SLOPE INSTRUMENTATION USING MULTIPLE-POSITION BOREHOLE EXTENSOMETERS

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An unstable slope encountered during construction posed a serious hazard to men and equipment in the lower dam area of the Cabin Creek hydroelectric complex in Colorado. Following a series of rock slides, remedial work was undertaken to reinforce and stabilize the slope. As a part of the remedial program, multiple-position borehole extensometers were installed to permit the measurement of slope behavior and to provide safety monitoring for the protection of activities and facilities in the downslope construction area. The extensometers were read continuously when men and equipment were in the downslope area and intermittently at other times. All readings were immediately scanned to identify unusual or accelerating slope deformation. The readings were later processed by computer to permit a more detailed analysis of the nature, distribution, rate, and acceleration of displacements in each drill hole and an interpretation of the general behavior of the slope in the unstable area. Early in the Cabin Creek program, a method was developed for the comparison of displacement and displacement acceleration information by means of which surficial slumping and rebound influences could be isolated from other responses. The same comparisons were then used to identify periodic or continuing events related either in time, in space, or in both time and space. A final detailed interpretation of overall slope behavior was made on the basis of these space-time relationships. The Cabin Creek instrumentation illustrates the use of an economical and reasonably unsophisticated measurement program in support of other engineering activities in the diagnosis and solution of a serious construction problem.

•THE Public Service Company of Colorado Cabin Creek Project is located in the Rocky Mountains about 35 miles (56 km) west of Denver. The project, constructed in 1964-1966, consists of a 325-MW power generating-pumping plant, located at an elevation of about 10,000 ft (3050 m), and two embankment dams impounding reservoirs at about 10,000 and about 11,200 ft (3050 and 3400 m) (Fig. 1). The upper reservoir and the generating-pumping plant are connected by a 4,300-ft (1280 m) pressure tunnel excavated in rock. The generating-pumping plant discharges directly into the lower reservoir.

During periods of peak power demand, power is generated by the release of water from the upper reservoir, through the generating-pumping plant, into the lower reservoir. During periods of low power demand—usually late at night—the turbine-pumps are reversed and water is pumped out of the lower reservoir and back into the upper reservoir. The pumping operation requires about 356,000 horsepower, which is provided by Public Service Company of Colorado's steam generating plants in the Denver area.

The lower Cabin Creek dam is an earth and rock fill embankment with a sloping, compacted, impervious core and an impervious upstream blanket. Crest length is 1,180 ft (359 m), and height above bedrock is a maximum of about 80 ft (24 m). The dam provides about 1,800 acre-feet of usable storage. The upper dam, also an earth and rock fill embankment, impounds approximately 1,400 acre-feet of storage. Crest length is 1,490 ft (454 m), and maximum height above bedrock is about 200 ft (60 m). The interconnecting pressure tunnel averages about 14 ft (4 m) in diameter and is concrete lined, with an additional steel liner in the lower section. Net maximum head in the upper reservoir-tunnel-generating plant system is 1,190 ft (363 m).

GEOLOGY AND GEOGRAPHY

The Cabin Creek complex is located in one of a prominent series of glaciated, north-south trending valleys near the west edge of the Colorado Front Range. The lower dam, reservoir, and generating-pumping plant are located on the floor of the valley. The upper dam and reservoir are located in a small hanging valley tributary to the main drainage. The main valley—the valley of the South Fork of Clear Creek—is moderately U-shaped in profile and ranges from a few hundred feet to perhaps 2,000 ft (approximately 75 to 600 m) in width in the general vicinity of the project. Several old rock slides are evident, at least two of which temporarily blocked the valley, forming lakes in which varying sequences and thicknesses of stream sediments, lakebed sediments, and organic sediments were deposited. The small hanging valley—the valley of Cabin Creek—enters the main valley from the southwest at a point more than 1,000 ft (305 m) above the valley floor.

