PROTECTION MEASURES AGAINST MINE SUBSIDENCE TAKEN AT A BUILDING SITE[1]

by

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Abstract. With little mining information old abandoned coal workings were grouted beneath a proposed building site. Mine stabilization was found necessary after an investigation of subsidence potential was performed. The investigation indicated that the 220 ft deep abandoned mine, although old, still had not collapsed and consequently presented a significant risk of subsidence in the future. Furthermore, based on the history of subsidence over old mines in the area, mine grouting was recommended.

To stabilize the mine, about 15,000 cy of grout were pumped. The grouting was designed to account for the significant amount of rubble which existed in the mine. Permeation, squeeze (or intrusion) and compaction grouting was performed per the project specifications. Also, to economize on the amount of grouting necessary, subsidence resistant features were incorporated into the design of the building.

Introduction

This paper describes an engineering project involving the investigation, design and application of subsidence mitigation measures at a building site. The proposed building is for housing the Illinois Department of Natural Resources at the State Fairgrounds in Springfield, Illinois. The site for this new building was found, however, to be undermined. Because the site is undermined both shallow and deep subsurface investigations of subsurface conditions were required. The work consisted of the following objectives: investigate subsurface conditions as they relate to foundation design as well as at mine level; determine the potential for mine subsidence at the site; and determine and recommend the appropriate remedial measures including foundation design considering any potential effect from future mine subsidence movement.

The site for the new DNR building is located in the northwest part of the State Fairgrounds in Springfield, IL. The building is about 120 ft wide and 440 ft long and has 3 stories above grade with a basement level. As shown in Figure 1 the building is oriented appropriately north-south and will have east and west ponds on both sides. The proposed location of the building foundation represents a cut and fill situation with cuts in the north up to about 25 ft and in the south up to about 15 ft and fill at the ponds as high as about 15 ft. The basement floor level is designed to be 3 ft above the pond levels.

In this paper information is presented on the geologic and geotechnical site conditions, the mining conditions, the potential subsidence, the shallow foundation measures taken, mine grouting design, grout performance, and lastly the summary and conclusions.

Geologic Conditions

The objectives of the predesign exploration program were to assess: the shallow foundation conditions; the rock overburden conditions; the presence of any subsidence features; and the mine conditions. A total of 24 borings were performed with 15 soil borings and are shown on Figure 2. The soil borings were 12 to 40 ft deep with 9 bored into the bedrock (i.e., "B" holes.) The soil borings drilled to 12 ft were called "SB". The nine deep borings were drilled through the mine interval. The deep borings are called SD-1 through SD-9 and are also located on Figure 2. These deep borings were drilled to total depths of 217 to 250 ft and into the mine

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floor from 7.5 to 23 ft. After the drilling was completed 5 holes were surveyed with a borehole camera.

A geologic cross-section through the site (depicting only the deep borings) is shown in Figure 3. The soil present above the rock consists of primarily loess overlying glacial till which rests directly on the bedrock surface. The till is generally fine grained, sandy in places, contains wet sandy pockets several feet thick, and an occasional boulder. Locally some surfacial fine grained fill soils are present. Based on the site specific subsurface drilling, the bedrock is 16 to 34 ft below the ground surface at the project. The site is located within the Illinois Basin, a structural geologic feature which exists in western Indiana and northwestern Kentucky as well as throughout most of Illinois.

As can be seen in Figure 3 there were three coal beds intersected by the project borings. They are in descending order Danville No. 7 Coal, the Herrin No. 6 Coal, and the mined-out Springfield No. 5 Coal. Where present, the Danville No. 7 Coal was found generally at Elevation 540 ft (or from about 20 to 45 ft below the ground surface). The bed thickness ranged up to 1.6 ft, but appeared to be absent in places. The rock cover above the No. 7 Coal elevation (where present) consisted of up to about 15 ft of carbonaceous to silty to clayey shale. The Herrin No. 6 Coal Bed was found at elevations of about 400 - 410 ft (or 150 to 180 ft below the ground surface) with bed thickness up to 3.2 ft where present.

The rock interval between the No. 7 and No. 6 Coal is approximately 135 ft thick. The majority of this rock consists of clayey shale with beds of silty shale as the second largest constituent. The remaining 2 to 7% of this rock interval consists of coal, limestone, siltstone, and carbonaceous shale beds.

