Evaluation of Rockfall and Its Control

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In the face of the requirements of "practical stability" and "comparative safety," the design phase of a rock cut is an ever-pressing problem. The situation is difficult because the fundamental relationships are complex and cannot be readily translated into a basis for design.

This study deals with the mechanics of rockfall from cliffs and talus slopes and discusses various ditch sections and rock fences that proved most effective in containing it. A mathematical consideration of rock trajectory is presented.

An intensive statewide study was initiated to determine what actually happens to a rock when it falls. Examples of falls were recorded in slow motion on 16-mm color film. Field work was conducted under varying conditions found in State-owned quarries and on existing highways. Natural and man-made talus slopes were also used.

It is concluded that the present standards dealing with rockfall design are inadequate, unrealistic, and even dangerous. Considerable expenditures are being made in an unsuccessful attempt to design for rockfall; and such expenditures have not resulted in safer roads. Design criteria describing a more realistic relationship among the variables of cliffs, angle of slopes, depth of ditches, and width of fallout areas are presented.

• ROCKFALL has been a plague to the design engineer and continues to be one because modern requirements demand high rock cuts. Often, funds are not available to cope properly with the problem. This fact has stimulated many papers in an attempt to find an economical solution. Many factors have been studied and evaluated, but in spite of this previous work, few engineers today are willing to say that this design will stop all rocks from falling, or that design is safe. It is a common experience that long after construction has been completed, many portions of a rock cut may produce a sustained quantity of rockfall. The familiar sign "Watch for Falling Rocks" is also visual testimony to the continued existence of the problem. Fallen rocks must be kept off modern highways.

This paper deals with rockfall in such a manner that any rock that falls, incidental or continuous, can be contained, regardless of the angle of slope from which it comes. The approach is novel and rather radical, considering existing design standards; yet the new approach is of proven practical value and embodies the maximum safety possible even though it may create, at the same time, another problem of "comparative safety." From the research work presently completed, rocks falling from cliffs can be contained by a deep ditch or a combination of a deep ditch with a special rock fence, whereas rock roll (what occurs on talus slopes) may require only a rock fence in conjunction with a normal ditch.

THE PROBLEM

One reason that current standards are inadequate and proving ineffective is that the problem has not been fully understood. It is doubtful that anyone has made a project of watching rocks fall before. It has been generally assumed that there is a direct rela-

Paper sponsored by Committee on Landslide Investigations.

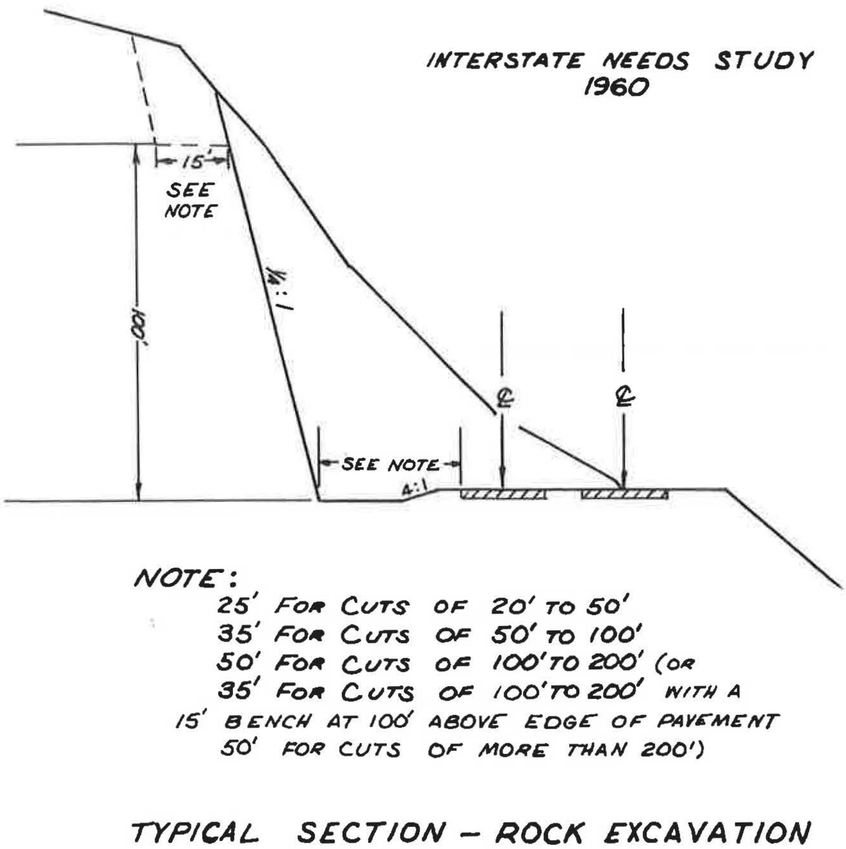


Figure 1. Current design standard.

tionship between the height of cliff and width of fallout area necessary to contain the material (Fig. 1). Figures 2 and 3 show that this relationship is in error. Present assigned values are arbitrary and unrealistic; hence, they are an unsafe solution. Another reason why the problem exists is that it is twofold in nature. Rockfall must take into consideration not only the minimum width of fallout zone determined by the frequency of stones making impact at a maximum distance from the base of the cliff, but also a means of stopping the stones after they have picked up angular velocity on impact. The latter feature particularly has not been emphasized enough.

Figure 4 shows a stone that is falling with but little angular rotation while in flight. After it makes impact, and especially if it strikes some inclined surface, it will begin to spin with tremendous speed. If the stone imbeds itself in debris on impact, much of this spin is dampened.

There is yet another reason why rock slopes continue to be particularly troublesome. The standard approach to the rockfall problem has been one of trying to restrain rocks from falling. This method does not consider or treat the case where a rock does fall. Most of the effort has been directed toward cutting more benches, flattening the slope, pinning down loose rocks, covering the area with wire mesh, etc. (Fig. 5). Actually, the choice of which restraining technique to use is, itself, so interdependent with other factors that at best it is an arbitrary solution. Too often the real answer is quickly covered by an avalanche of unruly factors that seldom go together neatly—and it is doubtful that attempts to restrain rocks from falling will ever develop into the proper approach for controlling rock slopes.

