Progress in Rock Slope Stability Research

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The U. S. Bureau of Mines and Kennecott Copper Corporation are engaged jointly in a research program directed toward the development of scientific tools for the design and control of rock slopes. Scientific methods are being developed and evaluated in the program to measure quantitively the effect of rock structure, stress, strength, and ground water on slope stability.

Stresses are being determined from strain or stress-relief measurements made with a borehole deformation gage developed by the U. S. Bureau of Mines or from piezometer measurements. The strength analyses are based on meticulous study of rock structure and strength, and the effect of rock structure and moisture on the strength of a slope. Superficial study of structure is being supplemented by observations inside boreholes with cameras. The slope strength is being investigated by laboratory testing of drill cores from the study area. These tests are to investigate the strength of the rock formations, the frictional resistance along fractures or fractured zones in the rock, and the effect of moisture on strength.

A successful conclusion of the research program should provide the tools to solve two major problems that are encountered with rock slopes: (a) detecting instability before failure develops, and (b) predetermination of precise, safe-maximum slope angles with known safety factors.

•MANY MODERN highways require the excavation of deep cuts in rock. The highway engineer is confronted with the problem of estimating the slope angles for the sides of a cut. The steepness of the slopes governs the quantity of rock to be excavated and it may be the determining economic factor as to whether a tunnel or cut is used in the construction of a new highway.

The mining engineer is confronted with a similar problem in open-pit mines. In these mines the steepness of a pit slope is of major economic importance because the slope predetermines the quantities and costs of waste material removal necessary to recover ore. The ultimate objective is to make the steepest safe slope possible so that the ore can be recovered with the least amount of waste stripping.

The slope stability varies widely for different areas of a pit. Some pit slopes are as flat as 20° from the horizontal, yet they tend to be unstable. Others stand to heights of 600 ft or more at 45° and show no evidence of instability.

Figures 1 and 2 show the importance of determining the various factors that cause slides so that slopes can be designed without risk of failures. Figure 1 shows a slide that occurred in 1930 in the Bingham Canyon pit of Kennecott's Utah Copper Division. About 8,000,000 tons of broken rock were involved in this slide. Figure 2 shows a 1957 slide at the Liberty Pit of Kennecott's Nevada Mines Division at Ruth. About 2,000,000 tons of broken rock moved in this slide and caused a production stoppage for several weeks.

The relationship between steepening slopes and decreasing waste removal requirements ahead of ore mining is apparent. Past and current pit design practices have

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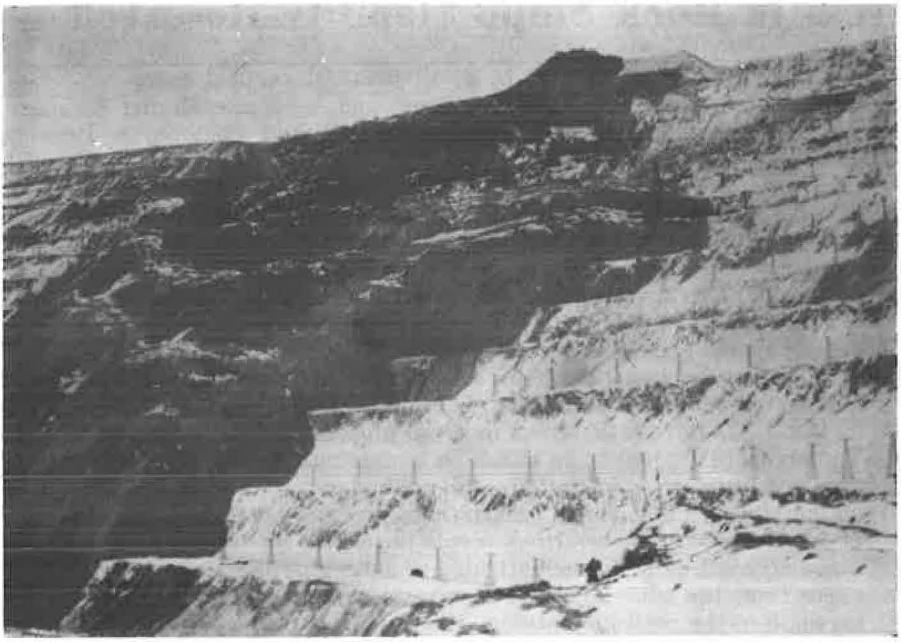

Figure 1. Slide at Bingham Mine.

