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Seismic Properties Investigation of the Springer Ranch Landslide, Powder River Basin, Wyoming

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1170-C

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By C. H. MILLER, A. L. RAMIREZ, *and* T. F. BULLARD

CONTRIBUTIONS TO GENERAL GEOLOGY

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SEISMIC PROPERTIES INVESTIGATION OF THE SPRINGER RANCH LANDSLIDE, POWDER RIVER BASIN, WYOMING

By C. H. Miller, A. L. Ramirez, and T. F. Bullard

ABSTRACT

A recent and rapid increase since the mid-1970's in commercial and residential development in the Powder River Basin, Wyoming and Montana, is caused by exploitation of vast coal and other resources in the basin. One geologic hazard to such development is landsliding. A landslide sufficiently representative of others in the area was chosen for detailed seismic studies. Studies of this landslide show that a low-velocity layer overlies a high-velocity layer both on the slide and away from it and that the contact between the volocity layers is nearly parallel with the preslide topographic surface. Computed shear and other elastic moduli of the low-velocity layer are about one-tenth those of the high-velocity layer. When failure occurs within the slope materials, it will very likely be confined to the low-velocity layer. The number and position of main shear planes in the landslide are unknown, but the main slippage surface is probably near the contact between the low- and high-velocity layers. The main cause of landslide failure in the study area is apparently the addition of moisture to the low-velocity layer.

INTRODUCTION

Exploitation of vast coal and other resources in the Powder River Basin, Wyoming and Montana, has caused a rapid increase in population and in commercial and residential development in the basin since the mid-1970's, and this rapid expansion is expected to continue. Results of engineering geology studies done by the U.S. Geological Survey will help ensure intelligent land utilization during this sudden expansion.

Landsliding is one of several geologic hazards to future development in the Powder River Basin. These landslides presently cause damage mainly to highways and agricultural land, but future construction may be inadvertently or necessarily sited on a potential slide or in its path. These landslide hazards are being investigated by the U.S. Geological Survey. The present report is a study of one landslide, here called the Springer Ranch landslide (fig. 1), by seismic-refraction and shear-wave techniques. The Springer Ranch landslide is sufficiently representative of the landslides in the area so that the principles learned from it can be applied to others. The results include a determination of the thickness and configuration of a low-velocity layer consisting of an incompetent mantle of weathered bedrock and colluvium which overlies

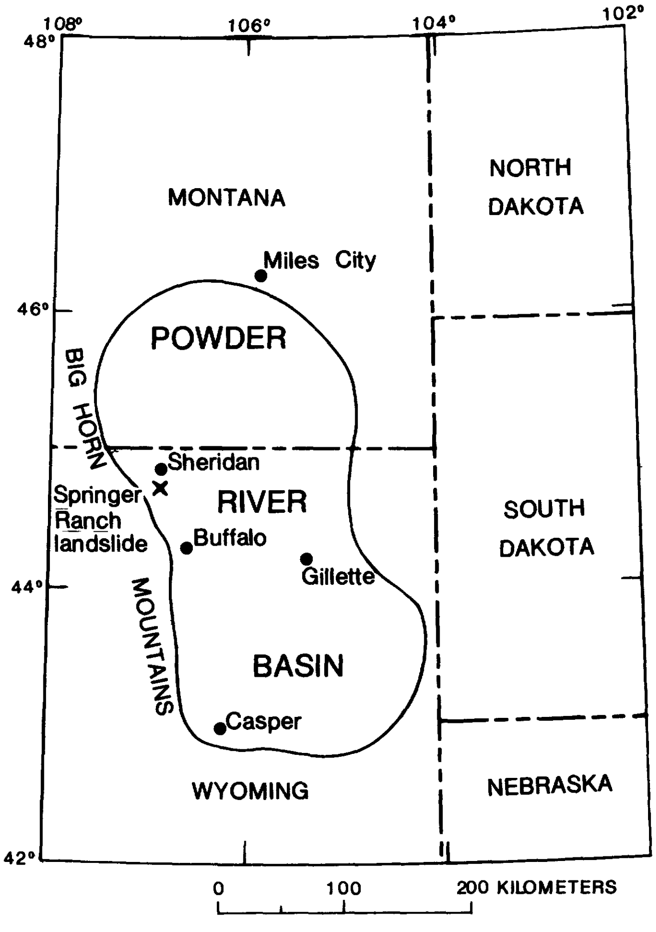

Figure 1.—Index map of the Powder River Basin, Wyoming and Montana, showing location of the Springer Ranch landslide.

moderately competent bedrock. The competency of the low-velocity layer is about one-tenth that of the underlying high-velocity layer and, therefore, the landslide is probably confined to this low-velocity layer.

