EVALUATION AND REMEDIATION OF AN ABANDONED MINING SITE

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ABSTRACT

This paper describes a geotechnical engineering investigation and some of the subsequent construction at a 50-acre (20 ha) site in central Pennsylvania, where it is proposed to construct a large food distribution and warehouse facility. This site is located within one of the anthracite coal fields and is characterized by extensive abandoned surface and underground mine workings. Detailed investigations including historical research, geophysics, and test borings were performed, and the various mechanisms associated with mine subsidence were identified and evaluated. An assessment was made of the risk potential for future mine subsidence to occur, and appropriate site development and building design provisions were recommended to accommodate the risk potential. The site development grading construction included maximums of about 60 and 50 ft (18 and 15 m) of excavation and fill, respectively and a total of about one million cubic yards ($765 \times 10^3$ m$^3$) of earthmoving, and deep dynamic compaction.

INTRODUCTION

URS Corporation was engaged to perform Geotechnical Engineering investigations at a site in Northumberland County, Pennsylvania. The food distribution and warehouse facility proposed for this 50-acre (20 ha) site includes an initial building with an area of about 250,000 ft$^2$ (23,200 m$^2$) and future expansions, as shown on Figure 1. The site area around the building is to be developed for parking, access, and truck loading and maintenance. Throughout the existing site, the topographic relief is greater than 100 ft (30.5 m), and a significant amount of excavation and fill construction were needed to develop the building pad and the adjacent areas.

This site is within the Western Middle Anthracite Field where coal mining has been performed since the 19$^{th}$ Century. It was reported that surface and underground coal mining had been performed within the area encompassing the site, and evidence of this mining was readily apparent throughout the site. Accordingly, with the abandoned mine workings, there was a concern about the potential for future mine subsidence that may have a detrimental effect on the proposed facility. Addressing this concern is in addition to the customary geotechnical considerations for site grading construction, foundation support, and building design.

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Figure 1. Site Plan, Proposed Buildings, and Boring Locations
The site contains a number of significant features that are all oriented in a generally east to west direction. From north to south, there are in succession a low trough, a high ridge area that continues to the east, and a relatively flat low area in which there is a linear array of potholes and another low trough to the further south. The proposed building, with a floor elevation of 1,032 ft (314.6 m) encompasses the high ridge area where the existing surface elevations range from approximately 1,030 ft to over 1,090 ft (314 to 332 m). Sand and gravel size soils with gravel to boulder-size fragments of light brown to black sandstone, siltstone, and shale were observed at the ground surface throughout the ridge area. The trough north of the proposed building, with side slopes at about 45°, was reportedly a former strip mining area, and the grade at the bottom of the trough ranges approximately from 970 ft to 1,020 ft (295.7 to 311 m).

To the south of the proposed building area, the ground surface generally slopes moderately downward in elevation from approximately 1,020 to 980 ft (311 to 299 m). There are about a dozen individual depressions with circular to elongated shapes, and depths of 10 to 15 ft (3.0 to 4.6 m) and lengths of about 30 to 70 ft (9.1 to 21.3 m), along the toe of the slope down from the ridge area. Outcrops of gray to black siltstone and sandstone were noted in these potholes. The bottom of the trough further to the south was about 20 to 30 ft (6.0 to 9.1 m) below the surrounding ground surface. This trough was reportedly also a former strip mining area.

The warehouse was proposed to be a steel frame building with insulated panel walls. In the storage areas, the column spacing will be on the order of 34 to 42 ft (10.4 to 12.8 m), and column loadings of about 70 to 110 kips (312 to 489 kN) were anticipated. Handling and truck loading areas will be located along the south side of the building and the column spacing in one direction will be increased to 75 ft (22.9 m), resulting in column loadings of about 160 kips (712 kN). The maximum tolerable differential settlement between the columns was reported to be ¾ inch (1.9 cm). Within the freezer area, there will be an insulation layer and subfloor heating to prevent ground freezing. The refrigeration supply and return lines will be located on the roof of the building. A two-story office structure constructed with steel columns and precast concrete elements and the refrigeration plant are located extending from the south side of the building.

**PRELIMINARY INFORMATION**

Mine maps and representative cross sections of some of the mine workings at this site were provided by the property Owner. The portion of the No. 11 Vein map encompassing the site is reproduced as Figure 2 and one of the cross sections is reproduced as Figure 3. This information identified that the site is underlain by a generally east to west oriented synclinal structure in which there are several coal veins that have been mined to varying extents. Strip
Figure 2. No. 11 Vein Mine Map
mining was indicated at the outcrops of the No. 11 and No. 10½ Veins and resulted in the existing troughs to the north and south, respectively, of the ridge area. As shown on Figure 2, tunnels and openings were mined through the coal on the flanks of the syncline and pillars of coal were left in a process termed “first mining”. “Robbing” was subsequently performed by removing some of the pillars, and the pillars thus mined are shaded on the maps. No mining is indicated close to the axis of the syncline. Similar mining conditions were shown on the map of the No. 10½ Vein. There are notations on the map of the dates of mining, the surveyed elevation and thickness of the vein, and some of the mining conditions that were encountered. The underground mining in these two veins is indicated to have been performed in the 1940’s and the strip mining in the 1950’s.