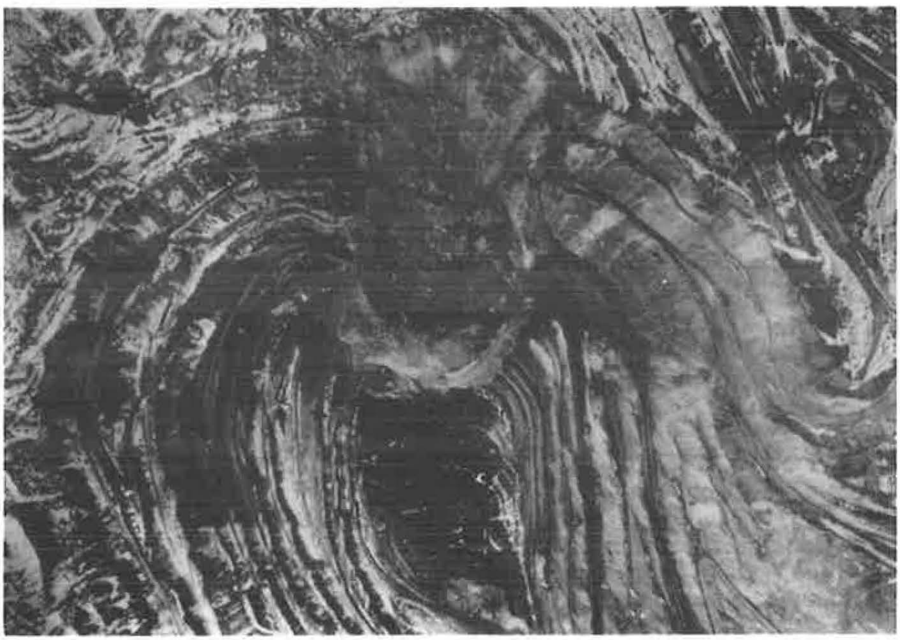

Figure 2. Slide at Liberty Pit.

been and still are based on "cut and try" methods. The two slides shown did result in new empirical design criteria for the pits involved. These experiences, however, are limited largely only to those portions of the pits in which the slides occurred. The remaining sections of the pits are subject to still other stability factors, which are, for practical purposes, unknown or at least unquantified.

Kennecott first sought to employ soil mechanics for determining slope stability in rock on the theory that such methods might apply because the pits are so large that over-all stability might be independent of the size of the largest rock particle, regardless of whether these were several inches or several tens of feet in size. Studies thus far do not support this thinking.

These studies do indicate that the application of soil mechanics is limited in open-pit mines to slopes composed of soil, or to slopes in active slide areas in which the broken, sliding rock mass possesses physical properties similar to soil. Also, as may be expected, the ground water in back of the slope appears to have a major influence on the stability of the slope. But perhaps equally important is the indication that unique combinations of rock structure are the primary cause of rock slope failures, with water seepage through the structures promoting the failures.

RESEARCH PROGRAM

A research program has been undertaken to develop and evaluate scientific methods to measure quantitatively the effect of rock structure and other factors on slope stability. Briefly, it is planned to determine the strength of the west slope of the Kimbley Pit at Ruth, Nev., and to estimate slope angles with safety factors within definite confidence intervals. This is a joint project of the U. S. Bureau of Mines and Kennecott Copper Corporation.

The basic working hypothesis of the program is that the stress in and the strength of a slope govern its stability. Slope failure develops when the slope stress exceeds the slope strength. The slope strength is not merely a function of the strength of the rock constituents, but is limited primarily to the strength of the weakest structural feature and/or lithologic member along which ground movement is unrestrained in the slope.

The west side of the Kimbley Pit has been selected for study in the research program. Mining in this pit was completed several years ago with over-all slopes of 45° and with bench slopes standing at about 54°. The vertical depth of the pit is about 500 ft. The faces of the slopes are generally free of loose rock and the structural features are fairly discernible.