ACKNOWLEDGEMENTS

We thank C. A. "Dick" Springer for permitting access to the landslide on his property and for his enthusiastic support. S. L. Obernyer participated in the seismic surveys. K.A. Hewitt, J.K. Odum, and P.S. Powers did the drilling and much of the core testing. We thank Frank W. Osterwald for his technical assistance.

GENERAL GEOLOGY

Geology and coal resources of part of the area under consideration, were described by Mapel (1959), and ground-water resources were described by Lowry and Cummings (1966). Preliminary landslide investigations in the western Powder River Basin were made initially by T. C. Nichols, Jr., and then by Chleborad, Nichols, and Ebaugh (1976) and Ebaugh (1976, 1977) as part of continuing engineering geology studies. These investigations have included much of the western part of the basin, but emphasis was placed on an area of 300 km^2 southeast, south, and west of the city of Sheridan, Wyo., where extensive slope failures have occurred (fig. 1).

Bedrock in this area of greatest slope failure is comprised of shale, fine-grained sandstone, and coal sequences of the Fort Union Formation and of the overlying Wasatch Formation. Both of these Tertiary formations dip slightly to the east away from the Bighorn Mountains and toward the Powder River Basin (fig. 1).

A mantle of unconsolidated or weathered bedrock, clay, silt, sand, gravel, boulders, and soil covers much of the bedrock in the study area. Terrace and pediment deposits of the area are as much as 14 m thick, floodplain deposits are as much as 30 m thick, but the thickness of colluvium seldom exceeds 3 m on the slopes, according to Mapel (1959). Incompetent weathered bedrock, however, may underlie the colluvium.

The landslides generally show both slump and earthflow types of movement (Chleborad and others, 1976). Many of the landslides are actively eroding present-day slopes, but some of the landslides have probably been active since prehistoric time or have, perhaps, been reactivated since then.

The immediate cause of most slope failures in the study area is probably an increased moisture content from either precipitation or irrigation. Rain and snow are most abundant in the Sheridan area during the spring; a very wet snow in April 1973, for example, is reported to have greatly increased the incidence of slope failure. Much of this precipitation presumably penetrates vertically from the ground surface. Landslides associated with irrigation, however, have been reported downslope from irrigated fields or unlined ditches. This moisture has apparently migrated laterally. The amount of slope failure contributed by either vertically or laterally migrating moisture is unknown.

In a detailed study of the factors that promote landsliding in the Big Horn quadrangle, which includes the Springer Ranch landslide, Ebaugh (1977) found that most slides occur on slopes facing in the direction of bedrock dip. He concluded that, on these slopes, artesian pore-water pressures can develop where clayey colluvium seals an outcropping bedrock aquifer. Through the principle of effective stress, these high pore pressures act to reduce effective normal stresses and thus to reduce the material's frictional strength. Ebaugh believes that failures tend to occur at the base of the colluvial layer.

Slopes that are cut in unweathered bedrock for highways and coal strip mines do not readily fail. The strip-mine walls are nearly vertical and as much as 30 m high, but they rarely fail within a few months' time, and their lifespan may be years. Most highway cuts are of lower angle slope, and the lifetime of these bedrock cuts may be decades of time. Slope failures that were promoted by highway construction and by streams that undercut the toes of potentially unstable slopes most likely are confined to the mantle of alluvium, colluvium, and unconsolidated or weathered bedrock. Unweathered bedrock apparently is not included in these failures.

SPRINGER RANCH LANDSLIDE

The Springer Ranch landslide is about 14 km south-southeast of Sheridan, Wyo. (fig. 1). It was selected for special study as representative of other slides in the area because of its geometry, slope, and orientation. The authors did detailed seismic-refraction and elastic moduli investigations in conjunction with other members of the USGS, who drilled the slide and installed piezometers and inclinometers in the drill holes. The drill holes were geologically logged, and static water levels and some physical properties of the mantle and underlying bedrock were measured.

