Geologic Research at the Straight Creek Tunnel Site, Colorado

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The cost of constructing tunnels in the Rocky Mountains of Colorado, and in many other places in the world, usually has exceeded the estimates of the cost, sometimes by a wide margin. In most instances the reason for the increased cost has been geologic. The U. S. Geological Survey, in cooperation with the Colorado Department of Highways, is conducting a research project at the Straight Creek tunnel site, on I-70, in order to apply and evaluate new ideas in the use of geology and geophysics for prediction of geologic conditions at depth, in the belief that more accurate predictions of geologic conditions can reduce the cost of construction.

The surface outcrops in the vicinity of the tunnel were mapped in detail; particular attention was given to the percentage of different rock types, the attitude of the foliation of the rock, and the attitude and spacing of faults and joints. The surface observations were supplemented by the drilling and logging of two core holes; records were kept as to the percentage of rock types, the attitude of the foliation, and the attitude and spacing of faults and joints.

The geologic investigations were supported by geophysical logging of the drill holes—including resistivity, gamma-ray, and gamma-ray density—by seismic profiles at the surface run parallel and at right angles to the tunnel line, and by laboratory measurement of physical and engineering properties of samples from the surface and the drill holes.

From all these data a statistical model of the geology at tunnel level was constructed. Then from this model it was possible to calculate the probable rock loads, spacing of sets, spacing of lagging, probable sections of the tunnel that should be tested by feeler holes, probable amount of grout that would be required to seal badly broken ground highly saturated with water, probable amount of water that would flow from the portal of the tunnel as the face was advanced, and probable initial amount of water that might be expected to flow from a fault zone within any interval of the tunnel. Construction of a pilot bore for the Straight Creek tunnel has recently been started. Geologic and geophysical investigations are being made in this pilot bore to determine the accuracy of the predictions that were made, and in the hope that this information will lead to new ideas that will give even better predictions of the geology for tunnels to be constructed in the future.

•THE COST of constructing tunnels in the Rocky Mountains of Colorado usually has exceeded, sometimes by a wide margin, estimates of their cost. This also has been true in other areas of the United States, and in other parts of the world. The reason for the increased cost, in nearly every instance, can be attributed to the presence of geologic conditions that, from an engineering point of view, either were not known or were not fully understood before the construction of the tunnel.

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Examples in Colorado of excessive cost for tunnel construction, as a result of adverse geologic conditions, are the Moffat and Leadville tunnels. The Moffat tunnel, which was constructed in 1923-27 to take water and the Denver and Rio Grande Western Railroad through the Continental Divide, cost about 4 times the estimated cost (Lovering, 4, p. 339). According to Lovering (4, p. 338), the original estimate was based on the assumption that the tunnel would be driven in solid rock, but actually about 2 mi of the tunnel was in weak material that required much support. The worst zone encountered, the Ranch Creek fault, was about 1,000 ft wide and required 2 tons of steel per running foot of tunnel to reinforce a concrete lining that averaged about 30 in thick. The Leadville tunnel, which was constructed in 1943-45 and 1950-52 to drain the Leadville mining district in Colorado, cost almost twice the estimated amount (1, 6). The principal reason for the increased cost in the Leadville tunnel was a water-saturated, gravel-filled glacial stream channel 4 to 12 ft above the roof of the tunnel. The tunnel roof collapsed, filling part of the tunnel with unconsolidated material and necessitating the construction of a bypass tunnel. Construction costs for many other tunnels in Colorado have been substantially higher than the original estimates, owing primarily to some unpredicted geologic feature or features.

The most recent tunnel completed under the Continental Divide in Colorado is the Harold D. Roberts tunnel. This tunnel, which was constructed by the Denver Board of Water Commissioners to bring water from the western to the eastern side of the Divide, is about 23 mi long. The route for the tunnel was selected after several years of geologic study of possible routes by T. S. Lovering, E. E. Wahlstrom, and others. The cost savings of these studies can only be estimated, but comparison with problems encountered in other tunnels suggests that the construction cost was reduced by at least 25 percent.

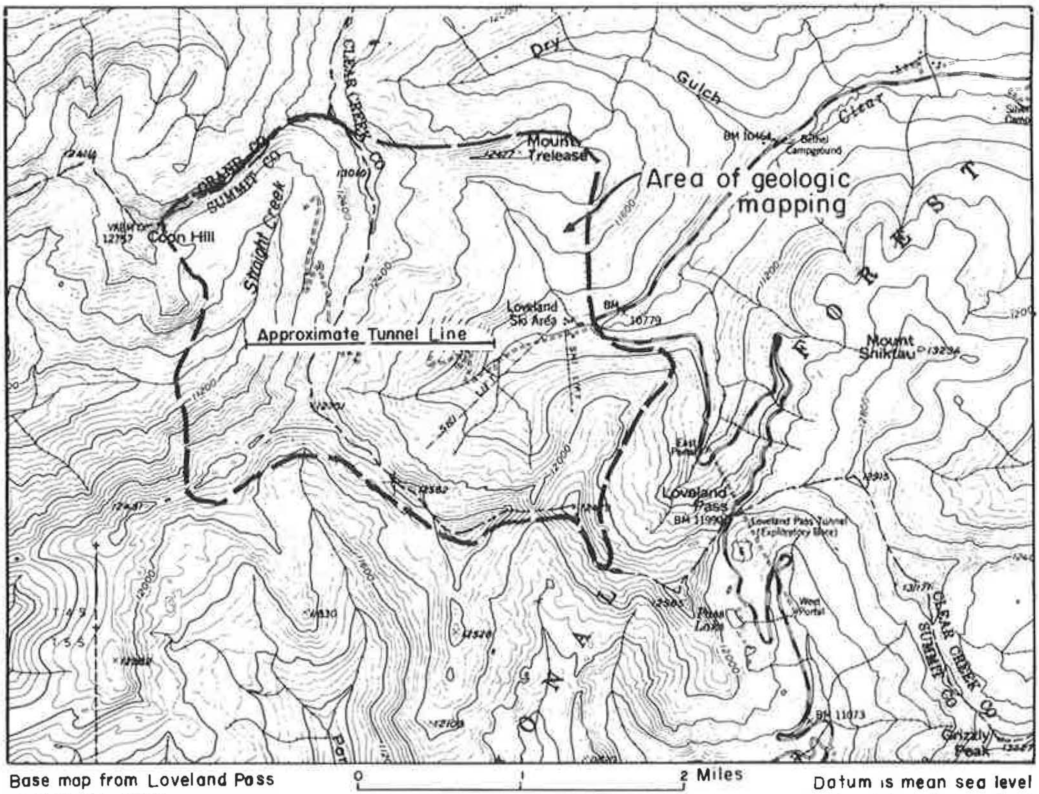
The present research investigation of the Straight Creek tunnel site is the direct result of a post-construction study of the engineering geology of the Roberts tunnel by the U. S. Geological Survey in conjunction with E. E. Wahlstrom and L. A. Warner. Some of the preliminary results of the Roberts tunnel study have been published by Wahlstrom (8); Wahlstrom, Warner, and Robinson (1961); Wahlstrom and Hornback (1962); and Wahlstrom, Robinson, and Nichols (in preparation).