Certainly there has been an ever-growing need for a better method of predicting the state of stress in a rock slope or of discovering criteria for evaluating the many factors

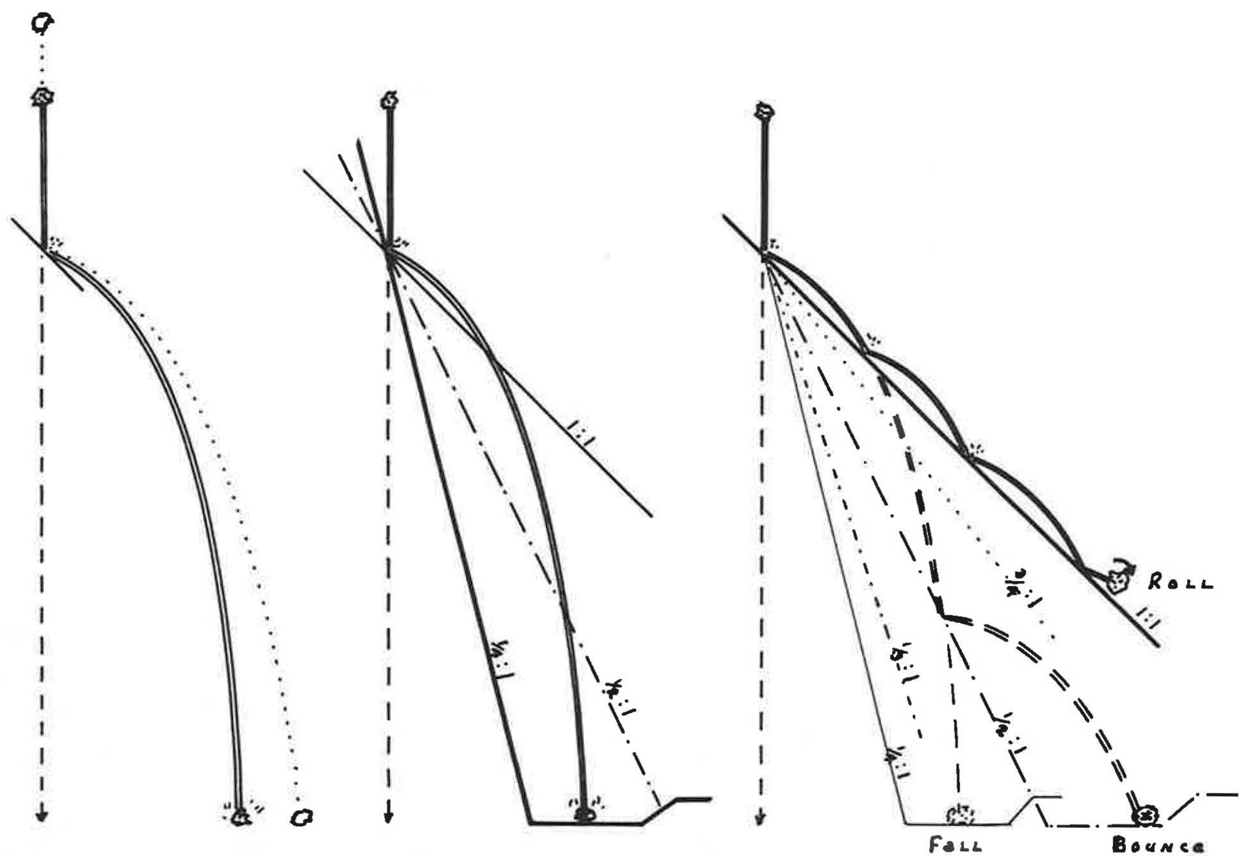


Figure 2. Path of rock trajectory superimposed on variable slopes.

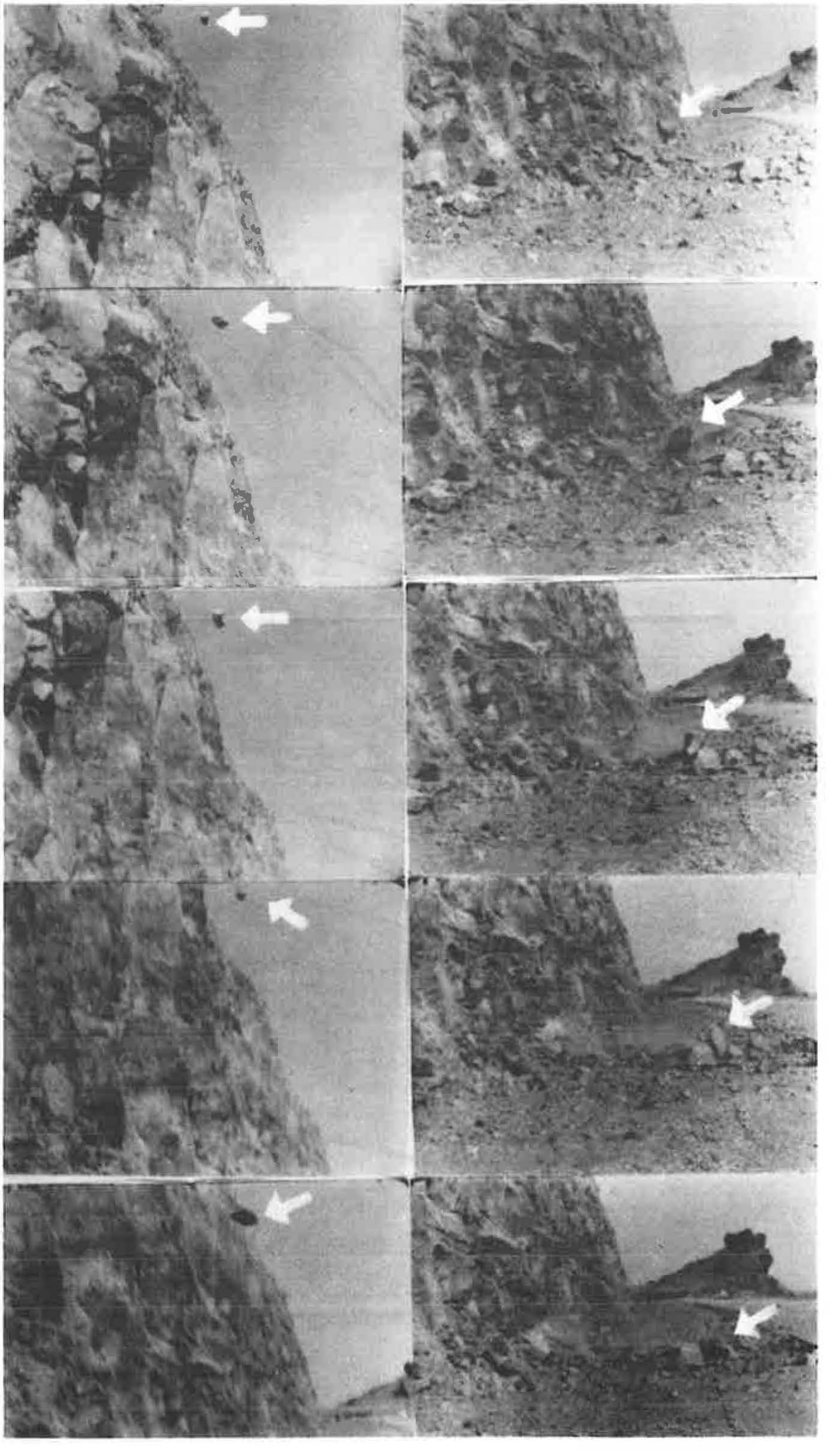


Figure 3. Rock in trajectory, showing that the further it falls, the closer it comes to base of cliff.