An area near the south outcrop of the No. 11 Vein has pillars drawn in dashed lines and is identified as “bootleg workings”. Such notations are frequently associated with older, unsurveyed mine workings that were usually accessed from surface openings and conducted without a systematic mining plan. It is noted that the line of potholes is oriented along this south outcrop of the No. 11 Vein. These conditions of mapped first mining and robbing, undocumented bootleg mining, and the pothole development indicated the need to evaluate the potential for future mine subsidence.

Figure 3. Typical Mining Cross Section
The cross section of the coal veins, Figure 3, identifies the No. 12 Vein located structurally above the No. 11 Vein and positioned approximately through the middle of the proposed building area. Indentations in the ground surface indicate that some strip mining may have been performed at the outcrops of this vein, and projections indicate that the lowest portions of this vein may be about 50 ft (15.2 m) below the proposed building floor level.

**MINING AND SUBSURFACE CONDITIONS**

More extensive exploration was performed to explore the mining conditions of the Nos. 12 and 11 Veins and the geotechnical conditions at the site. These explorations would provide data needed for analysis of the subsidence potential and for the project design and construction. Research of historical documents, a geophysical survey, and boring exploration were performed.

**Historical Research**

Most of the early to mid 20th Century mining in the anthracite region was well documented and many of these records have been preserved in public and private archives. Research located maps of the coal veins and identified that additional underground mining had been performed in the Nos. 9 ½, 9, and 8 Veins that are beneath the No. 10 ½ Vein. In general, these deeper veins were mined on the flanks of the syncline and not mined near the axis of the syncline, which left unmined areas beneath the building location. First mining and partial robbing were performed in these veins between 1943 and 1959. These deep mining conditions are summarized on Table 1

<table>
<thead>
<tr>
<th>Vein No.</th>
<th>Lowest Mining Elevation, ft.</th>
<th>Unmined Width, ft.</th>
<th>Vein Thickness, ft.</th>
<th>Mining Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>732 (223 m)</td>
<td>110 – 150 (33.5–45.7 m)</td>
<td>5.0 – 9.0 (1.5–2.7 m)</td>
<td>First mined with extraction ratio of 0.65; north flank partially robbed, south flank mostly robbed</td>
</tr>
<tr>
<td>10 ½</td>
<td>533 (162.5 m)</td>
<td>130 – 180 (39.6– 4.9 m)</td>
<td>5.0 – 6.0 (1.5–1.8 m)</td>
<td>First mined with extraction ratio of 0.65 - 0.70, North flank robbed, South flank robbed below El. 780 +/- ft</td>
</tr>
<tr>
<td>9 ½</td>
<td>530 (161.6 m)</td>
<td>650 +/- (198 m)</td>
<td>3.0 – 5.0 (0.9–1.5 m)</td>
<td>First mined with extraction ratio of 0.65; North flank robbed, south flank partially robbed</td>
</tr>
<tr>
<td>9</td>
<td>330 (100.6 m)</td>
<td>700 – 900 (213–274 m)</td>
<td>5.0 – 6.0 (1.5–1.8 m)</td>
<td>First mined with extraction ratio of 0.65; North flank mostly robbed, south flank partially robbed</td>
</tr>
<tr>
<td>8</td>
<td>530 (161.6 m)</td>
<td>900+ (274 m)</td>
<td>5.0 – 7.0 (1.5–2.1 m)</td>
<td>First mined with extraction ratio of 0.65, partially robbed</td>
</tr>
</tbody>
</table>

The maps showed drill holes and rock tunnels interconnecting the veins so that there is now a common mine pool of ground water. Historical records indicate the mine pool fluctuating
in elevation between 796 and 906 ft (242.7 to 276.2 m) in the period of December 1962 through April 1977. There are additional coal veins below the No. 8 Vein that were not mined at this site. Of particular importance was the discovery of a surface map indicating that the No. 12 Vein was strip mined at least along the outcrops that are located through the center portion of the proposed building area.

Geophysical Survey

Electrical resistivity techniques have been previously used at mining sites to locate the limits of strip mining and to indicate areas of underground mining (Sheets, 1992) and caving. Resistivity survey traverses were performed along eight lines across the site, oriented in a north to south direction, and using the dipole-dipole electrode array. Electrical resistivity imaging (ERI) processing of the survey data produced cross sections indicating zones of different electrical resistivity that generally followed the synclinal structure beneath the site, as shown on Figure 4. This ERI survey provided a more extensive and economical depiction of the subsurface conditions than could be accomplished by test borings. Possible strip mining of No. 12 Vein was indicated by the ERI and the test boring program in this area was modified accordingly. Otherwise, there were no significant anomalies to the subsurface conditions indicated by this survey.

Figure 4 Typical Cross-section of Electrical Resistivity Survey

Boring Exploration

Test borings were drilled at 46 locations to explore the geotechnical conditions related to the building design and site development construction and to the mining conditions. Combina-
tions of conventional soil sampling, rock coring, and rotary air drilling were used, and the boring depths ranged from 6.5 to 261 ft (2.0 to 79.6 m). Most of the deep borings were targeted to the No. 11 Vein, with the depths initially estimated from the elevations shown on the mine map. Borehole video logging was used to examine the rock conditions in the borings that were air rotary drilled. This combination of techniques resulted in a more economical and efficient exploration program than could be accomplished using only rock cores.

