A Problem in Highway Slope Stability

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This paper describes the application of soils engineering to the correction of an unstable highway slope.

During construction of a highway cut through clays, silts, and sands of glacial outwash origin, the cut slope became very unstable. Extensive sloughing and erosion, with some slope movement, developed as excavation of the cut proceeded. A heavy flow of ground-water seepage developed in the cut slope. Drainage methods used to control this seepage are described.

After excavation of the cut area was complete, further slow movement of the slope face was observed. Successive cross-sections showing rate and nature of movement are presented. Additional field explorations employing continuous sampling techniques were made to determine cause of movement. Methods of sampling and testing are described. Investigation revealed slickensides, resulting in low-strength zones, in a soil mass that had general high-shear strength. Also, a zone of soft low-strength elastic clay was disclosed at a critical location below subgrade.

Observations indicated movement on a failure plane approaching the shape of a circular arc. Analyses by the Swedish circular arc method and the critical height of slope method are discussed. Results of further study to determine the slope section required to attain stability are presented. Corrective treatment used is described, and principles and techniques used in this solution that are considered to have general application to similar problems are summarized.

Pictures illustrate conditions from the beginning of construction to final completion of corrective work in September 1960.

● THE PROBLEM described in this paper occurred during the construction of a 21-mi section of Interstate 70 on new location in central Ohio, between Columbus and Zanesville, at a point immediately east of the structure carrying Ohio 668 over Interstate 70. The general location with respect to the Ohio highway system is shown by Figure 1.

GENERAL ROADWAY DESIGN FEATURES

In general, the roadway section is comprised of two 24-ft pavements separated by a depressed 50-ft median. The pavement consists of 9 in. of reinforced portland cement concrete on 6 in. of granular subbase. The median is graded to an 8:1 slope downward to a center ditch.

Paved shoulders are provided adjacent to both edges of each concrete pavement, with the outside shoulders 10 ft wide and the median shoulders 5 ft wide. Composition of the paved shoulders consists of 6 in. of granular subbase, 6 in. of crushed aggregate base, 3 in. of bituminous macadam base, and a double-seal surface treatment.

Subsurface drainage is provided by four lines of longitudinal pipe underdrains, with a line located under each shoulder 5 ft outside each pavement edge. The underdrains consist of 6 in. extra-strength drain tile, with porous backfill extending up through the subbase to contact with the bottom of the stabilized crushed aggregate base in the shoulder.

Standard plan slopes employed are 2:1 (horizontal: vertical) for fills over 10 ft high, 4:1 for fills 10 ft or less in height, 2:1 for cuts in excess of 5 ft deep, and 3:1 for cuts of 5 ft or less in depth.

GEOLOGY, TOPOGRAPHY, AND GENERAL SOIL CONDITIONS

Geologically, the problem area lies at the southeastern boundary of glacial advances, which, in past geologic history, covered approximately two-thirds of the State. The slope instability developed at a location within the limits of the Illinoian ice advance and beyond the limits of the Wisconsin ice advance. The location in relation to glaciation is shown in Figure 2. Soil deposits involved in the cut slope are of marginal glacial outwash origin of considerable depth. Topographically, the terrain is hilly primarily as a

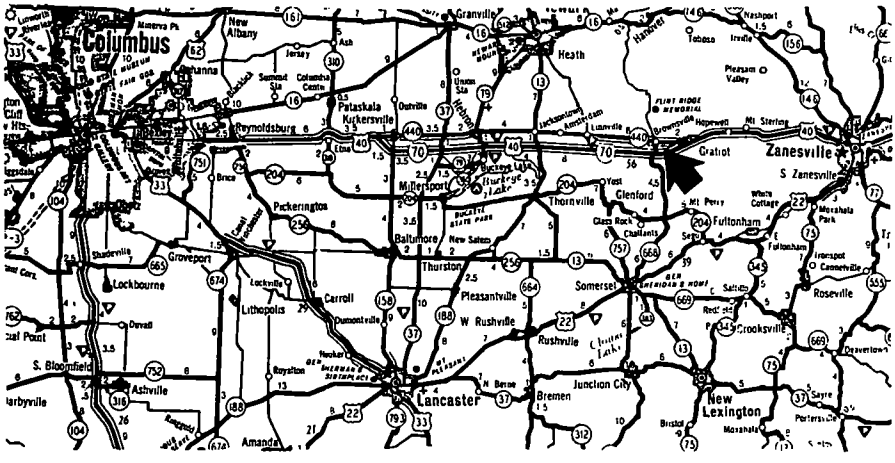

Figure 1. Partial Ohio Highway Map, showing location of slope instability with respect to highway system between Columbus and Zanesville.

result of stream abrasion. The general surface relief is shown by Figure 3. Maximum relief of the area in the general vicinity of the problem is approximately 150 ft.