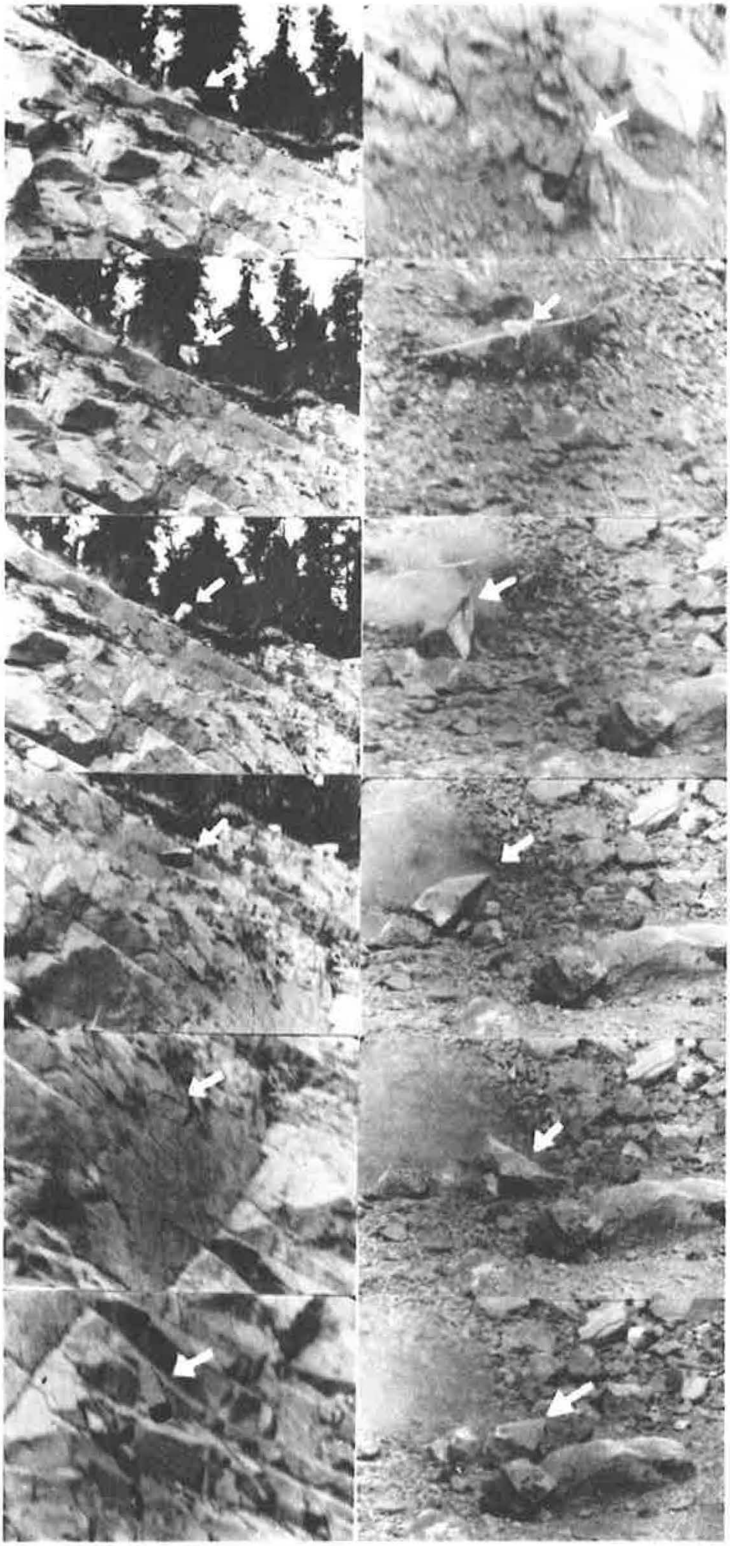


Figure 4. Angular stone with little initial angular rotation rolling after impact (pictures every 10th frame on slow-motion speed of 32 frames per second).

that may suggest what the ultimate strength of a rock mass might be. There is also a need for a means of predicting the stability of the material on the surface of a rock cut. So far, these factors remain elusive and many engineers approach the problem with apathy, as though walking up to a stone wall and half-heartedly demanding that the wall give up its secrets and come under their slide rule.

The unyielding rockfall problem is much like the proverbial wall. A simple method has not been devised for putting together effectively the many factors that govern the stability of rock slopes. At best, an analysis of the existing natural slope is but a clue to the expected internal stability of a rock mass, yet many valley walls are already at the critical angle with active erosion on the surface. A loose rock would seldom stop before reaching the bottom. In this sense, the plane of stability is the surface of the slope, and the problem that faces the engineers is one of determining what the proper slope angle for the proposed rock cut must be, if one is to keep loose rocks from falling onto the highways. The answer is not simple.

Figure 5. Wire netting, rockfall area on old construction.

To illustrate further the complexity of the problem, there is an unweathered granite mass having cubical jointing with its basalt joint system nearly horizontal or slightly tipping into the slope. This, as a rule, produces a combination of factors that tends toward the greatest stability possible. Now, the condition of the degree of weathering of the mass (which does not readily lend itself to a numerical consideration) is introduced. This quality will be especially crucial if the weathering takes place as spheriodal weathering of the joint blocks. In this case, the remaining unweathered round cores of each block have little to do towards strengthening the rock mass as a whole, even though the original joint pattern, which is one of the major controlling factors in stability, is still in the desirable direction. Because of a high degree of weathering, the expression "direction of joint pattern" has been relegated to a factor of little consequence in the stability formula, and is of diminishing value as the degree of weathering of the mass increases. Finally a point is reached where the remaining unweathered cores of each block no longer line up or interlock at all so as to receive support one from another. In this State, the degree of weathering has introduced values of such great uncertainty that there is no clear-cut answer as to the proper slope design. The engineer is required to fall back on educated guess or trial and error.

Over and above such things as degree of weathering, there are still many other physical properties within a rock mass that must also be juggled together to come up with, not the safest but the most practical, stable design. To keep rocks from falling at all would be very desirable, yet it takes only one loose rock for a potential accident. The most practical safe design based on foreknowledge, therefore, has not been constructed to date. Also, the proper slope treatments for any one area may vary widely from those used successfully elsewhere, and both physical and chemical properties of rocks vary widely within States and even more so within national boundaries. Even within the same rock cut not all zones produce the same problem. This condition points up the fact that there cannot be a common formula using the restraining technique, because there are just too many factors involved.

In the North Appalachian and New England areas one can find a great many varieties of rocks, many of which (due to their thickness or lamination, strike, dip, physical and chemical properties, climatic, and other factors) will require different slope treatments. Yet, it is impractical to change slope design within short limits, as would be required.

