# *SLICKENSIDES IN RESIDUAL SOILS AND THEIR ENGINEERING SIGNIFICANCE*

## *LES MIROIRS DE FAILLE DANS LES SOLS RESIDUELS ET LEUR SIGNIFICATION POUR LE GENIE CIVIL*

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SYNOPSIS Thin black seams, often slickensided, are found scattered throughout residual soils derived from igneous and metamorphic rocks. These seams are composed of complex iron-manganese organic compounds that filled old joint cracks in the original rock. The slickensided surfaces exhibit less than half the shear strength of the host soil; the unslickensided seams somewhat more. The black seams and particularly those that are slickensided, constitute planes of weakness along which landslides occur, although the host mass may be generally stable. They also focus soil expansion upon excavation parallel to their orientation.

## INTRODUCTION

Residual soils developed from the in-place weathering of igneous and metamorphic rocks often contain thin, black seams of weakness. Such seams have been observed by the authors in residual soils in India, Panama, Colombia, Puerto Rico, and at many locations in the Piedmont region of the Southern United States. Although they have generally been overlooked by engineers and geologists, the authors have found them to be directly responsible for numerous small but expensive landslides as well as other earth movements. It was the purpose of this study to investigate the nature of these weaknesses and their effect on the strength of the host residual soil, and to correlate their incidence with earth failures.

## THE BLACK SEAMS

The engineering nature of residual soils from igneous and metamorphic rocks has been reported previously by Vargas (1953) in Brazil, Lumb (1965) in Hong Kong and Sowers (1963). They generally consist of sandy silts and silty sands with small amounts of clay and varying amounts of mica. All but the uppermost portions of most residual soil deposits exhibit structure of the parent rock in the alignment of minerals and the foliation and segregation of the minerals into bands of different colors. Such rocks that have decomposed to the texture of soils but retain the relic structure of the original formation are termed saprolites. Although their void ratios are high, because of the expansion that accompanies weathering, they are generally strong. Their drained strength is made up of both true cohesion, (probably from residual mineral bonds in the original rock and some cementing from iron oxidides) and internal friction. As a result the soils can often stand unsupported in deep vertical cuts and excavations.

Scattered at random in most of the saprolites the authors have examined are alien seams of a black mineral. The seams are thin, typically 1/8 in. to 1 in. or 3 to 25 mm thick. Over distances of about 100 ft. or 30 m they are plane or gently curved but they are warped and rippled as much as 15 cm from their general trend. Some appear to parallel the flow banding or schistocity of the rock, but most cut across the relic structure with random orientation. They are often concentrated in small areas or bands, less than 50 ft or 15 m across, and may be absent from an adjoining area of comparable size. The black seams are quite evident in fresh excavations where their black color contrasts with the reds, yellows and grays of the mass, like painted lines on the excavation face.

Similar black seams have been found in residual soils derived from sedimentary rocks, particularly sandstones and tuffs. The authors have not seen them in soils derived from shale. They have rarely found them in soils derived from sandy limestone and shaley limestone.

Some of the seams appear structureless as if they were made up of cemented coal dust. Many, however, are slickensided. If so, the seam breaks apart along a smooth, waxy surface, that sometimes has a slick feel in one direction and a rough feel in the opposite that is characteristic of slickensiding. Striations, also typical of slickensiding, are common.

Although some cross striations suggest slickensiding or movement in more than one direction the orientation of the black seams and the slickensiding does not appear associated with any known tectonic movements or with fossil landslides. These surfaces are intimately associated with fresh earth movements that occur in deep cut slopes for highways, railroads, and canals unbraced or poorly braced excavations, and in building foundation. Gupton (1965) blamed them for a number of failures. The authors have investigated a number of cases where failures have focused on the black seams and where conventional stability analyses, based on the strength of the residual soil mass as a whole, have found adequate margins of safety.

## LABORATORY STUDY OF BLACK SEAMS

In order to investigate the properties of the black seams in detail more than 50 samples were secured from a fresh cut slope in the Atlanta Cultural Center. The residual soil profile at the site is shown in Fig. 1 and is typical of the region.

