Surface and Underground Geophysical Studies At Straight Creek Tunnel Site, Colorado

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Seismic and electrical resistivity measurements were made in the Straight Creek tunnel pilot bore during and immediately after the period of construction. These underground geophysical measurements were interpreted to obtain the seismic velocity and electrical resistivity of rock behind the disturbed layer surrounding the pilot bore. Velocity and resistivity values were correlated statistically with the following economic and engineering parameters: time rate of construction, cost of construction per foot, rock quality, set spacing, percentage lagging and blocking, type of steel support required, height of tension arch, and vertical load. The quality of these correlations was quite good, with correlation coefficients ranging from about 0.8 to nearly 1.0 in absolute value.

Results indicated that if correlations such as these were established during the early stages of construction of a tunnel, or if they were established from previous measurements in another tunnel of similar dimensions, constructed by similar techniques, and in rock of a similar type, predictions of economic and engineering parameters could be made to guide construction in the new tunnel. Predictions could be based on geophysical measurements made on the surface above the tunnel, or on measurements made underground in feeler holes drilled ahead of the working face.

The accuracy of predictions based on surface geophysical measurements was tested by making seismic and resistivity surveys on the surface and in holes drilled from the surface along the line of the pilot bore. Results indicated that reasonably accurate predictions are possible from surface measurements. Greater accuracy and more detailed information would be obtained if predictions were based on geophysical logging measurements made in feeler holes drilled ahead of the working face. Because the cost of geophysical surveys is small compared with the cost of tunnel construction, it is concluded that predictions of this type would reduce the total cost of tunnels by increasing construction efficiency.

•THE U. S. Geological Survey made surface and underground geophysical measurements in the area of the Straight Creek tunnel pilot bore as part of a general program of research conducted in cooperation with the Colorado Department of Highways. Geophysical measurements of seismic velocity and electrical resistivity were made underground along the walls of the pilot bore. Additional measurements of velocity and resistivity were made on the surface and in holes drilled from the surface over the line of the bore.

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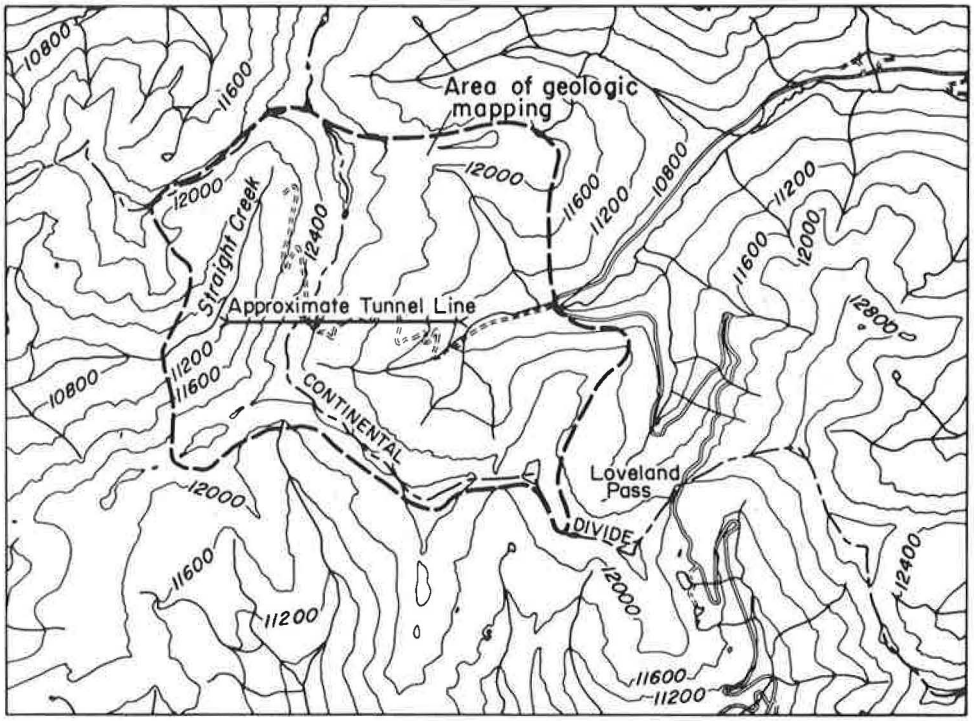
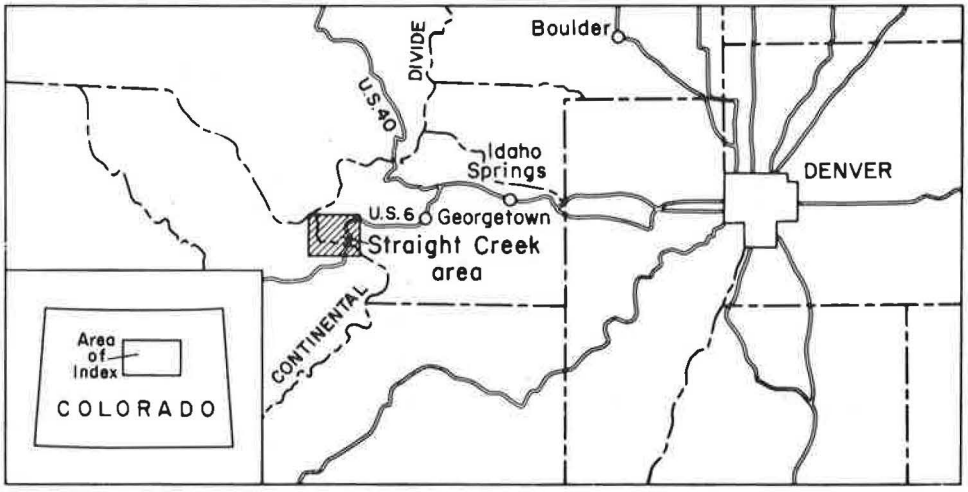


