Chapter Seven

Prevention of Landslides

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Preceding chapters have been devoted to the nature, classification, recognition, and investigation of landslides, all of which are of only academic interest unless they are utilized in the prevention or correction of landslides. On the other hand, a knowledge and understanding of these subjects will be of invaluable assistance in the selection and design of the most economical and effective methods of preventing or correcting landslides, which should be the ultimate objective of the reader for whom this book is primarily intended.

There is no sharp line of demarcation between prevention and control or correction of landslides; the basic principles governing them are the same, and many of the general methods of treatment are similar. However, there are significant differences which justify separate chapters on the two phases of slide treatment, even though this results in some duplication or repetition.

The treatment of potential landslides, where there is no evidence of any previous slide movement, would clearly be preventive in nature. Likewise, there would be little doubt that treatment of landslides developing during or subsequent to construction should be classified as corrective in nature. Where old landslides are involved, however, treatment might be considered as either preventive or correctional — if the landslide is geologically old and has been quiescent for centuries, treatment could scarcely be classed as correctional; on the other hand, treatment of old landslides which apparently have been inactive for a number of years, rather than of centuries, might be considered as either preventive or correctional.

Any attempt to classify an existing slide according to age or degree of quiescence would be confusing. Accordingly, prevention of landslides as discussed in this chapter will apply not only to unstable areas and potential landslides, but also will include all existing landslides which might be disturbed or reactivated by proposed construction, either by imposing additional load or by excavation. The category of slide correction, treated in Chapter Eight, then includes all landslides which develop during or subsequent to construction.

As would be expected, most of the treatment methods for the prevention of landslides are also used for correction or control purposes. On the other hand, some of the corrective measures are seldom if ever applied as preventive treatment. Table 4 is a summary of the more common methods of treatment for both correction and prevention of landslides. For convenience of reference the numerous methods of treatment have been listed under four general types, with a fifth category for miscellaneous methods, most of which are used less frequently. In this table there is no reference to the cause of the landslides. This omission is feasible only because it is not always essential to know the cause or causes of a landslide as such in order to prescribe treatment. Frequently there is no one single cause for a land movement, but a combination of two or several contributing factors.

TABLE 4

SUMMARY OF METHODS FOR PREVENTION AND CORRECTION OF LANDSLIDES

Effect on Stability of Landslide	Method of Treatment	General Use		Frequency of Successful-Use[1]			Position of Treatment on Landslide[2]	Best Applications and Limitations
		Prevention	Correction	Fall	Slide	Flow		
Not affected	I. Avoidance methods:							
	A. Relocation	x	x	2	2	2	Outside slide limits	Most positive method if alternate location economical
	B. Bridging	x	x	3	3	3	Outside slide limits	Primary highway applications for steep, hillside locations affecting short sections (parallel to c/L)
Reduces shearing stresses	II. Excavation:[3]							
	A. Removal of head	x	x	N	1	N	Top and head	Deep masses of cohesive material
	B. Flattening of slopes	x	x	1	1	1	Above road or structure	Bedrock; also extensive masses of cohesive material where little material is removed at toe
	C. Benching of slopes	x	x	1	1	1	Above road or structure	
	D. Removal of all unstable material	x	x	2	2	2	Entire slide	Relatively small shallow masses of moving material
Reduces shearing stresses and increases shear resistance	III. Drainage:							
	A. Surface:							
	1. Surface ditches	x	x	1	1	1	Above crown	Essential for all types
	2. Slope treatment	x	x	3	3	3	Surface of moving mass	Rock facing or pervious blanket to control seepage
	3. Regrading surface	x	x	1	1	1	Surface of moving mass	Beneficial for all types
	4. Sealing cracks	x	x	2	2	2	Entire, crown to toe	Beneficial for all types
	5. Sealing joint planes and fissures	x	x	3	3	N	Entire, crown to toe	Applicable to rock formations
	B. Subdrainage:							
	1. Horizontal drains	x	x	N	2	2	Located to intercept and remove subsurface water	Deep extensive soil mass where ground water exists
	2. Drainage trenches	x	x	N	1	3		Relatively shallow soil mass with ground water present
	3. Tunnels	x	x	N	3	N		Deep extensive soil mass with some permeability
	4. Vertical drain wells	x	x	N	3	3		Deep slide mass, ground water in various strata or lenses
	5. Continuous siphon	x	x	N	2	3		Used principally as outlet for trenches or drain wells

Increases shearing resistance	IV. Restraining Structures:							
	A. Buttresses at foot:							
	1. Rock fill	x	x	N	1	1	Toe and foot	Bedrock or firm soil at reasonable depth
	2. Earth fill	x	x	N	1	1	Toe and foot	Counterweight at toe provides additional resistance
	B. Cribs or retaining walls	x	x	3	3	3	Foot	Relatively small moving mass or where removal of support is negligible
	C. Piling:							
	1. Fixed at slip surface		x	N	3	N	Foot	Shearing resistance at slip surface increased by force required to shear or bend piles
	2. Not fixed at slip surface		x	N	3	N	Foot	
	D. Dowels in rock	x	x	3	3	N	Above road or structure	Rock layers fixed together with dowels
	E. Tie-rodding slopes	x	x	3	3	N	Above road or structure	Weak slope retained by barrier, which in turn is anchored to solid formation
Primarily increases shearing resistance	V. Miscellaneous Methods:							
	A. Hardening of slide mass:							
	1. Cementation or chemical treatment							
	(a) At foot		x	3	3	3	Toe and foot	Non-cohesive soils
	(b) Entire slide mass		x	N	3	N	Entire slide mass	Non-cohesive soils
	2. Freezing	x		N	3	3	Entire	To prevent movement temporarily in relatively large moving mass
	3. Electro-osmosis	x		N	3	3	Entire	Effects hardening of soil by reducing moisture content
	B. Blasting		x	N	3	N	Lower half of landslide	Relatively shallow cohesive mass underlain by bedrock Slip surface disrupted; blasting may also permit water to drain out of slide mass
	C. Partial removal of slide at toe	-	-	N	N	N	Foot and toe	Temporary expedient only; usually decreases stability of slide

[1] 1 = frequently; 2 = occasionally; 3 = rarely; N = not considered applicable.
[2] Relative to moving or potentially moving mass.
[3] Exclusive of drainage methods.

Moreover, the methods listed in Table 4 and described in this and the following chapter can only be applied successfully if the nature and history of the slide are thoroughly understood; whether or not such understanding is translated back into terms of the causes of the slide is immaterial to solution of the problem. All of the landslide treatments which improve the stability of an active or potential landslide mass do so either by reducing the activating forces which tend to induce the movement, or by increasing the shearing resistance or other forces that resist the movement. It is apparent, therefore, that any treatment which accomplishes either of these two effects will be of some benefit in preventing or minimizing landslide movement. For any particular landslide, however, not all types of treatment will be equally effective or economical. The selection of the best method of treatment is an engineering problem, requiring the evaluation of many factors which will be discussed later in this chapter.

The *prevention* of landslides is, in many respects, more difficult than *correction*, from the standpoint of both analysis and design. The limits, type and depth of an existing active slide can usually be determined by exploration and investigation; in contrast, the prevention of an incipient or potential landslide requires: first, recognition of the hazard, which may not be at all evident from superficial examination; second, anticipation of the character and magnitude of movement which may occur; and third, design of suitable treatment which will prevent any land movement during or following the proposed construction. Perhaps a fourth requirement should be added — decision by those in control that the hazard is sufficiently real to justify the expense of treatment.

One type of landslide, because it is so prevalent and costly to correct, is particularly troublesome to highway engineers; this is the roadway "slipout," a landslide which occurs at or below roadway grade, with a portion or all of the roadbed moving downward and outward. Such slipouts usually occur where the roadbed is partially on embankment, and typically do not extend above roadway grade. However, if the surface of rupture is deep and the highway is on sidehill, cut and fill section, the head of the slipout may be within the cut slope above the road.

In the entire field of landslide prevention and control, no other type of landslide presents such a challenge to the soil engineer and geologist, or affords such an opportunity for effecting savings in cost. Even though much less spectacular than the large landslides in slopes above roadway grade, the slipout of a large embankment is difficult and costly to correct. Often a nominal expenditure for treatment during construction would prevent the subsequent occurrence of a slipout which might seriously impair the usefulness of the highway and cost tens of thousands of dollars to correct.

This chapter considers only those embankment slipouts in which the surface of rupture is wholly or partially in original ground beneath the fill. Embankments may fail within themselves due to improper slope design, poor compaction, or similar causes. Although these failures are true landslides, according to the definition used in this book, embankment slope failures above natural ground are not discussed here. Similarly, embankments placed on level terrain — that fail solely because of displacement of weak foundation soil — are not treated here.

It will be noted that throughout this book the landslides most frequently cited or discussed are on highways. This is appropriate, not for the reason that the writers are principally highway engineers, but because the field of highway engineering will derive the greatest benefit from the application of sound engineering to the problem of landslide prevention and correction. Most of the references to highways would apply also to railroads; however, the mileage of new railroad construction is negligible compared to roads, and the problem of the railroads is primarily control and correction of landslides on existing roadbeds. In the design and construction of dams and similar large structures thorough investigation of landslides is more common practice than is the case with highway construction, hence it can be presumed that most of the facts contained here are well known to the engineers in those fields.

Recognition of Existing Landslides

Recognition and investigation of unstable areas and the design of preventive treatment should be considered as essential phases of the preliminary planning and design of any project on which the proposed construction might induce land movements. It must be remembered that landslides may be caused by two general types of construction activities: (a) the imposing of additional load, such as by embankments, dams, or other structures; and (b) the changing of existing ground slope by excavation, erosion, or other causes. It is true that landslides may occur where the existing ground is undisturbed by man; this is evidenced by the numerous landslides which occur in many areas remote from any construction activity. The possibility of such landslides affecting proposed facilities should not be overlooked, particularly if the new facility is located on or crosses an old landslide. There have been many instances of residential developments on old quiescent landslides, where various conditions, perhaps unrelated to the residential construction, have caused the landslide to become active, resulting in damage to buildings and structures within the slide area. Development and construction over a large area may obliterate all evidence of the original landslide, leaving the purchaser blissfully unaware of any hazard.

In highway construction the proposed location may cross an old inactive landslide of such areal extent that it is overlooked in the usual routine soil survey. Or, the engineer may recognize and treat small local unstable areas without realizing that they are merely manifestations of large-scale land movement. It is seldom that any large-scale landslide, however old, does not leave some telltale evidence which can be detected by an engineer trained to look for the proper features. Many old landslides can be most readily recognized by the proper interpretation of aerial photographs, as described in Chapter Five. Once the slide area is identified by this or other means, a detailed ground study will commonly reveal further evidence of previous land movement. Field methods for recognizing and identifying old landslides are described in Chapter Four.

Having identified an existing landslide, active or latent, the engineer can then determine whether avoidance is economically practicable; if the slide cannot be avoided the necessary investigation can be made to determine the extent and nature of preventive treatment required.

Investigation

Recognition, classification and investigation of landslides have been discussed in previous chapters. All of the previously described techniques for detecting old landslides should be utilized during the reconnaissance or preliminary stages of a project in order to recognize and identify any old landslide, whether active or quiescent.

Recognition of existing landslides, although important, is not sufficient. A geologically ancient landslide may now be quite stable, so far as being affected by proposed construction. On the other hand, the excavation or loading involved in the construction may induce land movement even where there is no evidence of previous landslides. Where preventive measures are to be applied the investigation would, in general, be similar to that described in Chapter Six. Investigation in connection with landslide prevention does, however, differ in some respects from that to be applied to an inactive landslide: unstable areas must be explored, even though no prior slide movement is suspected, and a study made of the possible effects of the proposed construction. If the proposed highway or structure will be located upon or across, or may be affected by an old landslide, an analysis must be made to determine whether the slide area will be stable under the conditions which will be imposed by the construction. In both cases the limits of the potential or incipient landslide are necessarily unknown, in contrast to slide correction investigations in which an active slide of definite extent already exists.

In any area of inherently low stability, especially where slides are known to be prevalent, the design of any major structure should be preceded by thorough investigation. Particularly in the construction of embankments on steep slopes in localities of questionable stability, each such site should be viewed with suspicion and thoroughly explored during preliminary stages of the project. Similarly, the design of cut slopes in such areas should be carefully scrutinized; in regions where instability is evidenced by land movement on existing routes, exploration of all proposed major excavation may be required. One error which is all too prevalent in the investigation of potential landslides is that of basing the analysis and design on data derived from shallow borings or test pits. All too often the material recorded in shallow borings as "solid formation" or "bedrock" may be merely float rock, boulders, or a thin layer of hard material underlain by a dangerously weak horizon. In excavation areas the borings should extend below the proposed grade; the foundation for embankments or other structures should be explored to whatever depth might be affected by the proposed loading.

A common justification for failure to make thorough exploration of potential landslides is that such exploration is too costly and would result in curtailed highway construction. It may be true that detailed soil surveys and landslide investigations are not economically practicable on certain unimportant roads, but for the freeways, toll roads, and other high-standard highways which comprise the major portion of the current highway programs, the engineer can afford only the best available practice in detecting and preventing landslides. The cost of controlling one preventable slipout or major landslide on a project will often more than offset the cost of a proper preliminary investigation on the entire project. It may not be possible or economical to design a highway to preclude the possibility of an occasional landslide, but this fact should merely emphasize rather than minimize the need for better engineering in the recognition and treatment of unstable areas.