Figure 2 shows the topography and geologic structure of the Springer Ranch landslide. The slide is on a northeast-facing slope. The limits of the slide are defined by either fresh fractures or sudden changes in slope, where healed fractures are evident. It is about 75 m long by 75 m wide and has moved down a gradient of about 5:1 (11°). Bedrock dip in this area is about 1° northeast.

Tensional and shear failure, with resulting slumps and open fractures, occurs at the head of the slide. The conspicuous main scarp at the head of the slide has at least 3 or 4 m of horizontal displacement and 0.6 m of vertical displacement. Many small scarps are evident uphill from the main scarp.

Shear failure, with accompanying earthflow, is apparent in the toe of the slide. Net movement to the northeast was accompanied by an "overthrust" bulge and apparent relocation of the course of a small intermittent stream. The horizontal distance that the bulge has overthrust onto the old land surface is unknown.

Five holes (fig. 2) were drilled and studied in the slide area. Lithologies (Ebaugh, 1977) included clay, shale, and fine-grained and poorly consolidated sandstone. Both fresh unweathered bedrock and the overlying weathered zone were defined on the basis of the state of relative oxidation: fresh bedrock, considered to be in the reduced state, is dark gray to blue gray; the oxidized weathered zone above is brown, orange, and yellow, in verying proportions; and the contact between the weathered zone and the fresh unweathered bedrock is gradational. Drill hole CHP penetrated bedrock at 10.7 m, but bedrock was not found in the other four holes, whose depths ranged from 5.9 to 7.3 m.