In this area, the alignment traverses a gentle upland slope of only about 6 deg. At the location of instability, the alignment traverses a gentle topographic depression that tends to concentrate surface water runoff from higher terrain to the left of the alignment. The terrain before construction is shown by Figure 4, taken on centerline viewing forward and by Figure 5, taken at about 125 ft left of the centerline and viewing forward. Both views show the gentle topographic depression.

A cross-section of the proposed cut is shown by Figure 6. This figure also shows logs of test borings of the roadway subsurface investigation drilled prior to detailed design and construction plan preparation. These borings disclosed soil deposits of much greater depth than anticipated at this location. They further disclosed the deposits to be of marginal glacial origin and to consist of silts and fine sands underlain by clays directly overlying bedrock. Bedrock is composed of firm fine-grained sandstone and argillaceous shale with thin sandstone interbeds.

The subsurface investigational practice for this project entailed test borings for the general roadway to a depth of 8 to 10 ft below proposed grade at intervals along centerline averaging approximately 300 to 400 ft. Test borings of anticipated depth of 20 ft or less were drilled by faster truck-mounted bit-on-kelly-type augers and were 9-in. diameter holes. These borings were advanced in increments of from 0.5 to 1.0 ft, the bit being retracted after each increment of advance and the material inspected. Representative samples of each layer penetrated were taken and submitted for laboratory classification tests. Borings in excess of 20 ft in depth were drilled by slower split-spoon sampling techniques, with samples taken at about 5-ft increments of depth and submitted for laboratory classification tests.

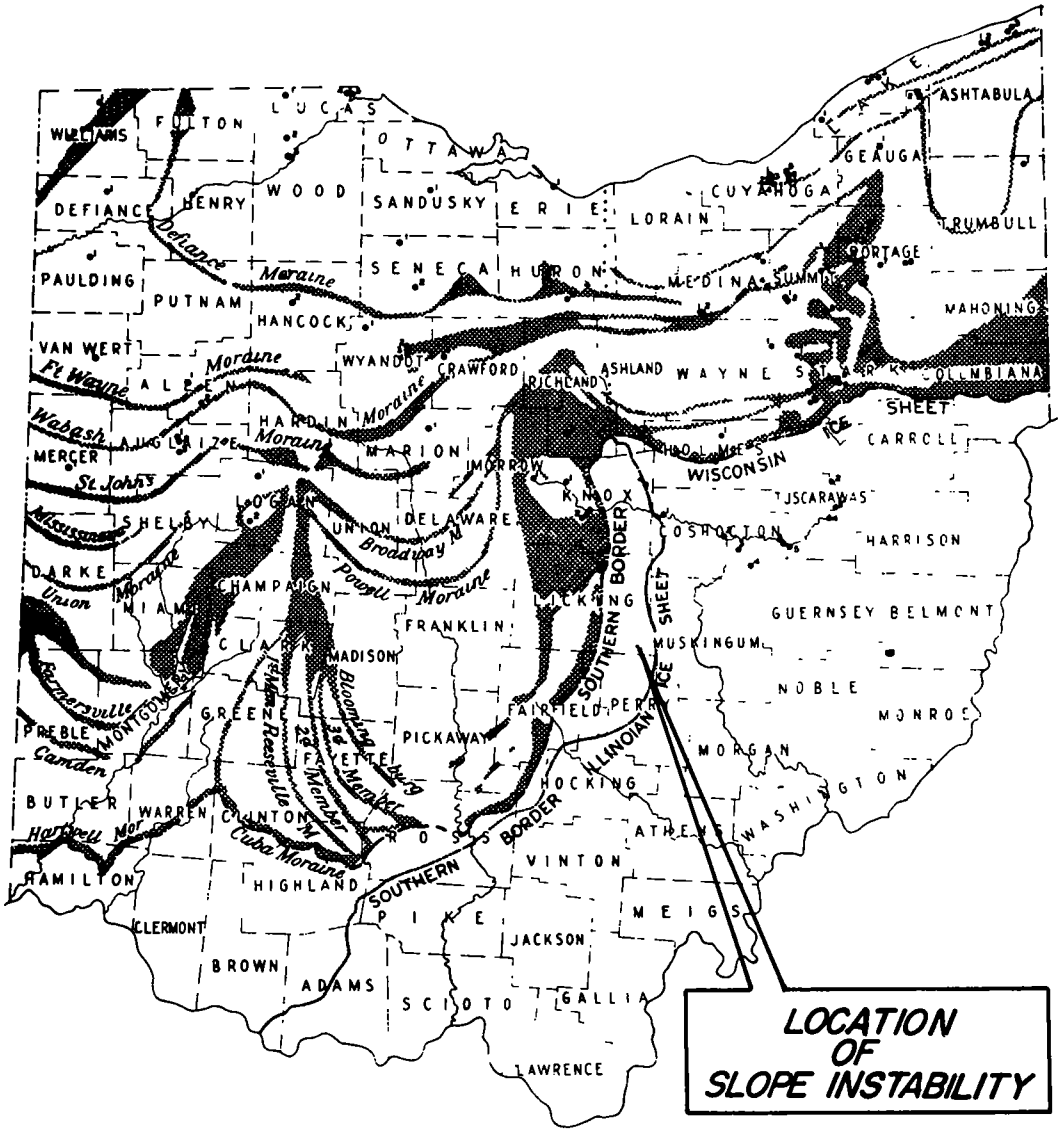

Figure 2. Map of Ohio, showing boundaries of glacier advances, and location of slope instability.

