Subsidence Control for Structures Above Abandoned Coal Mines

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Subsidence of the ground surface above abandoned coal mines can cause serious damage to highways, buildings, and other facilities. Two categories of techniques used in controlling subsidence are selective support for structures and filling of voids caused by past mining operations. The particular method used must be adapted to the local geologic setting and the mining methods that were employed in extracting the coal as well as the support requirements of the structure, because these factors vary within any given site and from one locality to another. This paper presents a case history of subsidence control for an electric substation. The subsurface stabilization techniques used included drilled piers and piling for support of the structures, and grout columns and dry fly ash injection for support of the roadways.

The expansion of highways, housing, commercial structures, and other facilities has required the use of many areas that are underlain by abandoned coal mines and will continue to do so. Movement of the ground surface, i.e., subsidence, often results from collapse of rock and soil strata overlying these mines into the voids remaining from the coal extraction.

This subsidence can be extremely damaging although its effects vary greatly, depending on the extent of the mining, the soil and rock conditions, and the structural design. There are cases where portions of buildings have fallen into sinkholes that have developed over large mine voids (1). In other cases, mine subsidence has caused severe cracking of structures resulting in their abandonment or need for extensive repairs. In other situations, extension or compressional strains have caused minor cracking and increased maintenance costs.

There are numerous abandoned mine workings in the anthracite fields of northeastern Pennsylvania, and in the bituminous fields of the Appalachians, the Illinois Basin, the Rock Springs, Wyoming, area, and other areas of the United States. In both the dipping anthracite seams and the nearly flat-lying bituminous seams, various room-and-pillar patterns of mining have been used, with considerable variation in the percentage of coal extracted. The progressive deterioration of pillars, mine floors, and mine roofs by exposure to air and water may later result in the collapse of strata over the mine entries, and the crushing of the remaining coal pillars or the bearing failure of the mine floor and strata beneath the coal pillars. Subsidence then results as the collapse reaches the ground surface in the form of differential strains, depressions, cracking of the ground, and sinkhole development.

A number of techniques, often referred to as subsurface stabilization, have been developed to control subsidence above mined areas (2). These vary because the geologic and mining conditions vary from one location to another, and because the support requirements vary according to the type and sensitivity of the surface structure. They may be grouped into two categories as follows:

1. Selective support of structures or areas, usually by supplementing the existing subsurface support by the remaining coal pillars. These methods include construction of piers within the mine, deep foundations such as drilled piers and piling, and grout columns.
2. Filling void spaces in and above the mine leaving little or no room for caving of the overlying strata. The filling materials also help maintain the existing coal pillar support by providing confinement for the pillar sides and protecting the pillars from spalling and weathering. Filling methods have varying effectiveness depending on the completeness of filling and the compressibility of the fill material.

This paper presents a case history describing the investigation and exploration of mine conditions, the design of a stabilization program including several subsidence control or stabilization methods, and the construction procedures used for structure and roadway stabilization. An undermined electric substation site in the Appalachians about 240 by 270 m (800 by 900 ft) that is used to transfer power from a 1950-MW coal-fired generating station to the transmission system presented an unusually difficult and challenging foundation design problem. The substation was underlain by mine workings in various stages of collapse, and elaborate and detailed methods of inspection were needed to

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thoroughly map the soil and rock conditions and the extent of undermining and subsidence. After the subsurface investigation, drilled piers and piles were used to support structure foundations, and grout columns and dry fly ash injection were used for roadway stabilization.

GEOLOGY AND MINING

The substation site is underlain by alluvial soils of variable thickness consisting of relatively poorly graded sands, silts, and clays. These soils have been modified by grading, and part of the facility is located on compacted fill. Beneath the alluvium are beds of coal and limestone interbedded with thick shale and claystone that belong to the Monongahela group of Pennsylvanian age.

Much of the mining in the area occurred early in this century. However, large-scale mining activities continued until immediately after World War II when many of the coal pillars were mined to extract the maximum amount of coal prior to collapse of the mine roof.

Investigation showed that the substation area had been extensively undermined, with only a thin rock cover remaining above the mine. Large sinkholes were present at the ground surface, and exploration indicated numerous voids that would probably result in additional subsidence of the ground surface at the mine level.