The investigation aimed at slide prevention should be a cooperative project by the geologist and the soil engineer, or be made under the jurisdiction of an engineer who is thoroughly familiar with both of these phases of engineering.

To be of greatest value, the geologic and soils studies should be both general and specific. That is, a general or regional knowledge of the soils and geology in the area under investigation will be helpful in estimating the landslide potentials on a specific project, but such knowledge cannot take the place of detailed studies along the proposed right-of-way.

Much of the desirable general information on geology and soils can be obtained from available maps or from geologists or soil specialists who are familiar with the area. In a given geographic region, landslides tend to be more prevalent in one particular geologic formation or soil type than in others. Many of these "bad actors" are known in various parts of the country. The questionnaire upon which parts of this volume are based elicited a long list of geologic formations that are known to be landslide-susceptible. The list is not reproduced here because it is known to be incomplete for some parts of the country, a situation that could lead to a false sense of security in places. Moreover, it is not safe to label any entire geologic formation as landslide-susceptible; landslides generally result from a combination of conditions or "causes" and stratigraphic sequence or rock type alone do not necessarily presage land movement. Nevertheless, if the engineer is familiar with the geologic formations and soils in his region that are especially susceptible to sliding, investigations can be made to determine the presence or absence of other contributing factors.

Methods of making detailed studies of the geology and soils of the construction site itself are described in Chapter Six. Both surficial and bedrock geology should be studied, for many of the most troublesome slides are confined to the mantle soil or weathered zone. A geologist trained in the study of surficial materials — and in the practical application of his results — can aid the soil engineer in his application of the theories of soil mechanics to the analysis of actual or potential slides in earthy materials. In the case of bedrock or rocky formations, of course, the geologic survey may provide the most useful information obtainable.

Analysis

Regardless of how comprehensive or thorough the investigation and exploration may be, the utilization of the data thus obtained depends on proper interpretation and analysis of those data. Methods of analyzing landslides and determining the effect of control treatments are described in detail in Chapter Nine. Practical applications of analytical methods have also been described by Baker (1952). In many cases the area being investigated is not amenable to the classical, theoretical methods of analysis; nevertheless, application of the principles of soil mechanics usually makes possible a rational comparison of various treatments, even though the absolute stability cannot be accurately computed.

Correct interpretation of the geological, geophysical, boring and test data derived from the investigation of a potential or actual slide area constitutes the most difficult phase of the engineering pertaining to landslide prevention or correction. Familiarity with local conditions and a background of experience in landslide work will, of course, assist the engineer in exercising the sound judgment which is essential to the solution of the specific problem involved. Soils are characteristically nonuniform; the stability of an embankment or excavation is influenced by a great many factors; and the geology and subsurface water conditions are often complex. Because of these conditions, the analysis of landslides and the design of control treatment cannot be standardized or routine; however, an understanding of the types, causes, and mechanics of landslides will make possible the application of certain basic principles having general validity.

Prevention of all types of landslides may be accomplished by one or more of the following methods: (a) reduction of activating forces, (b) increasing the forces resisting movement, and (c) avoidance or elimination of the slide.

Reduction in the activating forces can be accomplished by two general methods — removal of material from the portion of the slide which provides the driving force tending to cause movement, and subdrainage to eliminate hydrostatic pressure and/or to diminish the weight of the soil mass by reducing moisture content. However, the stabilizing effect of subdrainage is generally due primarily to increasing the shear resistance rather than by reduction of the motivating forces.

There are a great many methods for increasing the forces resisting slide movement, including the following: subdrainage, in order to increase the shear resistance of the soil; elimination of weak zones or potential surfaces of rupture by stripping or by breaking up or benching of smooth sloping surfaces; construction of restraining structures such as piles, walls, cribs, or toe support fills; and solidification of loose granular material by chemical treatment.

The most obvious and sometimes the most economical, but often overlooked, method of preventing landslides is by avoidance. Methods by which this may be accomplished include: relocation of the proposed highway or structure to avoid unstable terrain, complete removal of an existing slide; or bridging the unstable area.

Evaluation and Comparison of Various Treatments

Avoidance of Potential Slides

It is not often feasible to avoid a potential slide by changing the location of a proposed highway or structure, but the possibility should not be overlooked. In some cases the highway can be shifted into stable ground by a slight change in alignment. Even though it may not be feasible to avoid an old landslide or an unstable area completely, it may be possible to so locate the highway that the slide area is crossed at the safest location, and where the construction would be least likely to induce further slide movement.

Where the proposed excavation will cross formations that are susceptible to bedding plane slides, the slide hazard can sometimes be reduced by adjusting the alignment so that the cut slopes will intercept the beds at a more favorable angle to the bedding planes. In some places, for instance, it may be possible to choose the opposite side of a valley or hill, where the bedding planes of the rock will dip into the cut slope rather than dipping toward the roadway.

In Chapter Four, there are listed nine ways in which proposed construction of cuts or fills may induce landslides. These factors are not repeated here, but they should be kept in mind when evaluating the probable effects of the new construction; recognition and consideration of these factors are essential in determining whether an attempt should be made to forestall a potential landslide by avoidance.

Prevention of landslides by avoidance does not necessarily require a change in alignment or location of a highway or structure. In some cases a revision in the grade line of a proposed highway may be equally effective in preventing slide movement. For example, where the most desirable grade line for new highway construction requires excavation and undercutting of an unstable slope, it may be possible to adjust the profile grade of the road so as to avoid any excavation at the toe of the hill, and instead to provide additional support by construction of an embankment which will act as a toe support or "strut."

If there is no way to avoid a potential slide and if preventive treatment will not assure stability, it is sometimes necessary to construct a bridge across the unstable area. The cost of a bridge is usually prohibitive, however, and extreme care must be exercised to design a structure which will not itself be damaged by moderate slide movement.

Bridging may be done in conjunction with the prevention method listed under II-D in Table 4, "Removal of all unstable material." The removal of all or a portion of the unstable material may be necessary to protect the structure from damage should slide movement occur. Figure 63 shows a bridge constructed across an active landslide which would not support an embankment and which could not be avoided by change of alignment of the highway. The bridge was so constructed that the superstructure could be shifted laterally on extended pile caps, in order that the alignment of the bridge could be maintained as the substructure moved with the landslide. By periodically sluicing out the slide material above the bridge, the slide movement at the bridge site has been held to a minimum, and the proper position of the bridge superstructure has been maintained.

A more common application of the bridging method of slide prevention is the sidehill viaduct. On a sidehill cut and fill section with a steep transverse slope the terrain below the highway grade may be too unstable to support the heavy embankment required. In such a case it is sometimes more economical to

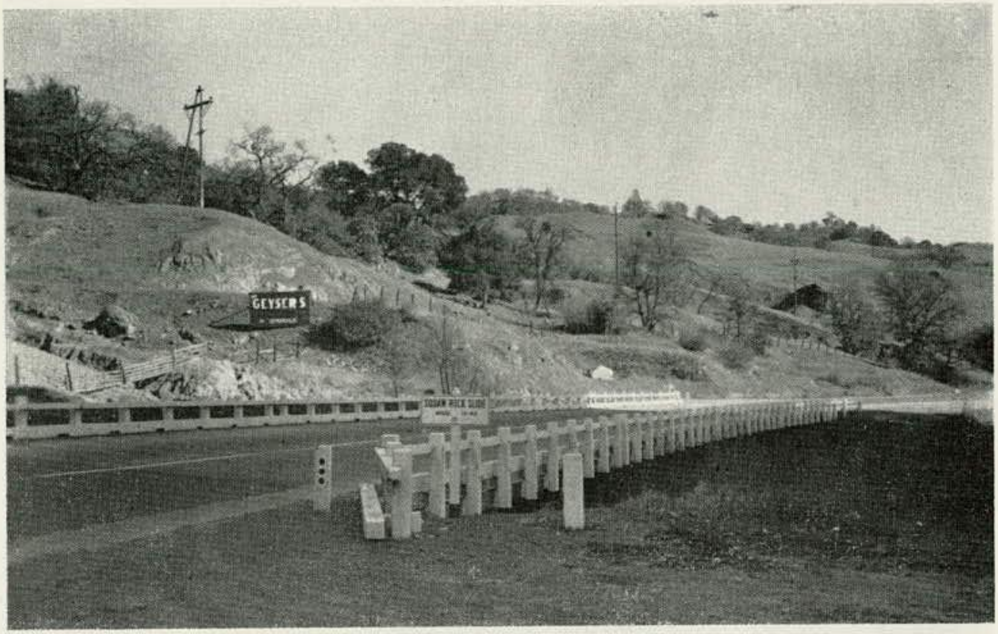

Figure 63. Landslide avoidance by bridging. Bridge on piling constructed across foot of active landslide near Hopland, Calif. Bridge incorporates provision for realigning superstructure if further sliding should cause shifting of piles. (Photograph courtesy of California Division of Highways)

support the outer half of the roadway on a viaduct, rather than to stabilize the foundation to support an embankment. Figure 64 illustrates the sidehill viaduct type of bridging.

In addition to such actual avoidance methods, many precautions may be observed which will minimize the possibility of land movement as a result of the proposed construction. Many of these precautionary measures are phases of design which should be considered whenever a structure is proposed in a location where ground movement might occur. Use of lightweight embankment material might be mentioned as an example of a design method to prevent landslides. If tests of the foundation soil in a proposed embankment area indicate that the soil will not support the load with the desired factor of safety, it is sometimes possible to substitute lightweight embankment material (such as cinders, volcanic tuff, or similar material), thereby reducing the embankment load sufficiently to provide a satisfactory factor of safety against sliding of the embankment. If the engineer has an understanding of the nature and mechanics of landslides, there will be less likelihood of necessary design considerations being overlooked.

In deciding whether to avoid an unstable area or to adopt preventive treatment, an economic comparison of the alternate locations will often supply the answer. Such cost comparisons should, however, consider the total cost rather than the cost of construction only. Proper consideration should be given to such factors as maintenance costs, probable service efficiency of the facility, and possible interruption in service or structural damage by land movement. It is true that an accurate appraisal of the last factor may be difficult; nevertheless, a rational comparison of alternates is impossible without consideration of the

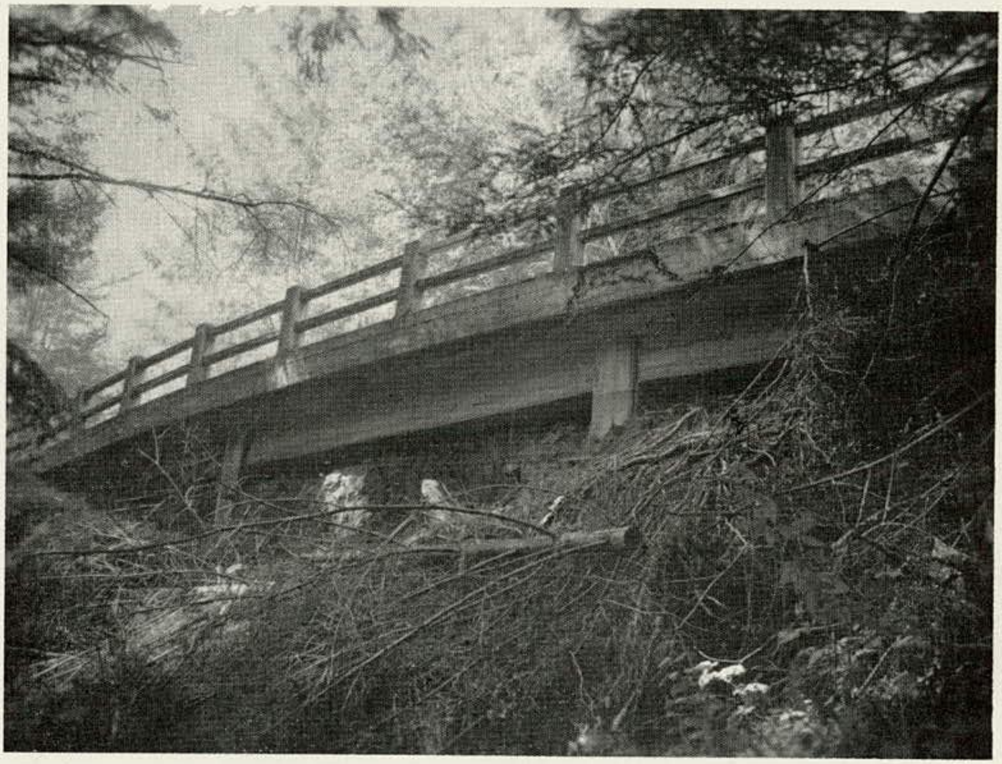

Figure 64. Landslide avoidance by bridging near Santa Cruz, Calif. Sidehill viaduct constructed across short unstable area (Photograph by Bruce Utt, courtesy of California Division of Highways)

risks involved. A choice between alternate locations based only on construction costs may be fallacious; frequently, a large initial investment may be most economical if the total costs for the life of the structure are considered. In practice, however, the method of financing a project may be such that immediate availability of funds will control the design. As a result, the selection of the most economical alternate may not be feasible, and the adoption of a less safe or less economical design with lower initial cost must be accepted as a compromise.

In such a case, the engineer in charge would probably be well-advised to see that a complete record of the investigation and predictions, as well as the reasons for the compromise, be placed on permanent file.

