Design of Rock Slopes

SHAILER S. PHILBRICK, Office of District Engineer, U. S. Corps of Engineers, Pittsburgh, Pa.

The design of rock slopes is discussed in this paper much as if an actual cut slope in rock were being designed. First, the engineering requirements of the cut; second, the geologic conditions of the site of the cut are established. These two define the problem. Then, using six basic principles, a generalized design to meet certain engineering and geologic conditions and the reasoning for it are presented.

In the design of cut slopes in rock, safety is emphasized because shear failures in rock are rare. For that reason the emphasis is on a cut slope that will yield very few rockfalls and will be structurally stable. In durable rocks the controlling factor in the angle of the slope, and hence the design of the cut, is the shape, geometric attitude, and stability of the rock segments to be exposed and activated on the cut slopes.

• IN THE DESIGN of rock slopes, the first step is to ascertain the purpose, depth, width, extent, geographic and topographic location, and orientation or azimuth of the cut. These are the engineering requirements of the cut.

What is the purpose of the cut? Or in connection with what kind of a project is the cut to be made? And in what stage of the project will the cut be made? For how long will it be open? Will it be over a restricted work area as adjacent to a bridge abutment? Who or what is going to be beneath or above the cut? If it is a channel change in massive granite in an isolated area where not even a stray fisherman will be at the foot of the cut, then slope design becomes of little concern as long as the hydraulic requirements of the channel are met. Conversely, if the cut is to supplant an existing tunnel on a turnpike or an Interstate route and is to be several hundred feet high and thousands of feet long, surely its design is a matter of great concern in regard to ultimate cost and safety.

Geographic location must be known because climate varies with geography. Hence, precipitation, which means slope saturation and necessity for drainage, can be anticipated. Depth and degree of weathering vary with climate. The number of cycles of freezing and thawing per year are tied to the climate. The topographic location affects the depth and degree of weathering, the movement of ground water, and the thickness and character of the overlying soil. The orientation of the cut slope fixes the exposure of the slope to the sun and therefore affects the number of cycles of freezing and thawing, and wetting and drying per year. It suggests the length of time that ice would form on the slope during the winter. Beyond the temperature effects of orientation are the equally fundamental relationships of centerline to geologic structure. Is the major joint system striking parallel and of great importance or normal to the centerline and therefore unimportant, or is it the common case of diagonal orientation to the centerline? In most cases it can be assumed that the data on the cut—centerline dimensions, purpose, etc.—are readily available and there is actually concern only with the characteristics of the rocks of the cut, or the geology of the cut.

Geology

The next basic step is the establishment of the type and characteristics of the bedrocks which must be shaped in the excavation to form a stable, enduring, safe slope

Paper sponsored by Committee on Landslide Investigations.

that will cost a reasonable amount to produce and a minimum amount to maintain. Interest in the geology of these rocks is limited to those geologic characteristics and features that determine whether the slopes will be permanent; whether they will be structurally stable; and what the yield in rockfalls will be. Only those geologic characteristics, which affect the behavior of the rocks as slope-forming materials, are important.

The mineralogy of the rocks is pertinent to the point that the stability or instability of the minerals under the new conditions of stress and exposure is known and the minerals are recognized sufficiently to establish identity of the rock for contractual purposes. Also for contractural purposes, the top of rock, structure, relative hardness, degree of weathering, and similar properties of rocks need be determined.

The structure of the rock is required to define the probable size, shape, and orientation of the rock segments that will form the slope. Rock segment is the in-situ piece of rock that becomes the rockfall when it falls out of the slope. Knowledge of the structure of the rock is needed to define the attitudes and spacings of the planes that will cut the rock within and at the surface of the slope and form the rock segments. Thus, the centers of gravity of the rock segments and presence of sliding planes on which otherwise stable rock segments will move can be recognized before the slope is cut.

Geologic Investigations

The surface and subsurface investigations of the geology of the cut site should define the following:

1. Materials—rock and soil types, thickness, sequence, distribution;
2. Shear strength of the rocks;
3. Structure and tensional strength across and shearing strength along the structural planes;
4. Rock segments—size, shape, orientation, stability;
5. Depth of weathering:
    a. General disintegration—top of unweathered or sound rock slope;
    b. Along bedding, joints, fractures—top of inherent tensional and shearing strength of the structural planes;
6. Slope angles of these rocks in old or mature cuts;
7. Rate of weathering of these cuts; and
8. Water table and subsurface drainage.

The investigations should include both surface and subsurface conditions. The geological characteristics of the rocks as expressed in their outcrops and the lithology and structure of visible rocks are fully as much a part of the study as are the examination of the cores from the test borings.

The addition of geologic mapping may be somewhat difficult for those who are used to studying cuts mainly from the borings. However, it is far easier to determine from outcrops which are the important structural planes cutting a rock formation than from a series of borings. It is suggested that the borings themselves not only be directed toward establishment of the lithology and thickness of the several rock types but also be oriented to intersect the major joints and bedding so that the bounding planes of the rock segments can be determined before the beginning of slope design. The size, frequency, and method of drilling of the test borings are functions of the local geology and beyond the scope of this paper. Sufficient physical testing should be performed to establish the strength of the rocks where it is unknown.

