THE FOLIATION SHEAR ZONE — AN ADVERSE ENGINEERING GEOLOGIC FEATURE OF METAMORPHIC ROCKS

by
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Introduction

A surprisingly large number of engineering projects constructed in recent years in metamorphic rocks have encountered poor rock conditions locally that have significantly affected the difficulty of construction. Both the cost and time of construction have been increased. In some cases remedial measures or redesign of project elements have been required.

An analysis of the problems shows that in nearly every case the cause of the difficulties was the local presence of thin sheared zones along the foliation of the metamorphic rocks. This shearing, inherited from the geologic past, had occurred inevitably along the weakest layer of the metamorphic rock, often in a mica schist zone with a high mica content (Patton and Deere, 1970, 1971). Such mica-rich zones occur in thick schist sequences but, more importantly, also in the massive metamorphic gneisses and quartzites as thin interbeds.

These sheared zones parallel to the foliation (layering of the platy minerals) may be termed "foliation shear zones" or "foliation shears". In the following sections the characteristics of these shear zones, their possible mode of origin, and the manner in which they can adversely affect an engineering project are discussed.

Characteristics of the Foliation Shears

The writer has examined foliation shears in more than a dozen construction projects where the number of foliation shears ranged from only 1 or 2 per site to 10 or more. While the variations in physical characteristics were noted to be considerable, certain generalizations may be made.

Thickness

The typical thickness of the foliation shear is in the range of 1 to 4 inches. Some zones have been seen as thin as ¼ inch to ½ inch although continuous over distances of 100 feet or more; only rarely will one be found as thick as 3 feet. Typically, the zones will thicken and thin somewhat. The rock adjacent to the zone will also be weaker than normal, as noted later.

Brekke and Howard (1972) use the term "seam", indicating "a minor, often clay-filled zone with a thickness of a few inches . . . seams may repre-

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sent very minor faults or altered zones along joints, dikes, beds or *foliation*" (emphasis added). The foliation shear of this paper, then, fits their definition of seam. In the field, they are often referred to as "slips" or "mud seams".

Continuity and Structural Attitude

The foliation shears may be traced for distances up to several hundred feet. However, at many construction projects the exposed rock is of limited area and the full length can not be seen. Experience would indicate that they are not strictly local occurrences of just a few tens of feet extent but of at least several hundred and, in some cases, probably a few thousand feet.

The shears trend parallel, or in some instances subparallel, to the strike of the foliation. They also follow the dip of the foliation but locally may cut across it where the foliation flattens or rolls. Because the foliation is typically steep in the meta-sedimentary rocks of the eastern United States, and in many other parts of the world as well, the foliation shear zones typically occur with dips of 50°-80°.

Shear Zone Materials

The weakest material in the shear zone is the ground-up rock material — typically a crushed mica schist gouge. Grain-size analyses of several samples of gouge from foliation shear zones in the mica schist of New York City Water Tunnel No. 3, currently under construction, indicated that the materials are essentially moist, plastic well-graded mixtures of clayey, silty sand and occasional rock fragments with average percentages as follows: 15 percent clay-size (less than 0.002 mm), 35 percent silt size, and 50 percent sand size. For the seven samples tested the clay-size percentage ranged from 7 percent to 30 percent (Fig. 1). Also shown in Figure 1 is the grain-size analysis of a gouge sample from a foliation shear in Washington, D.C., and the limits of 12 samples of fault gouge (the latter from Brekke and Howard, 1973).

The clay mineral analysis by X-ray diffraction of the New York samples (Wahl, 1973) indicated that the most plastic, slippery gouges contained montmorillonite or montmorillonite-chlorite (interlayered) as the main clay-size constituent. The less plastic ones had predominantly vermiculite or vermiculite-montmorillonite in the clay-size fraction. It is believed that the montmorillonites, vermiculites, and chlorites were formed by alteration of the primary micas and feldspars in the original rock by the heat, pressure, and fluid migration present during and immediately following the shearing. Surface weathering may also cause an increase in the clay content near the surface. Brekke and Howard (1972, 1973) emphasize the complexities of