Bedrock in the project area consists primarily of Precambrian quartz monzonite and hornblende gneiss, cut by scattered pegmatite dikes. The rock is hard and durable except where subject to local hydrothermal alteration. The altered zones, which are few in number and small in areal extent, are characterized by a general softening of the rock and by the development of clayey textures in the most intensely altered materials—generally along particular fractures and at complex fracture intersections. In addition to the landslide and lake sediments previously noted, the valley floor and walls are covered, from place to place, by varying thicknesses of outwash sediments and glacial moraine.

Each valley wall is paralleled by a pronounced set of joints, which exercise a broad control over the attitude of the slopes. These joints, attributed to stress relief occasioned by the melting of the valley glaciers, appear to become more widely spaced—and finally to disappear—at depth behind the valley walls. Other identifiable joints include a set striking parallel to the valley and dipping steeply toward the west, a set striking parallel to the valley and dipping gently toward the west, and a set striking more or less east-west—across the valley—and standing vertically. Foliation is pronounced in the gneiss, with laminae predominatly oriented north-south, dipping 60-80 deg west.

ROCK SLIDES IN THE LOWER DAM AREA

One of the first steps necessary in the construction of the lower dam was the relocation of an existing county road. The road was moved from the valley floor to a new alignment about 75 ft (23 in) above the floor on the west side of the valley. During the relocation, several small rock slides were encountered in a small area near the west abutment of the lower dam and almost directly upslope from the intake portal of the lower dam spillway tunnel. The slides were minor in extent and did not appear to reflect larger movements. The hillside was graded to an apparently stable 3/4:1 slope, and construction of the lower dam and spillway tunnel proceeded as planned.

The spillway tunnel, which is approximately 14 ft (3 m) in diameter and 700 ft (210 m) long, was excavated in competent rock with a minimum of difficulty. Following the completion of excavation, work was begun on a reinforced concrete intake structure at the upstream tunnel portal. During construction of the intake, a substantially larger rock slide occurred without warning. The slide, which started directly upslope from the relocated county road, was approximately 250 ft (76 m) wide, extended about 200 ft (61 m) up the slope from the road, and contained an estimated 85,000 yd^3 (65 000 m^3) of rock. The slide overflowed the county road and covered the spillway intake structure with approximately 40 ft (12 m) of debris.

Immediately after the slide an engineering investigation was undertaken to evaluate the implications with respect to the entire project. Had such a slide occurred in the same or a comparable location when the reservoir was full, a serious safety hazard would undoubtedly have resulted in the downstream area. Consequently, it was necessary to completely review the overall safety aspects of the location of the lower dam, the design of the spillway intake structure, and the alignment of the relocated county road.

As a result of the investigation, a remedial program was developed consisting of seven principal steps:

1. Removal of the slide debris and reshaping of the slope to the most favorable possible attitude.
2. Installation of rock bolts to varying depths in the slope, the bolting to be accomplished as the slide debris was removed and the slope reshaped.
3. Diversion of surface drainage away from the slope, particularly in the area immediately above the slide. This was accomplished by the relocation of one small stream to drain to the downstream side of the dam, by the construction of paved drainage ditches upslope and downslope from the slide, and by drain holes drilled in the slope itself.
4. Redesign of the spillway intake structure to withstand greater earth loads and to protect valve controls and operators from falling rock.
5. Relocation of the inlet to the spillway structure 150 ft (46 m) out into the reservoir. This was accomplished by using two 6-ft (2-m) diameter steel pipes.
6. Construction of a load surcharge at the toe of the valley slope below the slide area. The surcharge was formed by wrapping the upstream side of the dam around the spillway structure and extending it for a short distance upstream from the slide area. The surcharge also served to cover and protect the inlet pipes leading to the intake structure.
7. Development of a monitoring program to evaluate the stability and safety of the slope both during and after the remedial program.