The geological investigations should include a study of the old cuts in similar rocks in the area of the proposed cut. This study should find out the angles of slope that these rocks assume under prolonged exposure, and the rate of weathering of these rocks. The slope angles are readily recognizable and measurable. The rate of weathering or retreat of the cut slope may be measured in inches per year as on some of the indurated clays or compaction shales in the Pittsburgh area or a zero rate on some of the resistant limestones in Tennessee. The measurements may be based on comparison of the present position of a point on the slope with its former position using as a

datum an adjacent structure built into the slope, such as a tunnel portal or a resistant layer whose outer edge was probably on the original cut surface. From these studies it may be learned that slope-protection devices (such as those installed on the Pennsylvania Railroad in eastern Ohio probably 50 years ago) are still entirely satisfactory. The stability of certain high cuts may be observed in which the shearing stress acting over many decades as a long-term load test has not caused the indurated clays or compaction shales to fail. In another cut, a failure may be found and thus may be perceived the order of magnitude of the strength of the stressed layer under field conditions or the effect of a different loading condition caused by a high water table or a dipping-joint system.

The findings should be recorded graphically:

1. The vertical and horizontal limits of the several rock types;
2. Base of mass rock disintegration;
3. Base of weathering along the planor elements, which is the approximate upper limit of any significant cross-plane or parallel plane strength in the rock;
4. Approximate, even if schematic, distribution of the planor and linear elements that will affect the stability of the rock segments; and
5. Water table and subsurface drainage.

The resulting drawing shows geologic data for the purpose of helping to solve an engineering problem. Therefore, the geologic attributes of the materials must be emphasized. The soils shown thereon may be identified under an engineering classification such as the Bureau of Public Roads or the Unified Soil Classification System of the Corps of Engineers. In addition, they must be described in such detail that the correlation with the unweathered or unaltered equivalents at other locations on the same section or on adjacent sections can be established without question. The typical slope angles of the weathered and unweathered materials to be encountered in the cut should be indicated. The rates of weathering of the several materials and the kinds of weathering products ought to be recorded. Finally, the approximate shearing strength of the materials should be noted for comparison with the estimated shearing stress.

PRINCIPLES OF SLOPE DESIGN

There are six basic principles to be considered in designing slopes:

1. Fitting the slope to the material, not the material to the slope;
2. Predetermining the shape and orientation and thus the stability of the rock segment that could become the rockfall;
3. Preforming the cut surfaces;
4. Protecting the cut surfaces;
5. Fitting the benches to the dangers; and
6. Draining the surface and subsurface waters.

Material and Slopes

The simple principle of fitting the slope to the material is one of the cardinal principles in dealing with soils, but when rocks are encountered this principle seems to be overlooked. This may possibly result from an engineering concept found at many drafting boards that all rocks are brothers under the skin and should be cut on ¼ to 1 and from an adjunct theory which holds that once a rock always a rock because rocks do not weather during the life of the cut. Both of these ideas are incorrect, and there are maintenance costs and maintenance men in many districts which can disprove them rapidly. There are all sorts of rocks and what is a good slope for one type in one situation may be an extremely poor slope for that same rock in another situation or a different rock in the same situation. Hence, the emphasis earlier on the geologic and site conditions and the behavior of those rocks in comparable cuts, because a table of slopes for all rocks under all conditions has not yet been developed. A start on this was made when such a study was conducted in the Pittsburgh area in connection with Youghiogheny Dam in 1941 and the results published in 1953 (3) and 1960 (4). In due course such studies should be conducted for other areas, but until they are available, field studies should be made to determine appropriate slopes for individual rock types.

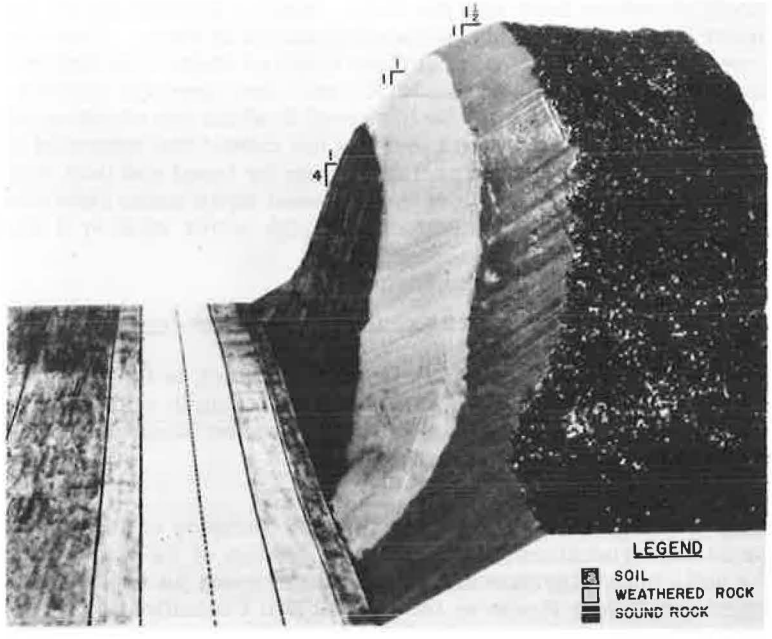

Figure 1. Oblique view, model of simple cut.