In some areas, sandstones, limestones, dolomites, and shales are most common. The coastal plains contain crystalline rocks with high mica content. There are massive granite bodies in New England and other areas. Sandstones vary widely in their physical make-up and structural properties. Individual grain sizes vary from fine to coarse, and the bonding agent varies from weak to strong. Some are permeated by numerous hairline cracks. Others are massive and thickly laminated. Some rocks are soft, others hard and brittle. Joints which sometimes are numerous may break in blocks or at acute angles. Alternate layers of hard and soft shales present special problems, especially if they are interspersed with high organic zones. Many of these qualities are within the same rock cut.

Although limestones and dolomites are structurally similar in character, they vary widely in thickness and hardness. Crystalline rocks present special problems, especially where micaceous softer portions separate the denser and thicker seams. Structural qualities of a rock become important—particularly when taken into consideration with road alignment, in which the road may change directions with the prevailing strike and dip of the rock mass, and thus concentrating special unfavorable conditions that may result in landsliding or exceptionally heavy rockfall. In view of these many variables of design, it is easily understood why many areas continue to create a rockfall problem, and that the concept of trying to restrain every rock from falling is faulty. There have been some steps taken in a new direction which use the concept of containing the rocks if they do fall, but this is not going far enough.

Although current designs are taking into consideration fall-out zones, they do not keep the rocks off highways. This shortcoming touches on the related problem of comparative safety, which has inhibited a reasonable solution. If one safety measure comes in conflict with another, it is only reasonable that a subordinate position must be assigned to it for the sake of a new and better design.

As a rule, safety measures do not conflict; but if they do, the preferential one should be that which would cancel out the greatest danger. This point is pertinent in the case of rockfall, because there is a conflict. When gentle off-shoulder slopes, designed for the open road, are brought into rockfall areas, they provide the ramps for stone to come up on the highway. Therefore, there are urgent and compelling reasons to substitute a steep shoulder design in place of the gentle one; for what was thought to be a feature contributing to the overall safety of the highway has now been proven to be, in rockfall areas, a detriment and a hazard.

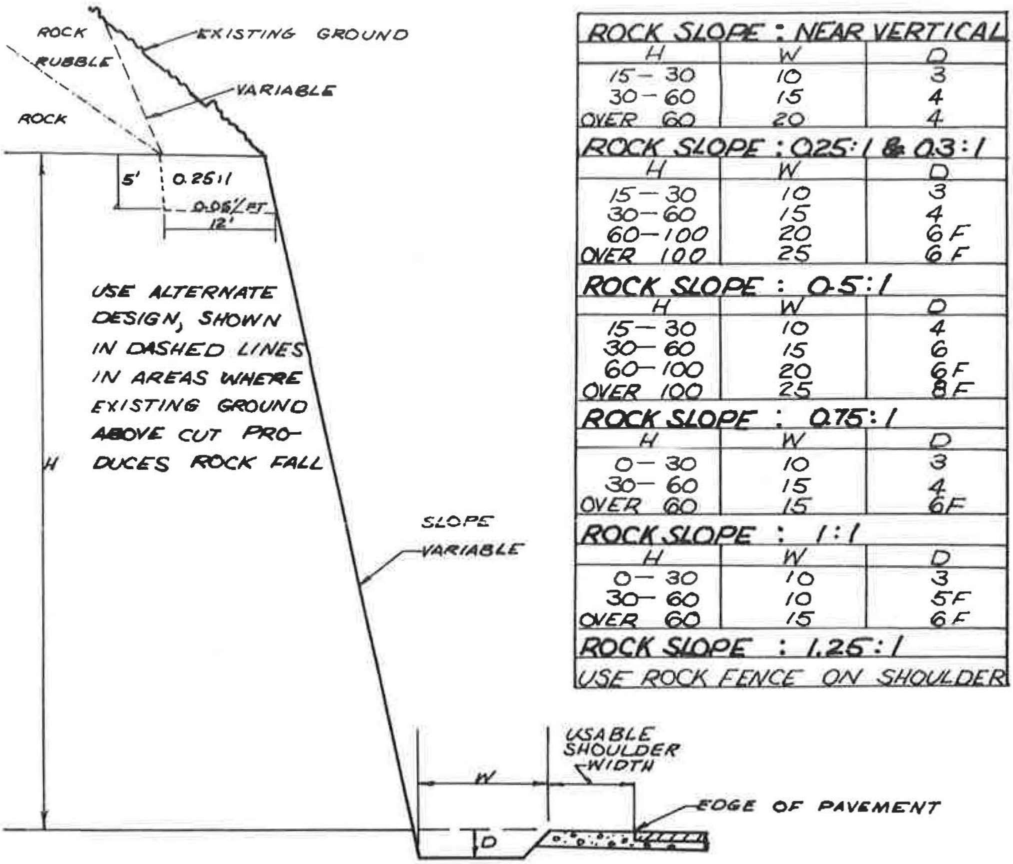
DATA COLLECTION

At the outset it became apparent that a full-scale test was necessary to be able to evaluate properly rock trajectory and other characteristics of rocks in flight. For this reason a 16-mm slow-motion camera was used to make it possible to record hundreds of conditions of rockfall. To keep a pictorial record of these conditions, reference lines (both vertical and horizontal) were employed. It was found that plastic flagging tape was excellent for this purpose, being both colorful and tough. The vertical line was held aloft by small helium-filled weather balloons. The ground end of the tape was anchored to a rock 20 or 25 ft from the base of the cliff. The balloon end was pulled towards the top of the cliff so that the reference tape would be essentially parallel to the face of the cliff. A position of advantage was chosen so that the camera viewed the rockfall from the side to observe its trajectory. Other reference lines were used running parallel along the base of the cliff at 10-ft intervals. It was thus possible for the camera to record the path of trajectory and point of impact by such means. From a study of the impact areas, it was possible to determine the necessary width of the fallout area required for any particular set of conditions. The vertical reference made it possible to determine whether the rocks, at any point, went wider than the proposed fallout zone.

Most of the study was conducted in hard basaltic rocks of all sizes. This proved to be a rock of high resilience and rebound characteristics. Softer rocks, such as sandstones and scoraceous basalts, were much less violent on impact. It is assumed, therefore, that the values in Table 1 giving the relationship between width of fallout vs height and angle of slope will satisfy the maximum demand in most rock work.

TABLE 1

RELATIONSHIP OF VARIABLES IN DITCH DESIGN FOR ROCKFALL AREAS



H	W	D
ROCK SLOPE : NEAR VERTICAL		
15 – 30	10	3
30 – 60	15	4
OVER 60	20	4
ROCK SLOPE : 0.25:1 & 0.3:1		
15 – 30	10	3
30 – 60	15	4
60 – 100	20	6F
OVER 100	25	6F
ROCK SLOPE : 0.5:1		
15 – 30	10	4
30 – 60	15	6
60 – 100	20	6F
OVER 100	25	8F
ROCK SLOPE : 0.75:1		
0 – 30	10	3
30 – 60	15	4
OVER 60	15	6F
ROCK SLOPE : 1:1		
0 – 30	10	3
30 – 60	10	5F
OVER 60	15	6F
ROCK SLOPE : 1.25:1		
USE ROCK FENCE ON SHOULDER		

When required for slope stability the use of benches is satisfactory; however, they do not alter the design and values shown. Ordinarily their use will be a result of the soils study and be on the recommendation of the materials engineer.