Most of the borings located within the center portion of the proposed building area encountered from 21 to 76 ft (6.4 to 23.2 m) of fill materials that extend a maximum of 44 ft (13.4 m) below the proposed floor level. The fill consists of brown to dark gray silty coarse to fine sand to sandy silt with varying amounts of gravel rock fragments and occasional coal. N-values in the fill range from 2 to greater than 50 blows per foot (30 cm) (bpf), and are typically in the range of 4 to 12 bpf. These findings indicate that the No. 12 Vein was almost completely strip mined throughout the site and backfilled with generally loose to medium dense materials, and that there is a significant depth of these fill materials below the proposed building grades.

The deep borings encountered varying thicknesses of soil and decomposed rock overlying relatively intact layered sandstone, siltstone, and shale with occasional anthracite coal. Core recoveries ranged from 22 to 100 percent and averaged 91 percent, and RQD ranged from 0 to 95 percent and averaged 36 percent. Five of the borings were cored through 3.5 to 8.5 ft (1.1 to 2.6 m) of coal, and one of the borings encountered 4.5 ft (1.4 m) of void at a depth of 143.5 ft (43.8 m). Thin voids and fractured rock in five other borings indicated possible collapse zones at depths ranging from 108 to greater than 200 ft (32.9 to 61 m). These findings are all consistent with the elevations and other information interpreted from the map of the No. 11 Vein. The coal and void were encountered in borings located over first mined areas or large pillars, and the indications of possible collapse zones are in robbed areas. Measurements of the ground water in the borings indicated a mine pool level at about elevation 924 ft (281.7 m). The present mine pool level has been at a historic high for several years, and is expected to remain since the level is controlled at an overflow to the north of the site.

**MINE SUBSIDENCE MECHANISMS**

Mine subsidence is typically associated with trough or bowl shaped depressions in the ground surface, and with active mining operations. A generalized approach to evaluate the potential for future ground surface subsidence related to abandoned mine workings primarily in the anthracite region has been developed (Mabry, 1973) and refined over a period of time and through many similar projects. Through this approach, the possible subsidence mechanisms that
may be present at a specific project site are first identified and assessed based upon relevant criteria. Credible subsidence mechanisms are then further evaluated for the level of risk and the potential ground surface movement that may result. Similar approaches have been proposed and utilized in bituminous coal regions (Hao and Chugh, 1992, and Marino, 1998) where there is a significantly greater data base of subsidence occurrences.

**Pillar Crushing**

Most of the areas of deep mining at this site have been robbed so that pillar crushing would not become a consideration. However, there are limited areas of remaining coal pillars that are within a zone of influence for the proposed building facility and the future additions. The average level of stress within these coal pillars is primarily a function of the coal extraction ratio and the vein depth, and the average pillar stresses are increased to allow for weathering and related effects that could reduce the pillar sections with time. Inundation of the veins reduces the stresses from the as-mined condition by a buoyancy effect and is generally believed to inhibit weathering of the coal. The average pillar stresses are determined through the expression:

$$p_p = \frac{p_o - u}{c(1 - R)}$$  \hspace{1cm} (1)

where,  
\(p_p\) = average pillar stress  
\(p_o\) = vertical stress from the overlying soil and rock  
\(c\) = weathering coefficient, usually 0.9  
\(R\) = extraction ratio from first mining  
\(u\) = hydrostatic pressure of the mine pool

In general, the strength of coal pillars increases with the pillar width and decreases with increasing mined height of the vein. From the several formulas for calculating coal pillar strength (Hustrulid, 1976), the Bieniawski formula has been selected for use. This formula was developed based upon laboratory and field experience in the South African coal fields. It is understood to be presently used with confidence in active mine operations in the United States bituminous regions, and also compares favorably with some historic data of pillar strengths in the Pennsylvania anthracite coal (Bunting, 1912). Additional relevant data are obtained from a series of laboratory tests of coal strength from the anthracite fields of Pennsylvania (Griffith and Conner, 1912). The Bieniawski formula for determining pillar strengths is:

$$p_m = p_c \left[0.64 + 0.36(\frac{W}{H})\right]$$  \hspace{1cm} (2)

where,  
\(p_m\) = pillar strength  
\(p_c\) = cube strength of coal as determined from the unit coal strength, \(k\), in
\[ p_c = \frac{k}{\sqrt{H_c}} \]

\( W = \) pillar width  
\( H = \) pillar height  
\( H_c = \) cube dimension of coal

In the development of coal pillar strength formulas, the unit strength of coal was found to decrease with increasing cubical size and reach a minimum value at a cubical dimension of about 36 inches (91 cm), which is then used for the calculation of \( p_c \).

The remaining coal pillars that may affect the proposed building are in the No. 11 Vein, and these pillars were analyzed for different conditions, as summarized in Table 2. Stress ratio, the ratio of the pillar strength, \( p_m \) (Eq. 2), to the average pillar stress, \( p_p \) (Eq.1) is used to identify the analysis results rather than safety factor, which may connote an unwarranted implication of safety. This is demonstrated by the occasional finding that pillar strengths calculated from different formulas are significantly less than the average pillar stresses where mining has been successfully performed (Peng, 1992). For the determination of average pillar stress after mining, a value of 1.0 is used for \( c \) since there has been no exposure time for weathering and \( u \) is set to zero since there is no mine pool water pressure. The post construction condition represents the stress reduction from the excavation that is to be performed to attain the finished site grades.