Base map from Loveland Pass quadrangle, 1958

0 2 MILES
CONTOUR INTERVAL 400 FEET
DATUM IS MEAN SEA LEVEL

Map of Straight Creek area



0 20 40 MILES

Location of Straight Creek area

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

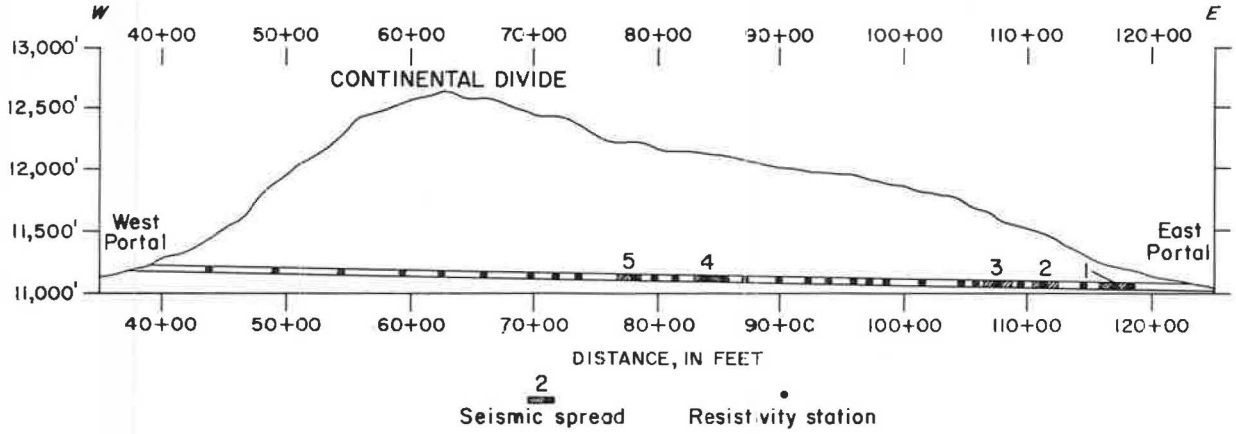


Figure 2. Cross section of Straight Creek tunnel pilot bore showing locations of underground geophysical measurements.

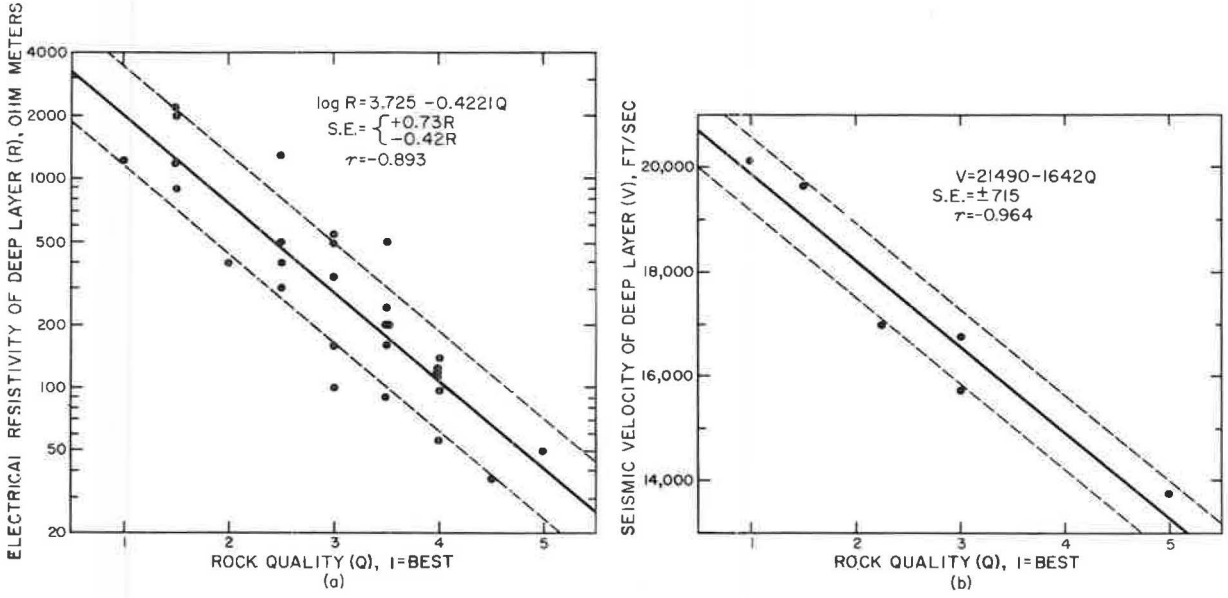


Figure 3. Rock quality (see Table 1) plotted against: (a) electrical resistivity of deep layer and (b) seismic velocity of deep layer.

This report discusses the results of the underground studies, the statistical relationships developed from them, and the results obtained from geophysical measurements made on the surface and in holes drilled from the surface.

The pilot bore in which the geophysical measurements were made is approximately 13 ft in diameter and 8, 300 ft long. The bore is located about 55 mi west of Denver, and passes beneath the Continental Divide between the Loveland ski area on the eastern slope and the headwaters of Straight Creek on the western slope of the Rocky Mountains (Fig. 1). The pilot bore was driven to obtain geologic and engineering information required for efficient construction of a twin-bore highway tunnel to be part of I-70.

GEOLOGY

A detailed surface geologic mapping program in the vicinity of the Straight Creek tunnel pilot bore was completed before construction of the bore (1). Results indicated that bedrock in this area consists chiefly of Precambrian granite (about 75 %) with inclusions of Precambrian metasedimentary rock (about 25 %—composed of biotite-rich gneiss, schist, and migmatite), and a few small dioritic dikes of probable Tertiary age. The bedrock is extensively faulted and sheared and is locally altered. Regional geology and major faulting in the area are described by Lovering and Goddard (2). Although outcrops are plentiful, most of the bedrock is overlain by thin deposits of colluvium, talus, landslide material, and swamps. Results of the pre-construction surface geologic mapping were used to predict general geologic conditions and engineering characteristics of the rocks at the depth of the pilot bore. These predictions, and the information on which they are based, are described by C. S. Robinson and F. T. Lee (3).

UNDERGROUND GEOPHYSICAL MEASUREMENTS

Electrical resistivity and seismic refraction measurements were made in the pilot bore at locations shown in Figure 2. Measurement locations were chosen so that the full range of rock quality existing in the pilot bore was sampled. Rock of lowest quality was characterized by intensive fracturing and severe mineral alteration. Rock of highest quality was nearly free of fractures and mineral alteration.