Where the existing ground above the top of cut is on a slope approximating that of the cut slope, the height (H) shall include the existing slope or that portion of it that can logically be considered a part of the rock cut.

Ordinarily guardrail shall be provided where D is greater than 3. F permits diminishing D to 4 if fence is also used.

A statewide study was conducted using many quarry faces and conditions. Later, under controlled test procedures, traffic was stopped, and various existing rock cuts were checked. Newly completed rock work also was tested, which had been constructed with fallout zones. In one instance, cliffs from 90 to 130 ft high had fallout zones of 19 and 34 ft in width, and were cut on ¼:1 slopes. Although the excavations were completed with the exception of 4:1 off-shoulder slopes, many rocks rolled as much as 80 or 90 ft from the base of the cliff. Nearly all rocks made their initial impact within a 20-ft fallout zone. It became apparent that if one was to contain the rocks effectively it would be necessary to deflect them back towards the cliff, or provide a wall or buffer condition to stop the roll.

TEST TRAILER

Figure 6. Test trailer used as portable steep shoulder and ditch section (deck = $1\frac{1}{4}$:1 slope).

To implement the conclusion that some device must be placed at the edge of the fallout area to stop rolling rocks, a trailer (24 ft long), heavily-decked with planking and tipped to a $1\frac{1}{4}$:1 slope facing the cliff, was used (Fig. 6). The trailer deck could be set on the ground by removing a few pins and backing into the reach. In effect, the unit became a portable ditch section that was taken from place to place and was used as a deflector or a bumper for rock roll. Whenever the trailer was set at the edge of the fallout area necessary for that type of cliff, no rocks ever went over the top in flight. All rocks were stopped when they rolled up the deck, many of them looping over and falling back towards the cliff. When the trailer was used on flat slopes in the range of 1:1, it proved just as effective in stopping rocks as it did in rock cuts (Fig. 7).

If one replaced the trailer with a constructed slope, it is believed that the natural materials of the slope will enhance the rockfall design, because the rocks will dig into the ground rather than stay on the surface as was apparent with the trailer. One test area was selected which contains much blow sand from the Columbia River in conjunction with some newly constructed rock cuts. It was found that on impact, most rocks lost much of their rebound quality as they dug into the soft sand shoulder slopes. It is not necessary, however, to blanket a ditch area with sand, because fine quarry-run spoils are just as effective.

ROCKFALL FROM TALUS SLOPES

It is difficult to comprehend the magnitude of some talus slopes along mountain highways. It is still more difficult to realize that each of these stones has at some time fallen from the parent cliff and rolled to its present position, only to be buried by other rolling stones. If one lingers long with this concept, the ever-present danger of rolling stones becomes quite apparent (Fig. 8).

Rolling stones are just as dangerous as those generating from rock cuts and it is not uncommon to have talus stones roll completely across the highway, losing themselves over the hill, and obscuring the very existence of a dangerous condition by a mere lack of evidence. Talus slopes are an integral part of rockfall so it becomes necessary to study rock roll in great detail to see if it contains characteristics that might be helpful to the design engineer. Field work consisted of rolling many stones to evaluate their characteristics and to study how the deposits are formed.

The following are some observations that might prove useful: natural talus slopes have curved surfaces concave upward with their flattest portion near the base of the hill. The materials in them are graded imperfectly with the finest materials generally in the steeper portion next to the parent cliff. Each rock in the talus slope has theoretically found its assigned place according to its size, momentum, and slope angle, and conditions of the slope over which it has rolled. Ordinarily, it is the coarser materials that stand at a higher angle of repose; but on talus slopes, the larger materials are found far from the parent source in the flattest portion of the toe region. Obviously, many factors influence the distribution of the deposit; such as angular motion, the sizes of the material on the slope, the momentum of the piece, and subsequent fracture.

If a stone is rolling at high speed along an inclined surface, it touches only the high point of that surface with its own high points. Much of its time is spent in the air and its roll is similar to dice rolling on a rough inclined surface. If the stone is larger than the materials over which it rolls, its angular momentum usually increases until two basic factors begin to diminish its velocity: (a) a flatter portion of the slope, and (b) larger materials over which it must roll. As the rolling stone meets material of