EXCAVATION

Preventive measures in excavation areas consist primarily of proper slope design and drainage. It is usually more economical to design the excavation with slopes which will minimize sliding, rather than to excavate steep slopes and then flatten the slopes after sliding has occurred. This is especially true if the slides are of the slump type; for the reworked soil may have only a fraction of the strength of the in-place soil. For example, a material which would be stable if excavated on 2:1 (2 horizontal: 1 vertical) slopes may, after sliding has occurred on a steeper slope, require 4:1 slopes to prevent further sliding.

In dealing with a homogeneous soil, the strength of which can be determined

Figure 65. Multiple benching of cut slope to prevent landslides by unloading, by providing catchment areas for debris and by surface drainage. Inclined benches are used here to provide roadways for construction and maintenance equipment. (Photograph courtesy of Pennsylvania Department of Highways)

with reasonable reliability by laboratory tests, the slopes required for stable cuts can be computed with considerable accuracy by applying the theories of soil mechanics (Chapter Nine). It is seldom, however, that these ideal conditions prevail — homogeneity of large soil masses is rare, and the effective average strength of rocks can seldom be determined by borings and laboratory tests. Moreover, it is almost impossible to predict accurately what the hydrostatic pressures will be in the future or at time of failure. Nevertheless, a knowledge of the character of the soil, and of subsurface water conditions, is no less important because it cannot always be applied directly. Proper slope design requires that this information be as complete as possible. With this knowledge, and by applying the methods of stability analysis outlined in Chapter Nine, the soils engineer can estimate the improvement in stability effected by flattening the proposed cut slope or by removing material which might induce slide movement. Such analyses are helpful, even where the true shear strengths of the soil cannot be accurately determined by laboratory tests. Obviously, these analyses are impossible without a knowledge of the character and strength of the soil throughout the cut area. Preferably such information is obtained from borings, as well as from geologic or geophysical data.

A study of existing cut slopes of similar material in the region is helpful, but extreme care is required in comparing existing and proposed cuts. Existing cuts commonly are much shallower than the excavation on an improved location; for example, 1:1 slopes in a given formation might be stable for a height of 50 ft, but

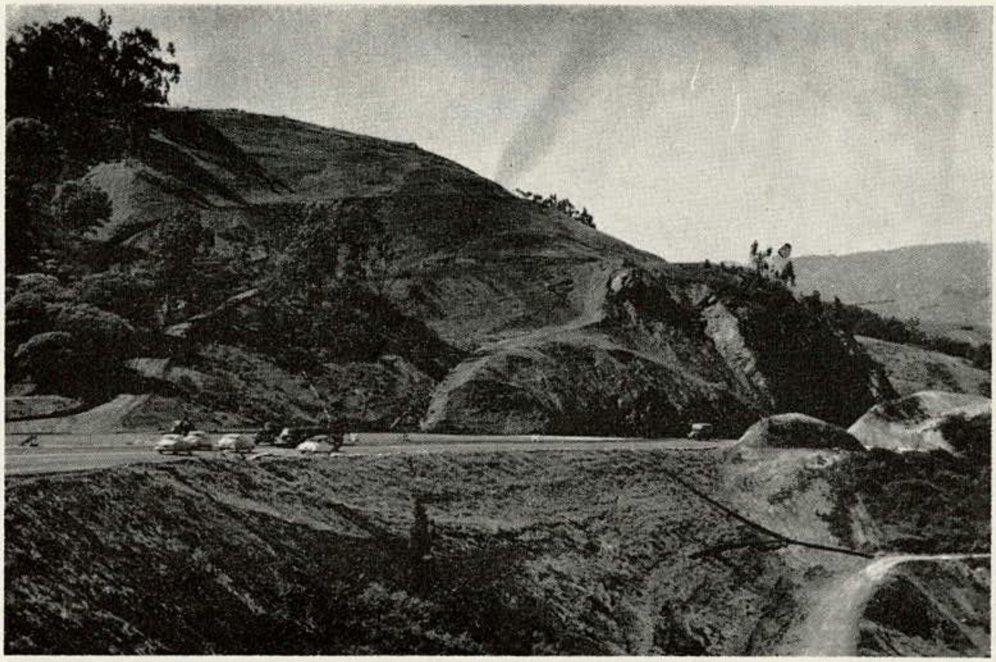

Figure 66. Prevention of landslides by flattening cut slopes near Waldo, Calif. Top of flat cut slope is at skyline in left background. Note bench construction of high embankment in foreground. (Photograph by Bruce Utt, courtesy of California Division of Highways)

the same slope might be much too steep for a 150-ft cut. Another pitfall to be avoided in basing slope design on existing slopes is the assumption that the soils and rocks, as well as the ground water conditions, will be identical in the proposed cut area as in an existing cut. Even though the distance between the two is small, conditions may be quite dissimilar. With proper consideration of these factors, the study of existing slopes can be a valuable guide, but slope design should be the responsibility of the soil engineer or geologist rather than the locating engineer. A background of experience in the same region and familiarity with local conditions are always helpful to the geologist or soil engineer.

In general, cut slopes constructed with benches or "berms" are considered preferable to equivalent uniform straight slopes. The benches should be constructed with a V or gutter section, with a longitudinal drainage grade, and with suitable catch basins and flumes or pipes to carry the water down the slopes. Paving of the gutters or ditches may be necessary to reduce erosion or to prevent percolation of water into pervious areas on the benches. The benches serve two purposes: to intercept and remove surface water or seepage from the cut face; and to prevent rocks, debris or sloughed material from falling on the roadway. The benches should be so constructed that they are accessible to maintenance equipment subsequent to construction, in order that any small slides may be removed and the drainage system may be properly maintained. Figure 65 illustrates the construction of benched cut slopes; Figures 66 and 104 illustrate slope flattening.

The first type of excavation listed in Table 4 — "A. Removal of head" — applies only to treatment of an existing landslide; the fourth one — "D. Removal of all unstable material" — would usually be practicable only in the case of an existing slide. However, these two techniques have also been applied in some parts of the country for controlling potential slides in talus material. In the case of an existing landslide, removal of material from the head of the slide reduces the activating force, and thus has a stabilizing effect. But such unloading is usually proposed only where the slide is to be undercut at or near the toe. The amount of unloading at the head should be sufficient to compensate for any reduction in support caused by excavation elsewhere. Here again, the application of the principles of soil mechanics, as described in Chapter Nine, will enable the engineer to estimate the effects of the proposed excavation, and to design the unloading and cut slopes to provide the required stability. In cut areas the removal of all unstable material is usually not necessary, and is seldom economical except for very small masses. Even this type of treatment requires sufficient investigation to determine the depth and areal extent of the weak material. If the yardage involved is small it may be desirable to remove all of the weak material; otherwise, the strength of the weak soil should be determined, and the cut slopes designed to provide stable excavation.

Where embankment is to be constructed over an old landslide area or other material having inadequate strength to support the proposed loading, removal of the weak material should be considered. If the weak soil layer is only a few feet thick, stripping of the weak material is usually more economical than other methods of treatment. If there is evidence of seepage — and the unstable condition is often caused by ground water — suitable drainage should be provided before placing the embankment. A blanket of pervious material, together with necessary underdrains, may be required to prevent reduction of shear strength and/or development of pore pressure due to subsurface water.

Economic Considerations

In the design of cut slopes to prevent landslides, economic considerations cannot be disregarded. If failure of a structure might result in loss of life and irreparable damage, as in the case of a dam or bridge, a high factor of safety is warranted, and may indeed be essential. It is seldom economical to design cut slopes sufficiently flat to preclude the possibility of landslides, and it is often better to remove or correct a few slides during construction or as a maintenance operation than to design with excessively flat slopes. Many secondary highways that traverse rough terrain could not be constructed with available funds except by accepting some risk of landslides.

The fact that a calculated risk of slide movement must be accepted at times is, however, no justification for lack of thorough investigation and adoption of all economical means of slide prevention. With adequate information on geology, soils and ground water conditions in a proposed cut area, the probability of landslides can be estimated and the consequences of possible slides appraised; only after such an evaluation can the most economical design be selected. Any risk should be a calculated one, rather than a mere gamble arising from lack of investigation and analysis.

DRAINAGE

Surface Drainage

Every precaution should be taken to prevent surface runoff water from entering a potentially unstable area. Any sags, depressions or ponds above the slope line of either an enbankment or a cut should be drained to minimize the possibility of surface water percolating into a weak or unstable area. If the new construction crosses an old landslide its surface should be reshaped as necessary to provide good surface drainage, but unnecessary removal of vegetation should be avoided lest excessive erosion may occur. Sealing of all surface cracks in any type of slide will be of benefit, both by preventing entrance of surface water into the slide mass and by reducing frost action in areas subject to freezing and thawing.

Although surface drainage alone will seldom correct an active landslide, any improvement in surface drainage will be beneficial. In the case of potential landslides, where no movement has occurred prior to construction, surface drainage may result in greater returns from the investment than any other type of preventive treatment, even though other preventive measures may be required in conjunction with the surface drainage. Surface runoff or the water flowing from springs or seeps should never be allowed to drain into or across an unstable area or potential landslide. Methods of improving surface drainage include reshaping of slopes, construction of paved ditches, installation of flumes or conduits, and paving or bituminous treatment of slopes.

Subdrainage

If the preliminary investigation reveals the presence of ground water which may induce slide movement, adequate subdrainage should be included in the plans. Such subdrainage is equally important in cut areas and under proposed embankments. The effectiveness and frequency of use of the various types of drainage treatment vary according to geologic formation and climatic conditions; they probably are influenced by local custom also. It is generally agreed, however, that for the majority of landslides ground water constitutes the most important single contributory cause; and in many areas of the country the most generally used successful methods for both prevention and correction of landslides consist entirely or partially of ground water control. This is especially true of the Pacific Coastal region.

Although most of the types of subdrainage treatment are applicable to the prevention and correction of both embankment slipouts and landslides in excavation areas, the differences in methods are considered of sufficient importance to justify separate discussion of subdrainage treatments applied to these two general types of landslides.

Drainage in Embankment Areas.—Slipouts may occur whenever the imposed embankment load results in shear stresses that exceed the shear strength of the foundation soil; or where the construction of the embankment interferes with the natural movement of ground water, and results in the development of pore pressure or hydrostatic pressures. Two factors must, therefore, be considered in the investigation of possible slipouts: weak zones in the foundation soil, which may be overstressed by the proposed embankment load, and subsurface water, which may either result in the development of hydrostatic pressure or may reduce the shear strength of the soil sufficiently to induce slide movement. Careful exploration will usually reveal these conditions before construction, but the investigator must be of a suspicious and inquisitive nature, as there may be no readily apparent surface indications of the unstable conditions. Some of the methods of preventing roadway slipouts are listed and discussed hereinafter.

As previously noted, if a surface layer of weak soil is relatively shallow and is underlain by stable rock or soil, the most economical treatment is usually that of stripping and wasting the unsuitable material, as illustrated by Figures 67 and 68. If seepage is evident after stripping or if there is a possibility that it may develop during wet cycles, a layer of pervious material should be placed before the embankment is constructed. This may consist of clean pit run gravel, free-draining sand, or other suitable local materials. If springs or concentrated flows are encountered, drain pipe may be required also.

Where subsurface water or soil of questionable strength is found at such

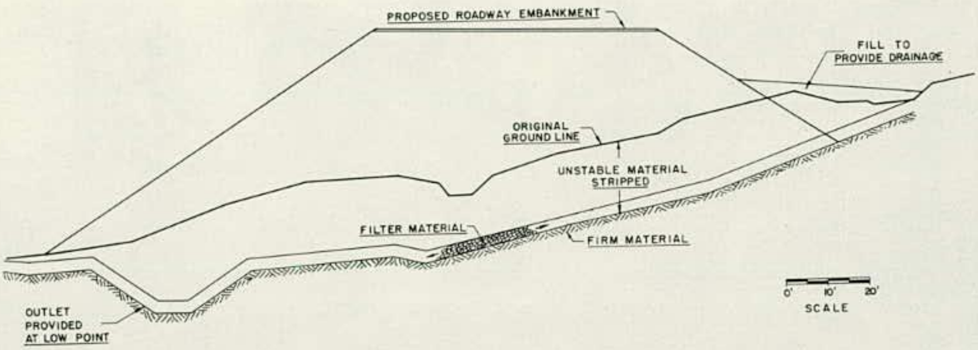

Figure 67. Stripping as a slide prevention measure. Typical cross-section of Redwood Highway in Humboldt County, Calif., showing stripping of unstable material before constructing embankment. (Drawing furnished by C. P. Sweet, courtesy of California Division of Highways)

great depths that stripping is uneconomical, deep drainage or stabilization trenches have been used successfully to prevent slipouts. Such stabilization trenches are usually excavated with power equipment with the steepest side slopes that will be stable for the minimum construction period; they should extend below any water-bearing layers and into firm material. A layer of pervious backfill material is placed on the bottom and side slopes (see Fig. 69), with an underdrain pipe in the bottom; then the trench is backfilled and the embankment constructed. Figure 70 illustrates combined use of stripping and drainage trenches.