The research program consists of the investigation of (a) regional or field stresses, (b) stresses existing in back of pit slopes, (c) stress changes in slopes caused by mining, (d) tangential slope stresses, (e) slope stresses caused by ground water, (f) rock structure, and (g) slope strength.

Stress Analyses

The stresses in a slope result from the natural forces tending to degrade or flatten it and from the horizontal or lateral forces in the rock in back of the slope. These lateral stresses result from the hydrostatic effect of the rock load and from the regional or residual stresses which may exist in the locality. The lateral stresses produce stresses in the slope which act tangentially to the slope surface. By measuring the absolute residual stresses it is theoretically possible to calculate the magnitude of the important tangential stresses.

Regional Stress Analyses.—Stress-relief measurements have been completed to determine if regional stresses exist in the Ruth district (Fig. 3). Measurement stations were selected because of their elevation and accessibility, and because of the coring characteristics of the rock found in the walls of the openings. The elevations of the stations roughly equal the pit floor elevations in the district.

Evaluation of the data indicates that the stress field in the Ruth district is attributable to the weight of the overburden and is not complicated by tectonic or regional stresses. Calculations were made using a computer in the final evaluation of the data.

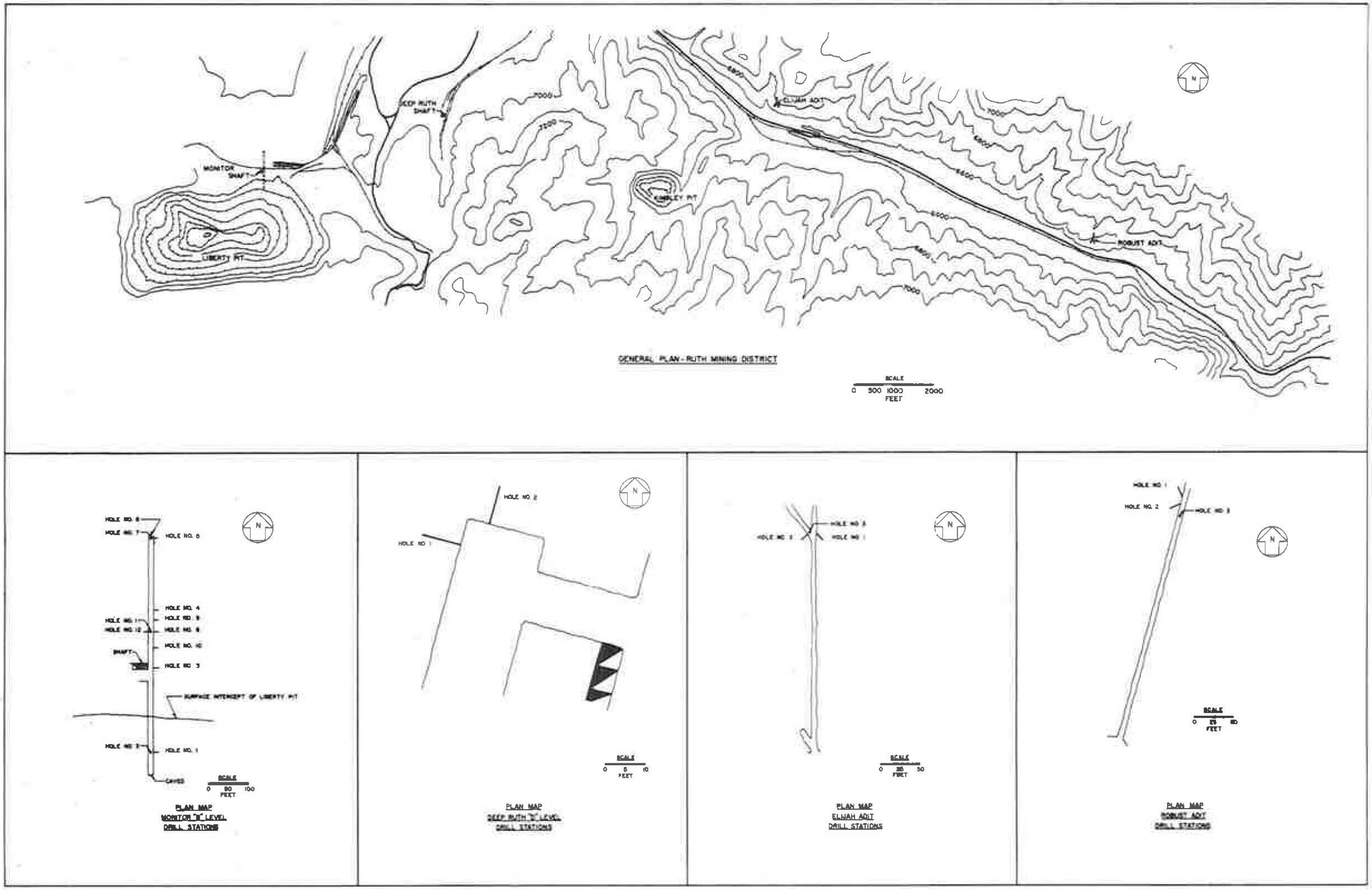

Figure 3. General plan and drill station details, Ruth mining district.

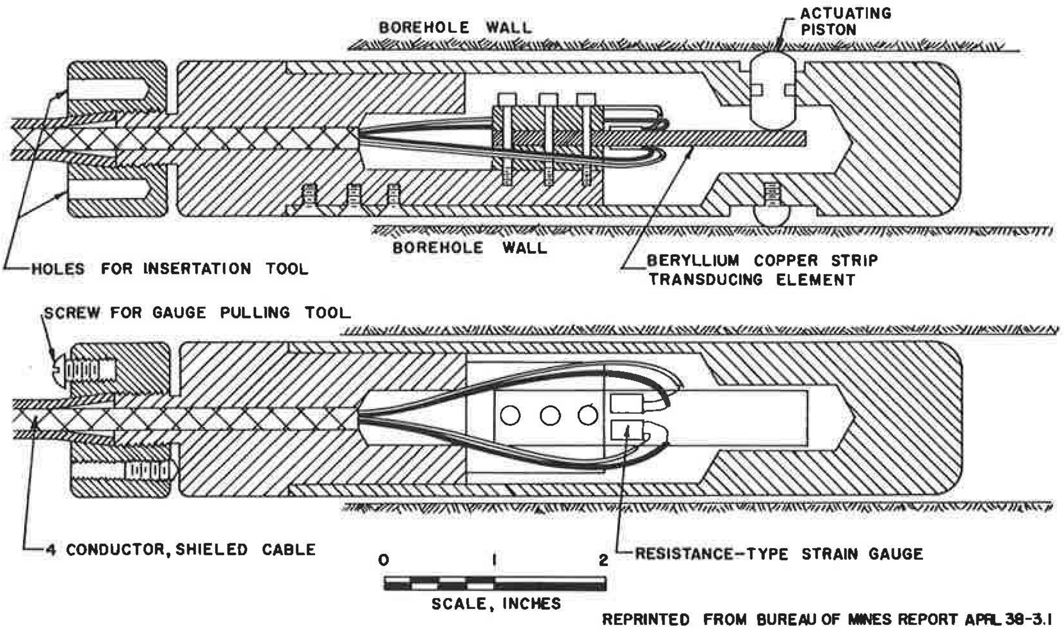

Figure 4. Sections through U. S. Bureau of Mines borehole gage (1).

The information gained will be very useful in the slope angle calculations to be made later in the program.

The strain or stress-relief measurements are made with a borehole deformation gage developed by the U. S. Bureau of Mines (Fig. 4). The gage operates on the principle that the stresses in the rock surrounding a borehole cause it to deform. The deformation of a borehole in a biaxial stress field is shown on an exaggerated scale in Figure 5. The deformation of the borehole is related to the mutually perpendicular applied stresses S and T. If the borehole deformation across three diameters (d_1, d_2, and d_3) is known, the magnitude and direction of the principal stresses, P and Q, and angle θ can be computed (1).