The rock interval between the No. 6 and No. 5 Coals was found to be about 45 - 55 ft thick. In general, this rock interval appeared siltier and harder than the rock material between the No. 7 and No. 6 Beds. Where mine roof caving had not interrupted this coal measure interval the makeup of the silty shale to siltstone ranged from 53 to 65% (60% ave.) while the clayey shale was only 17 to 31% (21.7% ave.) Generally, the rock sequence between the No. 6 and No. 5 Coals in descending order consisted of clayey shale, silty shale-siltstone, limestone and then carbonaceous shale immediately above the No. 5 bed. The limestone at the project site is fairly thin to nonexistent with a thickness of up to only about 1 ft. The black carbonaceous shale immediately above the Springfield Coal, however, appears to be continuous with a thickness ranging from 3.0 to 3.5 ft. The main immediate roof unit above the No. 5 Coal is silty shale to siltstone. Facies within this unit grade both vertically and horizontally with no known pattern. The more shaley sections of this unit are evident by lower strength, greater fissility and pitting in the rock core.

The No. 5 Coal is the mined out coal bed at the project site. The Springfield Coal was generally between 4.5 to 5.5 ft thick and was found at its base at an elevation of 350 - 360 ft or at a depth from about 190 to 225 ft below the ground surface. The bottom of the coal bed is locally shaley. Based on the project boring information and the mine floor elevations noted on the available mine maps in the area, the project site is located at the base of a localized coal basin with the lowest elevation of 350 ft.

During the exploration phase of the work a horseback was encountered in the immediate roof and No. 5 Coal bed in Boring SD-8. (Horsebacks are more or less irregular and branch fissures filled with clay or shale which extend downward from the roof into or through the coal bed.) Horsebacks or clastic dikes in the Springfield Coal bed tend to have some verticality but are reported to show no regularity of spacing or of direction. In some mines they can be 40 to 60 ft apart; in others they are spaced 200 to 400 ft or more apart. These clastic dikes also trend in various direction even in the same mine (Cady, 1921 and Smith et al, 1970). Also, areas which contain horsebacks in the coal were typically avoided (not mined) by miners because of the instability problems they present (Young, 1916).

The strata immediately beneath the No. 5 Coal appears to vary considerably even within the confines of the project site. These materials varied from a clayey shale to a silty shale to a limey siltstone. Where the immediate floor consists of clayey shale or claystone the rock generally becomes coarser grained with depth. These beds were also found to vary in hardness from very soft and friable with low to no core recovery to hard. At about 7 up to 11 ft below the No. 5 Coal, however, a 0.6 to 1.4 ft thick limestone bed was consistently found (see Figure 3).

Mine Conditions

Mining History

Beneath the building site the Springfield No. 5 Coal Bed was mined at depths of 190 to 225 ft by the room and pillar panel method. This room and pillar mine, which changed hands several times, was known as the Panther Creek No. 5 Mine and was operated from 1875 to 1952. The maps available indicate the portion of the mine which exists beneath the site was probably worked before 1929 (at least 70 years ago).

Mine Geometry

It is important to note that in the area of the site only the location of the mains and the submains (main tunnels) were depicted on the available mine maps and are shown on Figure 2. In other words, no maps were available which depict the production mine workings, but although not depicted on Figure 2, areas on both sides of the mains have been worked out. Because of the layout of the cross-mains the rooms in the panel areas (i.e., areas between cross-mains) probably have a north-south trend.

The mine map shows the mains and cross-mains below the site measure to have rooms, cross-cuts, and central pillars 15, 12 and 20 ft wide, respectively. The cross-cuts are spaced about 60-70 ft apart. On the final map of the Panther Creek No. 5 Mine dated 1952 the mining notes indicate that the extraction ratio within the panel area can be expected to be on the order of 65%. Also important is the stated presence of 30 ft solid barrier pillars on both sides of all main entries (or mains). This statement would appear to apply to north-south trending mains in the middle third of the site (see Figure 2). When discussing the Springfield mining district Young (1916) noted, however, that barriers and pillars can be gouged.

Mine Interval Observations

Based on the investigation of the geotechnical and mining conditions related to stability, the mine workings subjacent to the site do not appear to be collapsed. Except for localized caving in the mine rooms, the rock overburden was found to have remained intact. Because the underground mine workings have not failed there is a risk that significant surface subsidence movement could result in the future. The most likely mode of failure would be insufficient floor bearing capacity as a result of floor deterioration. A major cause of floor deterioration is the softening effect of water on undurable rocks such as the clayey shale floor (Marino and Choi, 1999).