Coal mining at shallow depths results in two types of subsidence at the ground surface: subsidence over a widespread area and sinkhole development. These ground surface movements occur both during and after mining. Widespread subsidence, after mining ceases, is generally the result of pillar failure due to weathering and stress concentrations that, in turn, result in spalling and eventual reduction of coal pillar size. Failure of one pillar overloads adjacent pillars, which accelerates their spalling and final failure. The formation of sinkholes may be sudden, when an entire section of rock strata above the coal mine void fails abruptly and the soils fall into the void space, or slow, when spalling of the mine roof creates a void that slowly propagates to the ground surface. Normally, sinkholes do not develop if the thickness of the rock cover above an abandoned mine in the bituminous coal fields of the Appalachians is more than about 12 m (40 ft). However, in this area sinkholes were present up to about 23 m (75 ft) above the mine.

Although substation facilities can sustain some movement, settlement in the amount that might be caused by coal mine subsidence could not be tolerated. Accordingly, the structures were supported on foundations extending below the mine. In addition, concern for the safety of construction and operating personnel required that roadways be stabilized where there was any possibility of subsidence.

INVESTIGATION

The initial phase of the investigation consisted of evaluating the surface evidence of subsidence and collecting the available mining data. Detailed reconnaissance showed that strip-mining had proceeded to just about the northern edge of the substation, so that the entire substation was underlain by deep mine workings. In addition, there were five large sinkholes, where subsidence in excess of 2 m (6 ft) had occurred, in the central and western portions of the substation.

Mining beneath the substation between 1900 and 1910 had used the room-and-pillar system. A system of entries was driven to the limits of the property to provide access, ventilation, and haulageways, and rooms were cut from large blocks of coal between the entries until discrete blocks of coal (pillars) remained. This mining terminated in the early 1920s with a substantial number of coal pillars in place as indicated in Figure 1. The mine was then leased to other coal mine operators and the pillars mined until about 1945, when roof conditions deteriorated so as to make further operation impossible. (The cross-hatching in Figure 1 indicates pillars that are known to have been removed. As indicated, most of the pillars were removed from the northeast portion of the substation.) The mining pattern was irregular in the southwest corner probably because of poor roof conditions that created safety problems. In addition, some areas beneath the substation, which were shown as reserves to support or protect gas wells, were probably also mined. Eight gas wells that had suffered subsidence damage were located during the investigation.

To determine the accuracy of the available mine map, an extensive drilling investigation was conducted. Eighteen standard test borings, in which split-barrel samples were obtained in the soil overburden and NX cores were obtained in rock, and sixty-four 150-mm (6-in) diameter rotary-air borings were drilled. The rotary-air borings were logged from the cuttings of the soil and rock strata penetrated. All sudden drops or jerks of the drill tools, phenomena that indicate broken rock strata or other related mine subsidence features, were noted. Rotary-air borings that encountered voids at mine level, caved rock strata, or crushed coal pillars were photographed with a stereoscopic vertical borehole camera. Photographs were taken in the rock strata above the mine at depth intervals of about 0.3 m (1 ft). The use of the borehole camera permitted the accurate location of any mine voids and provided a good record of the condition of the rock strata above the mine level. Once the voids were accurately located, a borehole camera having a self-contained light source and capable of taking horizontal pictures was used. The camera was rotated between photographs to obtain 6.3-rad (360-degree) coverage of the mine void.

SUMMARY OF SUBSURFACE CONDITIONS

The substation area varies in elevation from 320 to 302 m (1050 to 990 ft). It was graded to an elevation of 308 m (1010 ft) with fill in the central portion. The fill has a maximum thickness of about 6.1 m (20 ft) and is generally stiff in consistency. Colluvial soils up to 3.7 m (12 ft) thick were encountered in the borings along the east side of the substation. This colluvium is the result of mass wasting of the soils formed from weathering of the rock strata on the hill flanking the east side of the substation. Alluvial soils that varied from silty clays to fine sands were exposed on the surface of the remainder of the area. The thickness of the alluvial soil varies from 3.7 m (12 ft) along the north central portion of the substation to 18 m (60 ft) at its southeast corner. The alluvial soils underlie the colluvium on the east side of the substation and thin toward the west side of the substation. The upper portion of the alluvium ranges from soft to stiff cohesive soil. Laboratory consolidation tests on these soils show them to be moderately to highly compressible, with compression indices of 0.165 to 0.950. Granular alluvial soils, composed predominantly of fine sand and silty sand, underlie the cohesive soils throughout the substation. These soils are generally in a medium dense state.