<table>
<thead>
<tr>
<th>Location</th>
<th>Est. Vein Elevation</th>
<th>Pillar Width (ft)</th>
<th>Vein Height (ft)</th>
<th>After Mining</th>
<th>Present Condition</th>
<th>Post Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest Addition</td>
<td>915 (279)</td>
<td>7 (2.1)</td>
<td>6.5 (2.0)</td>
<td>2.5</td>
<td>2.6</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>915 (279)</td>
<td>5 (1.5)</td>
<td>6.5 (2.0)</td>
<td>2.2</td>
<td>2.3</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>822 (251)</td>
<td>7 (2.1)</td>
<td>6.5 (2.0)</td>
<td>1.54</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>North Central Building Addition</td>
<td>904 (276)</td>
<td>5 (1.5)</td>
<td>6.5 (2.0)</td>
<td>2.3</td>
<td>2.4</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>813 (248)</td>
<td>5 (1.5)</td>
<td>9 (2.7)</td>
<td>1.33</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>982 (299)</td>
<td>10 (3.0)</td>
<td>7 (2.1)</td>
<td>5.9</td>
<td>5.9</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>910 (277)</td>
<td>10 (3.0)</td>
<td>7 (2.1)</td>
<td>3.0</td>
<td>3.1</td>
<td>3.9</td>
</tr>
<tr>
<td>Northeast Addition - East Half</td>
<td>978 (298)</td>
<td>14 (4.30)</td>
<td>6 (1.8)</td>
<td>7.2</td>
<td>7.2</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>836 (255)</td>
<td>10 (3.0)</td>
<td>6 (1.8)</td>
<td>2.3</td>
<td>2.6</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>978 (298)</td>
<td>12 (3.6)</td>
<td>6 (1.8)</td>
<td>6.7</td>
<td>6.7</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>838 (255)</td>
<td>12 (3.6)</td>
<td>6 (1.8)</td>
<td>2.5</td>
<td>2.9</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>820 (250)</td>
<td>7 (2.1)</td>
<td>6 (1.8)</td>
<td>1.7</td>
<td>2.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>

In the “bootleg” mining area the configuration of any remaining pillars is known with less certainty than in the areas of mining that were surveyed. However, the indications are of
pillars of generally larger dimensions than in the mapped areas. This, together with the shallow depth to the vein and the results from the previous pillar analyses, leads to the expectation that any remaining pillars in this area may have generous stress ratios.

**Pillar Punching**

Punching of coal pillars into the floor or roof strata of the vein is a potential subsidence mechanism that is similar to a bearing capacity failure of a building footing and occurs where the strata around the coal vein are soft or are susceptible to significant softening over time. The most frequent reports of pillar punching are from the Illinois bituminous area (Marino and Choi, 1999) where the coal veins are underlain by soft shale, sometimes referred to as underclay. Experience has shown that the shale (or more frequently siltstone) beds in the anthracite region are hard and not susceptible to significant deterioration. Therefore, this mechanism does not apply to this site.

**Roof Collapse**

Another mine subsidence mechanism is collapse of the roof rock above mine openings and the collapse then propagating upward through the overlying rock. In order to quantify the overlying rock and make comparisons with different sets of conditions, primarily within the anthracite region, the Caprock Index parameter ($I_C$) was developed. This index is based upon the thickness of the rock and the quality of the rock as expressed by the RQD. The Caprock Index is determined from the equation:

$$I_C = \sum L_i(1 + RQD_i)$$  \hspace{1cm} (3)

where, $L_i$ = length of individual core run, and $RQD_i$ = RQD of individual core run.

Historical practice, as reported by some of the surviving mining engineers in the northern anthracite region, was to leave a minimum of 30 ft (9.1 m) of rock above shallow mine workings to protect ground surface facilities. This 30 ft (9.1 m) of rock could have RQD values ranging from zero to 100 per cent, and the $I_C$ would then range from 30 to 60 ft (9.1 to 18.2 m). Using the $I_C$ parameter, the overlying rock conditions at a specific site could be compared to this historical practice and to other sites where judgment evaluations have been made or other experiences noted. Based upon the mine map and the test boring information, there is a minimum rock cover thickness of 50 ft (15.2 m) over the first mined portions of the No. 11 Vein. The test borings that were cored through this rock disclosed a weighted average RQD of about 40 percent. On this basis, the minimum $I_C$ value would be about 70 ft (21.3 m). With the greater thickness and quality of rock toward the center of the building, significantly greater values of $I_C$ are expected beneath practically all of the building area. Thus, it is expected that within the influence...
zone, there is sufficient thickness of rock cover to contain any roof fall events that may occur in isolated remaining openings.