Evidence from drilling indicated significant floor deterioration has probably occurred but only to a depth of about 2-2.5 ft with some effect from pooling of water. About 1.7 to 2.6 ft of the immediate clayey shale floor was lost when coring was done in rooms while under pillars 100 percent recovery was obtained. It is interesting to note, however, that less core appears to be missing where the immediate floor consisted of silty shale.

The stoping (or caving) of the roof above rooms in the mine appear to be in various stages of development. Depending upon the location, little to significant rubble was encountered at the drilled sites. Where significant accumulations of cave were present a clear void of only about 0.5 - 1 ft was found at the top. In general, the effects of stoping were found up to about 30 ft into the mine roof (but were as high as 40 ft).

Mine Subsidence Potential

Pit subsidence results when the entire thickness of rock above an individual mine room collapses causing the soil above to fall into the ground surface. Because of this failure mechanism and the site conditions, a pit or sink hole-type subsidence is extremely unlikely. Bauer and Hunt (1981) report pits up to only mine depths of 165 ft. Furthermore, stoping above mine rooms appears only about 30 ft into the 160 ft thick rock overburden.

Future sag subsidence was a serious risk at the project site. Sag subsidence results from a massive collapse of the soil and rock overburden from an underlying area of pillar failure as well as floor or roof bearing failure. Based on the site conditions the most likely mode of failure would be a floor failure or a pillar failure induced by floor yielding. Marino and Bauer (1989) found from numerous case histories that for the Illinois coal mines the long term no risk bearing pressure was about 300 psi. Using a mine depth of 220 ft and the estimated extraction ratio of 65%, the average pillar bearing pressure is 690 psi which far exceeds the no risk limit of 300 psi. Also there have been recent severe subsidence events over these older abandoned mines in the same coal bed in Springfield.

The maximum subsidence can be derived from the modified subsidence factor, SF', which is defined as:

$$SF' = \frac{S_{max}}{He} \tag{1}$$

where S_{max} = maximum subsidence
H = extraction height (assumed at 5.3 ft)
e = extraction ratio (assumed at 0.65)

Based on some assumptions, empirical data, and the above equation, S_{max} is 2.8 ft. The empirical data was taken from sag subsidence-related measurements that have been collected over room-and-pillar mines in the Illinois Basin (Hunt, 1980; Bauer and Hunt, 1981; Marino, 1985; Marino and Bauer, 1989; and project files). Given the S_{max} value, the maximum slope and maximum profile curvature can be determined from empirical data.

If no mine stabilization is done the proposed building would need to be made resistant against subsidence potential. In determining the potential subsidence conditions the worst case scenario was assumed because the detailed mine layout is not known. In the worst case assumption the mine workings remain an undetermined factor, the sizes, shapes, and sequences of potential areas of mine collapses are undetermined.

Foundation Measures

The design system constructed to mitigate the potential subsidence movements involves the consideration and integration of a number of areas of engineering from mining to geotechnical to structural to architectural. This becomes evident realizing the significant factors that must be assessed.

- mine stability and nature of existing mine conditions,
- ground stabilization alternatives,
- specific nature of subsidence ground movement,
- subsoil reaction to ground movement and the foundation loading,
- structural response of the foundation,
- structural and architectural response of building and its appurtenances.

Combined with ingenuity, the greater the integration and understanding of these various factors, the more efficient and the less conservative the rendered design.

Given the subsidence potential, severe to catastrophic damage could result to the proposed DNR building. To avoid such an occurrence, measures to mitigate or abate subsidence are necessary. Mitigation measures which can be taken range from mine stabilization to resistant foundation construction to resistant superstructure construction. However, because of the level of potential movement and the nature of the building, simply providing resistant foundation and superstructure construction would not be acceptable in this case.

The most effective means to mitigate the building's exposure to subsidence would be to stabilize the subjacent mine area by grouting the mine voids. Mine grouting fundamentally mitigates the subsidence potential in three ways: 1. Merely filling the mine voids with grout essentially reduces the collapsible mine height; 2. Significant support is provided against failure by confining the roof, pillar and floor with grout; and 3. Coal measure materials susceptible to air-water breakdown in the mine are sealed to reduce deterioration.

The subjacent mine area which can affect the building footprint by mine subsidence is called the shadow area. The shadow area is determined by extending at some influence angle to mine level the surface area which must be supported (see Figure 4). If the influence angle equals the angle of draw and the entire shadow area was adequately grouted then by definition no subsidence would be realized by the supported structure. However, grouting a shadow area equal to a draw angle of 30° or more may not be as cost effective as using a lesser influence angle of 15° and implementing subsidence resistant features in the design of the building. It should be noted that extending the shadow area to conform to a 30° influence angle would increase the shadow area about two fold.

