

LONG-TERM FLOOR STABILITY OF AN INDIANA COAL MINE¹

by

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Abstract. For interstate pipelines long-term land support is a vital concern. Proper analysis and mine planning can be used to prevent subsidence damage. As a result a geotechnical investigation was conducted to assess the long-term stability of a room and pillar coal mine below an existing pipeline. The study site was the Illinois Coal Basin. The geotechnical investigation involved subsurface drilling, laboratory testing, and subsequent analyses. The critical stability condition was evaluated to be related to the deterioration and reduction of strength of the rocks in the mine floor. The results of this investigation of the mine floor are given in this paper.

Key words: Mine Subsidence, Floor Stability, Mine Stability, Long-Term Strength

Introduction

U. S. coal reserves unfortunately exist below gas or petroleum product distribution and transmission pipelines. This scenario is problematic as underground mining of coal reserves results in exposure of the pipeline to ground movement (subsidence) as a result of mining. These coal reserves are present from tens to thousands of feet below the ground surface over flat to mountainous terrain. An area of mining which could affect the pipeline or surface structure is called the Zone of Influence (see Figure 1). It is defined by the limits to be protected on the ground surface and some influence angle. Obviously, the larger the angle used the more conservative or less chance mining outside the Zone could affect the pipeline.

This paper relates to an investigation performed on the mine floor conditions under a pipeline in the Illinois Coal Basin. The purpose of this investigation was to assess the stability of the mine floor which supports the pipeline in question. Presented in the following sections

of this paper are the general background of the problem, scope of our investigation, a summary of the mine floor conditions encountered, an analysis of short-term as well as long-term stability of the floor, and finally a section on the summary and conclusions.

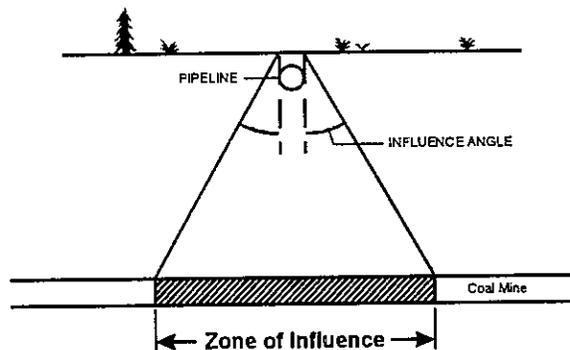


Figure 1. Definition Of The Zone Of Influence

Scope of the Investigation

Three borings (called AM-1, AM-2, and AM-3) were drilled along the pipeline in an area where future mining is planned. The location of these holes relative to the pipeline and proposed mine workings is shown on Figure 2. The holes were drilled to a depth of 84 m (275 ft) to 95 m (310 ft) and to about 6 m (20 ft) below the mined-out Danville No. 7 Coal. The drilling was done with mud rotary to about the middle of the No. 7 Coal

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whereupon 8 cm (3 in.) continuous core was taken to the bottom of the hole. Each core run was photographed, visually described, and measured for recovery and Rock Quality Designation (RQD). Where possible, the RQD was determined for each rock unit. In the lab, the rock core was reclassified and samples were selected for laboratory testing.

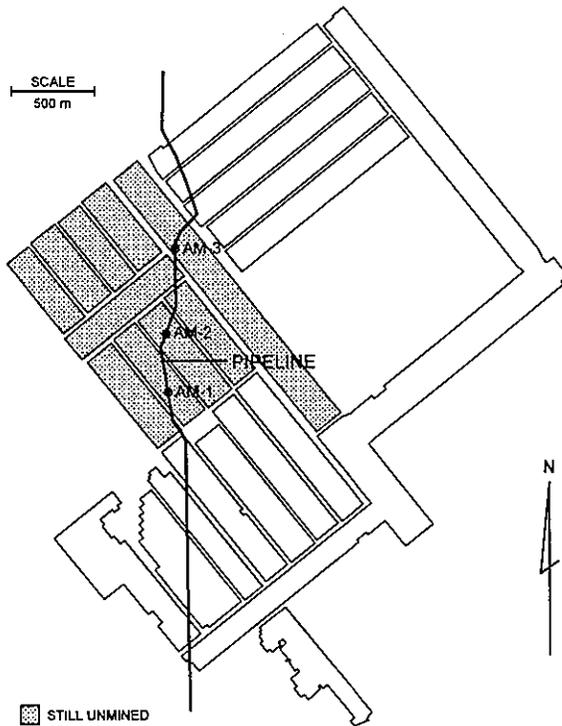


Figure 2. Boring Location Plan

Rock moisture contents were performed on the entire core at about one foot intervals. To assess the rock plasticity, Atterberg limits were done on air slaked and pulverized (ASTM D421) samples of the non-durable immediate shale floor. Slake durability tests were run on the immediate floor and on lower but harder rocks. The drilling and laboratory results were used to evaluate mine floor stability at each boring location. A global study was then performed by making certain assumptions and then combining the information gathered in this investigation with other data available on the mine.

Mine Floor Conditions

Floor Profile

The floor immediately below the mined-out Danville No. 7 Coal was found to be a light to dark gray silty shale at all three borehole locations (Borings AM-1, AM-2, and AM-3). Using the AASHTO classification, this rock unit

is soft to moderately hard (AASHTO, 1988) and can be also locally clayey, sandy, and fissile. Hole-to-hole, this silty shale unit contains localized to frequent slickensides with the natural fracture frequency resulting in RQD values of 38 to 77%. (Note that non-durable but intact rock was considered sound when RQD was measured.) The core recovery across this unit was 100%. This silty shale had natural moisture contents ranging from 6.5 to 9.8%.

At a depth of 1 m (3.7 ft) to 2 m (5.3 ft) below the coal seam (or into the mine floor) the rock becomes calcareous and generally harder. This 3 m (10.8 ft) to 4 m (11.5 ft) thick calcareous (or limey) harder zone consists of a gray silty to sandy silty shale and can have about 0.6 m (2 ft) of light gray fine grained sandstone at the bottom. Also, this rock interval generally becomes harder with depth and ranges from moderately hard to very hard. In most of the core there was only an occasional slickenside which is reflected in the measured RQD in the zone of 60 to 100% with an average value of 86%. In two of the three holes some portion of the shale in the calcareous zone can be, however, heavily fractured and contain slickensides resulting in RQD values of 13 and 53%. Core recovery within this zone was 100%. The calcareous shales had moisture contents ranging from 4.0 to 9.3%.

