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Landslides in shale at Rapid City, South Dakota

by

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Introduction

In the past 5 years several landslides have originated in hillsides at Rapid City, South Dakota, with resulting damage both to city streets and to private dwellings. The present investigation is a contribution to the continuing study of landslides by the U. S. Geological Survey, although a formal project of landslide investigation in Rapid City has not been established.

Nature of landslides in shale

In order to evaluate properly the causes, effects, and possible remedies of the Rapid City landslides, it is necessary to discuss briefly some critical relationships that have been observed in landslides in other areas.

Landslides in shale in South Dakota are most commonly of the slump variety in which movement generally occurs as a backward rotation of the block on a more or less horizontal axis parallel to the slope from which the slump block was derived.1/ The surface of

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1/ Slump is the downslope movement, or rotation with little downward sliding, of a mass of material that moves as a unit or as several subsidiary units.

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movement of slump blocks is typically concave, with the radius of curvature least at the upper end, greatest in the middle, and intermediate at the lower end. In order to avoid misinterpretation of the feature to which reference is made, the component parts of a slump are represented in figure 1.

Landslides are caused by one or more changes that affect slope stability. These changes are an increased load, a decrease in strength of soil or bedrock, and a less favorable stress distribution. The change in stress distribution might result from steepening a slope, from excavation at the toe of a slope, or from removal of some external support of part of the load. Many landslides are either started or re-actuated during or shortly after a rainfall. The movement can be attributed chiefly to an increase in pore-water pressure, which decreases the shearing resistance of the material. The added water also increases the weight of a unit mass and thereby might destroy its equilibrium. Under certain conditions and in some materials the added moisture might act as a lubricant.