The main features of the remedial work are shown in Figure 2. The remainder of this paper is a description of the measurement and monitoring program and of the principles developed for evaluation of the stability and general safety of the slope area both during construction and during the subsequent operation of the completed Cabin Creek facility.

INSTRUMENTATION

The principal instruments used in the Cabin Creek instrumentation program were wire-type multiple-position borehole extensometers. Generically, borehole extensometers are instruments designed to measure rock mass, soil mass, and structural deformation by means of the sensitive and reasonably precise measurement of changes in the lengths of drill holes or sections of drill holes. Extensometers are available for use in drill holes of virtually any diameter and of depths as great as several thousand feet (1 km or more). "Single point" instruments are used to measure changes in the total length of a drill hole. "Multiple point" instruments measure changes in the lengths of a selected number of drill hole segments as well as changes in the total length of the hole. Extensometer sensitivity is on the order of less than 0.001 in. (0.02 mm) to several thousandths of an inch (0.1 mm). Useful instrument range commonly varies, for different types of extensometer, from less than 1 in. (25 mm) to as much as several feet (1 m or more).

The type of multiple-position borehole extensometer used at Cabin Creek consists of an instrument "head" (Fig. 3) mounted at the drill hole collar and eight in-hole anchors, each secured tightly in position at a selected depth in the drill hole. Each in-hole anchor is attached by means of a high-strength, stainless-steel wire to an individual transducer in the instrument head. As the rock, soil, or structural mass is deformed, changes in the length of the drill hole are registered by the series of transducers in the instrument head and converted into either mechanical or electrical impulses, which may be read manually or recorded automatically for subsequent reference. Readout may be accomplished either at the instrument head or remotely, depending on

Figure 1. Cabin Creek pumped storage hydroelectric project.

Figure 2. Generalized section of project.

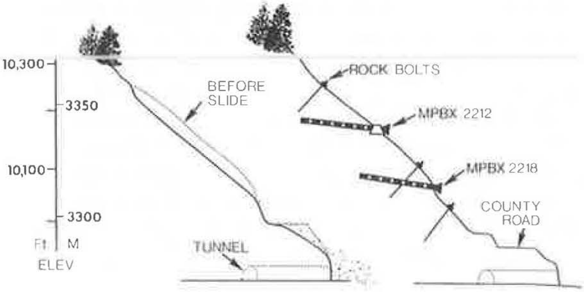
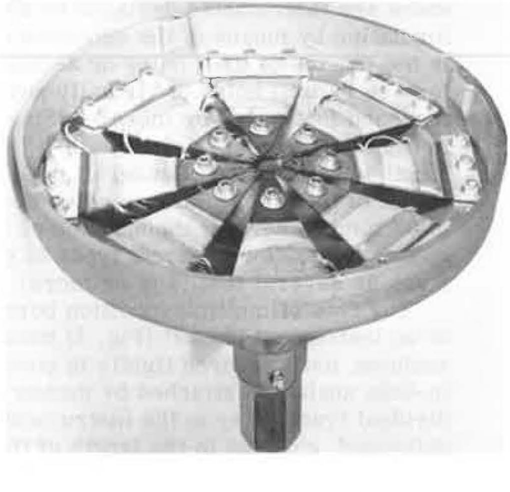


Figure 3. Instrument head, F-2 multiple-position borehole extensometer.



the circumstances of individual installations. In the Cabin Creek program, the instruments were read electronically from remote points well clear of the area of known instability.

The Cabin Creek extensometer holes were 2¼ in. (57 mm) in diameter, percussion-drilled, and of the lengths and attitudes listed in Table 1.

Inasmuch as an extensometer measures in a plane containing the length of the drill hole, the holes are customarily oriented to provide for measurement of the most favorable component of deformation in the plane or planes in which such deformation is most likely to occur. Other instruments are available for other applications.