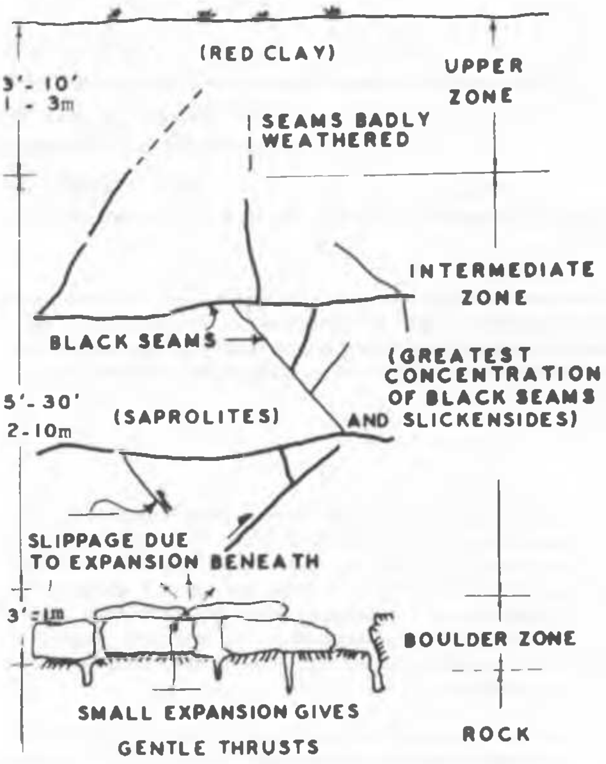

Fig. 1 Typical soil profile in residual soils derived from decomposition of igneous and metamorphic rocks

The upper stratum of red sandy clays is in a state of advanced weathering and the black seams are obliterated or badly altered by leaching. In the intermediate or saprolite zone they form a randomly oriented pattern of black lines superimposed on the candy-striped gneissic soil. Still deeper, the seams fade into the less weathered rock. Nearly all the seams at this site were slickensided.

The slickensides are generally centered within the seams with two similar surfaces, face to face. The surfaces can show one or more sets of groove marks indicating more than one direction of movement. The slickensides have a glossy or waxy texture with mica flakes oriented parallel to the slick. Often, the black materials within the seams appear as flakes elongated in the direction of movement and with the particle length and thickness increasing as the distance from the slick surface increases.

## PRELIMINARY TESTING

The samples were obtained by carefully driving 4 inch diameter, 12 inches in length, thin walled steel tubing into the soil. After the excess soil was trimmed from around the sample, the tube with the encased material was removed and the ends waxed. Prior to the driving, the sample tubes were positioned to orient the black seam on a critical plane for shearing. Samples of the host saprolite were also taken for comparative testing purposes.

The samples were tested for grain size distribution and the values were obtained as shown in Fig. 2. The results of this testing indicate there is no appreciable difference between the grain size distribution for the black seams with the slickensides and those without. The black seam materials tested are fine silty sands with no plasticity. The host soils were generally silts and sandy silts with plasticity indexes of less than 15.

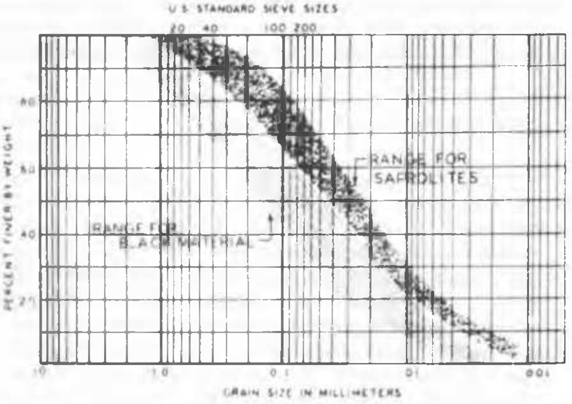

Fig. 2 Grain size distributions for host residual soil and black seams

Permeabilities of the black material were also measured. Samples with the black slickensides were placed in a falling head permeameter and the permeability measured across the seam. Values of 1 to 2 x 10-4 cm per sec were obtained from the test.

Chemical analysis were also performed on the black materials. The typical results are given in Table 1.

Table 1 Chemical Analysis of Black Seam

| | |
|---|---|
| Moisture Content | 21.5 |
| $Fe_2O_3$ (Per Cent by Weight) | 7.6 to 15.5 |
| $MnO_2$ | 0.0 |
| Loss on Ignition @ 600 C. | 9.5 |
| Chemical Oxygen Demand on Ignition | 0.0 |

The lack of oxygen demand indicates little or no organic material was present that could burn. The loss on ignition, however, could represent carbon dioxide from well oxidized organics or water tied into the crystal structure of the mineral.