Underground seismic measurements were made with high-resolution 10-channel refraction seismic equipment capable of detecting energy in the frequency range 10 to 4, 000 cps. Accelerometers, used to detect the seismic energy from explosive energy sources, were emplaced along the tunnel walls about 4 ft above the floor in linear arrays about 200 ft long. Spacings between accelerometers ranged from 5 to 25 ft. Small explosive charges (0. 1-lb dynamite) were detonated in 1-ft deep shot holes drilled into the rock at both ends and at the midpoint of each array of 10 accelerometers. Seismic energy was recorded on photosensitive paper by means of an oscillograph having a paper speed of 250 in./sec. The time intervals between detonation of the explosive charge and arrival of seismic energy at each accelerometer were determined from the oscillograph records, and were plotted on graph paper against distance between the shot point and each detector. Average rock velocity along the detector arrays was obtained from these graphs. Interpretations of velocity layering indicated that a zone of anomalously low velocity rock (4, 200 to 10, 800 ft/sec) surrounds the opening and has a thickness ranging from less than 1 ft to about 17 ft. The existence of this layer is attributed to blast damage and to movement of rock toward the center of the opening along fracture and fault surfaces in response to stresses created by the bore. This movement, confirmed by extensometer measurements, evidently causes the velocity of rock in the disturbed layer to decrease because of enlargement of gaps along fractures and faults. The velocity of rock behind the anomalous layer is characteristic of the undisturbed rock (13, 750 to 20, 150 ft/sec). A more detailed discussion of seismic instrumentation, field procedure, and interpretation methods is given by Scott et al (4).

Underground electrical resistivity measurements were made with conventional Gish-Rooney equipment and special sponge-rubber electrodes impregnated with a mixture of brine and bentonite to provide good electrical contact with the rock exposed along the walls of the pilot bore. Measurements were made using the Wenner electrode configuration with electrode spacings expanded from 1 to 30 ft in a stepwise manner,

keeping the array symmetrical about a center point and parallel with the tunnel axis. This procedure provided a means of interpreting resistivity layering from the surface to a depth of 10 ft or more. Apparent resistivity values obtained from these measurements were corrected for tunnel geometry and plotted against electrode spacing on log-log graph paper. The plotted points were then interpreted by curve-matching methods, using theoretically derived curves representing two layers having a variety of resistivity contrasts (5). Interpretations indicated that a rock layer having a relatively high resistivity (60 to 5, 300 ohm-meters) surrounds the opening and has a thickness ranging from less than 1 ft to about 10 ft. The anomalously high resistivity of this layer is attributed to evaporation of moisture from rock exposed to air. The depth of exposure is probably affected by the depth of severe fracturing caused by blasting. The resistivity of rock occurring behind this layer is characteristic of undisturbed rock (36 to 2, 200 ohm-meters). A more detailed discussion of electrical resistivity instrumentation, field procedure, and interpretation techniques for the underground measurements is given by Scott et al (4).

Interpretations of the geophysical data indicated that the layer of high-resistivity rock surrounding the tunnel was generally thinner than the corresponding layer of low-velocity rock. The difference in thickness may be attributed to a difference in the mechanism causing the anomalous layers detected by the two types of measurements. In electrical resistivity, the anomalous layer is probably caused by evaporation and fracturing chiefly within the blast-damaged zone which in most places is restricted to a depth of only a few feet. In seismic velocity, however, the anomalous layer is believed to be caused by the adjustment of rock in response to stress and subsequent enlargement of gaps along fractures and faults that may occur at depths of 10 ft or more in poor-quality rock.

STATISTICAL CORRELATIONS BASED ON UNDERGROUND MEASUREMENTS

Statistical correlations of underground geophysical data with engineering and construction data were based on the resistivity and velocity of rock behind, rather than within, the anomalous layers surrounding the pilot bore. The reasons for using values for the deep layer were (a) the correlations appeared to be more consistent than those made with data from within the anomalous layers, and (b) appraisal of the predictability of engineering and economic data from geophysical data obtained ahead of construction would require that the correlations be based on geophysical data from relatively undisturbed rock.

Rock Quality

Cursory comparisons of geophysical data and rock quality at various locations in the pilot bore suggested that as rock quality improved, seismic velocity and electrical resistivity both tended to increase. To test the degree of apparent correlation statistically, it was necessary to establish a numerical scale for rating rock quality along the walls of the pilot bore. An arbitrary numerical scale of 1 through 5 was established (4) in which 1 represented the best, and 5 the poorest, rock (Table 1). Quantitative criteria used for rating rock quality included fracture spacing and mineral alteration (% rock); qualitative criteria were faulting, foliation and schistosity, and rock type. The criteria are given in the table in descending order of importance in determining the numerical rating. Figure 3 shows rock quality plotted against electrical resistivity and seismic velocity of rock behind the disturbed layer. In this figure, and in all other figures showing statistical correlations, the solid line represents the regression line determined by the method of least squares, and the dashed lines represent plus and minus one standard error. Numerical values of standard error are indicated in the figures by S. E. and the correlation coefficient by r. Because the values of r in Figure 3 are numerically close to ± 1, the quality of the correlations between geophysical values and rock quality is very good. For a perfect correlation $r = \pm 1$, and for a complete lack of correlation $r = 0$.

In Figure 3, and in the other figures showing correlations, electrical resistivity data generally show a greater degree of scatter than seismic velocity data. This difference in

TABLE 1

ROCK QUALITY BASED ON GEOLOGIC CHARACTERISTICS—STRAIGHT CREEK TUNNEL PILOT BORE

Quality[a]	Fracture Spacing (ft)	Mineral Alteration (% rock)	Faulting	Foliation and Schistosity	Rock Type
1	>3	< 5	None	None; prominent banding in migmatite.	Predominantly granite or diorite dikes; sparse migmatite.
2	1 to 3	5 to 10	Minor; a few slicks and minor gouge.	Poorly defined; prominent banding in migmatite.	Commonly granite; sparse gneiss and migmatite.
3	0.3 to 1	10 to 15	Moderate; slicks common, minor gouge.	Poorly to well defined; may be absent in granite.	Granite and metamorphics, occurrences about equal.
4	0.1 to 0.3	15 to 20	Moderate to severe; slicks and gouge on most surfaces.	Well defined in metamorphics; may be absent in granite.	Commonly schist, gneiss, or migmatite; sparse granite.
5	<0.1	>20	Intense; frequency of gouge seams may be greater than fracture spacing.	Very well defined; may be absent in granite.	Predominantly schist; sparse granite.

[a]In this scale, 1 represents the best, and 5 the poorest, rock.

scatter is attributed to a difference in the volume of rock sampled by the two geophysical measurements. Velocity values represent averages over sections of the pilot bore that are 3 to 6 times longer than those from which resistivity data were obtained.

