EARTH CUT-SLOPE DESIGN IN NEW YORK STATE

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A method of designing stable earth cut slopes is presented for glaciated New York State soils conditions. The cut-slope design procedures were developed from detailed studies of natural landslides and highway cut-slope failures occurring during and after construction. These failures are classified according to mechanism of failures, and a description of corrective treatment is discussed for each classification. Emphasis is placed on essential design input considerations other than the mechanics of stability analyses. The design procedure relates the importance of investigative procedures, laboratory testing, stability analyses, alternate methods of treatment, and effects of changing conditions. Relations among cost of treatment, factor of safety, and dependability of data are discussed. Also, guides are given for selecting locations for cut-slope design investigation and for the amount of investigation and analysis required.

•CONSTRUCTION of highways using modern geometric standards has increased the frequency and magnitude of earth cuts. Failures of the cut slopes are often very expensive to correct and may result in loss of support to land and structures beyond the right-of-way. A design procedure is therefore needed to predict the degree of stability of cut slopes to be made in critical locations. Finding the "correct" method of stability analysis is only part of the answer to the cut-slope design problem. The design procedure must include suitable investigative techniques, stability analyses, methods of corrective treatment, and guides to interpreting the importance of all components of the design for the situation being studied.

The procedures described are based on studies of cut-slope failures in New York State. Failures are common in all types of glacial till deposits, but morainic deposits and "sloughed till" (colluvium) usually have a potential for greater problems. Dissected lacustrine clay deposits and fine-grained delta deposits also are prone to cut-slope failures. Average rainfall in New York State is about 3 ft per year, and the frost penetration over much of the state exceeds 3 ft. Because the stability of a cut slope depends directly on the geology and climate of an area, the procedures described may not be directly applicable to other situations.

CLASSIFICATION OF CUT-SLOPE FAILURES

An understanding of the types of cut-slope failures is needed before a design is started. Cut-slope instability can be classified into two basic categories: shallow failures and deep failures.

Shallow Failures

Shallow failures will not affect adjacent facilities or lands beyond the top of the cut slope and are usually handled by localized spot-maintenance procedures. Shallow failure mechanisms are categorized into three types (Fig. 1):

1. Sod slides are grass and sod that travel down the slope after the spring thaw or heavy rains (they usually occur on the north- or west-facing slopes on very dense or plastic soils),

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2. Piping failures are funnel-shaped washouts in areas of high seepage in sand or silt soils that often occur as isolated pockets or as a line of washouts where a sand or silt soil overlays a less permeable soil, and

3. Sloughing failures are seashell-shaped areas of sliding soil that occur in silty soils with high seepage.

Corrective treatment for shallow failures is largely cosmetic, consisting of cleaning the ditches where necessary, reseeding sod slide areas, and placing a 2-ft thick blanket of coarse stone in the areas of piping or sloughing. Installation of underdrains along the interface of a sand or silt soil to a less permeable soil is often included as part of the design to prevent loss of support of the upper materials.

The stone "slope protection" blanket lowers the groundwater and adds confining pressure at the point of seepage eruption. The stone used for stabilizing the shallow cut failures in New York State has the following gradation: a 6-in. top size, no more than 30 percent smaller than 2 in., and less than 10 percent passing the ¼-in. sieve. Where the cost has not been prohibitive, coarse-aggregate crushed stone has been used with success. This stone blanket is usually placed a minimum of 2 ft in thickness; thinner blankets will not work. The filter criteria (1) for the stone slope protection blanket are not satisfactory for many of the fine-grained soils that it has stabilized. However, the only distress evident from inspections of hundreds of successful applications was some minor silting in the ditch and in the toe of the stone blanket. The silting was traced to surface water entering the slope protection and flowing at the rock-soil interface with sufficient velocity to erode the surface of the soil. Diversion of surface runoff has stopped the silting. At one time New York State used a slope protection blanket that was fine enough to meet the filter criteria for most of the native silty soils. However, many failures of this type of material occurred because of inability of the slope protection blanket to carry away the seeping water without becoming completely saturated and sliding off the slope.