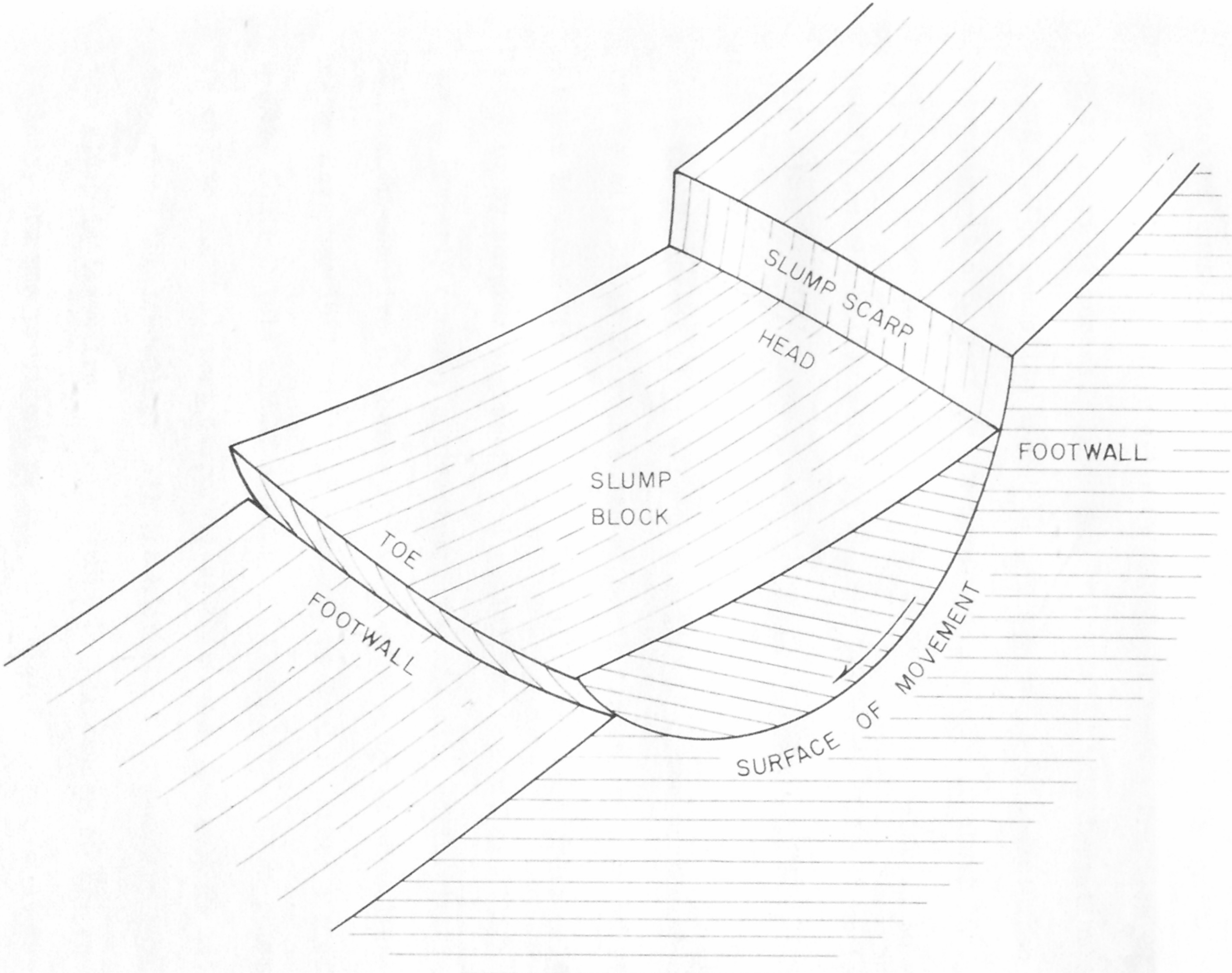

Figure I. Components of a slump

Belle Fourche shale

So far as known, the landslides described in this report are entirely confined to the Upper Cretaceous Belle Fourche shale. This formation consists predominantly of bentonitic shale and claystone and bentonite beds that range in thickness from a fraction of an inch to at least 12 inches. Less than 100 feet of this formation is exposed in the landslide areas. Where the shale is undisturbed by slumping, it dips east or northeast at an angle of about 10°. Two separate slump areas were studied; these will be referred to subsequently as the Hillcrest slump and the Reservoir Hill slump (see fig. 2).

Hillcrest slump

The Hillcrest slump affects a hillside at the northeast corner of the city block located south of South Street and west of Sixth Street in Rapid City (fig. 3). This slide has been previously studied by several engineers and geologists because of litigation among property owners, contractors, and the city administration. The most comprehensive of these studies is covered by an unpublished report dated November 1947, that was prepared by Earl D. Dake, a professor at the South Dakota School of Mines in Rapid City. Dake submitted the report to the Hillcrest Corporation, which was involved in litigation concerning the landslide. All the historical information regarding the slump is taken from Dake's report by permission of Mr. Paul Bellamy, who was president of the Hillcrest Corporation at the time the report was made.