The gage measures the diametral change of the borehole as the surrounding rock is stress-relieved by core drilling concentrically around the borehole (Fig. 6). The increment or decrement of the borehole diameter corresponds to the strain or stress-relief of the rock.

The change in the borehole diameter is measured in three directions as follows: The gage is first inserted in the borehole and oriented at 90°, d_1. The rock surrounding the gage is stress-relieved by core drilling concentrically around the borehole. Coring is stopped

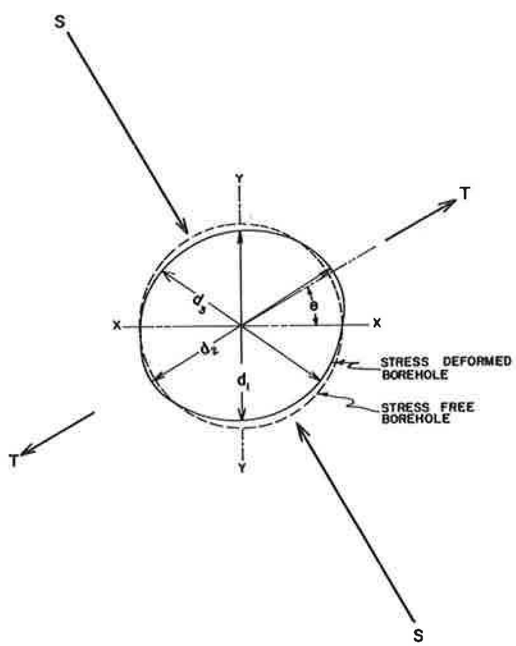

Figure 5. Cross-section of borehole in biaxial stress field.

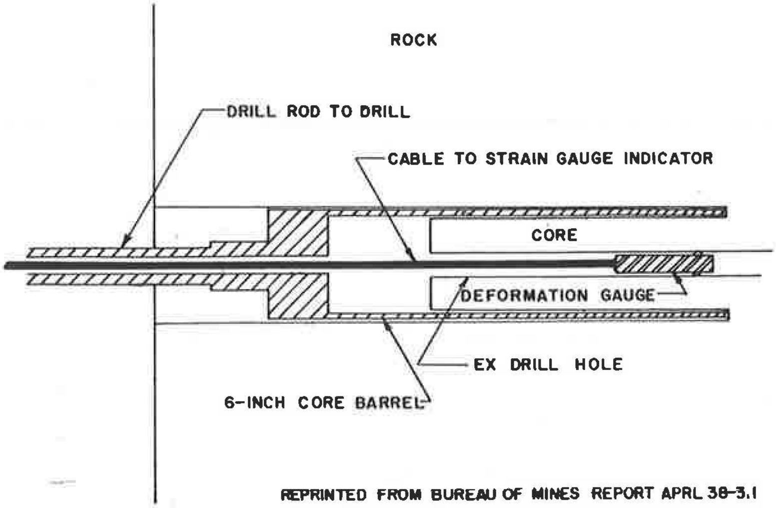

Figure 6. Section of gage and core barrel in borehole (1).

when no further diametral change of the borehole is detected by the gage. Next, the gage is moved past the core depth of the first step, oriented at 30°, d_2, and the stress-relief coring continued. This procedure is repeated for a gage orientation of 150°, d_3. Knowing the change in the borehole diameter in three directions, the magnitude and direction of the principal stresses are computed for the point. Inasmuch as the gage occupies some space, it is impossible to measure the diametral changes in three directions at a point, but if the distances between the three gage positions are known, the stresses may be interpolated for the point.

Deformation measurements are made and the stresses computed for successive points along the borehole until the stresses become constant. The constant stresses are the true residual stresses or field stresses caused by the overburden and are not affected by past mining operations or by the presence of mine openings.

The magnitude and direction of the principal stresses acting on the rock in a plane perpendicular to the axis of the borehole are determined from measurements in the borehole. The principal stresses in three dimensions can also be determined at a point in the rock, but then three mutually perpendicular measurement boreholes are required, which may be accomplished by drilling a hole in the face, floor, and rib at the end of a drift. The regional principal stresses of an area may be interpolated from the residual stresses measured in the three holes.

