TRANSPORTATION RESEARCH RECORD 717

Engineering Solutions to Environmental Constraints: I-70 Over Vail Pass

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Abridgment

Introduction to the Vail Pass Project

R. A. Prosence, Colorado Department of Highways, Grand Junction

When the original 64 400-km (40 000-mile) Interstate highway system was first approved by Congress in the 1940s, I-70 began in Washington, D.C., and ended in Denver, Colorado. Travelers who wanted to stay on the Interstate system west of Denver had to turn north to Cheyenne, Wyoming, and then west on I-80 or south into New Mexico and then west on I-40. Colorado and Utah jointly expressed concern over the fact that their state capitals were not joined by a more direct Interstate route. In 1957, as a result of lobbying by Colorado and Utah legislators, Congress authorized a 1600-km (1000-mile) increase in the Interstate system, increasing the authorized length of the system to 66 100 km (41 000 miles). Shortly thereafter, Utah and Colorado were granted over 480 km (300 miles) of this additional authorized 1600 km, and I-70 was extended west from Denver to a connection with I-15 south of Salt Lake City.

When the extension was granted in 1958, Colorado promptly began studies of possible alternative routes for I-70 through the Continental Divide and across the mountains west of Denver. After extensive studies and a great deal of discussion, a decision was made to generally follow the route of US-6 west from Denver through the Continental Divide at the Straight Creek location (where the Eisenhower Tunnels will soon be completed) and then west across Vail Pass.

During the course of the studies, it became evident that an alternative route bypassing Vail Pass was available. The alternative was known as the Red Buffalo route since it passed between Red Peak and Buffalo Mountain west of Dillon, Colorado. The Red Buffalo route would have reduced the distance between Dillon and Vail by more than 16 km (10 miles) and for that reason was favored by the Colorado Division of Highways. The alternative was studied in detail and presented as the recommended route at a corridor public hearing held in Frisco, Colorado, in 1966. The proposal immediately became controversial and was the stimulus for the first confrontation between environmentalists and highway engineers in the state of Colorado.

The westerly section of the recommended route emerged from a tunnel under the ridge that separates the Blue River drainage and the Gore Creek drainage and passed through a segment of the Gore Creek primitive area. The Wilderness Act allowed the Secretary of Agriculture to grant a highway right-of-way through the Gore Creek primitive area if he felt it was in the public interest to do so. Early in 1968, however, Secretary of Agriculture Orval Freeman issued a decision that it would not be in the public interest to grant a right-of-way through this area. Congress has since officially designated the Gore Creek area as wilderness.

Adverse geological conditions were the primary reason the Colorado Division of Highways had hoped to avoid constructing a four-lane freeway over Vail Pass. While making a survey for an improved two-lane highway over Vail Pass in 1956, the division had discovered that, in the 17 years since the existing road was constructed, in one area it had crept 15 m (50 ft) down the mountain from the location on the "as-constructed" plans. Many other evidences of geologic weakness were apparent even to unpracticed eyes.

Shortly after the negative decision was reached on a right-of-way for the Red Buffalo route, the Colorado Division of Highways began extensive preliminary studies of the Vail Pass route. The first study concerned geology. Division geologists were asked where it might be possible to build a facility of this kind, avoiding the unstable ground that we were sure would cause significant problems. So it can be said that geology largely controlled the location of I-70 over Vail Pass.

Early in public meetings, great concern was expressed about the effect the project would have on water quality on both sides of Vail Pass, since West Tenmile Creek on the east side and Black Gore Creek on the west side furnish water to adjacent mountain communities. The department approached the project with full knowledge that we were in an area of severe geologic problems, that the countryside was environmentally sensitive, and that maintaining water quality was an extremely important consideration. The papers in this Record detail how these problems were solved.

The Vail Pass route segment traverses some very beautiful mountain terrain. Early in the project, a team of professionals that included the highway division's consultant, International Engineering Company; personnel from the U.S. Forest Service and the Colorado Division of Wildlife; and our own engineers and landscape architects came together in a joint effort to produce a highway project that would not result in severe, permanent environmental damage to this part of Colorado. We acknowledge and appreciate the assistance and participation we received from all of these agencies and individuals.

Environmental Constraints on the Vail Pass Project

Austin B. Milhollin, International Engineering Company, Inc., Denver

Environmental constraints to a large degree controlled both design and construction of the 22.5-km (14-mile) long segment of I-70 through Vail Pass in Colorado. An interdisciplinary team composed of engineers, ecologists, aquatic and wildlife biologists, and architectural and landscape consultants evaluated every aspect of the highway with regard to its environmental impact from the determination of the alignment to the color of the concrete structures. A variation of the Design Alternative Ration Evaluation system was used to quantify eight environmental factors, and these factors were then used to rank alternative alignments. After the alignment was selected, measures were taken to mitigate adverse environmental consequences associated with highway construction. In some instances, the amount of terrain disrupted was reduced by substituting a structure for a cut or a fill. In other cases, terrain was restored by landscaping methods. Environmental constraints imposed on the project design made it necessary to adopt innovative design concepts. The principal environmental constraints and the solutions that resulted from the use of innovative design concepts are examined.

The subjects to be discussed in this paper are the environmental and geologic constraints that to a large degree controlled both the design and the construction of the Vail Pass project. The two constraints are closely interrelated since a number of the anticipated environmental consequences stemmed from the geologic conditions, which are discussed in detail in another paper in this Record.

Prior to the studies reviewed in this paper, the so-called Red Buffalo route for the I-70 extension (see Figure 1) had been deemed unacceptable. The only feasible alternative locations were those that lay within the corridor of existing US-6, which crossed the Continental Divide at Vail Pass. These alternatives were some 14.5 km (9 miles) south of the proposed Red Buffalo route and were approximately 16 km (10 miles) longer between common points. By the time this decision was reached, the National Environmental Policy Act of 1969 was in effect and had been ruled applicable to the Vail Pass location for I-70. Consequently, the design was postponed and an environmental study was initiated.

It was obvious that the study would play no part in the selection of a route since only the Vail Pass corridor remained to be considered. Thus, the study became simply one of determining (a) the environmental consequences of constructing a four-lane highway through a narrow corridor along the general location of existing US-6 between East Vail on the west side and Wheeler Junction on the east and (b) measures that could be taken to mitigate these consequences.

The Colorado Division of Highways elected to contract for a study that would not only determine the environmental consequences of a highway but also identify and evaluate specific alternative locations within the corridor. This evaluation was to include the factors of cost and operation as well as environment. In addition, a major objective of the study was to develop preliminary design concepts to minimize any adverse effects ordinarily associated with heavy construction through mountain terrain.

ENVIRONMENTAL BACKGROUND

The area studied was approximately 22.5 km (14 miles) long—about 14.5 km (9 miles) on the west side of the summit and 8 km (5 miles) on the east side. On the eastern slope, the location lies within the drainage of West Tenmile Creek. This stream meanders down a relatively flat drainage course bordered by extensive growths of willow trees and alpine meadows in the narrow bottom of the valley, which gives way quickly to steep, timber-covered mountain slopes (see Figure 2). West of the summit, the highway follows the course of Black Gore Creek, which twists and plunges down a steep drainage course at the bottom of a valley bordered on both sides by steep mountain slopes that are broken in places by precipitous cliffs. For the most part, the mountainsides are covered with light to moderate growths of timber.

The overriding problem on the west side of the summit, from a highway engineer's viewpoint, was the character of the geology. It was evident that any major roadway cuts could trigger earth slides and result in huge scars that would remain evident for generations (see Figure 3). Geology was thus a major factor in the environmental considerations.

ENVIRONMENTAL STUDIES

In environmental studies for the Colorado Division of Highways, approximately 40 factors were normally considered. Since no alternative corridor was under consideration in this case, it was apparent that a highway located anywhere within the corridor would serve equally well with respect to socioeconomic considerations. For this reason, all socioeconomic factors, except recreation, were eliminated. The proposed highway would serve an outstanding recreation area. At either end of the section are two major ski areas: Vail Village and Copper Mountain. The two drainage areas traversed by the highway serve the recreational activities of ski touring, snowmobiling, fishing, hiking, camping, and sightseeing. Except for a small community known as the Big Horn Subdivision at the western end, there were no problems associated with residential areas. For the most part, the problem became one of identifying and evaluating the adverse physical and ecological effects that might result from construction of a highway.

In 1970, the Colorado Division of Highways retained consultants to make a two-phase environmental study. The firm selected, now the Midwest District Office of International Engineering Company, organized a study team that consisted of staff engineers and geologists and several special consultants. This team collaborated with Charles S. Robinson, the consulting engineering geologist retained by the Colorado Division of Highways.

The first phase of the study was a general, overall environmental study to identify and evaluate the environmental factors that should be considered. This phase resulted in a report (1) that was used by the Colorado Division of Highways as the basis for their draft and final environmental impact statements. The second phase (2) evaluated various alignments within the limited corridor width and developed preliminary design concepts to serve as a guide during final design, emphasizing the development of concepts that would ameliorate damage to the terrain.

A perplexing problem arose when an attempt was made to quantify the various environmental factors involved in

Figure 1. Vail Pass I-70 location map showing rejected Red Buffalo route.

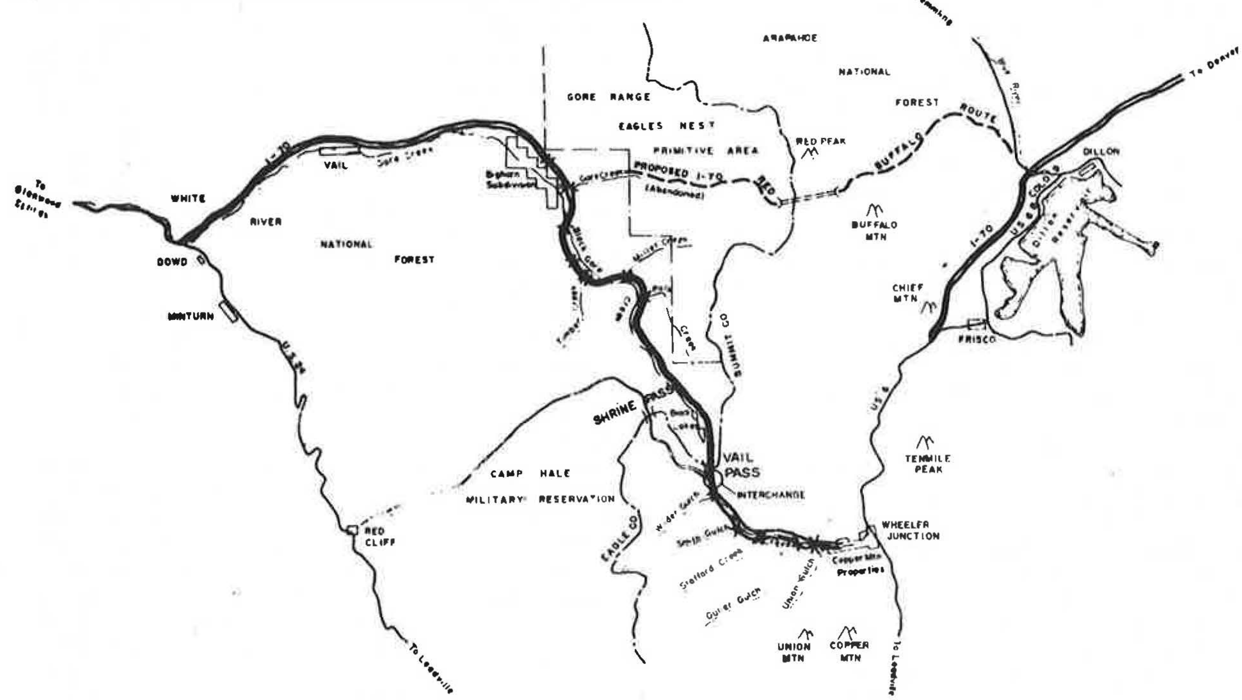

Figure 2. Typical timbered mountain slope.

Figure 3. Old construction scar along existing highway.

reaching a decision on which of several alternative alignments was preferable. The problem is an intriguing one: how to quantitatively compare a number of unrelated factors that are present in varying degrees in several alternatives. For example, how can it be determined whether the encroachment of a roadway fill into a fishing stream is preferable to the creation of a long-lasting, unsightly back-slope scar in the fragile alpine tundra of a mountainside?

The study team reviewed several methods of quantification that have been developed in recent years. The one selected is referred to as the Decision Alternative Ration Evaluation (DARE) system (3, 4). The DARE system describes a problem of selecting a site for solid waste disposal. The factors involved are, of course, different from those involved in selecting a highway location, but the principle is nonetheless applicable. The DARE system was used to quantify eight environmental factors and thus obtain a ranking of alternative alignments that established an environmental order of preference.

The study team consisted of specialists in the fields of botany, biology, geology, architecture, and highway engineering. Ecologists spent considerable time in the field taking an inventory of the trees in the area, which were predominantly aspen, lodgepole pine, and Engelmann spruce. They identified and delineated the location of the various types of trees as well as other forms of ground cover, mainly shrubs and grasses. Aquatic biologists made extensive studies of both Black Gore Creek and West Tenmile Creek by counting the fish and collecting data on their food sources along the banks of the streams. The fish count was taken by a small crew that waded up selected sections of each stream and, using electrodes, stunned and netted practically every fish in those sections. They measured and weighed each fish and in some instances sampled the stomach contents. In addition, counts were made of the number of fishermen using the various sections of the streams. A wildlife biologist observed the species of animal and bird life in the area and the ground cover that afforded them food and protection. Geologists studied existing geologic data and made field reconnaissance studies. Architects and landscape architects reviewed tentative plans in order to evaluate from an aesthetic viewpoint not only the proposed bridges but the highway as well. They concentrated on the way the alignment would blend with the ground forms and the scale effect of a four-lane highway within the restrictive corridor. They also analyzed the impact of the highway on recreational activities in the area.

PRINCIPAL CONSTRAINTS AND SOLUTIONS

The environmental constraints imposed on the design and construction that are most apparent to motorists are those related to the terrain itself. Since the final location generally parallels the two streams that flow in either direction from the summit, care obviously had to be taken to blend the alignment into the land forms as far from the streams as practicable. Considerable effort was expended in projecting the alignment on topographic maps.

In general, the alignment followed the contours of the mountainsides, crossing the contours as required to obtain the desired gradients, which in some instances were as high as 7 percent. This effort generated an alignment highly curvilinear in plan with no tangents longer than 20 stations in the entire 22.5-km (14-mile) section. Fitting the alignment to the topography served to minimize cuts and fills and resulted in an aesthetically pleasing alignment.

Associated with this constraint were those represented by the two streams and the trees and other vegetation, plus the critical factor, the geologic composition of the terrain in and adjacent to the construction area. All of these constraints influenced the location and alignment to some degree. With only one notable exception, encroachment on the two mountain streams was avoided. In some instances, this was achieved by constructing an elevated structure to carry the roadway above terrain adjacent to the stream. In other instances, the base width of the roadway fill was reduced by using retaining walls.

In one section, geologic constraints dictated a major encroachment on a stream, Black Gore Creek, on the western side of the pass. In that section (in the vicinity of station 425), in-place instrumentation indicated that the slopes on both sides of the creek were moving slowly, which suggested that roadway excavation on either slope might trigger a major landslide that would leave a defacing scar on the mountainside. Rather than run such a risk, it was decided to buttress both sides by constructing a large embankment over the stream and reconstructing a streambed at a higher elevation along the intersection of the newly placed embankment and the natural slope along the right bank of the creek. Before the embankment was placed, the stream was temporarily enclosed in a culvert pipe. The pipe was placed directly in the existing streambed, where the water flowed until the embankment was completed and the new channel constructed. The water was then diverted into the new channel, and the roadway was constructed on top of the embankment.

Design and construction were also influenced by a number of recreational considerations. The aquatic studies had indicated that neither West Tenmile Creek nor Black Gore Creek was a significant fishery. Both, however, support populations of small, beautifully colored brook and native (cutthroat) trout. Black Gore Creek is a particularly scenic example of a small mountain trout stream with tumbling waters and deep forest cover. Both streams are fast, clear, cascade types generally deficient in pool areas. This lotic environment, combined with cold temperatures and low productivity, limits the size of fish. The small size of the fish and the difficult access are probably responsible for the small numbers of fishermen at these locations. On Black Gore Creek, however, there are two small, manmade lakes that attract a number of campers to their shores, people who do fish in the lakes during the warm-weather months. It was considered necessary to maintain access to these lakes and to avoid any damage to the downstream reaches of the creek that might hamper fish from reaching the lakes.

The environmental study identified a number of birds and animals that inhabit the area. It was obvious that, with the construction of a four-lane highway, the killing of wildlife on the highway would increase. A single-span structure was constructed at station 436 to accommodate the crossing of deer, and a passageway was provided beneath all four lanes so that deer and other animals could gain access to the creek.

Early in the studies, there was some concern about the beavers that inhabit both streams. It was feared that the construction activities would drive the beavers out of their ponds and in some instances destroy the beaver dams. The wildlife biologist on the study team advised that, although construction noises would drive the beavers out, they would simply move to a nearby side drainage and construct their dams and ponds in new locations.

Trees and shrubs represented environmental constraints only to a limited degree. In selecting the location, the willows along West Tenmile Creek were avoided as much as possible. It was decided that the Engelmann spruce was to be favored over the lodgepole pine and the aspen, the other two predominating species. But, because of the preponderance of trees in the project area, no part of the final location was predicated on avoiding any particular group of trees.

On the west side of the summit, in the narrow confines of the canyon, avoiding encroachment on Black Gore Creek was a problem in several locations. If normal cut-and-fill construction had been attempted, embankment fill slopes would have tumbled down the mountainside and blocked the creek in several places. At some locations, the obvious answer was an elevated structure to carry the roadway over the terrain.

Twenty-one highway bridges in the project were designed so that they could be erected without falsework to minimize construction damage to the terrain. Eight of these were post-tensioned concrete segmental bridges (see Figure 4), 11 were welded steel box-girder bridges (see Figure 5), and 2 were poured-in-place concrete structures.

Figure 4. Precast concrete segmental box-girder bridge.

Figure 5. Typical welded box-girder bridge.

Figure 6. Terraced retaining wall.

In other places, a more economical solution was a retaining wall that would limit the base of the roadway embankment and confine all embankment materials on the hillside above the creek. In many places, the height of the required wall was so great that a concrete cantilever retaining wall would have been uneconomical as well as aesthetically unacceptable. The designers, therefore, set out to create another type of retaining wall that would be economical to construct and architecturally acceptable. The scheme devised consisted of a wall of any height and length composed of two basic precast concrete elements that could be easily fabricated and erected. The two basic elements were a precast concrete L-shaped piece, called a tieback, and a 12.7-cm (5-in) thick curved concrete precast facing panel. Units were assembled in the field to provide a wall of any desired height consisting of a series of tiers, each 2.4 m (8 ft) in height, with each succeeding upper tier set back a minimum of 1.2 m (4 ft) from the lower. Each setback provided a terrace that was topsoiled and planted with vegetation.

After the award of the first contract on the project, the Reinforced Earth Company requested consideration of a system of concrete-faced reinforced earth retaining walls as an alternative to the precast concrete walls. Predesigning the facing panels of the normal reinforced earth retaining walls resulted in an appearance that was nearly identical to that of the precast concrete walls (see Figure 6). Bids were taken on both types of walls on subsequent contracts, and the final overall project contains a number of walls of each type that are difficult to distinguish from each other unless examined closely. In two locations, the horizontal distance between the edge of the roadway and the edge of the creek was so limited that the setback type of wall was impractical. In these cases, the conventional reinforced earth wall with flat concrete facing panels was stipulated.

Another environmental consideration was the natural coloring of the rock formations. The natural slopes and cliffs in the area are composed of a reddish material known locally as maroon sandstone. Bridges and retaining walls of the conventional concrete gray would have introduced an undesirable contrast into the landscape. Therefore, in an effort to match the sandstone, varying percentages of iron oxide in the concrete mix were specified.

Normally, air pollution and noise represent environmental constraints, but this was not the case on the Vail Pass project. It was reasoned that the construction of the Vail Pass segment to Interstate standards would actually improve the air quality in the project area. The rationale for this position was that, since the Interstate highway had been constructed to a point near each end of the Vail Pass project and since there was no feasible alternate route, the increasing traffic would force itself through the 22.5-km (14-mile) bottleneck of the existing two-lane highway under conditions of increasing congestion and slow speed. Since the four-lane highway would accommodate the anticipated traffic at speeds up to 96.6 km/h (60 mph), fewer pollutants would be left in the area along the roadway.

Noise was of minimal consideration since most of the project is located in an unpopulated area within the national forest. The only residents are located in the Big Horn Subdivision at the western end of the project, and in that area the I-70 location is well above the valley bottom where the residences are located.

Another factor that influenced design and construction was the fact that the area along the highway is used for cross-country skiing in the wintertime and backpacking, hiking, and camping in the warmer months. The construction of the highway has done nothing to inhibit these activities. In fact, one feature that is still in the planning stage will serve to benefit them: A rest area located adjacent to the interchange at the top of the pass will provide toilet facilities and parking space at a strategic access point for snowmobiling and cross-country skiing and a trail head for hikers and backpackers. Also included in the architecturally attractive building that will house the toilet facilities will be a sizeable shelter room complete with seats and a large fireplace. The primary source of heat proposed for the buildings is to be solar energy. When excavations for the rest area were in progress, remains of ancient Indian campgrounds were found. An archaeological team recovered a number of Indian artifacts that date back 5000 years or more. It is the intent of the state to put these artifacts on display in the rest-area building as an added attraction.

CONCLUSIONS

The environmental restraints imposed on the design of the Vail Pass project necessitated the development of designs that would ameliorate the adverse environmental consequences so frequently associated with heavy construction. This became a challenge to all members of the team involved in the design and construction efforts. The measures taken on the project generally mitigated the disruption of the terrain in two ways: In some instances the design simply reduced the area affected by substituting a structure for a cut or a fill, and in other cases the terrain was restored by landscaping measures. With the passage of time, the massive construction should have less and less effect.

The measures taken were costly; how costly is hard to assess accurately. It will always be a matter of conjecture whether or not the additional expense was warranted. In my opinion, the extraordinary scenic qualities of the terrain justified the extraordinary measures taken to preserve them.

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Geologic Constraints on the Vail Pass Project

Charles S. Robinson, Charles S. Robinson and Associates, Inc., Golden, Colorado

The complexity of the geology in the Vail Pass area of Colorado and the many engineering problems it presented in the design and construction of I-70 are discussed. Precambrian igneous and metamorphic rocks and Pennsylvanian-Permian sedimentary rocks had been extensively folded and faulted. Glacial and stream erosion and deposition had modified the topography. Large, complex landslides that had developed in bedrock and surficial deposits and that could not be avoided by changes in highway alignment were the major geologic constraints. The engineering solution to the geologic problems and the integration of the engineering solutions with other environmental factors resulted in minimal environmental impact. The Vail Pass route of I-70 can serve as an example of the value of defining the geologic environment in an environmentally complex area and incorporating environmental constraints into the design and construction of a major highway to minimize environmental impact.

The geology of an area and the geologic processes operative within it determine the environment. The modification of this environment for any purpose must consider geology and geologic processes. Minimal environmental impact will occur when engineering design and construction practices are integrated with the geology and the geologic processes of an area. At Vail Pass every effort was made to integrate geology and geologic processes into the design and construction of I-70 in order to ensure a safe highway and minimize environmental impact and highway maintenance.

GENERAL GEOLOGY

I-70 across Vail Pass crosses terrain typical of the geology of the high mountains of Colorado (see Figure 1). The route follows the valleys of Black Gore Creek, which flows north from Vail Pass, and the west fork of Tenmile Creek, which flows south from Vail Pass. These streams flow along the west flank of the Gore Range, a northwest-trending mountain range bordered on the east by the Blue River. The Gore Range is an uplifted block of granite and metamorphic rocks, flanked on either side by sedimentary rocks—chiefly beds of sandstone, siltstone, shale, and some limestone. Figure 2 shows a generalized stratigraphic section of Vail Pass. Figure 3 shows a generalized geologic map of the area.

After the uplift of the Gore Range, the area was subject to glaciation and stream erosion. The deposits related to the glaciation, erosion, and weathering of the rocks are unconsolidated and locally, after their original deposition, slid to form extensive landslide areas. As a result of the extensive faulting of surficial materials and most of the areas of landsliding, the bedrock—with a few notable exceptions—is relatively stable. Construction across these deposits, however, could easily have caused new landslides or activated old landslides.

Previous geologic work done in the area was mostly

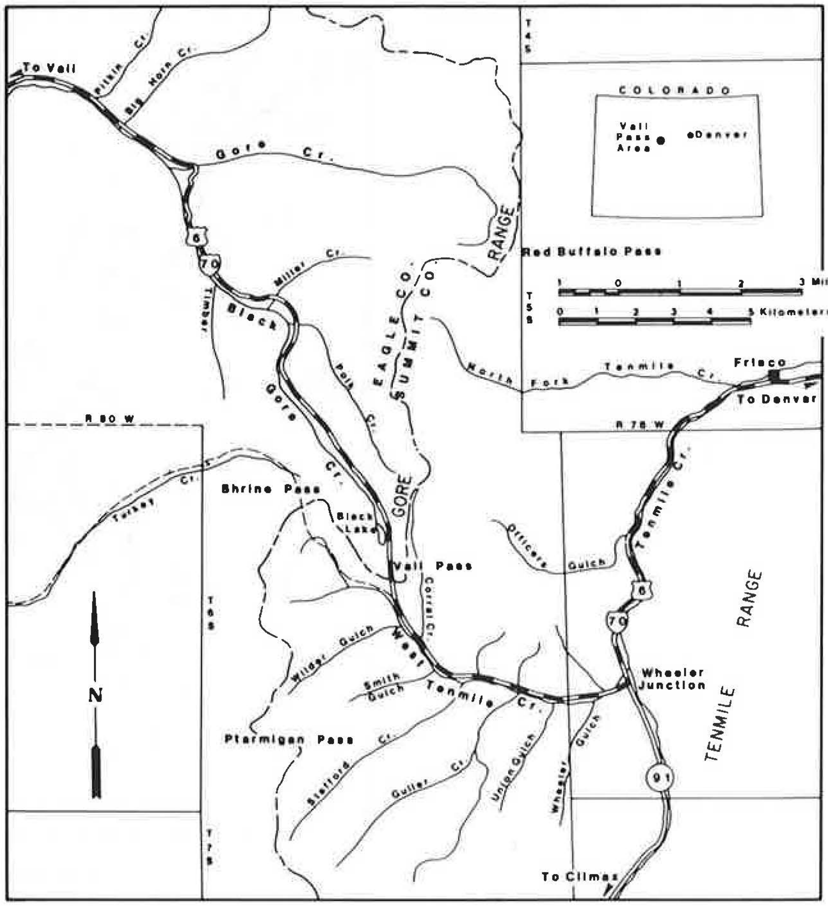


Figure 1. Index map of the Vail Pass area.