The studies of the Roberts tunnel showed that different types of geologic features—faults, veins, joints, and contacts between rock types—could be projected to tunnel level with different degrees of accuracy, and that the accuracy depended on a thorough knowledge of the regional geology—and therefore the origin of these features—and on a detailed examination of the surface over the tunnel route. It was also determined that the rock type was not as important in the construction of a tunnel as were the number of fractures per foot of tunnel, attitude of bedding, foliation, and fractures in relation to the trend of the tunnel, presence or absence of hydrothermal alteration, the type of clay minerals in fault gouge, etc. It seemed possible that a statistical compilation of such geologic features as the attitude of joints and faults could be projected to a tunnel level more accurately than could the individual features, and would give a better basis for engineering design and construction. It also seemed that known geophysical techniques could be used to supplement the data obtained by surface examination and core drilling—particularly in areas of poor outcrop and poor core recovery.

The U. S. Geological Survey, in cooperation with the Colorado Department of Highways, is conducting a program of geologic and geophysical research for the pilot bore for the Straight Creek tunnel. The purpose is to apply the ideas developed from the study of the Roberts tunnel to see if better predictions and engineering interpretation of geologic conditions can be made.

Although most of the methods of investigation of the Straight Creek tunnel site were based on studies of the engineering geology of the Roberts tunnel--which in part was constructed in a similar geologic environment—it is believed that with minor modifications based on the regional geology, most of the methods of investigation are applicable to determining the engineering geology of any proposed tunnel site. This paper describes the preconstruction geologic, geophysical, and laboratory investigations that have been made, and the engineering interpretation and prediction of the results.

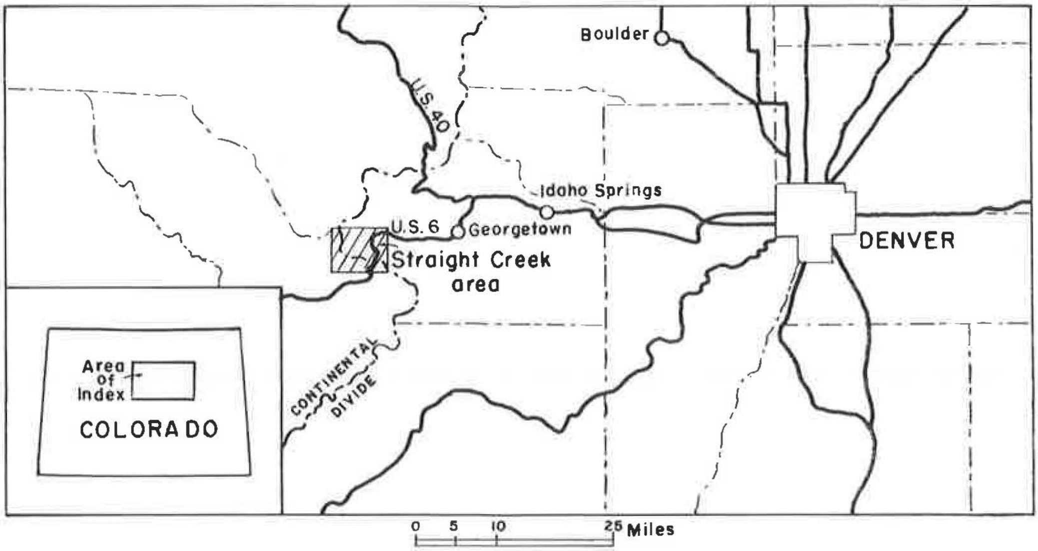
The Straight Creek tunnel site is about 50 miles west of Denver (Fig. 1). The



Base map from Loveland Pass quadrangle, 1958

Datum is mean sea level
Contour interval 40 feet

Map of Straight Creek area



Location of Straight Creek area

Figure 1. Index maps of Straight Creek area, Colorado.

Straight Creek tunnel will carry I-70 through the Continental Divide and so eliminate the use of Loveland Pass on present US 6. The pilot bore, on which construction was started in November 1963, will be about 10 × 10 ft and approximately 8,000 ft long. The final tunnel will consist of twin bores, each about 32 ft in diameter and 8,000 ft long.

GEOLOGIC INVESTIGATIONS

The geologic investigations were started in 1962, and consisted of the geologic mapping of approximately 6 sq mi in the vicinity of the tunnel site and the geologic logging of 2 core holes, the drilling of which was supervised by the Colorado Department of Highways.

Mapping

The surface mapping was done at a scale of 1:12,000; particular attention was given to the percentage of different rock types, the attitude of the foliation of the rock, and the attitude and spacing of faults and joints. Figure 2 is a generalized geologic map of the area showing the distribution of the different rock types.

Geologic Formations.—The area consists predominantly of Precambrian granite with inclusions of metamorphic rocks. The granite is medium to fine grained and consists of approximately equal amounts of quartz, potash feldspar, and plagioclase feldspar, and from 5 to 15 percent biotite. A distinct foliation is recognizable in most outcrops. The foliation is the result of a subparallel orientation of the potash feldspar grains. In some outcrops, particularly in those containing a higher percentage of biotite, the biotite is oriented parallel to the potash feldspar grains. The rock appears fresh, but petrographic examination shows that most of the biotite has been altered to chlorite and that the plagioclase feldspar has been slightly altered to sericite. The granite is extensively altered only in, or adjacent to, some of the shear zones and faults. Mapped with the granite were small pods and dikes of pegmatite, that consist predominantly of quartz and potash feldspar.

The metamorphic rocks consist of a variety of biotite-rich gneiss. Common types are biotite-quartz-microcline gneiss, biotite-quartz-plagioclase gneiss, hornblende-biotite-plagioclase gneiss, and sillimanitic biotite-plagioclase gneiss. These rocks generally are fine grained. Their foliation is the result of the concentration and orientation of the constituent minerals into bands that range from less than 1 to about 10 mm in width. In nearly all outcrops the biotite, and some of the hornblende, is altered to chlorite. In and adjacent to the faults and shear zones the metamorphic rocks are commonly altered to a green plastic clay, in which the foliation, although considerably contorted by folding, is still recognizable.

Diorite dikes, probably of Tertiary age, crop out north of the tunnel line; and might be encountered during construction of the tunnel. The dikes range from a few feet to about 1,000 ft in maximum dimension. They consist of fine-grained to aphanitic augite and plagioclase with varying, and smaller, amounts of biotite and hornblende.

The bedrock throughout much of the area is mantled by Quaternary surficial deposits. These include swamp and morainal deposits at lower elevations in the valleys and colluvial deposits of soil, talus, and landslides on the upper slopes.