Because it could be expected that nearly all engineering and economic aspects of construction would be affected to some degree by the quality of rock penetrated by the pilot bore, and because the geophysical data correlated quite well with rock quality, a series of correlations were made using the geophysical data and the following parameters: (a) height of tension arch, (b) stable vertical load, (c) set spacing, (d) lagging and blocking, and (e) rate of construction and cost per foot.

Height of Tension Arch

The height of the tension arch was determined from extensometer and load cell measurements. These measurements indicated that after the large initial stress associated with the advancing face had declined to a stable value, rock near the periphery along the back and walls of the pilot bore had moved inward toward the opening in response to tensional stress, and that rock at greater depths had moved outward away from the opening in response to compressional stress. The height of the tension arch was taken as the point of no movement that separated the two zones. At locations where extensometer measurements were not made, the height of the tension arch was estimated from load cell data, using the following formula:

$$H = L/D \tag{1}$$

where

H = height of tension arch, ft,
L = stable vertical rock load, psf, and
D = rock density, pcf.

Estimates based on this formula are considered justified because the load on tunnel sets is largely determined by the height of the column of rock in the tension arch above the tunnel.

Figure 4 shows the statistical correlations between the height of the tension arch and electrical resistivity and seismic velocity of rock behind the disturbed layers.

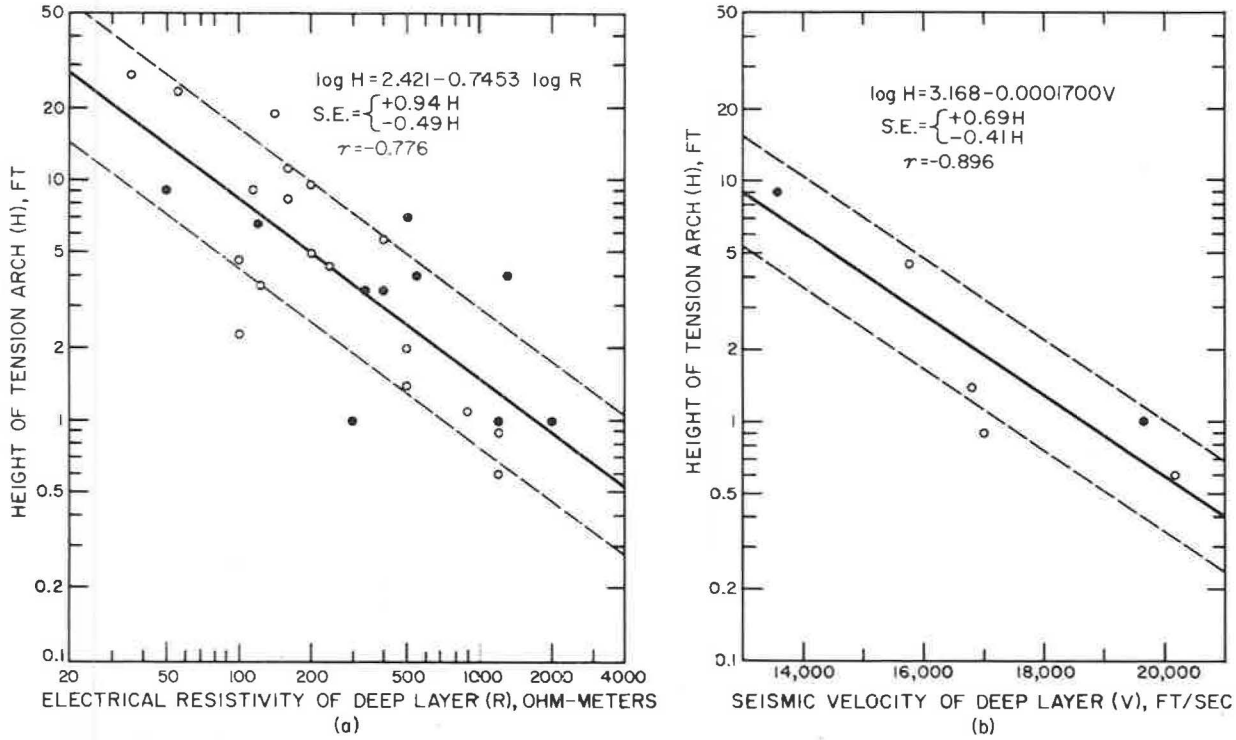


Figure 4. Height of tension arch plotted against: (a) electrical resistivity of deep layer and (b) seismic velocity of deep layer; solid circles represent values of H obtained from extensometer measurements and open circles represent values estimated from load cell data.