Deep Failures

Deep failures usually extend beyond the top of slope and are categorized into three types (Fig. 2):

1. Slumps are failures in soils with high groundwater seepage. This is a large slough or a series of sloughs that may extend to the top of slope.

2. Shear failures are circular arc failures in plastic soils that, in most cases, do not extend more than 20 ft beyond the top of the cut slopes. Occasionally failures result from oversteepening of the slope, which causes initial overstress and failure of the in-place (undrained) shearing-strength conditions. Also failures occur after a long period of time as a result of stress release when the residual (drained) shear strength (2) predominates.

3. Block failures are failures that are controlled by the subsurface profile. These are types of wedge failures with cracks starting near the top of the cut and secondary movements occurring beyond the top of the cut soon after the first movements. They usually result from shallow soils over sloping rock surfaces, thin layers containing high water pressure, or sloping plastic layers.

These three types of failure mechanisms result in loss of support for the ground beyond the top of the cut slope, and, as such, the damage that can result from any movements is often very costly. The design procedure described here is therefore confined exclusively to design of earth cut slopes to prevent deep failures.

CUT-SLOPE DESIGN PROCEDURES

Cut-slope design is a complex study of the consequences of instability versus the cost of reasonable treatment to prevent the instability. Soil strength and groundwater conditions in earth cuts usually change with time, which makes the design process more difficult. Cuts in overconsolidated soil result in a release of overburden stress and a loss in shearing strength of the soils with time. Many overconsolidated soils in

New York State have had major cut-slope failures 8 years after construction. In granular soils and many of our complex, multigrained till soils, the water level draws down over a period of time. As a result, cut-slope failures that occur when the initial cut is made will be permanently stable as soon as the water table reaches equilibrium after grading is completed.

The soils engineer must decide whether to institute a design for an earth cut slope or to take a chance on using a "standard" slope angle. Facilities are not available to provide a detailed investigation of all cuts on highway projects. However, it is imperative that an investigation be made of all cuts that support important adjacent lands or structures. It is also essential that locations of existing landslides be identified before the highway alignment is fixed. Stabilization of existing landslides into which a cut has been made is perhaps the most expensive change precipitated by "unknown" soil conditions. Therefore, all locations with topography not consistent with the geology of the area should be investigated to determine whether it is an old landslide.

Investigative Techniques

Development of proper input for a cut-slope investigation depends on understanding the mechanism of failure. A simplified expression of the stresses applied to a natural slope is shown in Figure 3. More detailed discussions of the failure mechanism are available, but it appears that the current inability to obtain exacting input of present and expected conditions precludes the use of most of the more rigorous solutions. The basic inputs required for cut-slope stability analyses are surface geometry, subsurface geometry, shearing strength of the critical soil (or soils), groundwater conditions, and changes in the groundwater conditions and soil strengths that can be expected.

Surface Geometry—For surface geometry, cross sections and topography are required including accurate locations of utilities, streams, roads, etc. For side hill conditions, cross sections must be carried up to the top of the hill or to a controlling feature such as a rock outcrop.

Subsurface Geometry—The location and characteristics of the critical soil strata are usually obtained by taking continuous split spoon samples in borings located strategically along the proposed cut. A minimum of two borings on a cross section are needed, one in the ditch line and one at the top of slope. Additional borings may be needed above the top of cut if the slope continues to rise. The number of borings required longitudinally depends on the continuity of the soil conditions and the extent of the possible problems. The use of test pits is helpful in obtaining undisturbed samples. Also, knowledge of the continuity of subsoil conditions (if the critical soils are not too deep) is helpful.

Twenty-three borings were taken at one landslide location with only two borings giving an indication of clay near the surface of the rock. Deep test pits were then used to determine the cause of failure. These showed a thin, discontinuous clay layer at the rock surface. Now, for geologically similar areas where thin clay over rock is expected, it is first assumed that the clay layer exists, and then the exploration program tries to prove that it does not.

