UPHOLE SEISMIC MEASUREMENTS AS AN INDICATION OF STRESS RELIEF IN GRANITIC ROCK TUNNELS

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Abstract.—Seismic velocities obtained in holes drilled into the walls of a tunnel in granitic rock show the presence of a low-velocity zone ranging in thickness from 0 to 8 feet. The low-velocity zone is attributed to the effects of movement of rock into the tunnel. The detection, thickness, and velocity of the zone appear related to the presence of fractures rather than to the size of the tunnel. The seismic velocities measured in this environment appear related to rock competence rather than to the thickness of the low-velocity layer. Research into the quantitative relationship of the velocity differences to actual stress distribution around a tunnel opening is required.

The anomaly of stress around a tunnel due to the disequilibrium of forces arising as a consequence of the opening has been described by numerous investigators. Obert and others (1960) utilized mathematical analyses to describe the state of stress around a tunnel opening. Studies using photoelastic methods have also been used for similar analyses (Frocht, 1941). Both of these methods, however, suffer from the limitation that simplifying assumptions must be made regarding the conditions of analyses. In mathematical analyses, homogeneous elastic media must be assumed, and Hooke's law is assumed to apply; and in photoelastic methods a homogenous material is used in the tests. The addition of inhomogeniety complicates the solution of the problem. These methods do, however, provide a basis for understanding of the problem of support requirements around underground openings.

Depending on the initial distribution of stress in a rock—a distribution related both to geologic environment and tectonic history—the rock will tend to rearrange itself in the vicinity of an opening in such a manner as to recreate equilibrium conditions. Consequently, a stress pattern is created around the tunnel opening. When the magnitude of these stresses becomes sufficiently large, support is required to prevent rock from moving destructively into the tunnel. Consequently the in situ determination of the zone of stress anomaly is of importance in support design, and any measurements which aid in defining its geometry can be of considerable value in tunnel engineering.

One means of observing the variation in stress around a tunnel is to measure the variation of seismic velocity in the rock in the immediate vicinity of the tunnel. Although such measurements must be made after the excavation has been made, the measurements are desirable for two reasons: (1) they contribute to basic data on rock behavior in general, and (2) they may enable support requirements to be predicted, on the basis of the geology over the major portion of a tunnel, from selected measurements obtained during the initial stages of construction.

The velocity-stress dependence of rocks is an observed phenomenon (Wyllie and others, 1958). The tendency of seismic velocities in rock to increase under increasing compressive stress and to decrease under tensile forces due to the changes in transmission characteristics across grain contacts and microfractures suggests an indirect method of measuring stress. Because of the movement of rocks into a tunnel, tensile forces may be expected to produce a low-velocity zone around the tunnel opening. We choose to define this zone as the zone of stress relief. It is realized that this layer possibly includes some effects due to blast damage. It is felt, however, that the magnitude of the velocity layering obtained at many of our stations is not compatible with blast damage.

Some indirect evidence that the low-velocity zone is not a function of blasting was recently obtained by Scott.

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Seismic methods indicated a 16-foot-thick low-velocity zone in a section of tunnel in the Straight Creek pilot bore in Colorado. This section—a granite shear zone—yielded by plastic deformation; the floor moved up by more than 1 foot, necessitating additional support in the section. Because movement was by squeezing, the affect of blasting may be considered nil in opening fractures. Consequently, the low-velocity zone was not a function of blasting in this instance but probably of stress relief. Although this evidence does not eliminate the possibility of a low-velocity layer caused by blasting it does suggest that blasting alone cannot account for the low-velocity layer in all places. We prefer to consider the low-velocity zone noted in our present study as being, in most instances, due to stress relief, but we do not exclude the possibility that blast damage caused some of our shallower anomalies.

Other things being equal (for example, rock composition, degree of weathering, and fracturing), the ability to discriminate velocity changes arising from changes in stress in a rock is strongly dependent on porosity. In general, the incremental velocity change for a rock with high pore porosity is greater for a given incremental stress change than is that for the same rock type with lower porosity. On the other hand, at low pore porosities a great many rock types exhibit little velocity change with increasing compressive stress until failure. In such cases, however, the presence of secondary porosity (fracturing) can greatly decrease velocity. The present investigation deals with rocks of this type.

