# Slope Failures in Foliated Rocks, Butte County, California

A. L. O'NEILL, Chief, Project Geology Branch, Division of Design and Construction, California State Department of Water Resources

The slope failures discussed occurred during relocation of Highway 40A and the Western Pacific Railroad around the proposed Oroville Dam and Reservoir near Oroville, Butte County, Calif. The relocations are routed along the edge of the Sacramento Valley and through the rugged foothills of the Sierra Nevada, where 8½ miles of the relocations pass through metamorphic rock of the Calaveras group. Most slope failures occurred in a rock type called phyllite, which has been tightly compressed and intensely folded during metamorphism.

Design criteria called for numerous ¾:1 cut slopes, some in excess of 100 ft in height. Benches were used in many of the deeper cuts; however, some large cuts were constructed without benches. Slope stability problems were most serious when cuts were made in directions parallel or near parallel to the direction of foliation of the rock. Very little trouble was encountered when cuts were made at right angles to the foliation. The nature of the failures with respect to geologic structure, the type and consistency of cracking on planes of foliation, and the direction of the displacement along the planes of foliation suggest that stress relief was part of the mechanism contributing to ultimate failure of the slopes.

• PHYSICAL properties of rock and its weathered counterparts can today be determined with a high degree of accuracy in laboratories. Such determinations lead to predictions of the stability of these materials for construction purposes; however, in some cases the rock fails to behave as anticipated. Many failures can be attributed to varying conditions of the rock mass which are not indicated in the sampling and testing. Other than the actual physical properties of the rock, one of the major considerations is the geologic setting. Consideration of the geologic setting should include an analysis of the geologic history of the area and all relationships that the rock and its structure will have with respect to the proposed works, including the state of stress in the rock and the effects that might be anticipated due to rebound or stress relief of the rock mass.

As modern techniques and efficiency for excavating rock and its weathered counterparts increase, it becomes economically feasible to design progressively and construct deeper cut excavations for highways, railroads, and major aqueducts. Obviously, the deeper the excavation, the more critical becomes the cut slope design, because the economy depends on the optimum angle of slope. Mining companies, engaged in large strip mining operations, are keenly aware of this fact because many millions of yards of excavation can be saved by designing the optimum cut slope for their deep pits.

To be able to design deep cut slopes in rock properly, it is becoming increasingly apparent that knowledge of the factors contributing to stress relief must be increased and that these factors must be considered in the investigations and design. The relationship of the geologic setting and the phenomenon of stress relief was well illustrated by slope failures that occurred during construction of some large roadway cuts in foli-

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ated metamorphic rocks during relocation of Highway 40A and the Western Pacific Railroad around proposed Oroville Dam and Reservoir near Oroville, Butte County, Calif. Oroville Dam, now under construction, will be a 735-ft earthfill structure impounding 3½ million acre-feet of water. The dam is a key unit in the California State water facilities which provide for a large aqueduct system to transport surplus Northern California waters to dry portions of Central and Southern California.

The relocations are routed along the edge of the Sacramento Valley and through the rugged foothills of the Sierra Nevada before joining the original routes above the elevation of reservoir tail water. Approximately 8½ miles of the relocations pass through metamorphic rocks of the Calaveras group, which ranges in age from Mississippian to Permian. Rock types encountered included both the metasedimentary and metavolcanic types. Metasediments included slate, phyllite, schist, sandstone, conglomerate, chert, quartzite, and limestone. Phyllite was by far the most predominant metasediment encountered. Metavolcanic rocks included schistose and massive types of low-grade metamorphism. Vulcanism evidently continued intermittently through the period of deposition of the Calaveras group, because in many areas, beds of metavolcanic rock are intercalated with the metasediments.

Most of the slope failures occurred in the phyllites. These rocks, ranging from slate to schist, are normally moderately hard when fresh and will almost always fracture along well-developed planes of foliation. The depth of weathering is variable and appears to depend somewhat on the steepness of the slope, length of exposure to weathering processes, schistosity, fracturing, and localized mineralogy. The planes of foliation provide access for percolating water which contributes to oxidation and deep weathering of the rock.

There is a predominant northwesterly structural trend in the metamorphic rocks. Except for localized deviations, the average strike of foliation is N35°W and the dip ranges from 60°NE to 60°SW. Both the metavolcanics and the metasediments have been tightly compressed and intensely folded during metamorphism. Geologic mapping, done primarily for information along the railroad alignment, indicates that there is much interfingering of the two major rock types. It has been considered that many of the tongue-like projections represent traces of plunging folds. Folding was intense, as illustrated in some localities by repetition of beds within a few feet. It is very difficult to see or appreciate the intense structural deformation in near-surface exposures because of weathering: however, the deformation in railroad tunnels driven for the relocations was observed. Tunnel mapping also helped to amplify the fact that considerable intrusion of the sediments by volcanic rocks took place before, during, and after folding.