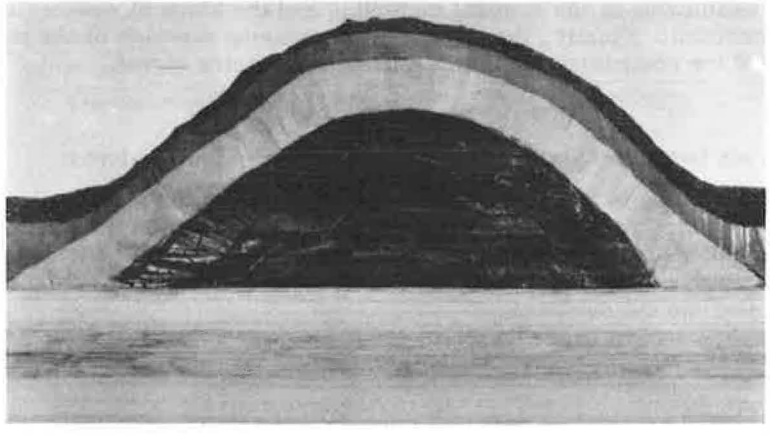

Figure 2. Front view, model of simple cut.

One of the most prevalent problems with material-controlled slopes is the simple three-layer condition of soil, weathered rock, and sound rock. This condition is most noticeable when the sound rock slope is ¼ to 1, the weathered rock slope is 1 to 1, and the soil is 1½ on 1. The effect of topography on the design of rock slopes is shown in Figure 1, which is a slightly oblique view of a model of a cut through a ridge composed of these three materials. The soil is gray colored with 1½ on 1 slope. The weathered rock is light gray with a 1 to 1 slope. The sound rock is dark gray in color with a slope of ¼ to 1. The black, white-flecked surface at the right of Figure 1 was a bright-green reflective surface representing grass on the model.

It can be seen from the front, as in Figure 2, that the sound rock core of the hill is mantled by weathered rock and that, in turn, by soil. It can also be seen that the ¼ to 1

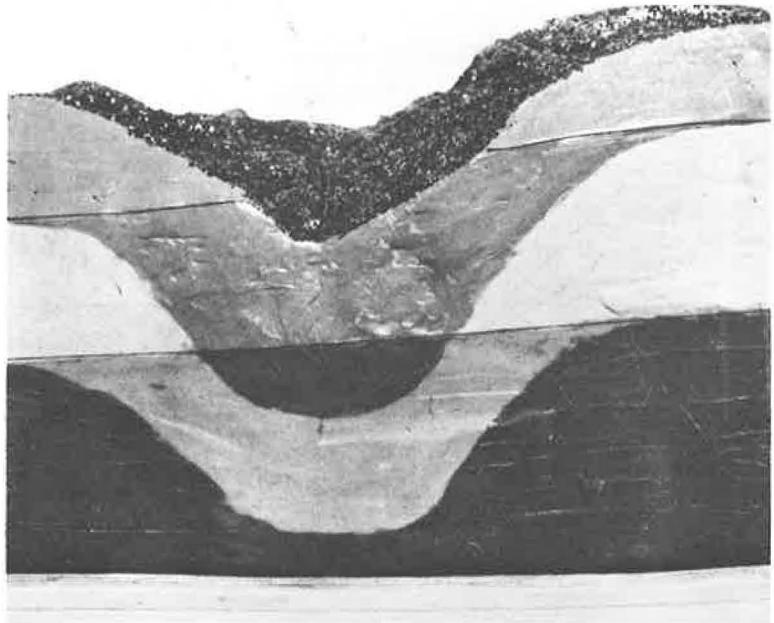

Figure 3. Front view, model of cut through ravine.

slope on the sound rock is mantled by 1 to 1 on the weathered rock and that, in turn, by 1½ on 1 on the soil. The slope of the cut is dependent on the spot where the cut is made; that is, through the soil only, through the soil and weathered rock, or through all three materials. A uniform slope is not appropriate throughout the full length of this cut but must be fitted to the material at each station in the cut.

Another variable may be added to this last model and the crest of the ridge may be creased with an old ravine in which weathering has progressed to some depth. Figure 3 shows a replica of a design that fails to consider the effect of weathering and the change in materials with change in topography. The soil and weathered rock zones descend with the side slopes of the ravine and encroach into the slope zones established for the cut on the basis of conditions on the ridge crests on either side of the ravine. Such a design which develops 1 to 1 and even ¼ to 1 slopes on soil is going to be a nuisance if not a disaster to the traveler and the maintenance man. Therefore, the slope whould be matched to the material.

Another example of material-controlled slopes is shown in Figure 4, which is a geologic section through a double-track railroad cut. Two rock types occur in the cut, both of which show weathered as well as unweathered zones. The basal rock is a sandstone which was cut on a slope of ¼ to 1. The cap rock of the cut is likewise a sandstone but it is deeply weathered and therefore is cut on a flatter slope of 1 on 1. In between these two rocks is a clay shale, a very fine-grained but somewhat cemented rock, which requires a flat slope of 1 on 1 in both its weathered and unweathered expressions. The rock segments in this cut are random, unoriented, somewhat tabular, flat-lying shapes which are mainly stable with these cut slopes. Nevertheless, a narrow bench at track level was provided.

