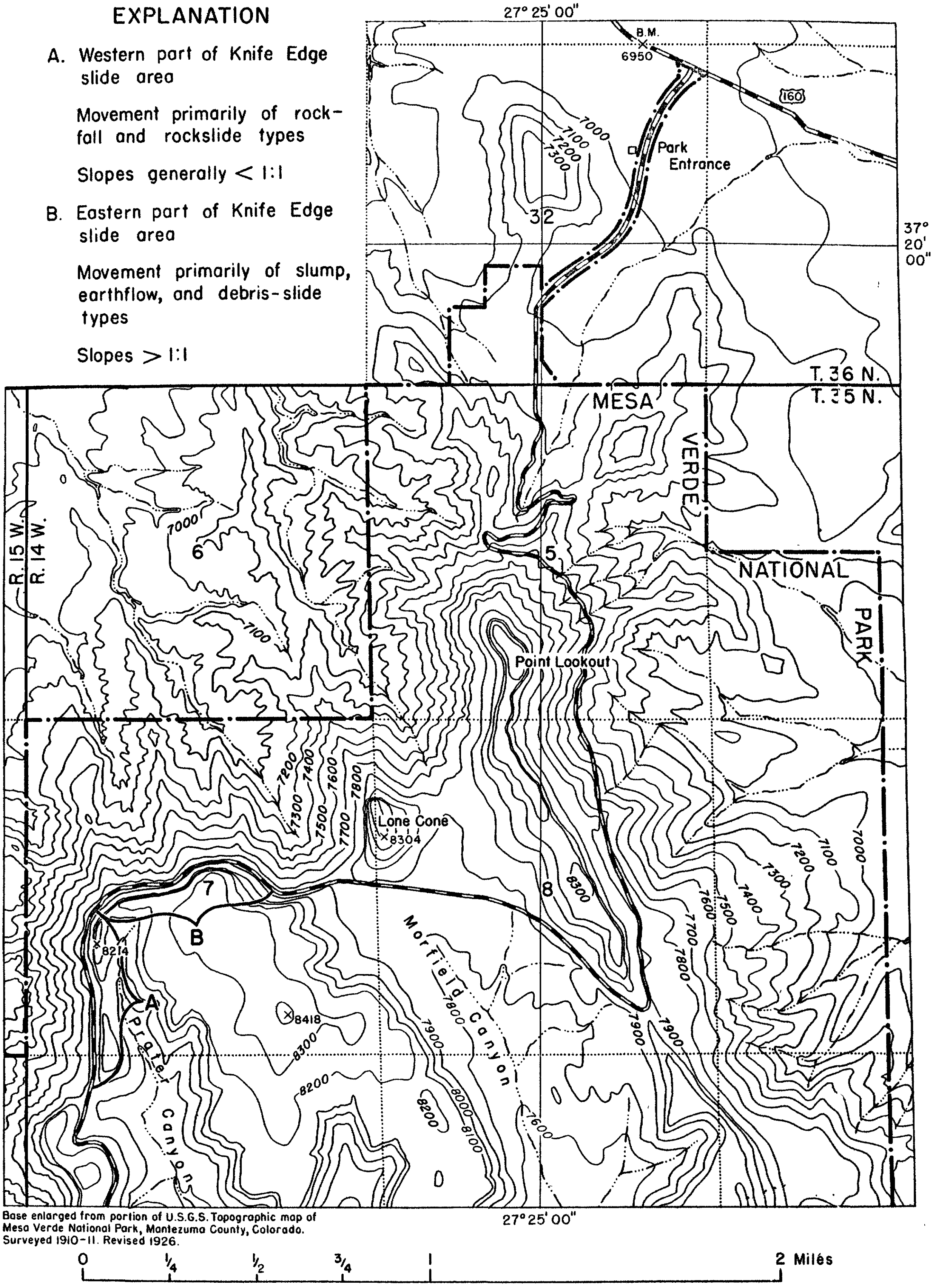
At its highest point, the upper end of the slide area is about 100 feet above the road, leaving 50 to 70 feet of undisturbed material between the slide and the overlying sandstone. Because blocks continue to break off and the position of the slip surface migrates backward and upward toward the sandstone cap, this zone of undisturbed shale is steadily reduced in width.