PROGRESS OF CUT EXCAVATION

Excavation of the roadway cut, about 45 ft deep, between Stations 1509 and 1516 was begun in May 1958 and completed to rough grade in October of the same year. High moisture content of the soil and strong flow of ground water from the north slope of the excavation at numerous locations made working conditions difficult and rate of progress slow.

The excessively high moisture content of the soil resulted in adequate bearing for efficient operation of heavy earth-moving equipment. A drag line, working on mats, was used for much of the excavation as shown by Figure 7.

Much of the soil from the excavation was wasted at the option of the contractor. Ohio specifications provide that soil with moisture content in excess of optimum plus 8 percent may be wasted, even though suitable when drier.

Figure 3. Map of Ohio, showing surface relief of State and location of slope instability.

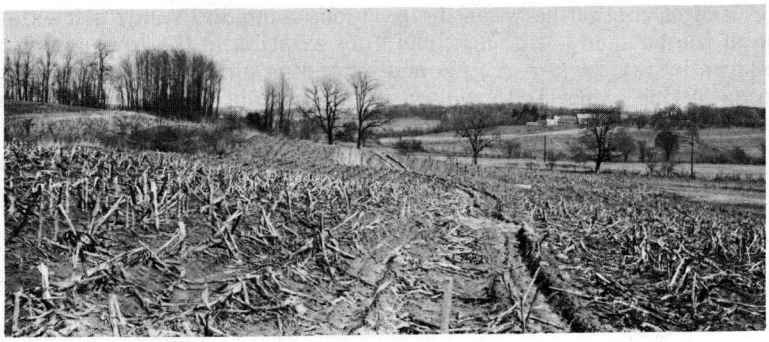

Figure 4. Foreground shows topography prior to construction along proposed centerline in area where cut is to be made.

Figure 5. This farm drive, prior to construction, is located at about the top of the proposed cut slope. Note sag in topography, and direction of surface drainage along gentle slope from left to right.

During excavation, longitudinal side ditches 10 to 15 ft deep were maintained between the bottom of slope and the material being excavated. The purpose of these ditches was to collect and divert seepage water from the slopes and to drain water from the saturated material being excavated, thereby improving conditions for operating earth-moving equipment. A view of one of these ditches (Fig. 8) shows that seepage from the side slopes caused erosion and localized sloughing and required frequent restoration of the ditch flow line by repeated excavation. The generally soft condition of the material during progress of excavation is shown by Figure 9, taken at the time the excavation was approaching rough grade.

Construction was suspended for the winter, with the cut completed to rough subgrade elevation.

COMPLETION OF CONSTRUCTION

When work resumed in this area in the early spring of 1959, the first operation was to excavate from the left ditch material that had accumulated there during the winter. This ditch-cleaning operation was repeated several times during April and May.

Ground water seepage occurred at a number of locations along the slope. This seepage caused localized sloughing of the slope, severe erosion of the slope face, obstruction of the roadway ditch, and ponding of water in the ditch and shoulder area. This became a major obstacle to completion of installation of roadway subgrade drainage and construction of the paved shoulder through this area. Seepage was particularly pro-

nounced along the line of contact between the pervious sand and sandy silt existing in the upper portion of the cut and the dense gray clay existing in the lower portion of the slope. This is shown by the darker gray zones extending along the slope in Figure 10. Localized sloughing of fine sands and sandy silts at the point of seepage breakout and erosion channels on the face of the slope are shown in detail by Figure 11. To control this seepage and associated slope damage, a system of subsurface drains was installed in the slope.

The pavement and other roadway items of this contract were completed and with this, a 21-mi continuous section of Interstate 70 was opened to traffic.

DEVELOPMENT OF MAJOR SLOPE INSTABILITY

Between May 1959 and January 1960, concurrently with completion of this construction contract, a number of observations were made disclosing very slow but progressive movement of the slope, indicative of major instability.

The first significant observation was that of a tension crack opening in the service road at the top of slope. The crack appeared approximately parallel to and 190 ft left of centerline, between Stations 1512+50 and 1516+00. The occurrence of the crack was also accompanied by some vertical displacement at the top of slope. This is shown by Figure 12.