In the Cabin Creek program, some or all of the extensometers were read continuously whenever men or equipment were present in the downslope construction area. The readings were made manually by an engineer or qualified instrumentation technician, who also was responsible for making an immediate sight interpretation of the data and for maintaining a continuous visual surveillance of the slope and adjoining areas. The engineer or technician was charged with the responsibility for immediately sounding an alarm in the event of a departure—however slight—from an acceptable pattern of instrument or visual responses. All instrument readings were later processed by computer to permit a more detailed analysis of the nature, distribution, rate, and acceleration of all measured displacements in each drill hole, in order to obtain a more definitive interpretation of the behavior of the slope in the unstable area.

REPRESENTATION OF EXTENSOMETER DATA

In slope investigation applications, the extensometer instrument head is most frequently located in the unstable area and thus undergoes more displacement than do the successively deeper in-hole anchors. The deepest in-hole anchor, usually situated beyond or outside the principal zone of deformation or displacement, thus constitutes a point relatively "fixed in space" toward which—or away from which—the instrument head is displaced. The intermediate anchors are also displaced away from, or toward, the deepest anchor in proportion to their individual locations in the deforming zone. It is sometimes convenient to visualize the instrument head as a yo-yo attached by its string (the measuring wire) to the deepest in-hole anchor or to some intermediate anchor.

The yo-yo analogy is also useful in understanding the format of the standard multiple-position borehole extensometer displacement plot (Fig. 4), in which the zero ordinate (of displacement) is taken, by definition, as a straight line representing the trace of the deepest in-hole anchor. All changes in distance between the instrument head and the deepest anchor are, therefore, attributed to displacement of the instrument head rather than to displacements involving a change in the position of the deepest anchor in space.

Figure 4 is a displacement-acceleration representation of data obtained from MPBX 2212, MPBX 2218, and MPBX 2219 during the Cabin Creek instrumentation program. For MPBX 2218, the zero displacement ordinate is the trace of the deepest 98-ft (30 m) anchor. Each of the other traces is labeled with a notation of the interval it represents; i.e., the 98-80 ft (30-24 m) trace defines the displacement of the 80-ft (24-m) anchor relative to the 98-ft (30-m) anchor. The 98-0 ft (30-0 m) anchor, by this token, defines the displacement of the instrument head at 0 ft relative to the 98-ft anchor. The abscissa is elapsed time (months) since instrument installation.

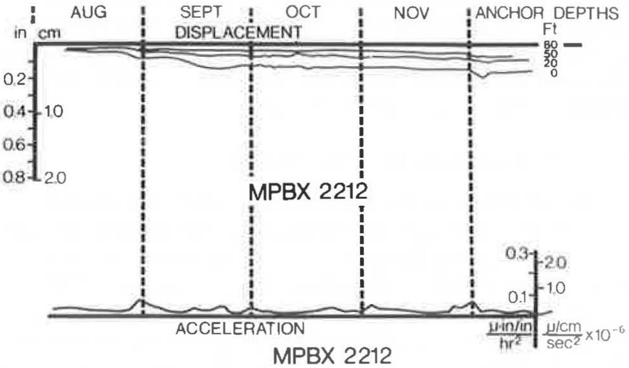
In the companion curve, the acceleration of displacement is represented versus elapsed time for the single interval 98-0 ft (30-0 m) comprising the entire length of the MPBX 2218 drill hole. This "average acceleration" curve is a useful adjunct to the displacement representation in defining the development of potentially adverse deformation in time. An inspection of the displacement representation will show that, although all values are plotted as functions of time, the factors that emerge most clearly in that particular format are those relating primarily to the spatial distribution of deformation in the drill hole. The use of both formats, therefore, permits the ready identification and analysis of deformation in both space and time in one drill hole. By combining the information with equivalent information from other extensometers in other drill holes, the space-time analogy can be extended in another plane to comprise all or part of the area under investigation.

Table 1. Multiple-position borehole extensometer data.