X-ray and microscope studies indicate the black material occurs as very thin coatings on mineral grains, most commonly on micas. The coating is so thin that it is virtually impossible to separate it from the mineral surface. Thus, wet chemical techniques are of little value for studying the composition of the black material.

X-ray fluorescence and electron microprobe studies of the smooth black surfaces and the material underlying the black surfaces show that manganese (Mn), iron (Fe), and carbon (C) are concentrated in the black material. In the few samples studied both Mn and C appeared to be more abundant than Fc. One sample was treated with a variety of reagent to get the black material into solution. Analysis of the solution showed it was composed of 20.3% Mn and 79.7% of a tanninligin-like substance. The black material reacts violently with $H_2O_2$ indicating the presence of carbon and manganese.

It is hypothesized, therefore, that the black material is composed of a humic substance combined with varying amounts of Mn and Fe. In surface and near surface soils humic compounds commonly coat mineral surfaces, particularly the clay minerals and micas, and are so strongly bonded to the mineral that they are not soluble in alkaline solutions.

Samples of weathered biotite and kaolinite were added to humic acid solutions extracted from the A horizon of a saprolite. Over periods ranging from several hours to several days, the humic material was removed from solution and deposited on the mineral surfaces. This was accompanied by a decrease in pH.

## STRENGTH TESTS

Representative samples of three basic soil types were selected for consolidated undrained (CU or R) triaxial shear testing: a series of samples representing the host saprolite, a second series containing the black seams but not the slickensides, and the last series containing the black seam with slickensides. The samples were oriented with the seams crossing the specimens at an approximate angle of 45 degrees. The virgin soils were also oriented with a foliation crossing the sample at approximately 45 degrees. The results show typical experimental scatter but the average values are given in Fig. 3.

The results indicate the seams with slickensides have lower strengths, generally half to 2/3 of the strength for the host or virgin soils. The black seams without the slickensides have somewhat higher strength values but are still lower than the values for the surrounding residual soils. Both the $\phi$ and c values were lower in the black seams than in the host soils. When the seams were present, shear movement was confined to the seams rather than the host material. The observed angles of internal friction, 10 to 15 degrees, for the slickensided and host materials suggest that the test orientation was not the most favorable to failure on the seams and that angles 50 to 53 degrees between the seams and the major principal plane would have been better. A graphical construction, however, demonstrates that the error was less than 5 per cent.

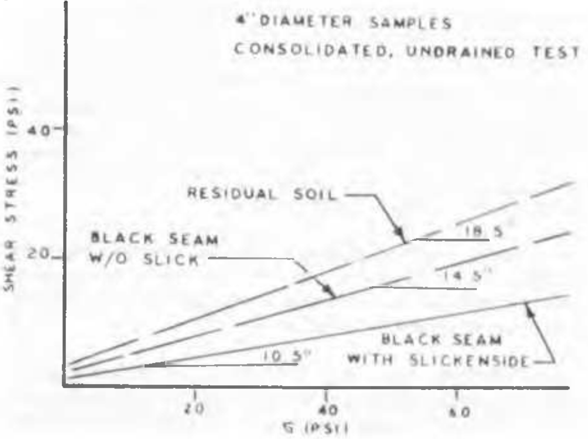

Fig. 3 Comparison of Mohr envelopes of strength for residual saprolite with black seam without slickensides and with slickensides

Previous tests have shown that when the seams are oriented across potential shear planes that failure is confined to the host material and that the seam does not materially influence the strength.

## ORIGIN OF THE SEAMS

Little research has been previously reported to explain the geologic origin of the black seams or their enclosed slickensided surface. Terzaghi and Peck, (1967), suggest that chemical process may be involved in the development of slickensided surfaces. Gupton, (1965), suggests that the black seams may result from filling of old joints and cracks within the rock mass by ground water activity. He states the black color results from iron and manganese precipitates. He also suggest that the slickensides may result from movement along the seams during landslide activities.

The authors, based on many observations of the seams within the Piedmont Area and other parts of the world, also believe the black seams are joint or crack relics.