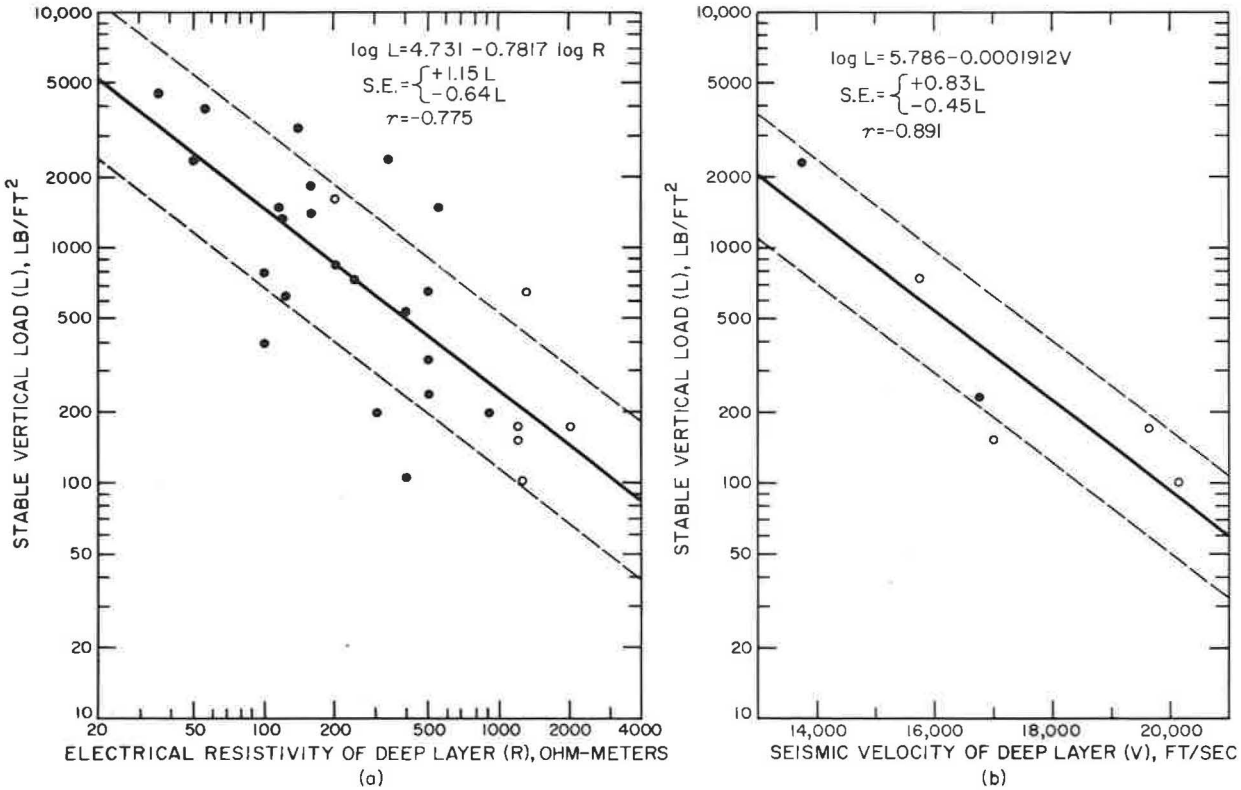


Figure 5. Stable vertical rock load plotted against: (a) electrical resistivity of deep layer and (b) seismic velocity of deep layer; solid circles represent values of L obtained from load cell measurements and open circles represent values estimated from extensometer data.

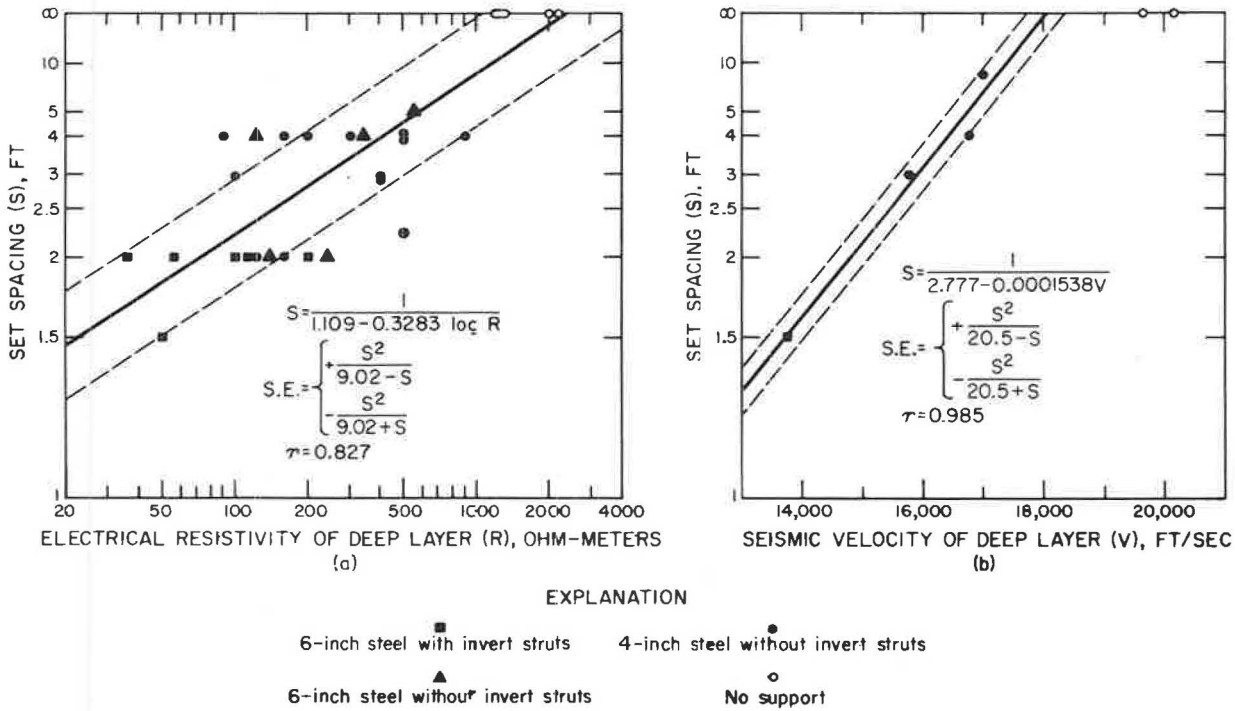


Figure 6. Set spacing plotted against: (a) electrical resistivity of deep layer and (b) seismic velocity of deep layer. (In graph b data points representing no support, open circles, were omitted in calculating the equation of the regression line because the data suggest an abrupt change of slope.)

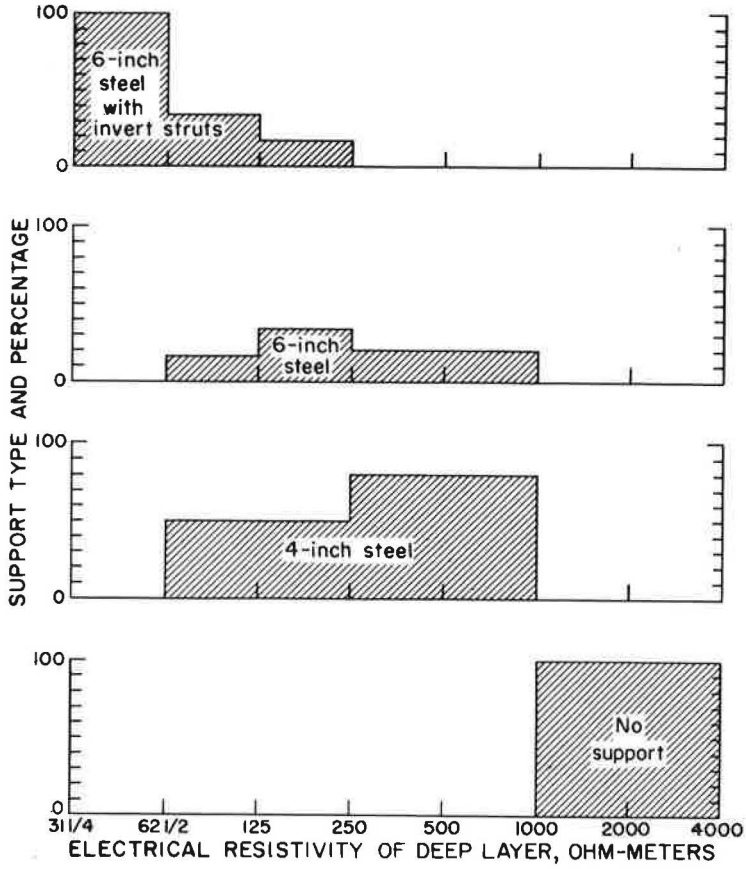


Figure 7. Support type and percentage used in rock classified on the basis of electrical resistivity of deep layer; resistivity class intervals are logarithmic.