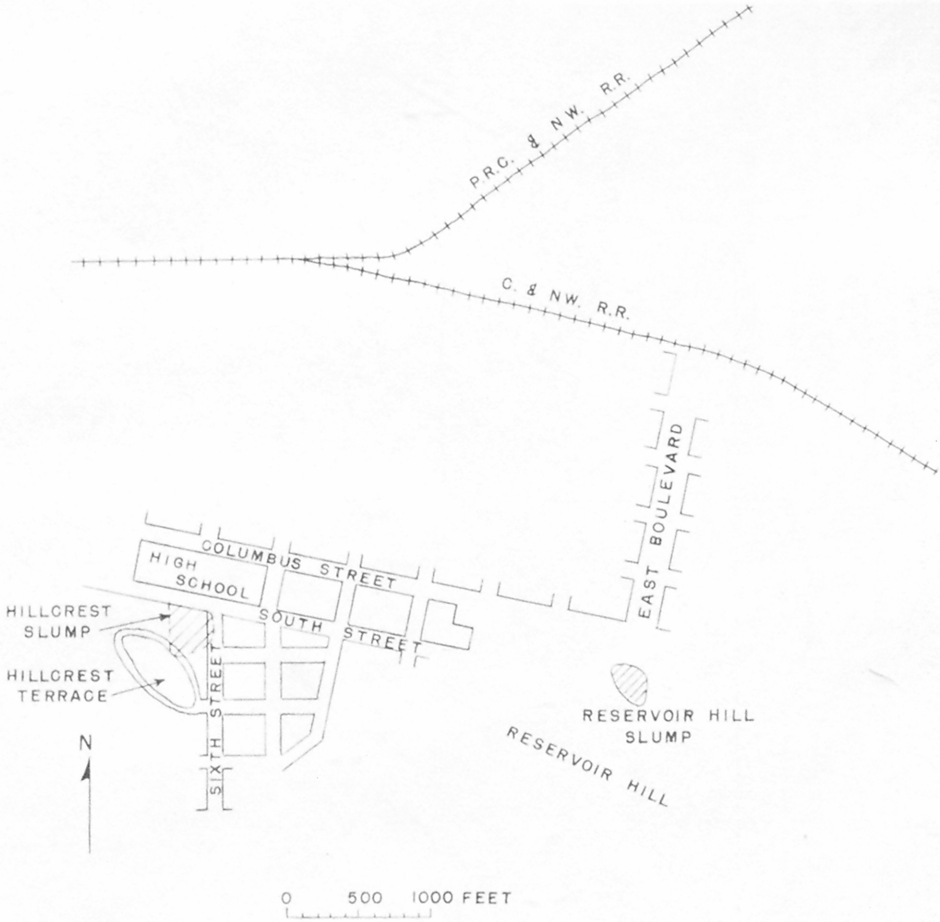

Figure 2. MAP OF PART OF RAPID CITY, SOUTH DAKOTA SHOWING SLUMPS DESCRIBED IN REPORT

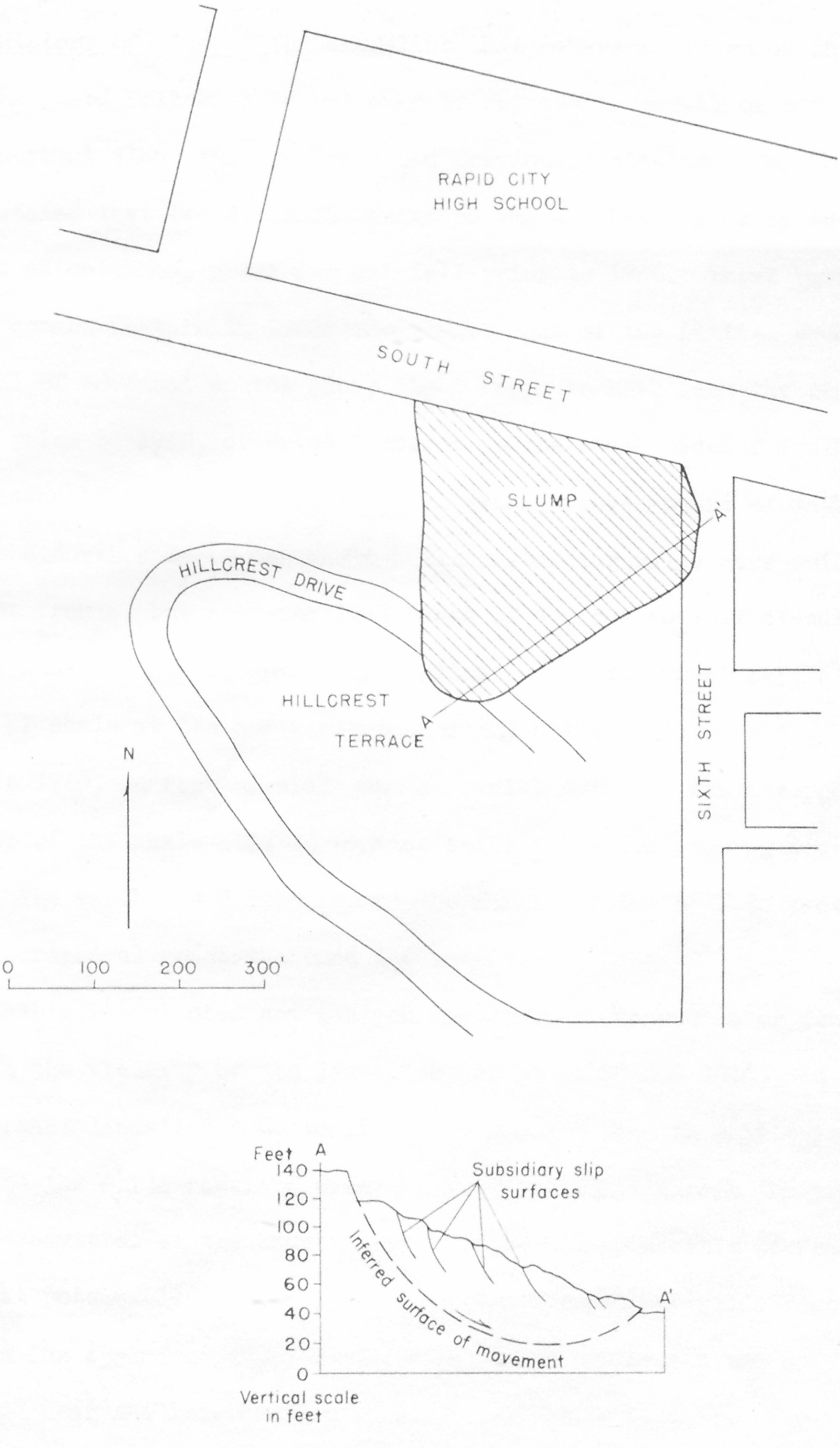

Figure 3. Location map and inferred cross section of Hillcrest slump. Map taken from unpublished report by E. D. Dake, dated November 1947.

History of slump.- The landslide that caused destruction in 1946 and the years following is believed to represent renewal of movement in a dormant slump that probably had previously attained equilibrium. Dake stated that two distinct basins on the northeast side of the hill served as catchment areas for rainfall prior to 1946. These basins are a common feature in landslide areas. One of the initial causes of renewal of movement on the slump block seems to have been the construction, prior to 1940, of several houses on the south side of South Street. This necessitated the excavation of a considerable amount of material from the north side of the shale hill. Retaining walls were built at the lot fronts, but near-vertical banks of shale were left standing back of the houses. Subsequently, excavation for Sixth Street left steep banks of shale at the northeast toe of the hill.

In 1940, 24 feet of shale and surficial material was stripped from the top of the shale hill to provide space for a new housing development. The earth was dumped around the margin of the hill to provide for a peripheral roadway around the summit.

Dake's report does not mention any further excavation or construction in the vicinity of the landslide between 1940 and 1946. In 1946 the dormant landslide came to life. It appears that in this 6-year interval the slide remained essentially quiescent, although the previous excavation at the base of the hill must have greatly decreased, at least potentially, the stability of the dormant landslide block.

In the spring of 1946, some residents of the area noted a "spring" near the intersection of Sixth and South Streets. The "spring" was found to be caused by a broken sewer pipe that had served a house on the corner of the block. In addition to the general soaking of the ground by the water from the broken sewer, two additional periods of exceptionally heavy precipitation saturated the slide area. During one of these periods a large excavation made for a water main through the landslide was filled with