SEISMIC INVESTIGATIONS
FIELD SURVEYS

Seismic investigations of the Springer Ranch

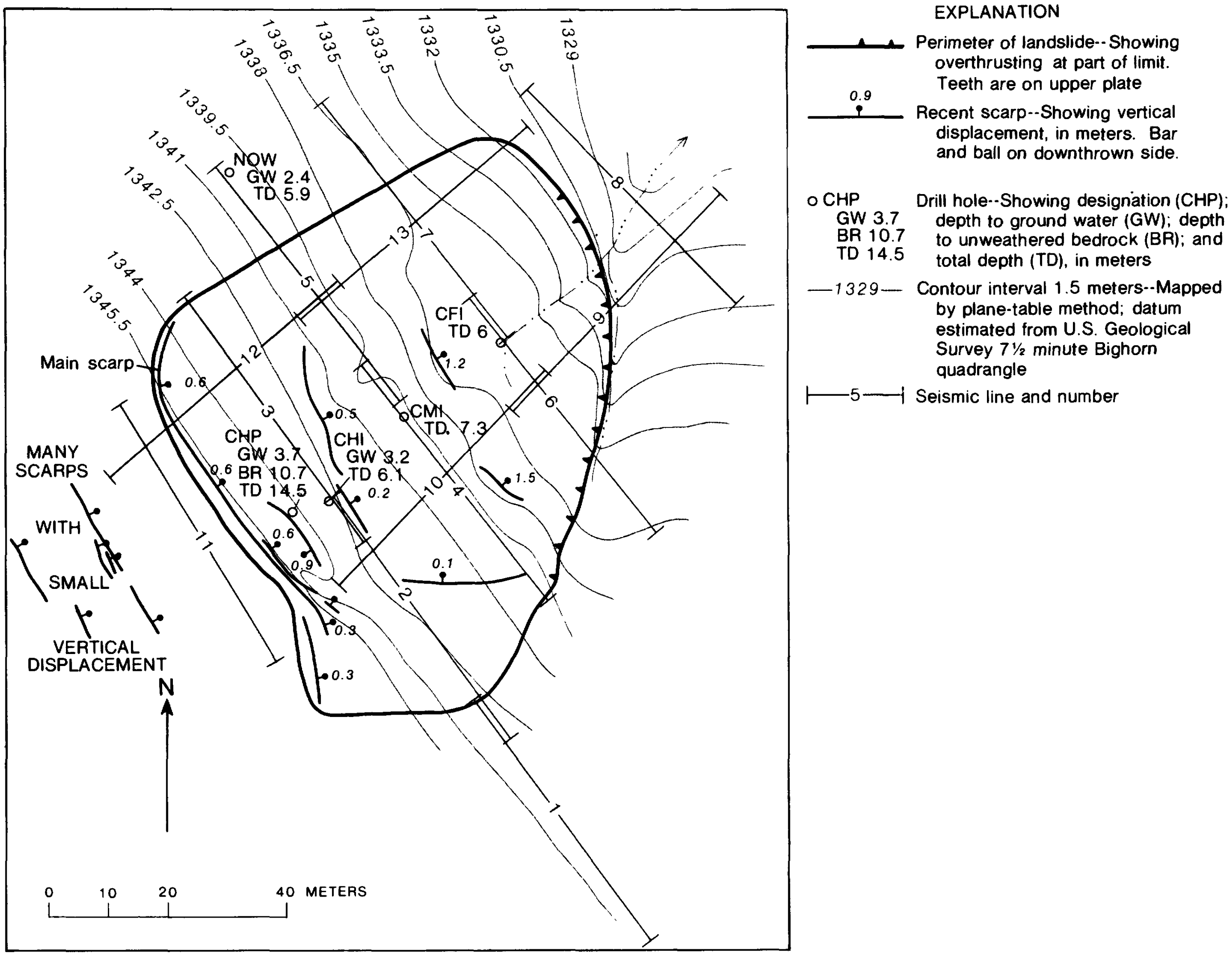

FIGURE 2.—The Springer Ranch landslide, showing geologic structure, topography, and locations of seismic lines and drill holes.

landslide were comprised of a refraction (compressional-wave) survey to determine the thickness and configuration of the slide and a shear-wave survey to determine the shear modulus of both the landslide and the underlying material that had not failed.

Thirteen seismic-refraction lines (fig. 2) were run, and one shear-wave line reoccupied the position of refraction line 2. The seismic lines were oriented mainly either parallel or perpendicular to the hillside, and lines were extended to the perimeter of the landslide. Line 1 was located completely off the landslide to provide seismic data that could be compared with data from lines on the slide.

Twelve seismometers were emplaced along each line at 4.2-m intervals for both the refraction and shear-wave surveys. Each line was 50.3 m long, and where the lines were end to end, they were overlapped 8.4 m to provide continuous information at depth. The shotpoints for the refraction lines were directly under the end seismometers and were in shotholes that were about 0.6 m deep. Charges in the shotholes were equivalent to about 50 g of 60-percent dynamite, which was detonated with electric caps. The energy source for the shear-wave line was also at the end seismometers of line 2. This source was a wooden plank, weighted down and perpendicular to the seismic line. Horizontally oriented geophones were planted for the shear-wave surveys, and the ends of the plank were struck with a sledge hammer. The blows were alternated for each seismogram, so that reversed particle motion could be observed on the seismogram.

LOW-VELOCITY LAYER

Figure 3Y shows the time-distance curves for seismic lines 1 and 2. The methods of measurement along each line are the same, but line 1 is off the slide, whereas line 2 is on it.

Two velocity layers are clearly defined by the time-distance curves (fig. 3Y) of either line 1 or line 2: a low-velocity layer that overlies a high-velocity layer. These two velocity layers are also defined by all the other seismic lines on the landslide. In addition, other seismic lines that have been run in the northern part of the Powder River Basin and away from the Springer Ranch landslide (R.A. Farrow, C.H. Miller, and A.L. Ramirez, written commun., May 1977) also define two velocity layers. The average velocity of the low-velocity layer along line 1, off the slide, is 380 m/s, while the average velocity of the 12 lines on the slide is 407 m/s. The average velocity of the seismic lines in other parts of the basin is 390 m/s. We conclude, therefore, that (1) there is no appreciable velocity contrast in the low-velocity layer between the landslide and adjacent undisturbed ground, (2) the low-velocity layer extends into at least part of the Powder River Basin, and (3) the low-velocity layer includes the landslide, but any buried main surface of rupture of the slide may not necessarily coincide with the lower boundary of the low-velocity layer.