In the western part (A in fig.4), the plane of movement between the weathered and the unaltered shale has retreated to the base of the sandstone caprock. Old slide blocks below the present road grade indicate that slumping was once the primary type of movement. Most of the slopes are now greater than ½:1, however, and current movement is primarily of the rockfall and, to a much lesser extent, the rockslide types.

Causes of landslide movements

Conditions favoring movement.—The Mancos shale is a dense, impervious mudstone and shale when freshly exposed, but it is quickly reduced to slippery mud when in contact with water. On exposure to air it decrepitates rapidly, so that a fairly thick cover of unconsolidated silt and clay will develop even under semiarid conditions. Addition of water to this loose material can easily transform it into a moving mass.

The weak Mancos shale is overlain by a thick, relatively competent sandstone sequence, which is much more resistant to weathering. The sandstone, a part of the Mesaverde



EXPLANATION

A. Western part of Knife Edge slide area

Movement primarily of rockfall and rockslide types

Slopes generally < 1:1

B. Eastern part of Knife Edge slide area

Movement primarily of slump, earthflow, and debris-slide types

Slopes > 1:1

Base enlarged from portion of U.S.G.S. Topographic map of Mesa Verde National Park, Montezuma County, Colorado. Surveyed 1910-11. Revised 1926.

Contour Interval = 100 Feet

FIGURE 4 — KNIFE EDGE LANDSLIDE AREA AT NORTH END OF MESA VERDE NATIONAL PARK

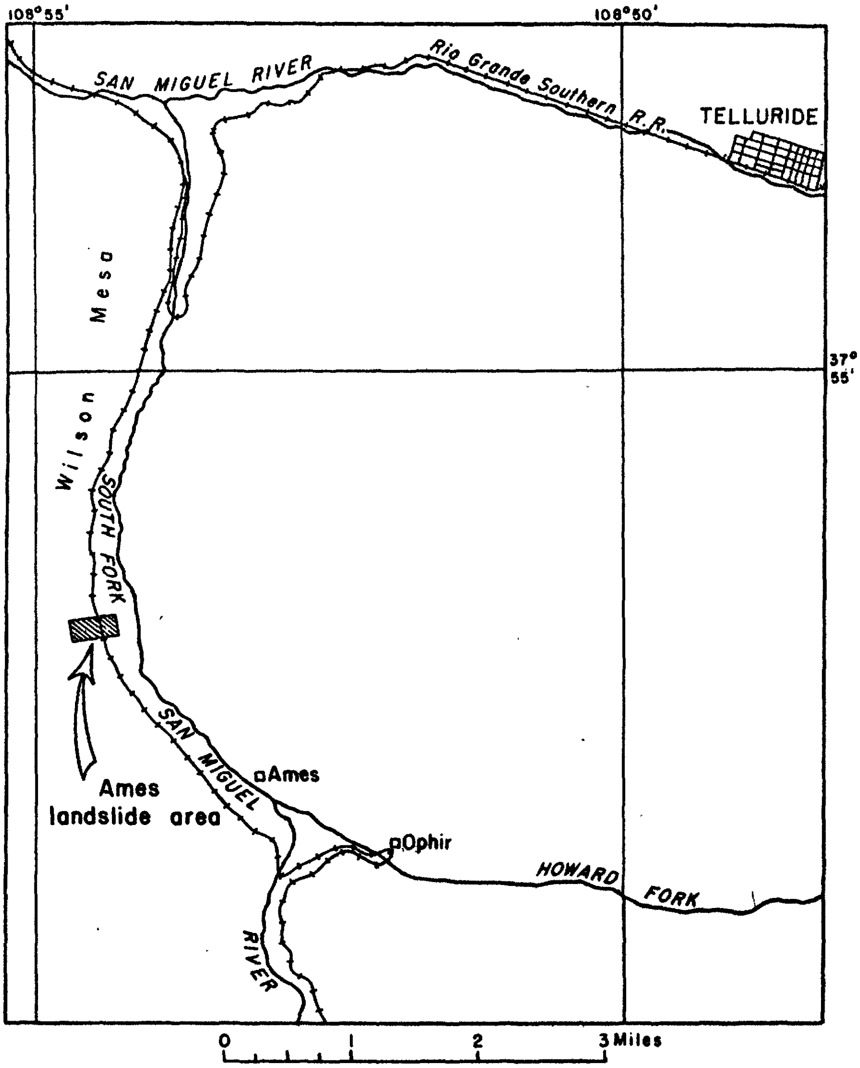


Figure 5.—Index map of the Ames landslide area.

formation, stands in vertical cliffs in most places and partly protects the weaker Mancos shale from weathering, so that the shale stands at steeper angles than is normal in areas where the sandstone is lacking. The oversteepened shale slopes, capped as they are by sandstone cliffs, are more susceptible to failure, both topographically and geologically, than lower, less precipitous slopes.