Tension cracks at the toe of slope, as a result of bulging of the lower portion of the slope, are shown by Figure 13. Such tension cracks resulting from bulging may easily be misinterpreted as erosion channels, particularly in the early stage of development. Close inspection of such cracks will disclose that they cross high points of the slope surface and therefore are not characteristic of surface runoff channels.

In the foreground of Figure 14, diagonal tension cracks are shown in the mid-portion and upper portion of the slope. Such cracks also might be misinterpreted initially as

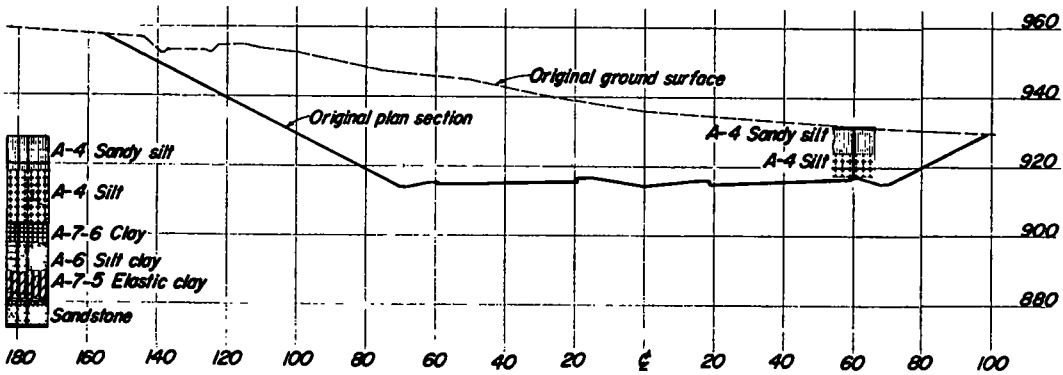

Figure 6. Cross-section of proposed cut, showing original ground surface, original plan section, and logs of borings for roadway subsurface investigation.

Figure 7. Excavating soft wet soil by using drag line working on mats.

Figure 8. Deep side ditch maintained through cut during excavation, showing erosion.

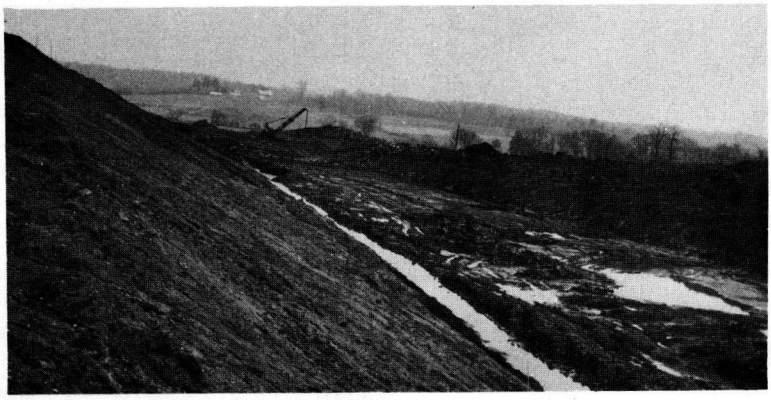

Figure 9. View showing soft wet condition of soil during progress of excavation.

early development of surface erosion courses. Close inspection discloses characteristics similar to the bulging cracks mentioned. Diagonal cracks normally occur in the area of the upper lateral limits of the sliding mass. Also in the upper right portion of the view of Figure 14, a sharp break and vertical downward displacement of the slope is seen.

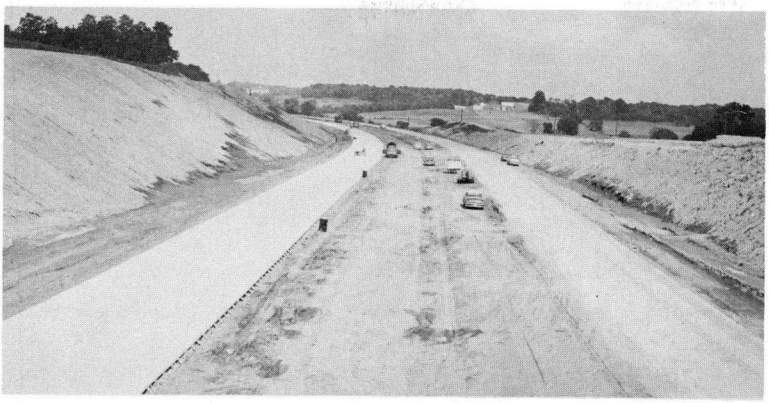

Figure 10. View showing seepage in left cut slope along line of contact between sand and sandy silt in upper portion of cut and clay in lower portion of cut.

In Figure 15, at the left and at the right of the view, two cracks are shown running generally along the face of the slope, with the intermediate soil mass displaced downward. This denotes general outward movement having occurred in the lower portion of the slope, accompanied by block failure in the upper portion of the slope.