Also, the building footprint was positioned over the main north-south entries below the site. The available mining information shows 30 ft barrier pillars are present on both sides of these main entries. By locating the building within this area the volume of injected grout needed will be less compared to the higher extraction areas to the east and west. Furthermore, solid coal areas present less mine stability risk and probably less room collapse areas which are more difficult to grout.

Because the proposed building was structurally flexible the exposure to potential fringe subsidence effects could be handled by designing the foundation to be resistant to tensile ground movement. The foundation scheme used to resist any of such outward lateral movement is shown in Figure 5.

Mine Grouting

Based on a site investigation and subsequent analysis of the results it was determined that the best solution would be to combine foundation resistant features to the building as given above with deep mine grouting. By doing this, the area of grouting was reduced to half the necessary volume resulting in a savings of 1.5 million dollars. Grouting costs were further reduced by positioning the building over and adjacent to an expected lower excavation area.

To provide a cost-effective grouting plan, detailed drilling and borehole camera work was done in order to adequately identify the range of mine void conditions. The grouting of the 220 ft deep mine was found to present a unique problem. The exploration results indicated the mine contained extensive piles of loose fallen roof debris on the mine floor up to 30 ft. high. These piles of roof debris consisted of large rock slabs to rock which had deteriorated to a soil consistency. Needless to say, this loose and softened debris, containing very coarse to fine particles, could not be relied upon to provide any overburden support. In other words, merely filling the more accessible mine voids with grout would not provide enough support against mine collapse.

By combining primary, secondary, and then tertiary grouting procedures with the use of appropriate grout mixes and the specified high grout pressures, the required grouted condition was achieved. This resulted in squeeze and compaction of the rubble while also maximizing permeation. Figure 6 shows the actual locations of the grout holes and grout quantities.

The specified (low-shrink) grouts had a wide range of flowability ranging from efflux flow rate of 30 to 40 seconds to a 4 inch slump with a minimum grout strength of 250 psi required. Table 1 shows the proportions of different mixes used in the project. A Type D set retarder additive was also specified. Performance specs were used in order to allow the contractor to design their own mixes and provide the most economic in-place grout costs. The mix used was determined in the field on a hole to hole basis using previous grouting results, void-rubble conditions from drilling and MEA borehole camera results, and the grouting stage (i.e. perimeter versus infill grouting and if primary, secondary, or tertiary injection). The grout pump specified was capable of pumping 70 yd^3/hr and achieving pressures over 1000 psi. Grouting of any hole was terminated after achieving refusal within the mine void interval. Refusal was defined as achieving a pressure of at least 800 psi and pumping at a rate of less than 0.5 cu. ft. over a period of 5 minutes.

Hole to hole grout flow was monitored by measuring changes in electrical resistance at mine level. Grout return has a distinct electrical resistance. Grout detection in open drill holes allowed these holes to be water-flushed prior to the grout setting up and eliminated redrilling of those holes. Also a meter was manufactured to conveniently measure the cross-hole resistivity. Using these measurements an indication of presence of solid coal, grouted rubble or an open mine void can be obtained (see Figure 7). Probably the most important feature of this cross-hole work is the ability to assess solid coal between the holes especially in older mines. Even if available, older mine maps typically do not show the proper pillar locations. Note on this project only main haulways are shown (see Figure 2). With cross-hole solid coal measurements unnecessary injection holes can be eliminated. Also more confidence can be obtained in the layout of pillars and consequently in the grouting results.

Overall the grouting beneath the building was first carried out on the perimeter followed by infill grouting. A total of 328 grout holes were drilled over 200 feet deep. This was about 20% less than anticipated. The project took 14,940 cy of grout which is close to the estimated quantity of 14,760 cy despite having incomplete mining geometries and having to account for the significant amount of rubble in the mine.