At about 5 m (15 ft) below the No. 7 Coal (and immediately following the calcareous zone) a very soft to moderately hard silty to sandy silty shale with some clayey shale is present. The shale is fissile in most places, heavily fractured, with frequent to isolated slickensides. The significant fracturing is consistent with the measured RQD values of 10, 33 and 55%. Core recovery was 74 to 100%. The shales had moisture contents ranging from 5.9 to 12.5%. This shale stratum is 2 m (5.3 ft) to greater than 2 m (7.1 ft) thick. Borings AM-1 and AM-3 terminated in this rock.

In Boring AM-2 a medium hard to hard light gray micaceous sandy siltstone to a fine-grained sandstone was encountered at the bottom of the hole (6 m (20.9 ft) to 7 m (23.6 ft) below the coal seam). The rock had an RQD of 100%. Rock moisture measured in this unit was 2.6%.

Engineering Properties of Floor

Estimated Operational Short-Term Strength

The short-term strength of the mine floor is based on an empirical relationship of natural moisture content and operational (or field) compressive strength where the apparent "operational" cohesion (or undrained shear

strength), c_1 , of most immediate non-durable rock zone is determined by (Speck, 1979):

$$c_1 = 1.03[2070 - \overline{NMC}(167)] \text{ in kPa} \quad (1)$$

where: \overline{NMC} = weighted average by distance between measurements of the natural moisture content for h_1 , %.

h_1 = thickness of c_1 layer

Based on rock moisture about every 0.3 m (1 ft) in depth for the three "AM" borings drilled into the mine floor, the top 1 m (4.6 ft) to 2 m (5.3 ft) of the floor consistently showed higher moisture contents than the rock immediately below. The weighted average natural moisture content, \overline{NMC} , ranges from 7.2% to 8.3% resulting in a field undrained shear strength, c_1 , of 707 kPa (102.6 psi) to 896 kPa (130.1 psi) when the above associated relationship with moisture is applied.

The rock immediately below this higher moisture content shale (which can be calcareous at its base) is a silty to sandy silty shale. This rock is harder but only one representative intact sample could be tested for uniaxial compressive strength. This test resulted in a compressive strength of 21,325 kPa (3,095 psi) which appears representative of the harder limy shale. Another sample of this limy shale was tested to have a uniaxial compressive strength of 18,210 kPa (2,643 psi) but developed a horizontal break during test preparation. This strength is consequently a nominal value.

In order to obtain a greater understanding of the limy shale strength the available uniaxial compressive strength data for this mine was summarized with the results from this study in Figure 3. The strengths included in Figure 3 are for floor rock classified as "limy claystone" by the mine. As can be seen in Figure 3, the correct strengths ranged from 6,683 kPa (970 psi) to 37,323 kPa (5,417 psi) with the strength determined in this study in the middle of this range. For all the tests listed the average compressive strength is 20,525 kPa (2,979 psi).

Using the average value from the strength data shown in Figure 3 the operational shear strength, c_2 , for this lower calcareous layer was found to be 6,156 kPa (893.5 psi). The value of c_2 is determined by one-half the average of all the strength results from uniaxial compressive tests multiplied by a reduction factor of 0.6 (Speck, 1979).

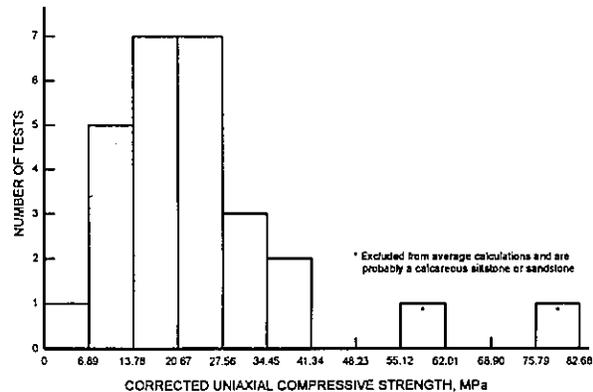


Figure 3. Reported Uniaxial Compressive Strengths For "Limey Claystone" and Limey Shale

A uniaxial compressive test was also run on the lower portion of the harder calcareous material which consisted of a fine grained sandstone. The compressive strength was significantly higher than the calcareous shales immediately above at 82,377 kPa (11,956 psi). Assessment of floor strengths below the calcareous zone was not required for stability analysis.

Estimated Operational Long-Term Strength

In order to assess the long-term stability of the mine floor it is necessary to determine the long-term strength of those floor rocks which will significantly soften over time from creep (strain) or exposure to water. It is, however, as important to identify and verify the presence of the most immediate rock zone which will remain to a large degree essentially intact. For this study, a Durable Rock Zone is considered as a continuous rock zone of 0.6 m (2 ft) or greater in thickness where all DR_{SM} measurements are 70% or above. A Non-Durable Rock in the floor is considered as a rock exhibiting a Mass Durability Rating of less than 70%. Consequently, the depth of the Non-Durable Rock Zone is the vertical hole depth where the a Mass Durability Rating of less than 70%. The DR_{sm} or the Mass-Durability Rating, DR_{SM} , is based on Richardson and Wiles, 1990 and is:

$$DR_{SM} = 61.6 + 2.5354e^{0.0273I_{D2M}} - 2.1562(NMC) \quad (2)$$

where:

NMC = natural moisture content, % as determined by ASTM D2216

I_{D2M} = Mass-Slake Durability Index = $REC(I_{D2})$

REC = core recovery over rock zone in question

Table 1. Rock Durability Results

HOLE	DEPTH, m	ROCK DESCRIPTION	UNIT THICKNESS, m	CORE RECOVERY, %	SLAKE DURABILITY, % (2 CYCLE)	MASS SLAKE DURABILITY, %	NATURAL MOISTURE CONTENT, %	MASS DURABILITY RATING, %
AM-1	77.9 - 78.0	Gray Silty Shale	1.13	100	0.2	0.2	7.3	48.4
AM-1	78.8 - 78.9	Gray Calcareous Silty Shale	0.48	100	22.8	22.8	7.1	51.0
AM-1	79.1 - 79.2	Gray Calcareous Sandy Silty Shale	2.11	100	89.5	89.5	5.9	78.1
AM-2	89.2 - 89.3	Gray Calcareous Silty Shale	3.35	100	97.7	97.7	4.5	88.4
AM-2	90.1 - 90.2	Gray Calcareous Silty Shale	3.35	100	98.2	98.2	4.8	88.3
AM-3	85.0 - 85.2	Gray Calcareous Sandy Silty Shale	1.42	100	97.8	97.8	4.5	88.5

I_{D2} = 2 cycle slake durability index as determined by ASTM D4644

The rock durability test results are given in Table 1 and are plotted on Figure 4. Note, Figure 4 also contains all the test data available from the mining company. Based on visual classification of the floor rock strata and the moisture and slake durability tests the immediate non-durable rock thickness was ascertained to range from 1 m (4.58 ft) to 2 m (5.32 ft). The Mass-Durability Rating, DR_{SM} , for this zone was about 50% with 2-cycle slake durability values of 0.2% and 22.8%. It is important to note that the upper part of the calcareous shale which is of softer and higher moisture content than the lower portion of this unit was also found to be non-durable.