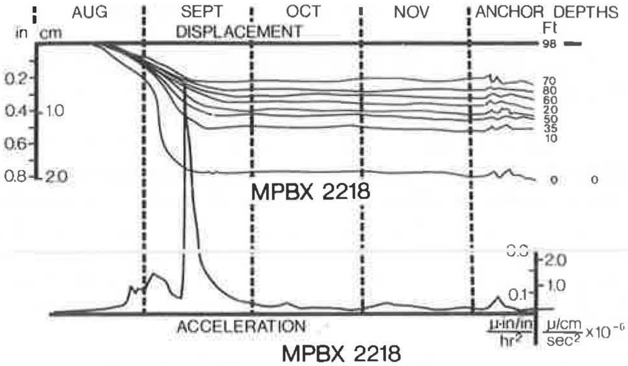
MPBX S/N	Hole Depth (ft)[a]	Inclination (deg)	Anchor Depths From Hole Collar (ft)[a]
2212	80	+5	10, 20, 30, 40, 50, 58, 70, 80
2213	77	+5	10, 20, 30, 40, 50, 60, 70, 77
2218	98	+7	10, 20, 35, 50, 60, 70, 80, 98
2219	100	+4	10, 20, 30, 85, 100
2220	150	+9	30, 50, 70, 90, 110, 130, 150
2221	125	+7	10, 25, 45, 65, 85, 97, 115, 125
2221-A	93	+15	5, 15, 25, 40, 53, 70, 85, 93

[a] 1 ft = 0.3048 m.

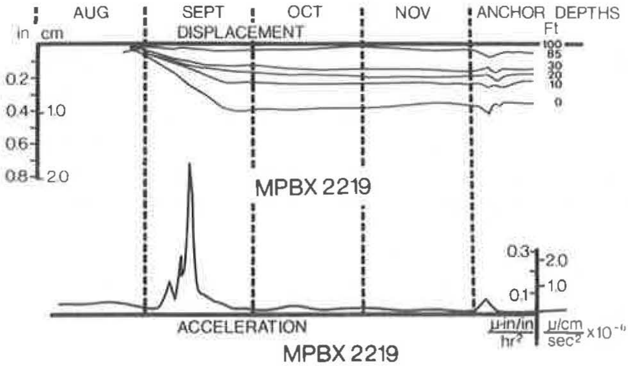
Figure 4. Displacement and acceleration graphs.



MPBX 2212



MPBX 2218



MPBX 2219

The MPBX 2218 representations are cited as an informative example because of an unusually complete pattern of responses initiated by a heavy 4-in. (100 mm) rainfall to which the slope was exposed prior to completion of the remedial program. Referring first to the displacement representation and then to the average acceleration curve, these responses were more or less as follows:

1. Displacement—The first active reading (FAR) of MPBX 2218 was made at an elapsed time (ET) of approximately 21 days. Subsequent early readings showed a pattern of continuing displacements, proceeding at a reasonably constant rate, which were attributed to rebound induced by the slide and by the additional removal of superincumbent load during stripping and shaping of the slope. The displacement rate was about 4.0×10^{-4} in. per hour (3.0×10^{-4} μm per second), equivalent, in a 98-ft (30-m) hole, to a strain rate of 0.3×10^{-6} in. per in. per hour (10 μm per cm per second).

At an ET of approximately 8.0 days, the slope received over 4 in. (100 mm) of rain in a 24-hour period. Shortly thereafter, at ET 11.9 days, displacements rapidly accelerated, accelerating still further at about ET 13.1 days. Soon after the onset of the accelerated displacements, some surficial slumping and considerable rolling rock could be seen on the slope. By this time men and equipment had already been removed from the downslope area, the judgment having been made on the basis of the instrument data at about 12.3 days ET.

The displacement rate reached a maximum at about 14.5 days, thereafter subsiding gradually until about 16.9 days, at which time a relatively constant low gradient was reestablished. The new gradient was at an appreciably lower rate than the gradient measured prior to the rainfall. By about ET 31.2 days, displacements in the vicinity of MPBX 2218 had essentially ceased. The perturbations in the curves at about 85.4 days resulted from ice accumulation in the instrument head following an interruption of electric power to the heated instrument enclosure and hence do not reflect real data.