LOCALE AND METHOD OF MEASUREMENT

The seismic-velocity measurements were made in tunnels located in the Climax stock at the U.S. Atomic Energy Commission Nevada Test Site, Mercury, Nev. The tunnel complex was constructed at a depth of 1,500 feet in quartz monzonite and granodiorite. Primary porosity in these rocks is extremely low, commonly less than 2 percent, and consequently stations for measurement were selected in order to sample both rock types on the basis of the wide range of fracture conditions which existed. The locations ranged from sections in both rock types wherein several tens of feet of unfractured rock were available, to extensively sheared rock sections of similar extent. At the selected stations, 3-inch-diameter holes were drilled normal to the main axis of the tunnel to depths of 20 to 30 feet. In most places holes were drilled in both ribs, the back, and the floor. At 9 stations a total of 36 holes were sampled by measuring uphole traveltimes. Measurements were obtained by detonating a dynamite cap at the hole collar and observing the arrival time at 3 accelerometers located in the hole on 2-foot centers out from the collar. The accelerometers were positioned deeper in the hole on successive shots until a time-distance plot of seismic arrivals was obtained throughout the length of the hole. Details of the instrumentation and of the uphole positioning apparatus have been published elsewhere (Carroll and others, 1966).

The tunnel complex in the Climax stock, in general, was unsupported at the time of measurement, with the exception of a few sections where rock bolts were required.

RESULTS OF MEASUREMENTS

The results of measurements made in a section of moderately to severely fractured quartz monzonite are shown in figure 1. This station, located where two drifts converge, permitted a check on the usefulness of the velocity method to investigate the zone of stress relief. It allowed a two-way check on measurements by penetrating both drifts with a single hole, thus affording the opportunity to record from both ends of the hole. As shown in figure 1, the velocity contrast between rock near the tunnel and that farther away is marked. There is a tendency for the low-velocity zone to increase in thickness as one approaches the intersection of the shop and supply drifts. This seems reasonable in that there is more open tunnel to be supported by the adjacent rock as one moves toward the intersection. Consequently, the measurable zone of stress relief might be expected to increase in thickness.

In other sections of the tunnel however, the thickness of the low-velocity layer was not a noticeable function of the tunnel dimensions. This was true even at stations where the tunnel diameters were 3 to 4 times that of the shop and supply drifts. A summary of the measurements and pertinent data is shown in table 1.

The results of measurements made in holes in the periphery of the tunnel, at the northernmost station in the shop drift (fig. 1), are shown in figure 2. The low-velocity zone indicates that stress relief is sufficient on all sides of the tunnel to yield a noticeable velocity contrast. The two-way observation of the low-velocity zones between the shop and supply drifts is noteworthy.

In contrast to the results obtained in the fractured quartz monzonite section shown in figures 1 and 2, figure 3 shows the results of measurements made in a relatively fracture-free section of quartz monzonite in the main access drift of the complex. Here a low-velocity zone was not detected. In general, similar results were obtained at other locations in the tunnel (table 1), that is, the more pronounced the fractures