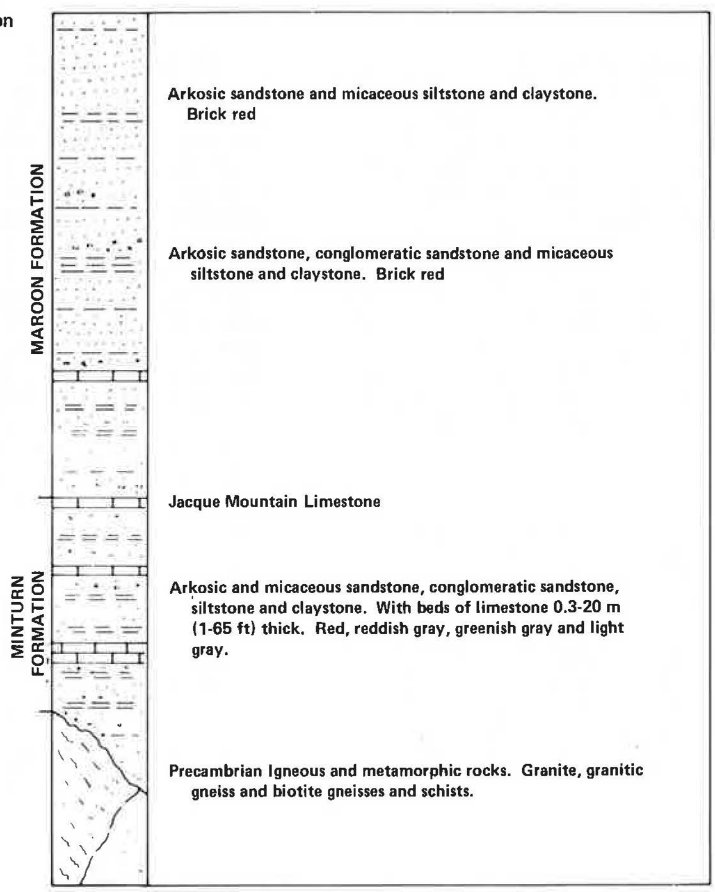
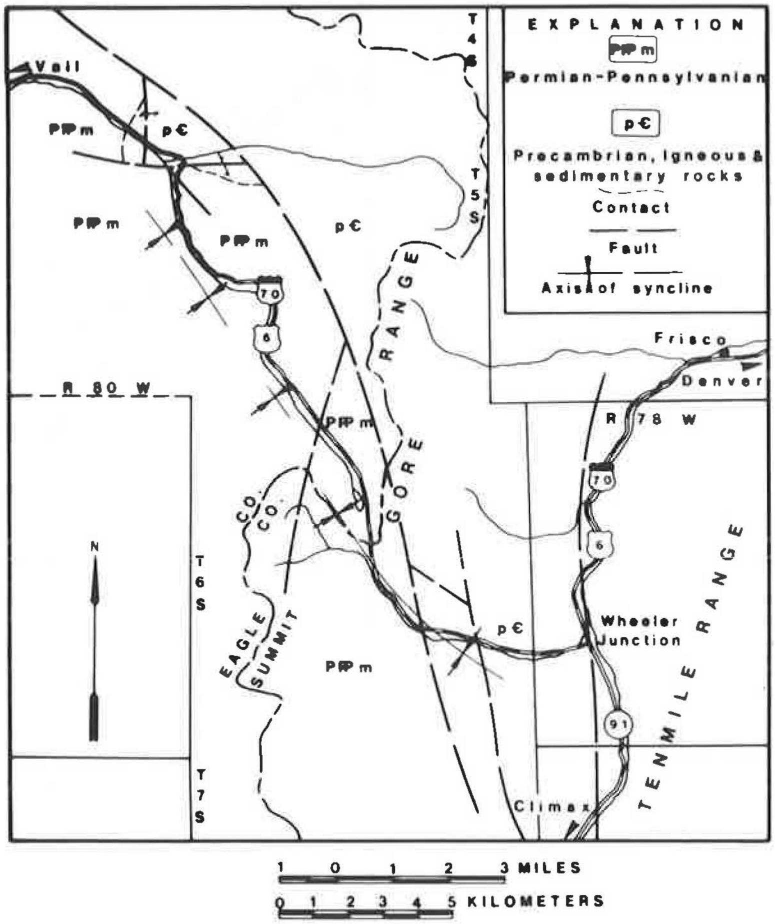


Figure 2. Generalized stratigraphic section of the Vail Pass area.

Figure 3. Generalized geologic map of the Vail Pass area.



general in nature and not specifically for engineering purposes. An exception to that is the work done by Wahlstrom, Warner, and Hornback for the Denver Board of Water Commissioners. They made geologic investigations in connection with proposed water collection, diversion, and storage projects in the vicinity of Miller and Black Gore Creeks, between Black Gore and Gore Creeks, and between Gore and Booth Creeks (Figure 1). Those data have been made available to me. General geologic studies that have included parts of the area of interest are those of Lovering and Tweto (1) on the geology and ore deposits of the Minturn quadrangle, Bergendahl (2,3) on the geology of the Tenmile Range and the Dillon quadrangle, and Tweto (4) on the geology of the Gore Range-Eagles Nest Primitive Area.

GEOLOGIC CONSTRAINTS

The intermediate geologic investigations defined the geologic conditions and processes that were to be considered in the location, design, and construction of I-70 through the Vail Pass area. Active landslides and the potential for reactivating old landslides or creating new landslides were the principal constraints in the location, design, and construction of the highway. The existence of groundwater and groundwater drainage, foundation conditions such as swamp areas, and suitable footings for structures were considered based on the intermediate and subsequent detailed geologic investigations.

LANDSLIDES

Geologic studies of the Vail Pass area showed that more than 50 percent of the alignment of US-6 north of Vail Pass and 10 percent of the alignment south of Vail Pass had been constructed on landslides (see Figure 4). It was recognized that I-70 could not be built across Vail Pass and avoid all the landslide areas. The initial geologic studies and later, more detailed studies were able to define the landslides and their activity, and an alignment was chosen to avoid the more active areas.

The area along the west flank of the Gore Range has long been subject to landsliding. Most of the landslides were not the result of human activity but of geologic processes. Landsliding has occurred in the area before and since glaciation. Most of the older landslides are now stable. The landsliding has involved the bedrock, which constitutes the larger and older of the landslides, and the surficial deposits, which constitute the younger and more active landslides.

Table 1 gives the locations and dimensions of the larger areas of landsliding along the highway alignment.

Bedrock

Large areas of bedrock in the Vail Pass region have failed, forming landslide areas. The failure of the areas of bedrock is related to faulting or to oversteepening of the valley walls as a result of erosion related to glaciation. The landslides in bedrock have involved igneous, metamorphic, and sedimentary rocks.

An area of landsliding in the igneous and metamorphic rocks occurs south of the Gore Creek Campground (see Figure 5). In this area, blocks of bedrock separated by arcuate faults form a series of steps from Gore Creek up the mountain to the south. The slope of the steps is

Figure 4. Map of Vail Pass landslide areas.

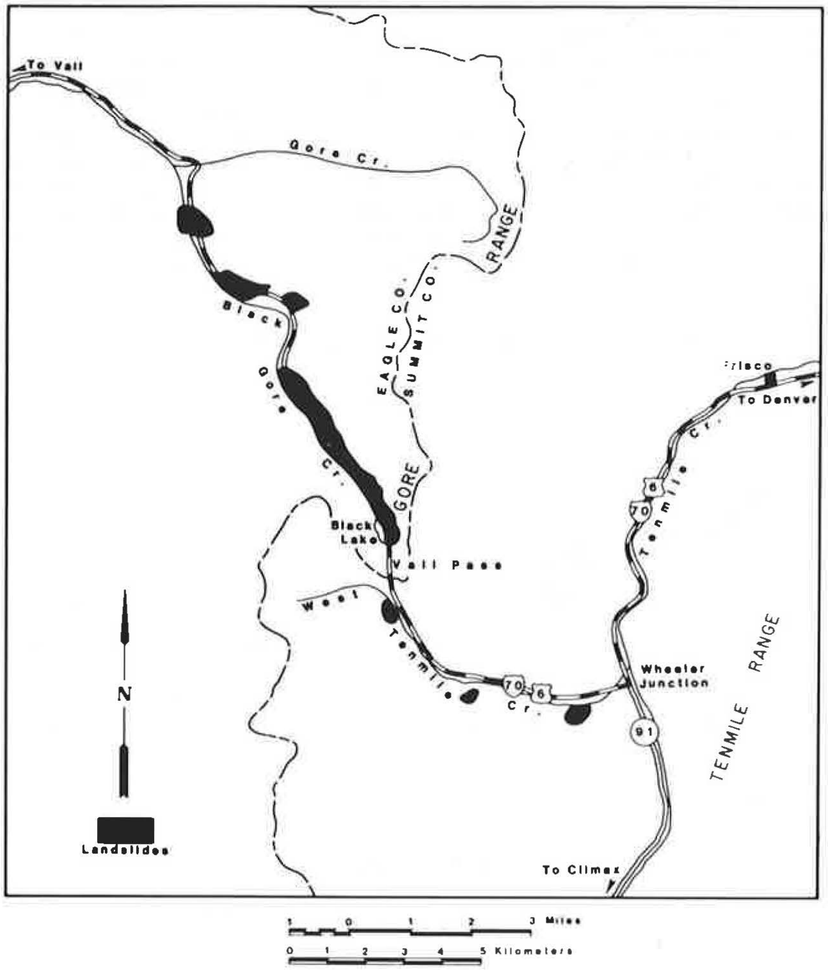


Table 1. Description of major Vail Pass landslide areas.

Approximate Stations	Description
380 to 390	Stabilized landslide in igneous and metamorphic rocks (not outlined as active landslide area)
415 to 440	Bedrock slide of sedimentary rocks with cover of moraine and colluvium; two slides, one on either side of Black Gore Creek
480 to 520	Bedrock slide of sedimentary rocks with cover of rocky colluvium
540 to 560	Surficial slide in moraine and colluvium; older slide with active segments
610 to 675	Bedrock slide of sedimentary rocks with cover of moraine and colluvium
735 to 775	Bedrock slide of sedimentary rocks with cover of moraine and colluvium; very active locally
785 to 800	Bedrock slide of sedimentary rocks with cover of moraine
845 to 855	Bedrock slide of sedimentary rocks with cover of rocky colluvium on alignment of eastbound lane
	Copper Mountain slide; talus material, south of proposed alignments

toward the mountain to the south. Undrained depression or small draws developed at the back of the steps as a result of erosion along the fault or landslide slip plane. The faults or landslide slip planes were formed before glaciation since the outcrops show evidence of glaciation. The southern limit of the steps is a major northeast-trending fault. There is no evidence that there has been any recent movement of the landslide blocks, and the landslide is considered to be stable.

The largest landslides in the Vail Pass area involve bedrock of sedimentary rock. These landslides developed as a result of faulting and the erosion of Black Gore Creek. Most of the sedimentary rock landslides occur on the west or north side of Black Gore Creek north of Vail Pass (Figure 1). Only one landslide in sedimentary rock occurs south of Vail Pass. Most of the bedrock landslides are covered by surficial deposits (see Figure 6). These surficial deposits are also moving locally because of movement in the bedrock or depositional instability. In such areas, landslides are sliding on landslides Most of the areas of sedimentary rock landslides are stable; only locally within an area of a landslide are blocks of bedrock sliding.

The upslope limit of the landslide areas is typically a fault scarp. The faults are generally parallel to the valley and are believed to be related to the Gore Fault to the east of the area (1). The downslope limit of the landslides is Black Gore Creek.

Typical of the areas of sedimentary bedrock landslides are large, undrained depressions that resemble sinkholes in a karst region. These depressions generally have an elongated, elliptical shape. They range from less than 0.5 m (1.6 ft) wide and 2 m (6.5 ft) long to tens of meters wide and hundreds of meters long. Some depressions represent very old movement since they have trees as large as 0.3 m (1 ft) in diameter growing within their limits (Figure 7). Other landslides show, as evidence of recent movement, cracks in the sod in the bottom of the depression. Some of these cracks have been probed to depths of more than 5 m (16 ft).

Blocks of sedimentary rock are exposed in the landslide masses. Some of the blocks are tumbled, but most are about parallel in strike to the beds of the undisturbed bedrock, although the dip is greater. The blocks within a landslide area move different amounts at different times, as the differences in age of the depressions indicate. The blocks of sedimentary rocks are like randomly oriented and shaped wooden shingles on a steep roof; if one shingle is moved, support is removed from one or more other shingles and they also move, which in turn allows others to move until equilibrium is again established.

For the sedimentary rock landslides, Black Gore Creek erodes away a piece of a sedimentary rock block, which allows the block to move toward the stream. Blocks upslope will then move downslope. This process has been going on over a long period of geologic time.

Figure 5. Cross section of bedrock landslide in igneous and metamorphic rock.

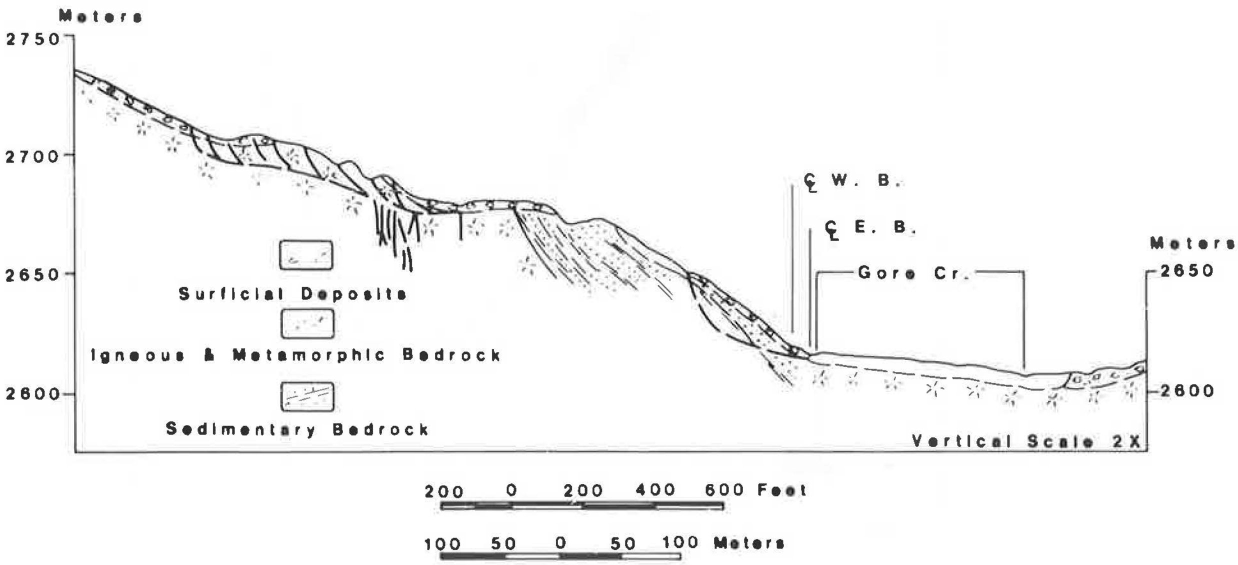
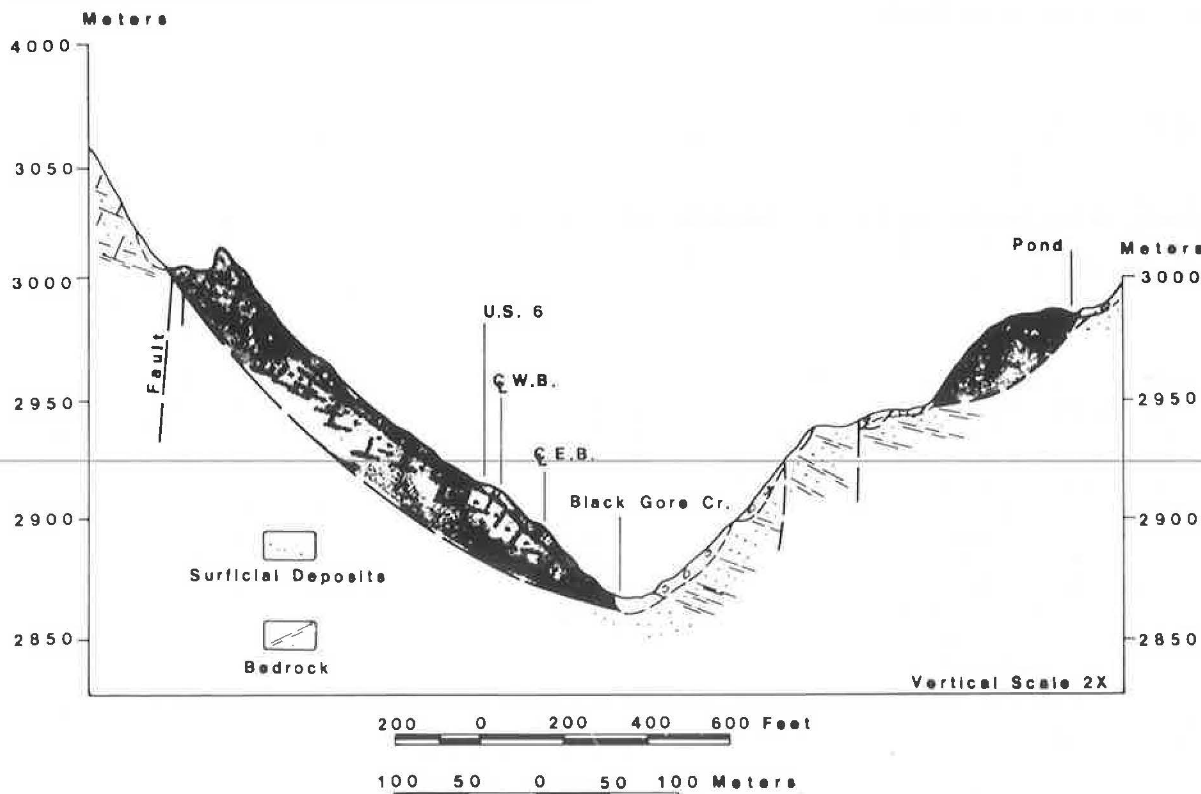


Figure 6. Cross section of bedrock landslide in sedimentary rock.



Because these landslides are composed of blocks of sedimentary rock, and the movement is generally along and about parallel to the bedding, the landslides are not thick. Drilling and the installation of instruments have indicated that the maximum depth of movement in this type of slide ranges from 6 to about 21 m (20-70 ft). Movement does not occur along a single slip plane; rather, there may be several parallel slip planes in a single area of a landslide. Movement occurs along weak bedding planes between beds in a single block of sedimentary rock or between overlapping landslide blocks of sedimentary rock.

Surficial Deposits

Landslides have developed in the surficial deposits on both sides of Vail Pass. The landslides are the result of the deposition or accumulation of surficial deposits on steep bedrock slopes and then the periodic movement of the deposits (Figure 8). Failure has been the result of steepening of the slopes by erosion, by changes in the groundwater regime, or by movement of the bedrock. All types of surficial deposits are involved in landslides, but most of the landslides are found in the moraine or colluvium.

The scarps of the individual slumped areas are recent. Most indicate movement of the surficial deposits during historic times; many show annual movement. The individual scarps range in length from 1 to about 150 m (3.3-500 ft). They average about 60 m (200 ft) in length. The vertical offset across the scarps ranges from less than a meter to several meters. The abundance of scarps in an area of landslides and their relative short length and small offset indicate that the depth of movement is relatively shallow. Drilling has shown that the individual landslides in the surficial deposits are generally less than 15 m (50 ft) thick.

The individual scarps may represent a single small landslide or an active segment of a large landslide area. The landslide area may be (a) a bedrock landslide in which the scarp represents slumping in the surficial material as a result of movement in the bedrock or (b) a large landslide in the surficial deposits. The individual scarps indicate the active segment of the large landslide.

A landslide in the surficial deposits is the result of the deposition of these deposits on a bedrock slope that was oversteepened by glacial erosion. The deposits were poorly drained at the time of deposition, and many swamps developed. The permeability of the surficial deposits is different in different areas, and numerous springs occur throughout. During much of the year when the surface is not frozen, the deposits are saturated with water. With the spring runoff there is a period of rapid erosion during the time of maximum saturation. This results in minimum stability in a mass of poorly sorted and unconsolidated material on a steep slope, the lower edge of which is at a stream channel. Along Black Gore Creek, downcutting of the creek has not been able to keep up with the movement of the landslides into the valley. The gradient of the creek above the landslides has been lowered and alluvial deposits have formed because the landslides have partially dammed the creek (Figure 9).

Figure 7. Trees growing in landslide scarp depression.

Figure 8. Cross section of landslide in surficial deposits.

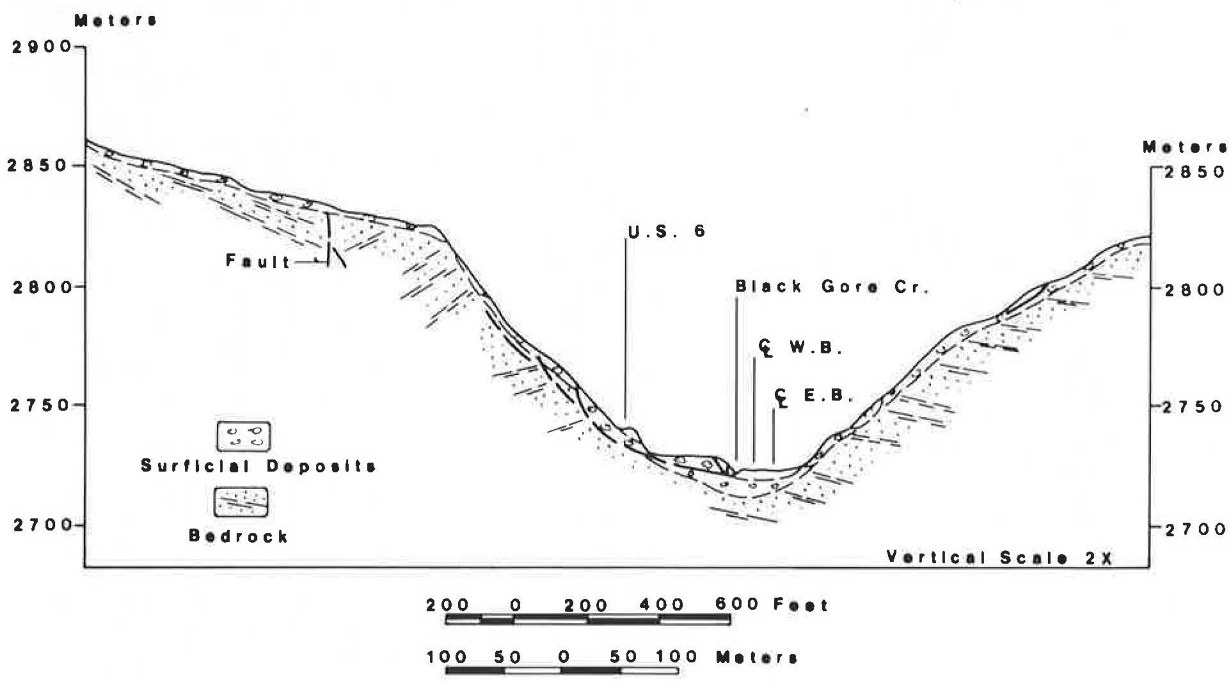


Figure 9. Alluvial deposits as result of damming of stream by landslides.

GROUNDWATER

In the Vail Pass area, snow accumulates to a depth of a meter or more during the winter months (generally November to April). Most of the snow melts in a relatively short time (April to July), and the streams are full from the spring runoff. Precipitation during the summer months is in the form of thundershowers—local, heavy precipitation during a short period of time and heavy runoff. Because of the accumulation of the snow pack, the ground is saturated with water part of each year. The time of total saturation depends on many factors, including source, porosity, permeability, and altitude.

Groundwater occurs in the fractures and the pore space of the bedrock and in the surficial deposits. The fractures and granular pores of the bedrock are probably saturated most of the time but the incidence of fractures and granular porosity in the bedrock is low. Most of the groundwater in the Vail Pass area is in the surficial deposits. Of particular importance is the groundwater in landslide areas.

The occurrence of groundwater was determined by mapping and by the use of drillholes. The locations of swamps and springs were mapped during the geologic investigations. The estimated flows of springs ranged from <1 to 265 L/min (<0.264 to 70 gal/min). The springs occur at the edges of surficial deposits and bedrock outcrops, at the margins of landslide areas, at the heads or toes of slump areas, along draws or stream valleys in surficial deposits where there is a thinning of the deposits, at contacts between different types of surficial deposits, and at the toes of surficial deposits adjacent to the major streams.

FOUNDATION AND SLOPE STABILITY

The foundation and slope stability of the geologic materials of the area was defined by the geologic studies, and this information was considered in the final location, design, and construction of the highway.