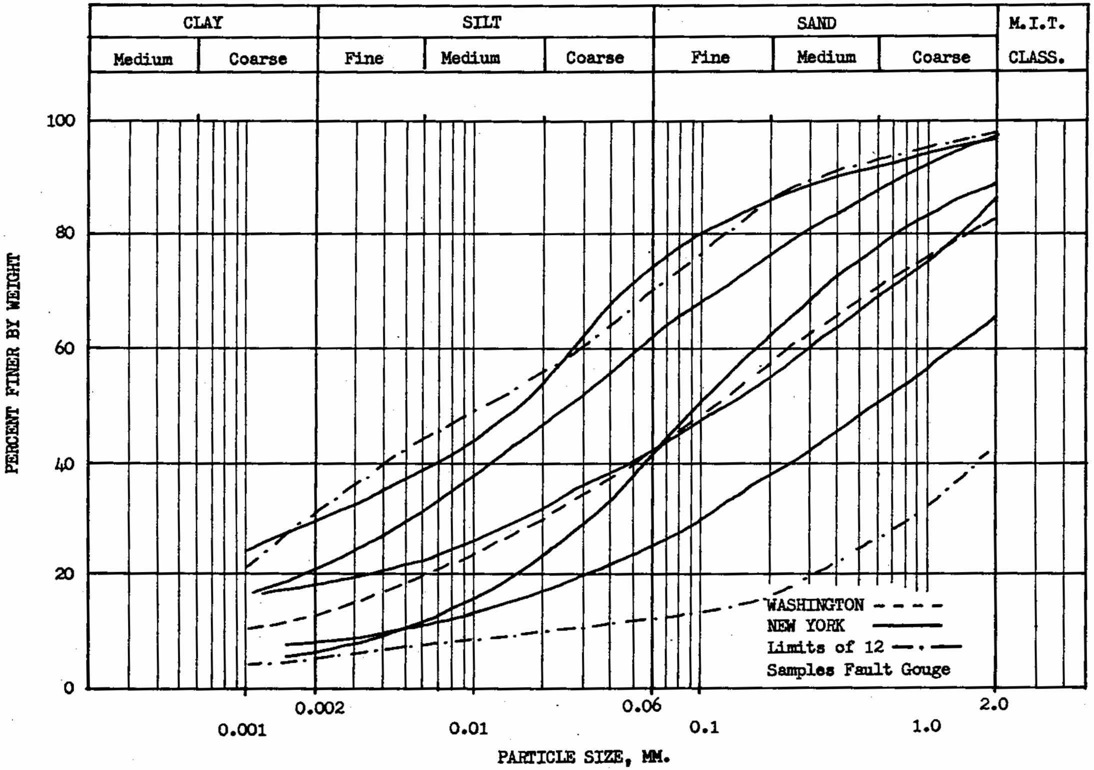

Figure 1 — Grain-size Distribution Curves of Foliation Shear Gouge from Washington, D.C., and New York City. (Also shown are the limits of 12 samples of fault gouge from Brekke and Howard, 1973).

fault gouge and the hydrothermal alteration of gouge materials which commonly occurs.

In addition to the plastic gouge which may be only a fraction of an inch to several inches wide, the remainder of the shear zone consists of partially crushed, sheared and slickensided rock. This zone often exhibits fracture cleavage. The gouge layer usually occurs on one (occasionally on both) sides of the shear zone where it is plastered against the adjacent hard rock. At times, the gouge layer, or thin branches of it, will occur in the middle of the shear zone.

The joints in the hard rock adjacent to the shear zone may be somewhat disturbed with some loosening, slickensiding, and chemical alteration (thin clay or chlorite coating on the joint surface). Thus, it is not just the few-inches thick shear zone itself that is weak; the slightly disturbed rock on either side may form a zone several feet wide that is substantially weaker and more compressible than the surrounding rock. Thinner foliation shears may occur parallel or sub-parallel to the main one at distances of several feet.

Spacing

The spacing of foliation shears is extremely variable, as one would imagine because of the great variety of metasedimentary rock types and the diverse stress conditions both regionally and locally to which they are subjected. On one project, the Churchill Falls Hydroelectric Project, Labrador, five foliation shear zones were found in about 6,000 feet of underground workings, giving a true spacing of from 500 feet to 1500 feet.

In the Washington, D.C., Metro, along Connecticut Avenue at the DuPont Circle Station currently under construction, the average spacing is about 25 feet. In some of the New York City tunnels the true spacing (calculated normal to the strike and dip) was found to be in the general range of a hundred to a thousand feet.