rain water. A short time later, water from a broken fire hydrant flooded part of the slump. The shale banks on Sixth Street began to fail by sliding into the gutter and road. The slumped material was removed from time to time by grading and excavation. During the summer, two garages adjoining houses on the north side of the hill were destroyed by movement of the material on which their foundations were built. During this period, residents at the north toe of the hill were forced to haul shale from their back yards almost daily in order to keep the active slide from burying the yards and pushing against the houses. The houses were removed in 1947 because of disrupted foundations. With the continued removal of support at the base of the slide, the area affected by earth movement moved uphill, and ultimately caused failure of a segment of the peripheral roadway at the top of the hill.

Since 1947 the chief source of trouble has been movement of the slide into Sixth and South Streets. The current remedy for this is periodic excavation of the toe of the slump. It seems highly probable that some of the houses on the crest of the hill eventually will be affected by the slide, particularly if more effective remedial measures are not undertaken immediately. Although one of these houses is but a few yards from the uppermost slump scarp, no signs of exceptional foundation movement were noted by casual observation in August 1951.

The recent failure of a retaining wall at the southeast corner of the Rapid City High School, north of South Street, caused fears that the Hillcrest slide ultimately would destroy the school. However, the surface of movement that crops out on Sixth Street appears to dip southwest. Extrapolating from this observation and by analogy with similar landslides in shale in the Missouri River trench in South Dakota, it seems fairly certain that the landslide does not extend beyond the approximate locations of Sixth and South Streets. A stone and mortar retaining wall at the south side of the school property appears to be intact, which indicates that earth movement is largely confined to the south side of the street. Dake proposed that the failure of the retaining wall at the corner of the high school was caused by "horizontal earth pressure of a local nature and not by continuation of the Hillcrest slide."