Structure.—Geologic structures probably are the most important factors in increasing the cost of tunnel construction above the estimates. Accordingly, they were given, particular attention during mapping. The structural features mapped were the attitude of the foliation and the attitude and spacing of faults, shear zones, and joints.

Foliation is the result of the orientation and layering of mineral grains. In the granite, the foliation is not a principal direction of weakness and should not affect the engineering properties of the rock. In the metamorphic rocks, however, the foliation is a major direction of weakness; those layers that are composed predominantly of biotite are relatively much weaker than those composed predominantly of quartz and feldspar.

Faults and shear zones are numerous in the area mapped. This area lies within a wide zone of regional faulting and shearing that is probably related to the Loveland Pass fault (Lovering and Goddard, 1950, pl. 2). Figure 3 is a generalized map of the

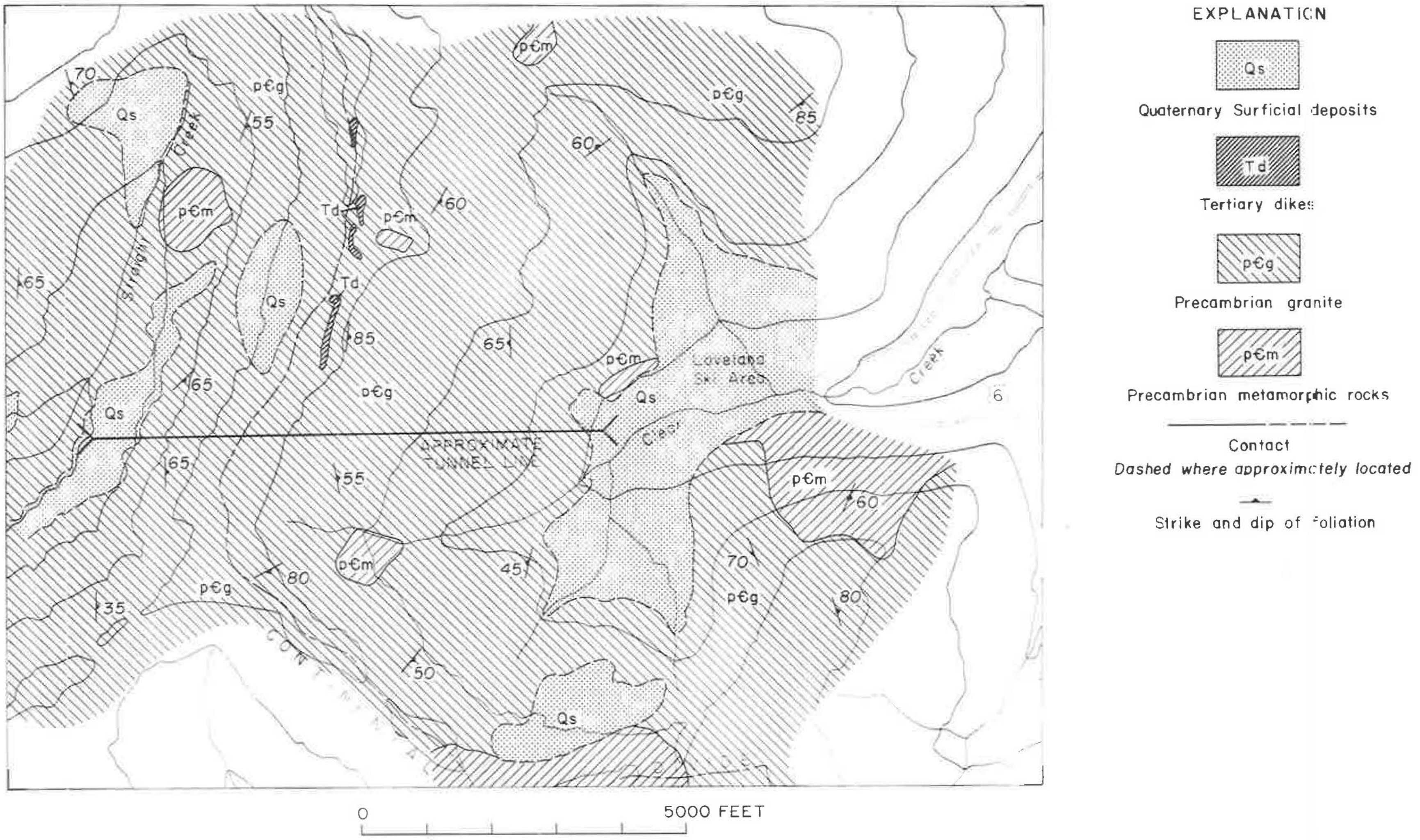


Figure 2. Generalized geologic map of Straight Creek area showing distribution of rock types.

faults and shear zones of the area. The distinction between faults and shear zones is one only of magnitude; faults are elongate areas of crushed rock from 5 to 50 ft wide and shear zones are elongate areas more than 50 ft wide. Faults less than 5 ft wide are too numerous to be shown on this generalized map.

The faults and shear zones consist of rock showing varying degrees of crushing or shearing. The borders of these zones are gradational—the intensity of shearing decreasing outward from the center of the zone. Near the margins, the rock consists of slivers from less than 0.1 to 1 in. wide bounded by slickensided shear planes. Where the shearing was more intense, the rock has been crushed to a coarse to fine sand and the shear planes are less than 0.01 to 0.5 in. apart and lie in all directions. Where the most intense shearing occurred--probably accompanied by some alteration—the material consists of clay (fault gouge) with variable amounts of quartz and/or feldspar grains. The gouge usually does not occur near the center of the sheared zone but is nearer one margin than the other—most commonly adjacent to the footwall of the zone. The gouge occurs as disconnected streaks elongated parallel to the trend of the shear zone.

The faults and shear zones vary in width within short distances. The individual faults or shear zones pinch and swell and may end abruptly against relatively unbroken rock. Some shear zones contain blocks of rock, up to about 100 ft in maximum dimension, that are relatively unsheared although surrounded by intensely sheared rock. The shear zones and faults, because of their general discontinuity, were not projected through covered areas. For this reason, the abrupt ending of most of the shear zones, as shown in Figure 3, is the result of cover and not the result of an observed abrupt ending of the zone. Most of the fractures recorded as joints are microfaults and shears. In mapping, the attitude and the maximum, minimum, and average distance between joints in each set were recorded. An effort was made initially to distinguish between tension and shear joints, but nearly all joints showed some evidence of shearing.

Logging

Two core holes were drilled, approximately equally spaced between the portals of the proposed tunnel, to determine the geology in the vertical dimension. Four holes had previously been drilled during preliminary investigations in 1955. At the start of the present investigation, the drilling of more than two holes was proposed. Detailed surface mapping in this type of geologic environment, however, was considered to be of more value—and much less expensive—than additional drill holes. A core represents only about a 2-in. diameter sample (for an NX hole) for a part of the length of the hole. The significance of this sample can be evaluated, and the information obtained by drilling extrapolated, only on the basis of detailed geologic mapping and a thorough knowledge of the regional geology.