Permeability

The foliation shear zones, like many faults, are both dams and drains (Patton and Deere, 1971). Because of the fine-grained gouge, they have a low permeability in a direction crossing them. Therefore, water is often found perched above them and the shear zones act as dams. The zones adjacent to the foliation shear may be more permeable because of the disturbance and opening of the joints. Thus, ground water may travel more easily parallel and adjacent to the zone than in the main rock mass and the shear zones act as drains.

Offset Along Foliation Shears

Additional observations are needed in order to document much better the range of offsets along foliation shears. In many cases, it is probably just a matter of a few inches. In others it may be a few feet. A recent observation in Washington, D.C., showed 5 feet offset of a pegmatitic quartz dike.

It has been suggested that foliation shears should be termed foliation faults since there is evidence of some shearing displacement. However, since they are probably associated primarily with folding and stress relief, have no great depth of penetration, are of local extent of a few hundred to a few thousand feet, and have only inches to feet of offset, it would appear that the term foliation shear is more appropriate.

Origin of Foliation Shears

One may speculate on the origin of foliation shears. It is likely that severely different processes are responsible — one operating in one set of environmental conditions of stress, temperature, and lithology and others operating in other circumstances. Three modes of origin will be considered.

Differential Movement Associated with Folding

It is well known that in folding the adjacent layers must slide differentially to satisfy kinematics. The differential movement would tend to concentrate in the weaker layers which would be the mica schist layers (or, in other cases, chlorite schist, talcose or graphitic schists, or slates or argillites). The massive, thickly-bedded or foliated gneisses, quartzites, marbles, amphibolites, etc., tend to fracture upon folding with the shearing being concentrated along one or more of the weak schistose interbeds.

The dimensional extent of the shearing would depend on the scale of the fold. For foliation shears to extend from hundreds to a few thousands of feet the extent of the fold limb would have to be of equal or greater dimensions. Smaller drag folds of a few feet amplitude would be expected to produce strictly local shearing (as was recently noted at the foundation excavation for a dam in Brazil).

Under some conditions the weak bed might be sheared and thinned on the flanks of the fold and thickened, contorted, and sheared on the crest. For example, during construction of the Kariba arch dam across the Zambesi river a so-called "mica seam" of contorted, sheared, and pulverized biotite schist was encountered on the right bank in Rhodesia (Lane, 1963, 1964). The seam occurred in the middle of a thick quartzite sequence over one hundred feet thick. On the flank of a fold the sheared mica shist was only 5 feet thick. Where encountered near the trough of the syncline it was 30 feet thick. Since the arch dam was to abut directly across the seam, it had to be mined out by tunnels and shafts and replaced with concrete.

It would appear that the main mode of origin of foliation shears may well be that associated with folding. Igneous intrusions may also introduce stresses in adjacent metamorphic country rock which may induce local warping and differential slippage between beds causing foliation shears as has been postulated for the underground powerhouse foliation shear at Churchill Falls, Labrador (Merritt, 1972).

Stress Relief

Erosion of hundreds to thousands of feet of surface rock results in great stress changes in the underlying rocks. The various rock types will respond differently because of their differences in shear strength and modulus. Lateral movements will be associated with valley cutting and vertical rebound movement with general lowering of the ground surface by erosion. The response of the metamorphic rocks could well induce differential movements between adjacent beds, again with the movement being concentrated in the weak layers.

This mode of origin has been postulated for the shearing of thin shale interbeds in limestone and sandstone sequences forming "shale mylonites" along valley slopes. Some of the foliation shears no doubt have similar origins.

Thrust Faulting

It is possible that some major thrust faults in metamorphic terraines die out in a number of 'horsetail shears'. Some of these might be concentrated along the weak layers of the metamorphic rocks forming the foliation shear zones observed. Also, in isoclinal folding shearing often occurs along the axial planes producing structures similar to the described foliation shears.