When the Hillcrest slump was visited in June 1951, it consisted of a great mass of individual slump blocks, each bounded by a deep crack and in some places by a shallow depression (fig. 3). The main slump scarp at the rear of the slide ranged in height from several feet to about 20 feet.

Although the north toe of the slump had bulged a short distance into South Street, both this street and Sixth Street were relatively clear of debris and were open to traffic. When the slump was revisited in August 1951, the north toe of the slide had pushed out over South Street, reducing that street by about one-third of its original width. The surface of movement crops out in Sixth Street about 25 yards south of the South - Sixth intersection; upward and outward movement along this slip surface had nearly closed Sixth Street to traffic. By October 1951, the toe of the slump had moved still farther out and over Sixth Street and vehicular traffic was limited to passenger cars, and even these could pass only with some difficulty.

Causes of the slump.- Excavation of the toe of what evidently was a dormant landslide probably was the most important cause of renewal of large-scale movement. The trigger that started the movement appears to have been an addition of a large amount of water to the landslide in the spring, summer, and fall of 1946, both by natural and artificial means. Once movement began, cracks in the surface of the slump block allowed penetration of surface runoff into the slide. This added moisture greatly lowered its stability. It has been suggested that an important factor was the stripping of the top of the shale hill. The natural slope of the hill was thereby destroyed, and rainfall did not run off as readily as before. This is not believed to have been a determining factor by the writer, inasmuch as copious amounts of water were known to be introduced into the landslide area by other means.

Remedial measures.- In his report, Dake proposed several measures to minimize the destruction caused by the landslide. These are quoted below.

"1) Establishment of a slope capable of providing good surface drainage. 2) Prevention of entrance of water into present and/or future cracks. 3) Construction of adequate drainage system on Hillcrest Terrace. 4) Thorough sub-soil investigation. 5) Piling (if remedy #4 warrants it)."

Prior to Dake's report, the only remedial measures taken were to haul material from the toe of the slide and to move earth from the toe to low spots on the landslide block in order to establish a uniform slope. Following Dake's report, a system of storm sewers was installed on Hillcrest Terrace in June 1947, so as to prevent terrace drainage from entering the slump area.

Dake's proposals no. 1 and no. 2 are perhaps the most effective steps that can be taken to stop further movement. The surface of the slump block is now cut by dozens of deep cracks that trap all the rainfall that drains into the landslide area. So long as the cracks are allowed to remain open, and so long as the city maintenance crews continue to remove the toe of the landslide by grading and excavation on South and Sixth Streets, the slide will remain active. The ultimate destruction of several houses on Hillcrest Terrace is certain unless steps are taken to halt the slide.

Probably the only effective way of stopping the slide at this late date is to grade the entire slide area on as low an angle as possible from the intersection of South and Sixth Streets up to Hillcrest Drive. So as to minimize the infiltration of water, a layer of impermeable material should be spread over the graded surface. Erosion of this layer could be retarded by covering it with a layer of soil on which a shallow-rooted vegetative cover could be established. Vegetation started on the graded surface without an intervening impervious layer would retard erosion by decreasing the velocity of run-off, but this decrease in velocity might afford a greater opportunity for the water to penetrate below the soil and decrease the stability of the slump block.

Reservoir Hill slump

The Reservoir Hill slump is on the north side of a hill about 100 yards south of the intersection of Columbus Street and East Boulevard (fig. 2). The summit of the hill is a high terrace underlain by coarse sand and gravel. These terrace deposits overlie Belle Fourche shale.

In July 1951, an excavation for a new road to the summit was made a short distance upslope from the north toe of Reservoir Hill (fig. 4). Three weeks after the completion of the cut, a crack appeared about 175 feet upslope from the floor of the excavation. It is the impression of a worker that an initial vertical movement of about 1 foot occurred in the space of a few seconds (Mr. Kenneth Shabino, oral communication). The initial movement took place during a long period of dry weather, and no other external change of conditions is known to have affected the area. On October 18, 1951, the main crack at the head of the slump was 1 to 3 feet wide and as much as 8 feet deep. On that date the maximum total vertical displacement was about 4 feet.