Figure 4 is a section of a geologic log of one of the drill holes. This type of log gives a maximum amount of geologic information for engineering interpretation. It differs from standard logs primarily in that the sizes—range and average length—of the pieces of core have been recorded. The size should be indicative of the competency of the rock and the way the rock will break during mining operations. In addition, because the rock has a distinct foliation, it was possible to measure the attitude of the joints in relation to the strike of the foliation.

GEOPHYSICAL INVESTIGATIONS

The geophysical investigations consisted of resistivity, radioactivity, and gamma-ray density logging of the drill holes, and seismic profiles at the surface along and at right angles to the proposed tunnel line. The geophysical investigations were conducted to experiment with new instruments and techniques for determining the engineering properties of rocks in situ, and to obtain supplemental data for the geologic interpretations.

Figure 5 is part of a geophysical log of one of the drill holes. Shown on the geophysical logs are the geologic column, a description of the geology and the casing size, date of installation of casing, and cemented intervals. For the example given (Fig. 5), the casing was installed after the geophysical logging.

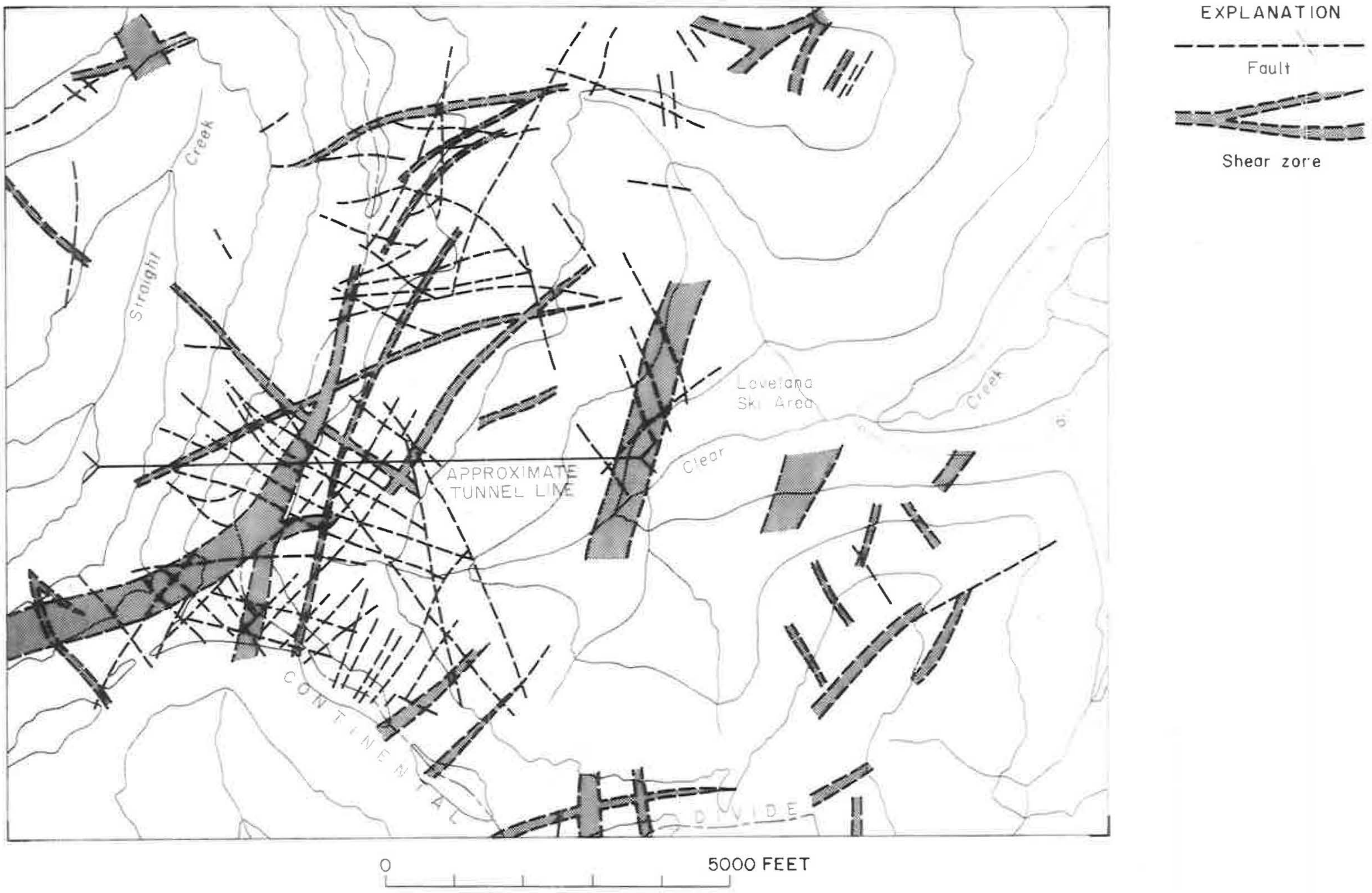


Figure 3. Generalized map of faults and shear zones of Straight Creek area.