Summary and Conclusions

This paper summarizes the investigation, design and performance of measures taken for a building proposed over a mined-out area. Old mine maps show the entire project site is undermined. The mine exists about 210 ft below the ground surface and was called the Panther No. 5 Mine. The mine extracted coal from the Springfield No. 5 Coal Bed from 1875 to 1952. Based on the subsurface information obtained the mine is not collapsed but has caved up to about 30 ft into the roof. Also, mine collapse at some time in the future is possible. The most probable mode of failure would be by yielding of the mine floor from deterioration. Significant floor deterioration occurs as a result of material softening from exposure to mine water. Our investigation revealed the mine is not flooded but probably contains small pockets of pooled water on the mine floor. Empirical data indicates the maximum subsidence (probable worst case) which could occur at the site is 2.8 ft. Further, because the building can not be positioned over solid coal areas it could be exposed to the entire range of associated subsidence movement.

To mitigate building subsidence mine grouting was done within a shadow area defined by an influence angle of 15°. However, mine collapse adjacent to the grouted shadow area could still result in some subsidence in the supported surface area. These limited movements, which could occur under this scenario, were taken under consideration in the design of the building.

With detailed borehole logs, camera work, grout pump requirements and the grout scheme the desired grouted condition was achieved. The use of proper mixes guaranteed better flowability and maximum penetration as well as mine rubble compaction. Electrical resistivity measurements were implemented to minimize redrilling of holes by monitoring the holes neighboring the hole being grouted. If the grout was detected in a hole, the hole was flushed with water to keep it open.

The total amount of grout pumped on this project was 14,940 cy (14,760 cy was estimated). The number of grout holes drilled was 328 and was about 20% below the estimate.

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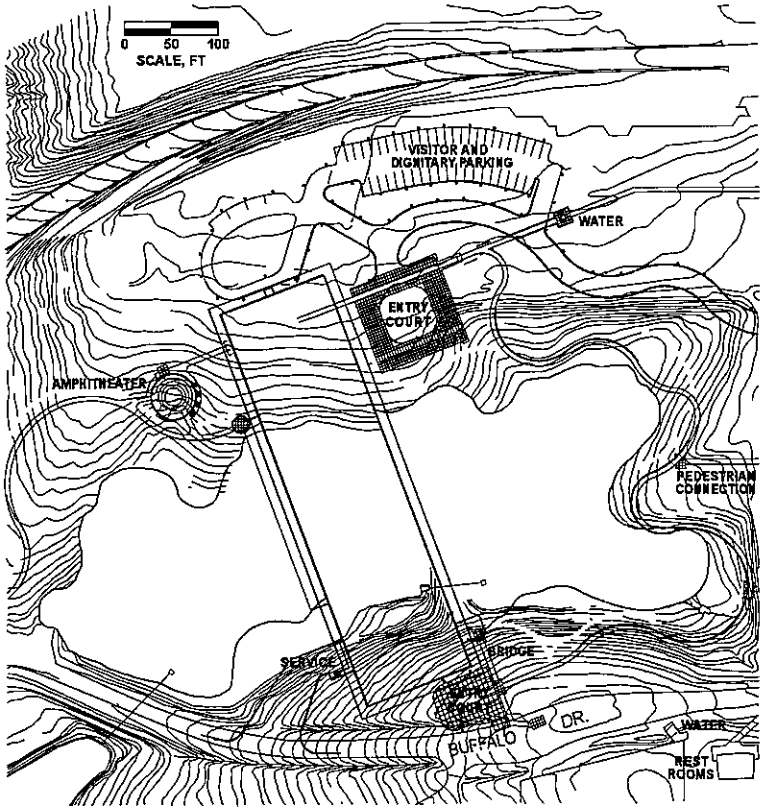

Figure 1. Proposed Building Site Plan.