Rock Segments

The second principle in slope design is the predetermination of the shape, orientation, and stability of the rock segment that could become the rockfall.

Usually, individual grains in granular materials have an essentially random orientation. However, the chances are much greater in many rocks that the segments are oriented rather than unoriented. Because this is a matter of probabilities, it is profit-

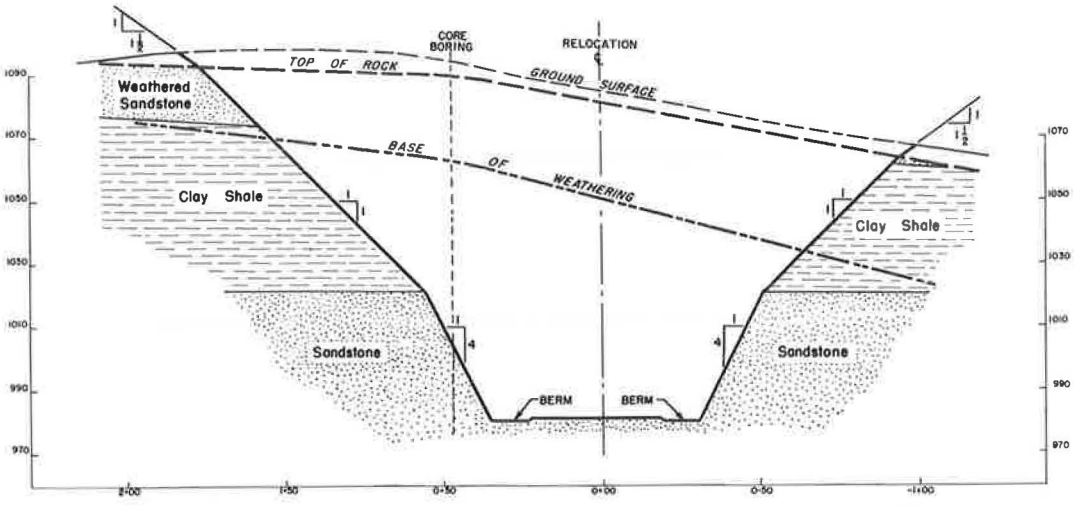

Figure 4. Through cut in rock.

able to examine the orientation of the rock segment. As long as the orientation is stable, the segment will remain in place in the rock slope as just another rock segment, but if it is unstable it will fall down on the road surface to become a menace.

The orientation of the rock segment depends on its shape and the attitude and spacing of its bounding planes. The attitude and spacing of sets of bounding planes can be established by common methods of study of surface and subsurface geology. If the outcrops in the vicinity of the proposed cut are of sufficient size and number, then the planes can be identified and their attitudes and spacings observed and measured so that a reasonably reliable, although not a statistically reliable, estimate may be prepared. If rock exposures are missing or rare, then normal subsurface investigation must be supplemented by directional drilling to hit the planes being investigated.

Identification of these planes as geological features rather than just as geometrical features bounding geometric shapes will hasten the recognition of the probable shapes of the rock segments. In the sedimentary rocks, the most prominent planes are the bedding planes. Because sedimentary rocks underlie most of the region from the Piedmont to the Rockies, bedding planes may be the most important single structural feature in the rock and fortunately one of the most easily recognizable. With bedding planes forming the top and bottom of horizontal segments in horizontally bedded rocks, then the other bounding planes would be identified usually as joints of one sort or another, generally nearly normal to each other and the bedding planes. By inspection it appears that the general case in segment shape in sedimentary rocks is a slab varying between a paper-thin sheet (as in a fissile shale) through a thicker slab in the massive sandstones and limestones to a cubic form in coal. The orientation and, hence, the stability of these segments will depend on the local geological structure at the site of the cut.

In the metamorphic rocks the bedding planes of the sediments have a counterpart in the foliation and cleavage planes of the schists and gneisses and slates, although the probability is that these planes are not as weak as the bedding planes. In the igneous rocks, original flowage, crystallization, cooling, and shrinkage structures provide planor elements which shape the rock segment. They are much less easily recognizable, except in the lavas, than the bedding planes in the sedimentaries. Other surfaces of the rock segment are formed by joints of one sort or another.

The original segment shape, regardless of the rock type, may have been changed by later processes which formed other sets of planes to cut the segment into smaller pieces with different shapes. Because of the different attitudes of these later planes the present shapes may not be stable on the slope which was stable for the original

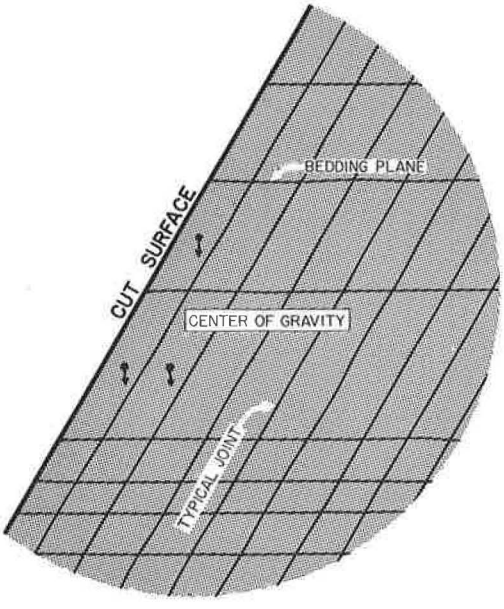

Figure 5. Stable rock segments.