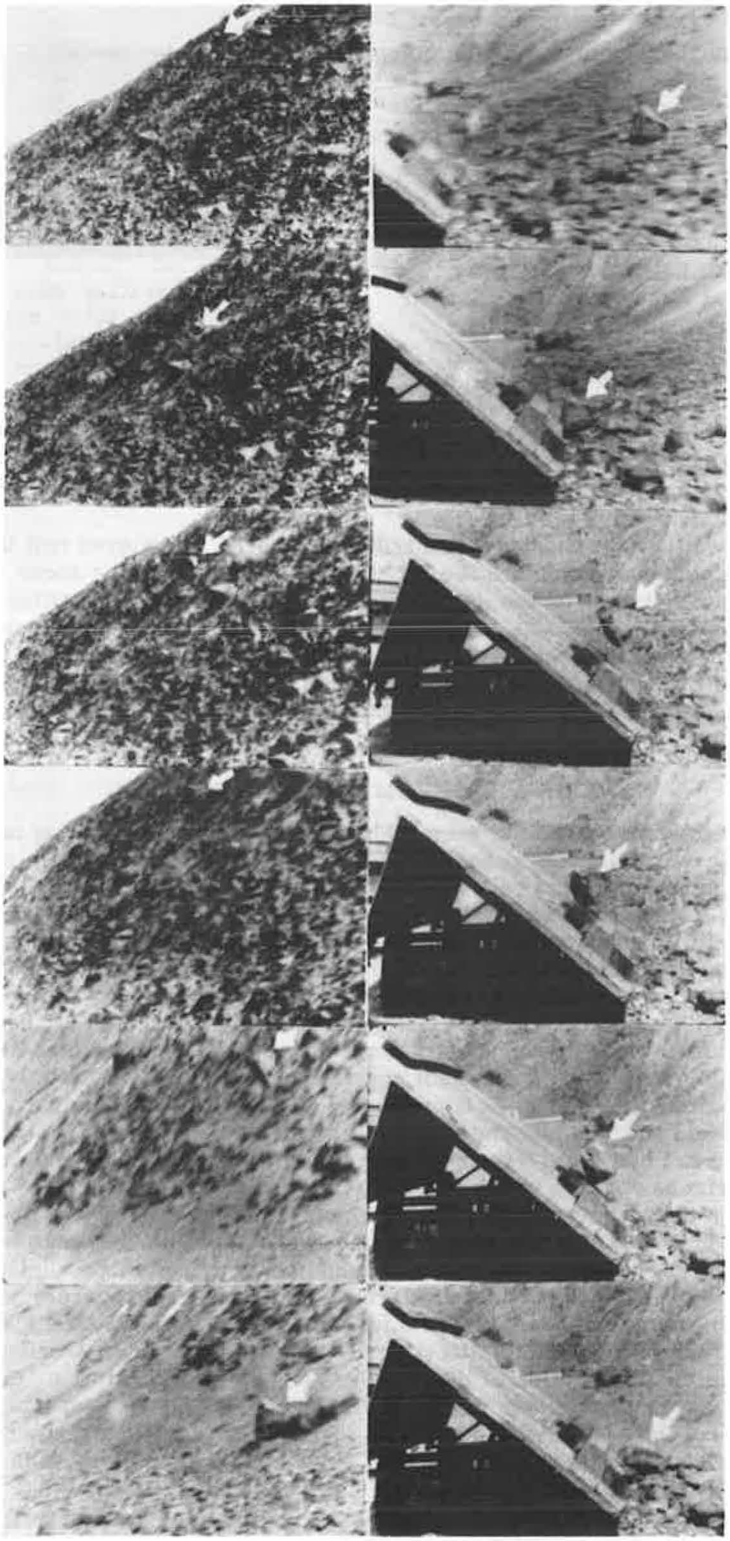


Figure 7. Test trailer used on 1:1 slope of compacted basalt rubble (height of cliff = 110 ft); rock finally rolling backward off trailer deck.

Figure 8. Double talus slope along Columbia River, Wash.; height of cliff in middle background = 400 ft.

its own size, it begins to collide against common pieces, losing energy at first by impact. Progressive slowing-down causes it to fall lower and lower into the irregularities of the surface of the slope so that, as it proceeds, it must raise itself repeatedly over comparable stones. This deceleration process crescendos markedly as the speed of the stone diminishes, so that the stone is soon trapped in voids between stones of its own size, resulting in a segregation of the materials. If for some reason a large stone gets stopped on the slope higher than normal, it may cause a deposition of similar material around it which would not ordinarily have stopped there (Fig. 9).

Continuous rockfall causes talus slopes to grow so rapidly that original conditions will change at any one elevation. Talus slopes, therefore, become stratified and closely resemble the cross-section of a river delta. Once a stone is trapped on the surface, it never, of itself, begins to roll again (although much of the material may move about by debris sliding). On mature natural slopes, rock roll is seldom a problem for highways located near their base; but an excavated slope is not a talus slope because it now stands at the angle of repose of the material. In many cases, cut slopes or backslopes may reach hundreds of feet above the roadbed and a stone once started on this slope cannot stop until it reaches the roadway below. Figure 10 shows a talus slope cut just steeper than the bedding plane of the deposit. This causes popouts and progressive failure of the slope. In cases where long backslopes in talus material exist, some protection for the traveling public is most desirable, if not mandatory.

If a roadway location is placed high on the slope it generally requires a greater amount of material to be handled than one lower down for any given roadway width. This is due to the curvature of the talus surface and the flatter angle of repose of the finer materials near the top of the talus pile. Of course, this is true only for locations that do not intersect the cliff face above. Generally, there is a critical maximum for a roadway width. Any additional widening beyond this critical point, such as the construction of wide ditches as a means of containing rock roll, becomes economically prohibitive. For this reason, a special rock fence was tested and is offered as a device to arrest rock roll in lieu of a wide ditch area as a catch basin feature.

ROCK FENCE

The rock fence is designed to decelerate a rolling stone and to retard its angular velocity. Nearly all rocks stay very close to the talus surface while they roll. This characteristic permitted a chain link fence only 6 ft high to encounter all rolling stones. The fence is novel in that it is not mounted like an ordinary fence, but is suspended like a curtain from a cable. The cable, in turn, pulls on a compressive spring to absorb the shocks of the rocks. The spring that was used for the test was one taken from an old cable guardrail set-up. The cable is supported by fence posts every 50 ft to keep the top of the rock fence essentially in a horizontal line. The installation is mounted on the slope above the ditch line, or on the back side of guardrail posts on the shoulder of the road (Fig. 11).

SOME OBSERVATIONS ABOUT ROCKFALL

There are many factors to analyze in considering the characteristics of rock trajectory. Some of these are size and shape of the stone involved, angle of slope, surface characteristics of the slope, height of cliffs, broken slope features, kind of rock, gravity, and time. Common to all rockfall, however, is the factor that rocks start

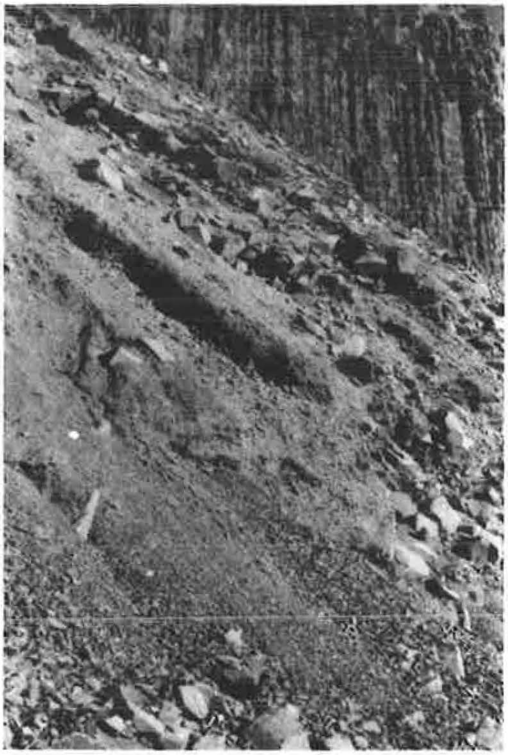


Figure 9. Partial cross-section through talus material, showing fine grading of materials under surface layer of boulders.

Figure 10. Bouldered layer on surface in Fig. 9 stripped off, showing segregated strata deposited flatter than angle of cut slope.

from a static position by rolling and then begin their descent. Depending on conditions, they will either continue to roll or take one or two bounces and go into flight (Fig. 12).

Rocks can arrive on the roadway after one or more of the following modes of travel: sliding, rolling, skipping, and vertical fall. Recent field studies have caused engineering assumptions regarding safety requirements to come into question. It is conceded that several simplifications are necessary to keep analytical considerations manageable, but it is felt that results agree rather well with empirical data advanced.

A spherical rock mass is assumed to be moving under the following circumstances.

Case 1. A smooth, uniform, inclined slope is assumed. (Experience shows that most rocks "stay put" on the slope up to an inclination of about $1\frac{1}{3}$:1. Steeper slopes cause the rocks to begin to roll at an accelerated rate.) If the stone and the plane are perfectly smooth, then the rock will roll continuously on that surface, regardless of the inclination of the plane. Although this condition is never reached fully in nature, it is approached when the slope is composed of fine materials.