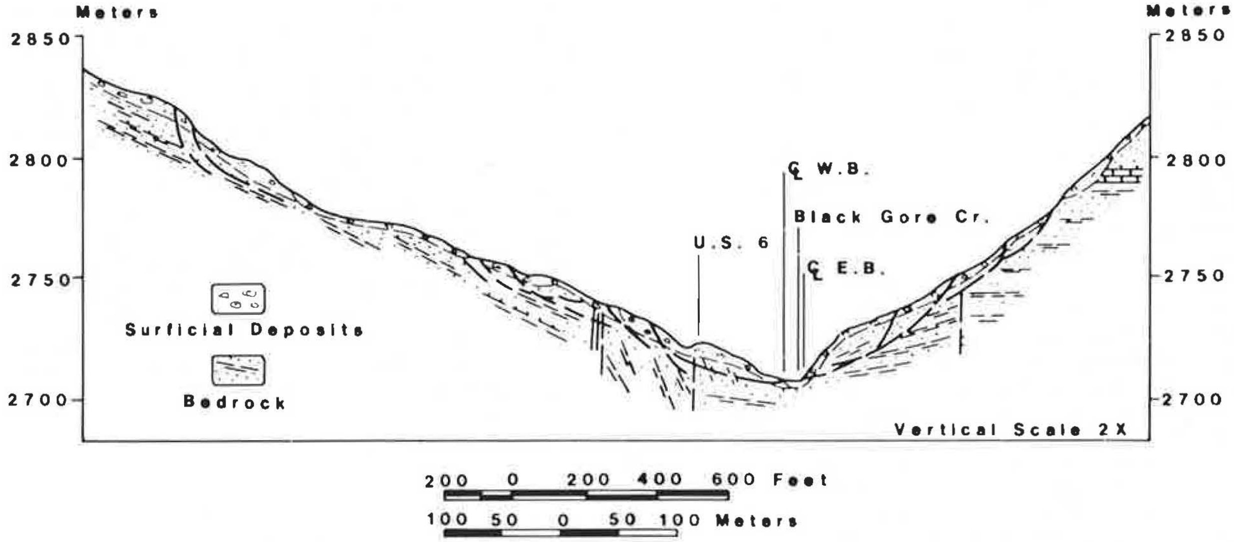
The igneous and metamorphic rocks include gneissic granite and migmatite. The gneissic granite is generally a massive, competent rock. The upper meter or so is rippable, but drilling and blasting were required for major cuts. Cut slopes in the gneissic granite stand vertically except where faults or joint systems approximately parallel the face of the cut. The excavated granite serves as excellent fill. Structures were founded on unfaulted and unaltered granite. Groundwater occurs in the faults and joints. In the placement of fill or the founding of structures on the gneissic granite, care was taken to ensure that the movement of groundwater through the fractures toward the streams was not impeded.

The migmatite is less competent than the gneissic granite because of the variation in composition of the layers. The biotite-rich layers, because of their micaceous structure, are weak compared with the granitic layers. Much of the migmatite is rippable. Drilling and blasting were required in some cuts where a high percentage of the rock was granite. The principal direction of weakness in the migmatite is the foliation. The rock is also jointed and locally faulted. Cut slopes in the migmatite were designed to the angle of dip of the foliation or the joint set that most closely parallels the direction of the cut. The migmatite excavated into tabular blocks, the longer dimensions of which paralleled the foliation.

The sedimentary rocks include a wide variety of lithologic types. These, in order of abundance, are sandstone, siltstone, shale, and limestone. The engineering characteristics of the sedimentary rocks are chiefly dependent on the grain size of the sand, the percentage of clay, and the structure. Sandstone constitutes about 75 percent of the sedimentary bedrock. The other types of clastic sedimentary rocks are interbedded and gradational with the sandstone. The sandstone is typically medium to coarse grained, conglomeratic [with pebbles of igneous or metamorphic rock to 0.15 m (6 in)], arkosic, micaceous, and poorly sorted. The rock is generally friable; calcium carbonate cementation does occur at the base of some beds. The typical sandstone grades into fine-grained sandstone and siltstone, which are micaceous and clayey and, in turn, grade into sandy and silty micaceous claystone or shale. Beds of limestone up to 10 m (30 ft) thick occur in the vicinity of stations 380 to 385 and stations 560 to 570.

The sedimentary rocks are generally massive, competent rocks. The rock is rippable at most locations but required drilling and blasting in high rock cuts. The design of cuts was dependent on the structure. The sedimentary rocks are jointed, and these joints form generally widely spaced sets [>0.5 m (>1.6 ft)]. Most joints are about vertical, and vertical cuts are possible. The alignment of the cuts was determined by the strike of the joint sets. Most cuts in sedimentary rocks ravel with time. The sedimentary rocks contain a small percentage of montmorillonite clay, which expands and contracts with changes in humidity and temperature. As a result, the rocks are repeatedly stressed, and small pieces work loose. The siltstone and shale beds, which contain a higher percentage of clay, ravel more, and overlying sandstone beds are undercut, which allows joint blocks of

Figure 10. Cross section through abutting landslides.



sandstone to fall. The sedimentary rock serves as excellent fill if properly placed. Structures on the sedimentary rock were founded on the massive sandstone or limestone beds. In the placement of fill on the sedimentary rock, particular attention was paid to the direction of the dip and to groundwater drainage.

The surficial deposits of the area include a wide variety of materials that have resulted from weathering of bedrock in place (colluvial deposits), transport and deposition by streams (alluvial deposits), transport and deposition by glaciers (morainal deposits), and residual deposits including terrace deposits, swamp deposits, and boulder trains.

Construction on the colluvial deposits presented problems. The deposits were at their natural angle of repose and, locally, were moving, if very slowly. Cut slopes of 1:1 in the dry material were possible, but allowance was made for continued raveling. The slopes ravel regardless of the angle if they are steeper than the natural slope because of continuing movement in the slope. Where the colluvial deposits were saturated with water, slopes of 2:1 or 3:1—depending on the average size of the rock fragments, the percentage of clay, and the height of the cut—were required for a relatively stable slope. In the maintenance of slopes, drainage was an important consideration, particularly in the colluvium derived from the sedimentary rocks that contain a relatively high percentage of clay.

The morainal deposits were also at their natural angle of repose, and cut slopes steeper than this angle would cause raveling and local failure. Slopes of 1:1 were relatively stable except for continued minor raveling in the dry morainal material derived from the igneous and sedimentary rock. Maximum slopes of 1.5:1 in the dry morainal material derived from the sedimentary rocks were relatively stable. When wet or subject to saturation, slopes of 2:1 or 3:1 would ravel and slump locally in either type of morainal material if they were not protected or planted. The control of drainage was important in the maintenance of stable cut slopes.

Construction on the alluvial deposits presented a few problems. The alluvial deposits in the major stream valleys had a limited bearing capacity. Test drilling and sampling were required to determine the suitability of these materials for footings for structures. Cuts intersected the toes of alluvial fans at the margins of the larger stream valleys. Most of these alluvial fans consisted of well-sorted and stratified granular materials that were saturated with groundwater. With adequate drainage control, slopes in these materials were stable at 1:1. Some raveling would be expected except that most of the slopes were laid back (flattened) and planted.

Classified as residual deposits were terrace deposits, swamp deposits, and boulder trains. The terrace deposits were characteristic of the alluvial deposits and presented similar problems in construction. The swamp deposits, which consist mostly of organic, rich, fine sand, silt, and clay, range from <0.1 to 3 m (<0.3-10 ft) in thickness. The swamp deposits were not suitable for use except as topsoil. These deposits were removed, and adequate drainage was developed before the placement of fill across a swampy area. The boulder-trains deposits range in thickness from 1 to 15 m (0.3-50 ft). Cuts through the boulder trains revealed a concentration of the finer material at depth. With adequate drainage, slopes of 1:1 were stable in the boulder trains.

ENGINEERING SOLUTIONS

The geologic environment and constraints were defined by the intermediate and detailed geologic investigations. These data were then integrated with the other environmental factors and constraints, and a preliminary alignment and design were established. This was chiefly the responsibility of International Engineering Company, with whom Charles S. Robinson and Associates worked closely.

It was not possible to avoid all landslide areas and still maintain highway standards. The studies, including the instrumentation, had indicated the landslide areas that were the most active and those that were relatively stable. The highway was designed to avoid the more active landslides. Where the highway crossed older landslides, the lanes were separated as far as possible in conformity with the requirements of standards for line and grade. The separation of the lanes allowed the height of cuts and fills to be held to a minimum. In several landslide areas, groundwater drainage was increased by drilling horizontal drains well below the level of the highway and the fills. The drainage across the old landslides was improved and carefully controlled to reduce infiltration into the landslide mass.

One landslide area was located between stations 415 and 425 (see Figure 10). Active bedrock landslides from either side of Black Gore Creek had their toes in the creek. The landslides on either side of the creek were instrumented, and their movement was monitored. The maximum movement occurred during the period of high groundwater levels, i.e., spring runoff. The solution to the stabilization of these two landslides was to fill the valley, transferring the thrust of one landslide against the other and putting the stream and the highway on the valley fill.

Slope stability was maintained by careful design of back slopes. The eastbound and westbound lanes were separated where space, line, and grade allowed, and the heights of back slopes and fills were kept to a minimum. Slopes in surficial material were laid back as far as was practical, contoured, covered with topsoil, and seeded. Particular care was taken to control surface and groundwater drainage on all cut-and-fill slopes. On bedrock slopes, the different types of material were treated differently depending on their ability to stand. The slopes in more competent units approached vertical, whereas those in less competent units were laid back and often seeded. The natural breakage of the rock—e.g., along joints—was followed, and the back slopes in bedrock conform in appearance to natural rock slopes.

One area of slope stability that was of particular concern was that between Gore and Bighorn Creeks. Along the alignment were surficial deposits, mostly glacial moraine, on Precambrian igneous rock. The surficial deposits were at their maximum angle of repose and were saturated with groundwater during most of the year. The choices for the placement of the highway were restricted by the presence of privately owned lands in the valley. Cuts in this area could have caused major slope failure. The solution was to put much of the highway on a structure.

ACKNOWLEDGMENT

In 1969, the Colorado Division of Highways entered into a contract with Charles S. Robinson and Associates, Inc., engineering geologists, and R.V. Lord and Associates, soils and foundation engineers, for an intermediate geologic study of the Vail Pass area. After completion of the geologic study in 1971, Charles S. Robinson and Associates were retained to work with International Engineering Company in the environmental studies of the Vail Pass area.

The geologic problems in the Vail Pass area were first recognized by R.K. Barrett of the Colorado Division of Highways (5). His report on the geology was the basis for the contract with Charles S. Robinson and Associates. The field investigations were conducted by Charles S. Robinson and Dale M. Cochran of Charles S. Robinson and Associates with the assistance of Gary T. Whitt of R.V. Lord and Associates. The contract was conducted under the supervision of Richard A. Prosence and Robert K. Barrett.

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U.S. Forest Service Involvement in and Overview of the Vail Pass Project

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The Vail Pass segment of I-70 was constructed across public land administered by the U.S. Forest Service. As the land-management agency, the Forest Service was responsible for ensuring that the construction would neither disrupt nor destroy the land's resources. The Forest Service carried out this responsibility by issuing environmental constraints for the construction, reviewing the construction plans and specifications in relation to these constraints, and periodically reviewing the construction work. A liaison officer was assigned to the project who, with the help of specialists, expressed the concerns of the Forest Service. This group assisted the Colorado Department of Highways in minimizing or eliminating the adverse environmental impacts caused by the construction of a highway to the standards of the Interstate system. Unique and innovative solutions to many sensitive environmental problems generated by the highway construction were found and applied through the effort and cooperation of many professionals and agencies. The result is an Interstate highway that lies lightly on the land and is compatible with the surrounding mountain environment.

The Forest Service of the U.S. Department of Agriculture is responsible for management of the national forests. This includes authorizing both occupancy and construction activities in these areas. This responsibility is carried out by issuing "stipulations" for the conduct of the work, reviewing the construction plans and specifications in relation to these stipulations, and periodically reviewing the work in progress. A right-of-way or easement is granted on completion of the work according to the plans and specifications.

During the course of the legal transfer of national forest lands to the Colorado Department of Highways for the construction of I-70 over Vail Pass, three sets of stipulations, or construction requirements, were agreed on and implemented. The first set, which was rather broad in scope, was written into the easement deed between the U.S. Department of Agriculture and the U.S. Department of Transportation. The second set of requirements, which was somewhat more specific, was written into the memorandum of understanding between the Colorado Department of Highways and the Forest Service. The third set of construction clauses was included with the interim letter of consent (for construction) issued by the Forest Service to the Colorado Department of Highways under the heading "Stipulation". These requirements were still more specific but needed interpretation as to exact meaning.

EASEMENT DEED

The procedure for authorizing the transfer of lands to a state for construction of an Interstate highway was established by an Act of Congress dated August 27, 1958 (23 U.S.C., §§317, 107d), and amended October 15, 1966 (80 Stat. 931, 937, §6a1A; 49 U.S.C. §1651). Briefly, the Act states that, if the U.S. Department of Transportation (DOT) deems it necessary for an Interstate highway to cross federal lands, the Secretary of Transportation requests an easement from the agency that is responsible for managing the lands and DOT grants the right-of-way to the state after the easement is issued.

The granting of the easement to DOT, in this case by the U.S. Department of Agriculture, carries with it certain considerations, obligations, and responsibilities. An easement deed contains 11 stipulations agreed on by the two agencies. These stipulations must be executed by the state highway agency involved before the easement deed is consummated. The implementation of the stipulations becomes the responsibility not only of the state highway agency involved but also of DOT, working through the Federal Highway Administration, and the U.S. Department of Agriculture, working through the Forest Service.

The stipulations in the easement deed include the following:

1. The state and the Forest Service will determine the need for archeological surveys.
2. The easement will be used only for Interstate highway construction in accordance with the approved plans.
3. The highway will be built to Interstate standards.
4. The plans and specifications will be reviewed by the Forest Service and, if necessary, changes will be made to protect national forest interests.
5. The final plans and specifications must be approved by the Forest Service prior to construction.
6. Natural resources outside the construction limits must be protected during construction operations.
7. Erosion must be prevented during construction, and construction scars must be revegetated when the work is completed.
8. Facilities such as borrow areas, camps, and storage areas may not be established unless they are approved in final plans or unless approval is given by the regional forester after approval of the final plan.

MEMORANDUM OF UNDERSTANDING

Under the law, a further delegation of responsibility is given to the regional forester of the Forest Service. A memorandum of understanding must be executed between the Forest Service and the state highway agency responsible for the construction of the highway—in this case the Colorado Department of Highways. This was accomplished in June 1970.

The memorandum of understanding establishes procedures and responsibilities from the inception of federal-aid highway construction or reconstruction through the location and planning stages, the environmental impact statements, on-the-ground survey and joint reviews, preconstruction meetings, and construction activities. It includes the procedures for coordinating the transfer of national forest lands to the state for the construction of an Interstate highway. The memorandum elaborates on the stipulations already established by the easement deed between DOT and the U.S. Department of Agriculture. In this case, it recognized the need for cooperation to solve the problems of building a highway to the demanding standards of the Interstate system through the mountainous terrain of Colorado. Some of the features recognized by this memorandum are

1. The need for joint cooperation to locate the highway in order to satisfy the objectives of both agencies;
2. Forest Service review of the preliminary plans and specifications of the Colorado Department of Highways;
3. A joint office review to resolve any differences or make changes in the plans and specifications;
4. The need for sections of the plans and specifications to recognize Forest Service land-management concerns, such as (a) disposition of merchantable timber, (b) fire protection, (c) locations of detours and construction standards for haul roads, (d) control of air and water pollution and erosion, (e) aesthetic features in harmony with the surrounding terrain, and (f) restoration of disturbed areas;
5. Participation by the Forest Service during the preconstruction conference with the contractor;
6. The need for a Forest Service liaison officer to work with the state; and
7. The need for Forest Service representatives to make joint on-the-ground reviews with the Colorado Department of Highways during construction.

The magnitude of the problem of fitting an Interstate highway into the Vail Pass corridor became evident during the location phase of the project. The mountainous terrain within the corridor was steep and unstable. The route paralleled streams from which communities took their water supplies, and the corridor passed through the fragile subalpine ecosystem at 3230-m (10 600-ft) Vail Pass. The growing season was short, the weather was unpredictable, and construction operations would have to be limited to the summer months. Because of these restrictions, it was necessary to establish criteria to implement the conditions of the memorandum of understanding between the Colorado Department of Highways and the Forest Service.

Opinions varied on the interpretation of the memorandum of understanding and how to accomplish the goals it described. Many agencies were involved in reaching final procedural decisions, including the Colorado Division of Wildlife, the Federal Highway Administration, the U.S. Geological Survey, the Colorado Department of Public Health, and the U.S. Environmental Protection Agency. Innovative ideas were expressed and welcomed. The final decisions were agreed to and incorporated into the construction.

FOREST SERVICE STIPULATIONS

Before construction of the highway over Vail Pass began, an interim letter of consent agreeing to the use of the land for the construction was given to the state of Colorado by the Forest Service. Included with the interim letter was a standard stipulation required by U.S. Department of Agriculture regulations and implied in the stipulations of the easement deed between DOT and the U.S. Department of Agriculture. Special clauses or requirements could also be included in the stipulation for specific items unique to the project, but these first had to be approved by the Chief of the Forest Service.

The stipulation in the interim letter of consent was broad in scope, but most of the environmental concerns were included. Briefly, the standard requirements and conditions to be met by the Colorado Department of Highways were as follows:

1. Before any construction begins, prepare a fire protection plan, a clearing plan to include disposal of merchantable timber, a landscape and erosion-control plan, and a construction plan that specifies restrictions and delineates methods of construction to avoid environmental damage;
2. Comply with recommendations of the Colorado Division of Wildlife and the Forest Service for wildlife and fish management, such as (a) avoiding damage to fish habitats, (b) protecting live streams from soil deposits, (c) installing temporary bridges for hauling material across live streams, (d) prohibiting operation of mechanized equipment in live streams, (e) preventing oil or greasy substances from being washed into live streams, (f) permitting no construction activity within 7.6 m (25 ft) of the edge of a major stream, and (g) setting up a cooperative agreement with the U.S. Geological Survey to monitor the water quality in streams;
3. Dispose of waste materials from slides and surplus material from construction activities in areas approved by the Forest Service;
4. Return abandoned roads to a natural configuration;
5. Provide standard highway signs to identify Forest Service boundaries and features;
6. Permanently monument the right-of-way; and
7. Establish or restore public-land monuments disturbed or destroyed during construction.

COOPERATION OF AGENCIES

One unique aspect of the Vail Pass project was the opportunity for many government agencies to provide input into the project plans. When discussions first began, ideas were zealously argued. Later, as rapport and trust developed, the pros and cons of each idea were considered objectively and a decision was made. Generally, these decisions were agreeable to everyone. Many sound, innovative ideas evolved from this approach.

LANDSCAPE AND EROSION-CONTROL MANUAL

A Landscape and Erosion-Control Manual was prepared for the Colorado Department of Highways by International Engineering Company. Input for the manual was received from several sources, including the Forest Service, the Colorado Division of Wildlife, the Soil Conservation Service, and the U.S. Geological Survey. The manual addressed specific environmental problems associated with Vail Pass. It provided concepts to be followed for landscaping and erosion control and emphasized the molding of land forms such as rounded or undulated slopes, staggered benches, and accentuated draws or ridges. It discussed leaving rock in place to blend with the natural surroundings and specified methods for erosion control and treatment of sediment-laden water.

Although the information contained in the manual was conceptual, it stimulated the innovative thinking needed to develop procedures to mitigate particular problems. Each problem, whether in landscaping or erosion control, was different and had to be dealt with individually. The manual became an integral guideline for the environmental work done on Vail Pass. The Colorado Department of Highways used the concepts set forth in the manual to develop contract specifications. The manual was a useful tool, and a similar approach is recommended for any project in which environmental problems are critical.

SPECIFICATIONS

It is imperative that correct, concise specifications relating to environmental concerns be written for a project such as that at Vail Pass and that the specifications be explained so that they are understood by everyone involved. With assistance from the Forest Service, the Colorado Department of Highways wrote special specification provisions to cover the stipulation in the interim letter of consent. Information for the specifications came from the Landscape and Erosion-Control Manual, specialists' proposals (modified by engineering concerns), and engineers who understood the problems involved and how to cope with them.

Without the specifications, planning, memorandums of understanding, and stipulations would have been fruitless. It was essential that the specifications be carefully written to avoid confusion and to indicate to the contractor precisely what was required. A great deal of time was spent on making the specifications as clear as possible. As the project progressed and unforeseen misinterpretations were encountered, alterations were made to the specifications. The specifications were also modified to fit the different locales.

DESK REVIEW OF PLANS

A desk review of plans was an essential part of the memorandum of understanding between the Forest Service and the Colorado Department of Highways. It was important for the Forest Service to provide an experienced engineer who could interpret the plans and specifications and understand what was proposed. Cross sections were not included with the preliminary plans, so it was necessary to interpret from the plan and profile sheets the extent of cuts and fills and their locations. Topography and the boundaries of existing vegetation were included on the plan sheets. By extrapolating from elevations shown on the profile sheet, it was possible to determine the dimensions of cuts and fills so that erosion treatments could be planned for a particular area or landscaping could be conceptually planned before the area was seen. If there were specific questions regarding cuts or fills, cross sections were available at the desk review. In one instance, the cross sections showed that long sliver fills were planned. The length of the sliver fills was shortened considerably by placing a 1.2- to 1.5-m (4- to 5-ft) timber crib retaining wall at the point at which the natural ground line approached the face of the fill. In another instance, the grade was raised to accommodate the extra fill material that would be generated because of an extensive rock cut.

A desk review of project plans with all interested parties is highly recommended. It is also recommended that the representatives who attend have a background in engineering so that they can intelligently respond to the plans.

FIELD REVIEW

In conjunction with a desk review of the plans, it is essential that a field review be made with the plans in hand. It is not necessary to cover the entire project, but critical areas should be seen on the ground to visualize what the final product will look like. It is easier to do this after the road is staked for construction; however, if the guide is someone who is familiar with the project, it is possible to get an idea of what is intended.

It was important that someone from the Forest Service who had an engineering background be a member of the field review. The field review was also the time for hydrologists and landscape architects to contribute their ideas. On Vail Pass field reviews, it was often necessary for a geologist to identify potential problems of instability attributable to a north-south-oriented fault that parallels the highway location.

During the construction phase of the project, periodic field reviews were continued because of changing field conditions. Latent problems developed that could not be foreseen during the initial design. A spring might be uncovered, an additional culvert needed, a culvert moved to a different location to be more effective, or landscaping altered from the original plan to better harmonize with the surroundings. Sometimes there was excess material to dispose of, and at other times additional borrow had to be obtained. Topsoil for revegetation was scarce, and sources had to be identified and saved. Decisions for these problems had to be made on the ground, immediately, so as not to impede the contractor's progress. Most of the decisions were made after a multidisciplinary review governed by engineering constraints. A background in engineering aided the decision-making process.

PRECONSTRUCTION CONFERENCE

The memorandum of understanding stipulated that the Forest Service participate in the preconstruction conference held with the contractor. Much of the conference pertained directly to the construction itself, but it also afforded an opportunity to discuss the concerns of the Forest Service as expressed in the specifications written by the state. The specifications were unfamiliar to the contractors. It was usually necessary to emphasize and explain their purpose and the final result that was expected.

There were questions concerning fire control, such as who should be contacted in case of fire, when and how to burn during the clearing operation, and what fire equipment should be on hand at all times within the construction area.

It was necessary to point out to the contractor the role of each of the agencies during construction. The contractor was to deal with the state project engineer, who in turn was to respond to Forest Service concerns and requests. On rare occasions the contractor might respond directly to the Forest Service representative. These requests were limited to emergency situations when the project engineer was unavailable. Contacts with the contractor by the Forest Service representative were limited to problems involving aesthetics, pollution or erosion control, and water quality. Every request was later coordinated with the project engineer. These situations are usually unavoidable, but precautions should be taken to limit their occurrence.

During the preconstruction conference, the contractor was responsible for furnishing a plan for erosion control and water quality on the project. The plan was then discussed and sometimes changed to better fit the situation on the ground. The contractor was also obligated to designate one person to assume responsibility for the implementation of the plan. The specifications stated that, in case of an emergency involving water quality, equipment and personnel would be furnished immediately to correct the problem.

Preconstruction conferences proved valuable, not only to explain the various roles but also to emphasize resource-protection requirements and the methods to be used. The conference also gave the representatives of the various agencies a chance to become acquainted with the contractor.

USE OF SPECIALISTS

Forest Service specialists were used during the planning and construction phases of the project. Primarily, these specialists were limited to hydrologists, landscape architects, and geologists. Occasionally, the advice of a forester or a range conservationist was sought. The problems encountered during construction were multidisciplinary, and it was not expected that any one person could furnish expertise in all areas. Specialists were therefore consulted on how best to accomplish the objectives. Conflicts occurred when implementation of an idea was not feasible. Most of the ideas expressed were good, but many could not be executed without compromising engineering quality. Although specialists were consulted and their opinions were evaluated, all modifications recommended to the state project engineer were made by the Forest Service representative.

It is mandatory that the initial design of such a project include input from landscape architects. The Colorado Department of Highways recognizes this and now makes the landscape concept a part of the plans, with the understanding that these plans will be flexible as the project evolves.

One recurring problem was that slopes were finished by the excavation contractor before the landscape architects made their proposals as to what had to be changed to conform to the natural environment. Their proposals could usually be accomplished, but cost could have been reduced if the clearing limits and cut-and-fill stakes had initially been placed to include the landscaping.

The use of specialists is recommended. But the proposals put forth by specialists must be governed by sound engineering judgment.

LIAISON OFFICER

A liaison officer was assigned to the I-70 Vail Pass project by the Forest Service. All contacts with the Colorado Department of Highways were made through the liaison officer. It was his responsibility to review all plans and specifications and to attend the desk review of the plans and the preconstruction conferences. He received and reviewed the opinions of the Forest Service specialists and passed the applicable ideas on to the state. It was also his job to keep the land managers (district rangers and forest supervisor) informed of what was happening and express their concerns in correspondence with state officials. In turn, he received correspondence pertaining to the Forest Service from state officials. In this way, the state had to deal with but one Forest Service representative.

The liaison officer acted as an inspector for procedures taken to mitigate the environmental impacts of Vail Pass projects. He was expected to have multidisciplinary expertise, to be well aware of Forest Service concerns, and to apply this knowledge to the project.

The liaison officer spent three or four days each week at the construction sites. As many as a dozen projects were under construction at one time. This allowed little time to seek out the help of a specialist for each problem that arose. Most of the problems that came up required an immediate response. Likewise, little time was available for consultation with land managers, and the liaison officer had to respond to the state by using the broad objectives set forth by the land managers.

When more than two or three projects were going at the same time, the liaison officer was often hard pressed to accomplish his assignment. In these situations, assistants were used to help monitor the construction as it progressed. Most of these people, however, had to be trained before they were capable of performing adequately. The liaison officer position could be strengthened considerably by assigning qualified people, rather than trainees, as assistants.

Since road construction is primarily an engineering function, it is essential that the liaison officer have an engineering background to properly interpret the plans and specifications and, perhaps more important, to respond intelligently to other agency representatives. As an engineer, he or she is able to differentiate which ameliorative measures are feasible. Although the liaison officer may not be a specialist in hydrology, he or she needs a background in the principles of hydrology. On this project, it was easier for an engineer to recognize proper construction of erosion-control structures. It is also beneficial for the liaison officer to have a background in geology or geological engineering. On the Vail Pass project, this knowledge was needed on several occasions. For example, when the state project engineer wanted to cut the toe of a series of slumps—a procedure that could have triggered a chain reaction of earth slides—the liaison officer explained the possible consequences and the project engineer decided not to make the cut.