Underlying the soils is a thin veneer of decomposed rock that partially mantles the firm rock surface. The top of the rock, as shown in Figure 2, slopes steeply upward just east of the substation. However, in the major portion of the substation, the rock surface is relatively flat, varying between elevations of 296 to 299 m

(970 to 980 ft): It reaches its highest elevation of 306 m (1005 ft) in the northwestern corner of the substation. Thus, the depth to rock from the grade elevation of 308 m (1010 ft) varies from 1.5 to 12 m (5 to 40 ft).

Figure 3 shows the contours of the base of the mined coal seam. The coal dipped to the southeast and varied in elevation from 294 m (966 ft) at the northwest corner of the substation to 286 m (939 ft) at the southeast corner. Comparison of Figures 2 and 3 indicates that the interval between the top of the rock and the base of the mined coal varies from about 9 to 12 m (30 to 40 ft) at the southeast and northwest corners of the substation respectively. The average interval in most of the central portion is about 6 m (20 ft) but as little as 3 m (10 ft) in the southwest corner.

The rock strata within the substation from the top of rock to the lowest strata of importance with respect to foundation design and construction are (a) limestone, (b) claystone, (c) shale, (d) coal (mined seam), (e) siltstone, and (f) silty shale. Over much of the area, hard limestone, which is commonly interbedded with claystone and is a maximum of approximately 3 m (10 ft) thick, forms the rock surface. The limestone is for the most part a competent rock and frequently bridges over underlying mine voids. Where the claystone interbeds occur and the weathering is particularly advanced, the limestone is less competent and unable to span the mine voids. Underlying the limestone there is approximately 2.4 m (8 ft) of claystone, which is usually in a medium soft state. Frequently, the claystone has caved into the mine voids resulting in a soft clayey mass at mine level. The claystone is, in turn, underlain by 1 m (3 ft) of shale, which has also caved into the mine rooms and contributes to the clayey mass. Some of the borings encountered a similar soft material at mine level that could not be attributed to caving of the mine roof. This material, termed mine gob, is mine waste that was disposed of in abandoned entries and rooms.

The mined coal seam is usually about 2 m (6 ft) thick. However, in some of the borings, crushed coal pillars were encountered. In these borings, the coal was somewhat thinner and highly fractured. The conditions encountered at the level of the mined coal seam by the 82 borings are summarized below:

Condition	Percent of Borings	Condition	Percent of Borings
Coal pillars	48	Caved material	35
Crushed coal pillars	5	Large voids	12

The mined coal seam is generally underlain by a siltstone stratum that ranges from 2 to 3 m (7 to 10 ft) thick and varies from medium soft to medium hard. Frequent interbeds of claystone occur in the siltstone. Interbedded shale, silty shale, and siltstone underlie the siltstone stratum and extend to approximately 6.7 m (22 ft) below the base of the mined coal seam. Figure 4, a typical cross section through the substation, shows the thickness of the soil and rock cover above the mined coal seam.

The water levels measured in the borings show the water table to occur at or slightly above the base of the mined coal seam. In a few cases, local ponding of water has occurred in the mine workings because of roof falls or the presence of mine bulkheads, and in one large area along the northwestern side of the substation, the mine is flooded.

Figure 1. Map of abandoned coal mine beneath substation.