Through years of observational experience, various "rules of thumb" were developed about the behavior of rock above openings. One of these from the anthracite region is that localized roof fall propagates upward to a distance of three to four times the vein thickness before forming a stable arch, and similar observations are reported from other coal regions (Gray, 1988). Consistent with the No. 11 Vein thickness, such roof collapse would be expected to extend upward for about 20 to 35 ft (6.1 to 10.7 m). Another rule of thumb that is useful in evaluating the potential effects from roof collapse was developed in rock tunneling work where the underground openings are of limited width. Roof collapse was observed to propagate upward until a stable arch developed at a maximum height of one-third to one-half of the opening width (Proctor and White, 1968). For mine opening widths on the order of 25 to 30 ft (7.6 to 9.1 m) in the No. 11 Vein, roof collapse until a stable arch is developed would be expected to extend about 10 to 15 ft (3.8 to 4.6 m) up into the overlying rock. By these criteria, the minimum 50 ft (15.2 m) of rock above the No. 11 Vein is more than sufficient to contain any localized roof collapse within the mapped areas of the influence zone.

The bootleg mining is expected to be significantly older than the documented mining and, accordingly, any roof fall conditions in this area may have long since reached a state of equilibrium. Excavation and/or fill placement is expected for the site development work, and building design and construction measures might be considered to accommodate any potential roof fall conditions that may affect the ground surface.

**Mine Caving**

Somewhat related to roof collapse are mechanisms that follow the caving of mined areas as the result of near total extraction of the coal, primarily by robbing operations in the older anthracite mines. By one mechanistic concept, pieces of roof rock that fall down would be in a disoriented array and bulking of the fallen rock could eventually be equivalent to the volume of the coal removed plus the undisturbed volume of the fallen rock. At this point, a relatively stable equilibrium condition would be expected to develop. By another mechanistic concept, the caved, or rubblized, zone extends to a limited distance above the mined vein, but not to the extent of bulking up to compensate for the thickness of coal removed. To attain equilibrium, the uncaved rock strata then deflect or sag downward and are primarily supported on the caved rock. Some of the borings drilled at this site encountered apparent collapse zones extending about 15 to 21 ft (4.6 to 6.4 m) into the rock above the No. 11 Vein, which would be about 2 to 2.5 times the vein thickness and apparently less than one of the rules of thumb would indicate,
Potholes

The most common present day manifestation of mine subsidence effects in the anthracite region is the development of erosion potholes, typically where the coal veins were mined to a subcrop, the rock outcrop of a coal vein covered by soil. In such situations, the cover soil communicates directly with the mine voids and over time is eroded into the mine void system by surface water or rainwater percolating down through the soil. Potholes also develop where there is a thin cover of rock over older workings in the anthracite region. The occurrences of these mechanisms frequently have appearances similar to the sinkholes that develop in the solutioned limestone regions elsewhere in Pennsylvania.

The historical record and observations indicate potholes on this site associated with the Nos. 11 and 10½ Veins, and there appeared to have been very little change to the configurations and dimensions of these potholes over a period of about 40 years. However, the strip mining pits along the outcrops of these veins may have exposed the underground mining openings and present conditions for erosional pothole development. After the stripping, materials placed into the pits, including new fill for the site development, could be in contact with remnant coal vein openings and susceptible to subsurface erosion. This possibility for pothole development associated with the strip mining pits is believed to be both a present and future condition.

Time Effects

It is expected that equilibrium conditions with respect to most subsidence mechanisms are achieved in a short time span after the active mining. However, subsidence does not always occur contemporaneously with the mining activity. In at least one case study (Newhall and Plein, 1936), some residual ground settlement was noted when monitoring continued after the mining was temporarily discontinued. Some of the surviving mining engineers from the anthracite region have reported observations that delayed subsidence events are usually associated with mining at depths less than 300 ft (91 m) and stabilized conditions are usually attained within seven to ten years after the mining of sufficient extent to cause subsidence. These experiences with residual subsidence are all related to active mining operations.

Mine subsidence events have occurred in regions of abandoned mine workings at times many years after the mining. These are usually described as discrete secondary events that do not appear to be a continuation of subsidence directly related in time to active or recent mining operations. Studies in the Appalachian bituminous region (Gray, 1988) identify both pothole development and trough subsidence and indicate that the frequency of such secondary subsidence decreases with increased time after the mining. Also, the documented secondary subsidence events are usually associated with mine depths generally less than about 150 ft (45.7 m).
It is believed that these secondary events result from continuing changes to the mining and subsurface conditions after the immediate roof collapse and/or strata movements.

The more than 40 years since the cessation of mining at this site is believed to be ample time for equilibrium conditions to be attained. Significant changes to the equilibrium conditions, such as major pumping that would lower the mine pool and increase the pillar stress, are considered to be unlikely. Further, the rock in the northern anthracite area is generally regarded as being reasonably resistant to weathering. Thus, changes that could occur over the passage of time into the future and cause subsidence are believed to be unlikely.

**MINE SUBSUDENCE POTENTIAL**

Any credible subsidence mechanisms are then analyzed further and evaluated for their risk potential to propagate through the rock strata and develop into ground surface subsidence. The previous discussion identified some narrow coal pillars with lower values of stress ratio in the first mined areas of the No. 11 Vein, and areas of potholes on the site. Another area of concern has been identified to the south of the main building line where the “bootleg” mining was performed in the No. 11 Vein.