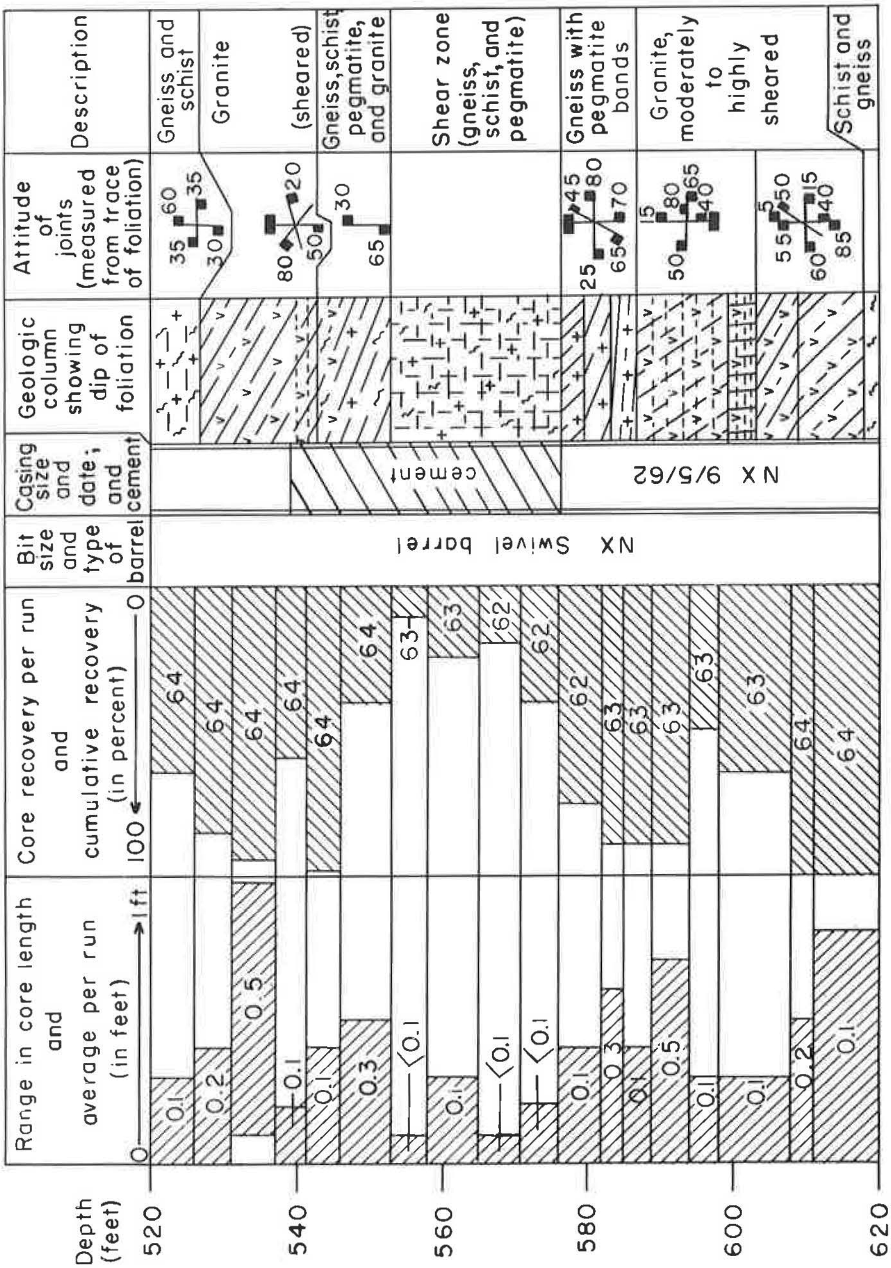


Figure 4. Example of geologic drill hole log, Straight Creek project.

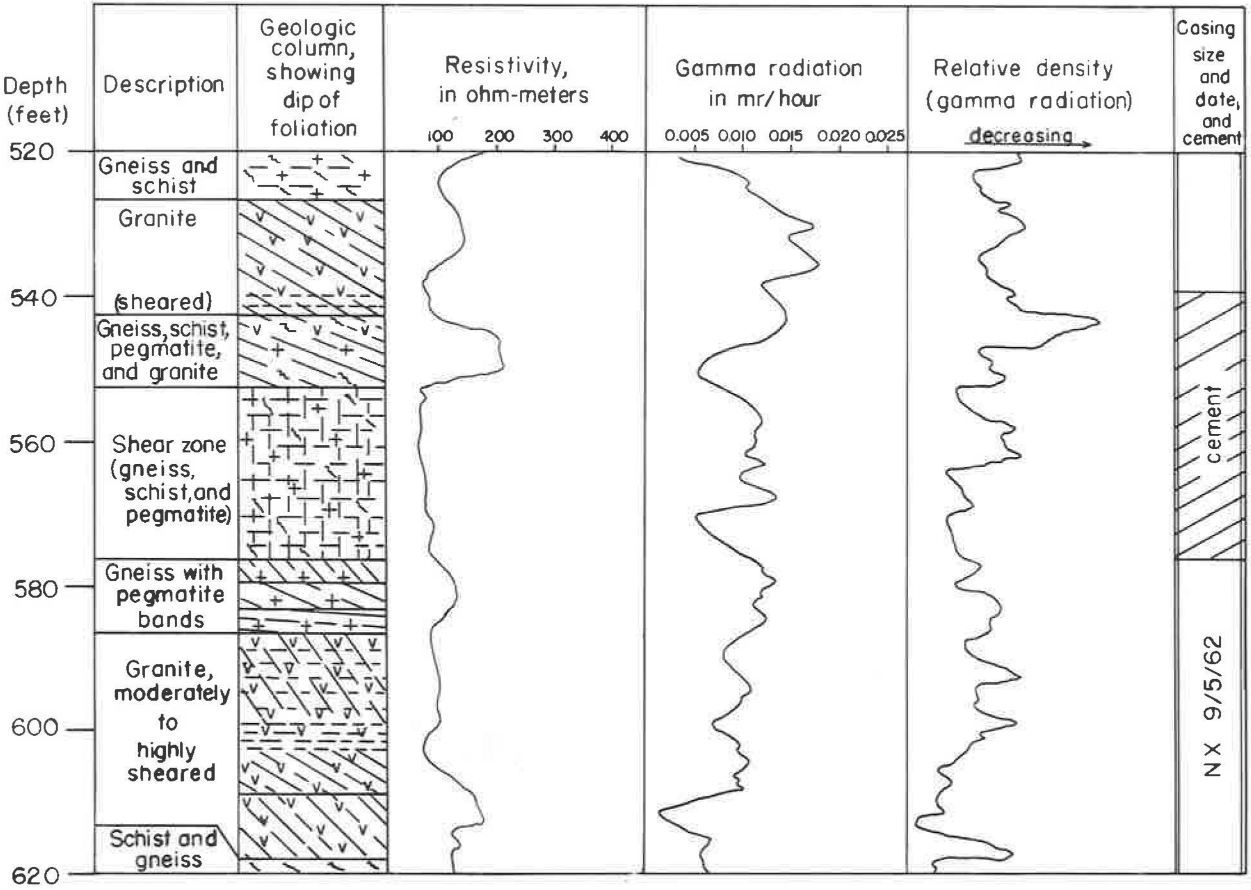


Figure 5. Example of geophysical drill hole log, Straight Creek project.

Resistivity values are largely dependent on the amount and nature of water contained within the rock mass, which in turn is dependent on the amount of fracturing. The resistivity logging supplemented the geologic logging and was used primarily to determine or confirm zones of shearing, particularly where core recovery had been poor. The resistivity logging was done by C. J. Zablocki.

The natural gamma-radiation logging was also primarily used to interpret rock conditions, particularly rock type in those intervals with poor core recovery. The Precambrian igneous and metamorphic rocks of this area, as with most rocks, have a characteristic natural gamma radiation. The natural gamma radiation of the different rock types is affected by the amount of shearing and alteration and the logging, therefore, where the rock type was known, gave a relative value for the amount of shearing and alteration.

The relative density of the rock in the walls of the drill holes can be determined by lowering a source of gamma radiation into the drill hole and measuring the absorption of the gamma rays. Such relative density logging gave a relative value for the amount of shearing and alteration. The gamma-radiation and density logging was done by W. A. Bradley.

All the logging encountered a common difficulty: those sections of the holes in badly broken ground caved (often within a few hours of drilling) so that the probes could not reach the bottom, or required cement or casing, which prevented the effective operation of one method or another.