The north end of the tableland has the greatest precipitation in the Mesa Verde area and is thus subjected to more rapid weathering and weakening of the shale. The relative abundance of old slides and rockfalls at the north end of the Park testifies to the effectiveness of the higher precipitation in this area as compared to the drier areas in other parts of the mesa. Furthermore, evaporation on the north-facing slopes is somewhat slower and snow remains longer, thus permitting more moisture to be absorbed by the overburden.

Although the mesa top supports relatively abundant growth, vegetation generally does not prosper on the shale, so that the cover on the slopes below the caprock is relatively sparse, leaving the shale largely exposed to weathering and wash.

Activating causes.—Removal of support through natural and artificial means is the outstanding activating cause of movement along the Knife Edge. Rapid weathering of the soft shales has continually undermined the resistant sandstone caprock, so that the escarpments are always retreating by means of rockfalls and slides. Construction of the road has considerably accelerated removal of the shale through weathering and washing as well as sliding.

Along the west half of the Knife Edge, removal of the shale by sliding has been largely a natural process accomplished before the construction of the road. Cutting into the shale to build the inner part of the roadbed, however, has undoubtedly increased the tendency to sloughing and sliding. Along the eastern half the steep-faced cuts on the inner side of the road have left the weathered shale and rock debris above the road without adequate support and have facilitated the breaking off and downward movement of several slump blocks.

Another factor producing movement is the overloading that resulted from construction of the road on unstable ground. Along most parts of the Knife Edge the fill was placed on old landslide masses or on slopes where the shale was undisturbed but in a precarious state of balance that could easily be destroyed by addition of extra weight. The settling of most parts of the Knife Edge road, which has been almost continuous since construction, can be attributed, at least in part, to overloading. Passage of traffic over this relatively unstable area may add to the overloading to a minor extent.

The fact that the area of greatest precipitation is also that of the most extensive and continuous slide activity indicates the importance of water as an activating cause of movement. Average annual precipitation is about 18 inches, of which 40 to 50 percent falls during the winter and early spring. Most of the earth movements along the Knife Edge occur during March and April, when moisture from the melting snow and thawing ground is augmented by the spring rains. Although the drainage area that feeds the slide is very small, the oversteepened slopes and the nature of the materials involved give a maximum effectiveness to whatever water reaches the unstable area.

AMES LANDSLIDE NEAR TELLURIDE, COLO.

Small slides in glacial till are fairly common in the mountains of southwestern Colorado. Many of them have caused damage to roads and railroads, and their economic significance is often greater than their size might indicate. One of the most troublesome is the Ames landslide, which is about 7 miles southwest of Telluride in the glaciated valley of the South Fork of the San Miguel River. (See fig.5.) This slide crosses the Rio Grande Southern Railroad about 4.2 miles south of the junction of the South Fork with the main stream of the San Miguel.

The Ames slide occurs largely in the thick glacial till that mantles the San Miguel valley. It is a long narrow zone of failure with a maximum width of about 400 feet and a minimum length of 1,600 feet. The actual length is not known because the toe of the slide, which emerged below the railroad grade, has been destroyed by the maintenance work necessary to keep the railroad in operation across the slide area.

Although the material involved in the slide is unconsolidated till rather than shale, the kinds of movement in the Ames landslide are the same as in the Cedar Creek and Mesa Verde landslides. The upper part of the slide was a downward movement of unified slide blocks; the lower part was a movement of earthflows.

As at the Cedar Creek slide, the outstanding cause of movement was an excessive amount of water locally in an area where general conditions already favored slope failure.