**Strata Behavior**

One of the most comprehensive investigations of mine subsidence behavior is from the Great Britain coal fields (National Coal Board, 1966 and 1975), where gentle bowl or trough shaped depressions frequently developed, Figure 5. In general, the maximum subsidence at the center of a trough or bowl, as a proportion of the vein thickness, the “subsidence ratio”, increases as the ratio of the mined area width to the vein depth increases. A critical width condition, where further increase in the mined area width does not result in an increase in the subsidence ratio, has parameter values of about 1.4 and 0.95 for the width to depth ratio and the maximum subsidence ratio, respectively. Other modes of ground surface deformation include horizontal tension and compression strains and tilting. Various charts relate the geometric parameters of the mining, such as the width and depth of mining and limited face advance, to the ground surface expressions of mine subsidence, Figures 6 and 7. It is described that these represent "average" conditions in the coal fields of Great Britain and that variation is to be expected. Further, it is pointed out that for specific applications, the charts, etc. should be adjusted where there is local data about subsidence behavior.
Figure 5. Typical Trough Subsidence (National Coal Board, 1975)

Figure 6. Relationship of Subsidence to Width and Depth of Mining (National Coal Board, 1975)
It is to be expected that the British subsidence evaluation procedures may not be directly applicable to the conditions in the United States coal fields. Subsidence monitoring data from active bituminous coal mining in the United States indicated maximum subsidence ratios as low as 0.5 for critical width mining (O’Rourke, et al, 1977). Trough-type subsidence depressions that appeared to be somewhat independent from ground surface topography, and significantly lower values for the subsidence ratio, developed at subcritical width mining (Dahl and Choi, 1975). A review of subsidence experiences in the bituminous regions (Bruhn, et al, 1991) indicated influences of mining method and the rock conditions, especially a decreasing subsidence ratio with increasing proportions of hard to soft rock. Some if this experience (Karmis, et al, 1992) has shown that with overburden consisting of 80 percent hard rock, the maximum subsidence ratio could be less than 0.2. Experience has shown that the sandstone, siltstone, and hard shale rock strata in the anthracite fields have greater strength and are more stable than the rock encountered in the bituminous fields. Thus, any potential subsidence at this site is expected to be substantially less than a prediction from the British procedures.

**Surface Settlement**

The integrity of the first mined areas at present and in the future is expected to depend primarily upon the supporting capability of the remaining pillars. If there are areas of question-
able pillar support, there may be a possibility of future mine subsidence affecting the ground surface. For purposes of analyzing mine subsidence and settlement potential, it is assumed that, if there should be future pillar crushing, areas of the veins where the pillar stress ratios are the lowest would be the most likely to collapse.

As shown on Table 2, the lowest value for the stress ratio from the pillar analyses is 1.33 for the after mining condition at a pillar about five feet (1.5 m) wide that is at about elevation 813 ft (248 m) beneath the north central portion of the building. At the present conditions and after the construction of the proposed facility, this stress ratio value is greater than 1.6. The next higher stress ratios of 1.54 and 1.9 for the after mining condition and present conditions, respectively, were found to be at a seven feet (2.1 m) wide pillar at about elevation 822 ft (251 m) beneath the northwest addition. All of the other calculated stress ratios for the present and after construction conditions are greater than 2.0. It is considered unlikely that there will be changes that will significantly affect the stress ratios of the remaining pillars in the first mined areas of the No. 11 Vein.

As a worst possible case scenario, the ground surface settlement resulting from collapse of the five feet (1.5 m) wide pillar is analyzed. Consistent with the proposed finished ground surface at about elevation 1,032 ft (314 m) the dimensions of this collapse area result in a maximum width to depth, or face advance to depth, ratio of about 0.32, which is at the “low end” of the National Coal Board subsidence estimating procedures. Nevertheless, a settlement estimate is developed by calculating the maximum trough subsidence and then reducing the estimate for the United States experience and the more competent rocks of the anthracite region. The calculation results then indicate a maximum ground surface settlement of less than one inch (2.5 cm). However, considering the dimensions of the assumed collapse area, it is expected that an arch would develop in the approximately 150 ft (45.7 m) of rock cover over the collapse, and there would be negligible ground surface effect. Accordingly, future ground surface settlement due to pillar crushing may not be a significant consideration for most of the proposed building and site development. With the conditions in the bootleg mining area, it may be prudent to consider that there is a possibility of future ground settlement in this area.

**Pothole Development**

Areas of potential pothole development are at the existing potholes to the south of the building location along the subcrops of the Nos. 11 and 10½ Veins and at the strip mining pits. Fill is to be placed at these areas for the parking and access areas to the building, and there is a potential for the fill materials to erode onto the existing potholes or into openings into the mined veins at the bottoms of the strip mining pits. Any potholes that might develop in these areas
would not affect the building, and are expected to be readily repaired. Design and construction measures similar to those used at sites underlain by solutioned limestone and having a potential for sinkhole development would be expected to reduce the potential for pothole development.