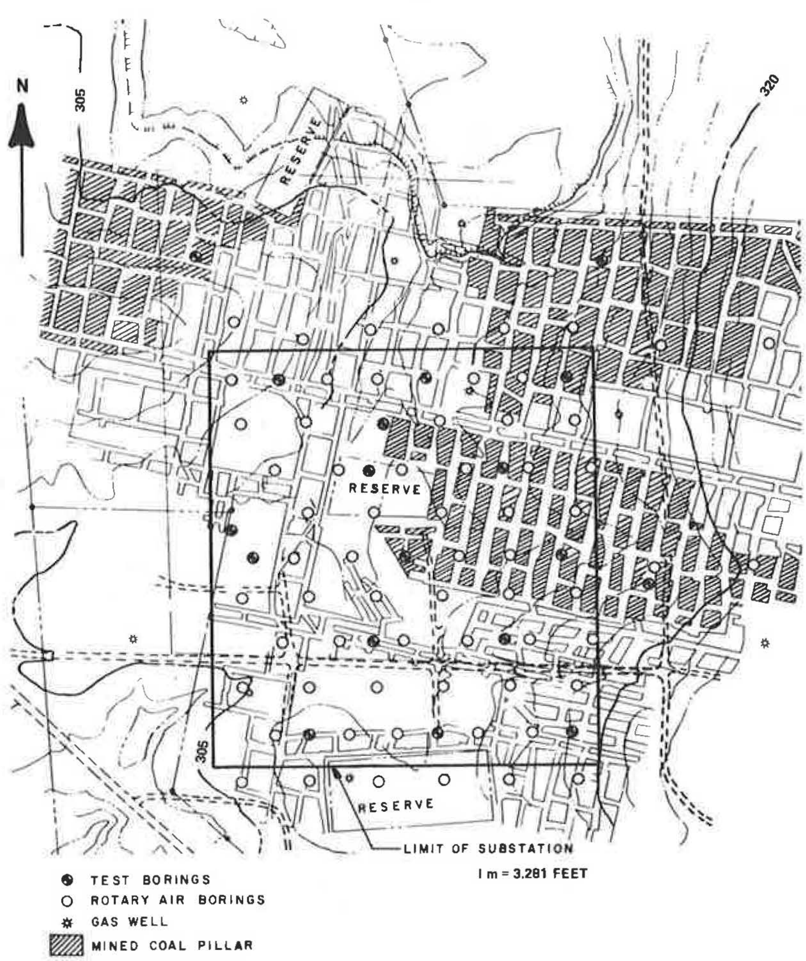


Figure 2. Contours of the top of the rock.

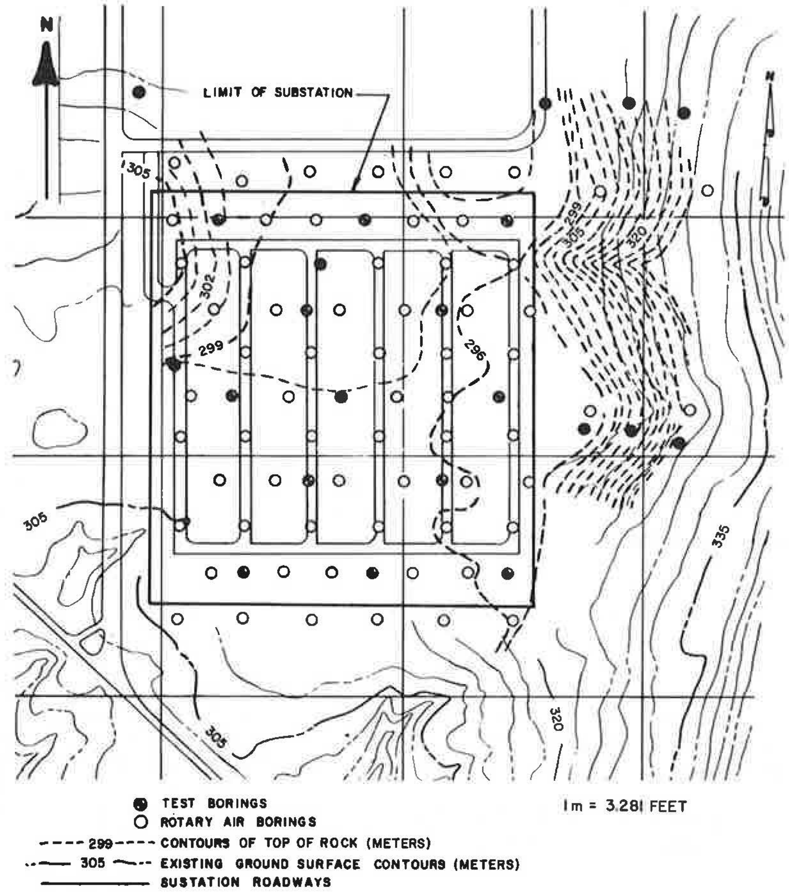
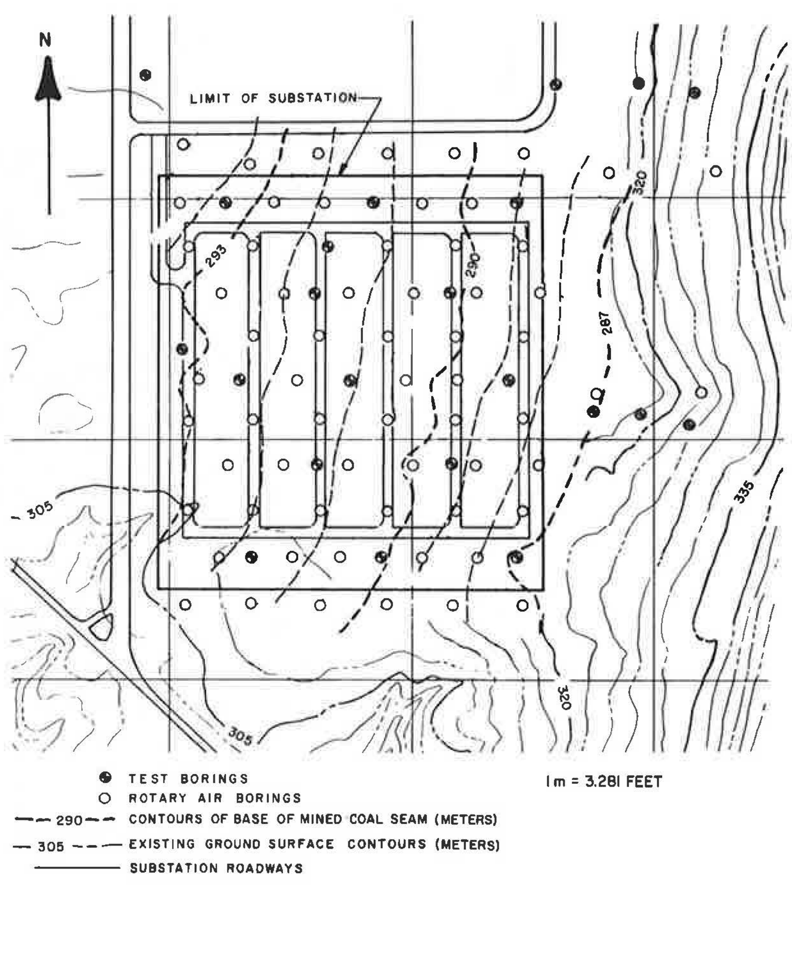