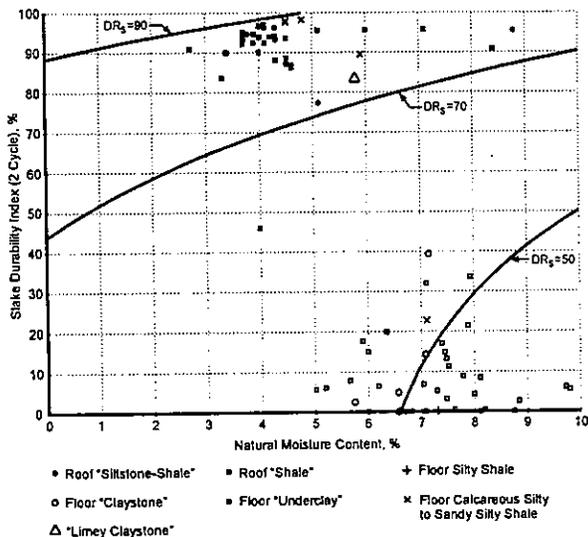


Figure 4. Durability Classification Of Coal Measures For Mine Under Study (after Richardson and Wiles, 1990)

Samples of the non-calcareous, non-durable shale were pulverized per ASTM D421 and tested for plasticity (see Table 2). These pulverized samples had liquid limits and plasticity indices ranging from 31 to 36% and 13 to 17%, respectively. Some samples were also broken down by slaking and tested in order to assess the sensitivity of rock plasticity to mechanical breakdown per ASTM procedure to that caused by wet and dry cycles. As can be seen from Table 2 the slaked liquid limits and plasticity indices were found to be 3 to 6% higher than the pulverized samples.

Mine Floor Stability Analysis At Borings

General

The short-term and long-term stability of the mine floor was assessed at each "AM" boring where the mine floor conditions have been ascertained. In performing the floor bearing analysis the room and pillar geometry beneath the pipeline was assumed as the same as the most recent pipe section undermined. Along this reach the support pillars were 13 m (42 ft) wide and 31 m (102 ft) long with mine room widths of 5 m (18 ft). The adjacent higher extraction areas have pillars which are 13 m (42 ft) square. This mined out section is shown in the northern part of Figure 5.

Also based on this most recent mining an Influence Angle of 45° was assumed. If the support pillars remain intact, an Influence Angle of 45° virtually eliminates pipeline exposure to all but nominal subsidence movements from a mine collapse which would result adjacent to the support pillars.

Table 2. Atterberg Limits for Floor Rocks

HOLE	DEPTH, m	ROCK DESCRIPTION	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX, %	COMMENTS
AM-1	78.1 - 78.2	Gray Silty Shale	34.3	17.3	17.0	ASTM D421 prep
AM-2	87.8 - 87.9	Gray Silty Shale	35.5	18.4	17.1	ASTM D421 prep, more clayey
AM-2	87.8 - 87.9	Gray Silty Shale	39.7	19.0	20.7	Air slaked sample, more clayey
AM-2	88.1 - 88.2	Gray Silty Shale	32.2	17.4	14.8	ASTM D421 prep
AM-2	88.2	Gray Silty Shale	38.3	18.8	19.5	Air slaked sample
AM-3	83.7 - 83.8	Gray Silty Shale	31.4	17.9	13.5	ASTM D421 prep
AM-3	84.1 - 84.2	Gray Silty Shale	30.7	17.6	13.1	ASTM D421 prep

Table 3. Summary of Short-Term Stability Calculations

HOLE	NMC	C ₁	C ₂	L _p	W _p	h ₁	N _c	k	β	E _c	N _c *	N _m	q _{uo}	e	Depth	σ _{pt}	SF
AM-1	7.2	896.7	6156	31.1	12.8	1.61	5.14	6.87	2.81	1.08	5.55	6.85	6145	40.5	77.60	3245	1.89
AM-2	8.1	741.4	6156	31.1	12.8	1.62	5.14	8.30	2.80	1.08	5.55	6.88	5102	40.5	87.45	3656	1.40
AM-3	8.3	706.8	6156	31.1	12.8	1.40	5.14	8.71	3.25	1.08	5.55	7.23	5108	40.5	83.45	3488	1.47

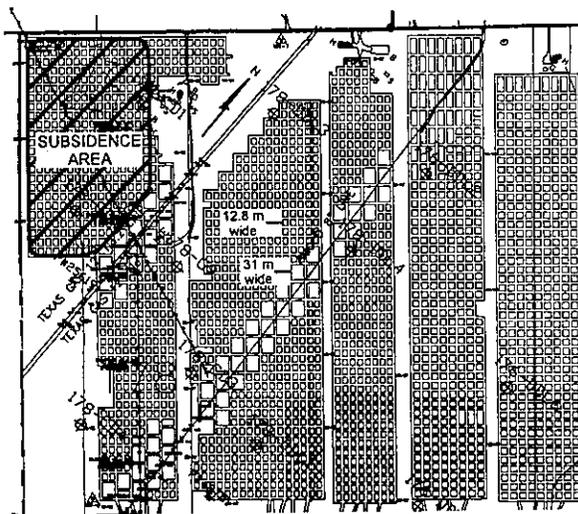


Figure 5. Mining Under Pipeline With Nearby Subsided Area. The Subsidence Resulted After Coal Processing Slurry Was Injected Into This Mine Area.

Short-Term Stability Analysis

The engineering properties used in analyzing the short-term stability of the mine floor are discussed and given earlier in the paper and are summarized in Table 3. Since the immediate underclay, claystone or clayey shale floor contains significantly more moisture and is softer than underlying rock the short-term ultimate bearing capacity, q_{uo}, was checked using the Vesic/Speck equation (Vesic, 1975 and Speck, 1979).

$$q_{uo} = c_1 N_m \tag{3}$$

N_m = modified bearing capacity factor
 =
$$\frac{KN_c^*(N_c^* + \beta - 1)[(K + 1)N_c^* + (1 + K\beta)N_c^* + \beta - 1]}{[K(K + 1)N_c^* + K + \beta - 1][(N_c^* + \beta)N_c^* + \beta - 1] - (KN_c^* + \beta - 1)(N_c^* + 1)} \tag{4}$$

where: K = c₂/c₁
 N_c* = E_cN_c
 E_c = shape factor = 1 + W_p / (L_pN_c)
 N_c = bearing capacity factor for φ=0° = 5.14

$$\beta = \frac{W_p L_p}{[2(W_p + L_p)h_1]}$$

W_p = width of pillar
 L_p = length of pillar
 h₁ = thickness of c₁ layer. Given a specific natural moisture profile of the floor, h₁ is determined by that thickness which results in the minimum q_{uo}.