The use of a liaison officer is an integral part of any project like the one at Vail Pass. It is recommended, however, that he or she be an engineer, preferably a civil or geological engineer, and that trained assistants be provided, preferably people trained in engineering, hydrology, or landscaping. Ideally, the liaison officer should have one assistant in each of these disciplines.

EVALUATION AND SUMMARY

A key element to a successful project is early planning and preparation before the project is designed. This point cannot be overemphasized. The groundwork must be laid so that there are fewer misunderstandings during construction. Another key element is cooperation and coordination among interested parties. All effort should be directed toward accomplishing the final objective. Everyone has something to contribute and everyone should contribute. This cannot be done if one agency feels it has final control and is jealous of ideas supported by another agency. Such a project is so large and complex that no one agency or person can have all the answers. The success of the Vail Pass project was predicated on the idea that all interested parties were to participate and contribute toward the final goal.

The goal of the Vail Pass project was to construct across a major mountain range an Interstate highway that would be compatible with the mountain environment. The completed highway speaks for itself. The success of the project lies in cooperation and coordination among many individuals and government entities. The entire operation was not smooth; it was often fraught with argument and frustration. But from this apparent chaos emerged innovative ideas and understandings that can be used in future projects of this magnitude. Certainly not everything tried at Vail Pass was successful but, overall, I would recommend few changes.

The Forest Service has officially commended the Colorado Department of Highways for its effort to cooperate in mitigating environmental damage in a very sensitive corridor of public lands.

Abridgment

Meeting the Challenges of Environmental Restrictions in the Vail Pass Project

Robert H. Lowdermilk, H-E Lowdermilk Company, Englewood, Colorado

Although many procedures for complying with Colorado water-quality-control regulations were developed in advance of actual construction of I-70 at Vail Pass, daily observation of the project revealed one thing clearly: Compliance is easier said than done. The actual work situation often dictated procedures other than those specified. Many problems were encountered that had not been anticipated. Meeting environmental requirements on the actual jobsite became a process of finding, analyzing, and solving problems on a continual basis. This resulted in a remarkable effort of cooperation among agencies and contractors.

The purpose of this paper is to provide a contractor's view of the problems encountered and the solutions developed during the Vail Pass experience so that future projects of this nature can be accomplished with greater efficiency and at lower cost to taxpayers.

COPING WITH THE MYSTIQUE OF ENVIRONMENTAL LAW

For the contractor, environmental restrictions meant a whole new way of thinking, even as early as the bidding process. The first thing the contractor had to overcome was a reluctance to bid because of a lack of understanding of the laws themselves.

A cursory reading of the Colorado Water Quality Control Act revealed that the regulations spoke in terms of absolutes: "...to provide that no pollutant be released into any state waters without first receiving the treatment or other corrective action necessary to protect the legitimate and beneficial uses of such waters." And the penalties were stiff: "Any person who fails to notify the division [of pollutant discharge] as soon as practicable shall, upon conviction thereof, be punished by a fine of not more than ten thousand dollars, or by imprisonment in the county jail for not more than one year, or by both such fine and imprisonment."

The science of earthwork has not yet developed to the stage where inadvertent deposits of earth into nearby streams can be totally prevented, let alone noticed and reported. Were contractors to risk heavy fines and imprisonment for the sake of working within laws that were apparently unrealistic?

The Colorado Department of Highways, however, had the foresight to educate contractors on these laws and their consequences before the letting of the project contracts. Thus, even at this early stage was begun the spirit of cooperation that was the basis for the solutions to problems encountered throughout the project.

COPING WITH THE COSTS OF ENVIRONMENTAL LAW

Environmental restrictions and compliance procedures are, of course, not without cost consequences. The direct costs of pollution-control systems and the indirect costs of scheduling, planning, and coordination problems that arise because of the restrictions (which are described below) combine to raise the normal cost of highway construction by more than 15 percent, according to estimates of the Colorado Department of Highways. We now believe the cost may exceed 20 percent.

Many of these costs are unpredictable from the outset. This raised questions at the bid table: How were contractors to be reimbursed for work on undesigned and unpredictable structures and systems for pollution control?

The problem was solved by specifications under which the Colorado Department of Highways separated the unpredictable costs from the normal contract items and paid for them on either a time and materials basis or by bid hourly equipment rates. Using hourly rates for equipment to be used in constructing pollution-control systems on the project greatly reduced the contractor's risk and served all parties equitably. It is recommended that the same procedure be followed on future projects of this type.

Work Scheduling

Many regulations and procedures imposed severe scheduling restrictions on contractors. The Colorado Department of Highways was able to minimize some of these problems by scheduling requests from landscape architects for the use of a contractor's equipment so that the removal of that equipment from a production group would have the least possible economic effect on the contractor. Other scheduling problems, however, simply resulted in increased costs.

One notable cost increase occurred when contractors were required to implant topsoil, seed, and jute mesh on cut or fill slopes each time these slopes extended vertically to a maximum of 9.14 m (30 ft). This specification, combined with the fact that extensive landscaping had to be done before topsoiling could proceed, caused severe scheduling and movement problems in the restricted areas in which the contractors worked. Efficiency was greatly reduced because the same equipment often could not be used on nearby cuts or fills. In some cases, the character of excavation materials varied to such an extent that available equipment was not economically appropriate. In other instances, the number of units of available equipment was not appropriate for the haul distance required (e.g., too many or too few haul units for a particular grade and haul length was a problem because of frequent moves). Other operations, such as pipe installations, occasionally reduced the options available to contractors.

Solutions to this problem were further hindered by the fact that erosion-control measures often could not be implemented far enough ahead to make new cuts and fills available when needed. Operations of landscape architects frequently took longer than expected, further delaying topsoiling, seeding, and other operations in a cut or fill area.

Cost increases occurred when, in response to these and other scheduling problems, contractors selected the solution that was economically the most appropriate. These actions ranged from (a) simply maintaining an excavation operation too long in a cut that really needed to be drilled and shot rather than ripped to (b) forcing extremely crowded and inefficient conditions in a cut or fill area by using excavation and topsoiling equipment simultaneously or (c) completely shutting down a potentially productive group and risking the loss of equipment operators in the process. All of these alternatives were costly.

Preconceived Procedures

It is recognized that specifications can be used to guide or encourage a contractor to accomplish a procedure, such as burning, in a pollution-free manner. The intention may be good, but rigid specifications that mandate a procedure or a type of equipment can be counterproductive. The actual work situation may dictate a different, more valid solution than the one specified. Appropriateness and economy require that a contractor not be tied down to inefficient procedures and equipment. The Vail Pass experience provided the following example.

Because of requirements in the specifications and state burning permits, contractors were required to purchase a generically named piece of incineration equipment for "smoke-free" burning of tree limbs and small trees cleared on the project. When mud-covered trees and limbs were fed into this equipment, the resulting cooking action caused smoke over a long period of time. Eventually, the use of small, portable fans was approved as a substitute procedure and the work was efficiently accomplished.

The Vail Pass experience showed that such interference with efforts to cope with the elements in an optimal way can raise costs and even defeat the original purpose. Freedom and flexibility can be important factors in controlling construction costs, even (or especially) under tight environmental restraints.

Techniques for accomplishing this type of earthwork construction are far more advanced now than they were before the Vail Pass experience. Contractors learned to keep water originating above the work areas from running through work areas and carrying loose earth into streams below by placing plastic-lined ditches or temporary pipes across the project area. We learned that water that originated in the work area could either be channeled into settling ponds and processed before going into streams or sprinkled onto nearby hillsides. We also learned how to more efficiently include landscaping, topsoiling, seeding, mulching, and the construction of pollution-control structures in the cycle of normal earthwork operations. And we learned that, through careful channel changes, we could even improve waters for trout fishing.

In the words of a spokesman from the Rocky Mountain Center on Environment, which recently bestowed an award for the work done at Vail Pass, "The project demonstrated that a highway of significant magnitude can be constructed in an area of delicate environment without inflicting permanent environmental damage." Yet much remains to be learned, not only from the standpoint of developing techniques for working within the laws but also from the standpoint of making the laws themselves more workable. Perhaps this can be a starting point.

Abridgment

The Vail Pass Project: View of the Colorado Department of Highways

Jack Kinstlinger, Colorado Department of Highways, Denver

I-70 was constructed over Vail Pass as part of the Colorado segment of the Interstate highway system. Many safeguards had to be designed and constructed so that the project would be consistent with the goals of the Colorado Department of Highways to improve travel efficiency and safety while preserving the environment of the state. An Interstate highway can cause great damage to the mountain environment, and the cost of minimizing these impacts is necessarily great.

Prior to 1973, Vail Pass was crossed by way of a two-lane highway that wound along the valley bottoms. Motorists had to take care to avoid on-coming automobiles, trucks, and campers while viewing the scenery. In those days roadside maintenance was extensive. Traffic was often delayed by stalled vehicles. Winter accidents multiplied as the skiing industry grew.

Today, Vail Pass is safely traversed on a four-lane Interstate facility. Stalled vehicles do not hold up traffic, and roadside maintenance is minimal. The roadway was designed and constructed to fit the land, and the end result allows the motorist many splendid views of the mountain landscape.

For a while it was thought that Vail Pass would go down in history for other reasons. Lawsuits were pending from local communities, the Bureau of Land Management and the U.S. Forest Service conducted critical on-site inspections daily, major geologic problems threatened the integrity of the facility, and local controversy over the project prompted daily newspaper editorials. Traffic delays caused by construction further fueled the controversy.

From this shaky beginning grew a form of interagency cooperation that has spread to other projects. To solve the mounting construction-related concerns, the department pulled together an interdisciplinary team composed of representatives from the U.S. Forest Service, local environmental organizations and citizens, staff geologists, engineers, hydrologists, and landscape architects as well as consultants and contractors to review project plans for potential impacts. Once the impacts were identified, techniques for mitigating them were developed and designed into the project. A project team was set up at the site to ensure that unforeseen problems were quickly solved.

The Vail Pass experience has produced a number of benefits not evident on the pass itself:

1. Credibility of the Colorado Department of Highways with the citizens and agencies of Colorado has been improved. All parties involved in the Vail Pass project now have an improved understanding of the department's capabilities, intentions, and limitations. In subsequent projects, both large and small, a smoother working relationship between the department and other agencies and a better understanding of each other's concerns have been demonstrated. This results in faster project turnover and savings in project costs.
2. The department's environmental impact statements are now more than just paperwork. Environmental design techniques tested at Vail Pass can now be outlined and specified to minimize potential impact areas. This makes the environmental impact statement a design document that directs rather than limits the future design and construction of a project.
3. The interdisciplinary approach has been strengthened and improved by the willingness of agencies and individuals to participate with the department on future projects. This is essential to the environmental impact statement process.
4. A valuable data base has been established on which the Colorado Department of Highways can draw for future projects. Construction techniques tested and used at Vail Pass can now be used with confidence and cost savings on other Colorado highway projects. Engineering and geotechnical applications and new materials and environmental design techniques are part of this data base. The department is now looking at projects constructed prior to Vail Pass to see if they are possible candidates for reclamation actions.

SUMMARY

Vail Pass has provided the Colorado Department of Highways a training ground for a wide range of design and construction techniques. The lessons gained on the Vail Pass project have produced a more cost-effective construction program and will continue to do so in the future.

Vail Pass is a milestone in Colorado highway construction history by which all past and future highway projects will be measured.

ACKNOWLEDGMENT

I would like to give special thanks to Michael Tupa of Engineering District 6, Colorado Department of Highways, for his assistance in preparing this paper.

Final Geotechnical Investigations on the Vail Pass Project

Robert K. Barrett, District 3, Colorado Department of Highways, Grand Junction

An overview of final geotechnical investigations on the 22.5-km (14-mile) Vail Pass I-70 alignment is presented. The geotechnical studies involved personnel of the Division of Highways, Colorado Department of Highways, and consultants from four engineering firms. The Interstate corridor traversed several areas where geologic conditions posed extreme difficulties. Unique and innovative designs were required to provide a stable, attractive, and environmentally compatible highway. Examples of the geologic problems encountered and the techniques used to surmount them are described. Approximately 30 person years of geotechnical expertise and 10 drill-crew years were required on the project. The geotechnical studies are estimated to have cost $2 million.

Final geotechnical investigations on the 22.5-km (14-mile) Vail Pass I-70 project began in 1971 after completion of preliminary investigations by a consultant in engineering geology. The preliminary and intermediate phases included four years of investigation by engineering geologists of the Division of Highways, Colorado Department of Highways; consulting engineering geologists; soils engineers; and rock-mechanics engineers.

Preliminary and intermediate investigations identified many kilometers of potentially unstable areas where the routing of a four-lane Interstate highway could be adversely affected by rock, soil, and snow slides. It was recognized at the end of these early studies that the final alignment would have to be selected in conjunction with a final, comprehensive geologic investigation.

From 1971 to 1977, geologists and soils engineers worked closely with both consulting design engineers and Colorado Department of Highways design and construction engineers in selecting the optimum location for the roadway. This report describes some of the investigations conducted during that period and explains, from a geologist's viewpoint, how and why various alignment and alignment-related features were finally selected. The geologic symbols used in the figures are explained in Figure 1.

GENERAL GEOLOGY

The final geotechnical investigations added the third dimension to the geologic maps assembled by Charles S. Robinson and Associates and R. V. Lord and Associates and provided soil and rock engineering properties and groundwater data. Aided by geologic maps; black-and-white, color, and infrared photography; and seismographs and drills, it was possible to create a complete picture of the recent geologic history of the Vail Pass corridor and to predict the impacts and consequences of various alignment alternatives.

It was discovered that a glacier had caused deposition of extensive silt, sand, and organic horizons high on the mountainside just east of Bighorn Creek at the west foot of Vail Pass (see Figure 2). It was probably this same glacier, originating from main Gore Creek, that dammed Black Gore Creek and caused widespread fine-grained lake sediments to be deposited on the hillsides for a distance of 1.6 km (1 mile) up Black Gore Valley.

Many of the bedrock failures were drilled, and much was learned about the failure machanisms. It was concluded that the failures originated on extremely weak, thin, fine-grained, silty, micaceous shale lenses within the predominately sandstone and siltstone bedrock. Bedrock failures on slopes as flat as 4° were observed. In the areas between stations 615 and 680 (Figure 2), both valley walls of Black Gore Creek have failed from near their crests to below the level of the creek—a vertical distance of more than 610 m (2000 ft).

Soils were sampled and tested for strength and permeability. The predominant soils at Vail Pass, classified AASHTO A-2-4 and A-4, were deceptively poor for highway purposes. These soils were highly micaceous and relatively impermeable. Although visually the soils all appeared to be similar, R-values determined by using the Hveem stabilometer varied from 5 to 82 (the stabilometer test is a measure of the relative stability of soils on a scale of 1-100), and triaxial tests indicated a wide variation in strength parameters.

SELECTED GEOLOGIC PROBLEMS AND SOLUTIONS

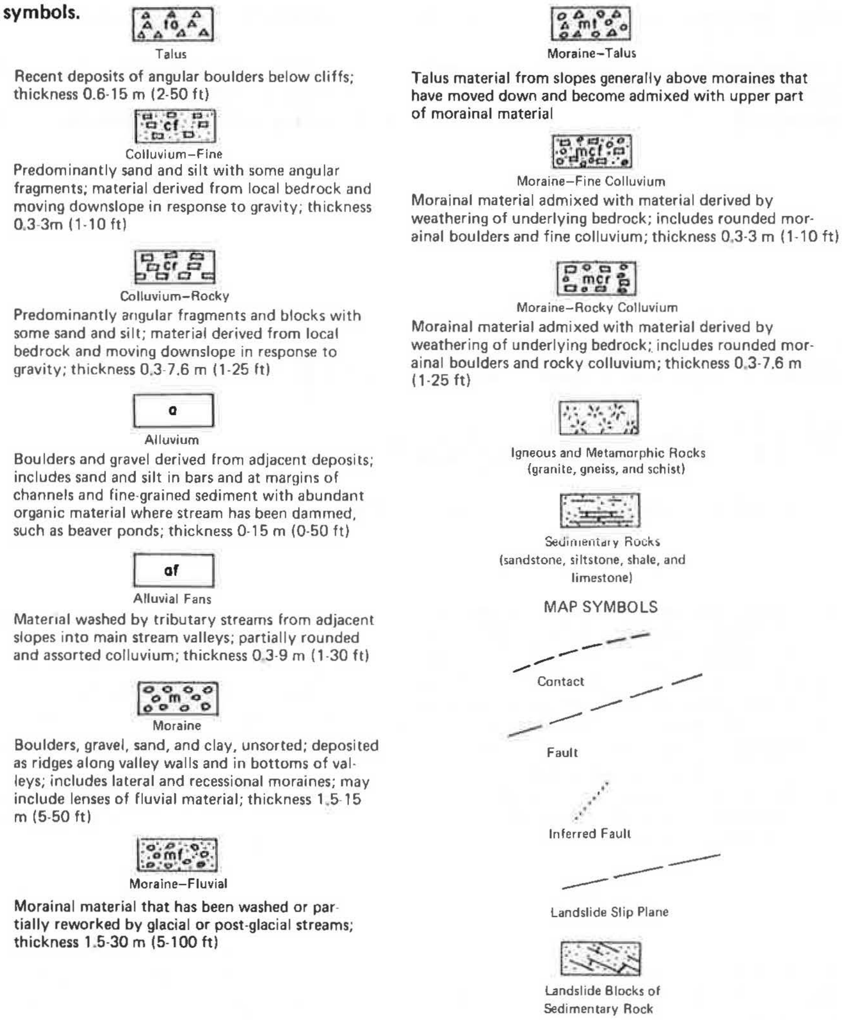
Stations 310-340

The consultant's preliminary studies concluded that the hillside in the vicinity of stations 310-340 probably contained deep deposits of unconsolidated materials. Concern was expressed about the extensive side-hill cuts proposed for that area (see Figure 3).

In 1972, drilling was initiated in the area. The soils initially selected for drilling consisted of granite boulders as large as 0.9 m (3 ft) in diameter in a matrix of sand, gravel, and cobbles. Since these materials could not be penetrated by the standard rotary drilling equipment owned by the Colorado Department of Highways, they were drilled by a private firm using a percussion drill.

The drilling program verified that deep, uncon-

Figure 1. Explanation of geologic symbols.



solidated glacial deposits were perched on the mountainside above the proposed extensive cuts. These deposits consisted primarily of sand overlaid by gravel and boulders and contained organic horizons at various depths. The deepest deposit exceeded 43 m (140 ft), and the water table was near the surface. Had cuts been attempted in this area, extensive failures—probably involving more than 900 000 m (1 000 000 yd)—would have resulted.

Based on the drilling information, it was recommended to the designers that no cuts be made in this area. Two alternatives remained: a standard fill slope or a side-hill viaduct. Partly because of extensive condominium development and high land values, it was determined that a viaduct was the better choice.

During foundation investigations for the structure, it was discovered that the cross-slope safety factor was only 2.0 in the existing hillside in the vicinity of one of the piers. Precedents established on Interstate projects required a 3.0 safety factor on structure foundations. After considerable review, highway department management and personnel of the Federal Highway Administration agreed to accept a factor of 2.0 in this area.

Station 425

In the area of station 425, geologic mapping and subsequent instrumentation by a geologic consulting firm defined an area in which two active landslides were moving from opposite sides of the valley and constricting Black Gore Creek. After intensive studies and analyses, it was decided that an extensive earth buttress would successfully stop movement in the slides. This buttress would fill the channel and floodplain of Black Gore Creek and cause the slides to push against each other (see Figure 4).

One major consideration in this decision centered around the fate of Black Gore Creek itself. Economically, it would have been desirable to place the creek in a large pipe under the embankment; that alternative, however, was deemed aesthetically unacceptable by practitioners of several disciplines.

Keeping the stream flowing on the surface posed major design problems. An impoundment was required upstream from the earth buttress and a rundown, or waterfall, was required on the downstream end. Because of the marginal stability of the area, design and construction procedures were quite complex. The technique chosen for the run-down included stepped gabion walls with deep foundations to act as cutoff walls and post-grouting to reduce permeability through the rock baskets.

Stations 438-450

In the area of stations 438-450, subsurface investigations revealed the presence of a lake deposit consisting of silt and fine sand perched on the hillside where a balanced cut-and-fill alignment was planned. The lake sands were saturated, and cuts into these deposits would certainly be unstable. Predrainage was not a practical alternative. Neither was a standard all-fill template, since moving the alignment out to an all-fill section would have required extensive rechannelization of Black Gore Creek. A channel change was not recommended because of the presence of unstable, unconsolidated lake deposits on the opposite hillside. It was also aesthetically unacceptable.

The remaining choices were a high wall or a side-hill viaduct. Because of foundation conditions and cost factors, a reinforced earth wall was selected. Before construction of the wall, organic soils in the floodplain of Black Gore Creek were excavated and a drainage blanket was placed over most of the wall foundation area and on the slope behind the wall. Extensive under-drain systems were installed to further ensure continued adequate drainage (see Figure 5).

Station 499

Instrumentation installed during the intermediate study identified an active landslide on the north side of Black Gore Creek in the area of station 499, a discovery that

Figure 2. Vail Pass location map showing elevation and stations along Black Gore Creek.

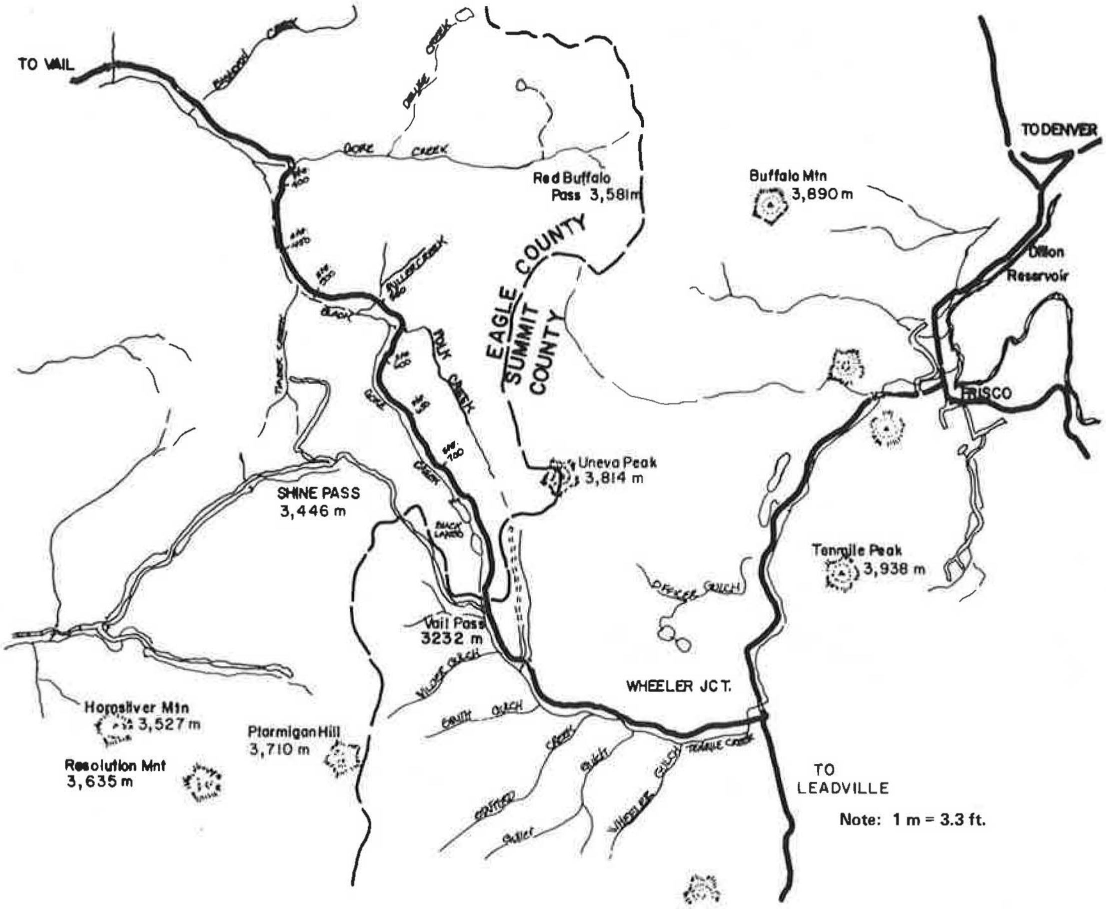


Figure 3. Geologic section: station 335.

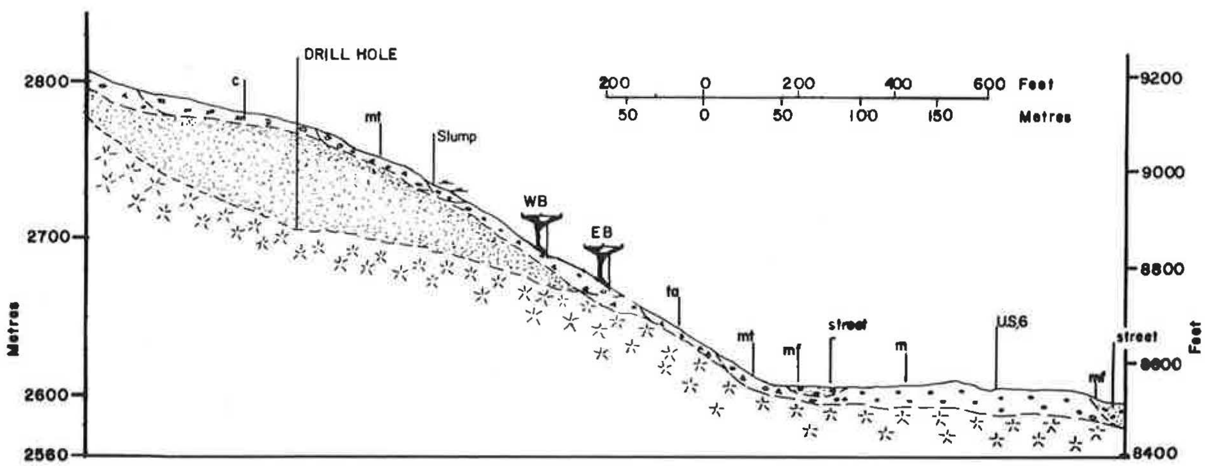


Figure 4. Geologic section: station 425.