Engineering Problems Associated with Foliation Shears

Significant Engineering Geology Features

Emphasis has been given in the past few years by the author in his classes at the University of Illinois (and as visiting professor at the University of Florida) to those few geologic features which have proven to be quite troublesome and costly on many projects. These were termed "significant engineering geology features" and were those that were not only troublesome but that were also very common. They were termed 'significant' because they affected adversely one of the mass properties of the in-situ rock — its *shear strength,* its *compressibility,* or its *permeability.* They included: (1) joints, bedding planes, or foliation planes; (2) shear zones and faults; (3) weathered rock; (4) groundwater conditions; and (5) rock type (or soil type and its pattern of distribution). It is clear that the foliation shear zone is a combination of (1) and (2). Some of the examples in the following sections should reinforce the idea that foliation shears are, indeed, significant engineering geology features.

Engineering Properties

Shear Strength — The foliation shear zone and the rock around it are low in strength, particularly in a direction parallel to the foliation shear. The shear strength in this direction is almost entirely that of the drained residual frictional strength of the gouge material. There is little to no cohesion or interlocking of rock surfaces and, consequently, no high peak strength. The frictional resistance is almost strictly a function of the grain size, shape, and alignment of the gouge and its mineralogy. This could be expected to be no more than 15 °-25°, in general, and less in some circumstances (Cording, Hendron, and Deere, 1971; Patton and Deere, 1971).

Compressibility — The compressibility of the shear zone and its effect on engineering projects would depend on the thickness of the gouge and heavily sheared rock plus the amount of adjacent loosening and fracturing. The gouge material itself might have a modulus of deformation as low as 25,000-50,000 psi and the entire affected zone several feet across of 100,000-250,000 psi, corresponding to very poor to poor rock with RQD values of 0 to 50. At two sites, seismic velocities across the zone were found to be in the 4,000-6,000 feet per second range.

Permeability — The permeability as mentioned previously would be highest parallel to the feature and could be expected to fall in the range of 10^{-3} to 10^{-5} cm per sec.

Concrete Dam Foundations

Arch dams are particularly affected adversely by the presence of foliation shears in the abutments. There may be a problem of potentially excessive deformation because of the low modulus requiring excavation and backfilling with concrete as at the 460-feet high Kariba arch dam in Rhodesia (Lane 1963, 1964), or requiring grouting and pre-stressing of an abutment slab by means of anchored tendons as for a dam recently constructed in Venezuela.

Sliding resistance of an arch dam abutment could also be a serious problem depending upon the orientation of the shear zone with respect to the dam thrust and the ground surface configuration.

Concrete gravity dams may also be adversely affected by the shear zones. The associated low modulus may require that the shear zone material be excavated and backfilled with concrete, as was done to a depth of 60 feet in a recent dam in western United States. Flat-lying foliation shears in the foundation rock of gravity dams would be very critical with respect to sliding stability.

Permeability considerations may also be important for any shear zone cutting across the abutment or beneath the dam foundation — not because of water loss so much as for the potential of piping. In addition to grouting, filtered drainage holes and perhaps weighted filters in the downstream outcroppings may be needed.

Stability of Cut Slopes

Where excavated cuts are made in rock so as to cause the day-lighting of a foliation shear zone, a critical stability condition would obviously be created (Deere and Patton, 1971; Patton and Deere 1970, 1971). Depending on the orientation, failure could occur on the shear zone alone or in combination with another fracture forming a wedge failure. The portal of the tailrace tunnels of Churchill Falls required heavy rock bolting to stabilize foliation slabs, some of which were sheared and all dipping directly down the dip slope of the hill into which the portal cuts had to be made.

Tunnels and Underground Chambers

Tunnels — Tunnels are susceptible to slabbing and slipouts along foliation shears. If the tunnel cuts across the zone at right angles or nearly so, the tunnel is only affected over a distance of a few feet and the weak zone may be handled by a few steel ribs or a nominal amount of rock bolts and shotcrete. This was the case at a few places in the Churchill Falls tailrace tunnels (Benson, Conlon, Merritt, Joli-Coeur, and Deere, 1971; Merritt, 1972).

If the tunnels are sub-parallel to the foliation shear, then the problem is much more extensive as stability problems will first be encountered on one wall of the tunnel, then the roof, and finally across the other wall of the tunnel. Depending on the angle between the strike of the foliation shear and the direction of the tunnel the poor rock condition may continue for several hundred feet and hundreds of steel sets or large quantities of shotcrete and bolts might be required, as in the current water tunnel being driven in New York, or the subway tunnels and stations in Washington, D.C. (For the latter case see Bawa and Bumanis, 1972; Cording and Deere, 1972; and Mahar, Gau, and Cording, 1972).