Figure 3. Contours of the base of the mined coal seam.



Often, the borings did not encounter conditions anticipated from the mine map. However, study of the horizontal borehole photographs indicated that the mine map should be shifted somewhat in relation to ground surface features. Once this was done, the map was quite accurate.

The substation was divided into three areas, based on the extent of mining indicated by the map and the conditions at mine level shown by the borings and photographs. In area 1, the southwestern portion of the site where the amount of rock cover above the coal was minimal, mining had not been extensive. Large coal pillars were shown on the mine map and all but a few of the borings encountered in-place coal. The voids that were encountered were the full height of the seam and contained little caved material. In area 2, the eastern half of the substation where the rock cover above the base of the coal varied from about 6 to 9 m (20 to 30 ft), removal of most of the coal pillars had resulted in almost complete subsidence. Most of the borings drilled in this area encountered caved material and a few moderate-sized voids and coal pillars. Area 3, the northwestern portion of the substation, was underlain by a fairly well-developed system of mine entries and rooms. No retreat mining involving coal pillar extraction had been conducted in this area, and the mine rooms were large and the coal pillars relatively small. The borings usually encountered either large voids or in-place coal. The rock cover above the base of the coal varied from 6.7 to more than 12 m (22 to 40 ft) in this area.

FOUNDATION DESIGN

As shown in Figure 5, the substation contains 10 circuit breakers, and the associated disconnect switches, lighting arresters, and metering and control equipment interconnected by rigid aluminum tube bus ducts with dead end towers for connections to the generating units and the 500-kV transmission lines. The control and communication cables are placed in precast concrete enclosed trenches. Because of the rigid bus duct connections, very little settlement or movement of the equipment can be tolerated.

The transmission and dead end towers exert relatively heavy lateral and vertical loads on their foundations. Therefore, because of the compressible soils overlying the rock surface and the abandoned coal mine, 0.76 and 1.22-m (30 and 48-in) diameter reinforced-concrete piers drilled in place were selected as the most suitable type of foundation for them. All of the drilled piers were socketed into rock below the base of the mined coal seam. The minimum diameter of 0.76 m (30 in) for the drilled pier construction was due to the necessity of hand cleaning the sides and bottom of the pier rock sockets. Permanent steel casing with a wall thickness of 8 mm (5/16 in) was securely seated into the rock at the base of the mined coal seam and extended to the ground surface to provide a form for the concrete in the abandoned mine workings. The casing also prevented bonding of the drilled pier to the rock strata above the mine, which might, at a later date, subside. In addition, the casing served as a protective liner for men working at the bottom of the drilled shaft.

Drilled piers bearing on medium hard or hard rock strata were designed for a maximum allowable end-bearing pressure of 960 kPa (10 tsf) for dead, live, and wind loadings. Rock sockets extending into medium hard rock strata were designed for load transfer between the drilled pier and the rock socket using a shear value of 350 kPa (50 psi). Where the strata at the base of a drilled pier were composed of soft to medium soft rock, drilled piers were designed for a maximum end bearing pressure of 380 kPa (4 tsf) for dead, live, and wind loadings. If the rock strata were medium soft, a design shear value of 140 kPa (20 psi) was used for load transfer between the drilled pier and the rock socket, and if the rock was soft, shear value of zero was assigned.