If the unstable area is in a natural draw or depression and of limited areal extent, one trench normal to the centerline of the road may be sufficient; in the case of large areas, an extensive system of stabilization trenches may be necessary, frequently in a herringbone

Figure 68. Stripping wet unstable material before placing embankment near Orick, Calif. Blanket of pervious filter material will be spread over stripped area. (Photograph courtesy of California Division of Highways)

Figure 69. Placing filter material in deep drainage trench near Orick, Calif. Filter material being dumped over side slope and spread in bottom of drainage trench with dozer. (Photograph courtesy of California Division of Highways)

pattern. The trenches, in addition to providing subdrainage, add considerable structural strength to the foundation.

This type of treatment for prevention of slipouts has been used successfully on numerous projects. An early example was reported by Root (1938). On a recent highway construction project 4.9

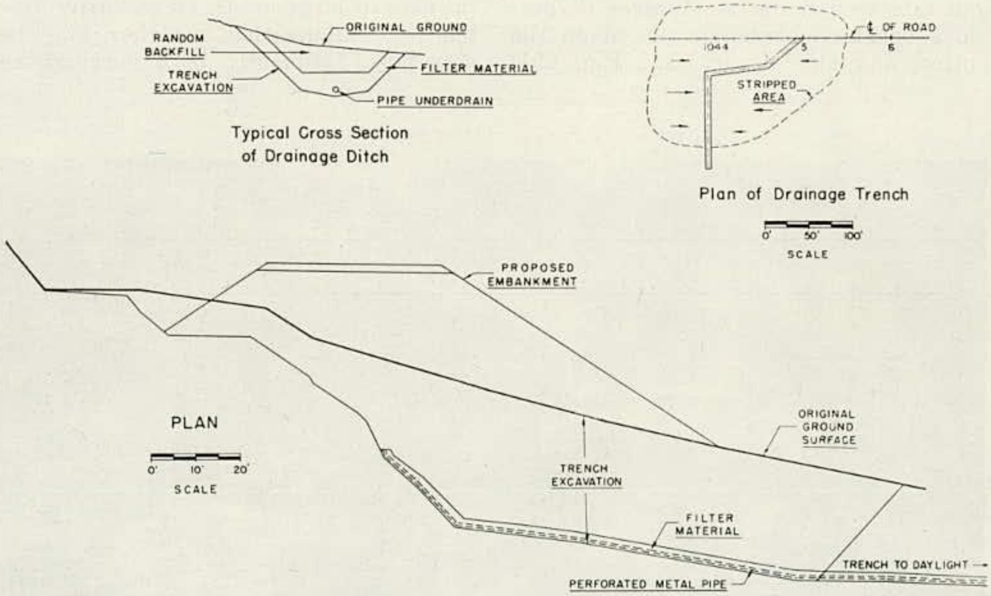

Figure 70. Slide prevention near Willits, Calif. by combination of stripping and drainage trench. Plan and cross-section of preventive treatment consisting of stripping unsuitable soil and constructing drainage trenches. (Sketch furnished by C. P. Sweet, courtesy of California Division of Highways)

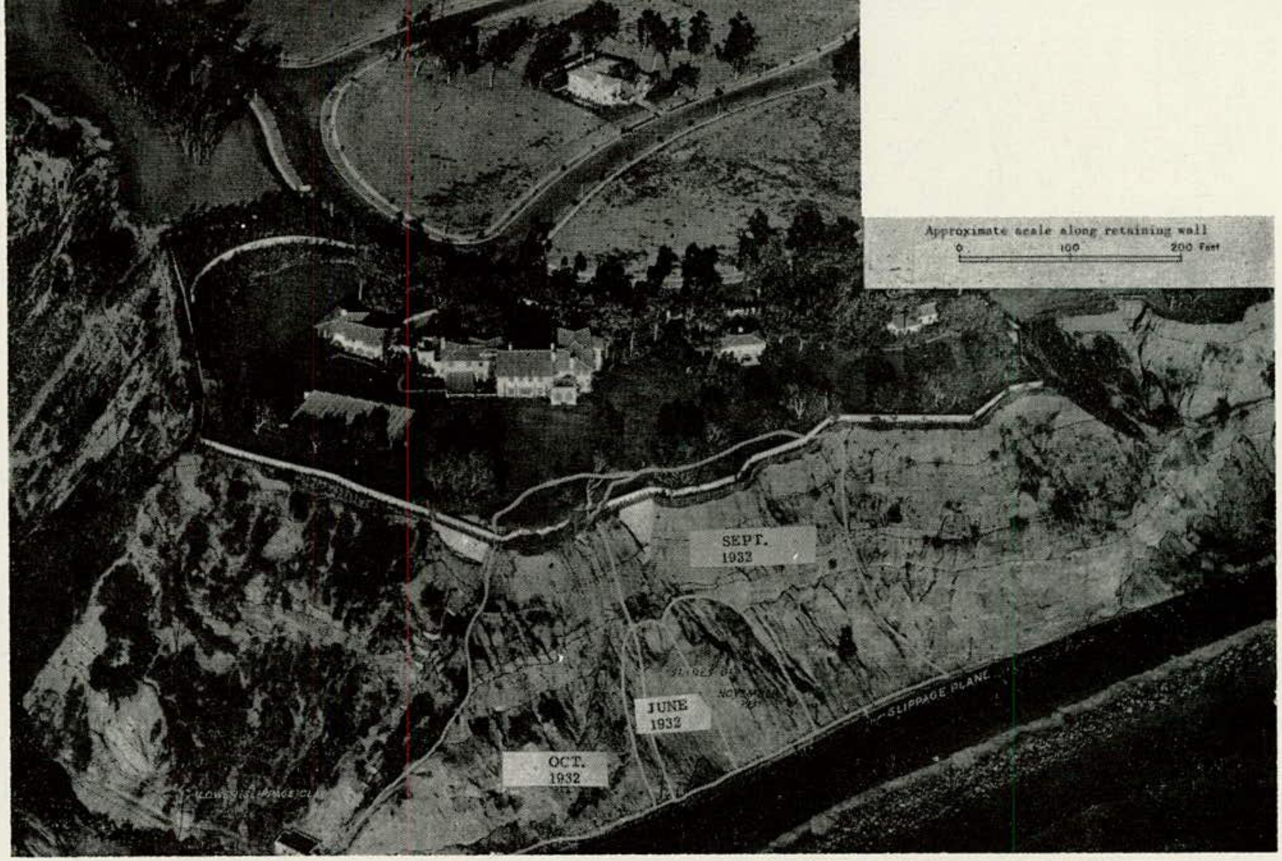

Figure 71. Large slide in the fall of 1932 northwest of Santa Monica, Calif. The highway was blocked by a sliding mass of 100,000 cubic yards, and a valuable estate was damaged through loss of approximately 100 feet by 200 feet of land. (Individual slides outlined in white, with dates.) Geologic studies indicated that movement began along slickensides in a nearly horizontal stratum of clay lying approximately 10 feet above the highway. Two exploratory tunnels were dug to drain water, believed to be lying on top of the clay stratum, and to determine the extent of the slickensides. No free water was encountered. It was decided that the most economical solution was to dry out the clay. Therefore, additional tunnels were drilled and a gas furnace was installed with blowers to circulate hot air. It was estimated that 3,000 lb of water per day were evaporated during the first six months. The furnace was in operation from August 1933 until approximately 1939, by which time movement was negligible. (Photograph by Fairchild Aerial Surveys, Inc., courtesy of Harry R. Johnson, Consulting Geologist)

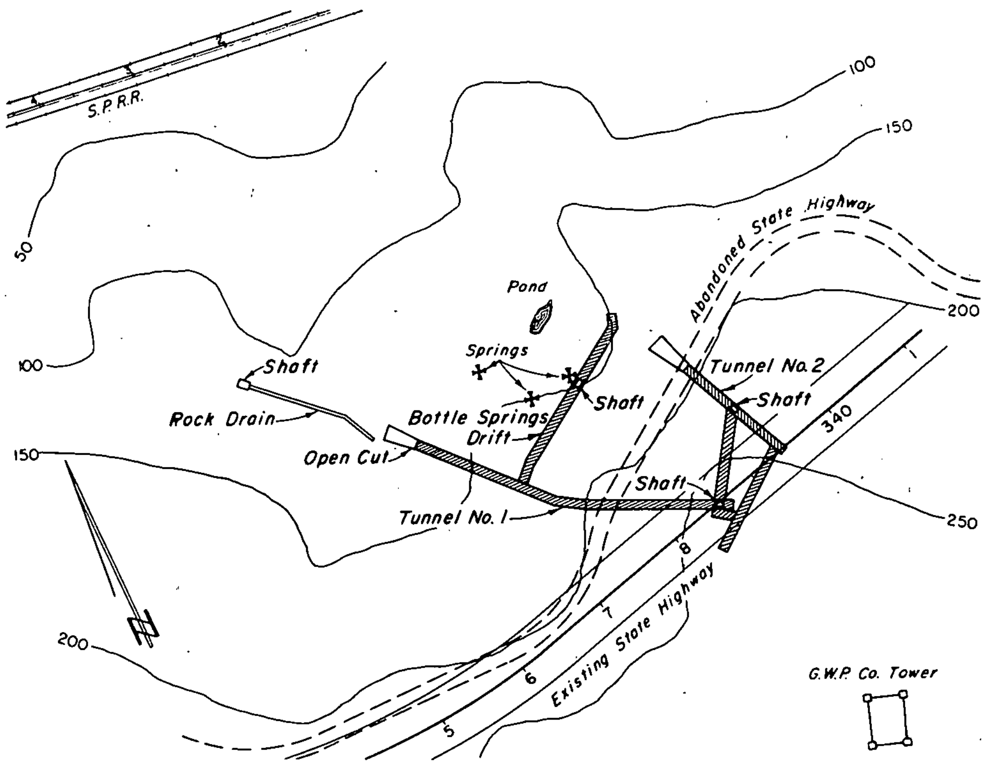

Figure 72. Drainage tunnels to prevent landslides. System of drainage tunnels installed during construction of new highway, designated as "Existing State Highway" on sketch, near Crockett, Calif. (Courtesy of California Division of Highways)

mi in length, the installation of stabilization trenches for slipout prevention required 65,000 cu yd of trench excavation; 107,000 cu yd of filter material were placed in drainage trenches and stripped areas; and more than 20,000 lin ft of perforated metal drain pipe were installed. Stabilization trenches of this kind have been constructed as deep as 40 or 50 ft. Although the cost increases rapidly with depth, this method of slipout prevention is often more economical than any other type of treatment which might be equally effective.

Where the depth to subsurface water is so great that the cost of stripping or drainage trenches becomes prohibitive, drainage tunnels are sometimes used. Although originally and more commonly used as a correctional treatment, drainage tunnels are sometimes constructed as a preventive measure. The use of drainage tunnels was fairly common at one time, both by railroads and by some highway departments; but at present this method is used rather infrequently, due largely to the relatively high cost. An elaborate installation of drainage tunnels, together with an ingenious hot-air furnace for drying out the soil, was used to control a large slide near Santa Monica, Calif. (see Fig. 71; Hill, 1934). Use of drainage tunnels in Oregon has also been described (*Roads & Streets*, 1947). These tunnels, usually about 4 ft by 6 ft in cross-section, must be excavated by manual methods; skilled tunnel workers are not normally employed on usual construction projects; and, of course, other methods of treatment which permit the use of construction equipment are likely to be less costly than the tunnels. Figure 72 shows an installation of drainage tunnels on a highway project.

Horizontal drains have, since their development during the past few years, supplanted drainage tunnels in many cases. As was the case with drainage tunnels, they were first installed as a corrective treatment. Although they are still used principally for this purpose, they have been installed at a number of locations as a preventive treatment (see Fig. 73). Horizontal drains usually consist of perforated metal pipe, often 2 in. in diameter, forced into a predrilled hole (generally 3 to 4 in. in diameter) at a slight angle to the horizontal; the gradient of horizontal drains may range from 5 to 25 percent (see Fig. 105). The length of these drains may be as great as 200 to 300 ft or more.

The origin of the horizontal drain is somewhat obscure; however, much of the early work in developing equipment and methods was done by the California Division of Highways beginning about 1939. There are numerous installations of such drains in California, as well as in Oregon, Washington, and several other states. Equipment and techniques for installing horizontal drains have been described by Stanton (1948) and by others. An example of the extensive installation of horizontal drains in slide control work is the Ventura Avenue oil field in California, where hundreds of horizontal drains, totaling more than 40 mi. in length, have been installed in the large landslides within this oil field (Mineral Information Service, 1954).