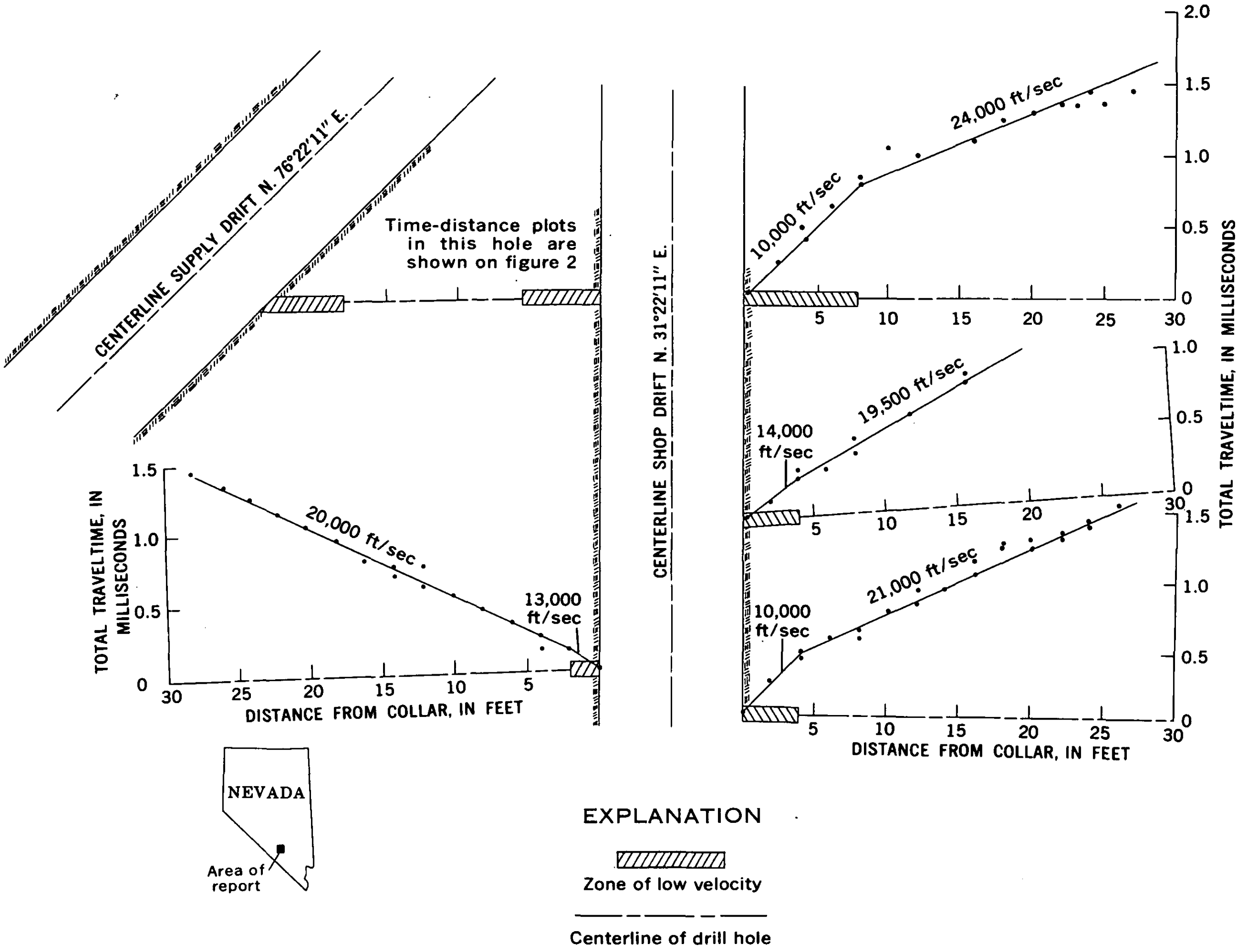

FIGURE 1.—Plan view of horizontal holes in shop and supply drifts within the Climax stock, Nevada, showing results of uphole velocity measurements in fractured quartz monzonite.

the greater likelihood of appearance of the low-velocity layer in the drill holes. Consequently, the presence or absence of a low-velocity zone around the tunnels of the Climax stock, or similar rock, may be expected to be strongly dependent on the fracture patterns in the rock.

SUMMARY AND CONCLUSIONS

Seismic velocities in the low-velocity zone ranged from 5,000 to 14,000 feet per second in tunnels in the Climax stock. No discrimination between granodiorite and quartz monzonite was evident on the basis of velocity. Velocities qualitatively exhibited an inverse relation to the degree of fracturing. Apparent velocities in rock behind the low-velocity zone and in sections where no layer was recorded ranged from 14,000 to 25,000 feet per second, with the higher velocities generally restricted to those sections where a low-velocity layer was recorded. This suggests that the rock behind the low-velocity layer may be under greater compressive stress than is the rock where no layer is present.

The thickness of the low-velocity zone ranged from 0 to 8 feet, and aside from its general association with fracturing, no relationship was found relating it to the size of the tunnel.

The low-velocity layer, where measured, exhibited asymmetry at many locations in that it was not recorded in all holes at a specific location. The layer was absent in no preferential direction—at various stations the layer was absent in either the back, floor, or ribs, while generally it was present in the other directions. The results of reconnaissance mapping showed no obvious correlation of the presence or absence of the low-velocity layer with the trend of any of the three major joint systems present in the tunnel complex. However, extensive studies along these lines were not pursued.

In one highly sheared section which required extensive support (crossdrift AR, section 2) the thickness