Note the irregular, saw-toothed pattern in all of the displacement curves at about ET 29.1 days (mid-September). This reflects an uncorrected temperature response for a daily temperature fluctuation of about 55 F (13 C), which was left in the data for reference and calibration purposes. The calibrated response of the Cabin Creek extensometers to temperature variations was slightly more than 0.02 percent per degree F (0.04 percent per degree C).

A quick inspection of the displacement curves from MPBX 2218 indicates that about half of the total displacement measured in the MPBX 2218 drill hole was localized in the interval between the 98-0 ft (30-0 m) and 98-10 ft (30-3 m) traces; i.e., in the surface 10 feet (3 m) of the hole, a condition strongly suggestive of surficial slumping in the disturbed slope material.

The presence of an appreciable interval between the zero ordinate and the 98-80 ft (30-24 m) and 98-70 ft (30-21 m) traces indicates that the deep part of the drill hole, at least to the location of the 80-ft (24 m) anchor, is not beyond the zone affected by the slope deformation. The progression of these deep displacements from ET 2 days appears, however, to be generally consistent with rebound rather than with the accelerating pattern of displacements registered by the shallower anchors after the 4-in. (100 mm) rainfall.

2. Average acceleration—Shortly after installation of MPBX 2218, a succession of discrete accelerations, each greater than the preceding one, was registered. The pattern cast some doubt on the "rebound" hypothesis, and the acceleration representation was watched closely for further developments.

After the rainfall, a succession of accelerating displacements was registered, the largest occurring at ET 14.6 days. The acceleration at ET 14.6 days was equivalent, in a 98-ft hole, to a strain change rate of 8.25 microin. per in. per hour per hour (6.35×10^{-5} μm per cm per second per second). Thereafter, the acceleration decreased gradually, approaching zero at about ET 23 days.

In considering the relationship between displacement magnitude, rate, and acceleration, several fundamentals are worth reiterating:

1. If the meaning of a "failure" is interpreted in its broadest sense; i.e., as an unexpected or unforeseen event constituting either a safety threat or an economic blow, it is apparent that neither displacement magnitude nor displacement rate are of much value in predicting when—or if—a failure might occur. Depending on the particular circumstances of a project and the types of materials involved, very substantial amounts of deformation can occur, at very appreciable rates, without constituting a failure in the broad sense.
2. Acceleration, on the other hand, is definitive. Acceleration, if continued, is certain to lead to a failure, whatever the sense in which failure is defined.
3. A preoccupation with acceleration, however, is not a simple answer. Large magnitudes of deformation, developing at high deformation rates, can occur without evidence of acceleration in instances in which the deformation is developing either at a reasonably constant rate or at a rate that is increasing in a series of spasmodic or periodic bursts of short duration with intervening periods of constant displacement at the progressively elevated rates.

Fortunately, the dual plotting formats previously outlined provide a ready and convenient means for evaluating each of the three major parameters of displacement, rate, and acceleration. Displacements and accelerations are, of course, measured directly from their respective curves. Rate can be readily determined by either measurement or inspection of the slope of the displacement (magnitude) curve.

From the foregoing discussion, it is apparent that different perspectives may be required in order to evaluate different situations and address different problems. It is also apparent that different sorts of information can be developed and slighty different conclusions drawn on the basis of different representations of the same fundamental information. The implications of these considerations are developed, for the specific Cabin Creek application, in the following sections.

INTERPRETATION OF EXTENSOMETER DATA

Figure 4 shows displacement and average acceleration measurements by three representative multiple-position borehole extensometers. Each of the sets of curves is arranged according to a single common time base in order to facilitate the comparison of data from instrument to instrument and the comparison of measured events with various other construction activities.