In places where medium soft rock was known to underlie the base of the drilled piers by less than 0.6 m (2 ft), a maximum bearing pressure of 380 kPa (4 tsf) was used. On completion of the rock socket, a 3-m (10-ft) deep test hole was drilled using percussion drilling equipment to evaluate the quality of the rock below the base of the socket.

Due to the difficulties in penetrating the hard limestone above the mined coal seam, the drilled piers were allowed to deviate from plumbness a maximum of 1 percent (6.4 mm/m, 1/8 in/ft). A maximum eccentricity radius of 25 mm (1 in) from the plan location was permitted. Figure 5 shows the area of the substation in which fill was placed. In this area, because of the settlement of the alluvium under the weight of the fill, all of the drilled piers were designed for a negative skin friction load of up to 68 Mg (75 tons) per pier. All of the drilled piers were designed assuming concrete with a minimum unconfined compressive strength of 24.5 MPa (3500 psi).

The circuit breakers, disconnect switches, lighting arresters, and metering and control equipment are relatively light and exert small loads on foundations. Therefore, this equipment was supported on less costly predrilled closed-end steel pipe piling extending to the base of the mined coal seam. The piles, which are designed for a maximum vertical load of 68 Mg (75 tons), were tied together by a grade beam system at the ground surface to provide lateral resistance. Evaluation of the reduction in strength of steel piling that would result from corrosion by the acid mine water (pH approximately 3.5) showed that use of conventional steel piling was not feasible. Therefore, relatively corrosion-resistant Yoloy (a copper-zinc-manganese alloy steel) pipe was selected for use. Study showed that extra strong, 0.2-m (8-in) nominal diameter Yoloy pipe filled with concrete would safely sustain the design load over a 30-year period, and to provide an additional safety factor the piling was filled with 24.5 MPa (3500 psi) concrete. The negative skin friction loads on piling installed in the filled area amounted to approximately 4.5 Mg (5 tons)/pile. Out-of-plumb variation was limited to 2 percent of the pile length. All piles were driven within 50 mm (2 in) of the indicated plan location.

Roadway safety was carefully evaluated to provide an economical stabilization treatment; Figure 6 shows the various stabilization methods used. No treatment was required beneath the sections of the roads that were underlain by solid coal or where nearly complete subsidence had occurred. At the few locations where isolated mine entries underlaid the roads, grout columns (Figure 7) were formed by placing a cone of gravel in the mine void and then grouting the cone to stabilize the mine roof. The remaining sections of roads were stabilized by injecting dry fly ash from tanker trucks into the mine voids.

CONSTRUCTION PROCEDURES

Foundation construction and subsurface stabilization were conducted during the winter of 1971. Due to the special nature of the foundation and stabilization work, three contracts were let: one for the drilled piers, one for the closed-end pipe piles, and one for the fly ash and grout column stabilization.

Drilled pier construction totaled sixty-four 0.76-m (30-in) diameter piers and twelve 1.22-m (48-in) diameter piers. These were drilled with Williams LLDH truck-mounted diggers using 0.91 and 1.37-m (36 and 54-in)

diameter soil and rock augers to depths up to 23 m (75 ft). The holes were drilled somewhat oversized in the soil and rock strata above the mined coal seam to avoid problems in placing the casing within plumbness tolerance. However, in some cases, deviations in plumbness necessitated lowering a man into the shaft to jackhammer the obstructions so that the vertical shaft would meet the specified tolerances upon placement of casing. Where the overlying limestone was relatively thick and hard, Calweld crane-mounted rigs using roller cone bits were used until the limestone was penetrated. Permanent steel casing was then inserted to the base of the mine and a 0.76 or 1.22-m (30 or 48-in) nominal diameter socket drilled into the underlying strata using rock augers. The annulus between the oversized hole and the casing was backfilled with gravel.

Figure 4. Typical east-west oriented cross section.