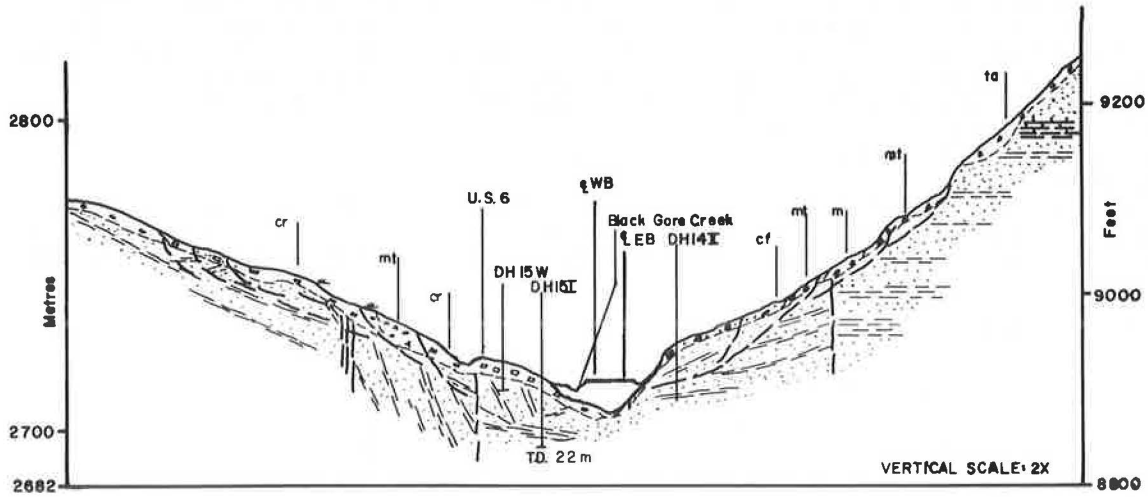


Figure 5. Geologic section: station 450.

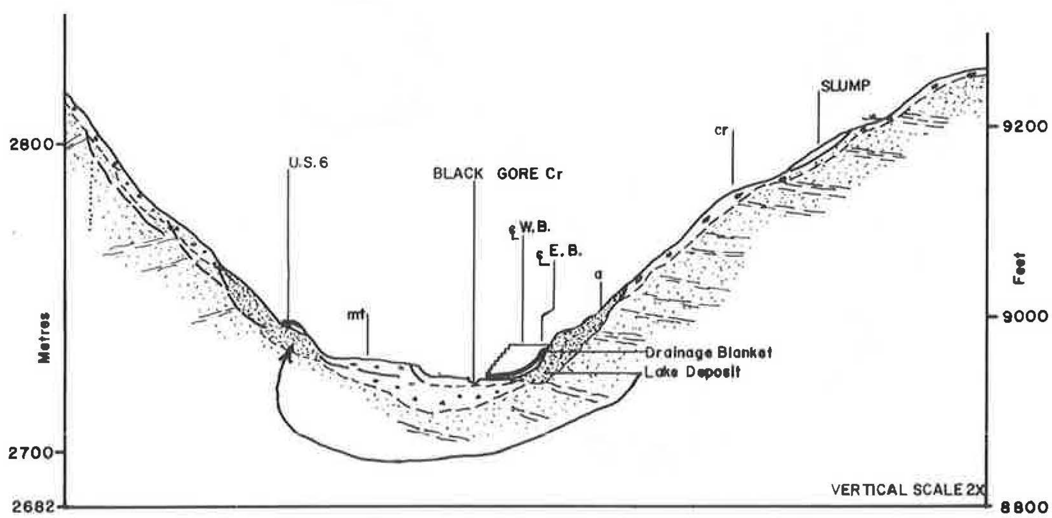
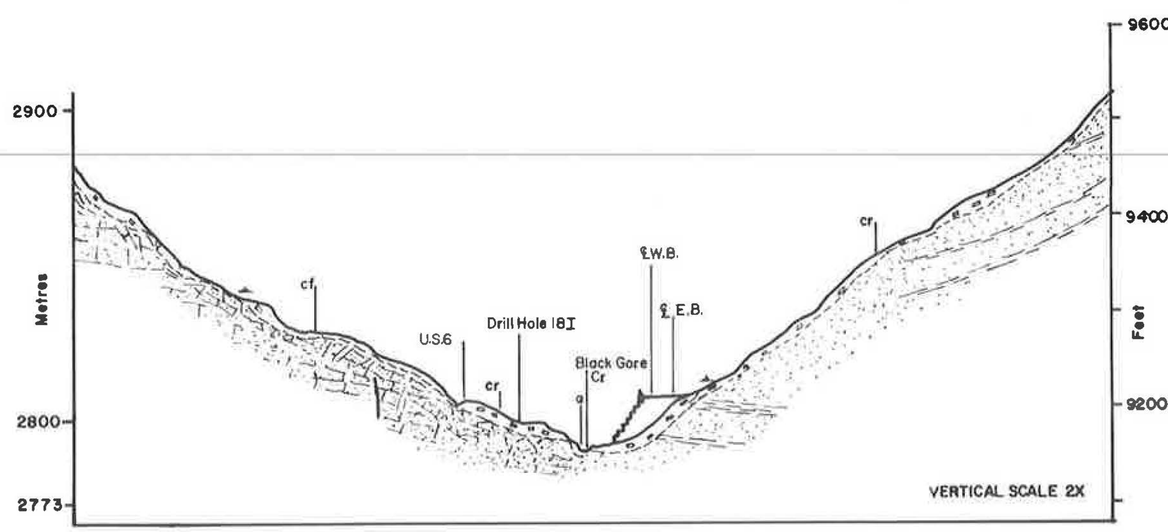


Figure 6. Geologic section: station 499.



resulted in the final alignment being placed totally south of the creek and requiring one high retaining wall. This retaining wall was the first precast tieback wall to be constructed on a highway project. There was a substantial amount of instrumentation on this wall, including load cells, inclinometers, and strain gauges. The wall system proved effective and efficient. Figure 6 shows the final cross section.

Stations 545-555

The most difficult and challenging problem for geotechnicians at Vail Pass was in the area known as the Miller Creek slide. This slide is over 1 km (0.62 mile) long, almost 1 km wide, and about 46 m (150 ft) deep. The slide consists of up to 21 m (70 ft) of surficial silty soils overlying some 24 m (80 ft) of failed bedrock. Water levels were erratic, varying from surface ponds in some areas to dry in other areas.

During the earliest drilling, the lowest failure plane was thought to be at the soil-rock interface. Two core samples from 6 m (20 ft) below this contact indicated intact sandstone and siltstone dipping by about 4°. This matched the geology in the surrounding area. It was found, however, that this did not match a deep core hole drilled previously by the Denver Board of Water Commissioners in conjunction with a proposed water-diversion tunnel. A third hole was drilled to 46 m (150 ft), and several obvious shear zones were found. Additional drilling revealed areas of completely disrupted bedrock. Competent, intact bedrock occurred below this zone. The bedrock failure plane corresponded with the 4° bedrock dip in the lower reaches of the slide.

During the course of the drilling, a buried soil profile was uncovered in the toe area of the slide. Carbon-14 dating showed that a sample of organic material from the soil layer was 1000 years old, plus or minus 70 years, which indicated that the movement was relatively recent.

The topography of the Miller Creek slide area, shown in Figure 7, included a deep canyon at the toe of the slide into which the slide would spill during active periods. Severe grade restrictions, both up and down station from the slide area, dictated that the alignment must cross the toe of the slide. In other critical areas, it was usually possible to vary vertical and horizontal alignment to optimize alignment and geologic conditions.

The first alignment investigated included major fills ramping onto and off the toe area and the roadway in cut and fill across the toe area proper. Cuts of up to 15 m (50 ft) were required. Because relatively recent movement had occurred, it was decided that the risk was too great. The safety factor would have been reduced by about 25 percent in the immediate area.

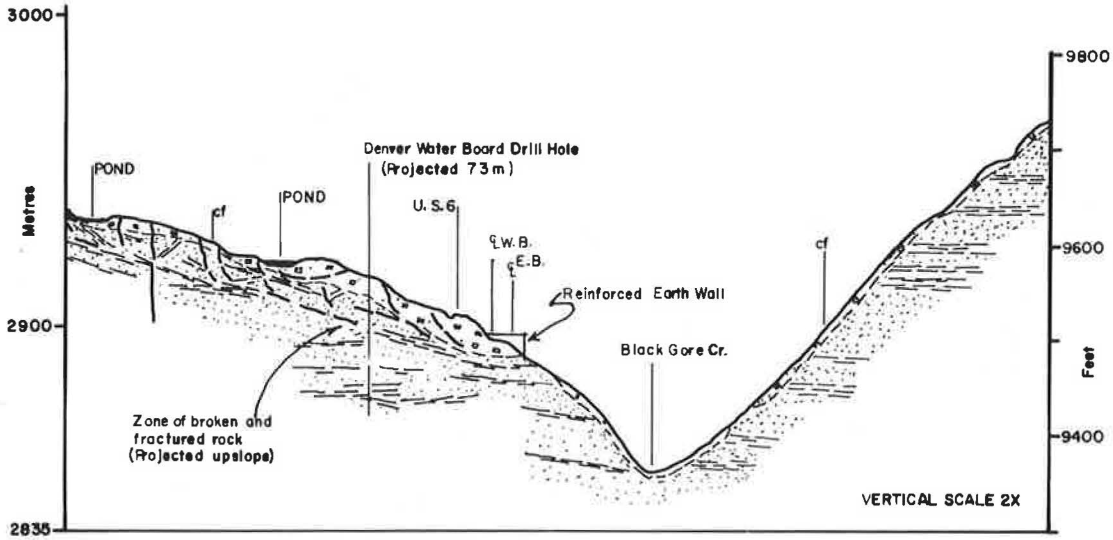
The second alignment investigated included twin bridges with caisson foundations into intact bedrock. In conjunction with this alternative, a consultant presented a European concept that included oversized, elliptical, concrete-lined caisson holes with free-standing caissons inside. This technique would keep horizontal pressures from acting on the caissons and allow monitoring of any creep that might develop. This alternative was ruled out based on evaluations of existing safety factors, required long-term monitoring, maintenance costs, and the consequences of failure.

The remaining alternative was a high, vertical, reinforced earth wall, the toe of which would be placed on the edge of the steep canyon wall and the base of which would have to be placed on intact bedrock. In place, this design raised existing safety factors insignificantly, but excavation of the toe of the slide to permit construction showed a mathematically significant reduction in the safety factor on the critical circle.

After a tentative decision was made to try the wall concept, a detailed geotechnical investigation was done. It was decided that, if the water table could be lowered about 11-17 m (35-55 ft) below the ground line as far as 91 m (300 ft) horizontally behind the excavation, it would be possible to construct the wall. Based on readings from several water-level-monitoring sites, it was also decided that the wall would have to be constructed during the winter months, the period of lowest groundwater levels and least groundwater recharge.

In March 1974, a series of horizontal drainage holes was drilled in an effort to lower the groundwater table. First, an attempt was made to construct an access road for the drilling equipment along the lower margin of the slide toe on the rim of the canyon. Because the area was saturated and not frozen [a 2.1-m (7-ft) snow cover had not allowed frost penetration], the dozer became helplessly mired. A second road was successfully built about 6 m (20 ft) higher. The minimum result

Figure 7. Geologic section: station 550.



expected from drainage holes at this level was that they would help to dry the lower area for a future drainage project.

The horizontal drilling proved successful and interesting. Some intact blocks of rock were as large as 24 m (80 ft) across and, almost invariably, great bursts of water would flood from the drill holes when the bit broke through into a shear zone. One such flow was measured at 757 L/min (200 gal/min). Most flows dropped off substantially in 30 min to 2 h.

Water levels were reduced by almost exactly 11 m (35 ft). Because of the low cost and the success of the drainage program, it was decided that it would be worthwhile to drill another series of holes at a lower elevation in conjunction with the construction project. When the second series of drain holes was completed more than two years later, the toe area had, in the interim, dried substantially. The second series lowered water levels to about 15 m (50 ft) below the ground surface.

Before construction, three inclinometer holes were installed up the slope to monitor any movement that might result from the excavation. The construction plan included very stringent procedures to minimize the amount of excavation in the toe area of the slide that would be left unsupported at any given time. These restrictions, coupled with a winter work requirement, caused considerable consternation among both highway department construction personnel and the bidding contractors. Some painted a bleak picture of the plan's prospects of success.

An unusually dry autumn and a snow-free early winter in 1976 permitted construction to proceed as planned. The backfill was all large gravel [2.5-20.5 cm (1-8 in)] and cobblestones (tailings from early gold-dredging operations in the Blue River), which was workable at all temperatures; thus, achieving density on subzero days was not a problem. The high [21-m (70-ft)], steep (1:1) temporary slopes to the slide toe remained stable, and the inclinometers detected no movement.

Stations 615-680

Bedrock failures were observed throughout the upper reaches of Black Gore Creek. One failure series was continuous from station 615 to station 750±. The alignment location was first split, the eastbound on the south valley wall and the westbound using the existing US-6 platform. This concept was abandoned when it was discovered that a bridge from the west valley wall would have to be located on marginally stable failed bedrock.

The remaining choice was to place both directions of travel on or near the existing US-6 alignment. The roadway template was minimized by using a median wall, which allowed a better fit on the steep hillside. Several attempts were made at defining critical failure circles and strength parameters through this area. None were felt to be entirely reliable, and the final design was accepted by geotechnical personnel on the basis that it caused the least disturbance—that is, the least reduction in safety factor on mathematical models. It was the consensus of opinion that the final alignment had a reasonable and acceptable probability of success (see Figure 8).

Stations 700-715

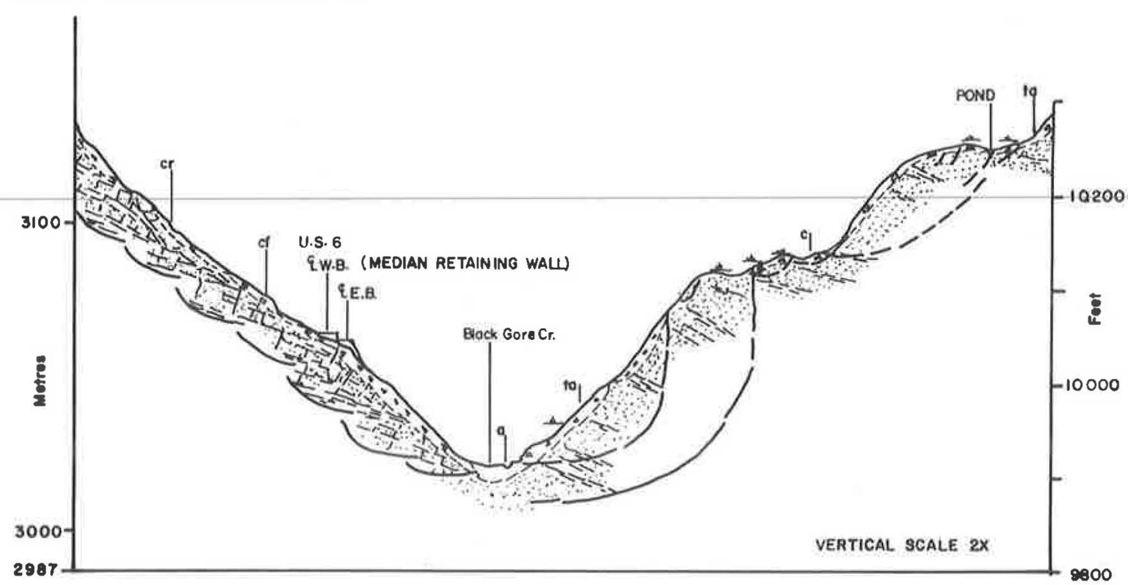
The alignment in the area of stations 700-715 traversed an area of extensive bedrock failure, a continuation of the failure that begins at station 615. Topographic restraints limited the choice of design to a through cut into failed bedrock or twin viaducts running above and parallel to the channel of Black Gore Creek. The cost for the cut section was estimated at $700 000 and that for the viaducts at $2 000 000. It was decided, for a variety of reasons, that the cut was also aesthetically and environmentally more acceptable. After geotechnical personnel estimated that any failure that might occur could be successfully controlled at less total cost and with less environmental damage than if the bridge alternative were used, the cut alternative was selected.

During construction through this area, two failed bedrock areas reactivated. They were stabilized by means of a grade adjustment, horizontal drains, and a rock buttress at a total cost of $810 000. Thus, the final cost was still approximately $500 000 less than that of the alternative that would have avoided failure.

GEOTECHNICAL RESOURCE EXPENDITURES

During the period between 1968 and 1977, geotechnical

Figure 8. Geologic section: station 640.



investigations were virtually continuous. It is estimated that 30 person years of geotechnical expertise and 10 drill-crew years were involved. Approximately 6100 m (20 000 ft) of vertical drilling and 2400 m (8000 ft) of horizontal drilling were completed. Several hundred standard split spoon samples and about 50 thin-walled tubes were obtained. Over a hundred meters of penetrometer holes were also accomplished.

The instrumentation used consisted of 32 inclinometers, 11 borehole extensometers, 12 piezometers, 40 gloetzl soil pressure cells, 63 electrical strain gauges, and 2 shear strips. Geophysical studies were conducted by the Colorado School of Mines and by the Colorado Department of Highways with single and multichannel seismographs.

The total expenditure for geologic investigation on the Vail Pass project is estimated to be $2 million. According to the study by the Robinson and Lord firms, approximately 11.2 of the 22.5 km (7 of 14 miles) traversed by I-70 was unstable to marginally stable terrain. Only one unanticipated failure larger than 153 m^3 (200 yd^3) occurred as a result of construction. This occurred during the spring of 1978 and cost about $75 000 to repair.

SLOPE DESIGN

Angles of cut-and-fill slopes across Vail Pass were based on geotechnical data and on experience in similar materials in similar climatic conditions. Many areas of Vail Pass required cuts and fills that approached critical heights.

At the highest cut, a 91-m (300-ft) high bedrock cut between stations 605 and 614, the highway department retained a specialist in rock mechanics to evaluate the slope design and to design and interpret an instrumentation system. In fact, all significant cuts and fills were reviewed by at least two geotechnical specialists in an effort to minimize stability problems during construction.

The final slope configuration, especially the molding and sculpturing effect now visible to the motorist, is the result of intensive joint efforts by landscape architects and construction and geotechnical personnel. Individual grading projects were staffed with landscape specialists who prepared conceptual plans for the final appearance of cuts and fills and other related features. These plans were reviewed by geotechnical personnel to ensure compatibility with on-site geologic conditions and with construction personnel to ensure that construction was practicable.

Slope design was thus yet another product of cooperation among practitioners of several disciplines.

CONCLUSIONS

Geologic conditions at Vail Pass were generally unfavorable for the construction and maintenance of a four-lane highway facility. Severe constraints and limitations were placed on designers by extensive areas of soil and bedrock failures, steep topography, and a cold and wet climate.

Successful completion of a project of this magnitude can result only from the combined efforts and cooperation of several disciplines under strong and enlightened leadership. These elements were present throughout the Vail Pass project. Geologic constraints were given appropriate consideration at every level and during each phase of project development. All of the geotechnicians involved appreciated the opportunity to participate in so challenging an undertaking, in a cooperative atmosphere.

The substantial amount of money expended for geotechnical aspects of the project was justified by the project's successful and timely completion. From a geotechnical point of view, this project stands as a model for future major engineering efforts in difficult geologic conditions.

ACKNOWLEDGMENT

Major contributors to the final Vail Pass geotechnical studies include J. B. Gilmore, R. P. Moston, and A. C. Ruckman of the Colorado Department of Highways; Charles S. Robinson and M. D. Cochran of Charles S. Robinson and Associates; Dwayne Nielson of International Engineering Company; Mike Bokovansky of Dames and Moore; and Horst Ueblacker of Ueblacker and Associates.

The figures presented in this paper are based on those in a Robinson-Lord joint-venture report and were modified by Jim Lance of the Colorado Department of Highways.

Abridgment

Landscape Treatments on the Vail Pass Project: Slope-Design Procedures

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During the construction of I-70 over Vail Pass, many landscape techniques were used to stabilize highway slopes and to achieve visual compatibility with the surrounding forested mountainsides. Although slope beautification was an initial objective, successful landscape treatments were soon found to be those that imitated existing landscape elements. Methods of erosion control, slope stabilization, and revegetation eventually merged into a format that has proved to be successful in preserving scenic quality.

Stable highway slopes were always the basic consideration in any treatment. At no time could landscape treatments take precedence over the engineered stability factors necessary for an Interstate highway.

Highway safety was also an important consideration. Treatments were designed to ensure the safety of the motorist. Median landscaping with large boulders and trees at the ditch line was used sparingly and only in areas where it was deemed safe for the motoring public. Shoulder landform treatments were kept within engineering requirements. Snow-removal operations also limited the extent of shoulder treatments to modified berms and minor plantings. Larger trees were only planted near the top of cut slopes and the toe of fill slopes to minimize snowplow damage and allow ample snow storage.

A landscape plan was developed for this project and was integrated into the construction plans. The intensity of the treatments varied according to the amount of landscape manipulation and the visibility of the area. The most visible areas received the greatest attention. On these sites, plantings, slope molding, and other treatments were used to the fullest extent possible. Slope molding and rock-cut sculpturing treatments were worked into construction operations before clearing began by modifying the placement of slope stakes.

To achieve the necessary blending, landscape work was generally concentrated near the base of fills and the top of cut slopes. This standard was used over most of the pass to satisfy requirements related to safety, snow removal, and visual quality.

The techniques used at Vail Pass developed from a design approach established early in the construction history of the project. It was recognized that a motorist traveling at 88 km/h (50 mph) would not be able to recognize detailed landscape patterns but mostly only landscape forms and linear qualities. Changes in colors and textures were minimal and often only seasonal.

In pedestrian areas or areas of slower traffic movement, landscape treatment concentrated on details that would properly relate the features of the landscape to the motorist. In areas of high traffic flow, landscape treatment reflected and extended existing landforms, vegetation patterns, and landscape features. Because of the lack of visual detail required in these areas, plant groupings often lacked the diversity of species typical of urban plantings. Plant groupings of one or two tree species were used without attention to understory shrubs and forbs.

The landscaping approach on the project was to completely eliminate visible transition points by modifying vegetation clearing lines and cut-slope lines and even median-ditch location. All treatments were adjusted to blend with existing or planted features and to simulate natural forms.

SLOPE MOLDING

In the past, cut-and-fill slopes were designed only to satisfy stability requirements and balance the quantities of materials. As a greater awareness of aesthetics and the final appearance of projects developed, it was realized that these maximum slopes were imposed on the landscape and limited the motorist's appreciation of the terrain. Slopes were designed with profile and cross sections, but little attempt was made to modify these typical sections in the field.

At Vail Pass, slope-molding techniques were incorporated into contract documents. Although many large cut-and-fill slopes were proposed, provisions were added to test new techniques. Standard slopes were established as a minimum slope treatment. In areas where minimum cut-slope treatments could be modified, the additional materials generated were used to mold and flatten fill slopes. Cross sections were studied to determine areas of possible slope molding. Slope stakes were then adjusted by the landscape architect and the survey crew to accomplish slope-treatment objectives inexpensively.

The types of slope treatments used are briefly described below.

Lay-Back Treatment

Where natural draws were encountered, the cut slope was laid back, or flattened, to match the grade of the draw (see Figure 1). This treatment resulted in cut slopes that had a natural appearance and added greatly to the overall success of the project.

Typically, cut slopes were designed to a minimum 2:1 slope. At natural draws, this standard slope was flattened to 4:1 or flatter to match as closely as possible the natural grade of the draw. This technique generated additional material that had to be hauled away. Alterations in the forest clearing line also had to be made.

The lay-back treatment was accomplished in several ways, depending on the phase of the project. On-site treatments were used in areas that were not designed or slope-staked for that treatment. Special project accounts were set up to accommodate this extra on-site dozer work. The contractor was directed to provide equipment hours to perform the special grading, and the landscape architect was available to direct the equipment operator to achieve the desired slope treatment at each location.

Most areas that required the lay-back treatment were identified at the slope-staking stage. Where cut slopes crossed natural draws, the positions of slope stakes were recalculated for flatter slopes. Changes made at this stage were generally more successful and less expensive. Topsoil and revegetation were done after final grading. Once the corrected slope staking was accomplished, the contractor's operation ran more smoothly.

Design-stage manipulation of ground forms was limited to matching grade contours. In the design of lay-back treatments, cut-slope lines were designed to parallel contour lines as much as possible in draw areas.

Accented Ridges

Where natural ridges were encountered, they were accented by steepening and rounding to a convex form. This is only successful over short distances. Where long ridge cuts were encountered, additional slope treatments were necessary. Although this treatment proved only moderately successful, it did smooth the natural to standard transition edge along the roadway. Again, slope stability was an important factor. Accented ridges were never constructed above stable limits. Normally, accented ridge slopes did not exceed a 2:1 ratio.

The treatment proved successful when it was used in combination with the lay-back technique described above.

The accenting of ridges was accomplished mostly by adjusting slope stakes. Slope ratios were reset at obvious ridge areas to produce a steeper slope. Ridge accents were staked so as not to run more than 30 m (100 ft).

Adjustments to steepen slope ratios are difficult to make once construction begins. Decisions to accent ridges were seldom made after a slope was opened up. A method of flattening nearby slopes and accenting the steeper ridge slope was used with some success (see Figure 2).

This treatment, like the lay-back treatment, is designed so that the staked cut-slope lines parallel existing contour lines.

Figure 1. Lay-back treatment.

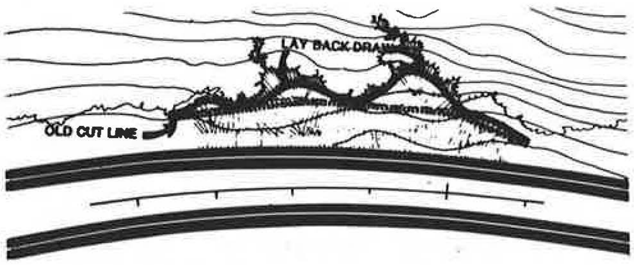


Figure 2. Accented ridges.