THICKNESS AND CONFIGURATION OF THE LOW-VELOCITY LAYER

Thickness and configuration of the low-velocity layer at the Springer Ranch landslide were interpreted from the seismic-refraction data by using the method of differences (Edge and Laby, 1931, p. 637–671, modified by J. C. Hollister, Colorado School of Mines, written commun., 1957; Redpath, 1973). The advantage of this method is that it accounts for variations in thickness of the low-velocity layer. The variations may be due to a change in the surface topography or in the topography of the buried contact between the low-velocity and high-velocity layers or in both. The results of the interpretation of thickness and configuration of the low-velocity layer at the slide are summarized by the isopach map and by cross sections *A-A′* and *B-B′* of figure 3.

Although the seismic lines were run over undulating topography, the contact between velocity layers does not undulate, and it is nearly parallel with the restored topographic surface. The thickness of the low-velocity layer ranges from about 3.0 m at the head of the slide to more than 7.5 m at the toe bulge. The thickness of the undisturbed low-velocity layer away from the slide ranges from about 4.5 to 6.0 m. The thickness of the low-velocity layer at the bulge, furthermore, is at least 7.5 m, which supports the observation that the toe of the slide is overthrust on a relatively undisturbed, low-velocity layer.

CORRELATION OF THE LOW-VELOCITY LAYER WITH WEATHERING AND GROUND WATER

Although the velocity curves (fig. 3Y) clearly show two velocities whose layers contact at the depth shown by the isopach map (fig. 3X), the refraction path is above fresh unweathered bedrock. The fresh unweathered bedrock, however, is defined by visual inspection of cores from only one drill hole, CHP. The seismic waves, nevertheless, "see a path" through the subweathered zone that is about four times faster than that of the low-velocity layer. The velocity of propagation of compressional waves depends upon the elastic moduli of the media, and the high-velocity layer is proportionately more competent than the