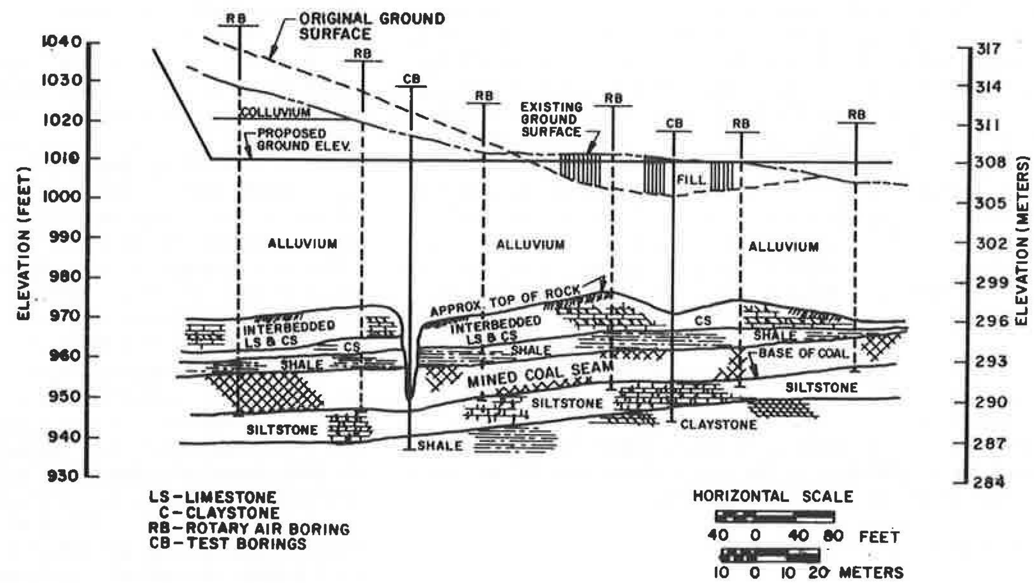


Figure 5. Fill area in substation.

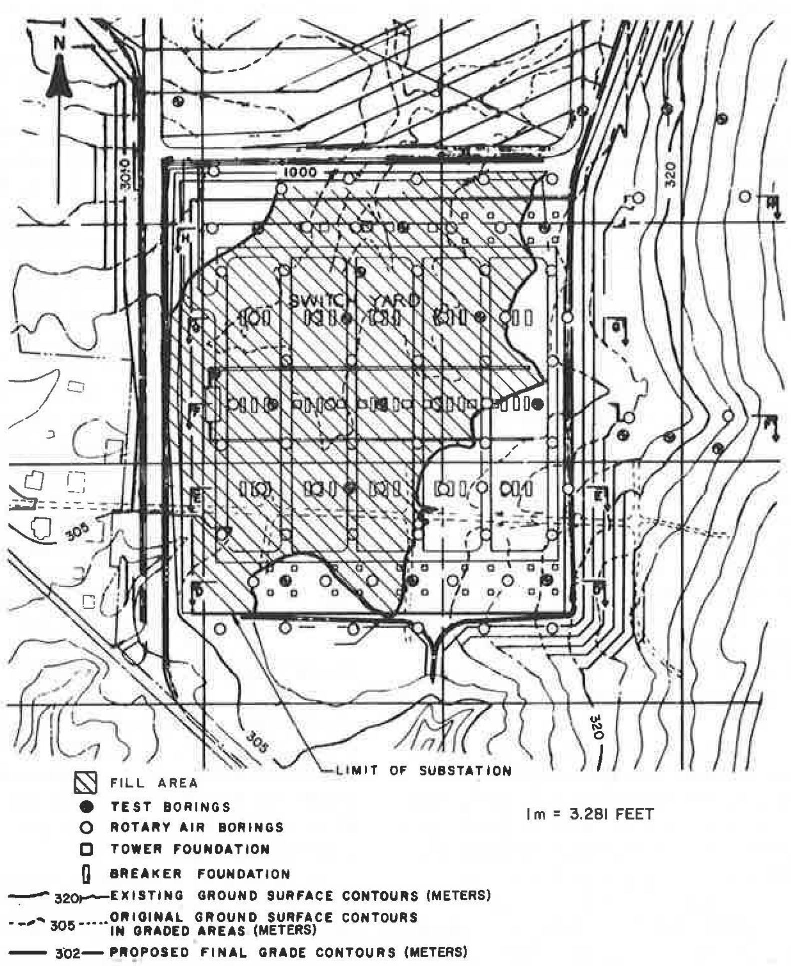
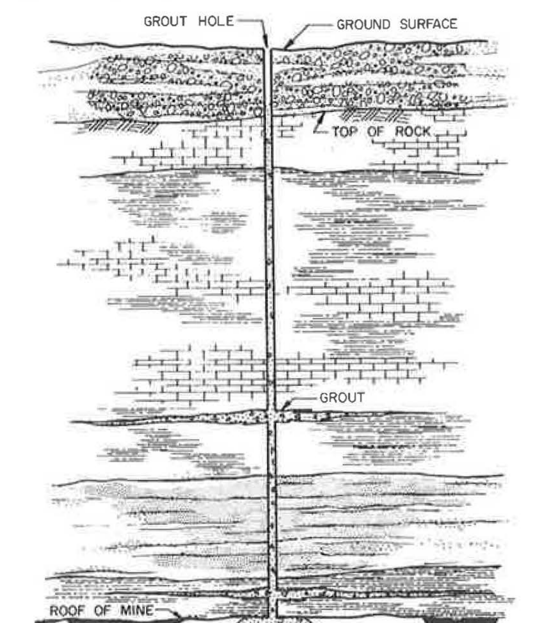