Seismic surveys were conducted along the tunnel line. The purpose was to determine the seismic velocities, and the changes therein, across the surface and with depth; it was hoped that these velocities could be correlated with the geologic mapping and its resulting definition of rock conditions. An excellent discussion of the application of seismic techniques to the determination of rock properties in situ has recently been presented by D. Wantland (1963) of the U. S. Bureau of Reclamation. The seismic surveys were under the direction of R. A. Black and B. L. Tibbetts of the U. S. Geological Survey.

Geophones were set both along and at right angles to the proposed tunnel line at the surface, and seismometers (specifically designed for the purpose) were placed in the two core holes. Records were obtained from charges detonated in drill holes in bedrock near the proposed tunnel portals and from airblasts aboveground. The results have not been as satisfactory as hoped for. The investigation was hampered by a lack of precedent on which to design the equipment and of tested procedures for such a survey. Additional seismic surveys with modified equipment and procedures are planned which hopefully will provide better records.

Another seismic survey was conducted by R. M. Hazlewood and C. H. Miller of the U. S. Geological Survey, in the vicinity of the east portal to determine the thickness of surficial material. On the basis of this survey the Colorado Department of Highways was furnished a map showing the surface and bedrock topography that allowed the calculation of the amount of surficial material that had to be excavated at the east portal.

LABORATORY INVESTIGATIONS

A continuing program of laboratory investigations is being conducted in coordination with the geologic and geophysical field investigations. The purpose is not only to furnish the necessary data for the interpretation of field geologic and geophysical information for engineering purposes, but also to attempt to correlate physical and engineering properties as determined in the laboratory with those determined in situ, and to conduct research on new techniques and instruments for determining physical and engineering properties in the laboratory and field. The laboratory investigations have been supervised by T. C. Nichols of the U. S. Geological Survey.

The mineralogy, porosity, grain density, dry bulk density, and saturated bulk density were determined for surface and drill-core samples. The elastic properties of selected samples have been measured by dynamic and static methods to determine if, from a geologic analysis (composition and structure), these two methods of measuring elastic properties can be correlated. Compressive and shear strengths have been determined under various confining pressures and are being correlated with a geologic analysis of the samples. A good correlation can be established between compressive strength and the mineralogy of the samples. Many of these laboratory investigations do not have a direct quantitative bearing on the construction of the Straight Creek tunnel because the samples tested were the most homogeneous geologically. It is hoped that correlation of geologic analyses with physical and engineering properties will in the future allow translation of laboratory data to field conditions and correlation of laboratory results with in-situ measurements.

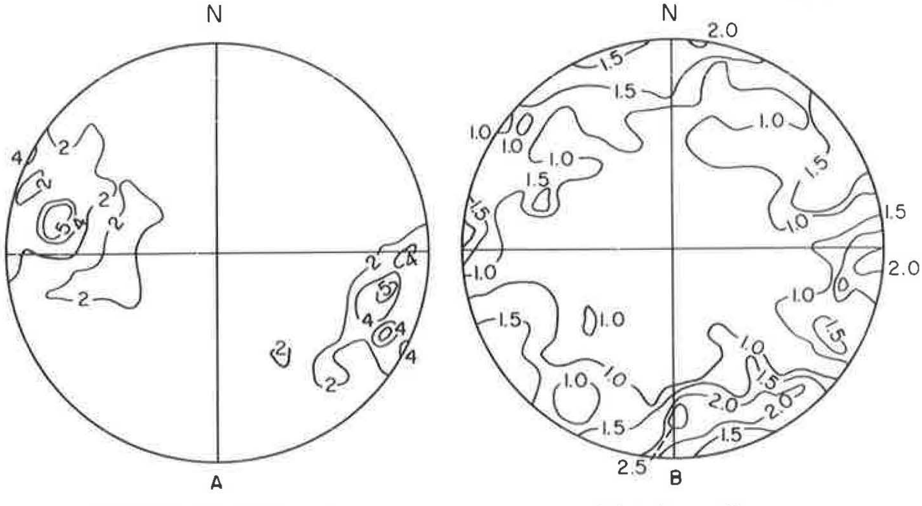
Of direct application in the construction of the Straight Creek tunnel has been the measurement of the swelling properties of the clay in fault gouge that results from the physical and chemical alteration of rock. As discussed by Wahlstrom, Robinson, and Nichols (in preparation), the relative swelling properties of clay can be determined by a PVC (potential volume change) meter (3). A knowledge of the swelling properties, including the final swell pressure, will allow the design of adequate support to contain this pressure.

COMPILATION OF RESULTS OF INVESTIGATIONS

In areas as complex as the Straight Creek site, the projection of surface geologic features to tunnel level has been unsuccessful (Wahlstrom, in press). A statistical compilation of the results of the geologic, geophysical, and laboratory investigations, however, can give estimates of the type and magnitude of the geologic features to be encountered in the driving of a tunnel.

A compilation of the data from the surface mapping and drilling shows that 75 percent of the Straight Creek tunnel will be in granite and 25 percent in metamorphic rock. The metamorphic rock occurs as inclusions in the granite ranging in average maximum dimension from less than 1 to 200 ft, and having an average maximum dimension of about 20 ft.

The attitudes of foliation of the granite and metamorphic rock along a 1-mi strip with the tunnel line at the center are shown in the equal area plot in Figure 6a. The diagram, compiled from 189 measurements, shows that the foliation in general strikes from N to N 30° E and dips from 60 to 90° NW or SE. The use of petrofabric studies and the methods of compilation, have recently been discussed by Friedman (2).



Foliation in granite and metamorphic rocks (189 poles)

Joints in granite (838 poles)

Figure 6. Lower hemisphere equal area plots of attitudes of foliation and joints: (a) foliation in granite and metamorphic rocks, and (b) joints in granite.

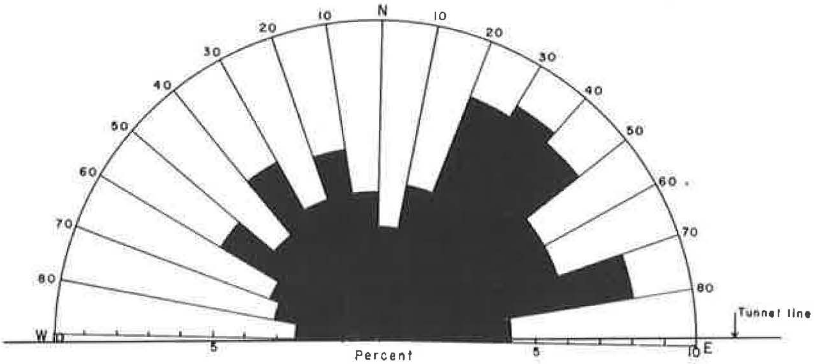


Figure 7. Strike frequency diagram of 284 faults and shear zones.

A contour diagram of the attitude of 838 joints measured in granite along the same 1-mi wide strip is shown in Figure 6b. The diagram shows that the joints strike in any direction and dip from 45 to 90° and average about 70°.