Cause of the slump.- The slump occurred on a slope that is smooth and appears to have been in equilibrium before the excavation. The hummocky topography and conspicuous breaks in slope profile that are so characteristic of landslide topography are lacking. Despite this lack of topographic evidence of previous slumping, movement of this slump probably represented reactuation of an old landslide that had attained a balanced condition. The unslumped shale at this locality dips 10° NE., whereas the beds in the slump block dip 30° S. The possiblity that there is a major structural displacement of the shale at this locality related to an uplift of the Black Hills dome has not been disproved, but it seems more likely that the discrepancy in dips is attributable to an earlier landslide.

The immediate cause of the slump was doubtless the removal of the toe restraint by road excavation. Other factors that might have influenced renewal of movement on the inferred dormant slump block are unknown. The delayed action, by which movement started 3 weeks after conditions favorable to movement had been established, is analogous to the period of stability from 1940 to 1946 in the Hillcrest slump. The trigger action that reactuated the Reservoir Hill slump might have been an earth tremor of such small magnitude that it was not apparent to the residents of the area. The slump could possibly have been reactuated after a prolonged period of continued stress by vibrations created by a freight train on the railroad a short distance north of the slide area.

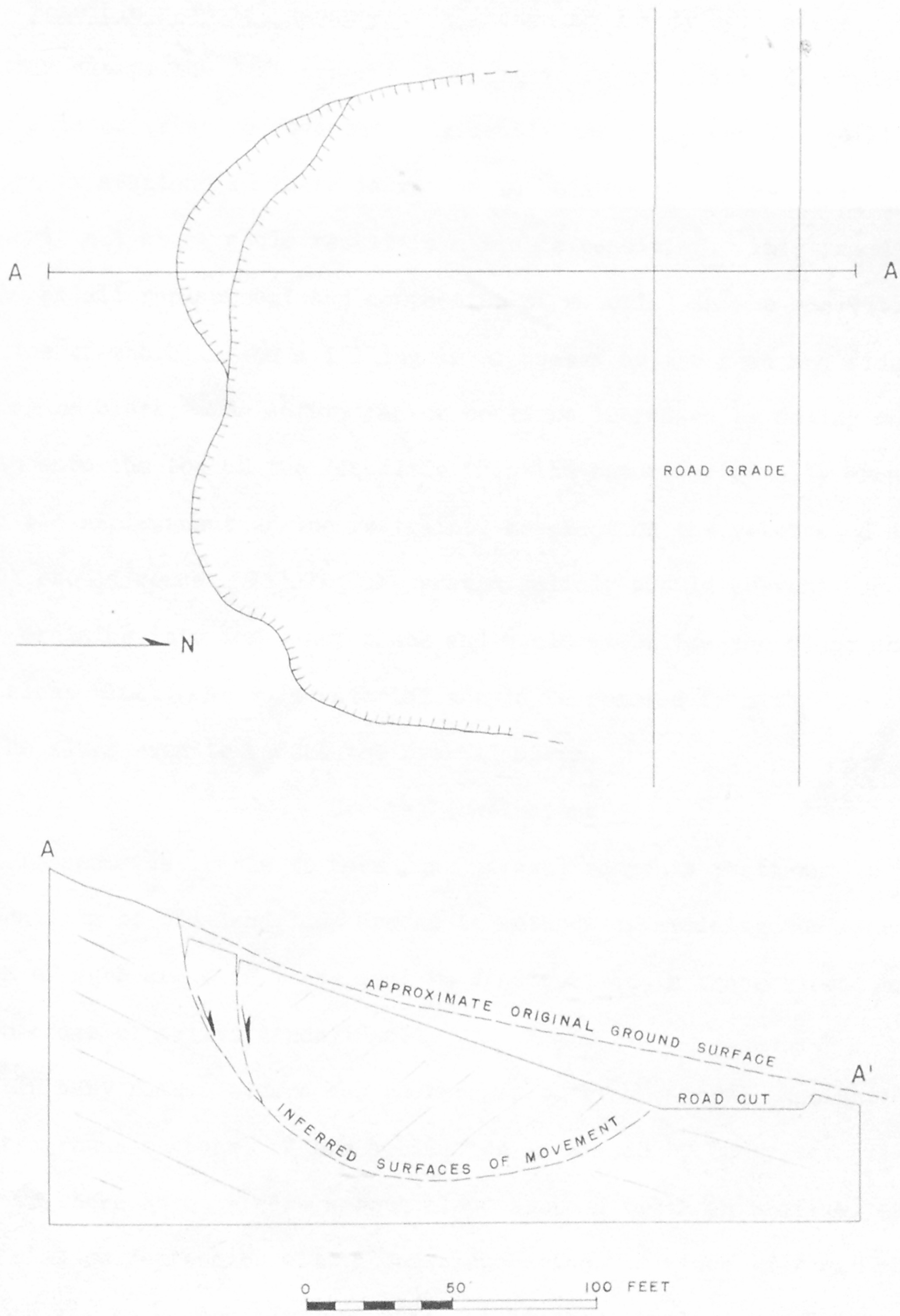

Figure 4. SKETCH MAP AND CROSS SECTION OF RESERVOIR HILL SLUMP

Possible remedial measures.- Although no remedy has yet been applied to this slump, the best program would be to re-establish the conditions that existed prior to movement. Evidently the slump was in equilibrium before excavation, so there is reason to believe that a restoration of the original slope would result in a stable condition. This remedy would entail replacement and compaction of material in the excavation at the toe of the hill and a filling in of cracks at the head and sides of the slump block. The safety factor could be increased by moving more earth onto the toe of the landslide than the amount originally excavated. With the replacement of toe restraint, movement on the reactuated slump block should cease. Filling the cracks solidly should prevent runoff from draining into the slump block and would stabilize the slope above the slump block. No more material should be removed from the toe area of the slump even to reduce the overall slope.

General conclusions

It seems desirable to make some general comments pertinent to the recognition of old landslide areas, to methods of avoiding the reactuation of such areas if there must be construction in these areas, and to remedies of active landslides.