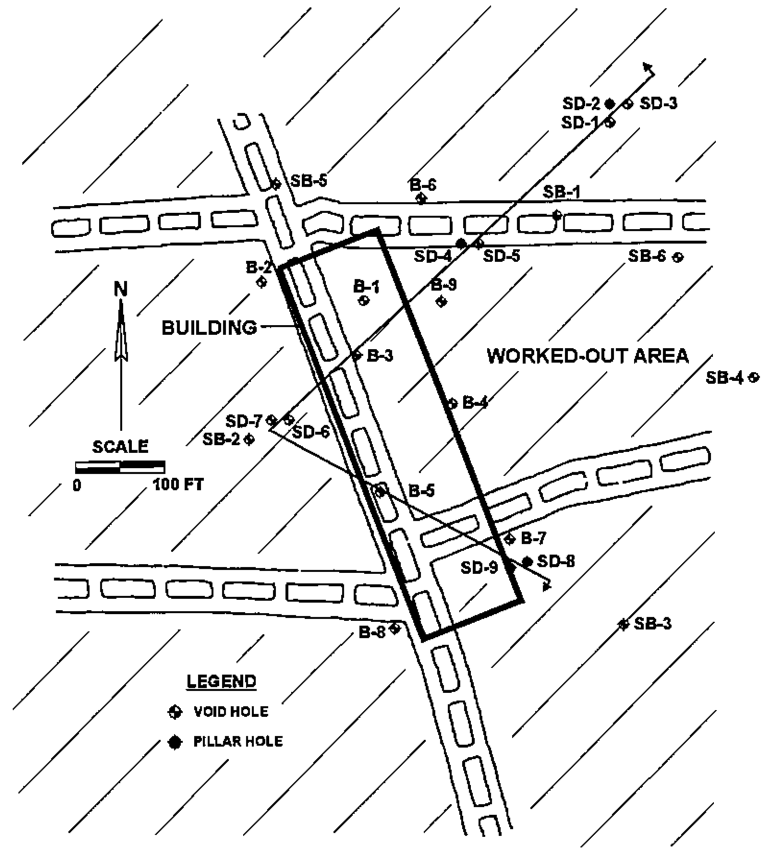

Figure 2. Shallow and Deep Borings
and Mining on Site Location Plan.

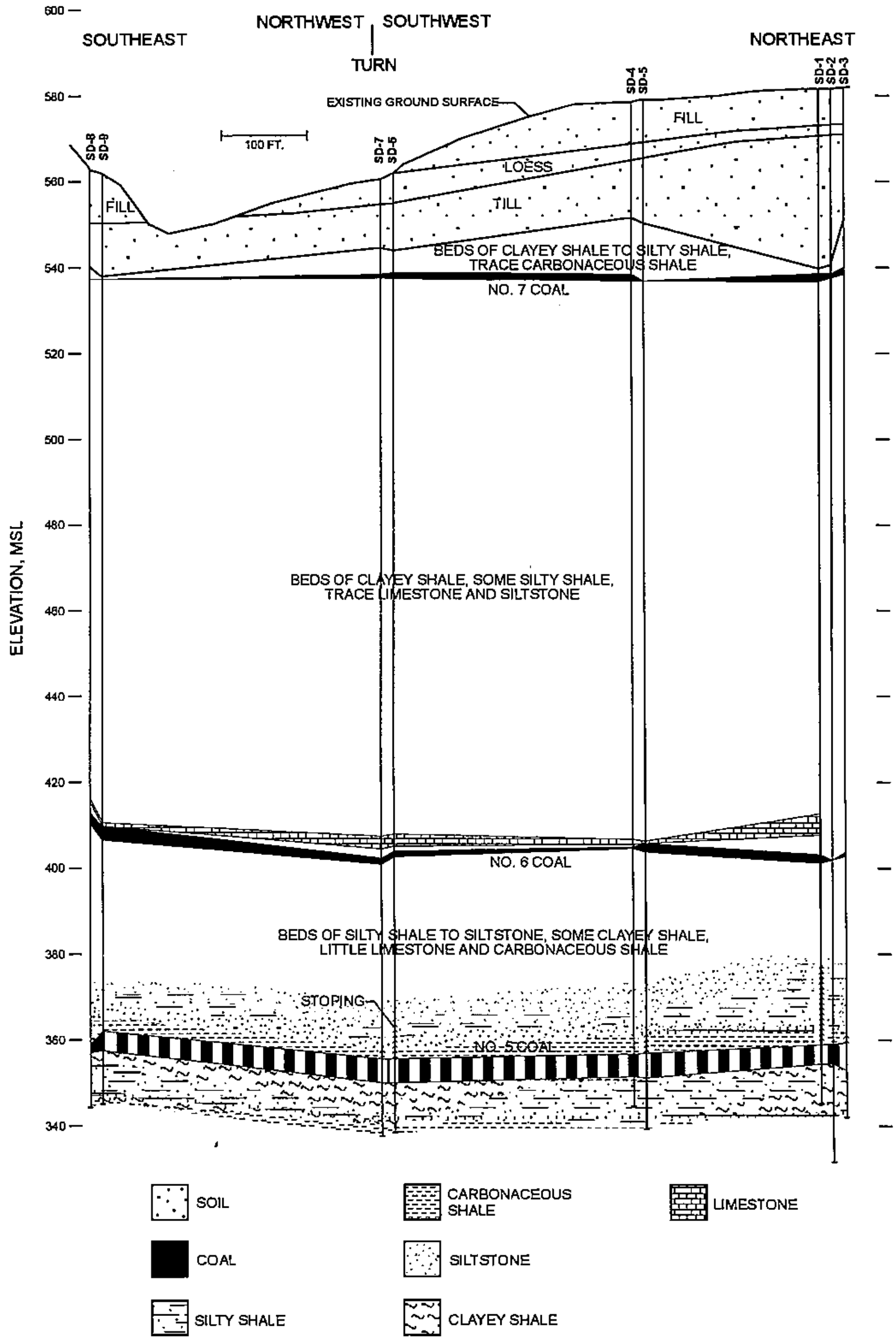

Figure 3. Geologic Cross-Section Across Site.