History

The railroad has had trouble from slides and mudflows along the South Fork of the San Miguel since 1890, but no large-scale movement had been recorded for 40 years until the winter of 1929-30, when the Ames slide started to move slowly, taking the track with it. Total horizontal movement amounted to more than 34 feet over a period of a month. As movement never exceeded one or two feet a day, the railroad was able to continue operation by keeping crews constantly at work resetting the track as it was displaced by the slide. Originally the alignment was straight along this part of the valley, but repeated movements since 1929 have necessitated relocation of the track around the toe of the slide so that it now has a 25° curve, the highest along any part of the line.

Geology and topography

The area near Ames is underlain by shale and sandstone of the Morrison, Dakota and Mancos formations. Exposures are numerous in the lower end of the South Fork valley, but in the upper part the rock is largely masked by glacial till. In the vicinity of the Ames slide till blankets most of the slope with layers from 5 to more than 60 feet thick. Scarps near the head of the slide show 18 to 25 feet of till overlying the black Mancos shale. The till is composed predominantly of rock flour and clay with only 1 or 2 percent of rock fragments. Most of the fragments are sandstone and monzonite and are less than a foot in diameter, although a few boulders of monzonite are more than 4 feet across.

The Ames slide has the same general topographic expression as the Cedar Creek landslide. The upper part is composed of a step-like series of blocks formed by downward slumping of successive masses of glacial till. The higher and younger slide blocks extend entirely across the width of the slide area and still retain much of their original form. The top surfaces slope gently toward the slip plane at angles of 5° to 15°. Three blocks hold small reed-grown ponds impounded on their inner margins. The lower and older blocks are smaller; none of them is more than about 50 feet wide. All are modified, to a greater or less degree, by erosion of the soft, unconsolidated till, so that they commonly resemble rounded hummocky masses rather than individual blocks. The oldest ones are difficult to distinguish clearly from the irregular earthflow terrain that forms the lower part of the landslide.

The earthflow masses are uneven and rolling, with poorly defined ridge-and-trough structure developed at right angles to the direction of movement. Slopes are relatively steep for this type of mass movement; angles of 25° to 30° are fairly common. The slopes are scarred by V-shaped ravines carved into the soft till by runoff during spring thaws and summer rains.

Principal causes of movement

Factors favoring movement.—Three factors are of primary importance in making the valley of the South Fork a potential area of landslides. First, the glacial till, the principal material involved in the landslide, is unconsolidated and has a very low shearing strength, so that it fails under relatively light loading. The steep slopes of the youthful glaciated valley of the South Fork also favor earth movements, as their angle is greater than that required for stability in the materials involved. A third factor is the seasonal concentration of precipitation. The area has a wide annual range in temperature and precipitation. Average annual precipitation is about 21 inches, of which more than 50 percent falls as rain or snow from January to the end of May. Because the combined factors of melting snow and thawing ground occur together with the spring rains during April and May, the lubricating action of precipitation and ground water in the till is concentrated into a relatively short period. Most of the earth movements in the Ames slide area occur during this time of maximum lubrication.

Influence of vegetation cover.—Although the long cold winters leave only a short growing season, the abundant precipitation helps perpetuate a heavy cover of vegetation and aids in the reestablishment of cover over barren areas created by new road cuts or by recent landslides. The valley is blanketed with a thick growth of aspen and scattered evergreens. An undergrowth of ferns, grasses, and low brush forms a continuous retaining mat over all but the cliffed slopes. The abundant vegetation cover has apparently been effective in preventing earth movements under normal conditions, in spite of the adverse factors of weak component materials and oversteepened slopes. Earth movements on the South Fork of the San Miguel River generally occurred where the vegetation cover or the slopes have been disturbed by man or where there was an abnormal supply of water.

Vegetation conditions vary considerably over different parts of the Ames slide. On the blocks near the head, part of the original vegetation cover has been retained. Although some trees were uprooted by the movement, many continue to grow but are usually tilted 10° to 30° away from the vertical. The tops of the blocks have good grass cover, and the ponds are already largely filled with reeds. The outer margins are partly covered by vegetation, mostly grass, which is helping to stabilize the ground since major movement has stopped.

The lower slide blocks and the earthflow parts of the slide have relatively sparse cover of vegetation. Apparently these parts have undergone a more thorough churning movement, which completely destroyed their original vegetation cover. Their present growth consists mostly of sparse low brush, grass, and some aspen saplings. Slope wash and gullying in this much disturbed material probably have been effective agents in preventing renewal of a continuous cover of vegetation.