The effect of tunnel size is also important. It is well known that stability problems with the roof rock increase with size. However, a second geometric effect comes into play when a foliation shear is subparallel to the tunnel. For a larger diameter tunnel the length of tunnel adversely affected is much greater than for a smaller one. For instance, if a 15-feet diameter tunnel were to be affected over a distance of 300 feet, a 30-feet diameter one would be affected over a distance of around 600 feet.

Berkey (1933) in Guidebook No. 9, New York City and Vicinity, for the XVIth International Geological Congress writes as follows regarding City Tunnel No. 2 which was constructed in 1928-1935:

> The tunnel is large. Much of the ground is closely jointed. The tunnel runs nearly parallel with the structure or schistosity for long distances and the schistose structure dips to the side at an unfavorable angle. All these conditions are unfavorable but the chief cause of trouble in construction arose from the fact that the tunnel so nearly parallels the structural trend.
>
> Whereas the rock is somewhat weakened by decay, soft and slippery secondary minerals lubricate the joints so that blocks thus bonded tend to fall out of the roof endangering the workmen and requiring extensive protecting supports for long distances. These conditions were to be expected of course but the extent to which protective measures have had to be used could not be predicted in advance.

Berkey did not specifically call these features foliation shears but there is little doubt but that the described features conform to today's concept of the foliation shear. Inter-office memorandum in 1933 by the project geologist referred to the features encountered while tunneling in the Yonkers gneiss and Manhattan schist by such terms as "shearing parallel to the foliation", "slabby walls", "overbreak along foliation", "shearing in the foliation weaving in and out of the walls", "rock plates in the walls", and "rock dangerous because of large slips along the foliation planes". Again, these features describe the presently used term *foliation shears*.

Tunnels excavated by means of tunnel boring machines (TBM) may also encounter trouble with foliation shear zones. Where the shear zone passes over the tunnel, fall-out is a common problem and immediate roof support must be placed — light half-circle steel ribs or liner plates supported on pins, rock bolts with steel straps, or shotcrete. Where the shear zone goes into the floor the machine may slowly sink by several inches or more. Jack-thrusting may also be a problem where the shear zone intersects the tunnel walls. All these problems occurred to some extent in the few shear zones that were encountered in the recently completed Queen Lane water tunnel in the Wissahickon Schist in Philadelphia and the Interceptor Sewer Tunnel along Riverside Drive in the Manhattan Schist in New York. Both tunnels are 11-feet in diameter and were quite successfully driven with Jarva TBM's.

Underground Chambers — Several large underground powerhouses constructed in recent years in metamorphic rocks have encountered shear zones parallel to the foliation. These include the Morrow Point powerhouse in Colorado (Dodd, 1967), the Oroville powerhouse in California (Kruse, 1971), and the Churchill Falls powerhouse in Labrador (Benson, Conlon, Merritt, Joli-Coeur, and Deere, 1971; Merritt, 1972). In all cases construction was slowed to some extent and remedial measures were necessary, involving one or more of the following: heavy rock-bolting, concrete backfilling with mesh and rock bolts, or tensioned deeply-anchored cables.

The DuPont Metro Station under construction in Washington is as large as most underground powerhouses (approximately 75 feet wide x 700 feet long x 45 feet high) and it has only 35 feet of rock cover, overlain in turn by 30 to 40 feet of soil and fill. Numerous foliation shear zones were encountered in the pilot exploratory tunnel driven prior to bidding along the crown position of the future station. These shear zones cut across the axis of the station at angles of only 20°-30°. Special design and construction measures were taken and extensive instrumentation was carried out (Cording and Deere, 1972; Mahar, Gau, and Cording, 1972).

Figure 2 (after Fig. 8, Cording and Deere, 1972) indicates in cross section the relative position and orientation of the foliation shears and the DuPont Circle Station. Figure 3 (after Fig. 8, Mahar, Gau, and Cording, 1972) shows in plan view the orientation and position of four foliation shear zones in the double track tunnel just south of the station. These were mapped from exposures of three of the shears in the existing tunnel and shaft and from the results of 4 angle core holes from the surface. Later excavation confirmed their presence and relative positions. One of the shear zones led to major fallout of the roof in one area, and to unequal loading and severe distortion of several heavy steel sets.