The cracks initially became filled with fine grained insoluble products of weathering clay minerals and fine mica, worked into them by circulating ground water. At the same time the humic organic compounds in the acid environment at the ground surface formed soluble complex compounds with the iron and any manganese present in the surface soil or A horizon. These solubles were leached downward into the cracks in the zone of partial weathering where chemical decomposition was taking place and the pH was lower. The increasing pH caused precipitation of the organic-iron-manganese complex as a thin film or coating on the mica, clay minerals and other particles that filled the cracks that were immediately adjacent to the crack. The coating remained tightly bonded–the black seam that is observed upon excavation.

The nature of the slickensides is much more difficult to explain although they do, as suggested by Terzaghi and Peck, appear connected to the chemical of weathering of rock strata. Various investigators including Brock (1943), have determined that the cations bonding the crystal structure of the metamorphic strata do not readily lose their identity when subjected to chemical weathering associated with H + ions. Instead most of the bonding ions tend to remain in their relative positions, even though their bonding forces are reduced or minimized. The reduction in bonding releases any mechnical stresses present in the original rock. As a result the weathering rock may expand or distort slightly. The non-uniform expansion and distortion produce the shear strain responsible for slickensides.

The evidence indicates that the soil-rock stratum, which is involved in expansion, is the 3 to 10 ft. or 1 to 3 m of partially weathered rock that is undergoing continuing decomposition just above the unweathered rock, Fig. 1.

It is the authors' hypothesis that the volume increases occur irregularly due to variations in the rock fabric and mineralogy and tend to gently heave the overlying soils. If the overlying materials contain natural planes of weakness, such as the joint and crack relics within residual materials, slow slippage could reasonable be expected along those seams, as shown in Fig. 1. In addition, the orientation of the force system would be expected to vary considerably from place to place and time to time causing a random orientation and the cross orientation of grooves and the slickensided surfaces.

Although chemical weathering resulting in expansion appears to account for the slickensided surfaces within the black seams, there are other possible conditions or force systems which could cause movement along the weak seams. These include consolidation, movements associated with excavation work or unloading of soils from erosion or glacial retreat, although the authors have not seen such seams in glaciated regions.

## PUERTO RICO ROAD

Deep cuts in a silty sand residual soil derived from weathered tuff suffered from more than 40 distinct slides in 3.5 miles of access road in a mountain rain forest. The slides occurred in cuts 20 to 80 ft deep with slopes between 1 to 1 and 1.25 (H) to 1 (V). Two distinct forms of shear occurred, depending on the orientation of the old slickened surfaces. The first form shown in Fig. 4, was the more common. Failure took place following an intense rain by sliding along a slickened surface that was flatter than the cut slope along a tension crack, and moved down into the roadway, blocking the drain ditch. New tension cracks appeared in the overhang left by the slide, and pieces of soil weighing 2 to 5 tons dropped out from time to time during the larger rain storms.

The second form occurred on intersecting slickensided surfaces steeper than the design slope, Fig. 5. The slickensides surfaces had no tensile strength, and they opened up when the soil expanded immediately after excavation. During a heavy rain the triangular wedge of soil defined by the slickensides surfaces slid outward by shearing the residual soil on a shallow curved surface. The new, steeper slope defined by the slickensides, remained stable.

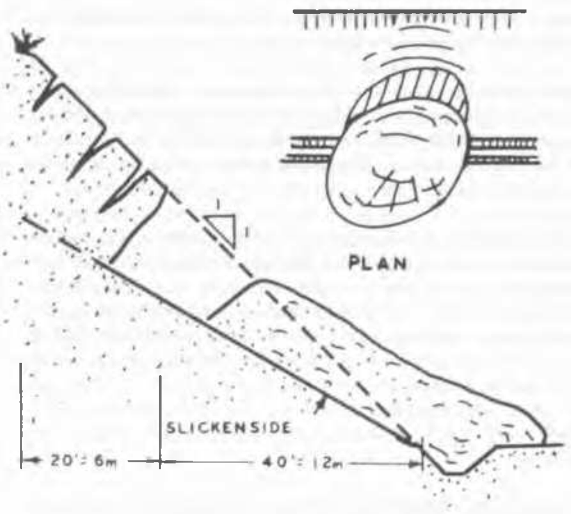

Fig. 4 Cross Section and plan of a slide on a gently sloping slickensided surface in weathered tuff in a road cut in Puerto Rico