TABLE 1.—*Summary of uphole-velocity measurement data*

Station	Location	Rock type	Rock support at time of measurement	Tunnel diameter (feet)	Degree of fracturing	Thickness of destressed zone interpreted from uphole seismic data (feet) [1]	Uphole velocity (ft/sec) in—	
							Low-velocity layer	High-velocity layer
Shop drift	West rib	Quartz monzonite.	None	10	Moderately fractured.	6.0	11,000	19,000
	do	do	do	10	do	2.0	13,000	20,000
	East rib	do	do	10	do	8.0	10,000	24,000
	do	do	do	10	do	4.0	14,000	19,500
	do	do	do	10	do	4.0	10,000	21,000
	Back	do	do	10	do	6.0	14,000	18,500
	Floor	do	do	10	do	6.0	13,500	21,000
Supply drift	East rib	Quartz monzonite.	None	10	Moderately fractured.	5.5	13,000	21,500
Main access drift, 4+25.	West rib	Quartz monzonite.	None	10	Extensively fractured.	5.0	11,000	18,000
	East rib	do	do	10	do	4.0	11,500	25,000
	Back	do	do	10	do	5.5	10,000	19,000
	Floor	do	do	10	do	4.0	11,000	24,000
Main access drift, 7+30.	East rib	Quartz monzonite.	None	10	Relatively free of fractures.	No destressed zone.	--------	18,500
	West rib	do	do	10	do	do	--------	18,000
	Back	do	do	10	do	do	--------	19,000
Main access drift, 9+20.	East rib	Contact between quartz monzonite and granodiorite.	None	10	Extensively fractured.	6.0	6,500	22,000
	West rib	do	do	10	do	6.0	11,500	20,000
	do	do	do	10	do	2.5	10,000	20,000
	Back	do	do	10	do	No destressed zone.	--------	18,000
	Floor	do	do	10	do	4.0	11,500	21,000
Main access drift, 11+60.	East rib	Granodiorite	None	10	Extensively fractured.	4.5	12,000	19,000
	West rib	do	do	10	do	4.0	13,500	19,000
	Back	do	do	10	do	5.0	12,000	21,000
	Floor	do	do	10	do	No destressed zone.	--------	19,000
Main access drift, 12+60.	East rib	Granodiorite	None	10	Relatively free of fractures.	No destressed zone.	--------	17,000
	West rib	do	do	10	do	do	--------	18,500
	Back	do	do	10	do	do	--------	18,000
Crossdrift AL, test section 6.	North rib	Granodiorite	None	27	Moderately fractured.	No destressed zone.	--------	17,000
	South rib	do	do	27	do	8.0	11,500	23,500
	Back	do	Rock bolts	27	do	4.0	11,000	23,000
Crossdrift AR, test section 2.	North rib	Quartz monzonite.	Rock bolts and wire net.	27	Extensively fractured.	6.0	5,000	14,000
	South rib	do	do	27	do	No destressed zone.	--------	16,000
	Back	do	Rock bolts	27	do	4.0	12,000	18,500
Crossdrift AR, test section 1.	North rib	Quartz monzonite.	None	44	Moderately fractured.	No destressed zone.	--------	19,000
	South rib	do	do	44	do	4.0	10,300	17,500
	Back	do	do	44	do	No destressed zone.	--------	18,000
Range of values						0.0 to 8.0	5,000 to 14,000	14,000 to 25,000
Average values						3.3	11,200	19,600

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[1] Where more than one velocity value is listed, more than one hole was tested.