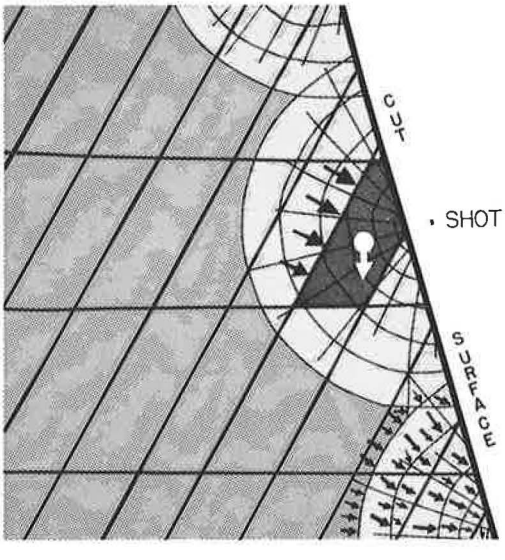

Figure 6. Potentially unstable rock segments.

segment shape. These later planes can be expansion joints parallel to hill slopes developing with the release of strain. They may be less complicated fractures caused by freezing and thawing. They may be tension cracks caused by cantilevering of beds above, when underlying strata were eroded along a slope. But these later planes always tend to complicate the pattern of the rock segments in the slope.

There is another structural feature which shapes rock segments—faulting. Rock segments adjacent to the fault as well as within the walls of the fault are affected. The feather joints trending out of the fault create a new system of fractures and new shapes of somewhat smaller size than the original rock particles. But within the fault zone itself the reduction in size may have proceeded to grains of sand size in the siliceous rocks and to clays in the argillaceous and calcareous rocks. Thus, the problem of slope design in rock, which must consider the size of the rock segment in the slope, may suddenly take on the aspects of a problem in soils, even if only for short distances.

Figure 5 shows a horizontally bedded rock cut by a series of joints dipping 60° to the left. The center of gravity of several rock segments near the cut face is shown with vertical arrows. These segments can be seen to be stable.

Figure 6 shows the same conditions but the site is on the left wall of the cut; therefore, the segments appear to lean into the cut. The apparent forces are shown by arrows against the side of a segment that is supported by a small triangular segment at the cut surface. As long as the cut-side segments remain in place, the rock mass is stable; but if those segments move or fall out, then the landward segments will topple and rockfall will result.

Preforming the Cut Surface

Much good design has been downgraded by poor construction methods—notably by overshooting of finished slopes with its resulting fracturing of remaining rock and production of material for rockfalls that did not exist at the time of design. Not only does the overshot rock fall down the slope, but the resulting face is so rough and broken that weathering is accelerated and high frequency of rockfalls continues long after it should have declined.

Figure 7 is a modification of Figure 6 and shows the effects of blasting put off at a point labeled "shot" located within the cut area. The original segments have been shattered into odd-shaped fragments within the blast areas by radial and circumferential cracks until the original segments no longer exist and new segments with new conditions of stability or instability occupy the sites of the original segments. The motion of these

fragmental segments as they move sooner or later into the cut is shown by the black arrows. Examination of the original segments, heavily outlined, shows that slope-side buttress segments are now shattered and ready to fall out. The pressure arrows of the landward, unstable fragments will soon force the fractured segments over the slope to be followed by others as rockfalls that will continue for a long time.

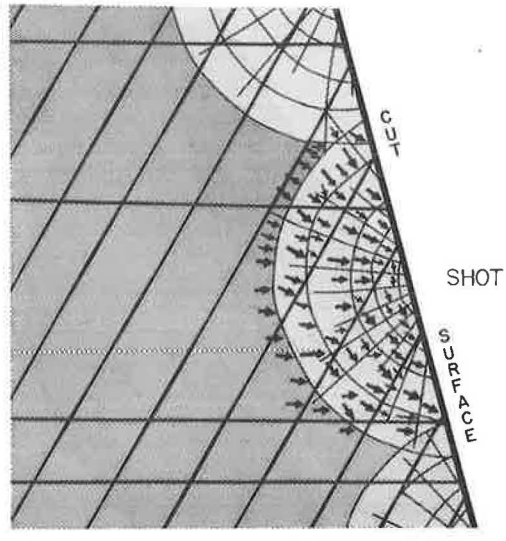

Figure 7. Segments shattered by blasting.

For many years, it has been standard practice to preform the sides of excavation where the concrete is to be placed against rock by closely spaced drill holes along the line of the excavation. In earlier days, the spaces between the holes were broken by broaching so that an actual crack was formed along the limiting line of the excavation. When the rock was shot, the break line usually followed the line of the drilling and broaching. This procedure has been much simplified by a process called presplitting which was developed to a high degree on the Niagara Power project, although it had been used nearly 30 years before. This procedure was used on the Southern Railway (ENR 5) as well as at Opekiska Lock, Monongahela River, W. Va. The limit line of the excavation if formed by drill holes on centers up to 4 ft in which small-stemmed charges of dynamite are suspended from Primacord at suitable vertical intervals in each hole and the charges detonated to crack the rock in a line between the drill holes. The resulting free surface effectively limits the disturbance of the wall rock during blasting to such a degree that overbreak is negligible.