Roadways for both highway and railroad have been constructed to modern standards with numerous large cuts and fills, some in excess of 100 ft. Design criteria called for numerous ¾:1 cut slopes. Benches were established at each 40-ft interval of height for railroad cuts. Benches were also used on highway cuts; however, highway criteria did not require benches at any regular interval. Railroad benches in all cases were 14 ft wide and were sloped to drain along the bench to the end of cut.

As might be expected, stability problems with the ¾:1 cut slopes developed only where the rock structure or foliation was oriented at certain angles with the roadway, or direction of cut. The most stable cut in the foliated rocks existed where foliation was at right angles to the direction of cut. One such cut along the highway alignment was constructed 100 ft high, without a bench, at ¾:1. There has been no trouble or signs of impending failure. On the railroad relocation, a large cut with roadbed width for three tracks was excavated at ¾:1 where the foliation was at approximately right angles to the direction of cut. This railroad cut was 120 ft high at its highest point, had benches established at each 40 ft of height, and penetrated mostly phyllite, ranging from the most strongly weathered at the top to fresh rock at the base of the cut. There have been no slope failures in this large cut and even the shallow soil mantle and the zone of strongly weathered rock (which extends about 30 to 40 ft in depth) have remained stable.

Most difficulties were encountered where cuts were made in directions parallel or near parallel to the direction of foliation. Ordinarily, one would expect failure to occur when or where the dip of the foliation was parallel to or out of the surface of the road cut. However, in this case, most of the failures took place on the side where dip of foliation was near vertical or where dip was into the cut slope.

Failures were always preceded by cracking on the cut faces, along the benches, and later, around the top of the cuts. In most cases, cracking took place slowly and developed into offset planes along the foliation. Apparent displacement amounted to as much as 3 to 4 ft before total failure took place. The time interval between the first evidence of cracking and failure ranged from days to several weeks. Displacement along the planes of foliation was somewhat unusual in that the uphill side of the plane was dropped in relation to the downhill side. This phenomenon was quite spectacular in one of the large cuts where the relative displacement was as much as 4 ft. Displacement continued to increase in magnitude until the rocks could no longer stand, at which time the slope failed by tumbling.

Almost all slope failures took place in strongly to moderately weathered rock. In all cases, the structure of the rock was plainly visible. Basically, the cause of some of the cut slope failures must be attributed to the simple fact that cuts were made at a steeper slope than was stable for the degree of weathering. However, similar materials failed in cut slopes made parallel to planes of foliation, whereas they were stable in cuts made at right angles to the geologic structure. The nature of the failures, with respect to the geologic structure, the type and consistency of cracking along planes of foliation and the direction of the displacement all suggest that stress relief, along planes of foliation, was part of the mechanism contributing to ultimate failure. It is believed that residual stresses existed in the weathered, strongly folded metamorphic rocks, and removal of large amounts of materials from the road cuts relieved the rock mass so that strain took place, allowing cracks to develop in the direction normal to the principal stress, or along the planes of foliation. As strain continued along foliation planes, the weight of the rock and soil above caused settlement, resulting in the apparent displacements. Circular cracking at the top of the cut then formed. Weight and pressure of the mass continued to push against the planes of foliation until total failure took place. Where water saturated the rocks, driving pressures from above were greatly increased, resulting in more rapid failure.

Where dip of foliation was in the same direction as the cut slope, much of the driving force due to weight of overlying materials was directed into the rock and along planes of foliation as the strain took place. Therefore, stress was relieved without the striking offsetting along the planes of foliation. Such slopes reached their maximum stability when cut at approximately a dip slope; however, minor slabbing might have been anticipated. Such a dip slope cut was made at one location along the highway relocation and that slope proved to be stable.

Because most cuts had been made to considerable depth before failures started, it was necessary to reslope to 1½:1 in order to provide room for grading equipment to work. The 1½:1 slopes proved stable in all cases except one large cut where hydrostatic pressure aggravated the problem. The upper portions of that cut, which was originally 110 ft high, had to be resloped from ¾:1 to 1½:1 and locally to 2:1. To provide relief of the hydrostatic pressures, 8,425 ft of horizontal drain at a cost of $33,600 was installed. Resloping of that cut involved 575,000 cu yd of additional excavation at a total cost of $460,000.

Relationship of geologic structure to stability of roadcuts was well illustrated in construction of these relocations. Also, the possibility of residual stresses being present in shallow and weathered foliated rocks has been suggested. The role of stress relief as a mechanism in contributing to conditions causing slope failure is certainly worthy of much study and cannot be ignored in design of deep cut excavations in rock.