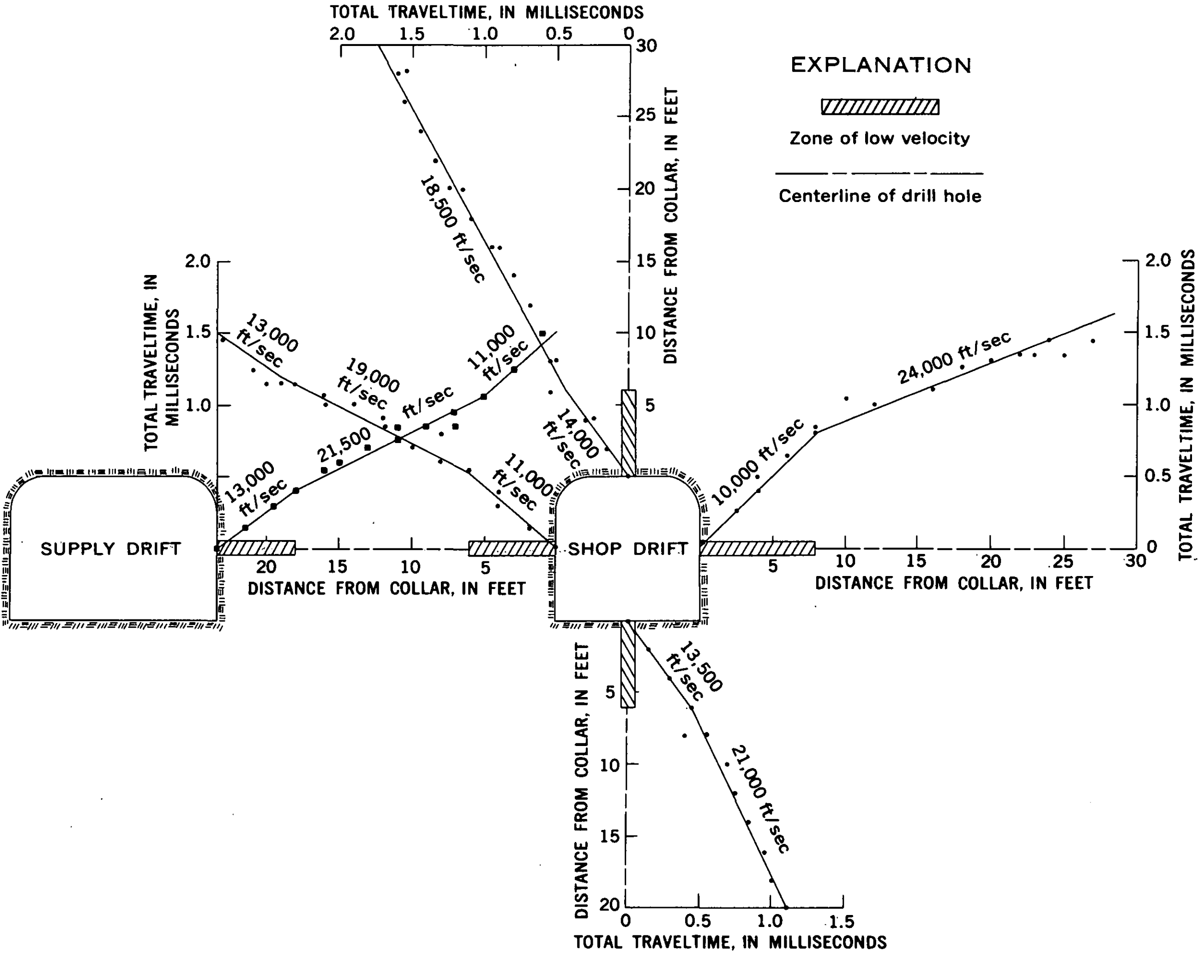

FIGURE 2.—Cross-sectional view of selected holes in shop and supply drifts, showing results of uphole velocity measurements in fractured quartz monzonite.

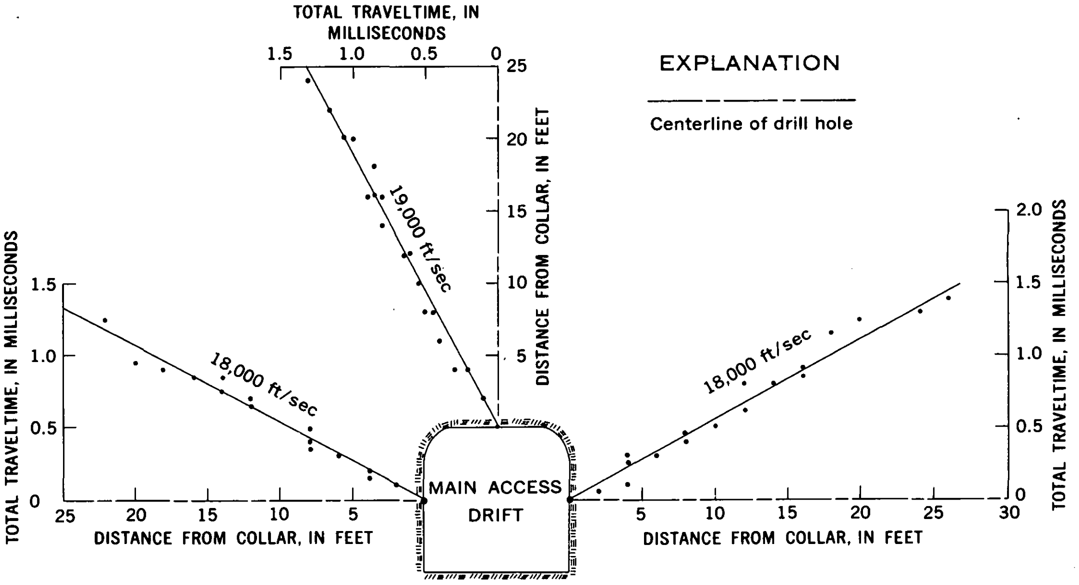

FIGURE 3.—Cross-sectional view in main access drift, station 7+30, showing results of uphole velocity measurements in relatively fracture free quartz monzonite. No low-velocity layer was detected at this station.

of the low-velocity zone was not significantly different from that at other stations, although the velocity was the lowest found throughout the tunnel. The presence of low seismic velocity was found to be more diagnostic of structurally weak sections than was the thickness of the low-velocity layer.

The presence of a low-velocity zone is considered significant because it may provide an estimate of the thickness of rock which may require support in tunnels. Additional research is required to determine the relationship between the low-velocity zone and the actual stress pattern around a tunnel opening. A comparison with uphole dynamic strain measurements which, hopefully, would indicate the extent of arching with time is considered desirable.

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