Stable Vertical Rock Load

Load cell measurements were used as the basis for correlations between stable vertical rock load, electrical resistivity, and seismic velocity. Stable vertical rock loads were calculated from the load cell measurements by the following formula:

$$L = W/A \tag{2}$$

where

L = stable vertical rock load, psf,
W = weight measured by load cell, lb, and
A = area of influence; sq ft = tunnel width × set spacing.

At locations where load cell measurements were not made, but estensometer measurements were available, loads were estimated from Eq. 1 solved for L.

Figure 5 shows statistical correlations between stable vertical rock load and electrical resistivity and seismic velocity.

Set Spacing and Type of Support

Average set spacing was determined over the intervals where underground geophysical measurements were made, and correlations were established between average set

spacing and corresponding values of velocity and resistivity. Figure 6 shows that reasonably good statistical correlations exist between set spacing and both electrical resistivity and seismic velocity.

Figure 7 shows that a relationship also exists between resistivity data and the type of support required in a section of tunnel. In the Straight Creek tunnel pilot bore, for example, 6-in. steel arches and invert struts were required in all sections where resistivity was less than about 62 ohm-meters, and no support of any kind was required in sections where resistivity exceeded 1,000 ohm-meters. A similar relationship could probably have been established between type of support and seismic velocity if sufficient velocity data had been available.

Predictions of set spacing and type of support required, based on geophysical measurements made in advance of construction, would improve the efficiency of tunneling by providing the contractor with estimates of required supplies.

Lagging and Blocking

Another statistical study was made using lagging and blocking data. Figure 8 shows that the percentage of lagging and blocking correlates rather well with both electrical resistivity and seismic velocity. For the purposes of this correlation, the percentage scale is based on the following extremes: 0 percent implies that no lagging or blocking was necessary, and 100 percent implies that all available space around the steel sets was lagged and blocked.

Rate of Construction and Cost Per Foot

The quality of the previously described correlations suggests that there might be a direct correlation between the geophysical values and the rate of construction and cost per foot. Cost and rate of construction information were obtained from Miles (8). Figure 9 shows that these correlations do exist. The cost per foot values were obtained by assuming a constant average cost per day and dividing this value by rate of construction. This is not completely valid, because cost per day fluctuated as the cost of labor and materials varied during the period of construction. However, the assumption of constant cost per day is considered sufficiently accurate for obtaining first approximation cost estimates from the correlations.

SURFACE GEOPHYSICAL MEASUREMENTS

Electrical resistivity and seismic refraction measurements were made on the ground surface and in holes drilled from the surface over the line of the pilot bore (Fig. 10).

Surface seismic measurements were made with five mobile seismic refraction units provided by the U. S. Geological Survey. These units are described in detail by Warrick et al (6). Geophones were placed on the ground surface over the line of the pilot bore at intervals of approximately 600 ft. In addition, probes containing geophones were lowered into and fastened to the walls of drill holes 2 and 3 at depths of 712 and 526 ft, respectively. Charges of 25 to 50 lb of dynamite (60% gel) were stemmed with water and detonated at depths ranging from 70 to 100 ft in shot holes drilled near the two portals of the pilot bore. Air shots of 15 to 20 lb of dynamite were detonated 4 ft above the ground surface at three locations between the portals to determine the thickness of shallow velocity layers not detectable from in-hole shots. Velocity layering interpretations were made by plotting the refraction travel times obtained from the seismic records against the distance between shot holes and surface geophones, and then computing the thickness of layers represented by the plotted points. Results of the interpretation indicated that three distinct layers of rock occur approximately parallel to the surface (Fig. 10). The upper layer has an average velocity of 5,070 ft/sec and extends to depths ranging from 35 to 90 ft. This layer probably represents rock that is badly weathered and heavily fractured. The middle layer has an average velocity of 12,400 ft/sec and extends to depths ranging from 180 to 465 ft. The third layer has an average velocity of 16,400 ft/sec and an unknown thickness. Underground seismic measurements indicate that the velocity of the third layer is somewhat higher than

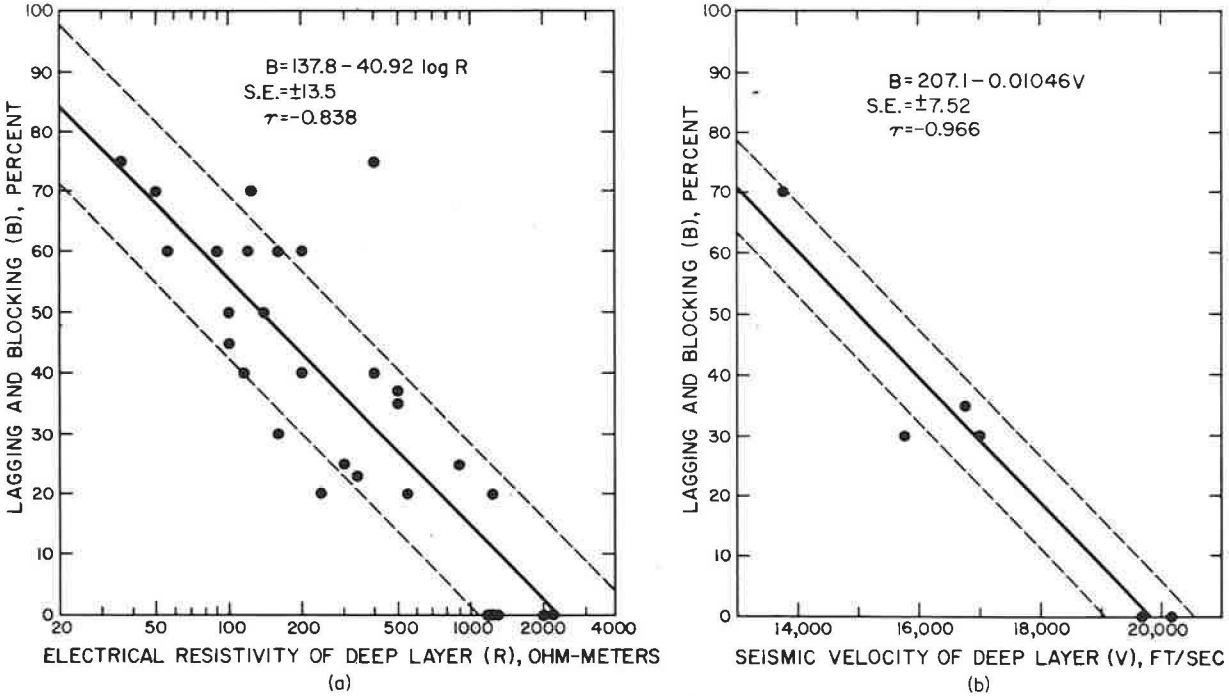


Figure 8. Lagging and blocking plotted against: (a) electrical resistivity of deep layer and (b) seismic velocity of deep layer.