Seismic investigations are the prime tool if the rock surface is a major influencing factor. Other investigators have had success with the electrical resistivity method of investigation. In New York State, however, resistivity methods have only been successful in determining the groundwater table.

Shearing Strength—Consolidated drained triaxial tests are run to determine the drained friction angle of the critical soil. A rate of shear of about one-tenth of the drainage rate determined from a consolidation test (3) is used.

Consolidated undrained tests are used for short-term analyses on plastic soils. Also, consolidation and permeability tests are used to estimate the rate of drawdown of the groundwater table and the rate of stress release.

Explorations in, and analysis of, existing landslides are helpful in evaluating the shearing strength in similar geologic soil deposits.

A preliminary relation between plasticity index and drained friction angle is shown in Figure 4. This curve is based on data taken from existing landslide situations that

were analyzed and checked against laboratory test data with reasonably good comparisons (1). It has been used with apparent success to advance development of designs when time is not available to obtain adequate tests.

Groundwater Conditions—Past landslide studies have shown as many as three indicated groundwater tables: one in the underlying rock, one in a granular layer within a glacial till deposit, and one within the glacial till. Therefore, the method of obtaining the groundwater condition must be capable of separating these tables. In New York State various methods are employed, use of which depends on the conditions expected from a geologic evaluation. Separate observation wells sealed into each soil or rock deposit are often used.

Changes in Condition—Normal seasonal groundwater fluctuations can be obtained from periodic readings on observation wells. However, the drawdown that occurs after the cut is made can only be estimated. An approximate theoretical solution for drawdown curves at different times is currently being checked by field instrumentation in New York State. These solutions are for uniform soils only because many layered soil systems do not exhibit significant drawdown.

Consolidated undrained triaxial tests give a good value for the shearing strength of a soil deposit when the cut is made. However, the stress release resulting from the excavation reduces the strength of overconsolidated soils to a value approaching that obtained from the consolidated drained test. The shear strength at failure is somewhat above the drained strength for slopes that have not moved before. For slopes that have failed before (old landslides), the shear strength at failure is the same as the drained strength. An approximate procedure to relate the rate of groundwater drawdown (improving stability) to the rate of stress release (decreasing stability) is being studied in New York State. Because of the length of time required for complete stress release (about 8 years for the upper 20 ft for some slopes), it is doubtful that a good method of estimating the time to failure will be developed for many years.

Stability Analyses

Various methods of stability analyses have been computerized and are available. Because most landslides and cut-slope failures that have been evaluated failed under conditions of drained shear strength with seepage forces (or artesian water pressures) included, the stability analysis should have these capabilities. New York State is currently using a computerized circular-arc stability analysis that has these and other capabilities (4). The modified Swedish stability analysis appears to provide the best correlation to field conditions for sliding types of wedge failures. Because this analysis has not yet been programmed for a computer, it must be done manually. However, a modified "NAVDOCKS" wedge (5) has been programmed for a desk-top calculator and is only slightly conservative for most cases.

In addition to the methods of analyses previously mentioned, a solution for the infinite slope stability analysis for the drained strength conditions with seepage forces has been presented in graphical form (6). An example of one situation applicable to silty glacial till soils is shown in Figure 5. The curves (Fig. 5) are used as a preliminary evaluation tool to help in determining whether a problem could be expected under generalized soil conditions, slope angles, and water table. These curves can be used where the failure mechanism is expected to be shallow by using the slope angle as the angle of the proposed cut. They can also be used with reasonable accuracy for a deep-seated failure on a subsurface plane, provided that the slope of the subsurface plane is taken as the slope angle on the curves.

Numerically, the following guides for acceptable factors of safety are used:

1. Factors of safety less than 0.95 for drained or undrained strength conditions are considered unsatisfactory because a failure will occur and treatment must be anticipated in design.

2. Factors of safety between 0.95 and 1.15 for the drained strength condition are considered conditionally acceptable for the plastic soils that are expected to lose strength with time, provided that the undrained factor of safety is in excess of 1.25 and the possible damages are not great. In most cuts, the groundwater table will draw

Figure 1. Shallow-cut failures.