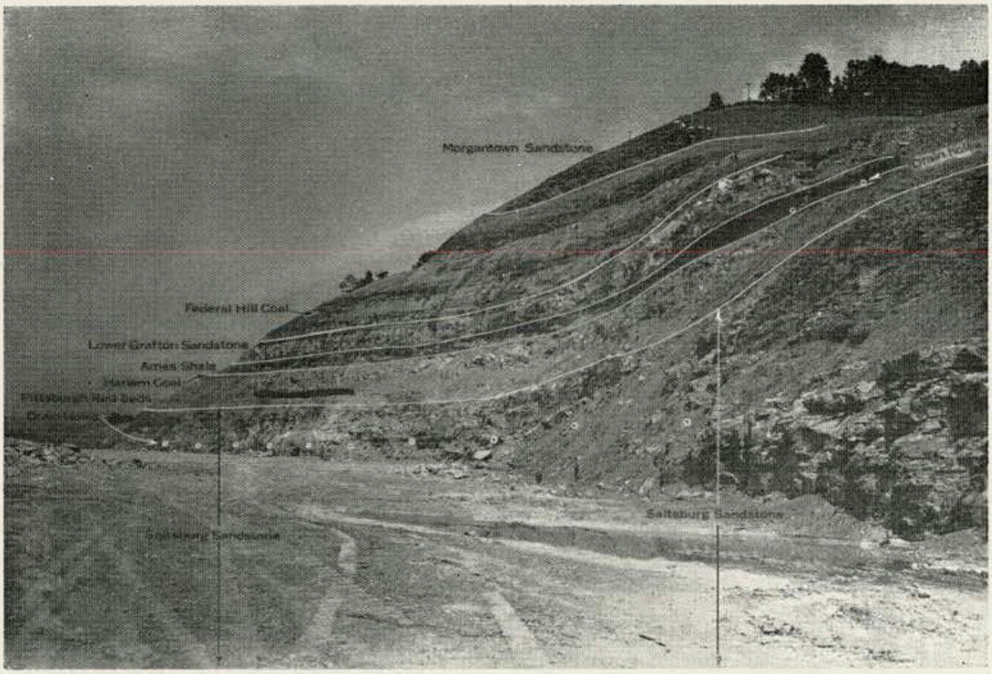

Figure 73. Horizontal drains used to stabilize cut in bedrock. The drains were placed 50 to 100 feet apart beneath permeable sandstones. One set is at the base of the Ames shale, beneath the Grafton standstone; the other at the top of a lens of indurated clay in the Saltsburg standstone. Note on skyline that cut slopes range from 1:4 (horizontal:vertical) to 1:1, depending on the character of each layer of rock. Spillway of Youghiogheny River reservoir, Pennsylvania and Maryland. (Photograph courtesy of Corps of Engineers)

Figures 76 and 77 show a system of horizontal drains that were installed as a slide prevention measure. Similar installations are frequently used as corrective treatment (Figs. 73, 104, and 106).

If wet areas or seepage zones which cannot be corrected by stripping and surface drains exist in the foundation of a proposed fill area, horizontal drains are likely to be the most effective means of removing subsurface water which might otherwise cause slipout movement. Preferably, horizontal drains should be installed in such a way that they can be inspected and maintained after the embankment is completed; this may necessitate placing a tunnel or large pipe to provide access to the drains. Thorough investigation of the unstable area, including test borings, will furnish the necessary information from which the elevation, gradient, and spacing of the horizontal drains may be determined.

Vertical drain wells for slipout prevention may be used for two purposes, as follows:

1. In conjunction with horizontal drains the vertical drain wells may provide a drainage path between lenses or strata of water-bearing material which are separated by impervious strata. If installed under an embankment, an outlet for the vertical drain well can be provided by means of a horizontal drain; such an installation is illustrated by Figure 74.

2. Vertical drain wells have also been installed under embankments to accelerate the consolidation, through removal of water, of weak compressible foundation soil. Such drains, usually 15 to 24 in. in diameter, are drilled or driven through and to the bottom of the saturated, compressible soil layers, then backfilled with coarse sand or other suitable filter material. A layer of filter material is placed over the area in which the vertical drains are installed, with outlets leading beyond the embankment slope line.

Design of this latter type of vertical drain well should be based on laboratory tests of undisturbed soil samples, from which the consolidation and strength characteristics of the soil are determined.

The continuous siphon is an ingenious method devised in the State of Washington for providing a drainage outlet for drainage wells or sumps (see Fig. 75). This siphon arrangement can be used to drain trenches, wells or sumps by siphoning instead of installing more costly tunnels, drilled-in pipes, or similar conventional outlet systems, and permits installation of subdrainage systems in areas not having readily accessible outlets. This continuous siphon method

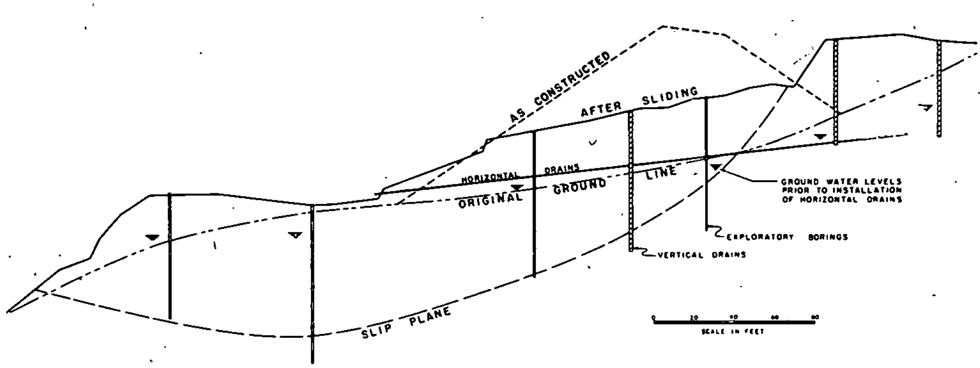

Figure 74. Slide treatment consisting of horizontal drains and vertical drain wells. This was corrective treatment of an active landslide at San Marcos Pass near Santa Barbara, Calif.; however, similar drainage treatment has been used as a preventive measure. (Courtesy of California Division of Highways)

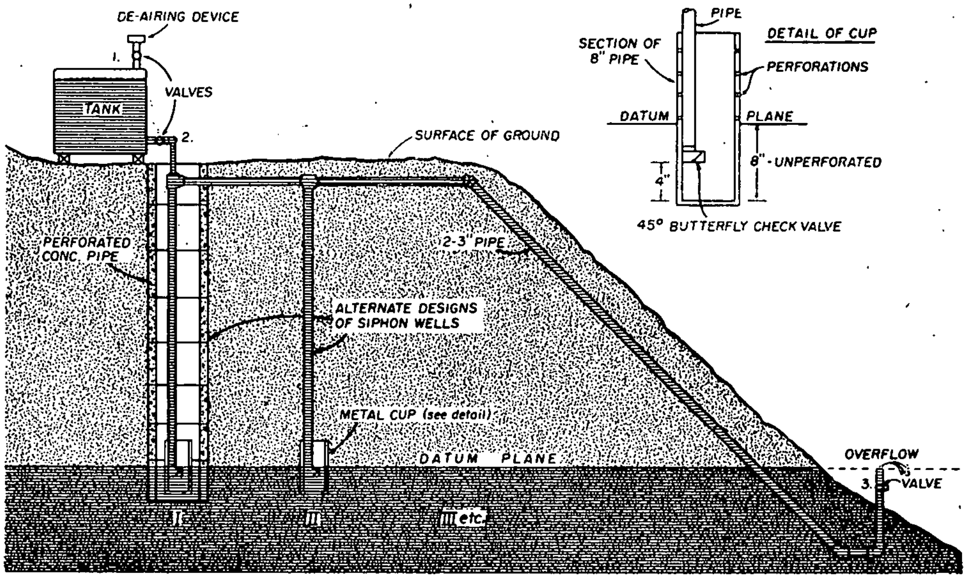

Figure 75. The Washington siphon. This system of vertical collector pipes and siphon arrangement has been successfully used by the State Highway Commission of Washington for lowering the water level and stabilizing landslides.

has the usual limitation of depth that is true of all siphons, but it is very useful where applicable.

Drainage in Excavation Areas. — All of the subdrainage methods discussed in connection with slipout prevention could as well be applied to prevention of landslides in excavation areas. Drainage trenches are sometimes installed as interceptors of subsurface water above the limits of the excavations, too often with indifferent success. There is seldom any assurance that such intercepting trenches will effectively cut off all ground water which might contribute to slope failure. If deep trenches are required the cost frequently becomes prohibitive, considering the probable effectiveness of the drainage trenches.

The most widely used successful method of subdrainage for preventing slides in cut slopes is probably the horizontal drain treatment. These horizontal drains are the same as previously described for slipout prevention. In excavation areas the drains are installed as the cut is excavated (see Figs. 76 and 77), often from one or more benches in the cut slope. Numerous cut slopes drained by this method have remained stable in spite of unfavorable soil formations and the presence of large amounts of subsurface water. It should be emphasized that if the treatment is delayed until after a landslide has developed, the cost of correcting the slide is likely to be much greater than the cost of installing drainage which would have prevented the sliding. And it is equally important to note that the need for such preventive treatment can be anticipated only if a thorough soil investigation is made before designing the project. In most cases test borings are required in addition to geologic studies or superficial inspection.

Restraining Structures

Retaining Walls and Bulkheads

Crib walls, piling, bulkheads, and other restraining devices are most commonly used as corrective measures after slide movement develops, too often with dubi-

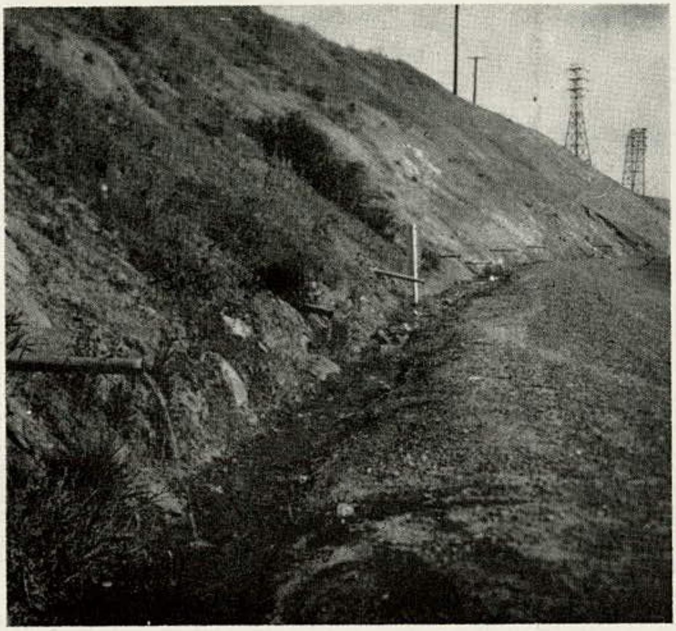

Figure 76. Horizontal drains for prevention of landslides. Horizontal drains installed from roadway grade during construction near Vallejo, Calif. Note flow of water from outlet of drain in foreground. (Photograph by A. D. Hirsch, courtesy of California Division of Highways)

ous success. These structures are more likely to be effective if installed as preventive treatment, before the soil mass has become weakened by slide action. The limitations of this type of treatment should be recognized. The increased resistance to sliding provided by any of these restraining structures is somewhat limited, and is dependent on the ability of the structure to resist (a)

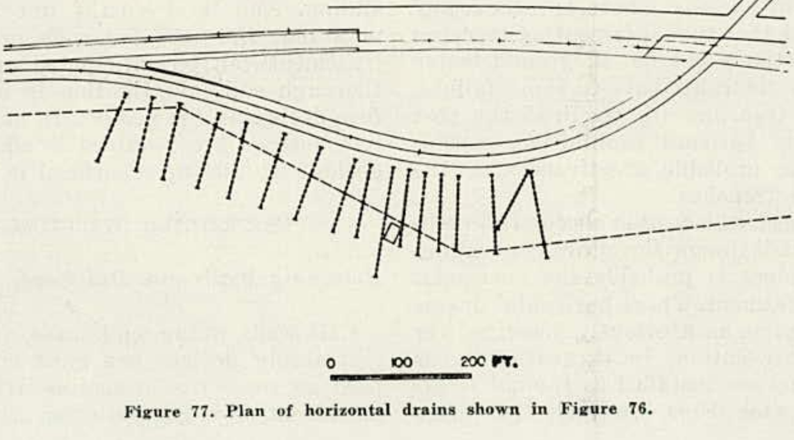

Figure 77. Plan of horizontal drains shown in Figure 76.

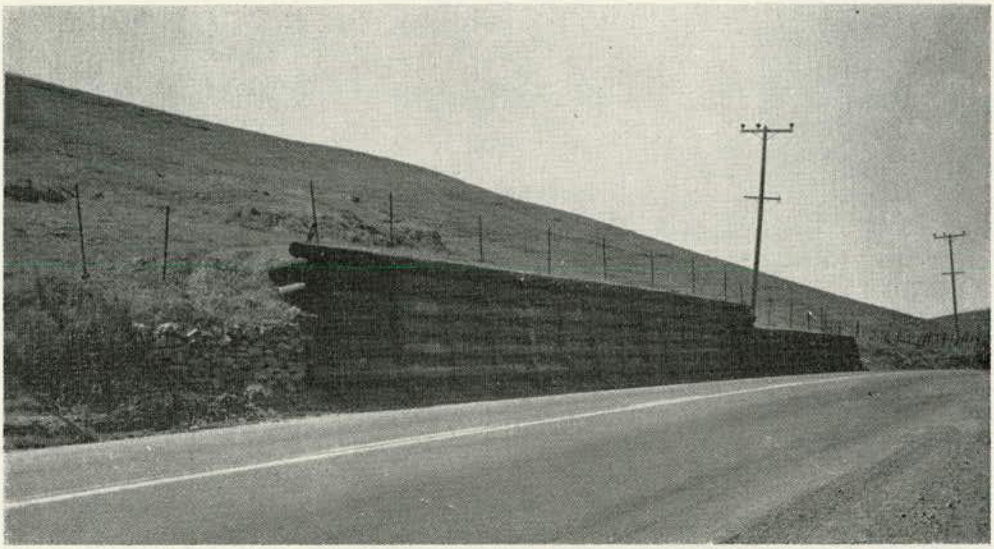

Figure 78. Log crib to prevent sliding near Napa, Calif. Note evidence of old landslides above cribbing and also near right skyline. (Photograph by Bruce Utt, courtesy of California Division of Highways)

shear action, (b) overturning, and (c) sliding on or below the base of the structure. If the forces tending to cause slide movement exceed the resisting forces by only a small amount, construction of some type of restraining structure may provide sufficient additional strength to produce stability and thus prevent slide movement.