The load on the floor was considered as the tributary pressure plus any abutment pressure. Abutment pressure is applied in the zone of influence where mined areas outside the zone have significantly higher coal extraction and could result in failure. The tributary pressure is defined as:

$$\sigma_{pt} = \frac{24.88D}{(1 - e)} \tag{5}$$

where: σ_{pt} = tributary pressure. σ_{pt} is in kPa.
 D = overburden depth to the bottom of the coal in the mine area in question. D is in meters.
 e = extraction ratio to the mine area in question

The average abutment stress, σ_{pa} , (kPa) is:

$$\sigma_{pa} = \frac{\bar{\sigma} - q}{(1 - e)(x_2 - x_1)} \left[C \left(e^{\frac{-x_1}{C}} - e^{\frac{-x_2}{C}} \right) \right] \quad (6)$$

where pillar is bounded at roadway centers of x_1 and x_2 (expressed in meters from the extracted panel). The peak abutment stress, $\bar{\sigma}$, (kPa), and the shape constant C (feet) are:

$$\bar{\sigma} = kq + s_1$$

$$C = \frac{L_s}{\bar{\sigma} - q}$$

where: k = triaxial stress factor = $\frac{1 + \sin \phi}{1 - \sin \phi}$
 ϕ = angle of internal friction, degrees
 q = cover stress, kPa, = $0.0098\gamma D$
 s_1 = intact coal strength, kPa.

For panel widths (P) greater than 0.6 times the depth of cover (D), (L_s) is:

$$L_s = (0.223) (\gamma) (D^2)$$

and for $P < 0.6 (D)$,

$$L_{ss} = (0.744) P \gamma [D - (P/1.2)]$$

where γ = unit weight of the overburden, kg/m^3 .

The average abutment pressure for the pillar, σ_p , was determined from the methodology recommended by Mark, 1990. The total design pressure on the pillar is therefore:

$$\sigma_p = \sigma_{pt} + \sigma_{pa} \quad (7)$$

where: σ_p = total average pillar pressure

Therefore, the floor safety factor is given by:

$$SF = \frac{S_p q}{\sigma_p} \quad (8)$$

where: SF = safety factor

The result of this mine stability analysis using the procedures are summarized in Table 3. At the three "AM" holes the short-term safety factor ranged from 1.4 to 1.9. These values are below a nominal SF of 2.0. This analysis, however, is not considered as reliable as the long-term stability analysis (which is given in below). Critical in the short-term stability determination is the weighted average natural moisture content, NMC , of the upper floor and the thickness of this higher moisture material, h_1 . By a linear relationship established by Speck, 1979, as referenced above, the parameter NMC is used to determine the undrained shear strength, c_1 . The h_1 thickness was taken as the clear change in moisture with depth.

Note the derived strength from this equation is not directly based on the actual operational strengths of past failures but on a relationship of sample compressive strength to moisture content. Further, the floor samples used to develop this relationship consisted of underclay from two adjacent mines in east-central Illinois in the No. 6 Coal Seam. The rock plasticity consists of an average Liquid Limit of 46% with a standard deviation of 6% compared to an average of about 35% $\pm 5\%$ for the Monroe City Mine. Lower plasticity of the floor investigated in this study indicates greater floor strengths. On Figure 6 the relationship given in Equation (1) has been superimposed on a plot of the floor strength versus moisture for the reported "underclay" and "claystone". As can be seen in this figure, the Speck Equation falls above almost all the "underclay" data for which it was intended. Furthermore, the "underclay" appears to have no relation in strength with moisture.

The combined test results of both the "claystone" and the "underclay" show considerable variation. For example, where the Speck Equation predicts a strength of 5064 kPa (735 psi) the test data indicates that the actual strength can be ± 4479 kPa (650 psi) at a moisture content of 8.0% (see Figure 6).

Long-Term Stability Analysis

The mine floor properties used in the long-term stability analysis are all given in Table 2 and are

Table 4. Summary of Long-Term Stability Calculations

HOLE	h_1 (m)	W_p (m) ($L_p=31.1$ m)	W_p/h_1	N_γ	δ_γ	δ_s	γ (kg/m ³)	q_u (MPa)	D (m)	e (%)	σ_{pt} (MPa)	SF	With Pillar Abutment Loads		
													σ_{pa} (kPa)	σ_p (kPa)	SF
AM-1	1.61	12.8	7.94	8.20	9.76	0.835	2,403	10.0	77.6	40.5	3.25	3.1	971	4,216	2.4
AM-2	1.62	12.8	7.89	8.20	9.56	0.835	2,403	9.87	87.4	40.5	3.65	2.7	1,240	4,892	2.0
AM-3	1.40	12.8	9.17	8.20	18.5	0.835	2,403	19.1	83.5	40.5	3.49	5.5	1,130	4,616	4.1

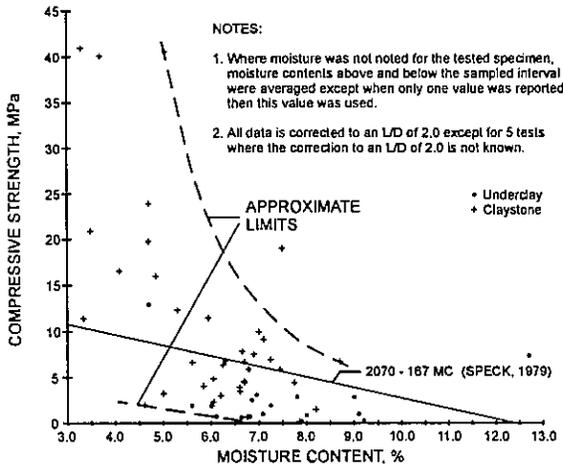


Figure 6. Compressive Strength Versus Moisture Content For Underclay And Claystone

summarized in Table 4. To assess the long term stability of the mine floor consisting of an immediate non-durable zone followed by a durable zone the following equation was used to determine the ultimate bearing capacity (Mandel and Salencon, 1972):

$$q_u = (0.0049)\gamma W_p N_\gamma \delta_\gamma \delta_s \quad (9)$$

where:

- W_p = pillar width
- N_γ = classical bearing capacity factor as given by Vesic, 1975.
- δ_γ = modifier to N_γ for limited thickness of non-durable rock, h_1 , followed by a rigid base. The top of durable zone is considered a rigid base δ_γ depends on the effective friction angle and W_p/h_1 .
- δ_s = modifier to N_γ for shape of pillar
= $1 - 0.4(W_p/L_p)$
- L_p = length of pillar

The results of this analysis at each of the "AM" holes are given in Table 4. As can be seen in this table the

safety factor, SF, against long-term floor failure ranges from 2.7 to 5.5. Long-term stability should be the most critical condition as the rock softens with time and exposure to water and therefore should result in the lowest and nominal safety factors. However, this is contrary to the short-term safety factors given in Table 3 which are lower than those calculated for the long term in Table 4. The results from the long-term analysis are more reliable, as the frictional strength used is based on actual long-term mine floor failures using the same bearing capacity equations considered in this study (Marino and Choi, 1999).