In many places slumps can be recognized by a careful examination of the ground surface. Where a hillside is marked by bumpy topography, or where an otherwise smooth slope shows a break in profile, such as a shallow depression with a conspicuous knob or ridge in front of it, one may be reasonably sure that the hillside includes landslide areas. A steep slope behind a depression might mark an old slump scarp.

Casual observation of a landslide area in semiarid regions often reveals a well-marked pattern in the distribution of vegetation. The moisture that collects in depressions is responsible for greener vegetation than on adjacent, drier hummocks.

If the bedding of the bedrock is horizontal or dips uniformly, sharp variations in dip might denote a slump block. This criterion alone is the evidence on which the Reservoir Hill slump is inferred to be an old slide in which there has been renewal of movement. Ideally, this evidence should be checked against topographic evidence of a slide area because such a variation in dip can also be caused by a crustal movement unrelated to slumping.

By using these criteria the writer has recognized three other landslides along the north slope of Reservoir Hill west of the Reservoir Hill slump described. One of these is active and two are dormant.

If construction must be planned through a landslide area, it seems advisable to build on fill on lower slopes as much as possible rather than to make excavations. Cuts are generally safer near the top of a hill than at the toe. Adequate drainage should be provided for cuts and fills alike so as to prevent undue soaking in of precipitation.

When slumps such as these are reactuated, the best possible remedy is to restore the pre-movement conditions, plus a safety factor, by the methods suggested for the Reservoir Hill slump. Keeping water out of a slide once movement has started is extremely important. Preliminary data on rate of movement of landslides at the Oahe dam site in central South Dakota indicate that movement always accelerates after a moderate to heavy rainfall (F. E. Foss, geologist, Corps of Engineers, oral communication). Removal of material from the toe of a landslide is only a temporary remedy and has a detrimental effect in a long-term program of landslide stabilization. It would be more logical, although probably less economical, to add material to the toe of the slump block.

The construction of retaining walls is advisable only after a detailed geologic and engineering study of the landslide has been made to determine the nature of movement, the shape and location of the surface of movement, and the availability of a stable foundation for the wall. It seems to the writer that the construction of a retaining wall alone would be inadvisable in stabilizing the two slides discussed in this report.