The transducing element in the Bureau gage is a strip of beryllium copper on which four conventional resistance-type strain gages are bonded to form a four-arm bridge (Fig. 4). The strip is actuated by a piston which senses the diameter of the hole. The strain in the strip changes proportionally to the diametral change, and this strain is measured by a conventional strain gage indicator.

Slope Stress Analyses. —Stress-relief measurements have been made along the entire length of the Monitor "B" level to develop a profile of the stresses existing in the back of the north slope of the Liberty Pit (Fig. 3). Study of the data indicates that the stressed zone, caused by the rock mass of the slope, occurs at an unexpectedly great distance behind the slope face of the pit. These measurements, a first in the field of stress analyses, provide a basis for estimating the area size in back of the slope that must be investigated in the research program.

The distance that the stressed zone occurs in back of the slope suggests that slope failure does not generally develop in this zone in a rock slope. This tends to confirm the hypothesis that slope failure develops in weak structural members closer to the pit face.

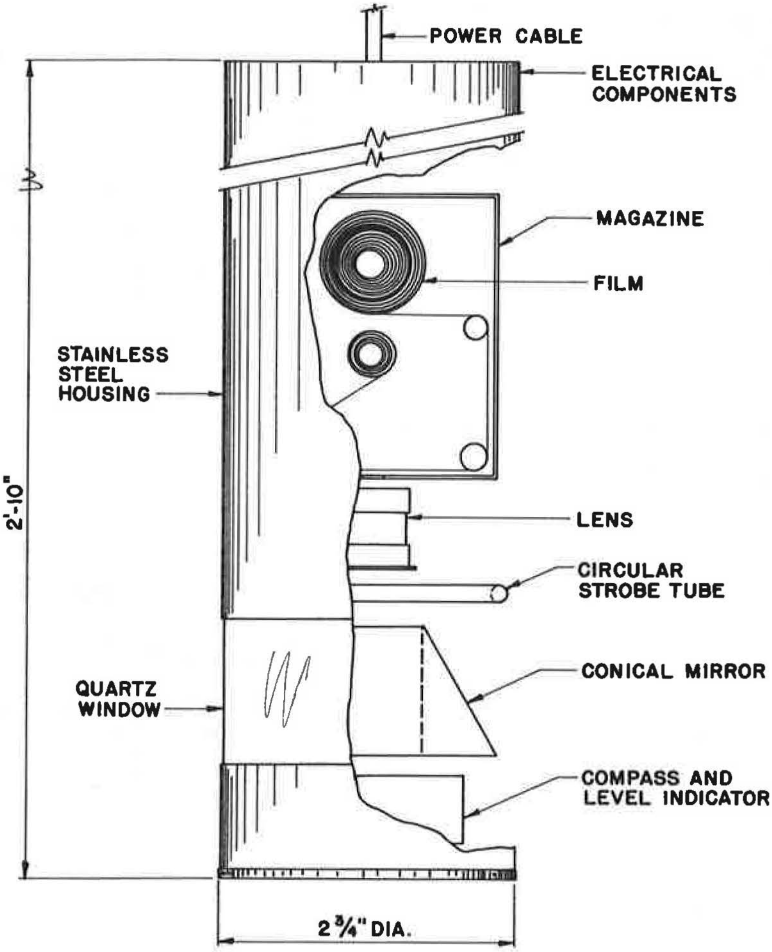

Figure 7. Borehole camera.

Work Stress Analyses.—The magnitudes of the changes in stresses caused by mining, stripping, and changing the degree of slope are unknown. Investigation of these changes could provide information that should be useful in the design of slopes and in the development of instrumentation to warn of impending slope failure.

Measurement of these changes will be made in old underground mine workings oriented roughly perpendicular to slopes being actively mined. This will be done by first determining the absolute stresses present in the slopes from stress-relief measurements made in the walls of the openings. The changes in these stresses caused by mining will be determined by measuring the deformation of the openings.

The stresses in rock surrounding an opening cause it to deform identical to a borehole. The deformation of an opening that occurs under a given stress in rock is proportional to its diameter or size. Therefore, it is much simpler to measure a small stress change in rock from a nominal size opening than from a small borehole.