Retaining walls and bulkheads of various types have been used: Figure 78 shows a redwood log crib; a bin-type concrete crib wall is illustrated by Figure 79; Figure 80 is an example of the metal bin-type crib wall; and Figure 81 shows a rubble masonry retaining wall installed to prevent a landslide. A unique restraining structure is shown in Figure 82, a modified slope paving as slide prevention; Figure 83 illustrates the use of coarse rock for slope paving. Figure 84 shows a masonry wall used to support overhanging rocks.

The principal use of crib walls or retaining walls is at the toe of an embankment slope where the normal fill slope would not "catch," or at the toe of a cut slope which must be undercut to provide lateral clearance for a roadbed or structure. Strictly speaking, such walls or cribs do not constitute treatment for slide prevention, but are actually a phase of the slope design. The limitations of these structures as slide preventive treatment should be recognized.

Unless the soil is free-draining, or it is known that no subsurface water will ever be present, the design and construction of any crib wall or retaining wall should include adequate provisions for drainage, including pervious backfill, drain pipes, and weep holes. The use of retaining structures is one of the earliest methods used for controlling landslides, but the results of this method, at least in the earlier attempts, were not encouraging. In 1928, Ladd reported numerous failures of retaining walls and suggested use of other methods, particularly drainage (Ladd, 1928). Figures 85 and 86 show striking examples of unsuccessful attempts to correct landslides by means of piles and bulkheads. These landslides were subsequently controlled by extensive subdrainage installations and by other means.

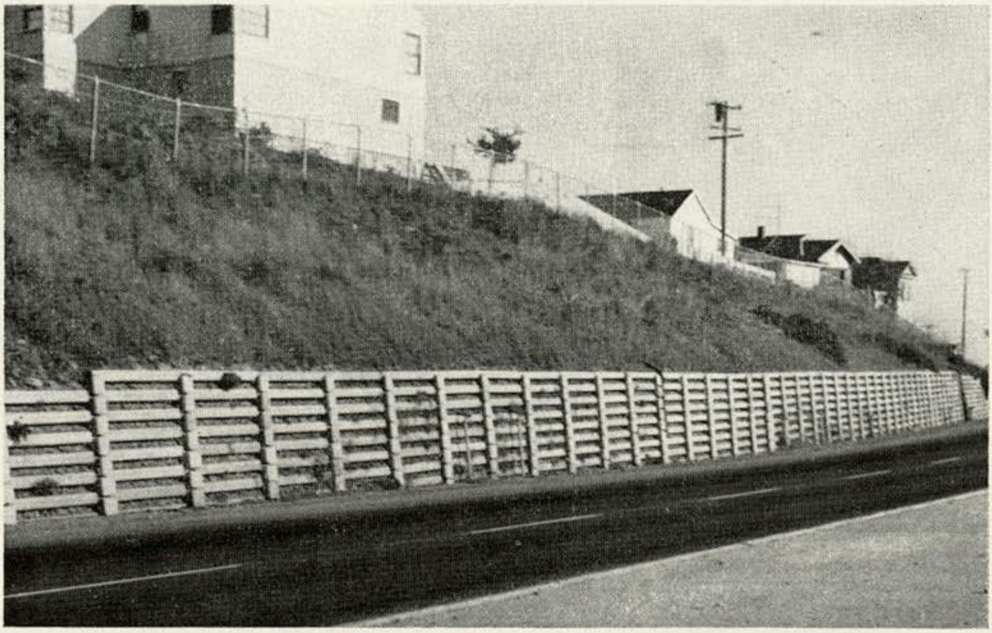

Figure 79. Restraining structure; concrete crib wall installed during construction to prevent land movement which might jeopardize dwellings located above top of cut slope at Arcata, Calif. Note gravel backfill. (Photograph by T. W. Smith, courtesy of California Division of Highways)

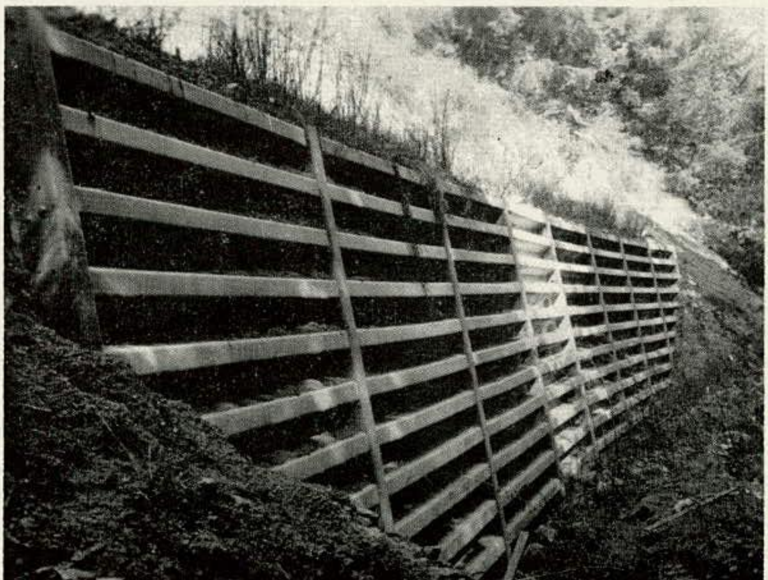

Figure 80. Restraining structure; metal crib wall near Santa Cruz, Calif. (Photograph courtesy of California Division of Highways)

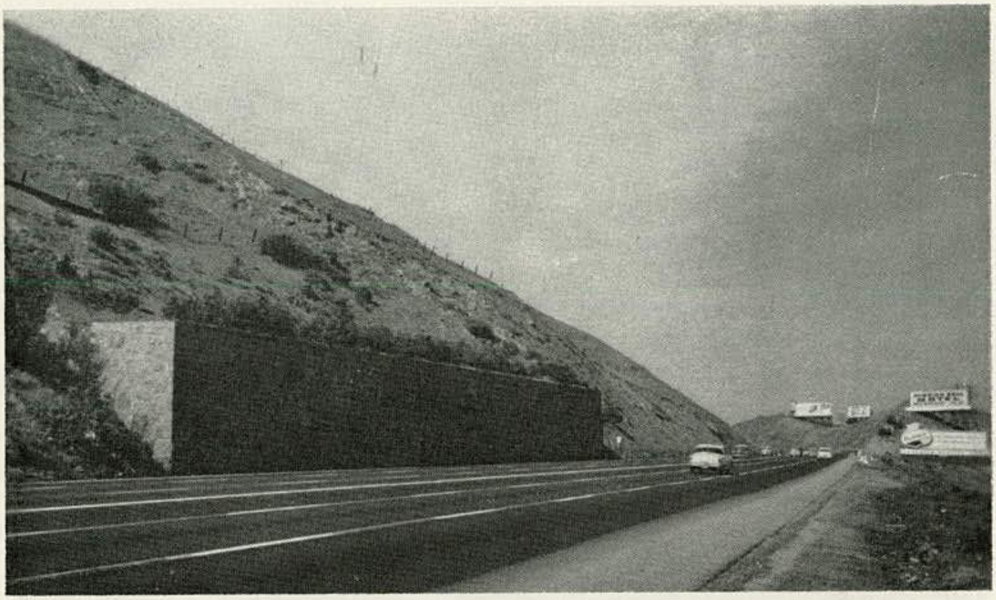

Figure 81. Rubble masonry retaining wall installed to prevent land movement in old landslide area near Brisbane, Calif. (Photograph by Bruce Utt, courtesy of California Division of Highways)

Figure 82. Restraining structure; concrete slope paving placed monolithically with an underlying grid of reinforced concrete beams, to prevent slide movement of unstable cut slope near Valona, Calif. (Photograph by E. W. Herlinger, courtesy of California Division of Highways)

Figure 83. Coarse slope paving as used along Route 2, Shelburne Falls, Mass. The bank to be retained is composed of fine sand and silt, probably 50 percent of it less than 200 mesh. The paving, 1 1/2 or more feet thick, is placed on a shaped bed. According to specifications of Massachusetts Department of Public Works, "stone for slope paving shall consist of field stones, boulders, quarry stone, or rock fragments. The stone shall have at least one reasonably flat face and a thickness perpendicular to the face of not less than 6 inches. At least 75 percent of the stone shall be 2 cubic feet or more in volume." Because rock was available from a nearby subgrade excavation the job shown here cost about $9 per square yard; usual costs are $12 to $15 per square yard. (Photograph by C. R. Tuttle, U. S. Geological Survey)

Timber bulkheads, when constructed with pervious backfill and drain pipes, have been utilized successfully to prevent the sliding of wet soil where the transverse slope is relatively flat. Most such bulkheads have little structural strength, and furnish only slightly increased restraint against sliding. Their success, in many cases, appears to be due to the drainage layer provided at the toe of the saturated slopes.

Buttresses

Buttresses at the foot of active or potential landslides are commonly used for prevention as well as correction. Such buttresses, consisting of either rockfill or earthfill, generally are used in connection with embankment construction, and seldom, if ever, to restrain slopes in excavation. The term buttress, as used here, includes earth or rock dikes installed for either of two purposes: (a) to provide weight at the toe of a landslide, such as "toe support" or "strut" fills; (b) to increase the shear strength of the soil by construction of a dike or buttress of material having substantially higher shear strength than the native soil.

In the typical slump type landslide the ground at the toe usually moves upward, forming a bulge or pushup. By adding

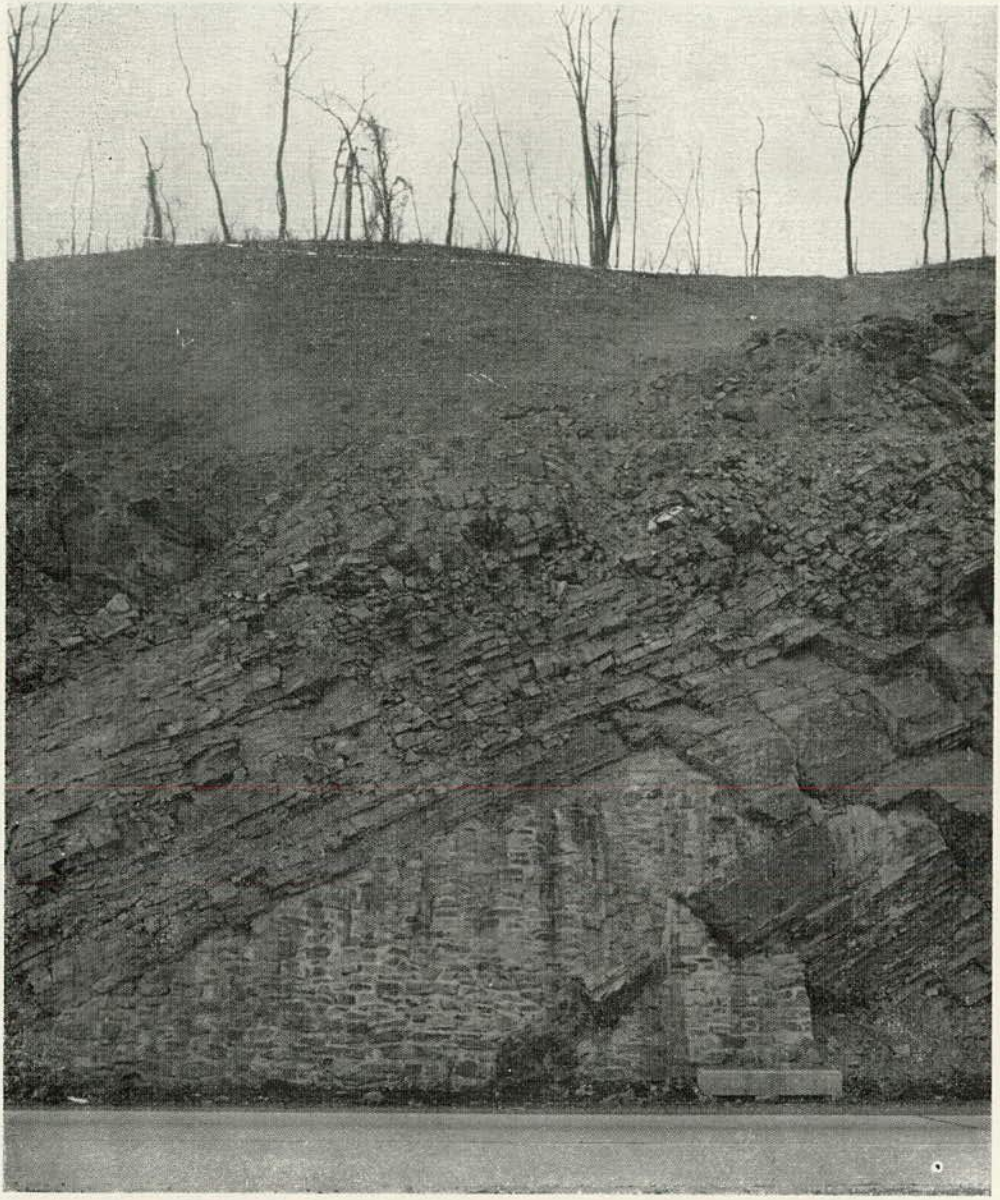

Figure 84. Masonry wall inset beneath overhanging layers of rock. This wall, plus bench on upper part of cut, serves to prevent or minimize rockfall. Note rocks in ditch, however, which represent a small but constant maintenance expense. (Photograph courtesy of Pennsylvania Department of Highways)