Similar diagrams for the attitude of the foliation and the joints were prepared from the logs of the drill holes. The strike of the foliation and joints could not, of course, be determined from the core. The average strike of the foliation in the core was assumed to be the same as that compiled from the surface mapping (Fig. 6a); it was then possible to orient the joint diagrams compiled from the drill core, as the strike of the joints in the core was measured in reference to the strike of the foliation. The diagrams prepared from the surface data differed from those prepared from the core data only in that the average dip for the foliation and joints in the core was about 50° as compared to 70° at the surface.

In most areas one or more principal directions to the strike of the joints are to be expected. By the use of statistical compilations it might then be possible to orient a tunnel to intersect the principal foliation and joint directions at a maximum angle. In the case of the Straight Creek tunnel, where there are no principal directions of strike, a change in the orientation of the tunnel would not improve construction conditions.

The number and magnitude of the faults and shear zones, and their attitudes in relation to the orientation of the tunnel, are the principal structural features that will affect the construction of the tunnel. The strike frequency diagram (Fig. 7) illustrates the relation of the trend of 284 observed faults and shear zones to the trend of the proposed tunnel. The diagram shows that most of the faults and shear zones intersect the proposed tunnel line at angles of greater than 30°, and that only about 4 percent of the faults and shear zones trend parallel to the tunnel. No fault or shear zone wider than 5 ft was noted at the surface that would be expected to follow the proposed tunnel line at depth. The dips measured on 74 of the 284 faults and shear zones ranged from 35 to 90°, and averaged 75°.

The average spacing between all types of fractures (faults, shear zones, and joints) was plotted on a geologic map and contoured. The contour intervals used represented an average distance between fractures of from less than 0.1 to 0.5 ft, 0.5 to 1 ft, and from 1 to 3 ft. The map could then be divided into a series of zones: (a) the zones of greatest fracturing, where the average distance between fractures was less than 0.1 to 0.5 ft (these were essentially the major shear zones); (b) the zones of intermediate fracturing, where the average distance between fractures was 0.5 to 1 ft, and about 20 percent of the area was represented by faults and shear zones; (c) the zones of least fracturing, where the average distance between fractures was 1 to 3 ft, and about 10 percent of the area was represented by faults and shear zones.

GEOLOGIC PREDICTIONS

The data compiled from the geologic, geophysical, and laboratory investigations were used to construct a predicted geologic section along the proposed tunnel line. Figure 8 is a generalization of this geologic section.

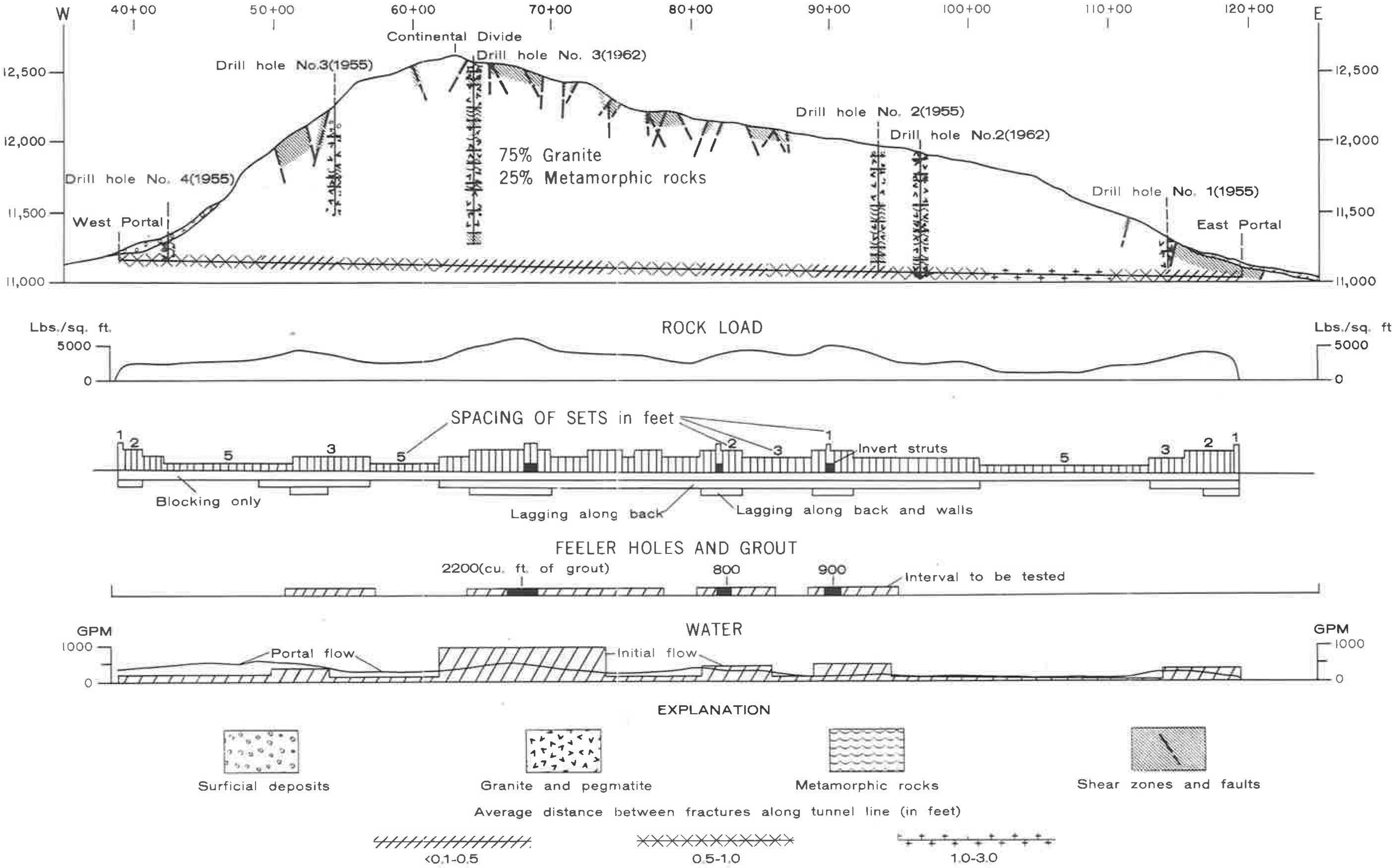


Figure 8. Predicted geologic section and engineering data along proposed Straight Creek tunnel pilot bore.

In constructing the geologic section, no effort was made to project individual rock units, faults, or shear zones to tunnel level. As previously discussed, it is impossible to predict the position of the metamorphic rock inclusions, because their maximum dimension averages only about 20 ft. It can be stated, however, that, as shown in Figure 8, 75 percent of the tunnel will be in granite and 25 percent in metamorphic rock. Rather than project the individual faults and shear zones from surface to tunnel level, the different zones of the average spacing between fractures as determined at the surface were projected to tunnel level, on the basis of the average dip of faults and shear zones as measured from the surface and the drilling data.