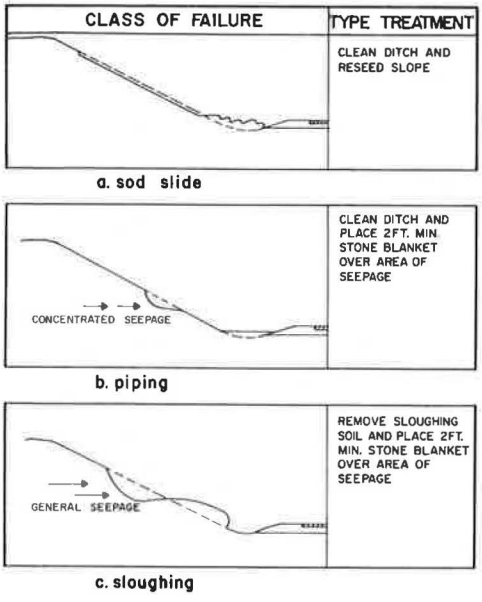


Figure 2. Deep-cut failures.

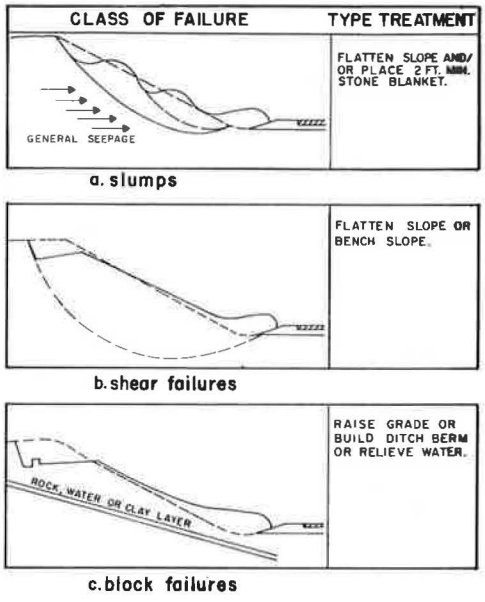


Figure 3. Simplified stresses on natural slopes.

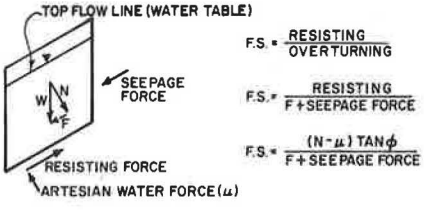


Figure 4. Drained strength and plasticity index.

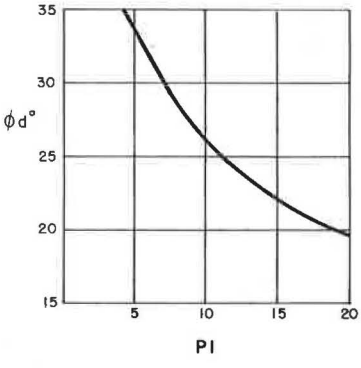
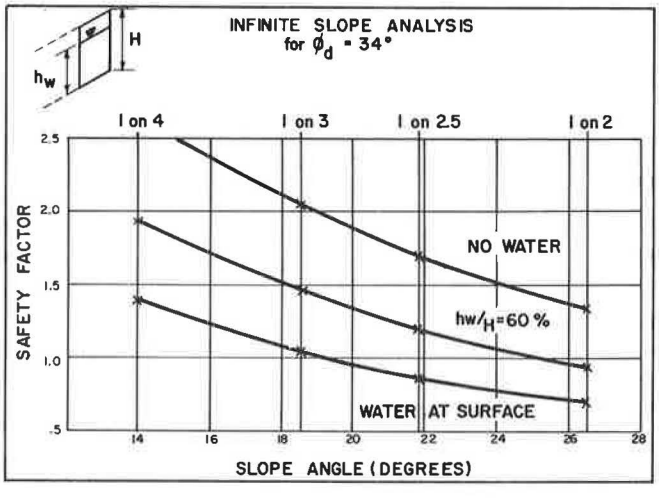


Figure 5. Infinite slope analysis.



down during the period of stress release, which improves the factor of safety to an adequate value before reaching a condition approaching the drained strength.