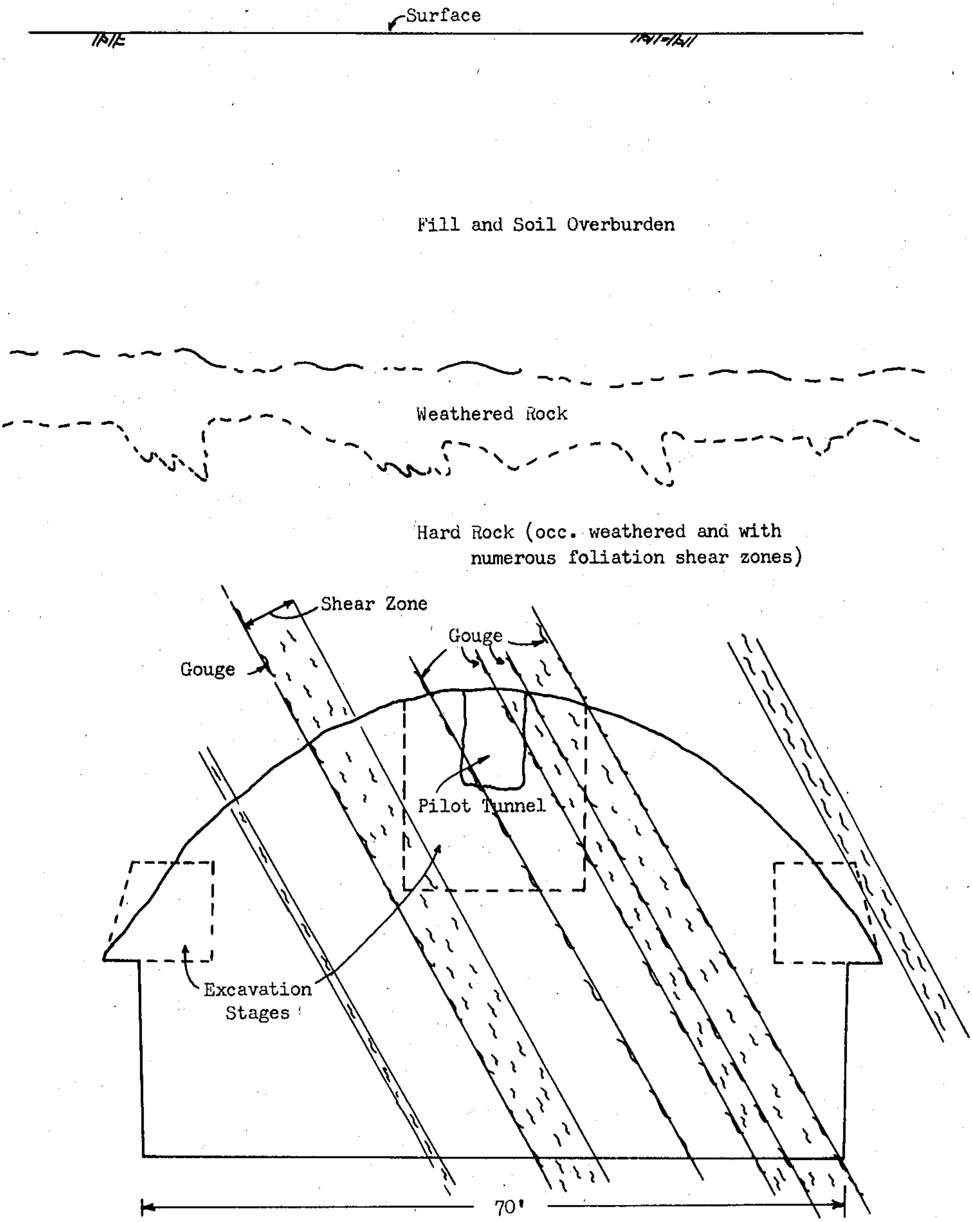

Figure 2 — Cross Section DuPont Circle Metro Station, Washington, D.C., Showing Typical Foliation Shear Zones (Schematic after Cording and Deere, 1972).