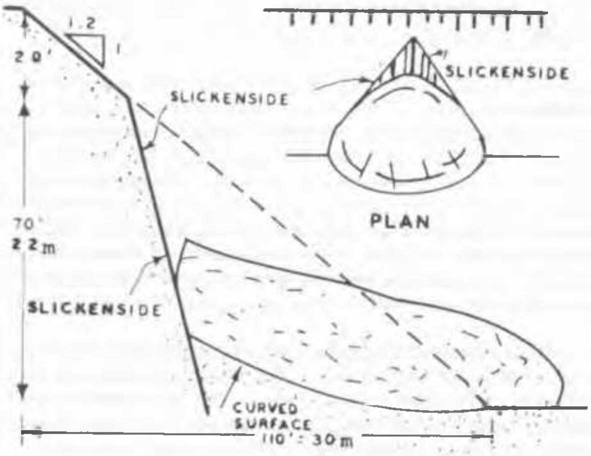

Fig. 5 Cross section and plan of a slide on a curved surface below two intersecting slickensided planes in weathered tuff in a road cut in Puerto Rico

## SHOPPING CENTER EXCAVATION

The parking lot for a large shopping center in Georgia required cuts 50 ft deep in residual soils derived from granite gneiss. The designer, after examining the weathered rock, utilized a slope of 2 (H) to 3 (V), as shown in Fig. 6. Much of the slope was stable. Later analyses based on drained shear tests of the intact residual soil found the safety factor to be nearly 2. However, there were numerous old slickensides in the residual soil, at a slope of about 1 (H) to 1 (V). A number of local slides occurred, involving wedge shaped masses weighing 5 to 10 tons, as shown in Fig. 6. One occurred under the designing engineer's field office. His resident engineer never realized the danger until the slide was pointed out to him by the project accountant, a month after it occurred.

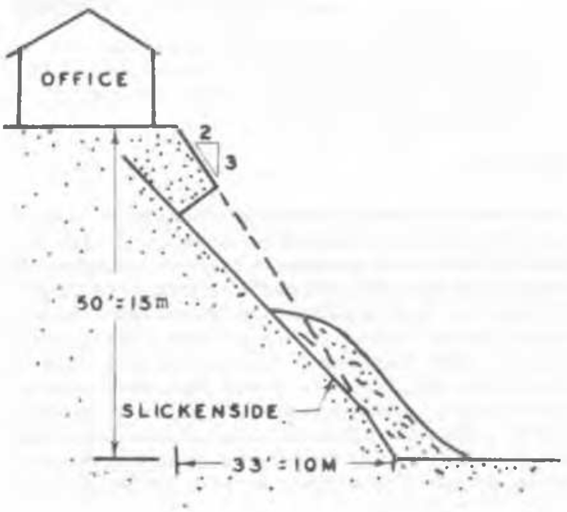

Fig. 6 Linear slide on a steep slickenside in an excavation in weathered gneiss for a shopping center, Georgia. Engineer's office was immediately above the slide

On the same project the footing excavations were made in the stiff residual soil without any forms, because the soil stood without support. In two cases, illustrated by Fig. 7, the footing was found to be 1 ft or 30 cm narrower than the plans required, and as a result the column was not centered properly. A study of the soil showed a sloping slickenside on the side of the footing that was too narrow. The micaceous soil had expanded and slipped down on the slickenside, moving the side of the excavation inward 1 ft or 30 cm and causing a small but unnoticed settlement of the ground surface adjacent to the footing.

## POWERHOUSE EXCAVATION

A 55 ft or 17 m deep excavation in a residual micaceous sandy silt derived from diorite in North Carolina was made with a slope of 3 (H) to 2 (V). The slope design was based on stability analyses utilizing drained shear tests and a safety factor of 1.5. The slope has been stable for 6 years despite a large crack about halfway up the slope. Fig. 8 and 9, which appeared immediately after excavation was complete. The soil above the crack is displaced outward 3 in. or 7.5 cm. The crack is an old slickenside; the soil above it expanded when the stress was released upon excavation.