Figure 16 shows the material forming the lower portion of the slope. This material consists of layers of clay size particles separated by thin layers of silt size particles. Planes of slippage were observed in this material. Sag at the top of the slope after a 6-month period of movement is emphasized by the row of guard rail posts shown in Figure 17. Heaving of the ditch, shoulder, and outer pavement lane is shown by Figure 18.

Figure 11. Sloughing of fine sands and sandy silts at point of seepage breakout, and erosion channels on face of slope.

Figure 12. Crack at top of slope, indicating slope failure.

DETAILED SUBSURFACE INVESTIGATION

Very slow movement of the slope continued and resulted in heaving of the shoulder and pavement, creating a hazard to traffic. The heaved pavement lane was closed to traffic and major corrective action was initiated.

In the development of corrective treatment, the initial step was the performance of a detailed subsurface investigation of slope conditions. For the purpose of procuring detailed information on the structural characteristics of the soil mass, continuous sampling procedures were employed from the ground surface to 10 ft below the bedrock surface. In soil, thin-wall samplers were pressed continuously, except in hard or dense zones where split-tube drive samplers were used. Upon encounter with bedrock, continuous diamond coring was employed. Two such borings were drilled, one at the top of slope and one at the toe of slope. Truck-mounted rotary drilling equipment of the type shown in Figure 19 was employed.

For more complete coverage of the condition, a number of faster and less costly borings were drilled along the toe of slope for procurement of disturbed samples to develop information at additional locations. These borings were drilled by means of truck-mounted bit-on-kelly auger of the type shown in Figure 20. Additional borings on the slope were drilled by hand auger.

All samples were subjected to examination, moisture content determination, and classification tests. Upon ejection from the tubes, undisturbed samples were closely examined and specimens were selected for laboratory determination of strength characteristics.

Figure 13. Tension cracks at toe of slope, resulting from bulging.

Figure 14. Diagonal tension cracks in the mid-portion and upper portion of the slope.

Figure 15. Cracks and downward displacement of intermediate soil mass.

Figure 16. View of lower portion of slope.

Results of the detailed investigation disclosed the soils for the most part to be erratic in deposition. The materials comprising the higher portion of the slope consisted of fine to coarse sands, silts, sandy silts, and clayey silts. Silty clays and clays were found to comprise the lower portion of the slope and the foundation. Findings of test borings are presented by the cross-section shown in Figure 21.

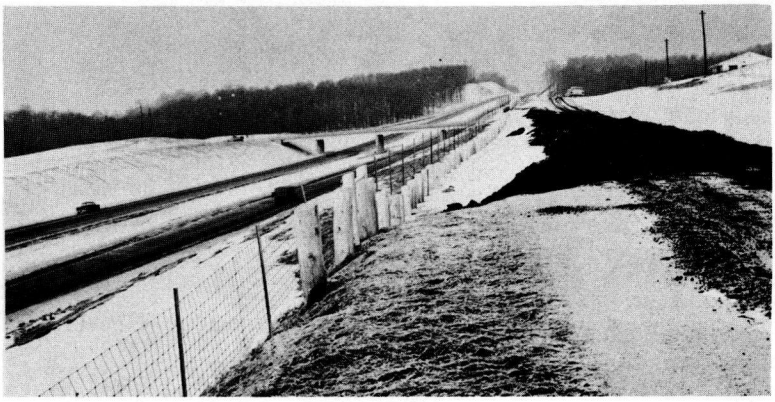

Figure 17. Sag at top of slope, shown by drop of guard rail posts.

In general, appearance of the samples and strength determinations indicated strengths of considerable magnitude. In the silts, sandy silts, and sand, values for angle of internal friction ranged from 25 to 50 deg, and values for apparent cohesion ranged from 0.02 to 0.3 tons per sq ft. In the silt clays and clays, values for angle of internal friction ranged from 15 to 35 deg and values for cohesion ranged from 0.10 to 1.20 tons per sq ft.

Test borings disclosed a persistent zone of elastic clay occurring in the slope foundation. In this zone, samples disclosed the natural moisture content to be consistently above the plastic limit of the material. Strength tests of specimens resulted in apparent values for angle of internal friction of only 3 to 4 deg and values for cohesion

Figure 18. View showing heaving of the ditch, shoulder, and outer pavement lane.

of 0.28 to 0.65 tons per sq ft. Slippage planes were also observed in undisturbed samples from this zone.

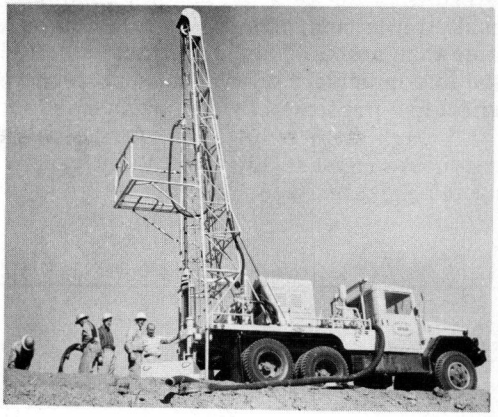

Figure 19. Truck-mounted rotary equipment used for continuous press sampling and coring.