Activating or initiating causes of movement.—Actual movement at the Ames slide did not take place until enough water penetrated the unconsolidated glacial till to overcome the internal friction of the mass and the retaining effects of the vegetation cover. In addition to precipitation, a considerable quantity of water was available from several small beaver-dammed ponds on the edge of the mesa. The localization of the Ames slide to the slope immediately below the ponds indicated clearly that this abnormally large supply of water was the factor that tipped the balance and started movement of weak material on oversteep slopes, notwithstanding the thick cover of vegetation.

Types of movement

In the upper part of the landslide, movement was primarily by slumping. Failure occurred as shearing along a definite plane, followed by the downward and outward movement of blocks of till.

The lower part of the slide has been shaped primarily by earthflow in the till that was pushed down by the sliding blocks. The buckled and fissured appearance that is so prominent in the Cedar Creek earthflows is scarcely discernible at the Ames landslide. This may be due in part to the steepness of of the slopes, which would translate part of the earthflow into mudflow masses and numerous miniature slump blocks. Rapid erosion on the relatively bare slopes would also tend to modify the typical earthflow structures.

Minor slumping and small mudflows, common as secondary types of movement, are now the only obvious indications of recent movement. Tilting of the trees and bushes indicates that creep is going on in the area around the landslide. In the zone immediately bordering the main slide area, this creep appears to grade into slow slides or earthflows.

REMEDIAL MEASURES

The final answers to problems presented by landslide areas have yet to be found. Even the most successful remedies are usually applicable only to a specific landslide and, in most cases, have served only to check movement, rather than to halt it completely and thus remove the danger of renewed activity. The measures taken on the three landslides considered in this paper have met with widely varying success.

Cedar Creek landslide.—The corrective methods employed in the Cedar Creek area have proved to be only temporary. Prior to 1947, the railroad crews kept the line open by clearing the debris from the railroad grade and by cutting back the adjacent slopes to low angles. These procedures did not stop the earth movements in any way; rather they tended to perpetuate the instability by leaving the unbalanced masses above the grade without support. In April 1947, a fill was built to carry the track around the landslide without cutting into the moving material in the hope that the undisturbed slide will stabilize itself.

Up to December 1946, no major drainage measures had been attempted at the Cedar Creek landslide. Probably the only effective one would be to cut off the supply of irrigation water to the land behind the slide for at least 2,000 feet south of the active face.

The older landslide areas bordering the Cedar Creek landslide appear to be more or less stabilized. Excavation into the lower slopes of these slides, however, would renew the danger of large-scale earth movements.

Knife Edge landslide area.—No satisfactory solution has yet been found for this landslide area. Although the drainage area supplying water to the slide faces is very limited, the extreme oversteepening in the weak shale gives the small quantity of water a maximum effectiveness. One section of the oversteepened shale face was coated with gunite in an attempt to reduce weathering and disintegration of the shale. Water working down from the capping sandstone and along joint and bedding planes and sandy lenses in the shale has caused most of the gunite to push away from the face and to spall off. Steel cribbing was installed along one stretch to hold the fill in place and to stop subsidence and sliding of the road. In general, this has proved successful, although some displacement of the cribbing has occurred.

Ames landslide area.—The methods employed at the Ames slide have demonstrated the effectiveness of stabilizing earth mass movements by raising internal friction along the slide plane and within the mass itself through removal or diversion of the water lubricant. Large-scale movement has been virtually halted since the beaver dams at the head of the landslide were destroyed, thus removing the principal source of excess water. However, the high-angle cut 70° to 90° maintained by the railroad across the slide, together with the relatively steep slopes of the earthflow masses above it, seem to harbor an unstable condition that might result in renewed movement in a season of unusually heavy precipitation. Up to the present, the minor slumping, sloughing, and small mudflows that commonly occur in the spring along this cut have presented no new major problems of maintenance.

CONCLUSIONS

The corrective measures noted above for the three landslide areas illustrate the general inadequacy of many common methods of landslide control and show the urgent need for more knowledge concerning landslides and for finding new methods of dealing with them.

In addition to aiding the search for new remedial measures, an understanding of the geology is needed in planning what can be done to stop such landslides before they start, as well as in the planning stages of any major construction project, so that areas in which conditions favor earth movement can be avoided, if at all possible. If construction in such areas cannot be avoided, a complete understanding of the geologic conditions may help in controlling the activating causes before slides occur or become serious.

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