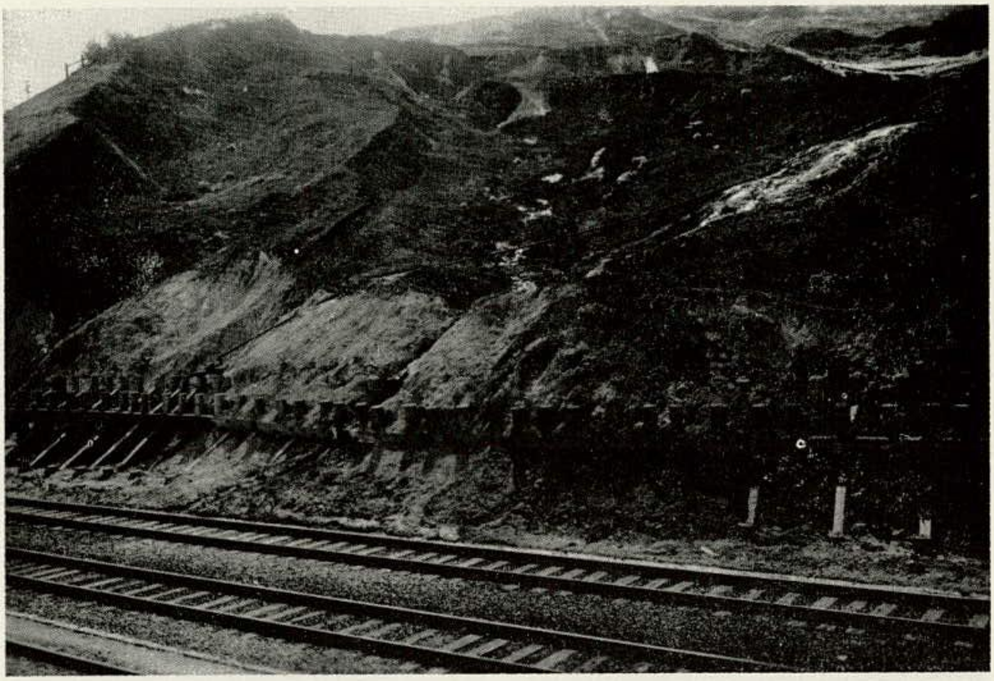

Figure 85. Failure of piles and bulkheads at Valona, Calif. Various types of piles, walls and bulkheads failed to correct this landslide, which was subsequently controlled by extensive subdrainage treatment. State highway crosses the slide near its head, at extreme top of photo. (Photograph by E. W. Herlinger, courtesy of California Division of Highways)

weight in the form of a toe support or strut fill where this upheaval would normally occur, the resistance against sliding is increased. This is one means of improving the stability of an embankment, but the strut fill must be carefully designed in order to utilize the weight most effectively and to assure that the toe support fill will not in itself be unstable. Unless a careful investigation and analysis is made there is always the danger that the additional load imposed by the toe support fill may increase the driving force rather than provide added resistance against sliding. Such fills are safest if the toe fill extends between the embankment and a natural stable bank or hill. Figure 87 illustrates this type of earth buttress. A properly designed toe support fill is more effective than merely flattening the embankment slope, because all of the added weight of the strut fill acts to resist slide movement, whereas part of the weight added in flattening the fill slope contributes to the driving force causing slide movement. Figure 88 shows a toe support embankment used as a slide preventive.

A highly specialized form of toe support to prevent slides is shown by Figure 4. Groins were built out into the water beneath an unstable slope; the groins caused shore currents to build up sand beaches at the base of the slope, thus adding weight and support to the toe. The upper slopes were also treated to retard erosion.

The rock buttress has been used as a slipout prevention measure with considerable success. If the rock buttress extends down to firm material, and is sufficiently massive, the resistance against sliding is appreciably increased by the high shear resistance of the rock buttress. Many rock buttresses have failed because they did not extend to sufficient depth; as a result, a surface of rupture passed below the bottom of the buttress, which then moved as part of the slide. Assuming that the necessary boring and test data are available, the improvement in stability effected by construction of either type of buttress can be estimated with reasonable accuracy by application of the principles of soil mechanics, as described in Chapter Nine.

A modified application of the buttress principle has been found effective in preventing sloughing or flowing of wet cut slopes. This method, which is really a combination of drainage and buttress, consists of placing over an excavated slope a heavy blanket of clean coarse gravel or similar pervious material. If the cut slope is excavated on a 1:1 slope, for example, the gravel blanket would be placed to a $1\frac{1}{2}$:1($1\frac{1}{2}$ horizontal:1 vertical) or 2:1 slope, thus providing a wedge-shaped buttress of gravel which allows free drainage of seepage from the slope and, at the same time, furnishes

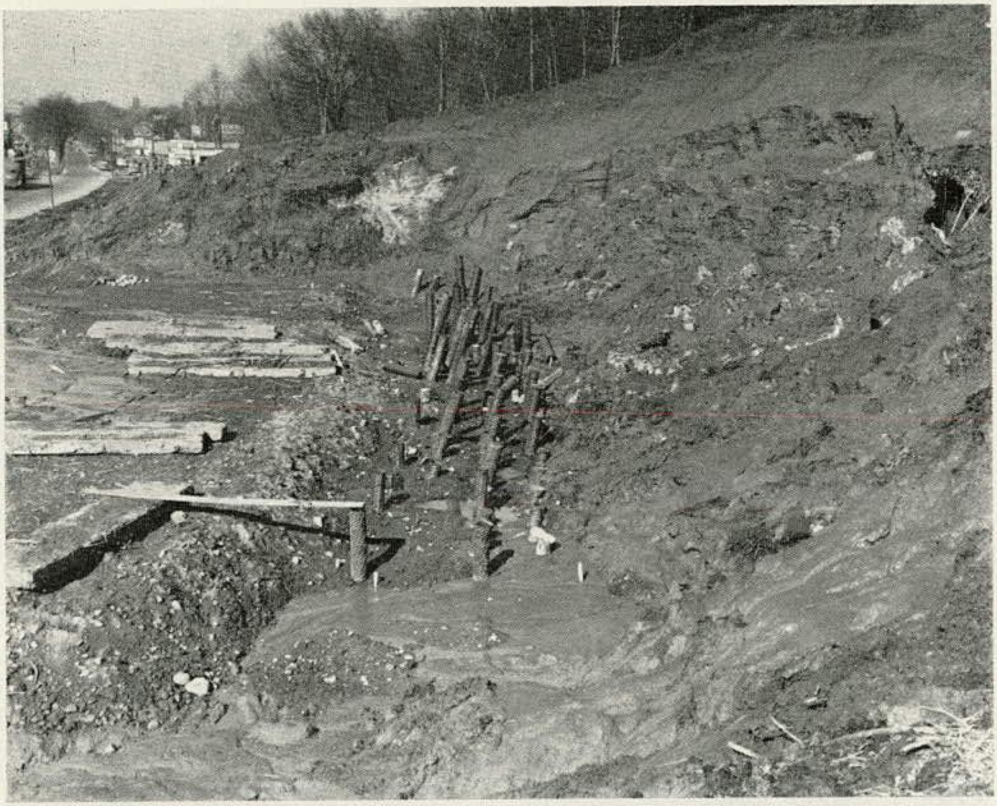

Figure 86. Failed piling in varved clay, 1 mile south of Springfield, Mass. This slump-earthflow, 300 feet wide, 75 feet high, and 60 feet deep, took place in 1954 in varved lake clays that dip 12° to 15° downslope. The summer layers are high in silt, hence provide much water for absorption by the winter layers. Slump was due to high water content, triggered by removal of toe and vibration of construction equipment. Piling having failed, the slide was corrected by a combination of rock buttress, partial removal and drainage at toe, reshaping of slope, and partial removal of head. (Photograph courtesy of Massachusetts Department of Public Works)

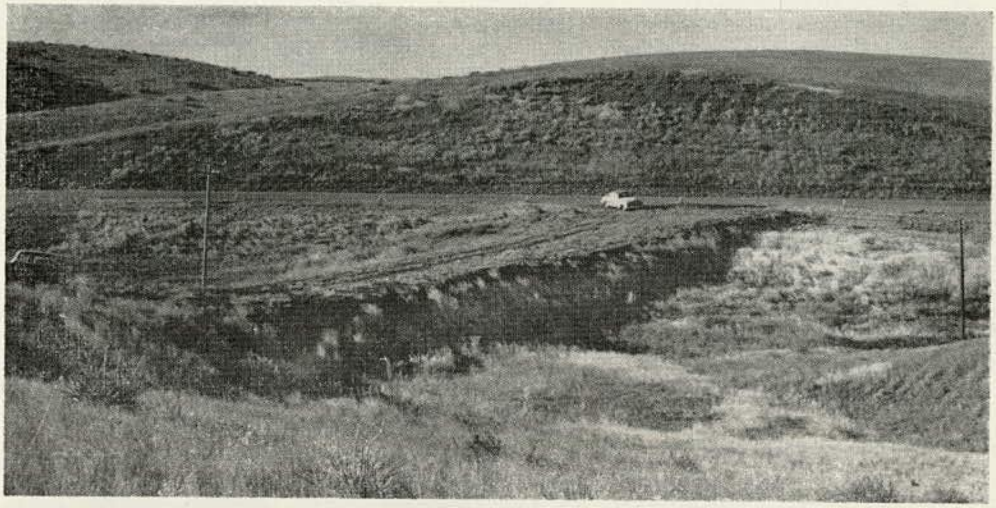

Figure 87. Earth buttress fill to prevent sliding. Earthfill constructed as buttress between highway embankment and opposite stable valley wall; culvert placed in creek channel under buttress. This particular installation (4 miles west of Pierre, S. Dak.) was for slide correction, but similar buttress fills are frequently constructed for prevention of slides. The horizontally bedded soft shale on far hill was moving down slowly and causing displacement of the highway fill toward the observer. (Photograph by D. J. Varnes, U. S. Geological Survey)

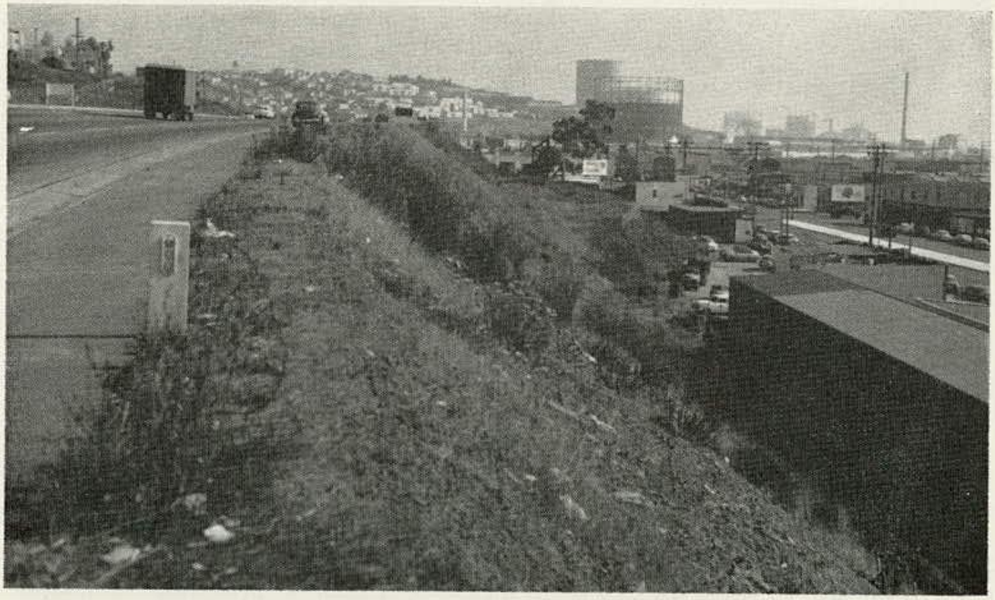

Figure 88. Restraining structure; where toe of fill extended over unstable marine clay, a toe support or earth buttress fill was constructed to prevent slipouts. Buttress fill is near middle of photo at extreme right, where right-of-way fence curves outward. Freeway near San Francisco, Calif. (Photograph by Bruce Utt, courtesy of California Division of Highways)

resistance against sliding. This type of preventive treatment is applicable only to relatively low-cut slopes, and would be economical only in locations where a plentiful supply of cheap gravel is available. The method is illustrated by the cross-section in Figure 89.