3. The normal factor of safety used is 1.15 provided that the maximum expected cyclical fluctuations of groundwater do not leave a factor of safety of less than 1.0.

METHODS OF STABILIZATION

Commonly used methods of cut-slope stabilization are shown in Figure 2 and discussed in this section.

Slumps

Methods of treatment include flattening the slope, placing a minimum 2-ft thick stone slope protection blanket over the slope, installing subsurface drainage controls, and correcting failures after they occur. Because cutting into the groundwater surface normally causes a lowering of the groundwater and resultant reduction of seepage force, it is often best to allow failures to occur during construction. If a stable condition is not reached before the end of the construction period, some positive method of stabilization must then be used.

Shear Failures

Methods of treatment include flattening the slope or constructing a wide bench in the slope. (Narrow benching of cut slopes to control runoff is not effective in the soils and climate of New York State. The drainage becomes blocked with ice and snow causing the top of the bench to become saturated and fail with resultant destruction of the bench.)

Cut-slope failures in the varved clays in New York State have been virtually eliminated. In most of our varved clays, stable slopes result at the following slopes: 0 to 20 ft (1 vertical on 2 horizontal), 20 to 70 ft (1 vertical on 3 horizontal), and more than 70 ft (flatter). These guides are based on laboratory testing and design analyses using the drained shear strength and anticipated water table and are verified by natural gulley slopes that have reached a stable inclination.

Block Failures

Methods of treatment are usually determined by the type of discontinuity in the subsurface profile. Some common methods of treatment are as follows:

1. Installation of subsurface drainage is made to reduce the seepage forces or artesian water pressure. This treatment has been used with only limited success in New York State because it is difficult to locate the source of groundwater and more difficult to design and install a filter system that will permit permanent drainage of the critical soil layer. In recent years a slotted polyvinylchloride pipe has been developed and is now available in the eastern United States. Because the width of slots can be very small and varied to meet soil conditions, this may be the solution to the filter problem.
2. Total removal of soils above the sliding surface is usually not economical and in some instances would require stripping a complete hillside. Flattening the slope is not a suitable solution in many cases because it may cause greater instability by reducing the overburden stress on the failure surface without reducing the water pressure.
3. Raising the roadway grade (or relocating the roadway) to reduce the effective depth of cuts is the best solution if it can be determined in the planning or early design phase before the highway geometrics are fixed.
4. Narrowing the roadway section and constructing a berm in the ditch requires placing underdrains in the ditch area and filter materials between the original slope and the berm. Narrowing the roadway section often reduces sight distance and causes snow-removal and pavement-drainage problems.
5. Constructing a retaining wall at the ditch line can only be used where the base of the wall can be located below the failure surface and becomes very expensive if the earth pressures are high. Generally, walls are not considered a satisfactory solution

because more serious failures may be started by the normal wall installation procedures. Drilled-in-place walls were used successfully in Seattle, Washington.

SELECTION OF STABILIZATION METHOD

Selection of a suitable stabilization method for a potentially unstable cut slope is somewhat difficult and confusing. Two examples relating factors that affect the choice of treatment may provide a better understanding of the problem.

Slump Failure

If we assume a 75-ft deep cut, the normal choices of stabilization in New York State would be (a) to flatten the slope from the normal 1 vertical on 2 horizontal to 1 vertical on 3 horizontal or (b) to dig out 2 ft of the surface materials and replace it with 2 ft of stone slope protection blanket. For the slope-flattening treatment, the factor of safety would be increased by approximately 0.4, and the cost would be in the order of $10,000 per station plus an increase of approximately 75 ft of right-of-way. For the second choice, using a slope protection blanket, the factor of safety would be increased only by approximately 0.1, and the cost would be in the order of $6,000 per station; however, there would be no increase in the right-of-way required.