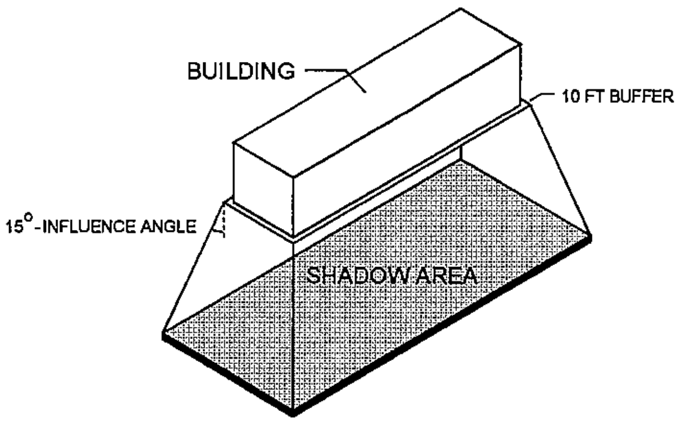

Figure 4. Sketch Depicting the Shadow Area at Mine Level Beneath a Building.

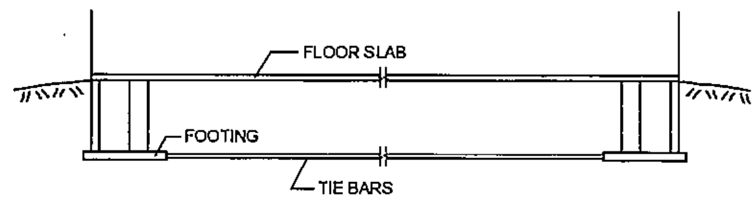

Figure 5. Cross-Section of Foundation Scheme Used to Resist Lateral But Limited Subsidence Ground Movements.