Case 2. A broken slope or a rough slope producing "ski jump" features are added to Case 1. This interesting phenomenon deals with impact. Impulsive forces act for a very short time, yet are of great magnitude. When there is impact of a falling particle against another body (such as a rock on a cliff face), there is a change of velocity that depends on the nature of the materials and angle of impact. (It is observed in nature that rocks originating on steep slopes first begin their descent by rolling, then, usually after one or two short bounces, go into trajectory. Seldom do these rocks touch the slope again within the practical limits of ordinary rock work. This is true especially for slopes that are $\frac{1}{3}$:1 and steeper.)

In view of the fact that some quality of both cases cited will always exist, theoretical

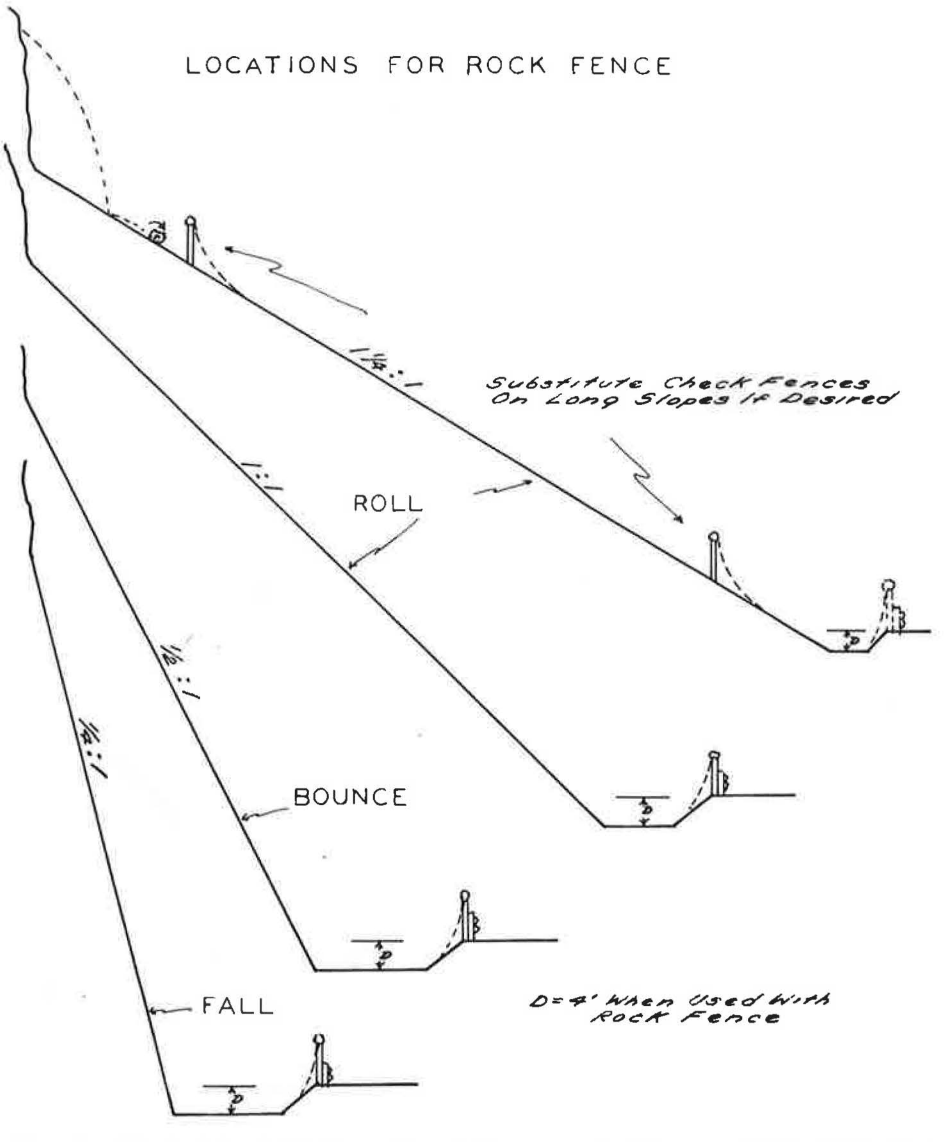


Figure 11. Position of installation of rock fence used either as check fence on slope or as protection on highway. Though ditch design for $\frac{1}{4}$:1 and $\frac{1}{2}$:1 for a 100-ft high slope is same, yet rock from $\frac{1}{2}$:1 slope must cover a greater distance before encountering same fence.

physics can offer a description of the motion of the falling rock. For example, a sphere is in trajectory with mass m, angular velocity a_o, translation velocity v_o, in trajectory at angle θ_o with the horizontal, impinging on a plane A-B that makes an angle of θ' with the horizontal (θ_o and $\theta' < 90^0$). To simplify the algebra, an origin is placed at time t_o when the sphere first comes under consideration. The X-axis is horizontal and the positive direction of the Y-axis is downward. The trajectory may be described parametically for any time t and for any inclination of plane A-B.

$$\text{(parabola)} \begin{cases} x = v_o (\cos \theta_o)\ t \\ y = v_o (\sin \theta_o)\ t + \frac{1}{2} g t^2 \end{cases}$$