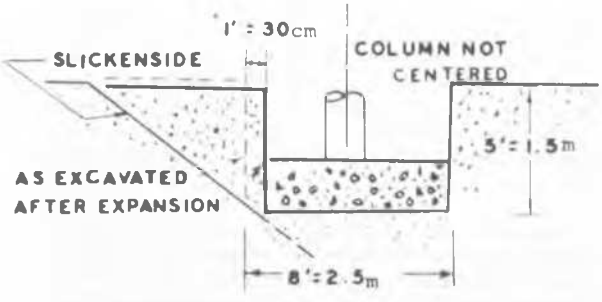

Fig. 7 Footing excavation narrowed by soil expansion along a slickenside, in weathered gneiss, in a shopping center, Georgia

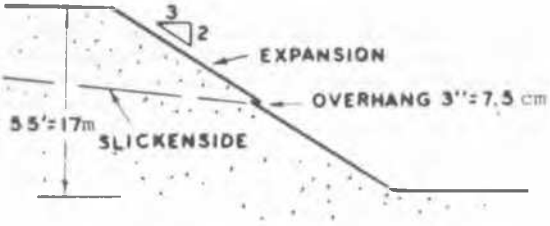

Fig. 8 Cross section of the face of a deep excavation in weathered diorite for a powerhouse in North Carolina, showing expansion on a slickensided surface

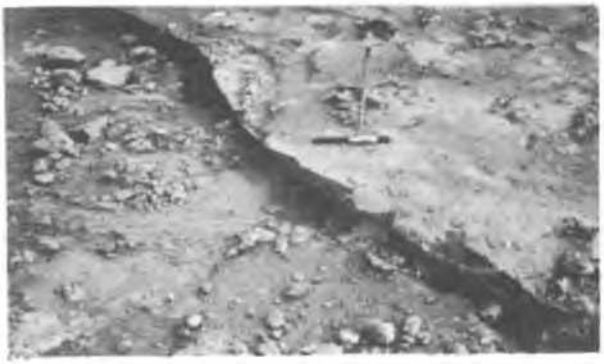

Fig. 9 Photograph of expansion crack of Fig. 8

## RAILROAD CUT – NORTH CAROLINA

A railroad cut 50 to 75 ft or 15 m to 22 m deep in the same project as the powerhouse in the previous example developed a very localized slide during construction. As can be seen in Fig. 10, the top of the slide commenced well below the top of the slope, focusing on a pair of intersecting slickensides similar to Fig. 5. A porewater pressure unbalance in the cracks probably precipitated the movement, because the excavation had advanced faster than the installation of drainage. The cut slope .7 (H) to 1 (V) was designed on the basis of consolidated undrained (CU or R) shear with c = 0.3 Kg per sq cm and $\phi$ = 22 deg. Standard penetration resistances, N, were 12 to 15 blows per foot in the deepest part of the cut and 9 to 12 at the ends.

The residual soils throughout the cut contained numerous slickensided seams concentrated in some areas and almost entirely absent elsewhere. Although the borings, spaced 200 ft or 60 m apart, disclosed the presence of the black slickensides neither their distribution nor orientation could have been predicted in advance. In spite of the large number of slickensides, only one pair were oriented favorably for sliding and the remainder of the 2500 ft or 800 m long cut was stable.

## BRACED EXCAVATION

A 60 ft or 18 m deep excavation in a micaceous silty sand derived from the decomposition of granite gneiss in Georgia employed 10 in. or 25 cm steel H-piles 10 ft or 3 m apart around the perimeter as soldier piles. Wood lagging was installed between them sporadically as excavation progressed. At the same time steel wales and rakers were placed to support the soldier piles. At several points chunks of residual soil weighing up to 4 tons slid between the soldier piles, moving an old slickenslided surfaces, Fig. 11. No failures occurred where the lagging had been installed, although the lagging had little flexural strength.

Fig. 10 Local slide in a railroad cut 75 ft or 22 m deep in weathered diorite in North Carolina which commenced on two intersecting slickensides similar to Fig. 5

Fig. 11 Slickensided surface that caused a localized sliding of soil between soldier piles 10 ft or 3 m apart in an excavation 60 ft or 18 m deep. Width of photograph approximately 10 ft or 3 m

## CONCLUSIONS

The black seams are complex iron-cemented filling in old cracks in the rock that remain in the residual soil as surfaces of weakness. Movement within the soil, produced by expansion accompanying weathering or by stress relief produced by excavation causes many of the seams to be slickensided. Slope designs, based on the strength of the host residual soil may be locally unsafe in zones containing the black seams because they have half the strength of the surrounding soil. The safety of such slickensided zones is difficult to predict because movement depends on the favorable orientation of the weak surfaces. The design alternatives are to be conservative and utilize only the slickenside strength for design or to assume the risk of local failure and local redesign after the incidence and orientation of the slickensides is exposed during excavation.

## ACKNOWLEDGEMENTS

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