It should be understood that the boundaries between the different zones for each section of the tunnel are gradational and indefinite—this is an interpretation—and that the location of each zone is based on the projection of statistical values. The length and position of each of these zones may be in error by as much as 50 percent, but the percentage of rock in the different zones in relation to the total length of the tunnel is probably correct within less than 25 percent. This then gives a basis for the calculation of engineering data necessary for estimating the cost of construction of the pilot bore tunnel.

CALCULATION OF ENGINEERING DATA

The engineering data calculated for estimating the cost of construction of the tunnel were the rock load, spacing of support sets and lagging, the need for feeler holes and grouting, and the amount of ground water. The calculations were based on the predicted geologic section and the laboratory data, and the results are shown in Figure 8 as a series of graphs below the geologic section.

Rock Loads

The calculations for rock load were based on the assumptions that the pilot bore, outside the timbers, would be about 10.5 ft wide and 11.5 ft high; and that the rates of driving the pilot bore and of installing supports—both factors will affect the rock load—would be as efficient as possible. The rock load, then, would primarily be the result of geologic conditions.

The calculations were made using the following formula, which is modified from Terzaghi (7, p. 61):

$$P = C(b + h) X W \tag{1}$$

in which

P = rock load in psf,
C = a constant depending on rock conditions,
b = width of tunnel,
h = height of tunnel, and
W = weight per cu ft of rock.

The value for W was determined to be 166.88 based on the measurement of the saturated bulk density of samples. The values for C ranged from 0.35 to 1.60 depending on the interpretation of the rock conditions expected and the possible presence of fault gouge. A maximum load of about 5,900 psf was calculated.

Support

Rock pressure, fracture density, and the amount of fault gouge or clay alteration products vary from place to place, although they are interrelated to a considerable degree. The total effect of these geologic factors on tunnel construction can be expressed, more or less quantitatively, by the amount of support that may be required. The estimates given in this report concerning support requirements should be regarded as only a relative measure of the severity of geologic conditions, and not as an attempt to formulate definitive engineering design requirements.

For purposes of calculation, it was assumed that the sets would be so designed as to support a maximum load of 10,000 psf and that the tunnel would be driven on a 3-shift-a-day basis. The principal factor then that will influence the amount of support is the fracture density. The results of the calculations are shown on a graph below the section in Figure 8. Note that invert struts may be required for some sections. These are the sections where wide zones of fault gouge may be encountered.

The prediction of the spacing of sets and amount of lagging is empirical. The spacing of sets and the amount of lagging that will actually be required can be determined only at the time of excavation. The purpose of the graph is only for estimating the probable total amount of timber that will be required and the approximate location where timbering problems may be encountered.

Feeler Holes and Grouting

The geologic conditions ahead of some sections of the tunnel should be determined by drill holes in advance of the face. The probable location of these sections is shown in Figure 8. Such feeler holes will test for badly broken or crushed rock that may be filled with water. Many such zones noted on the surface and in the drill holes might be expected to contain large volumes of water at the depth of the tunnel. If these zones are located in advance of the face, it may then be possible to seal off the water and consolidate the broken rock in advance of the tunnel.

Variations in the geologic conditions encountered will also determine the amount of grout. The sections in which the geologic conditions indicate grouting may be required are shown in Figure 8. The amount of grout given is based on the amount used in the Roberts tunnel, which averaged about 10 cu ft (sacks) per foot of grouted section.

It should be emphasized that the sections indicated to be tested by feeler holes and the sections to be grouted are predictions only. In practice, rock conditions at the face should be continually and carefully observed, and if there is any indication of a possible water-bearing section ahead of the face, the section should be tested by feeler holes. The cost of feeler holes is cheap in comparison to the cost of recovering a caved face.

Ground Water

The amount of ground water that will be encountered depends on the porosity and permeability of the rock and the height of the water table above the tunnel level. The porosity of the rock depends primarily on the average distance between fractures as calculated for each interval of the tunnel, and the number of faults and shear zones. The permeability of the rock depends primarily on the size and interconnection of the fractures. These factors were determined from field and laboratory investigations and equated with records of water flows in other tunnels and with test data from wells in similar rocks. In making these calculations the authors were assisted by George H. Chase of the U. S. Geological Survey.

The average amount of ground water that is expected to flow from the tunnel portal is shown by a graph in Figure 8. This graph is based on an estimated rate of advance of the heading of 1,000 ft per month. An increase in the rate of advance will increase the amount of flow, and conversely, a slower rate will decrease the amount of flow. If this rate is projected beyond the total time of driving the tunnel, the average flow at the portal should decrease to about 300 gal per min within 2 weeks and to about 100 gal per min within a year.

The maximum amount of flow that might be expected from the various fracture intervals of the tunnel is shown by a histogram in Figure 8. This amount is the maximum initial flow that might be expected from a fault or shear zone within the interval. This flow should decrease rapidly within 5 to 10 days. According to these calculations, the maximum average flow from the portal is estimated at about 500 gal per min; the maximum initial flow from any section of the tunnel is estimated at about 1,000 gal per min.

It should be understood that these figures are based on statistical averages that were obtained by comparing the predicted geologic conditions with well data for similar rocks and with records of flows from other tunnels. Within any section of the tunnel, the water will not issue at a uniform rate but will flow primarily from the faults and shear zones and the more closely jointed rock within that section.

FUTURE RESEARCH

Geologic, geophysical, and laboratory studies are being continued currently with the pilot bore construction, which was started about November 1, 1963. The primary purpose is to evaluate the geologic and engineering predictions so that predictions for future tunnels can be more accurate. The Colorado Department of Highways has included, as part of the contract for construction of the pilot bore, certain items of work that will allow the U. S. Geological Survey as well as the Department's consultants to conduct fundamental research on the measurement of physical and engineering properties of rock in situ.

Detailed geologic maps of the tunnel are being made as the face is advanced, and the related engineering data recorded. A recording flume has been installed at the portal of the tunnel to register the water flow from the portal; and the amount of water issuing from the face is recorded after each round. The amount of initial water flowing from the larger water channels is recorded, and the measurements repeated until the flow becomes constant. The amount of timber and the spacing of sets are recorded, as are the number, direction, and length of feeler holes and the amount of grout used.

The Colorado Department of Highways has retained Patrick Harrison, Inc., to instrument the tunnel to determine quantitatively the rock loads. This is to be done at 200-ft intervals—and as dictated by the geologic conditions—by the use of load cells in the sets and single- and multiple-position borehole extensometers. On the basis of the geologic conditions, these data can be extrapolated to the probable support requirements in the final twin bores.

The current geophysical investigations include resistivity and sonic velocity measurements along the walls and in drill holes. The purpose is to devise instruments and procedures, and to evaluate the use of such instruments and procedures based on these principles, for measuring engineering properties of rocks in situ. Also, these data will aid in the prediction of geologic conditions to be encountered in driving the final twin bores, and possibly in selection of the position for these final bores in relation to the pilot bore.

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