Figure 6. Roadway stabilization treatment areas in the substation.

Figure 7. Typical grout column construction.



The rock sockets extended 0.5 to 2.7 m (1.5 to 9.0 ft) below the base of the mined coal seam. Their sides were thoroughly scraped clean, and loose material was removed from the base of the drilled pier shaft prior to concrete placement. In most cases the rock sockets had only small inflows of water and presented few problems in placing the concrete. Where water was encountered, a pump was placed in the shaft bottom for cleaning and dewatering, and withdrawn immediately prior to placement of the concrete, which was placed from the top of the hole using a chute to prevent it from ricocheting against the casing. Anchor bolts or steel stub angles or both were placed at the cutoff elevation.

Piling was initially installed in holes drilled to the base of the mined coal seam using a crane-mounted auger to drill soil and an air-rotary drill to extend the hole through rock. About midway through the project the use of the auger was abandoned and the remainder of the holes were drilled solely by the air-rotary rig. (Problems had been encountered in the use of two drilling rigs to complete a hole as the soil and rock portions of the hole were frequently not co-axial.) A total of 393 piles were installed. The holes were a minimum of 0.24 m ($9^5/_8$ in) in diameter. The piles were seated at the bottom of the hole using a Vulcan 08 hammer rated at 35 kJ (26 000 ft-lb) at 50 blows per minute. In all cases, the pile penetrated to the mine floor and then reached a final penetration resistance of 10 blows/25 mm (1 in). Most piles were driven from 0.3 to 0.6 m (1 to 2 ft) into the rock strata below the base of the mined coal seam. Backfilling around the piles was done in a manner similar to that used for the drilled piers. The piles were checked for plumb tolerance and then concreted to increase their

structural strength and provide an added safety factor against corrosion. They were then cut off at the design elevation and completed with anchor straps. Field splices were not permitted; all piles were brought to the site at predetermined shop fabricated lengths and then cut off as required.

Subsurface stabilization was conducted through 150-mm (6-in) diameter holes drilled with air-rotary equipment. All holes were cased to the top of rock. In the northwest portion of the substation, a dewatering well was installed to draw down the water in a portion of the mine that was flooded. The bulk fly ash stabilization was performed first. The fly ash was transported to the site in 18-Mg (20-ton) pneumatic tank trucks. A connection to the casing was made and the fly ash blown into the mine through the casing inserted in the borehole at a maximum pressure of 100 kPa (15 psi) until refusal. Some holes refused fly ash, but as much as 180 Mg (200 tons) was injected into other holes; the total amount of fly ash placed in the 180 injection holes was 3500 Mg (3800 tons).

Grout columns (Figure 7) were constructed at 15 selected locations. The columns were constructed by placing gravel down the hole, spreading the aggregate with compressed air injected through a perforated pipe at the hole bottom, and then injecting grout into the aggregate pile. The aggregate used consisted of clean gravel 6 to 19 mm ($^1/_4$ to $^3/_4$ in) in diameter. The grout consisted of a fluid mix, 3 fly ash to 1 cement to 3 to 4 water, which was delivered to the grout pumping stations in agitator trucks from a local batch plant. A roof contact diameter of about 1.8 m (6 ft) for a grout column is adequate to support the mine roof.

During construction, a few small sinkholes formed at the ground surface, indicating the serious subsidence potential. Since the construction has been completed, no additional sinkholes have formed in the stabilized area.

REFERENCES

1. Underground Disposal of Coal Mine Wastes. National Academy of Sciences, Washington, D.C., 1975.
2. State of the Art of Subsidence Control. General Analytics, Inc., Appalachian Regional Commission, Rept. ARC-73-111-2550, 1974; NTIS, Springfield, Va., PB 242 465 AS.