SUMMARY OF MINE SUBSIDENCE EVALUATIONS

Evaluation of the mine subsidence potential proceeded through identification and evaluation of the mining conditions and the mechanisms associated with mine subsidence that could potentially be present at this site and affect primarily the proposed building and secondarily the other site features. The No. 12 Vein was concluded to be completely strip mined within the building area and backfilled, leaving conditions that are of concern for foundation support rather than mine subsidence. Historic pothole development and the mechanisms for potential future pothole development, and the bootleg mining area of the No. 11 Vein are located outside of the main building area and in the parking and access areas of the proposed project.

Crushing of remnant coal pillars is usually identified as presenting a potential for future mine subsidence. The remaining coal pillars in the few limited areas of deep mining within the influence zone of the building are in the No. 11 Vein, and these pillars appeared to have adequate supporting capability for the after mining condition. Most of these pillars have increased supporting capability for the present and future conditions due to the flooding of the veins and the excavation for the site development.

As an approach to further evaluating the subsidence potential, it is assumed that if mine subsidence develops, the initial occurrence of such subsidence would be associated with the mechanism(s) having the lowest supporting capability. Accordingly, a “worst case” scenario of vein closure from crushing of pillars with the lowest supporting capability was analyzed, and the consequent ground surface settlement was found to be almost negligible.

It was concluded that there are no credible mechanisms of future mine subsidence potential that could be considered as presenting a sufficient level of risk to make this site unsuitable for the proposed development. Based upon past experience with investigations of numerous abandoned mine sites in the anthracite region, this site compares favorably with many sites that have been developed with confidence and have histories of good performance. As a measure of prudence, remedial design and construction measures were incorporated into isolated areas of the project development.
SITE DEVELOPMENT AND BUILDING DESIGN

In formulating criteria for the site development construction and building design, the mine conditions and subsidence potential were considered together with the geotechnical parameters of the site. Discussions of the significant criteria are summarized herein.

Site Grading

In order to obtain the design finished grades, as much as 60 ft (13.7 m) of excavation will be required in the proposed and future building areas, and fill will be required at the southwest corner of the proposed expansion and in the parking area to the west of the building. Up to 50 ft (15.2 m) of fill will be needed in the area to the north of the building, especially in the No. 11 Vein strip mining trough. To the south of the building, the existing potholes at the No. 11 Vein outcrop and the strip mining trough of the No. 10½ Vein will need to be filled, and then as much as 40 ft (12.2 m) of additional fill be placed.

Primarily soil materials were expected to be within the No.12 Vein strip mining area, and a large volume of rock will be excavated from the surrounding area. With the rock excavation and the possibility of boulders within the No. 12 Vein area, crushing may be necessary to obtain materials that could be readily placed as compacted fill. Based on the laboratory testing results and visual classification, the soil materials consist mainly of silty sand and gravel, but occasional zones with as much as 50% passing No. 200 sieve and significantly higher moisture contents are also expected. Most of these soils were judged to be suitable for use as compacted fill, with the fine-grained soils possibly requiring moisture conditioning. Placing and compacting layers of fill in the confined potholes and strip mining pits could be difficult and time consuming, and careful coordination with the contractor was anticipated to be necessary at these locations.

Foundation Support

Conditions suitable for supporting shallow based foundations were expected in the rock excavation and compacted fill portions of the building area. The remaining uncontrolled fill materials within the No. 12 Vein strip mining area, extending to a maximum depth of 44 ft (13.4 m) below the proposed floor level and having N-values typically in the range of 4 to 12 bpf, are not suitable for supporting building foundations. Several alternates for foundations and improving the fill conditions were considered, and deep dynamic compaction (DDC) was investigated for improving the condition of the strip mine materials for foundation support.

Settlement analyses were performed to back-calculate the minimum soil properties needed for the expected foundation settlement to be within acceptable limits. It was thus determined that the DDC improvement of the strip mine materials should obtain a minimum N-value of 20 bpf within a depth of 30 ft (9.1 m) below floor grade, or to the depth of the strip mine ma-
terials, whichever is shallower. Considering the composition of the strip mine fill, this criterion would apply to materials that are smaller than gravel size. The depth of improvement by DDC would encompass the zone of bearing stress attenuation beneath the shallow foundations, and materials that are not improved may exist below this depth. Any settlement resulting from compression of these deeper existing materials was not expected to be significant because of the preloading effect of the approximately 30 ft (9.1 m) of strip mine fill that will be removed for the site grading. The improvement criterion was compared to published experience with DDC (Lukas, 1995) and found to be a realistic expectation with drop weights in the range of 16 to 20 tons (142 to 178 kN) and drop heights of about 80 ft (24.4 m). The DDC was first performed in test areas and the improvement results evaluated through test borings and N-value testing.

**Building Foundations**

The site grading and the DDC site improvement will result in conditions suitable for supporting conventional shallow based foundations throughout the warehouse area, including the future additions. A “worst case” evaluation of credible mine subsidence mechanisms indicated a potential for small areas within the future additions to experience subsidence on the order of the magnitude of foundation settlement that the proposed structures could tolerate. Accordingly, it was determined that building design measures to accommodate a potential mine subsidence event within the warehouse area were not required.

The building extensions from the south of the proposed warehouse building line are in the area of the No. 11 Vein bootleg mining, and the rock cover is estimated to be less than 50 to 60 ft (15.2 to 18.3 m). Considering the operational importance of these buildings and the uncertainties associated with the bootleg mining, continuous foundations with structural spanning capability were recommended as a measure of prudence.