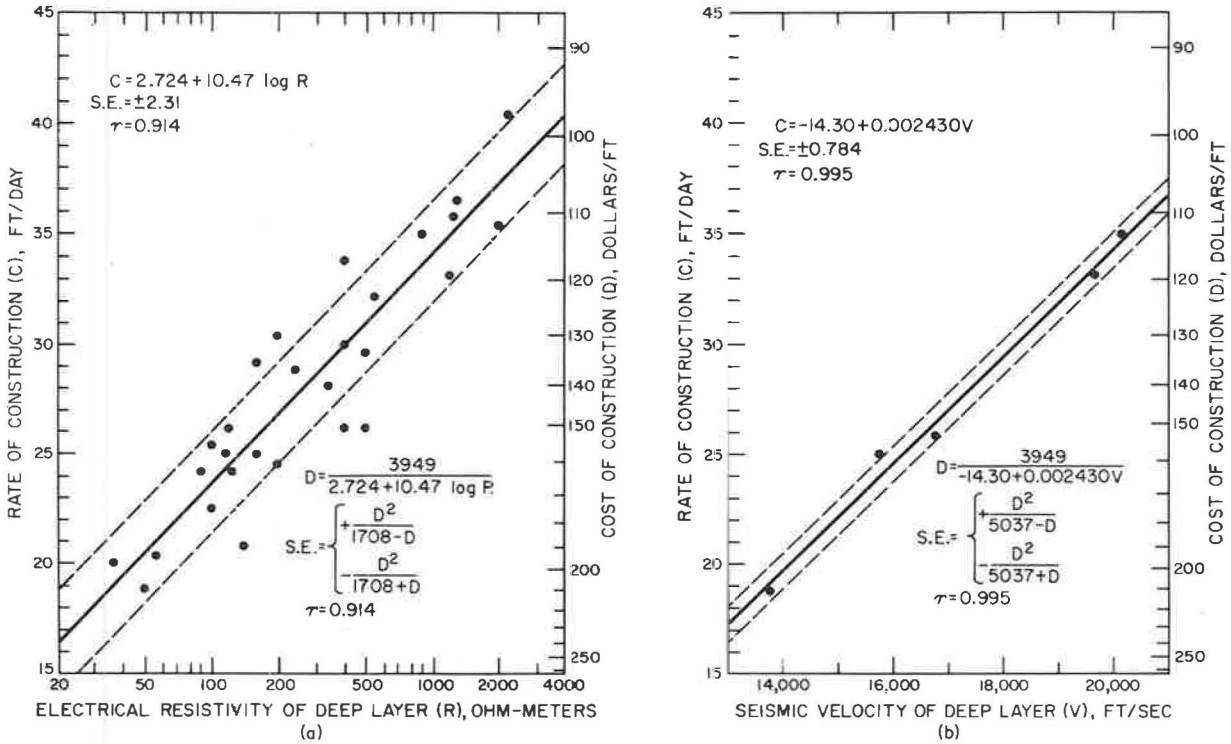


Figure 9. Rate of construction and cost per linear foot plotted against: (a) electrical resistivity of deep layer and (b) seismic velocity of deep layer.

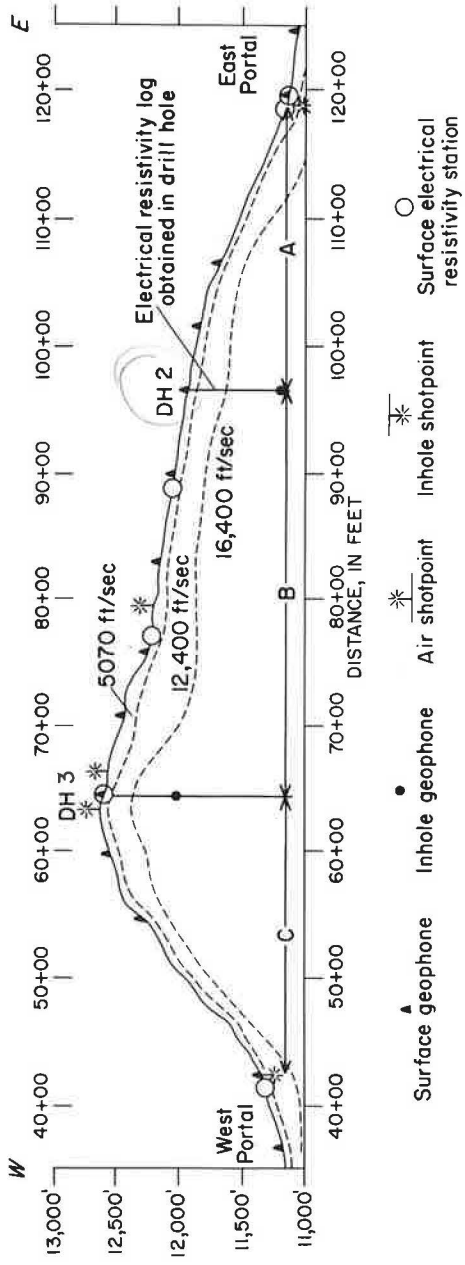


Figure 10. Cross section of Straight Creek tunnel pilot bore showing locations of surface and in-hole geophysical measurements and interpretation of seismic refraction survey. (A, B, C, indicate intervals discussed in text.)

the average velocity of rock occurring along the pilot bore. Because first arrival refraction energy followed this high-velocity layer, it was not possible to determine the velocity of rock at the depth of the pilot bore from the refraction seismic data. Fortunately, data for the direct seismic travel paths between the in-hole shot points and the in-hole geophones (intervals A, B, and C, Fig. 10) provided velocities that were more representative of rock at the level of the pilot bore. Estimates of engineering and economic parameters based on these direct travel-path velocities were made, using the correlations established underground. The results indicate that the estimates were reasonably accurate (Table 2).