As an extreme measure, landslides can be "remedied" by a nearly complete removal of the slump block. One landslide at the Oahe dam site was completely stabilized by the removal of about 140,000 cubic yards of shale from the head of the slump and from the slump scarp behind it. On the other hand, the removal of about 20,000 cubic yards of shale (10 percent of the total volume of the slump) from the head of another slump in the same area failed to stabilize it permanently. If excavation of the head of a slump block is undertaken, it is important to understand that removal of this material might very well cause another slump upslope. For this reason it generally is necessary to cut the slump scarp back to a low slope.

DEPARTMENT OF THE INTERIOR

INFORMATION SERVICE

GEOLOGICAL SURVEY

For Release JANUARY 18, 1952

REMEDIAL MEASURES SUGGESTED FOR RAPID CITY, SOUTH DAKOTA, LANDSLIDES

A program to reestablish the equilibrium of the ground that existed prior to landslide movements in Rapid City, South Dakota, has been suggested by the Geological Survey for slumps that have damaged city streets and private dwellings, Secretary of Interior Oscar L. Chapman announced today.

Although no formal project of landslide investigation was established in Rapid City, a study of the factors involved was made by Dwight R. Crandell, geologist, as part of a program of research undertaken by the Geological Survey into the causes, effects, and remedies of landslides. Other studies in this field are being made in the Missouri River Basin, in the Columbia River Valley and around the shores of Lake Franklin D. Roosevelt in the State of Washington, and in the vicinity of San Francisco.

The slides at Rapid City are confined to the Upper Cretaceous Belle Fourche shale, a formation consisting predominantly of bentonitic shale and claystone and bentonite beds that range in thickness from a fraction of an inch to at least 12 inches. Something less than 100 feet of this formation is exposed in two slide areas known as the Hillcrest slump and the Reservoir Hill slump. They are within a few city blocks of one another. Both landslides are of the type in which rotational movement of one or more large blocks of material is accompanied by a downslope movement. Such slides are frequently caused by a natural or artificial excavation at the foot of previously stable slopes.

A review of the history of the Hillcrest slump suggests that excavation of the foot of what was evidently a dormant landslide probably was the most important cause for renewal of movement. According to the report, the trigger that started the movement appears to have been the addition of a large amount of water to the landslide over a period of several months during 1946.

In the case of the Reservoir Hill slump, excavation for a new road to the summit was made a short distance upslope from the north foot of the hill in July of 1951. Three weeks later "reactuation of an old landslide that had attained a balanced condition" took place. The report adds that the trigger action might have been an earth tremor of such small magnitude that it was not apparent to the area residents, or that the slump could possibly have been reactuated after a prolonged period of continued stress by vibrations of heavy vehicles passing nearby.

The remedial action suggested is similar for both slides. Because the slump areas were in equilibrium before excavation, it is considered reasonable to expect that a restoration of the original slope would result in a stable condition.

At the Hillcrest site the surface of the slump block is now cut by dozens of deep cracks that trap all the rainfall draining into the landslide area. The report suggests grading the entire area on as low an angle as possible, and spreading a layer of impermeable material over the graded surface to minimize the infiltration of water. Erosion of this layer could be retarded, it is further suggested, by covering it with a layer of soil on which a shallow-rooted vegetative cover could be established.

At the Reservoir Hill site, replacement and compaction of material in the excavation at the foot of the hill is advocated, as is filling in the cracks at the head and sides of the slump block. The safety factor could be increased by moving more earth onto the foot of the landslide than the amount originally excavated, it is stated. Filling the cracks solidly should prevent runoff water from draining into the slump block and would stabilize the slope above. No more material should be removed from the foot area of the slump even to reduce the over-all slope, the report concludes.

Entitled "Landslides in Shale at Rapid City, South Dakota," the report not only aids in the solution of serious local problems but adds to data now being assembled to guide future planning, construction, and operation of engineering developments wherever similar geological conditions exist. It may be examined at Geological Survey offices, room 1033 (Library) and room G-206, General Services Administration Bldg., Washington, D. C.; at the Denver Information Office, 468 New Customhouse, Denver, Colo.; at the office of the State Geologist, University of South Dakota, Vermillion, S. Dak.; and at the library of the South Dakota School of Mines in Rapid City, S. Dak.

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