This method has been used in limestones, some of which carried shale partings. In the construction work of the Pittsburgh District, Corps of Engineers, presplitting has been used successfully in typical Conemaugh formation sandstone (a subgraywacke) and silt shale. Offsets and interior corners have been presplit and have held their shapes at Opekiska Lock.

Presplitting of cut slopes will reduce the disturbance of the slope-forming materials and reduce the quantity of rockfalls which will, in turn, decrease the maintenance costs. The reduction in rockfalls will also decrease the quantity of scaling required during construction and tend to offset the small cost of drilling and shooting to presplit the rock. It is believed that some positive measures must be taken to reduce the shattering of the slope rock which is one of the major causes of rockfalls. Preservation of the rock segments in their preconstruction condition permits design assumptions to be made and plans prepared without fear that construction procedures will invalidate them.

Protection of Cut Surface

Slopes may be structurally adequate, or almost so, if protected from weathering and deterioration. Like anything else in this work, the desirability of protecting slopes can be established on engineering and economic principles and should be undertaken on that basis. Protection of the cut surfaces includes everything from self-protection (using the in-situ materials to protect the surface) to construction of protective structures.

Here are three examples of self-protection. With rapidly weathering rocks, such as the indurated clays and clay shales, slopes may be protected by using an angle sufficiently flat to permit the retention of the insulating blanket of fine weathering products which soon forms and seeding such slope as the blanket develops. On the other hand, steep slopes in durable rock composed of large segments may be protected by holding the outer layer of segments in place by rock bolts set in grout. Instead of paving the benches that needed protection, a resistant bed has been used as the bench surface or the bench has been located immediately above a resistant bed.

Midway between self-protection and structural protection lies the area of surface protection. Here, coatings and meshes are used with and without rock bolts to secure the surface treatment to the rock mass. Surface protection against moisture loss and weathering may be done with bituminous coatings or portland cement bearing coatings. The life of these coatings may be as much as 25 years under rigorous conditions of weathering.

Structural protection usually in the form of slope pavement or support of overhanging ledges resulting from overbreakage or differential weathering may be far less expensive than additional excavation, particularly in areas of high relief and expensive real estate.

Last within this area of slope design is the protection of the rock surface from loss of moisture by directing the flow of available water over those rocks that hold their strengths only as long as they hold their moisture.

Fitting Benches to Dangers

Benches used in the design of rock slopes should be considered as rock catchers. They are not primarily access roads to some higher cliff nor are they devices to reduce the loading on the toe of slope. Benches are to catch rocks, not soil slides, from the overburden which can readily fill the benches and destroy their usefulness as rock catchers. Soil slides should be prevented by adequate soil design and protective planting.

If benches are to fulfill their function, they should have the following characteristics:

1. They should be located where they can catch rocks, preferably at base of the rockfall producing zones.
2. They should be permanent.
3. They should be accessible but the feature of accessibility should not be permitted to determine the location of the bench.

There is no basic reason why access to benches must be accomplished only within the limits of the cuts or why benches need be interconnected to the detriment of their rock-catching ability. Access roads to benches can be located outside of the limits of cuts in many places, thus keeping the bench snug beneath the rockfall zone and reducing the chance for the rockfall to skip over the bench and proceed down the slope to the roadway.

Drainage

The normal practice of diverting surface water from the face of the cut is excellent except in the rare case where moisture retention in the compaction rocks is necessary. Following the basic principle of diversion, water collecting on benches would be drained toward the hill and thence laterally to outfall drains within the cut limits or to the ends of the cuts.

Subsurface water unless drained through natural watercourses (such as fractures, joints, or bedding planes) can build up hydrostatic pressures which have in times past caused shear failures in rock slopes. To prevent this, the Corps of Engineers in 1943 drilled horizontal drain holes to depths of 250 ft beneath the top of the 300-ft deep cut at the Youghiogheny Reservoir spillway at Confluence, Pa. Admittedly subsurface drainage of rock slopes is rare, but it should be considered and installed where slope failure would result if hydrostatic pressure of critical magnitude is probable.

SLOPE DESIGN

After identifying the engineering considerations and the geological conditions, a rock slope may be designed using the principles that have just been reviewed. To make the design process a little easier rock slopes may be classified on the basis of the durability of the rocks composing the slopes. This would give three types of slopes:

1. On durable rock;
2. On nondurable rock; and
3. On combinations of durable and nondurable rock.

There is a final consideration. If the rocks are obviously far stronger than required