ANALYSIS OF FINDINGS AND OBSERVATIONS FOR CORRECTIVE TREATMENT

Environmental conditions adjacent to the right-of-way were conducive to correction by flattening of the slope. Procurement of additional right-of-way for this purpose involved only tillable land of average quality. This method of treatment involved only construction of the least costly type. Of further importance, this method of treatment did not involve further aggravation of slope instability during construction operations.

From the aforementioned field observations and subsurface investigation, a number of factors relative to the nature of the slope failure were approximately defined, thereby simplifying analysis. The approximate limit of the failure at the top of slope was defined by the tension crack and associated subsidence of the mass. The approximate limit of failure at the base of the slope was defined by the limit of heaving of the paved shoulder and pavement lane. The maximum depth to which movement could occur was defined by the test borings, sampling, and laboratory tests. They disclosed a softer plastic clay zone underlain by hard clay immediately over bedrock. Successive cross-section observations, showing the progress of slope movement, were interpreted to define the approximate location of a vertical plane containing an axis about which rotational movement appeared to be occurring. For purposes of analysis, these factors were assumed to define a circular arc approximately encompassing the failure mass. This is shown by Figure 22.

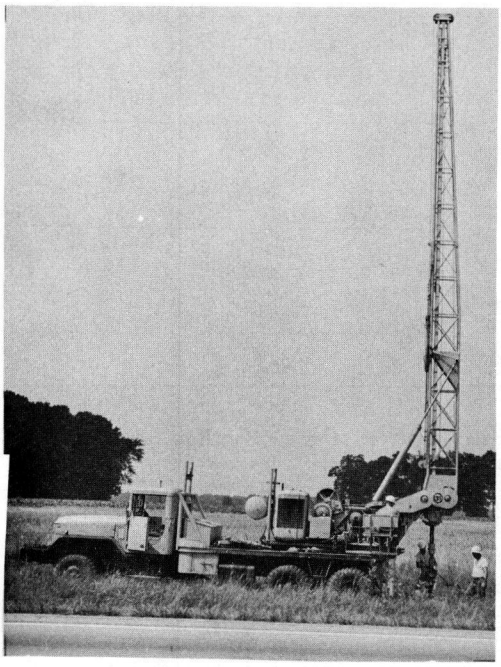

Figure 20. Truck-mounted bit-on-kelly auger for disturbed sampling.

As previously mentioned, strength values as disclosed by laboratory tests varied over a wide range. The effective strength of the mass, therefore, was not defined as readily as the geometric limits of the failure mass. Computations employing the higher shear strength values (15 to 50 deg) resulted in a critical height of slope greater than the height of the failed slope. However, computations employing the lower strength values (3 to 4 deg) indicated that these more nearly coincided with the effective strength of the soil mass.

For purposes of stability analysis, the entire mass was assumed to have an effective cohesion of 0.2 ton per sq ft and angle of internal friction of 5 deg. Critical height of slope computations indicated these values to be somewhat lower than the effective strength in the slope. Also, employing these values in the Swedish circular arc method of slices in the analysis of

the failure arc, as approximated from the observations and subsurface investigation, resulted in a computed factor of safety of 0.85, with this considered to be slightly lower than actual. The observed extremely slow movement of the slope was interpreted to be indicative of a factor of safety with respect to sliding more nearly approaching 1.0.

Although slightly low, the aforementioned assumed strength values were considered reasonably representative of effective strengths developed in the mass and were used in subsequent analyses for corrective treatment. The analyses pursued the course of