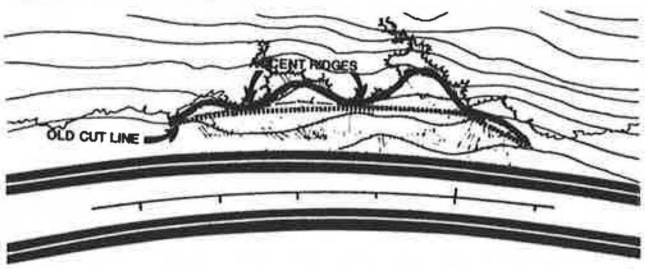
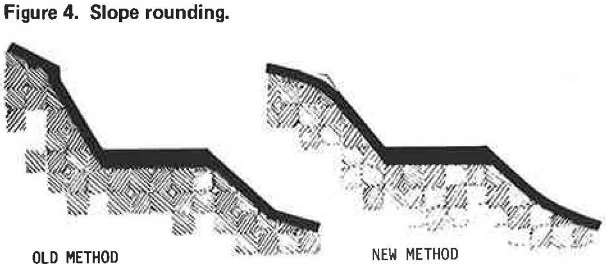


Figure 3. Created landform diversity.

Figure 4. Slope rounding.



Created Landform Diversity

On some large slopes, it was impossible to modify slope characteristics by just laying back draws and accenting ridges. On these slopes, diversity was created by modifying slope ratios and developing false draws and ridges along the slope. Large slopes were rarely left at their 2:1 ratio but were often flattened and rolled to reflect the natural character of the terrain.

This treatment was used in areas of extensive disturbance. Long-running ridge cuts were molded to create landform diversity and minimize the apparent size of the cut slope. Fill slopes and large borrow pits were also molded in this way (see Figure 3).

The methods used are similar to those used in flattening draws. Excess material generated on other project activities can be used to mold the fill slopes to match existing terrain. In larger work areas, such as borrow pits, contractor excavation operations can be coordinated to accomplish the desired effect.

It is essential to design for landform diversity. Detailed perspectives, grading plans, and typical sections are necessary. At Vail Pass, perspective sketches were found to be especially useful in that they could be posted in construction trailers and even carried by equipment operators. Once the end product was visualized by all parties concerned, the landform grading became an easier task.

Rounding

All cut slopes were rounded at the top to present a softer transition line between constructed and existing slopes (see Figure 4). This treatment was relatively easy, and results were significant. Additional right-of-way was needed and more vegetation was often disturbed, but the recovery time of the slopes was considerably shorter and visual scars healed faster.

Rounding was also effective at the toe of fill slopes. Again, the treatment was intended to blend the fill slope with existing terrain. Standard specifications that directed the contractor to round all slopes were set up.

REVEGETATION

The slope treatments used on the Vail Pass project were often designed for visual effects, but it was soon found that those completed slopes were more stable and promoted native plant growth. Although the revegetation techniques used promoted native plant species, slope treatments are felt to have assisted the revegetation process. Hence, the environmental stability of the Vail Pass roadsides is ensured by the establishment of natural plant communities on slopes of natural configuration.

CONCLUSIONS

In the execution of slope-design treatments at Vail Pass, no single feature of roadway design was compromised. Engineering, safety, geologic, environmental, and aesthetic requirements were all met, and to this is due the credit for the long-term success of the project. Slope-molding treatments provided natural form to the Vail Pass roadsides and ensured proper growing conditions for native plants.

Structure Design and Construction on the Vail Pass Project

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Cade L. Benson, International Engineering Company, Denver

Bridge construction on the 22.5-km (14-mile) long segment of I-70 through Vail Pass in Colorado presented unique problems to both designers and constructors because of the extraordinary care taken for environmental and aesthetic concerns. Span lengths and ratios, span-to-depth ratios, and structural member shapes were reviewed and established based largely on environmental and aesthetic criteria. Construction methods were established to minimize damage to the fragile terrain in the high-altitude environment. They included one of the first and most extensive uses of segmented post-tensioned concrete box-girder bridges in North America. Aesthetic, environmental, and engineering considerations also led to the design of a unique precast concrete retaining-wall system. The precast wall was alternated with a modification of a reinforced-earth-wall system of almost identical appearance.

Bridge and retaining walls used on the 22.5-km (14-mile) long segment of I-70 through Vail Pass were largely determined by the environmental constraints inherent in the design of the project. Environmental and aesthetic concerns played a significant part in the selection of the types and design of structures and the construction procedures used to erect them.

Early in the design process, the Division of Highways, Colorado Department of Highways, emphasized that the Vail Pass structures should be constructed so as to minimize damage to the natural terrain. Long cut-and-fill slopes were to be minimized as much as possible. In some cases, bridges and retaining walls were used to eliminate cut-and-fill slopes. In most cases, the total overall length of the structures was set by an effort to provide a smooth-appearing transition from roadway to bridge.

PRELIMINARY DESIGN

An April 1973 report (1) summarized the preliminary designs of the various types of bridges considered and made recommendations for the type of bridges to be used. The preliminary design studies were influenced largely by operational and environmental considerations: to provide safe driving conditions and minimize damage to the terrain. The objective of this conceptual study was to arrive at a recommended bridge type that would

1. Avoid during construction any terrain damage that would be difficult to remedy at such a high altitude,
2. Use a method of construction that would make maximum use of precast or prefabricated units,
3. Provide structures that would harmonize aesthetically with the forested mountain terrain and provide continuity of design and appearance over the entire length of the project,
4. Incorporate roadway approaches in such a manner as to avoid encroachment on streams, and
5. Provide a generous open space beneath bridges to encourage the growth of natural vegetation and accommodate the passage of hikers, skiers, and wildlife.

I-70 at Vail Pass is located at an altitude of 2590-3200 m (8500-10 500 ft) above mean sea level; winter driving conditions were thus of paramount concern. All bridges were to be two-lane, one-directional structures with a total width of 13 m (42 ft). Maximum grades on the project are 7 percent, and maximum superelevation on the bridges is 8 percent. Several structures are on a curvilinear alignment, and some combine tangent, spiral, and circular curves all in one structure. One factor that affected the type of structure used was the relatively short construction season (five months a year) at Vail Pass elevations higher than 2740 m (9000 ft).

Seven types of bridges were considered and studied in detail in the preliminary design phase:

1. Short-span precast concrete girders,
2. Tubular steel space frames,
3. Welded plate girders,
4. Precast concrete earth-filled arches,
5. Long-span open-spandrel concrete arches,
6. Long-span welded plate box girders with concrete deck, and
7. Long-span precast, post-tensioned segmental concrete box girders.

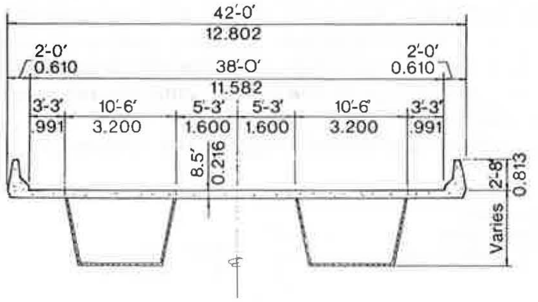
The first five were eliminated primarily on the basis of architectural considerations. Of the two remaining alternatives, the precast segmental concrete type of system seemed to satisfy all design criteria. Precast units can be manufactured at any time under carefully controlled conditions. This technique eliminates the problems associated with the short construction season, insofar as the superstructures are concerned. Cantilever construction of precast units requires a minimum of construction equipment on the ground in the immediate vicinity of the bridge. The void in the interior of the box girder also provides some insulation for the roadway surface.

Many of the advantages apparent in the segmental concrete system also apply to the steel box-girder system. The steel boxes can be erected in long segments, and the concrete deck can then be cast in place with minimum utilization of equipment on the ground underneath the bridge.

The preliminary studies led to the decision that relatively long-span prestressed concrete box-girder bridges should be designed for the project. It was also decided that the bridges should be erected by cantilever construction methods to minimize damage to the terrain in the immediate vicinity. Pier columns composed of precast elements supported on cast-in-place footings were recommended. It was also decided that all concrete exposed to view should be colored by adding iron oxide to the mix so that the structures would blend with the maroon sandstone color prevalent in the area.

The studies further indicated that the difference in cost between precast segmental bridges and structural steel box-girder bridges with a concrete deck would be very small. Consequently, steel box girders with cast-in-place concrete decks were recommended as an alternative to the primary recommendation of segmental concrete girders. This led to a decision to develop complete construction plans for and solicit bids on both structural types. Complete designs, plans, and

Figure 1. Typical section of steel box-girder bridge.



specifications were prepared for both alternatives for 17 bridges. Spans varied in number from two to five and in length from 9 to 79 m (30 to 260 ft).

STEEL BOX-GIRDER BRIDGES

Steel box-girder bridges were designed with a common cross section that included two welded steel box girders (see Figure 1). In all cases, the deck span between the top flanges of the box girders was the same. A length-to-depth ratio of approximately 25 was used. Each structure was designed with a constant depth and increased flange plate thicknesses in the areas of higher moment. Girders with variable depth were considered, but the architects preferred a constant depth and a high span-to-depth ratio to give the bridges a slim-line appearance.

American Association of State Highway and Transportation Officials (AASHTO) A-588 high-strength, self-weathering steel was used for the girders. A-36 steel was used for the diaphragms and stiffeners, which were left unpainted to minimize the time and cost of fabrication. The box girders were designed by using ultimate-strength procedures according to the 1976 AASHTO code and all applicable interim specifications. All stiffener plates were welded to the inside of the box girders to maintain a smooth exterior appearance. Diaphragms were used between the box-girder sections to provide the torsional stiffness required both during and after construction. The concrete deck was constructed of 21-MPa (3000-lbf/in^2) normal-weight concrete and was made composite with the girders by shear studs welded to the top flange plates. All of the steel box girders were fabricated in Denver and transported to the jobsite by truck. The maximum length between field splices was approximately 33.5 m (110 ft). Field splices were made with high-strength bolted connections.

Abutments for the steel box-girder bridges were constructed of cast-in-place concrete with an ultimate strength of 21 MPa. Several of the abutments were on spread footings, and others were placed on steel point-bearing piles. Piers were designed as precast concrete segmental units to be posttensioned to a cast-in-place footing in the field. The contractors were given the option of casting the piers in place and reinforcing them with milled steel bars. In all cases in which steel superstructures were utilized, the cast-in-place procedure was used. The pier cross section was diamond shaped, in accordance with the preference of the architectural team. All bearing devices were of the cylindrical pot type and made of a confined elastomeric material. These devices were equipped with a stainless-steel sliding surface resting against a teflon-coated steel plate at substructure units where longitudinal movement was accommodated.

Concrete barrier curbs of the "Jersey" type were cast in place on each edge of the deck. After all other construction items were completed, a 5-cm (2-in) asphalt wearing surface was placed on the concrete deck.

The steel box-girder bridges, with their self-weathering steel and colored concrete for deck, curbs, and substructure, resulted in a pleasing appearance that blends nicely with the soil and rock in the area.

PRECAST CONCRETE SEGMENTAL BOX-GIRDER BRIDGES

In 1972, when design of the Vail Pass bridges was started, the precast concrete segmental technique was quite new to American designers and constructors. The only such bridge built in this country up to that time was the Corpus Christi Bridge built by the Texas Highway Department. The cantilever erection technique and the precasting of bridge segments offered certain advantages that were particularly applicable to the Vail Pass project.

To understand the factors that influence the design of a segmental bridge built in cantilever, it is first necessary to consider the erection technique. Figures 2-11 show the erection procedure used for the precast segmental bridges. The abutments were designed to use cast-in-place concrete with an ultimate strength of 21 MPa (3000 lbf/in^2). Piers were designed as precast segmental units with a diamond-shaped cross section. Pier footings of cast-in-place concrete were designed with ducts to allow the stringing of post-tensioning tendons for the pier shaft. Figures 2 and 3 show the erection of a typical pier.

The shape of the superstructure cross section is shown in Figure 4. The webs and bottom slab of the segmental box were increased in thickness in the areas over the piers to provide for the high shears and moments in this region. A concrete diaphragm was cast into the superstructure segment immediately above the pier to provide for the heavy shears from the reactions. The 1.2-m (4-ft) long segment that contained the diaphragm weighed approximately 50 Mg (55 tons). The more typical segments (shown in Figure 4) were 2.2 m (7.3 ft) in length and weighed approximately 36 Mg (40 tons) each.

The cantilever erection procedure is shown in Figures 5-11. The diaphragm segment is first placed on the pier cap and fastened down with Dywidag bars. Cantilever erection then begins by adding segments alternately to each end of the cantilever and coating the faying surfaces with epoxy just before temporary post-tensioning, which is applied until the two matching segments are tensioned to approximately 206 kPa (30 lbf/in^2) across the adjoining faces. After each pair of segments has been attached to the cantilever, final post-tensioning tendons are stressed. This procedure is repeated until two cantilevers are erected, as shown in Figure 8.

A portion of the end spans next to the abutments is then placed on falsework to complete these shorter spans. The ratio of end-span length to interior-span length is about 0.6; this resulted in the final positive moments in the end span being approximately equal to the positive moments in the interior spans.

After the end span is completed and continuity prestressing is applied (as shown in Figure 10), the erection procedure is then repeated on the other piers in the bridge. Finally, the other end-span section is erected and the bridge is made continuous by the final post-tensioning operation (shown in Figure 11). Before final prestressing, however, the 20- to 25-cm (8- to 10-in) gap between abutting cantilever ends must be closed. This is accomplished by forming across the gap and pouring concrete in place.

The precast concrete used had an ultimate strength at 28 days of 38 MPa (5500 lbf/in^2). Prestressing steel was 18-MPa (2700-lbf/in^2), 1.3-cm (0.5-in) diameter strands, 12 strands making up one tendon. Epoxy was applied to all match-cast joints to make the structure watertight and to transfer the shear forces from one segment to the next.

The first precast segmental bridges were cast with the concrete rails, monolithically. Because of vertical alignment problems, however, the rails were omitted on subsequent precast sections and later cast in place after all post-tensioning was done in the completed structure. Two pot-bearing devices were used at each substructure support.

On the precast segmental bridges, the contractor

Figure 2. Placing of second pier segment.

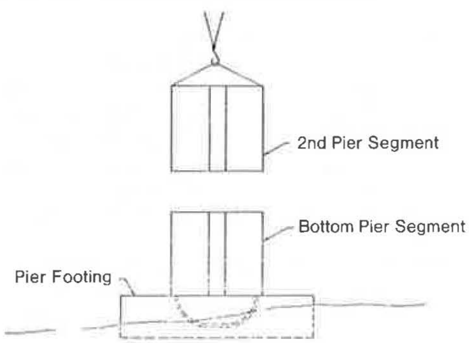


Figure 3. Completed pier with cast-in-place cap.

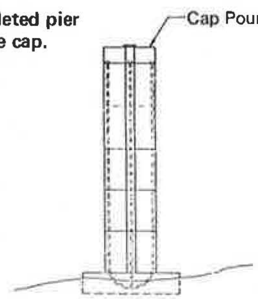


Figure 4. Section near midspan.

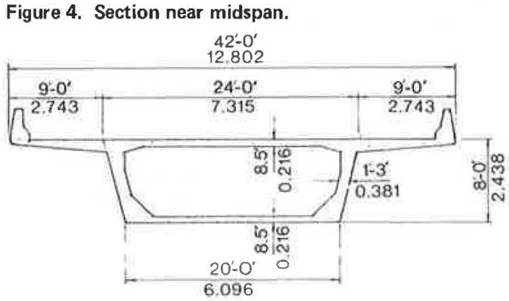


Figure 5. Lifting first (left) cantilever segment.

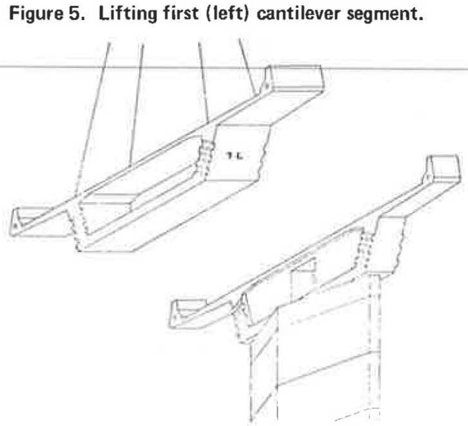


Figure 6. First left segment in place with temporary post-tensioning.

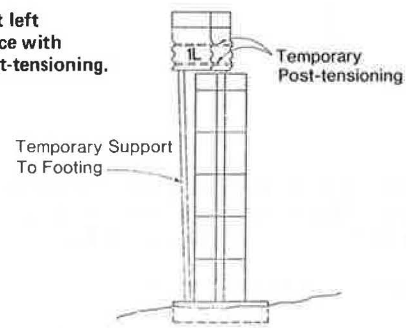


Figure 7. First right segment in place with temporary and permanent post-tensioning.

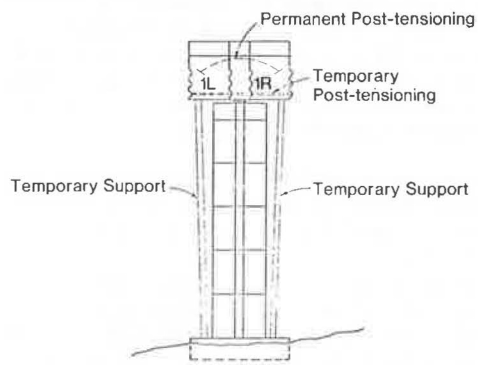


Figure 8. Completed cantilever.

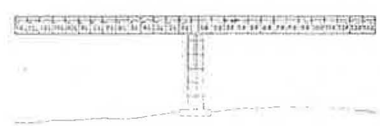


Figure 9. Segments near abutment 1 end on falsework before closure pour.

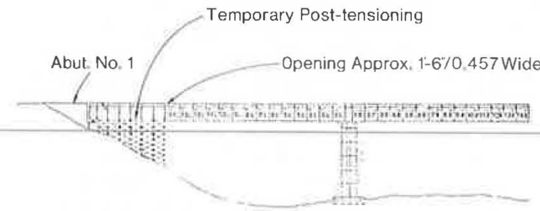


Figure 10. End span 1 complete with continuity prestressing (temporary post-tensioning removed).

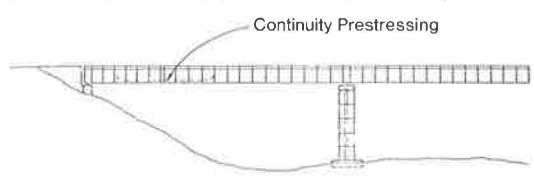
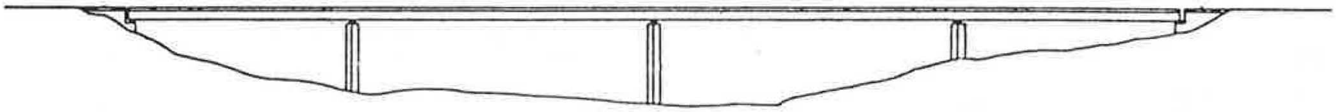


Figure 11. Completed bridge with all permanent post-tensioning in place.



used a 270-Mg (300-ton) track-mounted crane to lift the segments into position. The final construction specifications allowed a square area measuring 21 m (70 ft) on a side at the base of each pier on which the contractor could set his crane. From this location, the crane could reach to the end of each 32-m (104-ft) cantilever to set the last superstructure segment. This procedure required that the square area as well as a narrow access road be cleared under the bridges for the construction equipment. The original design concept called for overhead erection with either a high line or a gantry so that there would be no disturbance under the bridges. However, after each bridge site was reviewed and the cost associated with such an overhead erection scheme was considered, it was determined that the selected procedure was an acceptable compromise. With the exception noted above, the existing trees and larger foliage were left intact in the area of the bridge. Haul roads and platform areas for cranes were replanted after the completion of the construction to conform as closely as possible to their original condition.

For all segmental bridges, the contractors were given the option of either precasting the segments or casting them in place. In one project that contained four bridges, the contractor elected to cast the segments in place. Steel form travelers were mounted on the piers to hold the formwork required for casting the segments. After each segment was cast and post-tensioned, the form traveler was moved ahead and set up for the casting of the next segment. This procedure was repeated until the cantilevers reached midspan, which is much the same technique as that used for the precast segmental structures. The cast-in-place procedure has the advantage that all erection is done from overhead so that no equipment other than a light crane is needed on the ground in the vicinity of the bridge.

The same 38-MPa (5500-lbf/in^2) concrete was used in the cast-in-place and the precast bridges. The post-tensioning system was made up of strength Dywidag bars rather than the strand used in the other bridges. All substructure units were also cast in place. Steel pot bearings were again used at the top of substructure units to support the box girders. A final touch on all concrete bridges was the application of a waterproof membrane under a 5-cm (2-in) asphalt overlay on the driving surface.

SPECIAL BRIDGES

At two locations, specific requirements dictated that bridges be designed without the preparation of alternative plans. One of these locations was a crossing over a canyon that had steep walls. In this case, a structure with a main span of approximately 55 m (180 ft) and flanking spans of about 9 m (30 ft) was selected. This resulted in an uplift at the abutment ends. Steel box girders were selected for this crossing since any support settlement might induce bending moments of a magnitude critical for the precast concrete structure. Because of their flexibility, the steel structures would not be overstressed by the redistribution of moments that could occur if there were minor support settlement. The cross section of the bridge superstructure for these steel bridges is the same as that of other steel bridges in the Vail Pass project. Tiedowns at the end were constructed with prestressed rock anchors that were fastened to the abutment to hold it down.

The other location that required a special type of bridge was in an area where an underpass was required to accommodate the natural migration patterns of wildlife. The structures here, which are approximately 24 m (80 ft) in length, were made from cast-in-place concrete box girders that conformed to the shape of the precast segmental box girders used at other locations. The relatively short spans and the fact that these bridges were simply supported single spans made the precast segmental concept uneconomical.

RESULTS OF ALTERNATIVE BIDS

Of the 21 bridges designed and detailed for the project, 17 were completely designed and detailed in two alternative materials: steel and concrete. Contractors were then given both sets of plans and asked to bid on their choice. Table 1 gives data for the five construction contracts that involved the 17 bridges for which alternative designs were presented (approximately one year elapsed between the letting of the first and last contracts). Although there was considerable difference in the bid prices for steel versus concrete on individual projects, the total difference for all five projects, out of a grand total of over $17 000 000, was less than $80 000—a difference of less than 0.5 percent.

It is difficult to determine the overall savings in construction costs that accrued from the alternative bidding. The additional cost to produce a second set of drawings for a bridge designed for an alternative material was approximately 2.5 percent of the construction cost. In the opinion of the designers, the competitive bidding on the two alternative designs resulted in a savings of 7-10 percent of the construction cost.

RETAINING WALLS

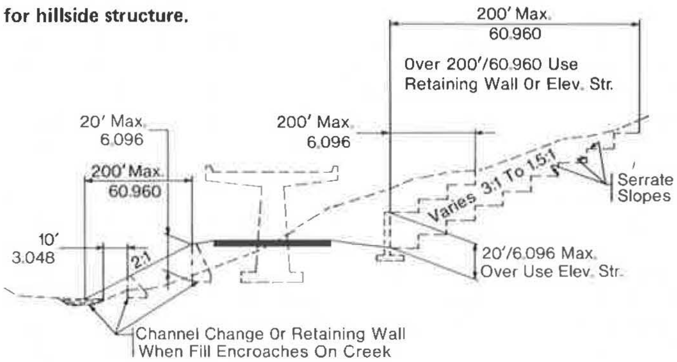
One of the main objectives of the design effort was to avoid as far as possible damaging the natural terrain. Conventional cut-and-fill construction in steep, mountainous terrain always results in extensive excavation of back slopes that are practically impossible to revegetate. On the embankment side, the fill slope may chase the mountainside all the way to the bottom before "catching", covering acres of mountainside vegetation. Such was the case at Vail Pass. On major embankments, a fill slope of 1.5:1 is common, but at Vail Pass the natural slope was frequently this steep or steeper. Consequently, such embankments would have covered the entire mountainside from the roadway shoulder to the creek at the bottom. One of the recommendations made in the early design concept study (2) was that fill slopes be limited to a maximum of 3:1 to facilitate revegetation; later, 2:1 was accepted as the maximum. If fill slopes would not catch within a reasonable distance, they were eliminated by constructing a hillside structure that could be either a bridge or a retaining wall (see Figure 12). In a number of instances, an economic analysis indicated that a retaining wall would be preferable.

Table 1. Results of alternative bids on Vail Pass bridges.

Project[a]	Bridge	Number of Spans	Length (m)	Low Steel Bid ($)	Cost per Square Meter of Steel ($)	Low Concrete Bid ($)	Cost per Square Meter of Concrete ($)
1	F-11-AX	4	222				
	F-11-AW	5	268				
	F-11-AV	4	210				
	F-11-AU	4	204				
Total			904	5 992 155	517.98	5 527 318	447.83
2	F-12-AK	3	67				
	F-12-AM	2	73				
	F-12-AN	3	107				
	F-12-AO	3	112				
	F-12-AP	3	183				
Total			542	3 777 549	544.56	4 111 170	592.57
3	F-11-AP	3	94				
	F-11-AO	2	68				
Total			162	994 347	479.00	1 053 364	507.43
4	F-11-AN	4	225				
	F-11-AM	4	227				
	F-11-AL	4	157				
	F-11-AK	3	137				
Total			746	4 257 771	445.75	4 108 057	430.14
5	F-12-AT	4	221				
	F-12-AS	4	221				
Total			442	2 298 409	405.70	2 598 938	458.78
Total			2796	17 320 231	483.85	17 398 847	486.00

Note: 1 mm = 3.3 ft.
[a]Projects are listed in the order they are advertised for bids.

Figure 12. Criteria for hillside structure.



The criteria for retaining walls established in the design concept studies can be summarized as follows (2):

> The design goal for all retaining walls should be a structure that is visually compatible with the existing terrain. Wall faces should be textured or patterned to avoid the smooth, flat surfaces foreign to the natural terrain. Again, the color of materials used should blend with the natural environment. All retaining wall schemes should consider the effective use of vegetation to partially conceal wall surfaces and break up the larger expanses.
>
> Wall heights should be scaled to the terrain from the roadway. The 6 m (20 ft) established as the maximum height to determine backslope distances should not imply that a 6-m (20-ft) high wall will be located immediately adjacent to the roadway. In such a case three walls, 1.8 to 2.1-m (6 to 7-ft) high and terraced to provide ledges for native shrubs and small trees, would be preferred over the single wall.

In short, the wall should be aesthetically compatible with its surroundings.

Conventional reinforced concrete cantilever and counterfort walls were ruled out for heights greater than 6 m (20 ft) on the basis of incompatible appearance and unduly high construction costs. The patented Reinforced Earth Company system with concrete facing panels was considered, since this system could be erected in a setback pattern so as to form terraces at intervals to support vegetation. The architectural consultants believed, however, that some other system should be devised to give a more interesting appearance to the exposed surfaces.