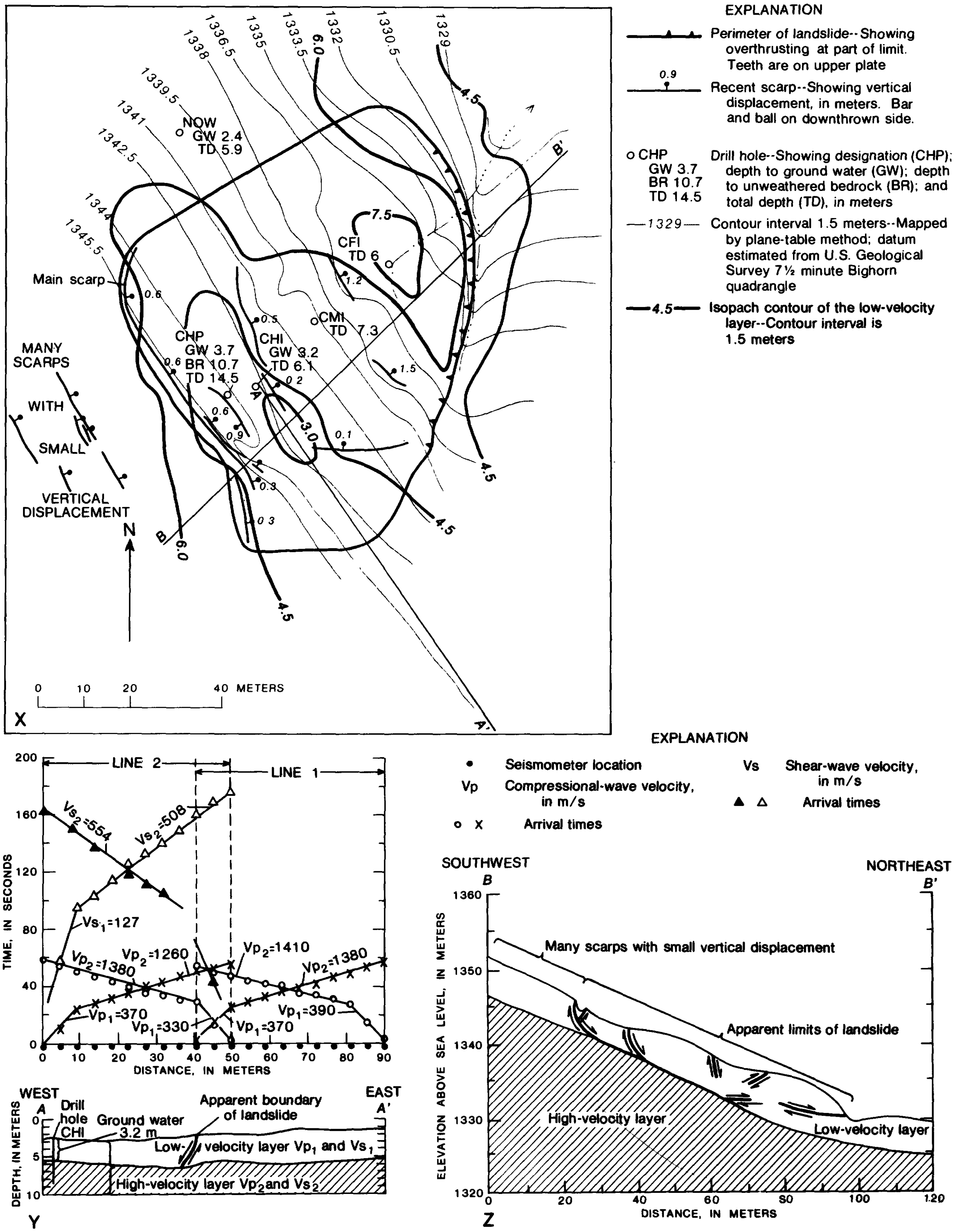

FIGURE 3.—Seismic investigation data and interpretations of high- and low-velocity layers across the Springer Ranch landslide. X, Isopach contours of the low-velocity layer determined by seismic refraction methods. Y, Time-distance curves and geologic interpretation along seismic lines 1 and 2 (fig. 2) and *A-A'*. Z, Cross section *B-B'* of velocity layering in the landslide.

low-velocity layer. Competent bedrock, therefore, is here defined by the high-velocity layer, and the incompetent mantle that overlies it is defined by the low-velocity layer. The mantle includes colluvium and unconsolidated and weathered bedrock.

Figure 3Y shows that three of the five drill holes penetrated static ground-water levels. The levels, however, are dependent on depth of casing and time of measurement, and these data are regarded as preliminary. There is no correlation between the thickness of the low-velocity zone and these preliminary static water levels. Density-moisture laboratory data from the five drill holes, moreover, show that the degree of saturation in the low-velocity layer ranges from very moist to almost completely saturated.

In an idealized, shale-free, unconsolidated sandstone that is saturated and under heavy static load, velocity of compressional waves shows an averaging effect between the velocity of sand grains and that of pore water (Wyllie, 1963, p. 130). The seismic velocity of water is about 1,525 m/s, while that of silica grains is about 5,000 m/s. This relationship does not hold, however, in fine-grained, near-surface sediments, and the propagation velocity may be much less than that of either the water or the sand grains (Bailey and Van Alstine, 1973). For example, a seismic line was run several kilometers away from the Springer Ranch landslide through a slough where ground water was within 0.5 m of the ground surface. The velocity of the 100-percent saturated layer, however, was only about half that of water. Evidently, the interstices of very fine grained rocks are ineffectively connected, so that neither fluid-borne nor grain-borne seismic waves are transmitted efficiently.

SHEAR WAVES AND ELASTIC MODULI

A seismic shear-wave line was also run along line 1 (fig. 2) to determine the shear-wave velocities of both the low- and high-velocity layers. The elastic moduli and Poisson's ratio (Leet, 1950, p. 38-40; 1960, p. 70-72) were computed from the shear- and compressional-wave velocities and from bulk densities measured on core. The results are summarized in figure 4.

Data show that the shear moduli and the other elastic moduli of the low-velocity layer are about one-tenth those of the high-velocity layer. Therefore, failure within the slope materials will very likely be confined to the low-velocity layer. The amount and position of main shear planes in the landslide are unknown, but in figure 3Z the main slippage surface is assumed to be near the contact between the low- and high-velocity layers.