The deciding factor for the choice of treatment is usually the amount of damage that could result if a failure did occur after the treatment was completed. A number of expensive residences along the top of slope make the slope-flattening treatment economically undesirable even for an increase in the factor of safety of 0.4. However, it might also be undesirable to increase the factor of safety by only 0.1 when some unknown, such as a series of sewage drain fields behind the slope, might cause failures that would destroy the valuable building.

When the choice of treatment is not clearly defined, more specialized treatments, such as horizontal drains or massive toe walls, are used to improve the factor of safety and reduce the possibility of large damage costs.

Shear Failure

A 70-ft deep cut was planned in a soft clay deposit within the Albany, New York, area. The slope stability analyses indicated that a 1 vertical on 3 horizontal would be satisfactory. For aesthetic reasons, the designers chose a longitudinal transition of slopes in this area from a 1 vertical on 2 horizontal in a stable gravel deposit to 1 vertical on 3 horizontal in the clay deposit under a proposed bridge. This resulted in an average slope through the clay deposit adjacent to the bridge site of approximately 1 vertical on 2½ horizontal, which still provided an adequate factor of safety against immediate failure (undrained strength conditions) but a marginal factor of safety for the long term (drained strength conditions). However, during construction the contractor further changed the design conditions by overexcavating behind one of the piers for the structure in the area. This resulted in a temporary equivalent slope of approximately 1 vertical on 1½ horizontal. Within 2 weeks there was a shear failure that filled the excavation and dropped the ground at the top of the cut slope, breaking sewer lines and endangering a house close to the top of the cut. Because of the contractor's operations, a failure had occurred, the strength of the clay was reduced, and excess pressures were induced such that there was a combination of drained and undrained phenomena occurring within the slope. A type of bench cut was designed adjacent to the bridge to account for the undrained strength parameters that applied as a result of the contractor's improper overexcavation. This required relocating the sewer lines and taking additional property at the top of slope. Additional expense was incurred to permit safe construction of the abutment near the top of the 1 vertical on 3 horizontal slope. This required changing the type of pile from cast-in-place to H-piles and using lightweight expanded shale aggregate as the backfill behind the abutment.

The original soils design report was not complete in that it did not point out the importance of controls during construction. It is not possible to estimate all possible situations that would cause a cut slope to fail. However, a greater effort is needed to

inform the construction personnel of the importance of temporary construction operations on the stability of cut slopes at critical locations.

The factors influencing the choice of cut-slope stabilization methods discussed here include indicated factor of safety, cost, dependability of the limits of variables, changing conditions, outside influences (aesthetics, special use properties, etc.), temporary construction conditions, and added costs resulting from failures. Other situations will include different influencing factors or will show a greater emphasis on certain factors than discussed in the previous examples.

The selection of an appropriate method of stabilization and an adequate factor of safety must be tailored to the individual situation being studied, with emphasis placed on the importance of the adjacent land.

CONCLUSIONS

Cut-slope stability studies must be approached in a manner different from embankment stability studies. With minor exceptions, embankment stability conditions improve with time as consolidation and strength gain occur, and changes in factor of safety with time are not considered to be detrimental. The stability of cut slopes, however, may improve or become worse with time after construction. Permanent water table drawdown improves the stability, but stress release and loss of shearing strengths reduce the factor of safety. Also, normal seasonal water fluctuations alternately increase or decrease the factor of safety. A season with unusually high rainfall may cause cut-slope failures that would never be predicted from prior records.

Currently, it is not possible to design all cut slopes without failures under all possible conditions. However, cut-slope failures at critical locations can and should be eliminated by adequate investigation and design.

Areas of old landslides can and must be identified because cut-slope failures in old landslides are usually the most expensive to correct.

Investigative techniques and design analyses are available now that can usually predict areas of major cut-slope problems where no surface indications exist. Although not yet perfected, these procedures can, with an intimate knowledge of the local geology, be used with reasonable success.

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