The displacement curves alone are quite ambiguous, particularly in regard to the events following the rainfall. One instrument, MPBX 2218, registered the very appreciable displacements already described. Another, MPBX 2212, registered little activity. The remaining instrument, MPBX 2219, indicated an intermediate low level of displacement. Although the curves develop a considerable amount of useful information in regard to possible rebound adjustments, possible surficial slumping, and the stability or instability of specific local areas of the slope—those areas in which each instrument was specifically located—the general progression and nature of the data offers little basis for evaluation of the probable stability of the entire slope. The best that can be said is that, in point of displacement magnitude and distribution in space, there is no definitive indication of the concerted movement of a single block of any appreciable size. The suggestion is, however, that the various parts of the slope responded to the same stimuli at about the same times and that only the magnitude of the response differed from hole to hole. This would imply that, given an adequately intense stimulus, the entire slope might respond in a violent or hazardous manner.

The acceleration curves, on the other hand, provide a substantially different view of the same events. On the basis of these curves the faintly ominous displacement events are seen to be spread in time. Neither the distribution nor sequence of the acceleration peaks—at least those associated with the rainfall—suggests a systematic dislocation of a block of any appreciable size. In other words, the overall response of the slope with respect to both displacement and average acceleration was substantially less disturbing than the displacement curves alone would have suggested.

A less reassuring aspect of the acceleration curves is a pattern of accelerations registered in late August and early November by MPBX 2212 and MPBX 2218 and at other times by other combinations of instruments. These accelerations, although slight, did appear to be aligned in time and thus may reflect influences potentially adverse to larger areas of the slope. For the specific events noted, reference to the displacement curves failed to reveal any evidence of appreciably increasing displacements. Nevertheless, any events common among groups of instruments with regard to either time or space should be watched closely for indications of potentially adverse long-term trends.

MPBX 2211-A

MPBX 2211-A was a special-purpose extensometer installed at the toe of the slope to measure the response of the toe area to the construction of the safety surcharge previously noted. The response of MPBX 2211-A, and lesser responses of MPBX 2219 and 2220 at about the same time, reflected a general compaction of the toe under the surcharge load.

SUMMARY AND CONCLUSIONS

The conclusions drawn from the extensometer information were as follows:

1. A slope disturbed by a slide and by the remedial measures occasioned by the slide undergoes a sequence of adjustments that include rebound and a certain amount of surficial sloughing and slumping. These adjustments, in and of themselves, have little structural significance.
2. With respect to the Cabin Creek slope, specifically, the remedial measures applied after the May 13, 1965, slide did effectively improve the stability of the slope, to the extent that it withstood a reasonably heavy rainstorm—before the remedial program was completed—with only superficial slumping and without indications of the instability of any block or area of appreciable or even identifiable size.
3. Insofar as the indicated safety factor of the slope after the rainfall and prior to completion of the remedial work was obviously greater than 1.0, the safety factor of the slope at the conclusion of the remedial program was considered to be substantially greater than 1.0 with respect to deformation of a structurally meaningful nature.

In the 8 years since the May 13, 1965, rock slide, no additional slope problems have been encountered.

The Cabin Creek instrumentation is an excellent example of an economical, practical, and reasonably unsophisticated program applied—in support of other engineering activities—in the evaluation and solution of a serious and hazardous construction problem. The data developed by the instrumentation program were used to guide and evaluate the remedial treatment of a known unstable slope, to reduce the hazards to men and equipment in a vital construction area, and in general to materially reduce the usual uncertainties in engineering judgments of rock mass and soil mass stability.

Perhaps an important final concept is that of practical, applied, instrumentation as a useful tool for engineers and engineering geologists, rather than as a separate—frequently obscure—technology wrought by practioners who are neither quite fish nor quite fowl. Extending this concept to more varied applications and more complex problems can only contribute to the further control of hazards, reduction of costs, and improvement of maintenance in both the construction and operation of engineering works.

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