The long-term safety factors given above do not consider abutment pressures from failure of an adjacent mine production (higher extraction) area. If failure is assumed adjacent to the Zone of Influence then additional loads from the failed area will be transferred to the support pillars. The additional abutment loads on these pillars reduces the SF values to 2.0 to 4.1 and are consequently still acceptable (see Table 4). Abutment loads were calculated using the method reported by Mark, 1990 and the method described above under the short-term stability analysis.

Global Mine Floor Stability

Rock Durability Assumptions

Because there were only 3 "AM" borings drilled it is impossible to extend the information gathered at these 3 locations across the entire length of the undermined pipeline. To make such an assessment, information available from the mine was used. There were two basic problems made with the use of the mine data. The first involved the problem of the inappropriate mine floor descriptions in the boring logs based on visual descriptions for the same rock core by the mine and MEA. By comparing these descriptions one important difference was the classification of rock as shale versus claystone by the mine. For silty shale the difference in classification implies a significant difference in durability and/or strength when the rock is described as claystone

and underclay by the mine which falsely indicates a rock of very low durability and poor strength.

The second problem with using the mine data was that the rock descriptions could not be correlated with the measured durability rating as performed for the "AM" holes as the mine performed only one slake durability test in durable floor rock. Therefore, in order to make some type of assessment of the depth of non-durable mine floor materials, some relatively gross assumptions were made. All the immediate floor rock described as "underclay" or "claystone" were considered non-durable.

Durable rock was considered when the rock beneath the "underclay" or "claystone" was classified as "shale", "silty shale", "sandy shale", "siltstone", "sandstone" or "limestone". Also because shale has been misclassified as claystone these logged rock intervals could be durable when limey or calcareous. Based on our laboratory data calcareous silty shale with a moisture content of 5.9% or less tested as sufficiently durable. Therefore a dry "limey claystone" may also be durable. Unfortunately, for the majority of the holes the mine did not collect sufficient moisture content data with depth. However, for 5 of the 9 holes where sufficient moisture information was available the dry "limey claystone" started at the top of this rock description. In remaining holes the drier rock was consistently present about 0.3 m (1.1 ft) to .4 m (1.4 ft) below the top of this rock description. This is consistent with the "AM" hole data. Therefore, although slightly liberal, the top of the durable rock was considered coincident with where the "limey claystone" description commences except for the four cases where dry "limey claystone" was ascertained to be a foot or so lower. With the above assumptions a contour plot of the thickness of the non-durable rock in the vicinity of the pipeline was generated and is shown in Figure 7.

Stability Calculations

Using Figure 7 and a contour plot of mine depth (see Figure 8) the distributions of safety factors along and adjacent to the pipeline without and with abutment loads on the pillars are given in Figures 9 and 10, respectively. Safety factors are determined for discrete areas with different support conditions. Each mine panel or main the pipeline crosses are numbered from south to north from 1 to 13. As can be seen when comparing Figures 9 and 10, the safety factors are higher when adjacent mine failures were not considered to result in load transfer of the overburden weight (abutment pressure).

Safety factors reduced to mainly 60 to 80% of their value without any abutment loads. Only in Areas 7 and 8

(under the pipeline), however, does the addition of the abutment loads on the support pillars result in a safety factor reducing to below the needed 2.0 (i.e. 2.4 to 1.8). Production (or higher) extraction areas adjacent to the pipeline support area either remained above 2.0 or were less than about 1.7 with any load transfer. Based on this analysis, however, only the higher extraction areas south and east of Areas 4 and 11, respectively, represent sufficiently stable conditions.

Because all pillar support areas have adjacent areas with insufficient floor strength, the potential for abutment loads is present and should be considered in the areas under the pipeline. With abutment loads the safety factors against long-term floor stability decrease northward from Area 1 to 8 from 18.3 to 1.8 (Note Areas 7 and 8 had a SF of 2.4 before adding the abutment load, see Figures 8 and 9). In Area 9 the SF is 2.7. Proceeding north from Area 9 the floor safety factors decrease as the non-durable floor thicknesses increase from about 2 m (6 ft) to 4 m (14 ft) deep (see Figure 7). From Areas 10 to 13 the SF values decrease from 1.4 to 0.6 indicating poor floor support conditions. Also Area 13 has a limited zone of support (or Zone of Influence) with an influence angle of only 24°, and although Area 1 is estimated to be sufficiently stable it similarly has a limited support zone in the south.

The northern end of the undermined pipeline as well as the coal reserves to the north appear to contain non-durable floor deposits up to almost 5 m (15 ft) deep which results in poor long-term support. Extrapolating the floor conditions from the available mine information the SF is as low as 0.6 at the north end. However, the actual floor conditions in the north may reveal a better condition if investigated by drilling and testing. Also with additional strength testing, rather than the assumed strength (back calculated from past mine failures), Areas 7, 8 and 10 may be found to have greater and possibly acceptable SF values.