**Pothole Prevention**

Various design and construction measures were recommended to minimize the risk of potholes developing during and after construction in the parking areas along the outcrops of No.11 and No.10½ Veins. The common theme of the various measures was to prevent water from percolating into the subsoils. During construction, the site grading should be conducted to promote drainage and avoid depressions that could accumulate rainwater. Storm drain systems in the vicinities of the outcrops should be designed and constructed with sealed joints to prevent water leakage. The pavement in the vicinities of the outcrops should be constructed with a dense graded asphalt aggregate mix to minimize infiltration.
CONSTRUCTION

The site development construction required about one million cubic yards (765,000 m$^3$) of materials to be excavated and placed as compacted fill, and deep dynamic compaction of an area of approximately 140,000 ft$^2$ (13,000 m$^2$). These components of the construction are described briefly below:

**Fill And Compaction**

The fill material generated from the on-site excavation generally consisted of a mixture of cobble to boulder-sized rock fragments, gravel, sand, and silt and it would be impractical to use the traditional laboratory compaction test as a control of field compaction quality. Therefore, a method procedure was developed through a test pad at the site. It was determined that using a 70,000 lb (311 kN) segmented pad roller with four passes on each lift, followed by four additional passes using a 10 ton (89 kN) heavy vibratory roller would produce a well-compacted, dense graded soil and rock mixture when the lift thickness is generally limited to 2 ft (60 cm). No yielding of the compacted material was observed when proofrolled using a 100 ton (890 kN) fully loaded dump truck. This method was used throughout the project successfully.

It was found that the blasting pattern used by the contractor for the rock excavation produced almost thorough fragmentation of the rock. There were only a small number of oversize boulders that were segregated out and then carefully embedded in compacted fill in the less critical areas of the project.

**Deep Dynamic Compaction**

The building area was excavated to a rough grade of about two feet (60 cm) below design subgrade, and the plan limits of the strip-mined area of the No. 12 Vein were defined by excavating a series of test pits. A minimum energy per drop was specified in order to produce a minimum N-value of 20 bpf to a depth of 30 ft (9.1 m) below the floor grade. Based on past experience, the contractor proposed to use a 16 ton (142 kN) weight dropping 65 ft (20 m) on primary and secondary pass grids of 13 ft (4 m) on centers.

A test pad of approximately 100 ft (30 m) square was first compacted to evaluate the DDC procedures. Measurements of incremental settlement were performed at selected drop locations to determine the optimum number of drops. It was determined that the increase in the crater depths tended to level off after six to eight drops, and six drops per point were subsequently used for the remaining test pad area. The DDC resulted in the grade of the test pad being lowered by about 1.5 ft (45 cm). Three test borings were drilled at selected locations in the test pad area, and one of these borings indicated N-values of less than 20 bpf in the range of 15 to 20 ft (4.4 to 6.0 m) below the ground surface. Subsequently, a 20 ton (178 kN) weight was brought...
to the site to re-compact the area. Following the primary and secondary passes, the near surface soils were compacted by an ironing pass with weight drops on an overlapping grid.

The effectiveness of the DDC throughout the building area was evaluated by a drilling a test boring at about each 7,500 ft² (700 m²) of the treated area, with the boring locations typically being where the craters were the deepest. A total of 22 test borings were thus drilled, and generally demonstrated that the existing fill was adequately improved by the DDC, as indicated in

![Figure 8. SPT Values Before and After DDC Treatment](image)

At the western end of the DDC treated area, some crater depths were significantly deeper than in other areas and severe heaving of the soils around the craters was observed. Laboratory testing of samples taken from the test borings drilled in this area indicated that the soils consisted of generally dark gray/black sandy silt/silty sand with coal and rock fragments, and with moisture contents of 19 to 30 percent. These results are similar to the boring and laboratory test results that were obtained from this area during the investigation. A comparison of the gradation
of the soils with the FHWA classification of treatable soils using DDC (Lucus, 1995) and other experience (Rollins, et. al., 1998, and Lukas, 1999) indicates that the soils are marginal for DDC to be effective. It was determined that improving the soils in this area by DDC would not be feasible. This area was then undercut to a depth of approximately 15 ft (94.5 m) and replaced with soil and rock fill materials that were compacted in layers.

On average, the ground surface after DDC was lowered by approximately 1.5 to 2.0 ft (45 to 60 cm). The entire DDC treated area was proofrolled to further densify the shallow depth soils and to detect any soft areas at the surface. Structural fill was then placed to bring the building area to the proposed subgrade levels.

SUMMARY

A thorough geotechnical investigation was performed for a proposed site development at a former anthracite mining site. Different investigation measures provided an efficient and cost effective solution for this site with complex subsurface coal mining and geotechnical conditions. These measures consisted of traditional testing borings, air-track drilling, down-hole video logging, and electrical resistivity imaging. Historical mining information is invaluable in evaluating subsurface conditions in abandoned and/or active mining sites. After performing detailed analyses, it was concluded that there are no credible mechanisms of future mine subsidence potential that could be considered as presenting a sufficient level of risk to make this site unsuitable for the proposed development. DDC was successfully utilized in improving the existing strip mine fill so that economical shallow foundations are suitable for the building.

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