The deformation changes of the openings in back of pit slopes will be determined by measuring the changes in the distances between pins cemented in the walls of the openings. The sections of the openings at the measurement stations will be made roughly circular, and the pins will be placed in the walls of the circular sections so that d_1, d_2, and d_3 can be measured at each section as shown for the borehole in Figure 5. Only changes in relative stress in competent rock can be determined by this method.

Miscellaneous Stress Analyses. —The existing tangential stresses are being determined from stress-relief measurements in the slopes of the Kimbley Pit. Such stresses develop from removing the lateral confinement of the rock by pit excavation. According to theories of elasticity, these stresses can be determined from the elastic constants of the rock, but it appears advisable that actual determinations from stress-relief measurements are necessary in the initial program. Techniques have been developed to permit stress-relief measurements at depths up to 100 ft.

Piezometers, placed in boreholes at the west end of the Kimbley Pit, will be used to determine the stresses caused by ground water if this appears advisable.

Strength Analyses

The strength analyses are based on meticulous study of rock structure, rock strength, and the effect of rock structure and moisture on the strength of a slope.

Structural Analyses. —The structural analyses are to locate the structural weaknesses in the west end of the Kimbley Pit. Fractures, joints, faults, stratification and foliation planes, chemical planes, orientation of rock constituents, grain boundaries, and other structural features in the rock of the slope are being investigated.

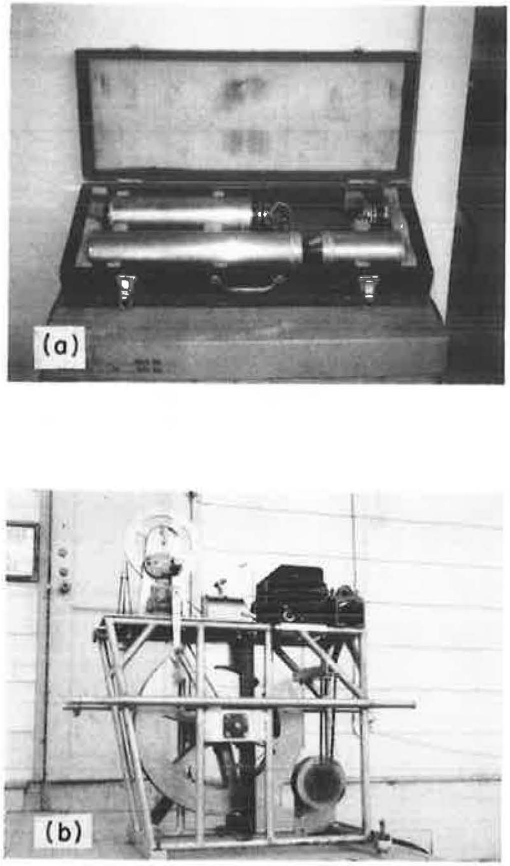

Figure 8. Borehole camera (a) and lowering mechanism (b).

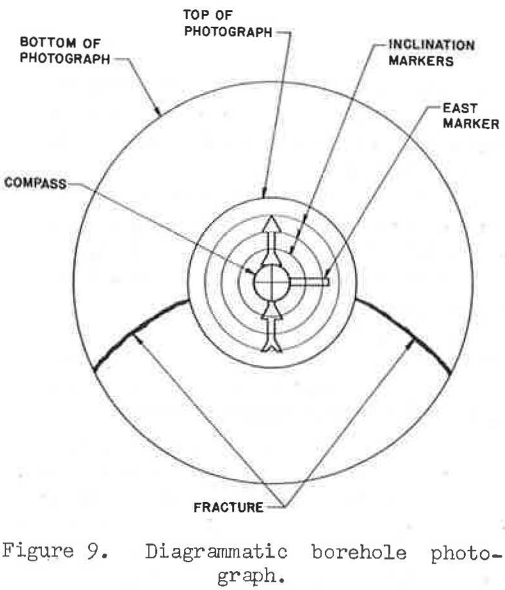

Figure 9. Diagrammatic borehole photograph.