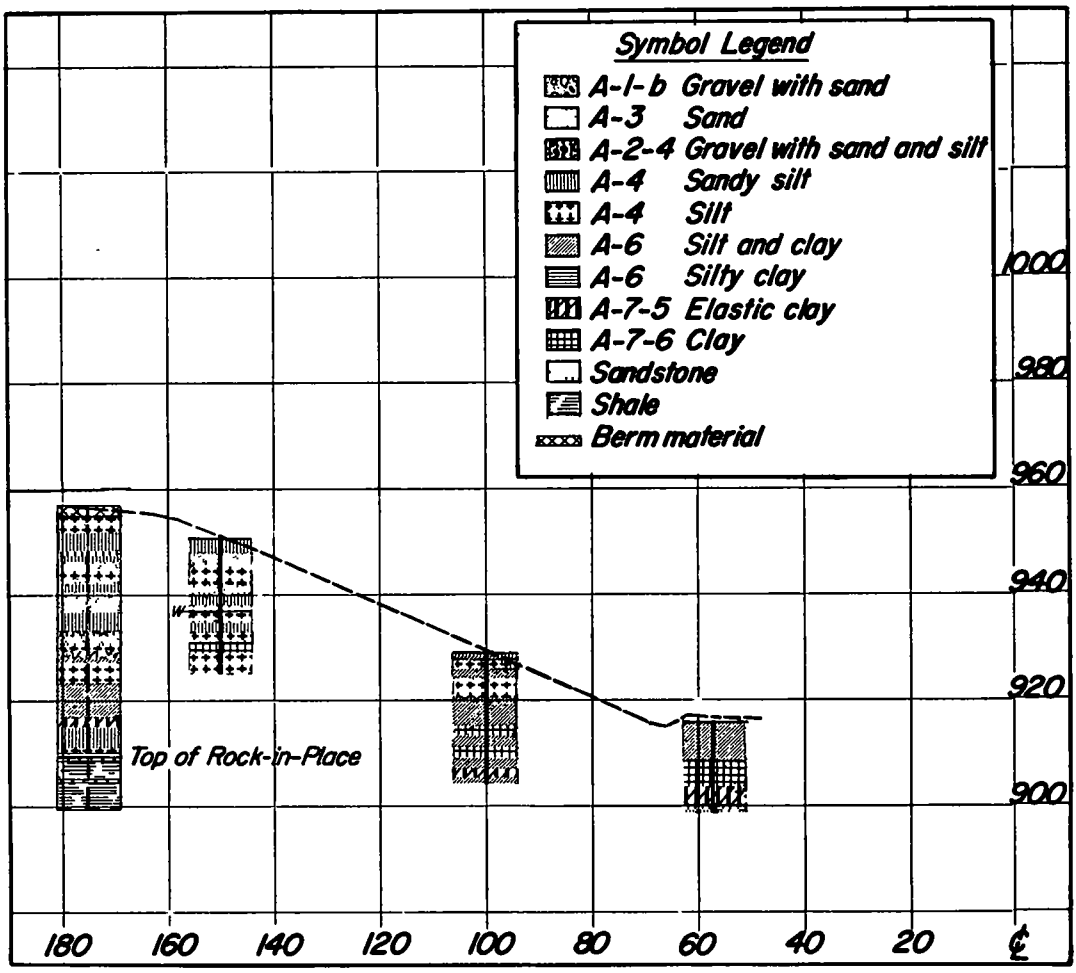

Figure 21. Cross-section of original cut, showing logs of several borings made for the detailed slope investigation.

investigating various trial slope sections by the Swedish circular arc method of slices. The driving forces, tending to actuate slope movement, were reduced through employing a combination of benches and reduced degree of slope.

The slope section selected for final corrective treatment of the problem was computed to have a factor of safety with respect to sliding of approximately 1.2. It is considered that a factor of safety slightly in excess of 1.2 most probably will be realized,

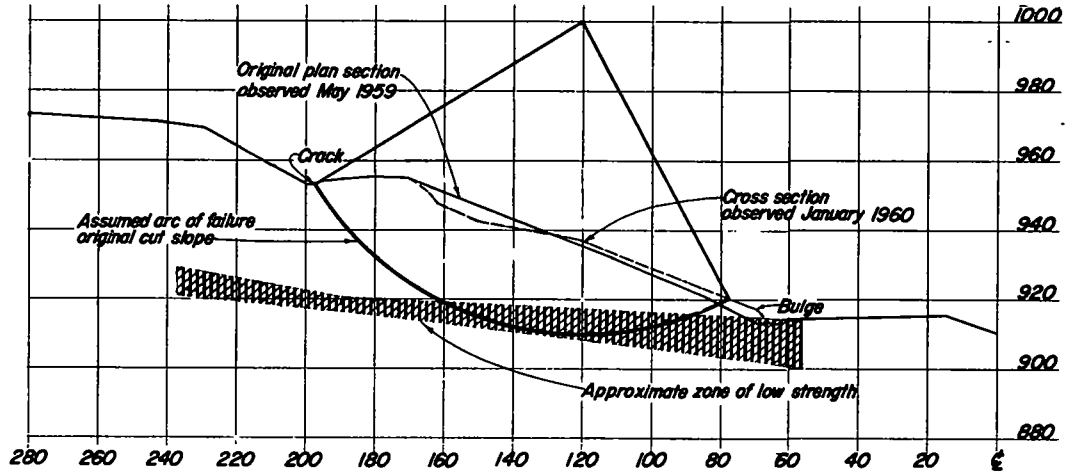

Figure 22. Cross-section of original cut, showing original plan section, failure section (including crack and bulge), zone of low strength, and approximated arc of failure.