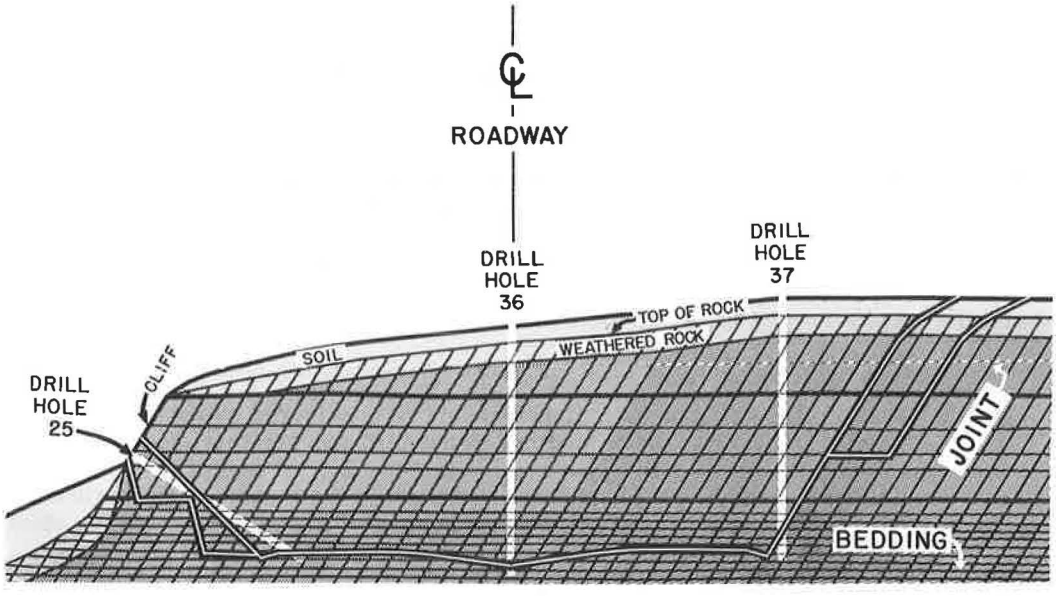

Figure 8. Geologic section of cut.

by the estimate of the expected shearing stress of the slope and the rocks will remain of relatively the same strength and not disintegrate during the life of the slope, then the shearing strength does not control the over-all slope angle. If, however, the shearing strength closely approaches or is less than the estimated shearing stress, then the slope must be redesigned against a shear failure.

Durable Rocks

In the strong rocks, the slope should be designed as steep as the geologic structure of the rocks and the stability of the rock segments will permit. The upper limit would be that where the cut was to be made entirely within the limits of one rock segment. This is possible in a massive rock free of all bedding and joints. Then the cut would be made vertical or even overhanging. If a choice is made to design, under normal geologic conditions, steeper than the geologic structure permits, the rock segments will become unstable and rockfalls will result, requiring increased maintenance. The oversteepening should be limited so that the increased cost of maintenance does not exceed the construction savings expressed as an annual charge composed of the items of amortization and interest over the life of the slope.

In considering the costs of increased maintenance vs increased construction costs, liability should not be overlooked. The courts have a tendency to examine the causes of landslides to ascertain whether they are natural phenomena or the results of actions by individuals, corporations, or public bodies. It seems that the trend is to hold the public construction agencies responsible for negligence. Thus the savings created by reduced construction costs must be weighed not only against increased maintenance costs but also against a possible catastrophe where proof of negligence would wipe out the construction savings in a moment.

Figure 8 shows a geologic section of a cut with a roadway. The problem is to construct the slope rising from the back side of the ditch to the ground surface in such a way that both construction and maintenance costs are at a minimum and the road is safe to drive at the design speed at all times. Now comes the need for all the information from each of those borings which seemed so numerous when they were planned and now seem so few.

From the top of rock down to the base of primary weathering where the rock becomes truly rock-like in character—unweathered and hard—the slope angle should be designed

on the basis of the shearing strength and resistance to erosion of the material. A slope of not steeper than 1:1 would be appropriate. In the unweathered rock below, the slope angle that would develop from a vertical cut would be dependent on the orientation, nature, and behavior of the rock segments composing the slope-forming rock. The section shows that the grain or rift of the rocks, represented by the joints, dips to the left at an angle of about 60° with the horizontal. This is a convenient and not unusual angle for a slope and so it is chosen for the right side of the cut. The rock segments in that area of the cut are defined by the attitude of the bedding and the joints. The second joint which cannot be represented on the section is in the plane of the section and serves to form a rhomboidal rock segment. By inspection, it is clear that the segment will not fall into the cut. Thus, the right side of the cut is stable when cut on the joints as shown in Figure 5.

On the other side of the cut, the joints dip into the slope, as shown in Figure 7. In such a situation the common methods of blasting will leave a jagged surface partially on the overhanging joints (the underside of the segments) and partially across the joints; that is, through the segments. The stability of the fractured segments remaining adjacent to the left slope surface depends on where the cut slope passes through the fragment and how much of the next roadward fragment remains as a buttress. The rock segment is a high, slabby piece of rock with a narrow base which does not underlie the center of gravity of the segment and is unstable. Most assuredly, a large number of the fractured segments are going to come falling down on the roadbed as rockfalls unless something is done to hold them in place, catch them, or cut the slope in such a way that such shapes are not formed. It would seem wise to presplit the left slope.

Catching the rockfalls is quite acceptable unless the room required for the benches equals or exceeds the width required to flatten the slope to the point where the segments are stable and rockfalls cease to occur. In this case less excavation would be required by a 1 on 1 slope than by a steeper slope and a bench.