Thousands of structural measurements are being made and interpreted statistically by graphical representations and computers. Superficial study of structure is being supplemented by camera observations inside boreholes. The technique is similar to that described by L. Müller (2) and used by the U. S. Corps of Engineers. W. R. Crane (3) of the U. S. Bureau of Mines first used statistical structural analyses to investigate the stability of the slopes of Kennecott's Bingham Canyon Mine in 1928.

The borehole camera can photograph approximately 75 ft of drill hole without reloading and takes sixteen 360° photographs per foot. Standard 8-mm color movie film is used in the camera. The essential components of the camera are shown in Figure 7. Magnetic north and the camera inclination are recorded on each photograph. Figure 8 shows the camera and lowering mechanism.

A diagrammatic borehole photograph is shown in Figure 9. The radial distance between the top and bottom of the photograph represents approximately 1¼ in. of actual hole walls in a 3⅝-in. diameter drill hole. This distance varies in different diameter drill holes. The east mark is used to eliminate the possibility of viewing the film backwards. The fracture shown in the figure strikes east-west and dips 60° to the south in a vertical hole. The borehole photographs are viewed on a converted microfilm reader at a magnification of slightly less than 1½ times.

Using techniques developed on the job, each fracture photographed is orientated and its true dip and strike are calculated. The data are recorded directly on specially designed computer cards for reduction and evaluation.

Structural data are also collected by visual observations. Large-scale structural features such as faults, major joint systems, and lithologic boundaries are recorded. The data have been plotted on a polar equal-area net and contoured. The results show that the fractures are not randomly scattered but have definite preferred orientations.

Slope Strength Analyses.—The slope strength will be determined by core sampling the study area and by making laboratory tests on these cores. The tests will investigate the strength of the rock formations and the frictional resistance along the fractures or fractured zones in the rock. These tests will investigate also the effect of moisture on strength.

The core sampling will be done by drilling about an 8-in. diameter hole to a prescribed depth by rotary drilling. At the prescribed depth, diamond drilling will be used to recover about a 6-in. diameter core. Several feet of core will be taken at different elevations and spacings in the formations until consistent laboratory data are achieved for specific formations. Special core sampling will be made across areas of particular structural interest. Areas or formations in which core samples cannot be recovered will be classified as areas with minute strength or the formations may be strengthened in the test zone with chemical or cement grout and the actual strength of the formations investigated.

Using the information from the stress analyses, the rock specimens will be loaded to simulate the increased stresses that will develop if the pit walls are steepened. The results of these tests will be of particular importance in determining the strength of the toe of the pit.

OBJECTIVES OF PROGRAM

It is expected that this research program will develop definite conclusions as to the maximum safe slope related to specified safety factors within given confidence intervals. A second program will test these conclusions by redesigning the west end of the Kimbley to the defined ultimate slope and actually mining to it. The accuracy of the safety factor will be determined also by further mining to the slope defined at unity safety factor or to failure.

If successful, the research programs will provide the tools to solve two major problems that are encountered in open-pit mines: (a) detecting instability in a rock slope before any failure develops, and (b) predetermining a precise safe-maximum slope angle with a known safety factor for a rock slope.

A successful conclusion will permit the predetermination and continued maintenance of the optimum safe mining slope. The economies to be realized from mining such a correctly engineered slope will greatly outweigh the cost of testing. These economies will be realized because the maintenance of the optimum pit slope throughout the life of an ore body will constantly permit safe and efficient mining under slopes of known stability, and so eliminate the practice of advanced stripping or excessive stripping to increase the safety factor in areas of uncertain rock strength.

The ultimate goal is to develop methods that can be used in conjunction with the exploration program of a new ore body, such as using the exploratory holes to make the optical soundings. Knowledge of a safe mining slope for a possible open-pit operation would be invaluable in calculating the recoverable ore reserves and in determining the economic potential of the ore body.

It must be emphasized that only the preliminary work has been completed in this research program and that the working hypothesis described in this paper undoubtedly will require changes during the studies. The results gained as the studies are made will dictate the direction and amount of work required in a specific study of the program.

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