The strength assumption used to assess long-term stability of the floor is based on mine floor failures in rocks with, in general, higher clay content than those non-durable rocks in the mine studied. Typically, the liquid limit was 45 to 50% compared to 31 to 40% for this site (in other words about 5-20% lower). This indicates that the friction angle assumed may be too low and thus too conservative. Based on this difference in plasticity it would not be surprising if the actual friction angle of the floor material in question was 5° higher than assumed (i.e. friction angle, $\phi = 28^\circ$ versus 23°). If this was tested to be true, it would result in an increase in the allowable non-durable floor thickness at a factor of safety of 2.0. In

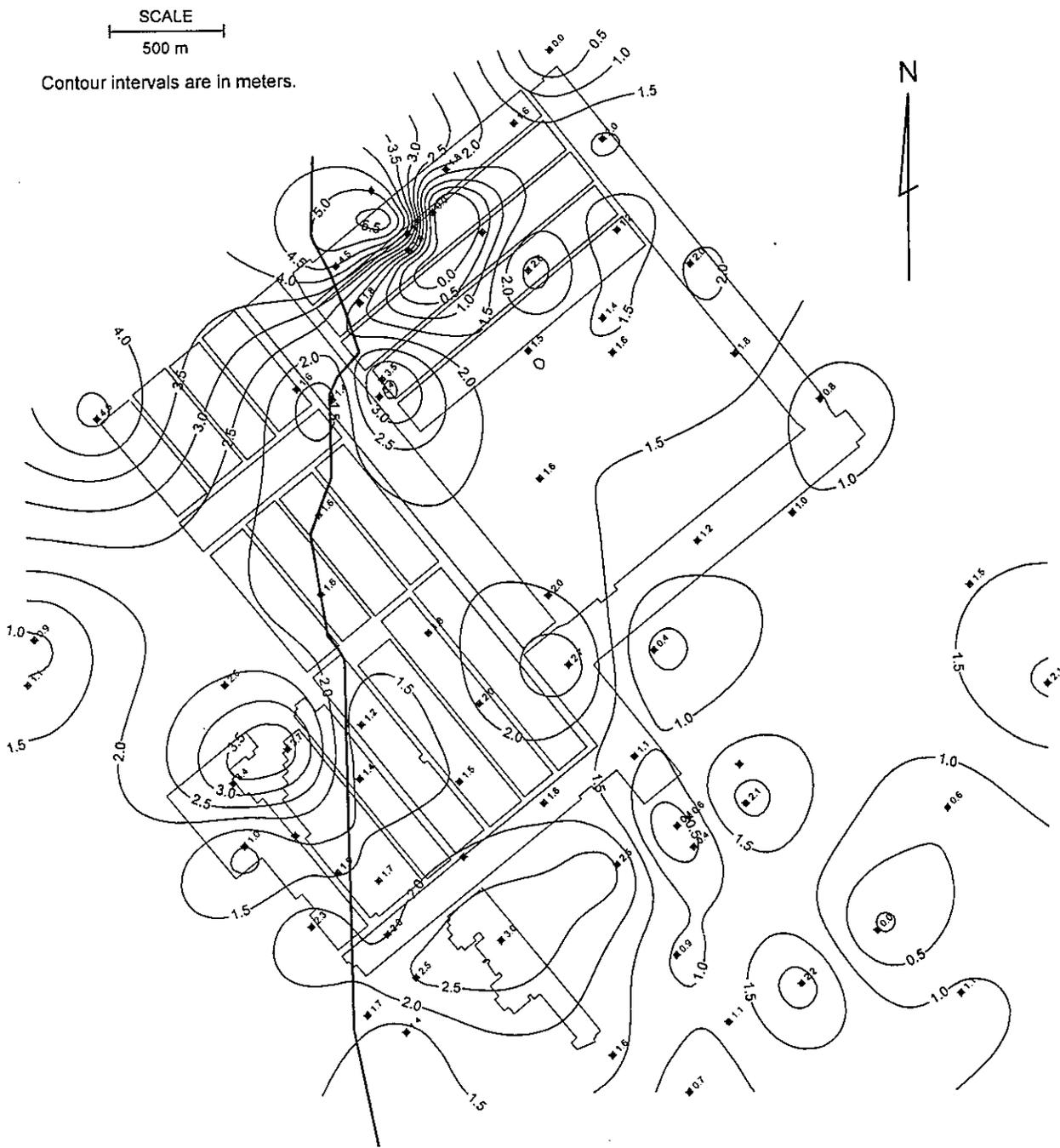


Figure 7. Estimated Thickness Of Nondurable Floor

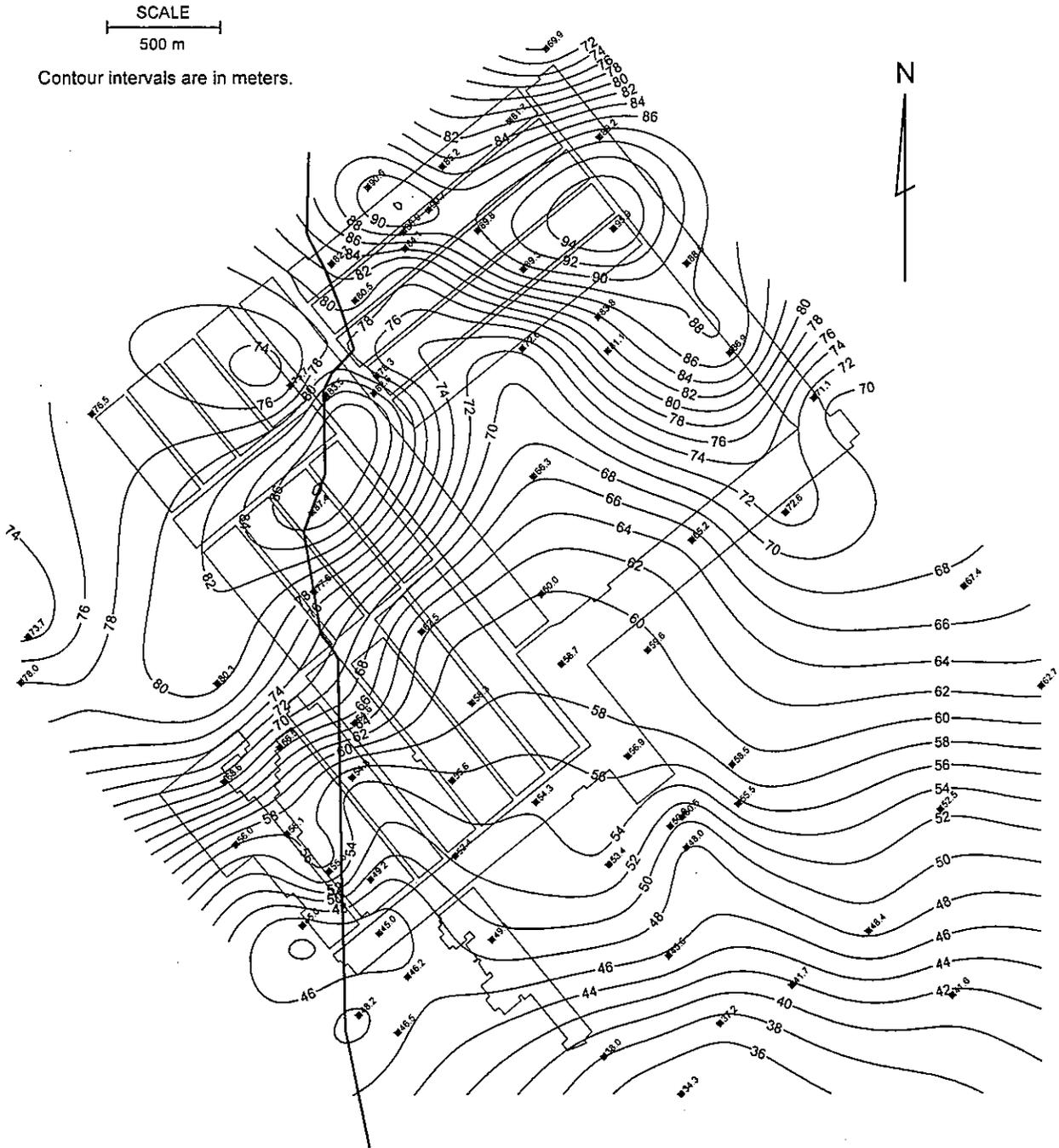


Figure 8. Total Depth to Bottom of Coal