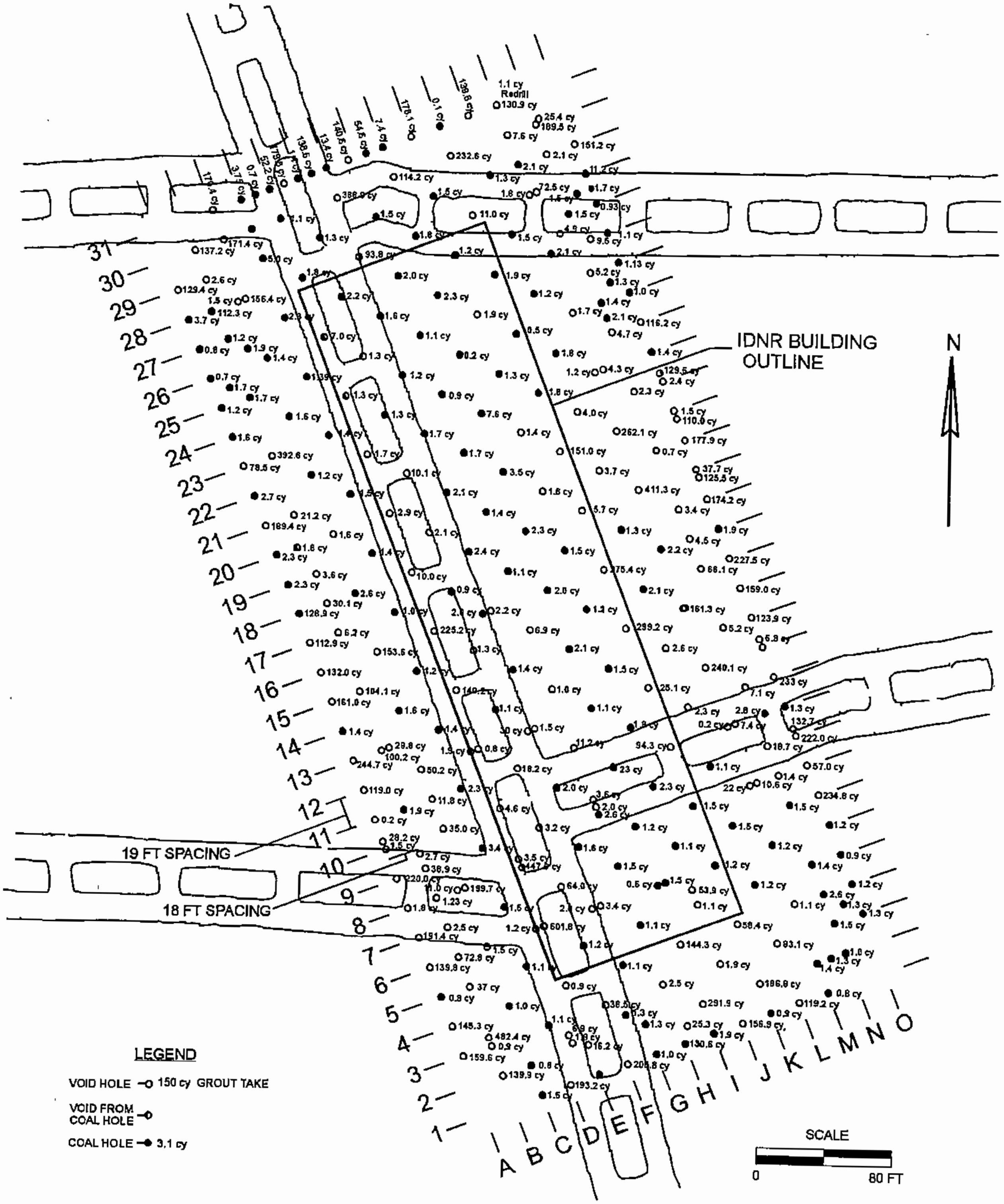

Figure 6. Plan of Grout Holes and Cubic Yards Injected into the Mine.

Table 1. Grout Mixes with Flowability Characteristics.

Mix Type	Cement (lbs)	Fly ash	Sand (10% moisture)	Water added (gallons)	Initial flow (sec)	30 Min flow (sec)	60 Min flow (sec)	120 Min flow (sec)
A	10	90	100	3.5	30 (flow cone)	38 (flow cone)	43 (flow cone)	60 (flow cone)
B	10	90	200	3.25	6.5" (slump)	6.25" (slump)	5.5" (slump)	5.25" (slump)
C	20	180	400	5.8	3.75" (slump)	3.75 (slump)	4.00" (slump)	3.50" (slump)

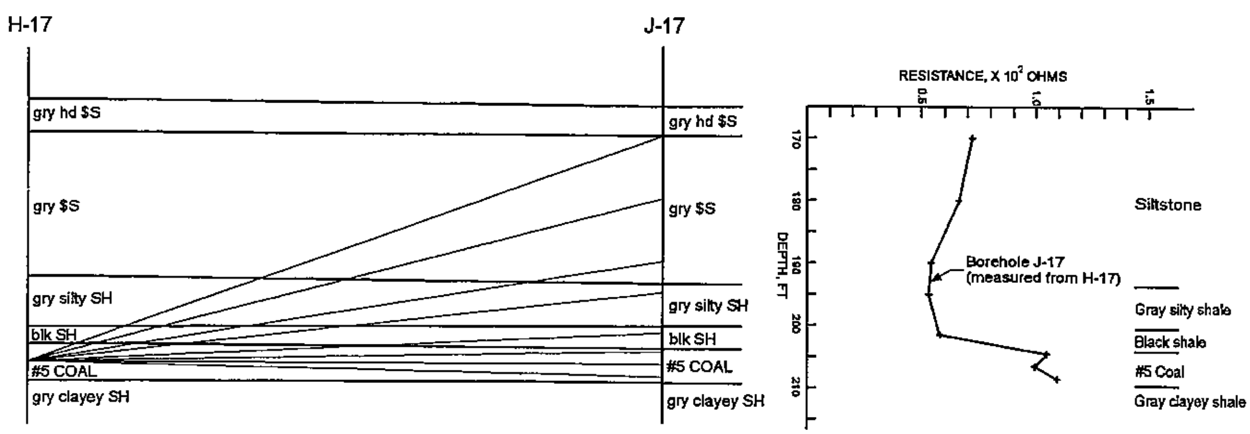

Figure 7. Cross-Hole Electrical Resistance Measurements Across Solid Coal.