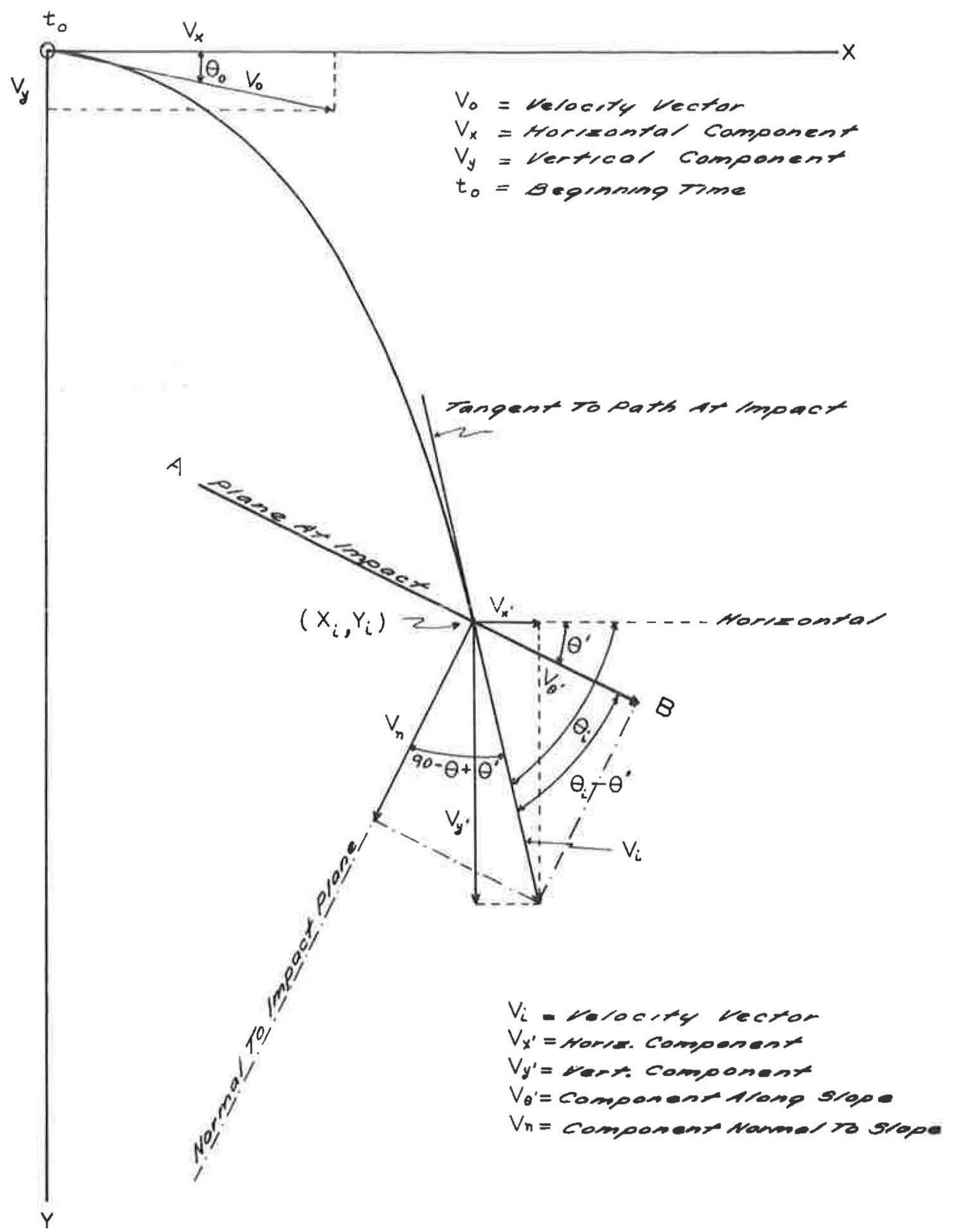


Figure 12. Theoretical consideration of rock trajectory.

in which g = acceleration due to gravity.

If (x_i, y_i) is the point of impact on A-B, and it is assumed that $a_o = a_i$ and a_i = angular velocity at t_i,

$$v_i = \sqrt{v^2_{x'} + v^2_{y'}}$$

$$\text{(constant)} \quad v_{x'} = v_o \cos \theta_o$$

$$v_{y'} = v_o \sin \theta_o + gt_i$$

$$v_i = \sqrt{(v_o \cos \theta_o)^2 + (v_o \sin \theta_o + gt_i)^2}$$

$v_{x'}$, $v_{y'}$ are the horizontal and vertical components of v_i.

On impact, two major actions occur: First, the sphere rolls down the slope due to both its angular velocity and gravity. Coefficient of friction and stability of surface are factors of considerable importance on talus slopes but are of less importance in rock cuts. Second, compression and restitution phases of impact based on elasticities tend to send the sphere into trajectory. The worst condition possible (greatest horizontal impulse) is given when the vector of v_i (velocity at impact) makes an angle of about 45^0 with the plane A-B. In either situation, the force normal to the impinged plane should be determined. If θ_i is the angle with the horizontal that the sphere makes at t_i, then

$$\tan \theta_i = v_{y'}/v_{x'}$$

$\theta_i - \theta'$ = the angle between the trajectors at t_i and the plane of impact; $90^0 - \theta_i + \theta'$ = the angle between the trajectory and the normal to the plane; $V_{\theta'}$, the component along the slope, will accelerate the roll during contact; V_n, the component normal to the surface, will be a factor in the rebound from the surface.

If the impinging mass is not spherical an appreciable movement will be imparted, causing a change in angular velocity.

Angular momentum is a very pertinent part of the rockfall study and it is not only involved in rock roll on cliffs and on talus slopes, but is one way by which the inertia from a rock in trajectory is dissipated and transferred on impact. It was observed that even a falling stone revolving backward from the direction of normal roll would, after impact, pick up angular momentum in the opposite direction. Further, if a falling stone had considerable angular velocity to start with, it could be immensely increased after impact.

In a general way, rocks that roll on ½:1 slopes are given the greatest horizontal impulse, and are the most dangerous as far as controlling them is concerned. In the rare cases where a rock may strike the face of a steep cliff the second time, the piece is traveling at such high velocity downward that even though it rebounds again, it does not have time to cover much horizontal distance; hence, it still makes impact within the fallout zone. Such stones have tremendous horizontal momentum, however, and roll considerable distances after impact. If a rock falls from a vertical cliff, it usually has little or no angular momentum or horizontal impulse to start with; thereupon, after making impact at right angles to the ground, it calmly comes to a stop. In considering the kind of backslope to design, the height of a cliff is very important. A rock falling from a 40-ft high cliff on a ¼:1 slope may roll further from the base than a rock starting from the same height on a ½:1 slope. This is due to the fact that there is not sufficient time in the latter case for a rock to gain appreciable momentum, whereas the falling rock picks up momentum quickly. But with higher slopes, in the range of 100 ft, the ¼:1 slopes permit a rock to make nearly vertical impact, whereas ½:1 slopes induce a rock to have tremendous horizontal momentum and angular velocity.

Size and shape of a rock have little bearing on its falling or rolling characteristics. The greatest difference is with large rocks that stay close to the face of the cliff and may from time to time touch on the way down. The shape of a rock has little importance unless it is long, like a pencil, which retards roll and gives eccentric action. Flat or angular-shaped rocks made little difference. Perhaps this is analogous to dropping a handful of pennies and dice on the floor and noting the distances that they roll from point of impact. Rocks that fall in trajectory seldom give a high bounce after impact but rather, change their linear momentum into angular momentum. It is this feature that permits a steep off-shoulder slope or a steep slope with a fence to contain them.

SUMMARY

Because a falling rock must obey certain natural laws of mass, energy, velocity, impact and restitution, as well as being influenced by friction, time, gravity, and other things that have been rather well-known since Newton's time, it seems only reasonable that the behavior of falling stones would lie between certain limits, limits that can be used as a basis for design to contain them.

Field work has supported this concept, permitting the use of (a) fallout areas in which to dissipate the enormous energy arriving at impact; (b) steep off-shoulder slopes to combat the angular momentum of the rock generated after impact; (c) rock fences as a flexible buttress and decelerating device to dampen off angular velocity and to smother the rock if it becomes necessary to contain it.

A new approach to the rockfall problem has been opened. Old concepts have been evaluated in the light of new data and must be discarded along with other obsolete ideas, such as "the larger the rock, the faster it falls."

Practical value has resulted from this study in that untold savings will result from new design, and a generous share of practical safety has been served to the traveling public.

ACKNOWLEDGMENT

This study was sponsored by the U. S. Department of Commerce, Bureau of Public Roads, and the Washington State Highway Commission.