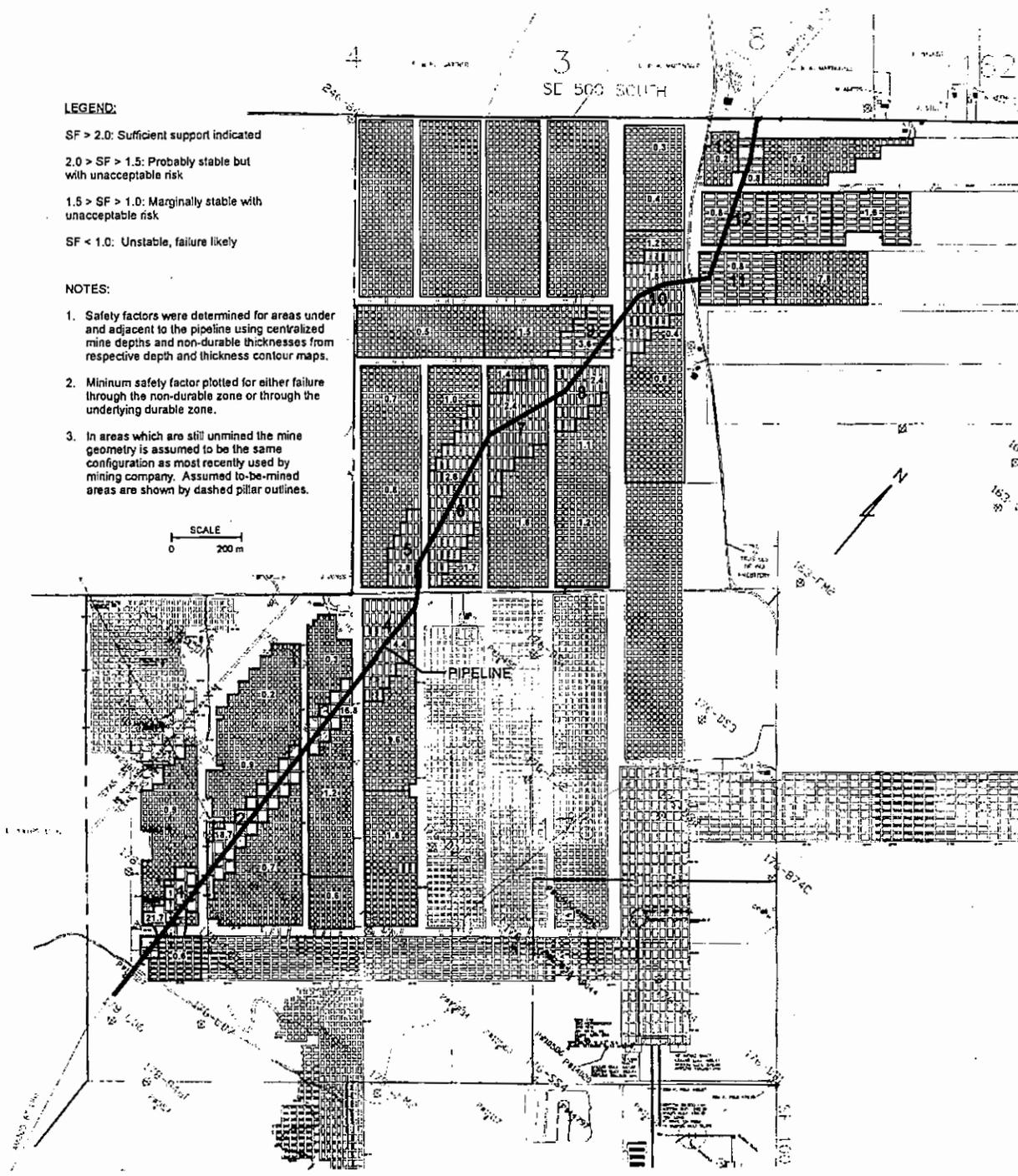


Figure 9. Distribution Of Safety Factors For Long-term Stability Of The Mine Floor Along And Adjacent To The Pipeline Without Load Transfer From Adjacent Areas With Safety Factors Less Than 2.0.

LEGEND:

SF \geq 2.0: Sufficient support indicated

2.0 > SF \geq 1.5: Probably stable but with unacceptable risk

1.5 > SF \geq 1.0: Marginally stable with unacceptable risk

SF < 1.0: Unstable, failure likely

NOTES:

1. Safety factors were determined for areas under and adjacent to the pipeline using centralized mine depths and non-durable thicknesses from respective depth and thickness contour maps.
2. Minimum safety factor plotted for either failure through the non-durable zone or through the underlying durable zone.
3. In areas which are still unmined the mine geometry is assumed to be the same configuration as most recently used by mining company. Assumed-to-be-mined areas are shown by dashed pillar outlines.