An early drawing from the design concept report (see Figure 13) shows an idea for a precast unit conceived during the design concept studies. In later phases, however, stability calculations indicated that the required dimensions of the unit would make the system uneconomical. Another system was then devised that consisted of two simple precast concrete elements that could be easily erected in a manner not completely unlike that used to construct the old miner's crib. An L-shaped precast concrete member called a tieback is used; this has a long horizontal leg that extends into the fill and a vertical leg that extends upward to provide a reaction for the earth-retaining panel that spans the 3-m (10-ft) space between tiebacks. For aesthetic and structural reasons, the earth-retaining facing panels were designed as parabolic curved units. The architectural consultants believed that the idea had aesthetic merit; from an engineering standpoint, it would have the added virtue of being very simple to cast and erect. But it soon became apparent that the soil mechanics involved were somewhat complex and that a

Figure 13. Typical precast concrete retaining-wall unit.

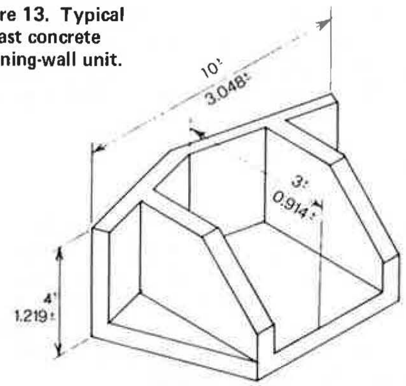


Figure 14. Sedalia test wall under construction.

considerable amount of development work would be necessary.

The analysis departed somewhat from the conventional, so it was decided to confirm the calculations by a full-scale test to confirm design assumptions and the analysis. A four-tier wall 10 m (32 ft) high that consisted of 31 tiebacks and 81 facing panels was designed. This wall was erected at a test site near Sedalia, Colorado (see Figure 14). Pressure cells were installed throughout the backfill to measure pressures acting at various points. Deflection measurements were made on each of the tiebacks to determine settlement and horizontal displacement. The test data verified most of the assumptions and generally validated the analysis. On some points, however, the data were inconclusive, and a need for additional investigation was indicated. The results of these tests are given elsewhere (3).

Engineers from the state and federal approving agencies reviewed the report. There was a lack of consensus as to whether the method of analysis was acceptable. Since construction schedules did not permit the time to resolve these differences, it was decided to use a different analysis in designing the structures to be constructed at Vail Pass, and this resulted in longer (and more costly) tiebacks for the lower tiers.

In an effort to resolve the differences of opinion that had arisen over the design analysis, it was decided that a major section of a wall should be instrumented during construction and the data collected to further evaluate the analysis procedure. A six-tier, 15-m (50-ft) high retaining wall was designed and constructed in the vicinity of station 498 (see Figure 6 in the paper by Milhollin elsewhere in this Record). This wall was instrumented to collect values that would be used in determining the safety factor against sliding and pressures acting on the face of the wall (the principal values in contention). The results of these tests, which are reported elsewhere (4), indicated that the pressures acting on the face of the wall were very low in comparison with those calculated by the Rankine formula. This was also characteristic of the information collected on the Sedalia test wall. The low pressures on the face appeared to result from a combination of the reinforcing effects of the tiebacks in the tier above, the setbacks, and soil arching within the embankment. Measured pressures followed the Rankine pressure distribution for only the first tier. In the upper tier of the wall, at a 15-m (50-ft) embankment height, the average face pressures were only about 30 percent of the Rankine calculated pressure.

In summary, it was the designer's contention that tiebacks of equal length in all tiers would result in a wall that could appropriately be analyzed as a battered wall. The opposing viewpoint was that a vertical wall analysis should be used and that tiebacks of varying lengths should be embedded in the fill so that their ends lay in a vertical plane. It is the designer's opinion that the results of both tests substantiate the design analysis based on the battered-wall concept and that this approach should be used on future designs to take advantage of the savings inherent in the shorter tiebacks. To further document design procedures, an eminent geotechnical engineer was retained to make an independent review. It was also his conclusion that the battered-wall concept was valid.

The Reinforced Earth Company suggested that competition might be sharpened if the plans included the reinforced-earth system as an alternative. They offered to redesign the facing panels to be practically identical in appearance to the precast units. On the plans for the projects subsequent to the one on which the above-mentioned wall at station 498 was constructed, the reinforced-earth system was included as an alternative. As a result, the entire Vail Pass project as completed includes a 6172-m^2 (66 432-ft^2) exposed face area of the precast concrete tieback type of wall, and 14 406 m^2 (155 066 ft^2) of the reinforced-earth type of wall with curved face panels. In addition, conventional flat-faced reinforced-earth walls were constructed in those areas where a high vertical wall was required. An attempt was made to evaluate the comparative costs of the two wall systems, but the results were inconclusive. It is our opinion that, if the precast concrete tieback wall is designed on the battered-wall concept and as contractors gain experience in its erection, it will prove to be quite economical.

To protect the Colorado Department of Highways from possible future litigation, the precast wall was patented (U.S. Patent 4,050,254). The department was granted royalty-free license to use the system. It can extend this license to other government agencies for use of the wall on highway projects constructed with federal-aid funds.

SUMMARY AND CONCLUSIONS

Bridge construction on the Vail Pass portion of I-70 presented some unique problems to both designers and constructors because of the extraordinary care taken for environmental and aesthetic concerns. Span lengths, span ratios, span-to-depth ratios, and structural member shapes were reviewed and established largely on the basis of environmental and aesthetic criteria. Construction methods were established to minimize damage to the fragile terrain in the high altitude of the

Vail Pass area. Careful selection and treatment of materials—e.g., the use of self-weathering steel box girders and the use of color in the concrete—were undertaken to blend the bridges into the natural color scheme of their surroundings.

Without these concerns for environmental protection, it is likely that the cantilever construction of segmental concrete box girders would not have been attempted. The experience gained in this popular European construction technique on the Vail Pass project, and on other projects more recently initiated in this country, will help to promote its more widespread use in future U.S. bridge projects. The alternative bidding technique used on the Vail Pass bridges indicates that, in the matter of cost, the segmental concrete structures can compete quite favorably with the more conventional types of structures.

Where retaining walls were applicable, environmental and aesthetic concerns also resulted in extraordinary measures to minimize damage to the natural terrain. A unique precast concrete retaining-wall unit was developed that was aesthetically acceptable and easy to cast and erect. As an alternative, panels of the patented reinforced-earth type of wall were redesigned to be practically identical to the precast units. An attempt was made to evaluate the comparative costs of the two wall systems, but the results were inconclusive. The cost of the precast concrete tieback walls can be significantly reduced if they are designed on the battered-wall concept.

The various structures at Vail Pass as they appear today provide evidence that major highway structures can indeed be constructed without serious damage to the environment. The Vail Pass bridges and retaining walls will stand for many years as testimony to the sincere efforts of various government agencies and designers involved in the project to preserve the aesthetic appeal of the area.

ACKNOWLEDGMENT

We would like to acknowledge the following firms and individuals who were involved in the various aspects of the Vail Pass project discussed in this paper: Frank Lloyd Wright Foundation, H. J. Meehen Engineering Company, James R. Libby and Associates, F. Dwayne Nielson of International Engineering Company, and Ralph B. Peck, geotechnical consultant.

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**A.B. Milhollin was with the Denver office of International Engineering Company when this research was performed.*

Cast-in-Place Segmental Bridges in the Vail Pass Project

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The design and construction of four cast-in-place segmental bridges that carry the Vail Pass section of I-70 over Miller and Black Gore Creeks are discussed. The free-cantilever method of construction is detailed. Measures dictated by special environmental and time restrictions on construction are also examined.

This paper describes the design and construction of four bridges that carry the Vail Pass segment of I-70, located about 11 km (7 miles) southeast of Vail. Two of these structures span Miller Creek and the other two Black Gore Creek.

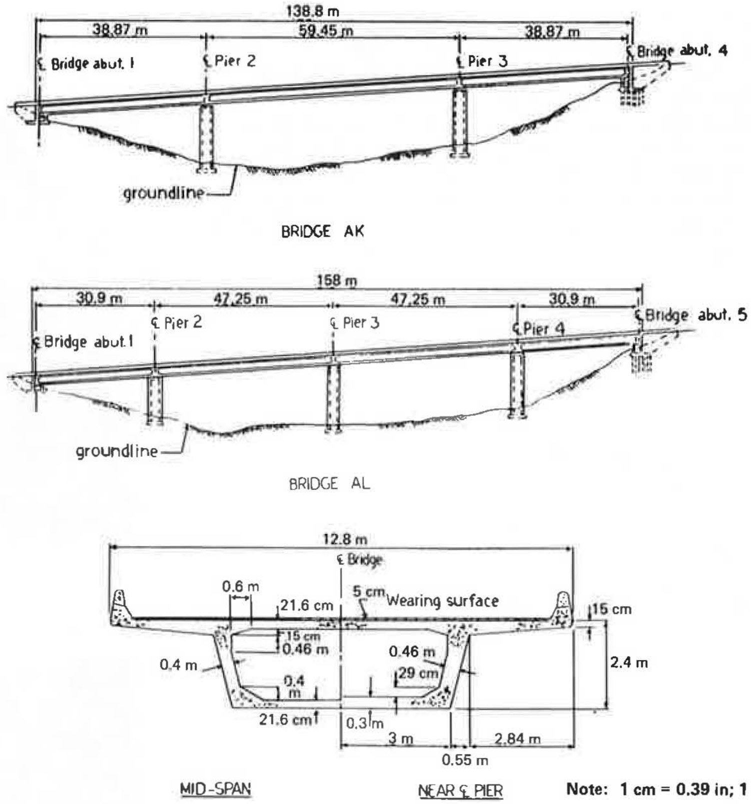
The configurations and cross sections of the bridges are shown in Figures 1 and 2. The spans are relatively short, but the strict environmental constraints specified in the contract documents limited possible construction techniques.

The owner prepared two completely different designs for bidding purposes—one with a steel superstructure and the other with a prestressed concrete superstructure. Although the concrete design was based on precast segmental construction, the cast-in-place method was allowed if the contractor preferred. To blend the structures with their surroundings, a light pink concrete color was specified to match the large natural rock outcroppings in the area.

Final construction was based on the cast-in-place segmental method, and the construction sequence was slightly different from that suggested in the original design. The piers, which varied in height from 6 to 21 m (20 to 70 ft), were cast-in-place hollow sections prestressed vertically. The substructure was constructed according to the original contract plans.

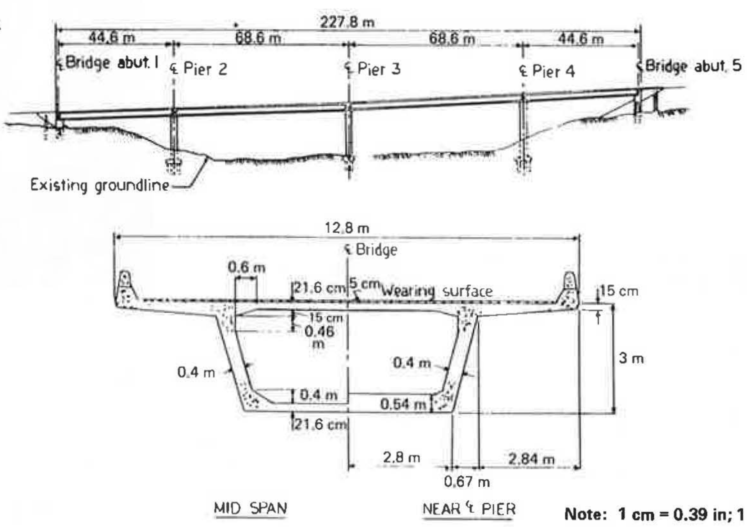
Construction of the superstructure of the Miller Creek bridges started in May 1977 and was completed in the first week of September. In August, construction of segments on falsework was started on the Black Gore Creek bridges; the cantilever segments of these bridges were started after the form travelers had been removed from the Miller Creek bridges. Construction of the Black Gore Creek bridges was completed in the second week of November 1977.

Figure 1. Elevations and typical section of Miller Creek bridges.



Note: 1 cm = 0.39 in; 1 m = 3.3 ft.

Figure 2. Typical elevation and typical section of Black Gore Creek bridges.



Note: 1 cm = 0.39 in; 1 m = 3.3 ft.

CONSTRUCTION METHOD

Because of the relatively cold climate in the Vail Pass area, the available time for construction was very limited. To meet the requirement that all four bridges be finished within one year, a very tight schedule had to be maintained. Because of the requirement that the environment should not be disturbed during construction, falsework construction was not permitted for most parts of the bridges.

Figures 3 and 4 show the construction schemes developed to overcome these restrictions. Figures 5-10 show various aspects of the structures themselves during construction operations.

Three types of construction schemes were devised: one for the two Miller Creek bridges and one each for the Black Gore Creek bridges. Both bridges across Miller Creek (structures AK and AL) were built by the cantilever method on temporary supports, as shown in Figure 5. For each bridge, two form travelers were assembled on top of 9-m (30-ft) segments of the superstructure at both abutments. The side spans were supported at every second segment by a temporary bent. For bridge AL, temporary bents were also used in the interior spans.

Construction started from the abutments and proceeded toward the center of the bridge, where one of the form travelers was dismantled and the closure pour, at midspan for bridge AK and at the center pier for bridge AL, was made by the remaining form traveler. This method was selected because the spans in these two bridges were too short for the classical free-cantilever method (balanced cantilever), which would have required assembling two form travelers at each pier and dismantling and transferring them to other piers after only a few segments had been cast. The method used here required that the form travelers be assembled and dismantled only once for each bridge. Another important advantage of this method was that construction material and personnel could be transported over the finished part of the bridge to the segment under construction.

Figure 3. Construction schemes for Miller Creek bridges: (a) bridge AK and (b) bridge AL.

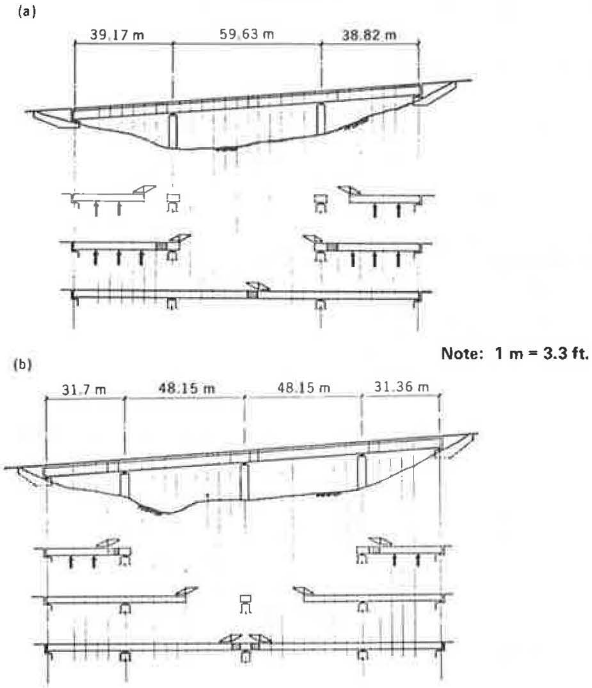


Figure 4. Construction schemes for Black Gore Creek bridges: (a) bridge AM and (b) bridge AN.

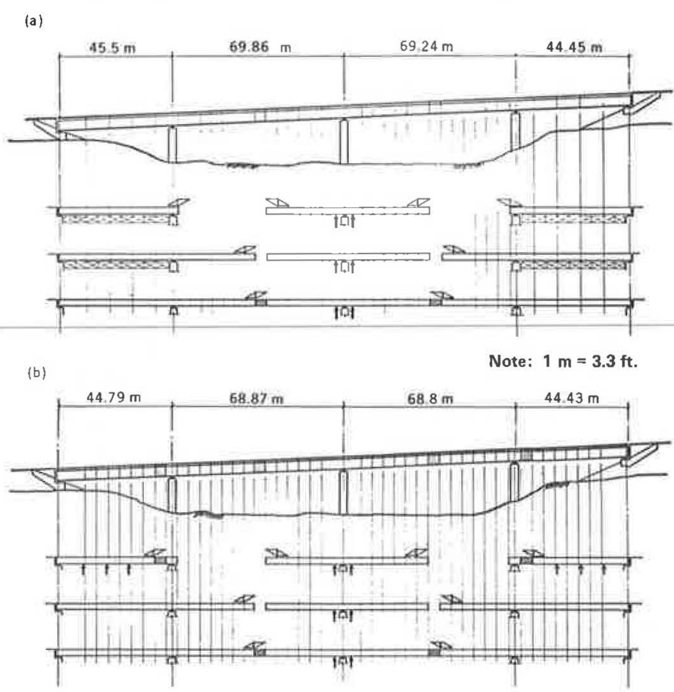


Figure 5. Side-span cantilever construction: bridge AL.

Figure 6. Free cantilevering from center pier: bridge AM.

Figure 7. Bottom view of free-cantilevered span: bridge AM.

Figure 8. Closure pour after removal of form travelers from other side of bridge: bridge AM.

Figure 9. Form traveler.

Figure 10. View of pier segment showing typical tendon arrangement: bridge AK.

The temporary bents consisted of two 30-cm (12-in) steel columns, wide flange and braced as required, to transfer vertical and horizontal loads. It is essential that the footing for these bents be carefully designed to minimize problems caused by excessive or differential settlement.

The bridges over Black Gore Creek (structures AM and AN) have slightly longer spans. Two different construction schemes were used for these bridges, mainly because of scheduling requirements (Figure 4). Since only six form travelers were available for the whole project, it was not possible to construct all four bridges simultaneously. To gain construction time, both end spans of bridge AM and one end span of bridge AN were built on falsework. Fortunately, this was possible because the clearance under the end spans was low and the falsework would not adversely disturb the environment. After these end spans were finished, the form travelers from the Miller Creek bridges were transferred to the segment over the side piers so that the rest of the construction could be carried out by the free-cantilever method.

The segment over the center pier on bridge AM was stabilized during construction by using steel columns supported on the pier footing, which rested on large concrete caissons (see Figures 6 and 7). During cantilevering, it was apparent that, as a result of overestimation of the allowable bearing capacity, the footing could not resist the specified construction forces without excessive rotations. This resulted in the pier being 15 cm (6 in) out of plumb and the ends of the cantilever deviating from the theoretical elevations by about 0.3 m (1 ft). Before closure, however, the cantilevers were rotated to the correct elevation. Later, remedial measures were taken to reinforce the pier footing. Figure 8 shows the closure pour on bridge AM after removal of the form travelers from the other side of the structure.

Free-cantilever construction was developed in the early 1950s by Finsterwalder of Dyckerhoff and Widmann and has been used since in the construction of many bridges. Until very recent times, this had been the only method of construction for long-span concrete bridges when falsework was not permitted or was uneconomical.

Figure 9 shows a typical form traveler. It is mostly hydraulically operated and can be adapted to various geometric layouts. Horizontal curvature, steep profiles, and cross slopes (such as those of the Vail Pass bridges) can be easily accommodated. The segments are usually between 3.6 and 5 m (12 and 16.5 ft) long. In the Vail Pass bridges all the cantilever segments are 4.5 m (15 ft) long. The use of a constant segment length simplifies construction, form setting, rebar cutting, and installation.

Normal cantilever construction is done in four-day cycles, which means constructing one segment at one form traveler every four days. The most critical item is the curing time of the concrete. Vail Pass specifications required a 24-MPa (3500-lbf/in^2) concrete strength at the time of post-tensioning and 38 MPa (5500 lbf/in^2) at 28 days.

In order to finish all four bridges within the specified period, a three-day construction cycle had to be achieved. Because the time required for placing rebars and tendons is quite constant, the construction cycle could be shortened by decreasing the curing time. For this purpose, a special water reducer was used to obtain a concrete strength of 24 MPa within 18 h. Toward the end of construction, the time required for each segment was reduced even further—to 2.5 days. Some honeycombing in the concrete did occur in the early stages of construction, probably because of the lack of experience in the use of the water reducer.

The superstructure was prestressed in the longitudinal direction only. Although transverse prestressing would have been suitable for the box-girder dimensions used in the Vail Pass bridges, the top slab was reinforced concrete as given in contract plans.

All post-tensioning consisted of 3-cm (1.25-in) diameter, 10.3-MPa (1500-lbf/in^2) threadbars. These bars were mostly two segments long [2 × 4.5 = 9 m (2 × 15 = 30 ft)]. They were extended by means of couplers to the required length and were terminated as required by the bending moments. Typically, four to six tendons were stressed and terminated at each segment so that sufficient post-tensioning was provided for the construction-stage loading. No temporary post-tensioning was required.

A typical tendon layout is shown in Figure 10. The amount of post-tensioning provided closely matches the force requirement so that the quantity of tendons is optimum.

STRUCTURAL DESIGN

In the tender document, only the precast segmental scheme was given. After the bid, a revised design was carried out for the cast-in-place cantilever construction and the modified construction sequence. This redesign took into consideration all the construction stages and the redistribution of stresses caused by creep, shrinkage of concrete, and relaxation of steel. However, instead of using analytical methods to account for the redistribution of moment caused by creep, the owner specified that a 1724-kPa (250-lbf/in^2) residual compression stress should exist at the end of construction in the bottom slab in areas of positive moment. The specification also stipulated that no tensile stresses were allowed under both construction and service loads.

To ensure tight elevation control at the jobsite, camber values and curves were provided for each loading stage. In general, two camber curves are required for the construction of each cantilever segment, one for the stage before the placing of concrete and one after the placing of concrete and post-tensioning. Deviations between the site-observed values and the calculated values are corrected during the construction of subsequent segments. The form travelers are equipped with hydraulic jacks for very fine adjustments in both elevations and horizontal alignment.

ACKNOWLEDGMENT

The I-70 project of which the Vail Pass bridges are a part was a federal-aid project managed by the Colorado Department of Transportation. The consulting engineer was the International Engineering Company in Denver. The general contractor was Peter Kiewit and Sons. The redesign and construction engineering were carried out by Dyckerhoff and Widmann. A computer program especially developed for segmental construction was used for the stress and camber analysis.

The completion of all four bridges in so short a construction period was made possible by the contributions and close cooperation of all the parties involved.

Water-Quality Considerations for Highway Planning and Construction of the Vail Pass Project

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Soil erosion and sediment control have long been concerns associated with road-construction activities. Several manuals that have been written on the subject provide excellent guidelines for estimating costs and implementing control measures. The construction of the four-lane segment of I-70 at Vail Pass has provided the opportunity to implement many of these control measures in a sensitive mountain environment. This report evaluates the performance of the structures used at Vail Pass for erosion and sediment control. The results are considered to be representative of what might be expected in other steeply dissected, mountainous terrain. The measures used are applicable to other land-disturbing activities, including timber sales, mining operations, ski areas, and all construction sites.

Construction of the four-lane segment of I-70 over Vail Pass began in 1973 and was scheduled for completion in 1979. Vail Pass is located in the central Rocky Mountains southeast of Vail, Colorado. Elevations range from 2526 m (8400 ft) near Vail to 3203 m (10 500 ft) at the summit. Precipitation totals 89-114 cm (35-45 in) annually, and 80 percent of it is in the form of snow. Climate conditions are typical of high-elevation areas that have a wide seasonal and daily temperature variation. Average monthly temperatures vary from -10°C (14°F) in January to 12.7°C (55°F) in July. The growing season is short, less than 60 days near the summit.

I-70 parallels West Tenmile Creek on the east side of the pass and Gore Creek on the west. Both creeks are municipal water supplies and are important for recreation, fisheries, and aesthetic and agricultural uses. Soil erosion and protection of water quality were key considerations in the design and construction of the highway.

Because the alignment of the 28.3-km (17.6-mile) stretch of road was limited by the steep mountainous topography, it was necessary to construct through highly erodible soils and isolated areas of active landslides. Soon after construction began and despite conventional control efforts, several soil-erosion and water-quality problems were encountered. As a result, many new and innovative erosion-control measures were implemented on the project. This report examines those methods and discusses their effectiveness in a sensitive mountain environment.

EVOLUTION OF THE PROJECT

Because of the sensitive subalpine environment at Vail Pass, water-quality stipulations were necessary to protect soil and water resources during highway construction. Stipulations were formulated and agreed on by the Colorado Division of Highways and the U.S. Forest Service. These stipulations, which applied to fish habitat, stream crossings, disposal of waste materials, and limitations on construction machinery in or near stream courses, became requirements and conditions to be met by the state of Colorado in order to obtain an easement deed from the federal government along the highway right-of-way.

To meet the constraints set forth in the stipulations, the U.S. Forest Service developed guidelines that would maintain water quality during and after highway construction. These guidelines were published as part of the Landscape and Erosion Control Manual prepared by International Engineering Company for the Colorado Department of Highways (1). The manual, which served as a guide for the design and construction of the highway projects at Vail Pass, discussed various techniques for landscape design, erosion control, revegetation, and control of water runoff.

Water-Quality Monitoring Program

To determine the effectiveness of the guidelines, a water-sampling program was established. Its goals were to gather baseline chemical and sediment data prior to construction at the three principal drainages—West Tenmile, Gore, and Black Gore Creeks—and to continue collection of these data throughout the entire construction project. This was done to determine the overall impact of the construction of the highway on water quality and the effectiveness of the water-quality constraints. This information is still being collected. After completion of the highway, an evaluation report will be prepared.

Water-Quality Plan

Even with the monitoring program and the erosion-control guidelines set forth in the Landscape and Erosion Control Manual, many water-quality problems arose during the initial construction season. Surface flows from the spring snowmelt and summer thunderstorms created many erosion problems on the newly exposed soil surface. As these problems became apparent, solutions were developed and corrective action was taken. But the solution often came too late to prevent much of the erosion and the subsequent degradation of water quality. The contractor was simply not aware of or prepared to handle the numerous soil-erosion problems encountered in such an extreme environment. It became obvious that, before much more construction was done, additional project control would be needed.

To alleviate these problems the U.S. Forest Service developed a water-quality plan, outlining additional guidelines necessary to protect soil and water resources. In March 1974, a draft of this plan was presented to the Colorado Division of Highways. After months of negotiations, the guidelines were adopted by the division, to be implemented the following construction season. They took the form of special provisions to the standard specifications for road construction in Colorado and became part of the requirements and conditions on which contractors bid for the construction projects.