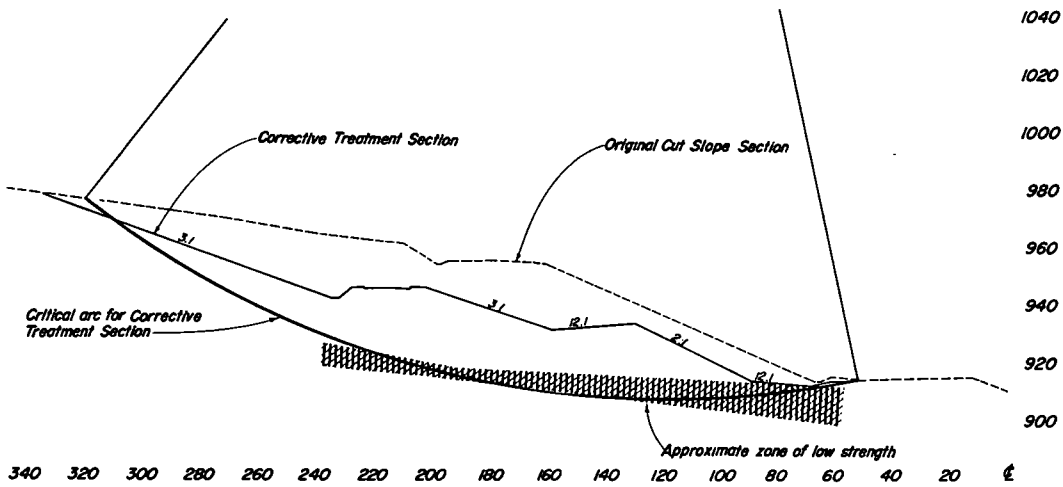

Figure 23. Cross-section of corrective treatment, showing zone of low strength and critical arc for the section.

for reasons mentioned in the foregoing paragraph. Design details of the slope section for corrective treatment are shown by Figure 23.

CORRECTIVE TREATMENT

Construction by change order was started in July and completed in October 1960. The correction involved a quantity of 65,000 cu yd of excavation at a cost of $52,000. Total cost of correction was $74,000. In addition to the earthwork, this total includes cost for removal and replacement of one pavement lane and paved shoulder, restoration of subgrade drainage, installation of subsurface drainage on the two upper benches, restoration of the service road, and other miscellaneous items.

Figure 24 is a view taken after completion of corrective work, showing the benches and slopes.

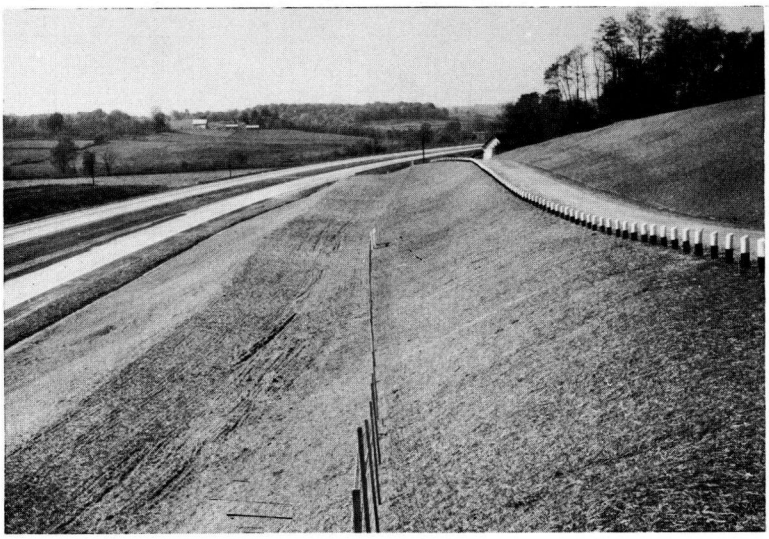

Figure 24. Slope after construction to correct slide.

CONCLUSIONS

This problem in general illustrates the effectiveness of applied soil mechanics in the investigation, analysis, and treatment of problems of slope stability. A number of considerations are emphasized:

1. Detailed subsurface information for reliable analysis of critical soil conditions is of utmost importance. Extreme care in sampling and a thorough record of observations during drilling is of basic importance. Information of critical importance can be missed when employing intermittent sampling procedures or procedures that totally disrupt soil structure characteristics in procurement of samples. Continuous sampling techniques, preferably pressed undisturbed samples, offer greatest assurance in developing reliable information.
2. Laboratory test results to be employed in the analysis of problems must be reviewed with extreme care for use in analysis. Close inspection of samples during each step in testing, from opening the samples through completion of tests, is required, with detailed observations recorded for correct evaluation of test data.
3. Field observations are of utmost importance in the definition of environmental factors and boundary conditions directly related to critical soil conditions and analyses of problems associated with highway design and construction. A thorough photographic record of such observations is invaluable.
4. Most effective solution of problems associated with critical soil conditions justifies the attention of specialists with technical training and experience in both theoretical and applied soil mechanics.

ACKNOWLEDGMENTS

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