SCALE
0 200 m

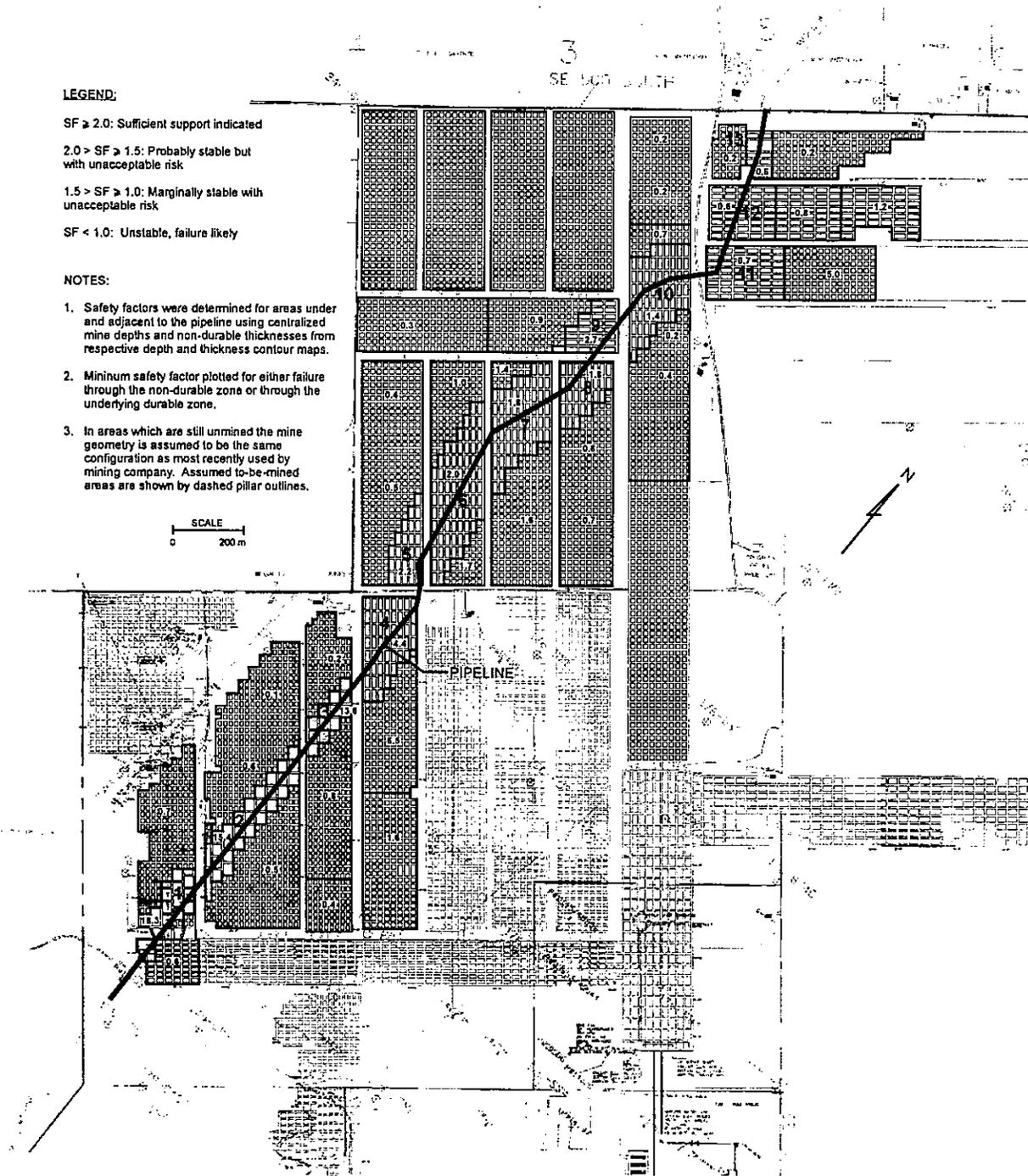


Figure 10. Distribution Of Safety Factors For Long-term Stability Of The Mine Floor Along And Adjacent To The Pipeline With Load Transfer From Adjacent Areas With Safety Factors Less Than 2.0.

Table 5, the allowable non-durable thicknesses are compared for some of the more typical mine depths without changing the mine support conditions. As can be seen from the table there is more than .3 m (1 ft) to about 0.6 m (2 ft) more non-durable material which would be allowable under the postulated tested strength.

Table 5. Allowable Floor Thickness

Mine Depth	Assumed Strength ($\phi = 23^\circ$)	Tested Strength ($\phi = 28^\circ$)
61 m (200 ft)	1.9 m (6.34 ft)	2.5 m (8.22 ft)
76 m (250 ft)	1.8 m (5.96 ft)	2.3 m (7.51 ft)
91 m (300 ft)	1.7 m (5.71 ft)	2.1 m (6.94 ft)

Summary and Conclusions

1. This paper describes an investigation of the mine floor stability beneath a transmission pipeline above a mine in the Illinois Coal Basin. This investigation consisted of drilling three borings along a yet-to-be-mined section. Continuous 3 in. core was taken in the floor and brought back to the lab for appropriate testing.
2. The borings found the mined-out Danville No. 7 Coal at depths of about 76 m (250 ft) to 88 m (290 ft). This is as deep as the coal is along the exposed reaches of the pipeline and consequently results in the greatest loads on the support pillars left in the Zone of Influence. The most critical floor condition to long-term stability is the thickness of the immediate non-durable rock. At the three borings this thickness was found to be 1 m (4.6 ft) to 2 m (5.3 ft).
3. Using the information collected the mine floor stability was calculated at the three drill sites. The calculations indicated that a long-term factor of safety of 2.0 or greater existed even when mined areas adjacent to the Zone of Influence failed. Therefore the mine floor at all three locations should have sufficient softened strength over time and from pooling of groundwater. Short-term stability calculations were also performed but resulted in safety factors of 1.4 to 1.9 against floor failure. This range is below 2.0; however, the method of analysis used is considered much less reliable than the long-term design procedures used in this paper.
4. An analysis was also performed across the entire

reach of the pipeline for long-term stability by including the available data from the mine. Because the mine did not collect the appropriate information for long-term failure analysis, some relatively gross assumptions had to be made in this study when using this data. Based on this global analysis, a majority of the pipeline was found to have sufficient long-term support. Of the total of about 3049 m (10,000 ft) of pipeline over the mine about 1098 m (3,600 ft) in the northern part of this reach was calculated to have insufficient floor support. However, the assumed floor strength may be conservative for the immediate floor rocks present in this mine. Consequently site specific strength testing may show an increased floor strength and result in the southern portion (approximately 640 m (2,100 ft)) of this 1098 m (3,600 ft) reach of inadequate floor support being sufficiently stable. Also in the southern portion of Area 1 and Area 13 the pipeline has less than the appropriate width of support pillars (Figure 9 and 10).

5. The floor conditions indicated at the north end of the undermined section of pipeline (about 457 m (1,500 ft)) as well as possibly the coal reserves to the north of the mine indicate poor floor support. Based on the mine's logs, floor rocks to almost 5 m (15 ft) deep have the capability to completely break down over time and exposure to pooling of groundwater. In fact, the mine depth and poor immediate rock depth are more severe than those indicated in the previous subsidence area over this mine. Additional drilling and testing in this area may result in an adequate safety factor in the long term.
6. Consistent and appropriate classification of the rock core is imperative to conducting the most accurate floor bearing capacity analysis. This classification should be based on sufficient and appropriate laboratory testing. Without such information (such as relying on driller logs) the mine floor conditions are subject to a wide range of interpretation which can lead to the stability analysis indicating the mine is sufficiently stable to being unstable.

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