The new plan continued the ongoing monitoring program and use of the erosion-control guidelines but added the requirement that each project would be monitored individually and, if at any time a water-quality problem occurred, the project engineer and the Forest Service liaison officer would be notified immediately to ensure that corrective action was taken. In addition, the water-quality plan required the contractor to do the following:

1. Prepare a contingency plan for erosion control and water quality and submit the plan for approval before beginning construction. The plan must address potential water-quality problems and outline methods for correcting them. The contents of the contingency plan vary depending on the location of the site. Projects located in steep terrain, adjacent to streams, require a more comprehensive plan than projects on flat terrain, away from stream courses. A contingency plan might include (a) methods of handling groundwater seepage into the construction site, snowmelt and rainfall runoff, and small creeks flowing through the project limits; (b) the control of haul-road or access-road drainage and locations of temporary culvert installations; and (c) locations of proposed features for water-pollution control, such as sediment ponds, collection ditches, pumping stations, and temporary diversion ditches.
2. Appoint an erosion-control and water-quality supervisor who is responsible for implementing control measures. Problems with soil erosion often go unattended simply because no one knows whose job it is to correct them. Erosion-control problems receive more attention when one individual is held accountable.
3. List the materials, machinery, and personnel available for erosion control. Because so many erosion problems occur spontaneously, the materials needed to control them must be on hand at the construction site. Erosion-control materials might include hay bales, culverts, irrigation pipe, sandbags, gravel, plastic, and flexible downdrains.
4. Agree to give erosion-control work priority over all other aspects of the construction projects. When a problem is encountered, the required personnel and materials will be released to correct it.

The Colorado Division of Highways also appointed a full-time specialist in erosion control and water quality to oversee the water-quality plan on all Vail Pass construction projects. His responsibilities were to review and approve the water-quality contingency plans submitted by the contractor, to monitor the water quality above and below each construction project, and when necessary to develop and implement measures to mitigate water-quality problems.

EROSION-CONTROL PLANNING

Many erosion and sedimentation problems can be avoided during road construction if they are anticipated and prepared for in advance. Planning ahead for these problems begins with the initial road design and continues through the actual construction period. During the Vail highway project, various erosion-control methods were implemented and evaluated so that their relative merit in controlling erosion and sediment problems in a sensitive mountain environment could be determined. The following sections discuss the permanent and temporary methods in detail and report the findings.

Permanent Erosion Control

The design of a road is very important, for it contains the permanent features of erosion and sediment control. The topography, geology, soils, and drainage patterns of the terrain must be evaluated in order to select a road alignment that is most favorable to road construction. At Vail Pass this was particularly challenging because the steep mountainous terrain and the risk of landslides limited location options.

Because the majority of the Interstate had to be located on highly erodible soils, special design considerations were included in the construction plans to overcome erosion and sediment problems. Some of these considerations included retaining walls, protected drainageways, subsurface drains, contour cut-and-fill slopes to dissipate runoff, energy dissipators below concentrated runoff points, and extensive buttressing below unstable land masses.

Revegetation

It is generally accepted that the best way to ensure permanent erosion control on disturbed sites is through a successful revegetation program. The materials and techniques used to accomplish this are well documented (2-9). The methods selected depend on the location of the project and the specific objectives established for revegetation.

At Vail Pass, an ambitious revegetation effort was undertaken to fulfill the objectives of erosion control and retention of natural scenic beauty. The specific techniques used were agreed on by the Forest Service and the Colorado Division of Highways. They consisted of one or a combination of the following activities: seeding with grass, fertilizing, mulching, applying protective matting, and planting or transplanting native trees and shrubs.

Revegetation began immediately after slope disturbance to take advantage of available soil moisture. As cut slopes were made, revegetation closely followed the earth-moving process. Only 9.1 m (30 ft) of exposed slope was allowed at one time. Application of the seed, fertilizer, mulch, and netting was completed immediately rather than being drawn out over a long period of time.

Revegetation was extremely successful at Vail Pass. The cost of the program was approximately $20 000/hm^2$ ($8000/acre).

Topsoil

Because of the coarse texture of the Vail Pass soils and their low nutrient content and water-holding capacities, topsoil was imported to cover all cut-and-fill slopes. The majority of the topsoil was collected from bogs and meadows and stockpiled on deposition areas along the right-of-way. Topsoil stockpiles must be in areas that can be protected from erosion. Some erosion problems occurred when topsoil was stockpiled too close to a live drainage.

Analysis of the topsoil was necessary to determine if the material had suitable texture, organic matter, and nutrient content.

The topsoil was spread 10-15 cm (4-6 in) deep over the cut-and-fill slopes by use of a drag line. Depths in excess of 15 cm (6 in) were subject to slumping or sliding as the soil became saturated during the spring runoff period.

Seeding

Two seed mixtures were used in the project because of differences in elevation and exposure. The Forest Service developed the seed mixtures from the best available research data and from its work on ski areas adjacent to the project. Seed species were selected that provided immediate and long-term erosion control. Many of the species commonly occurred in the immediate vicinity of Vail Pass. The seed was initially applied at a rate of 22.7 kg/hm^2 (20 lb/acre) by broadcast and 11.3 kg/hm^2 (10 lb/acre) by drilling. This rate turned out to be somewhat low and was increased to approximately 45.4 kg/hm^2 (40 lb/acre) by broadcast seeding.

In areas such as Vail Pass, which have frequent summer rainfall, the seeding operation can take place almost anytime during the summer as long as the stand of grass can be firmly established to avoid winterkill of the young, lush grass.

Fertilizer

Fertilizer is necessary for all high-elevation plantings (10). Low nutrient levels, coupled with a short growing season, slow processes of soil formation, and low decomposition rates, result in extremely harsh conditions for plant growth. In studies on adjacent high-elevation ski areas, it was found that 283.5 kg/hm^2 (250 lb/acre) of 16-20-0 ammonium phosphate-sulfate should be applied with grass seeding (11). A follow-up fertilization of 226.8 kg/hm^2 (200 lb/acre) of 16-20-0 can be used at the beginning of the second growing season for maintenance. It is appropriate, however, to regulate the amount of fertilizer applied according to the texture, organic matter, ion-exchange capacity, and depth of the soil at the project site. Generally, the application rate for soils at Vail Pass was 34-57 kg/hm^2 (30-50 lb/acre) of available nitrogen in the form of ammonium sulfate or urea and at least 113 kg/hm^2 (100 lb/acre) of P_2O_5.

Maintenance fertilization with nitrogen was necessary to ensure an adequate stand of grass. A light green or yellowing color in the grass and slow growth or thinning of the stand are good indicators that fertilization is necessary.

Mulch

Some form of mulch is essential to aid in germination of grass seed. The mulch helps to maintain soil moisture and reduces rapid fluctuations in soil temperature. The mulch also aids in temporarily stabilizing the disturbed soil while vegetation is being established. The most effective mulch used at Vail Pass was straw, applied by a straw blower or by hand at a rate of 3.4-4.5 Mg/hm^2 (1.5-2 tons/acre).

In the mountain environment, it was essential that the mulch be anchored to the ground to prevent its removal by wind, gravity, and water. Methods of anchoring the straw included use of a straw crimper or modified sheep's foot on the flatter slopes and plastic or jute netting on the steeper slopes.

Jute Netting

Because of the highly sensitive nature of Vail Pass soils, netting was used to hold the mulch in place on all slopes that exceeded 3:1. The primary netting used was a jute matting composed of heavy hemp material. The jute came in a roll 1.2 m (4 ft) wide by 68.6 m (225 ft) at a cost of approximately $35/roll. The netting proved extremely effective in providing immediate erosion protection for the sensitive soils of Vail Pass.

Some problems developed when the jute netting was not overlapped properly. During installation there should be a 10.2-cm (4-in) overlap on the matting to allow for shrinkage. The jute must be securely stapled to the ground and tucked into the slope at the upper end to prevent wind damage and surface erosion. It is also important that no concentrated surface runoff be allowed to flow over the slope. In several locations, the jute matting failed because flows crossing the slope were not confined in a natural drainage or rock-lined ditch.

Irrigation

Irrigation was used to a limited extent. Summer rainfall in the Rockies provides much of the water for stand establishment, and so there is much less need for irrigation than there is in other areas such as the Sierra Nevada. In some cases, however, it is still essential to carry new stands of grass through dry periods. Watering is particularly important for recently planted shrubs and trees.

One irrigation technique that was used at Vail Pass was a large water truck with spray nozzles. There were also opportunities to irrigate while pumping water from sediment ponds.

Shrubs and Trees

Many shrubs and trees were transplanted from areas in the project right-of-way for landscaping and long-term erosion control. It was found that shrubs and trees from higher elevations could be transplanted to lower elevations. The reverse, however, did not hold true: Results were very poor when plants were taken from lower to higher elevations. It is essential in transplanting to maintain the integrity of the root ball by means of a large mass of soil and to keep stored trees damp and in the shade.

Highway Maintenance

The success of a revegetation program depends on highway maintenance. After construction, care must be taken not to dump spoiled material over a vegetated slope. This is especially true in the spring when the drainage ditches are being cleared of sanding material and other debris. Designated dumping areas are necessary and should be identified in the water-quality plan. Educating maintenance crews to this idea is a necessity.

Permanent Drainage

To ensure long-term erosion control on cut-and-fill slopes, permanent protection from concentrated surface runoff is necessary. Surface-runoff patterns were evaluated during the initial highway planning phase, and culverts or protected drainages were planned where high runoff volumes and velocities were expected. On flat gradients, rock-lined ditches underlaid by a porous filter blanket proved effective for transporting water. On steeper slopes, shallow gabions underlaid by a filter blanket were more effective. When culverts were used, the outlets were placed in a location where discharge from them could be easily routed to a natural drainage or where it could be effectively dissipated and spread over undisturbed ground. When this was not done, severe erosion resulted.

Energy dissipators constructed from gabions were used to dissipate water runoff below steep, permanent slope drains. These structures were installed in areas where high runoff volume and velocities were expected. When properly placed and constructed, the gabions were very effective in checking high flows. But some problems were encountered when they were not properly placed or keyed into the slope. Soil erosion and eventual undercutting of the structure resulted from inadequate protection between the drainage outlet and the gabion structure.

Retaining Walls

It was found that, because of the close proximity of highway construction to live drainages, fills flattened out at 2:1 would often encroach on streams. To protect the integrity of the drainages and maintain good water quality, several types of retaining walls were used. Treated wood-crib retaining walls were used on small cut slopes, but the larger retaining walls were primarily precast concrete, dyed to match the color of the native rock and soil of the area. The retaining walls were very effective in reducing the encroachment of fill slopes on live drainages.

Temporary Erosion Control

In addition to the permanent erosion-control features incorporated in the roadway design, control measures must be anticipated and used during the actual construction period. These measures are temporary in nature and are designed to be removed once the construction is complete. They are extremely critical since the potential for water-quality and erosion problems is greatest during and immediately after construction. Temporary methods include sediment basins, sediment traps, and clear-water diversions.

Sediment Basins

A sediment basin is a natural or man-made depression used to detain runoff of turbid construction water. Water entering the basin is slowed to allow particulates to settle out before the water passes to downstream areas. The cleaner surface water is drained from the top of the basin, usually through a culvert or a rigid hose. Spillways are provided to protect the basin in the event their capacities are exceeded during storm periods. The size and the amount of particulates retained in a basin are a function of the volume of inflow water with respect to the size of the basin. Generally, given a steady inflow, the larger the basin is, the more sediment will be trapped.

Sediment basins are constructed by building a low head dam, excavating a depression, using a natural depression, or any combination of the three. All of these methods were used, with varying degrees of success, on the Vail Pass project. The effectiveness of the basins depended largely on the selected design, overflow drainage, and maintenance of the structures.

Design and Placement

Sediment basins were difficult to construct and maintain in the steep terrain of Vail Pass. The capacities of the basins were often below the design water inflow because of terrain restrictions. However, the basins were effective in retaining sand- and silt-sized particulates.

The excavated and natural basins were located in relatively flat terrain near the valley bottoms or on natural terraces. Construction runoff water was directed to the structures by temporary conveyances such as berms, culverts, flexible down drains, and plastic sheets. Overflow from the basins was discharged from a spillway to the undisturbed land or natural drainageways below the structures.

Dam-type basins were located in small natural drainages and usually in steeper terrain than excavated basins. The drainage bottoms were rounded out, and the excavated material was used to build a low head dam. Overflow from the basins was discharged, through a culvert drain, to the natural drainage below the structure. Spillways made of rock or plastic were placed on the dam face for overflow protection during storm periods.

Basins constructed by excavating depressions or using natural depressions (see Figure 1) proved superior to ones built with low head dams. Because these basins were located in flatter terrain, access for their con-

Figure 1. Excavated sediment basin.

struction and maintenance was generally easier. Their simple design did not require the construction and upkeep of a steep dam face. In contrast, the dam-type basins were located in narrow drainages that restricted the movements of construction equipment. Since it was often difficult to achieve adequate compaction, the fill material was allowed to become saturated during the spring runoff and summer rains. Consequently, dam faces would occasionally fail and send large amounts of sediment to downstream areas.

Overflow Drainage

Excavated and natural sediment basins drained the cleaner surface water over spillways provided at the low end of the structure. The spillways were protected from erosion by a covering of rock or plastic. The rock size varied, depending on the source, but was usually 10.2-15.2 cm (4-6 in) in diameter. Plastic coverings were 0.15-0.35 mm (6-10 mils) thick.

Both coverings proved effective, although rock was more durable if the basin was designed for more than one season. Plastic-lined spillways were reliable, but after a year of use the plastic tended to become brittle and suffered tear damage. Maintenance usually involved making sure that the plastic was anchored into the soil and/or properly weighted with rock. Rock-lined spillways required very little maintenance.

Dam-type sediment basins drain by drawing surface water through a metal culvert or flexible hose. The drains are connected to a culvert at the bottom of the basin, where the water is discharged to downstream areas. Variations of these drainage devices tried at Vail Pass included rigid hose, soft hose, culvert, and culvert with slits.

Flexible hose drains are buoyed to the basin surface by a float device, usually an airtight plastic bottle or a piece of wood. Continual problems arose in using these drains to provide unrestricted drainage. The soft flexible hosing would sometimes collapse or become twisted from the movement of the float device on the surface of the basin. In addition, the rigid hosing occasionally failed to provide good drainage: The hose was too buoyant and prevented water from entering the drain.

Culverts proved to be more effective outlet drains than flexible hosing. The 46- to 61-cm (18- to 24-in) diameter culverts generally required less maintenance and were more durable than the smaller 15.2- to 20.3-cm (6- to 8-in) diameter hose drains. Some culverts were constructed with slits in the upper foot to provide drainage before the basin capacities (at the top of the culvert) were reached. The Colorado Division of Highways discontinued use of this design because the slits became plugged with sticks and other debris.

Maintenance

The effectiveness of sediment basins depends largely on maintenance. The basins at Vail Pass were drained after a runoff event, to prepare for the next storm, by syphoning or pumping the collected clear surface water from the basin. Sediment basins were also periodically cleaned to retain their design trapping efficiency.

Disposal sites and the equipment necessary to clean the ponds should be planned in advance. A flat or depressed area, where the sediment can be spread and revegetated, serves as a good disposal site. Some types of recovered material can be dried and used as fill material on the construction job. Placing the accumulated material adjacent to the basin is not acceptable: The Vail Pass basins are of minimal size, and this served to reduce trapping efficiency because the sediment that had been trapped once washed into the basin a second time.

Sediment basins must be routinely inspected so that accumulated debris around drainage outlets can be removed. Failure to do this resulted in the drains being clogged and created the potential for overflow or washout. Provisions should be included in the water-quality plan to establish a maintenance schedule for the sediment basins and to designate the person who is to be responsible for inspection.

Sediment Traps

Sediment traps are temporary, small detention structures that operate on the same principle as sediment basins. The traps slow the velocity of runoff water, allowing the coarser particulates to settle. The cleaner surface water is passed on to downstream areas. Sediment traps cannot handle runoff volumes as large as those handled by sediment basins, but they are much easier and quicker to construct. They are generally used for one season or less, and the accumulated sediment and the traps are removed after the construction period. The location of the traps is usually determined in the field as the need for them arises. They can be constructed from a variety of materials, including straw bales, plastic, sandbags, filter cloth, and rocks.

Straw bales (see Figure 2) are perhaps the quickest and easiest type of sediment trap to construct. They are readily available and easy to transport and can be formed into a sediment trap just about anywhere. They must be firmly anchored to the ground to prevent failure underneath or between the bales. The standard procedure is to key them 10.2-15.5 cm (4-6 in) into the ground and to drive steel re-bars through the center. Anchoring the bales properly is extremely important in a mountain environment where steep gradients promote high runoff velocities. Most of the unanchored bales at Vail Pass failed after a short time.

Another effective and easily transported sediment trap is constructed by using a fabric filter. The fabric is made from filament fibers with randomly distributed pore openings. Water easily passes through the fabric, but soil is trapped. Figure 3 shows how the fabric is attached to a temporary wire fence. The bottom 15.2 cm (6 in) of the fabric is buried in the ground to prevent water from flowing under the structure. Construction runoff water is directed to the filter trap along berms, dikes, plastic-lined ditches, or culverts. For the best results, the water should be dispersed before it en-

Figure 2. Straw-bale sediment trap.

Figure 3. Filter-fence sediment trap.

counters the filter blanket. Fences in steep, narrow drainage ditches or swales should be avoided. The fabric has little lateral support and cannot withstand a force such as that caused by impounding 0.6-0.9 m (2-3 ft) of water.

Sandbags were also effective in trapping sediment at Vail Pass. They were considerably heavier and harder to transport than straw bales but were more durable and withstood high runoff velocities well. Although sandbags are heavy, they are pliable, which means they can be placed on steep sideslopes and across ground-surface irregularities. Because of their weight, sandbags can withstand a greater force per unit area than straw or fabric. This allows more water to be impounded with less risk of failure.

Small rock dams were occasionally used as sediment traps at Vail Pass. The rock size varied from 5.1-20.3 cm (2-8 in) in diameter. The rock dams worked well and provided a durable structure. They must be located in accessible areas because they are usually constructed, maintained, and removed by heavy equipment. These dams were most often used in areas where rock was abundant.

The key to the success of the sediment trap is, again, proper maintenance. In mountain areas like Vail Pass, the environment can be harsh. High winds, heavy rains, excessive runoff, and extreme temperatures can damage and reduce the effectiveness of the sediment traps. The inspection and maintenance of the structures must be performed regularly by the contractor. This should be part of the water-quality plan to ensure its enforcement.

Diversion of Clear Water

Many erosion and sedimentation problems can be avoided if runoff water is intercepted and conveyed around disturbed construction sites. A successful system of clear-water diversion intercepts the clean water above the project, transports it through the work area, and discharges it below with little or no degradation of water quality. This not only protects the integrity of the runoff water but also avoids on-site erosion and wet, muddy working conditions for the contractor.

Interception

Streams, springs, bogs, and shallow subsurface flows all contribute water to the construction zone. In mountainous terrain, these drainage patterns are complex and require an array of techniques to divert clean runoff water around disturbed construction sites. Some of the methods used at Vail Pass included shallow interception ditches, hay and plastic ditches, and small collection basins with pipe drains. Shallow interception ditches constructed above work areas were effective in routing clean water around the projects. The ditches were constructed on the contour and most often used on northerly slopes where numerous springs and wet subsurface conditions existed. The diverted water was routed to natural drainageways or culverts by which it was conveyed below the work zone. The ditches were either hand dug or trenched by using a small backhoe.

Hand-dug ditches such as the one shown in Figure 4 proved superior to backhoe trenches. The ditches were usually constructed on side slopes during the early construction season when conditions were wet. Backhoes had a difficult time operating in these conditions, often sliding and rutting the area adjacent to the ditch. It was also difficult to operate them in and around obstacles such as rocks and trees. Hand-dug ditches, on the other hand, had only minimal effects on the terrain and could be constructed through tight places such as forested hillsides.

Once constructed, the ditches held up well. Minor slumping and vegetative overgrowth were evident after one year of use. A jute netting or a similar product was often used to line the ditch at gradients of more than 6 percent to guard against erosion. Drainage was most efficient when gradients ranged from 5 to 8 percent; when gradients were less than that, water ponded and drainage was ineffective. Gradients of more than 10 percent that were not lined with a jute netting caused some scour and minor erosion.

Another, less effective method of diverting water along the contour was the use of straw bales lined with plastic. As surface flow came in contact with the hay and plastic, it was diverted laterally to a natural drainage or culvert. Both the straw bales and plastic were keyed 10.2-15.2 cm (4-6 in) into the ground. This system required more time to construct than hand-dug ditches and needed continual maintenance. The plastic and straw were difficult to keep anchored in the ground, and the plastic was subject to tear damage from wind, rocks, and tree limbs. It was also limited to diverting surface flows and did not reach the shallow subsurface water. It is recommended that this system be discouraged in favor of hand-dug ditches.

Collection basins were effective in impounding and diverting water where drainage problems were isolated to a few places such as a spring, a seep, or a small creek. Small basins were dug in the ground or con-

Figure 4. Hand-dug interception ditch above project area.

Figure 5. Failure of plastic-lined ditch.

structed by using sandbags at the water source. The impounded water was diverted into an irrigation pipe, a culvert, or flexible plastic down drains and directed through the work area. The water was then discharged into natural drainage courses below the construction site. Collection basins work well if they are inspected and maintained. The inflow pipe must be kept free of debris to prevent overtopping and subsequent erosion. As in the case of other temporary erosion-control structures, a routine maintenance schedule is imperative for collection basins and should be specified in the water-quality plan.

Transport

Once the clean water is diverted above the construction sites by either ditches or basins, the water has to be directed safely through the construction zone. Many different methods were used at Vail Pass, including metal culverts, flexible plastic down drains, irrigation pipe, and plastic-lined ditches. The method of transport depended on the anticipated water volumes, the duration of use, and the length and steepness of transport.

Metal culverts 46-61 cm (18-24 in) in diameter were the most effective all-around method of transporting water through work areas. They can withstand high runoff velocities and transport water great distances and can be expected to hold up for more than one construction season. Their disadvantage is that metal culvert is more expensive than some of the other diversion materials.

Irrigation pipe also worked well as a means of transporting water, but because of its size [20.3 cm (8 in)] it was restricted to intercepting small quantities of water. In addition, it required more maintenance to remove accumulated debris from the water-intake opening. During operations in late fall and early spring, ice accumulations would sometimes plug pipe inlets and restrict drainage. If the pipe is to remain functional, someone must be on hand to chop and remove the ice. This type of drain should be used only during the summer and should not be counted on to transport spring runoff water.

Flexible down drains and plastic-lined ditches are also reliable transporters of water, provided they do not have to carry heavy runoff volumes over long distances. These structures are more temporary than the metal pipes and require more maintanance. Flexible down drains are excellent on short, steep slopes. Their flexibility conforms to the water flow, maximizing friction and slowing water velocities. The drains were staked to the ground to prevent excessive movement caused by wind or internal water flow. Such movement may cause creases or bends that can fail under the force of the drainage water.

The use of plastic-lined ditches should be limited to diversion projects of short duration. The ditches require constant inspection and maintenance. The plastic is anchored in place by logs, rocks, stakes, or other means. Figure 5 shows how failures occurred at Vail Pass when the plastic slipped beneath its anchor and drainage water spilled on the disturbed soil. The plastic must also be durable so that water flow does not tear it on the irregular channel bottom. The plastic was at least 0.15 mm (6 mils), and preferably 0.35 mm (10 mils), thick.

Discharge

Discharging the intercepted water below the work area is the final stage of a water-interception system. In the steep terrain of Vail Pass, energy dissipators were often required below the drains to slow the runoff water to nonerosive velocities. A complete system carries the water through the project area and discharges it into an energy dissipator. A variety of temporary dissipators, including loose rock riprap, straw bales, and silt fences, were used.

Loose rock riprap or a wire and rock mattress placed below a drainage outlet was effective in checking erosion and undercutting. Loose riprap consisted of graded angular rocks, 10.2-25.4 cm (4-10 in) in diameter. The rock protection should extend to and around the drain outlet. The riprap should be at least 1.2 m (4 ft) wide to prevent drainage from circumventing the structure.

When water discharge is temporary because of construction activities, simple and less expensive energy dissipators are adequate. Straw bales keyed into the ground and lined with plastic were commonly used at Vail Pass. Maintenance was required to see that high velocities did not tear the plastic and break the straw bales. A silt fence (as described earlier) was placed in a semicircle behind the straw bales to retain sediment that was picked up during transport. These dissipators worked well when high runoff volumes were not encountered. The straw and plastic were most often used below 20.3-cm (8-in) irrigation pipe drains but were not used below 46- to 61-cm (18- to 24-in) culverts. Energy dissipators below high-discharge drains were made of rock even if they were temporary.

Temporary Roads

Many temporary roads were required during the early construction phases of the project. Proper location of such roads can eliminate many potential water-quality problems. Where possible, the roads at Vail Pass avoided streamside zones, potential landslide areas, and steep terrain. Adequate drainage in the form of well-spaced water bars, culverts, and temporary bridges effectively reduced water-quality problems while the roads were in use. When their use was completed, the roads were water-barred, seeded, fertilized, mulched, and closed to access. This was followed by field inspection to ensure that the site was properly revegetated and water bars were properly installed.

Temporary Stream Crossing

Because of the steep, dissected terrain of Vail Pass, many temporary stream crossings were required during construction. Temporary bridges, culverts, and low-water crossings were used. The selected design depended on the type of equipment that would cross the stream, the number of crossings required, and the duration of use.

Temporary bridges and culverts were installed in locations where heavy traffic was anticipated over an extended period. The temporary bridges were judged to be the best way to protect water quality. Very little fill material encroached into the stream channel and, once the bridges were in place, log cribbing prevented soil from sloughing into the water. The disadvantage of the temporary bridges was that they were relatively expensive to install and deteriorated somewhat under heavy use.

In contrast, culvert crossings held up well although disturbance of fill material during their installation and removal caused localized stream sedimentation.

Low-water crossings were originally permitted in a few locations where light equipment had to cross a stream only once or twice, but excessive disturbance caused by saturated soils and the absence of rock material adjacent to the streams eventually prompted elimination of this method and the use of small temporary bridges instead.

SUMMARY

Many erosion and sedimentation problems can be avoided during road construction if they are anticipated and prepared for in advance. Planning ahead for these problems begins with the initial road design and continues through the actual construction period. The preparation of a water-quality plan prior to construction activity is essential in protecting soil and water resources. Although the complexity of the plan may vary depending on project location and reclamation objectives, all plans should include provisions to

1. Prepare a site-specific contingency plan that addresses potential water-quality problems and outlines methods to correct them,
2. Establish a maintenance schedule for permanent and temporary erosion-control structures, and
3. Appoint a supervisor for erosion control and water quality who is responsible for implementing control measures.

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