For many persons, a bench on a rock slope, or at its base, is a necessity as an evidence of good practice and an insurance feature. The width of the bench is dependent on what kind of equipment is to be used to clean up the bench during maintenance. The spacing of the bench above the roadway is a matter of individual choice in most cases governed to some degree by the vertical reach of the maintenance equipment to be used in scaling the slopes for the prevention of rockfalls. Thus, the 40-ft maximum height suggested by Baker and Marshall (2) has a rational basis provided the location of the bench meets the criteria already set forth.

Figure 8 shows a bench at the base of the thick-bedded rock on the right side of the cut, placed mainly from habit, although it is believed that the rockfalls on this side would be of the rock-slide type with less tendency to fall free and bounce laterally. Were there a request to add a bottom bench, then the upper bench would be unnecessary. However, on the left side where the rock segments are going to strike rough surfaces during their descent and bounce in random directions, it seems wise to interrupt their descent with an intermediate bench as well as the widening of the roadway with a bench at that level. In doing this, it is found that a stable 1:1 slope involves less excavation, so benches are actually eliminated on the left side.

Nondurable Rocks

Nondurable rocks are rock-like in character in place but will disintegrate during the proposed life of the cut to soil-like materials, the depth and degree of disintegration being dependent on the original material and slope design. These are the materials that Mead called the "compaction shales" and others have called "immature shales"; these lie just beyond the realm of "stiff clays." If formation names are applied, the list would include familiar names like Bearpaw, Cucaracha, and Pierre, and less familiar names like Oaks, Pittsburgh reds, and Dunkard red shales. Yet these are mappable, geologic formations with specific lithologies, faunas in some cases, geologic structure and ages in the millions of years. By all standards except durability and hardness, they are rocks. Even during excavation they behave as rocks and look like rocks. Slopes to be cut on them are governed by preexisting planes of weakness; in some cases, faults, and in other cases, shear planes resulting from regional deformation as well as the

shearing strength of the rock. They are only briefly mentioned here because they will be discussed in detail in succeeding papers.

The design of the cut in the nondurable rocks must consider the eventual as well as the present character of the materials and should endeavor to preserve whatever strength these materials had before the cut. As the rock weathers, a flat slope will permit the formation of an insulating debris blanket and a weathered zone that will protect the underlying materials. If the blanket is absent and the slope steep, the entire mass may continue to weather to soil-like materials and the shearing stresses exceed the reduced shearing strengths. The slope angle will be controlled by erosion if the underlying rock mass retains its original strength. Preexisting, preslope zones of weakness will tend to control stability as with the durable rocks unless the nondurable rock is weaker than the shearing stress, which will then control the slope angle. Slopes on the nondurable rocks should be designed flat enough to prevent loss of the protective blanket on the surface as well as to prevent shear failure through the rock mass.

Durable and Nondurable Rocks in Same Cut

Designing with durable and nondurable rocks in the same cut is the typical situation in the Allegheny Plateau where durable sandstones are commonly underlain and overlain by less durable shales and clays. Here cuts are plagued with rockfalls coming from rocks in which there is rarely, except in the coal, a well-developed pattern of joints or fractures and the segments have a random orientation and distribution. Here, the drilling seeks to establish the sequence, thickness, lithology, depth of weathering, structure, and location of the beds that would form the slopes and the position of the water table. Because of the lack of a well-defined joint system, directional drilling would be employed nearer the hillside where expansion joints might have developed than in the middle of a through-cut area where only regional jointing would be expected. The water table studies would be directed to determining whether natural drainage would be sufficient to keep the slope mass drained or whether additional drainage by horizontal drains or tunnels would be required.

The author's (3) position on design of rock cuts in these materials 200 to 300 feet deep and now up to 20 years old was stated in 1953 and restated in 1960. Ackenheil discussed one of the really difficult slope designs in these rocks in a paper on the Fort Pitt Tunnel at Pittsburgh, Pa., (1). The following are the basic concepts:

1. Cutting each material to fit its characteristic weathering slope;
2. Addition of berms at the base of the rockfall producing zones;
3. Providing drainage to reduce the hydrostatic head behind the slope; and
4. Designing the over-all slope to be stable against shear failure.

ACKNOWLEDGMENTS

Harry F. Ferguson has provided constructive geologic criticism. Frank Pehr constructed the models and drawings in which he was assisted by Frank Tomasic. A. C. Ackenheil has critically reviewed the early drafts of this paper.

REFERENCES

1. Ackenheil, A. C., "Stability of the North Portal Area of the Fort Pitt Tunnel, Pittsburgh, Pennsylvania." Bull. Geological Soc. of America, 70:1559 (1959).
2. Baker, R. F., and Marshall, H. E., "Control and Correction." HRB Special Report 29:150-188 (1958).
3. Philbrick, S. S., "Design of Deep Rock Cuts in the Conemaugh Formation." 4th Annual Symposium on Geology as Applied to Highway Engineering, State Road Commission of West Virginia (1953).
4. Philbrick, S. S., "Cyclic Sediments and Engineering Geology." 21st Internat. Geological Congress, Pt. 20, pp. 49-63 (1960).
5. "Presplit Blasting—Paces Big Railroad Job." Eng. News-Record, 169:No. 19, pp. 38-40 (1962).