Electrical resistivity measurements were made along the surface, at locations shown in Figure 10, with electrodes arranged in the Schlumberger configuration. A series of measurements was made at each location by expanding the electrode spacings in a stepwise manner, keeping the center of the array at a fixed location. This procedure caused current to flow over a range of depths from the near surface to below the level of the pilot bore. Interpretations were made by the curve-matching technique using two-layer Schlumberger curves and auxiliary curves (7). Resistivity values interpreted from the surface measurements were used, together with resistivity values obtained from an electric log in drill hole 2, to estimate the average resistivity of rock over intervals A, B, and C (Fig. 10) in the pilot bore. Results of estimates based on these average values are given in Table 3. These estimates are less accurate than those based on seismic velocity (Table 2). One possible cause for the difference in accuracy is that seismic velocity was determined along straight-line segments near the pilot bore, whereas surface resistivity measurements represented a large volume of rock surrounding the bore. The discrepancies between actual values and estimates based on resistivity indicate that the resistivity of rock in the immediate vicinity of the pilot bore was generally lower than the average resistivity of the large volumes of rock that influenced the surface resistivity measurements.

CONCLUSIONS

The statistical correlations relating underground geophysical measurements to

TABLE 2

ESTIMATED VS ACTUAL VALUES OF ENGINEERING AND ECONOMIC PARAMETERS, WITH ESTIMATES BASED ON DIRECT TRAVEL-PATH SEISMIC VELOCITIES[a] AND STATISTICAL CORRELATIONS[b]—STRAIGHT CREEK TUNNEL PILOT BORE

Section	Parameter								
	Seismic Velocity (ft/sec)	Avg. Set Spacing (ft)		Avg. Lagging and Blocking (%)		Avg. Rate of Construction (ft/day)		Cost of Construction ($)[c]	
		Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.
Interval A	15, 360	2. 4	3. 7	46	51	23	17	420, 000	420, 000
Interval B	15, 260	2. 3	2. 9	48	35	23	26	560, 000	540, 000
Interval C	17, 360	9. 4	7. 3	26	13	28	29	370, 000	440, 000
East portal to west portal	15, 740	4. 5	4. 6	40	33	24	23	1, 350, 000	1, 400, 000

[a]Velocities measured between in-hole shot points and in-hole geophones (intervals A, B, and C, Fig. 10).
[b]Established from underground geophysical measurements.
[c]Data derived from Ref. 8.

engineering and economic parameters in the Straight Creek tunnel pilot bore indicate that the efficiency of tunneling, in general, may be improved by the judicious application of a geophysical program before and during construction.

Pre-construction geophysical measurements on the surface or in holes drilled from the surface would be useful for selecting a site if several alternative tunnel routes were under consideration. Although the correlations described in this paper would not be directly applicable to a tunnel driven in a different geologic environment, or to a tunnel of a different size driven in the same environment, the correlations do indicate that certain basic relationships exist between the measurable properties of rock and the economic and engineering aspects of tunneling. More specifically, in any given geologic environment, rock having high seismic velocity and high electrical resistivity is generally stronger and easier to excavate than rock having a low velocity and low resistivity. Therefore, even if appropriate correlations are not available, geophysical measurements would be useful for estimating the relative cost and difficulty of construction along each of several possible routes. If correlations are available from measurements made in a similar tunnel in the same environment, then quantitative estimates may be made.

After a site is selected, geophysical measurements made during the early stages of construction in long feeler holes drilled ahead of the working face could be used to establish correlations, or to improve existing ones. Then, when statistical tests indicate that sufficient data have been obtained to make the correlations valid, they could be

TABLE 3

ESTIMATED VS ACTUAL VALUES OF ENGINEERING AND ECONOMIC PARAMETERS, WITH ESTIMATES BASED ON SURFACE ELECTRICAL RESISTIVITY MEASUREMENTS, ELECTRIC LAG MEASUREMENTS[a], AND STATISTICAL CORRELATIONS[b]—STRAIGHT CREEK TUNNEL PILOT BORE

Section	Parameter								
	Electrical Resistivity (ohm-meters)	Avg. Set Spacing (ft)		Avg. Lagging and Blocking (%)		Avg. Rate of Construction (ft/day)		Cost of Construction ($)[c]	
		Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.
Interval A	177	2. 7	3. 7	46	51	26	17	380, 000	420, 000
Interval B	234	3. 0	2. 9	41	35	28	26	460, 000	540, 000
Interval C	606	5. 1	7. 3	24	13	32	29	320, 000	440, 000
East portal to west portal	332	3. 6	4. 6	37	33	29	33	1, 160, 000	1, 400, 000

[a]Drill hole 2.
[b]Established from underground geophysical measurements.
[c]Data derived from Ref. 8.

used to predict engineering and economic parameters ahead of construction. New data points could be added to the correlations as construction progressed, so that the accuracy of predictions would continue to improve throughout the period of construction.

Geophysical techniques and instrumentation are presently available for making measurements on the surface and in vertical drill holes before construction. Instrumentation for making seismic velocity and electrical resistivity logging measurements in feeler holes is not yet sufficiently developed to make measurements in a routine manner. It is considered feasible, however, to adapt standard geophysical logging equipment and techniques, most of which have been developed by the petroleum industry, to application in horizontal holes in tunnels. The main obstacle to overcome is that most standard logging techniques require the presence of fluid (water or drilling mud) in drill holes, so that it would be necessary either to develop methods for providing fluid in the feeler holes or to develop instrumentation capable of obtaining measurements in air-filled holes.

RECOMMENDATIONS

It is recommended that research be continued along two lines: (a) develop instrumentation and methods for making geophysical logging measurements in feeler holes drilled ahead of the working face, and (b) further test the validity of the correlations by collecting additional geophysical data, both on the surface and underground, in or near other existing tunnels. Eventually, if suitable geophysical instrumentation is developed, and if correlations are established for tunnels of different sizes constructed by various techniques in wide variety of geologic environments, it may be possible to make valid economic and engineering predictions for any tunnel from geophysical measurements made on the surface or underground in advance of construction. A predictive capability such as this would increase the efficiency of tunneling, and would probably eliminate the need for costly and time consuming pilot-bore construction.

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