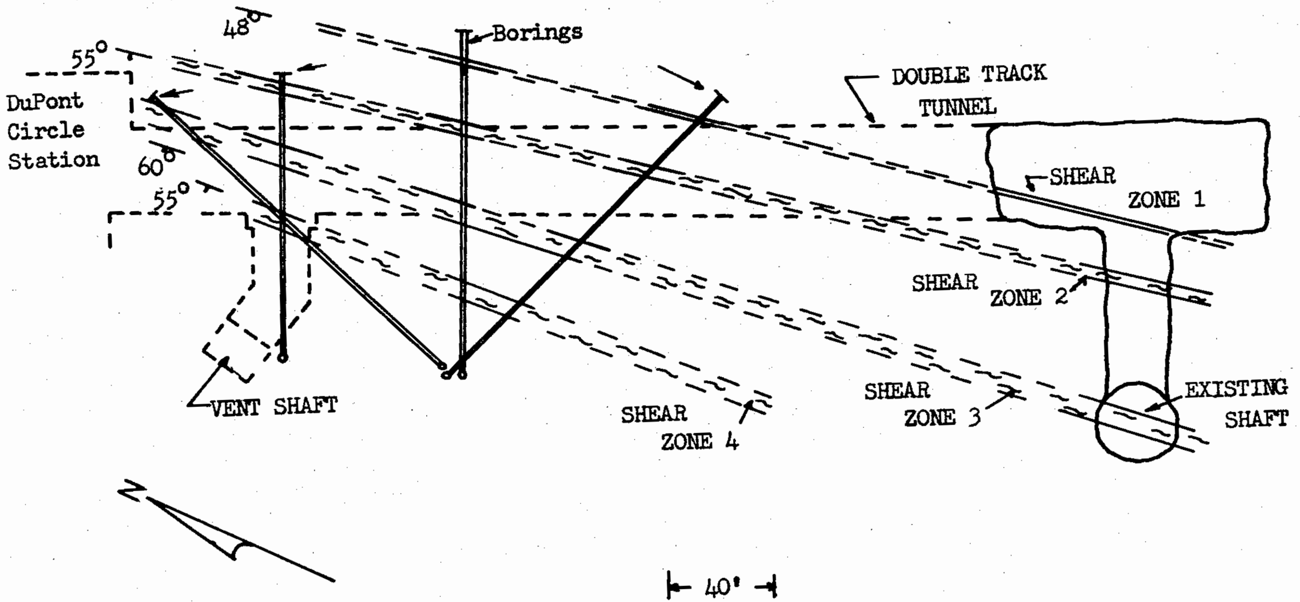

Figure 3 — Four Foliation Shear Zones Mapped from Exploratory Information, Washington, D.C., Metro DuPont Circle Station (after Mahar, Gau, and Cording, 1972).

Conclusions

Foliation shear zones are of common occurrence in metamorphic rocks. Although the gouge zone may be only a few inches wide, the overall affected zone with open or altered joints may be several feet wide and the extent of the zone along its trend may be from hundreds to a few thousands of feet. Differential slippage along weak micaceous interbeds during folding or stress relief probably accounts for the origin of most of them.

Many engineering projects have been adversely affected by the presence of these features because of their low shear strength and modulus. These projects include rock slope excavations, dams, tunnels, and underground chambers.

It behooves the engineering geologist and geotechnical engineer to suspect the presence of foliation shear zones at any site in metamorphic terraine and to devise an appropriate exploratory program to ferret them out or to disprove their presence. For large underground chambers and concrete dams exploratory adits, shafts, and trenches are almost a “must”. In other situations, core borings with triple-tube core barrels, borehole photography, or integral sampling (Rocha, 1971; Rocha and Barroso, 1971) should be judiciously used. Down-hole geophysical logging would also be of value.

Once the presence, location, and orientation of a foliation shear is established then its possible affect on the design and construction must be evaluated. Rock mechanics testing, either-in-situ or in the laboratory on undisturbed samples, may be desirable to help evaluate the shearing strength, modulus, and/or permeability.

Special design features may have to be incorporated. However, it is much preferred to do the studies during the design stage than to have to do it during construction as redesign to cope with the sudden appearance of a foliation shear. The purpose of this paper is to direct attention toward the desirability of specifically exploring for the ubiquitous foliation shears and of evaluating in the design phase their possible affect on the project. Experience has shown that a single foliation shear zone can cause serious construction delays and may increase costs from a few hundred thousand to several million dollars.

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