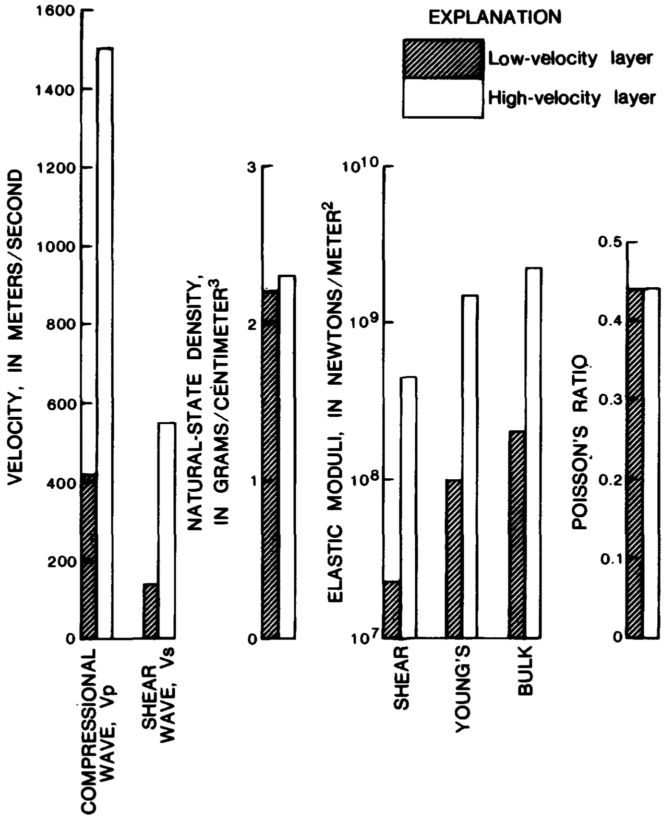

FIGURE 4.—Seismic velocities, natural-state densities, elastic moduli, and Poisson's ratio of the low- and high-velocity layers of the Springer Ranch landslide.

LANDSLIDE MODEL

These seismic investigations imply a shallow-slab landslide model in weak earth materials overlying shaly bedrock and with the toe of the slide at a break in the hillside slope similar to that described by Krynine and Judd (1957, p. 642-654). Their model has a relatively pervious layer developed over impervious bedrock. If the toe of the potential slide is near a decrease in gradient of the hillside, then any water introduced into the relatively pervious layer has difficulty discharging at the break in slope, where the gradient decreases. The ground water may not be visible at the surface, but in either case a hazardous condition is produced.

Cross section *B-B* of figure 37 shows that the toe of the Springer Ranch landslide is at a break in slope. The immediate cause of failure is unknown, but A. F. Chleborad and W.F. Ebaugh (oral commun., 1977) believe that moisture contributed to the weathered layer is the major factor. The moisture may be contributed by an artesian system beneath the weathered layer or by precipitation on the surface of the layer or by both. The moisture apparently promoted failure in two ways: (1) it increased pore pressure and lowered the shear strength of the already incompetent low-velocity layer, and (2) it added weight to the low-velocity layer.

SUMMARY AND CONCLUSIONS

Landsliding is a geologic hazard to the rapid development that is expected in the Powder River Basin. This paper reports the results of seismic-refraction and shear-wave surveys which are part of a detailed study of the Springer Ranch landslide south-southeast of Sheridan, Wyo. This landslide is sufficiently representative of other landslides in the area that the principles learned from it can be applied to the others.

The surveys determined that a low-velocity layer overlies a high-velocity layer, both on the landslide and away from it. The thickness and configuration of the low-velocity layer were determined by using the method of differences, which accounts for variations in thickness of the low-velocity layer. The variations may be due to a change in the surface topography or in the topography of the buried contact between the low-velocity and high-velocity layers or in both. The buried contact is nearly parallel with the restored topographic surface.

The low-velocity layer defines an incompetent mantle of colluvium and unconsolidated and weathered bedrock, and the high-velocity layer defines competent bedrock. Seismic data show that the shear moduli and other elastic moduli of the low-velocity layer are about one-tenth those of the high-velocity layer. Therefore, failure associated with landslides is confined to the low-velocity layer. The number and position of main shear planes in the landslide are unknown, but the main slippage surface is assumed to be near the contact between the low- and high-velocity layers.

The major immediate cause of landslide failure is probably the addition of moisture to the low-velocity layer. The moisture apparently promotes failure by increasing pore pressure, lowering shear strength, and adding weight to the incompetent low-velocity layer.

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