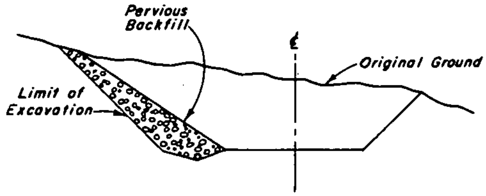

Figure 89. Modified buttress. Pervious blanket of gravel or rock prevents sliding of wet cut slope by providing drainage of slope and also by increasing strength of slope by buttress action. Typical of preventive treatment used near Boonville, Calif. (Courtesy of California Division of Highways)

Piling

Driving of piles to prevent or retard slide movement appears to have great appeal to the layman, and to some engineers, even though the majority of such installations have been far from successful. In general, the pile treatment is more likely to be effective as a preventive measure than in controlling an active landslide. The shearing resistance of a soil mass often can be considerably increased by driving piles, and the resulting increase in shear strength may be sufficient to prevent slide movement. The piles may, however, be ineffective because of (a) movement of soil between and around the piles, (b) overturning of the piles, (c) shear failure of the piles, or (d) development of a surface of rupture in the soil below the pile tips. The reasons for and means of preventing each type of failure are apparent. Too few engineers have a true conception of the magnitude of the forces which may be exerted in a landslide movement, and assume that a few piles will control or prevent sliding. In most cases a thorough analysis during the design stage would indicate such deficiencies in the design of the treatment. Of course, piles should not be driven in soils that become "quick" under vibration.

Dowels

Rockslides are not uncommon in cuts through hard durable rock, if bedding planes or joint planes are prevalent in the rock. Sliding is likely to be especially troublesome if the joint planes or bedding planes slope toward the excavation. If the cut slope is of great height, or if the rock face above the slope line is relatively steep, the sliding is likely to be progressive — movement of one block of rock removes the support from the rock in the face above, and the sliding progresses up the slope. The weakness along the joint planes may be aggravated due to percolation of water and weathering along the contact, and also by freezing in frost areas.

In many cases a small additional restraint will prevent the initial movement, although once a block of rock has started moving restraint would be most difficult. Dowels have been used successfully for preventing this type of slide. In the installation of the dowels, holes are drilled into the rock normal to and across the weak planes, then heavy steel dowels are grouted in the holes. The spacing and length of the dowels would depend, of course, on the degree of jointing and the dip of the bedding planes or joint surfaces. Control of a slide by installation of dowels has been described and illustrated by Laurence (1951). The use of dowels is seldom practicable unless the rock is durable and free from fragmentation.

Rock bolts, a modification of the dowel principle, are now used extensively to prevent movement of rock; these consist of heavy bolts with a wedge or expansion device at the lower end, which are installed in holes drilled in the rock (see Fig. 90). A large washer or plate is provided under the nut at the face of the rock. Because the tightening of the nut actuates the expansion device

Figure 90. Rock anchor bolts used to prevent slippage and fall of bedded rock in a railroad cut in northeastern Pennsylvania. The bolt consists of shank threaded at one end on which a nut and retainer plate are attached. At the end which is embedded in the rock the bolt has a forged slot. A steel wedge is forced into the slot to hold the bolt securely in the drilled hole. In some cases, slippage along very steeply inclined beds, such as those shown in Figure 20, can be prevented by means of rock bolts. (Photograph courtesy of Bethlehem Steel Company)

in the hole, no grouting is required. Such rock bolts, which have been commonly used in tunnel construction and in mines, are now frequently installed in slope faces of rock excavation, to anchor slabs or fragments of jointed rock before any movement occurs. These rock bolts, if properly placed, will often anchor key slabs of rock and thus prevent rockslides or rockfalls which might otherwise develop into large-scale movements.

Tie Rods

One of the causes listed for failure of retaining walls, cribs and piles was overturning or tilting of the retaining structure. Retaining walls frequently must be founded on such weak material that the unit pressure at the toe of the footing exceeds the bearing capacity of the foundation soil. When the restraining structure consists of piles, the material penetrated by the piles may not have sufficient shear strength to prevent tipping of the piles due to lateral thrust of the soil mass. When such conditions prevail, the use of tie rods may provide the required additional resistance against overturning. When tie rods are employed for this purpose they consist of heavy steel rods or wire rope securely fastened to rigid wales, piles, or vertical members of the restraining structure; the tie rods are anchored to deadmen placed in the most stable accessible material back of the structure, frequently in firm ground on the upper side of the roadway. This type of treatment is best adapted to the prevention of embankment slipouts, as it is seldom feasible to install the tie rods where the restraining structure protects a cut slope. Tie rods have been used to anchor log cribs, pile and plank bulkheads, and similar restraining structures (see Fig. 91).

Miscellaneous Methods

Many other methods of slide prevention have been tried with varying degrees of success. Most of these treatments have limited application and are effective only under certain combinations of conditions. Under "Miscellaneous" in Table 4 are listed a few of these less frequently used methods of slide prevention. Because most of them are still somewhat experimental or have very limited application, they are not discussed here in detail.

Hardening of Slide Mass. — By means of artificial cementation the individual soil grains are cemented together, thus increasing the shear strength of the soil. Cementation may be accomplished by injection of chemicals or by grouting with portland cement.

Most of the chemical injection processes use sodium silicate, in combination with one or more other chemicals, which react with the sodium silicate to form a silica-gel in the interstices of the soil. Several of these injection processes, such as the Joosten and K.L.M. methods, are proprietary. The injection methods are commonly applicable only to sandy soils with an effective grain size of at least 0.1 mm. The treatment has been used successfully to effect temporary stabilization of sands during the construction period in excavation of tunnels and trenches; as a preventive treatment against large-scale slides, it has been used to a very limited extent.

Portland cement grout injections have been used successfully for cementing coarse sands and gravel, but are general-

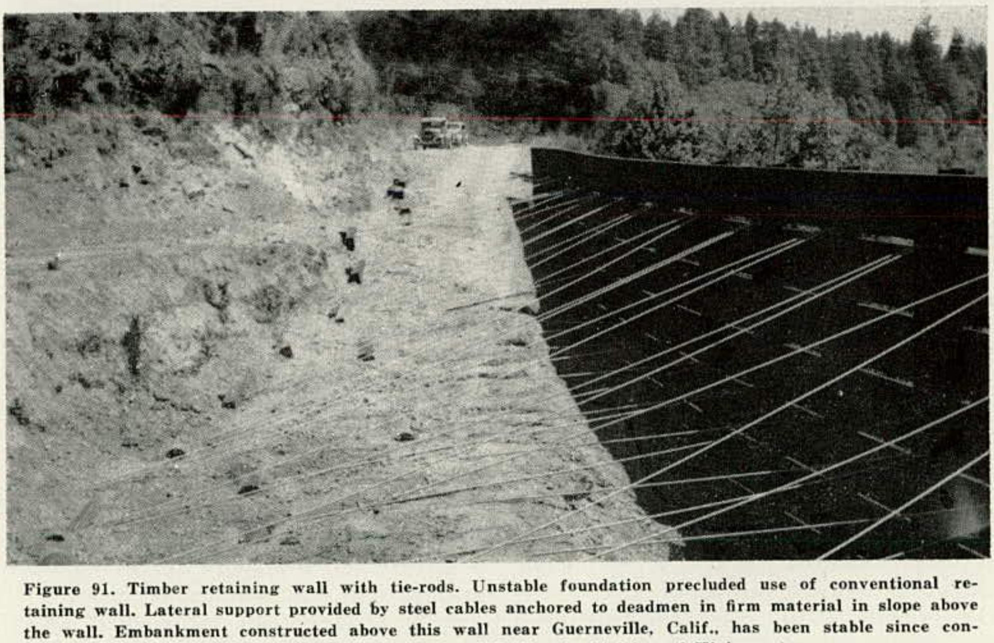

Figure 91. Timber retaining wall with tie-rods. Unstable foundation precluded use of conventional retaining wall. Lateral support provided by steel cables anchored to deadmen in firm material in slope above the wall. Embankment constructed above this wall near Guerneville, Calif., has been stable since construction in 1939. (Courtesy of California Division of Highways)

Figure 92. Fill stabilized with cement grout. Cement grouting was accomplished in 1949 in the Westgate Fill near Westgate, Va., by the Virginian Railroad. A highly micaceous soil was used in the embankment construction and compaction was very difficult. The inclined drain pipes shown at midslope were placed earlier, but were ineffective and were later abandoned. Injections were made along the slope with holes on a 10-foot gridwork. The grout was mixed to a proportion of one part cement to four parts of sand. The section was 540 feet long and the slopes were approximately 65 feet high. The cost of the correction amounted to $8,040 (Smith, 1950). (Photograph by Rockwell Smith, Association of American Railroads)

ly considered less effective with finer grained soils. However, some of the railroads have been applying grout injections as a slide corrective treatment, and report encouraging results even when the soil mass was heterogeneous or comprised largely of clayey materials (see Figs. 92 and 93). The grout was apparently dispersed through seams, cracks and fissures in the fine-grained soil, as well as into the interstices of the coarse sand and gravel. Even though the grout was not uniformly distributed throughout the soil mass, the treatment has, in many cases, effected sufficient increase in shear strength to stabilize the slide mass. The grout injection method might be less effective as a prevention treatment because of the absence of cracks and fissures, most of which tend to develop after movement occurs. Nevertheless, the method may be applicable to a greater variety of soil types than is generally believed.

Bituminous emulsions, having a lower viscosity than cement grout, will penetrate into the pore spaces of finer grained soils than will cement grout. The cost is greater than for cement grout treatment, and the emulsion is not suitable for use where ground water might remove the emulsion before setting occurs. There is also some question as to the permanence of the hardening, especially if ground water is present. The asphaltic emulsion treatment has not been used extensively as a landslide preventive treatment.

Freezing of soil to prevent sliding during construction is a unique method that has been used on at least one large project. A description of the operation has been published (Gordon, 1937). The freezing process is slow and relatively costly; obviously, it would be applicable only as a temporary treatment for slide prevention, and is mentioned merely as an example of an unusual means of effecting stability of a slope by an artificial hardening process.

Another method of increasing the shear resistance of a soil mass is by electro-osmosis, in which migration of water out of the soil pores is induced by causing an electric current to flow between electrodes driven into the soil. The moisture content of fine-grained soils can be reduced appreciably by the electro-osmosis process, with a concomitant increase in shear strength. The method has been used successfully on full-scale slope treatments in Europe, but most of the work done thus far in the United States has been of an experi-

Figure 93. Injection of cement grout to stabilize small fill on Southern Railway in northern Kentucky. The method used was similar to that described under Figure 92. (Photograph by Rockwell Smith)

mental nature. The process has been described by Casagrande (1948), Karpoff (1951), and others. Available information indicates that, because a rather strong electric current is required over a considerable period of time, the cost of electric power for this treatment may be prohibitive.

Another process, which is similar to electro-osmosis, is the electro-chemical hardening of clays. If aluminum electrodes are used in the electro-osmosis treatment, there is, in addition to the reduction in moisture content adjacent to the anode, a further hardening of the soil resulting from base exchange — the positive ions of the clay minerals are replaced by aluminum ions from the electrode, with a loss of metal from the electrode. The hardening effected by this process is apparently permanent. As with electro-osmosis, the power requirements are high, making the treatment costly.

Blasting. — Where a relatively shallow mass of cohesive soils is underlain by bedrock or other hard material, the contact between the two is sometimes a smooth sloping surface; such a contact plane is a potential surface of sliding, especially in the presence of subsurface water or if there is a thin layer of plastic material along the contact surface. Blasting is sometimes used to break up such a contact surface, thus providing a mechanical bond between the two surfaces. In effect the shear strength along the weak zone is increased by the shooting and breakup of the hard material. It is probable that this method has been most successful where the hard layer was underlain by a pervious formation, and the blasting provided drainage into the underlying pervious layer. The permanence of the blasting method has frequently been questioned, and there is evidence that in some cases a weak zone later developed along the original contact, due to migration of fine soil and "healing" of the fractured zone. There is, of course, the risk that the blasting, unless carefully handled, may induce slide movement during the construction treatment.

Partial Removal at Toe. — Partial removal at the toe of a landslide has been included under "Miscellaneous Methods" of slide prevention and correction in Table 4, although such excavation usually neither prevents nor corrects a landslide; on the contrary, it more often aggravates the sliding. Excavation at the toe of a landslide is sometimes necessary as an expedient to protect a structure temporarily, until the structure can be relocated or more permanent corrective treatment provided. This type of treatment is usually attempted after occurrence of a landslide, and could seldom be considered as even an attempt at prevention. The fact that a landslide sometimes remains quiescent for a considerable period of time after slide material is excavated from the toe, is merely evidence that the factors which activated the original slide were no longer present after the toe was excavated. For example, a large rockslide, involving more than a quarter of a million cubic yards of slide material, completely blocked a mountain highway a few years ago. Conditions were such that neither complete removal nor large-scale corrective treatment was feasible; sufficient material was removed at the toe of the slide, in this case at roadway grade, to permit opening the road to traffic as quickly as possible. Although no corrective measures were taken there has been no further slide movement. The slide occurred during a mild earthquake in the region, and it is probable that the slide will remain quiescent until there is another earthquake or some other changed condition reactivates the slide.

Conclusion

The number and variety of slide prevention methods discussed in the foregoing are evidence that there can be no rule-of-thumb system of prescribing treatment; and for a particular landslide or potential landslide there is seldom one and only one "correct" method of treatment. Frequently, the most economical effective means of prevention consists of a combination of two or more of the general preventive measures described in this chapter.

For most landslides, a majority of the possible preventive treatments can be eliminated at the outset, and only a few of the many methods need be considered. Frequently, the final selection can be made only after careful comparison of two or more alternate methods. But in spite of the complexity of landslides and the wide variety of control methods, the problem of landslide prevention and correction is amenable to a rational engineering approach, by proper utilization of available knowledge on the classification, recognition, and analysis of landslides.

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