

Abandoned mine subsidence prediction using British National Coal Board methods, Denver, Colorado

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Abstract: The role of mining in Colorado is rife with history. Gold, silver, molybdenum, uranium, and oil shale are only a few of the minerals that have been mined from the mountains and foothills. Included in this list is the occurrence of high quality sub-bituminous coal in shallow horizontal seams north of the Denver metropolitan area. Production began with the arrival of the railroads to Denver in early 1860's and continued more or less uninterrupted until the last mine was closed in 1978. During this 115 years 110,644,000 tons of coal was extracted from 222 mines covering approximately 21,300 acres of what was vacant agricultural land. Since the early 1960's and continuing to the present, the Denver/Boulder metropolitan area has enjoyed unprecedented economic growth. For the past decade the metropolitan counties have been in the top 10 growth areas in the United States. This emergence of Denver/Boulder as a major economic center has required that thousands of acres of farmland be converted to residential and commercial use. It is this encroachment upon abandoned mine land that gave rise to the need for subsidence prediction.

Almost no records of mining procedures and techniques remain. Mine maps, while usually accurate, provide little if no indication of surface effects from mining. Additionally, due to the remote location and minimal governmental oversight, subsidence, while indirectly documented, was never studied.

This paper presents over twenty five years of research into both the effects of subsidence on structures built prior to mining and an evaluation of subsidence/strain prediction methods to approximate, conservatively, the potential for future subsidence events. These studies have concluded that the British National Coal Board, Graphical Strain Profiling System, while developed from long wall mining operations, can be used to present "worst case" subsidence/strain predictions for the abandoned mines within the Boulder/Weld Coal Field.

Résumé: Le rôle des mines au Colorado est riche en histoire. L'or, l'argent, le molybdène, l'uranium et le schiste pétrolier ne sont que quelques-uns des nombreux minéraux qui ont été extraits des montagnes et des contreforts. Sur cette liste figure l'occurrence de charbon subbitumineux de grande qualité en fines couches horizontales au nord de la zone métropolitaine de Denver. La production débuta avec l'arrivée des chemins de fer à Denver au début des années 1860, et se poursuivit malgré quelques interruptions jusqu'à la dernière fermeture de mine en 1978. Tout au long de ces 115 années, 110 644 000 tonnes de charbon ont été extraites de 222 mines couvrant à peu près 21 300 acres de terre agricole jusqu'alors vides.

Depuis le début des années 60 jusqu'à aujourd'hui, la zone métropolitaine de Denver/Boulder a connu une croissance économique sans précédent. Ces comtés métropolitains figurent depuis dix ans parmi les 10 zones qui ont connu la meilleure croissance de tous les États-Unis. Pour que Denver/Boulder devienne un pôle économique de premier plan, des milliers d'acres de terres cultivées ont dû être transformées en zones résidentielles et commerciales. C'est cet empiètement sur les mines abandonnées qui a nécessité des prévisions d'affaissement.

Les procédures et techniques d'exploitation minière ont pratiquement toutes disparu. Les cartes minières, bien que généralement précises, fournissent peu ou pas d'indications quant aux effets de surface provoqués par l'exploitation minière. De plus, en raison de l'éloignement de la zone et de la surveillance minimale mise en place par le gouvernement, l'affaissement, bien qu'attesté par des sources indirectes, n'a jamais fait l'objet de véritables études.

Ce document est le résultat de vingt cinq ans de recherche quant aux effets de l'affaissement sur les structures construites avant l'exploitation minière, et à l'évaluation des méthodes de prévision d'affaissement/déformation. L'objectif était le suivant : évaluer, de manière conventionnelle, la possibilité de futurs affaissements. Ces études ont conclu que le système d'évaluation graphique des déformations du British National Coal Board, bien que développé à partir de longues opérations de taille, pouvait servir à prévoir les "pires" risques d'affaissement et de déformation au sujet des mines abandonnées se trouvant dans le gisement houiller de Boulder/Weld.

Keywords: Abandoned mines, coal mines, collapse, drilling, engineering geology, foundations, land subsidence, mapping, sedimentary rocks, subsidence, underground mining.

BOULDER AND WELD COUNTY COAL MINING HISTORY

Colorado has a rich mining history beginning in 1858 with the discovery of placer gold deposits along Cherry Creek, near what is now the City of Denver. This discovery led to the Colorado Gold Rush of 1859, characterized with the prospectors wagons labeled "Pikes Peak or Bust." These prospectors were generally the remnants of the California Gold Rush from a decade prior. This influx of people was the beginning of the first population explosion in Colorado and the greater Denver area. Population growth and the development of mills and smelters in the foothills of the Rocky Mountains led to the inevitable demand for an economic and reliable source of coal.



Figure 1. Underground minors near Lafayette (Boulder County) Colorado. Obtained from the Denver Public Library, Western History Collection, circa 1921

The occurrence of high quality sub-bituminous coal in shallow horizontal seams north of Denver in Boulder and Weld Counties provided the solution to these demands. The extension of the Union Pacific, Denver, Utah and Pacific, Burlington, and Missouri Railroads in the early 1860s to the coalfields facilitated the development of the resource. Extraction first occurred at the western edge of the fields where the sedimentary deposits had been uplifted adjacent to the Rocky Mountains. These outcrops offered the opportunity of accessibility to the seams, and the ability to exploit the deposits with rudimentary techniques. Coal development then progressed east to deeper mines with increasingly more sophisticated technology.

In a report entitled “A Study of Falls of Roof and Coal in Northern Colorado” Tomlinson (1933) describes the mining method used in five of the largest operating mines in the Boulder/Weld coalfield as “Pairs of room entries are advanced to a predetermined point, and rooms in sets of two to four are turned from one room entry or in some places from both entries. Room pillars are recovered immediately after the rooms have been advanced for the required distance, and a uniform break line maintained with each group of retreating pillars.” This method of coal mining is referred to as Pillar Retreat (Figure 2).

Coal mining continued in the Boulder and Weld field, more or less uninterrupted, from 1863 until the last mine closed in 1978. During these 115 years, 110,644,000 tons were extracted from 222 mines underlying approximately 21,300 acres of what was then undeveloped or agricultural land.

POPULATION GROWTH

Geographically, Denver sits at the base of the Rocky Mountains, which lie to the west. Denver’s central location within the continental United States, established major transportation corridors, and world-class airport, has contributed to substantial economic and population growth (Figure 3). Denver is quickly emerging as an economic and technologic center for the western United States. As a result, rapid population growth has led to the transformation of thousands of acres of farm land to residential and commercial developments. Much of the agricultural lands north of Denver are the same properties that are undermined within the Boulder/Weld coalfield. The public’s desire to reside within reasonable proximity to the Denver Metropolitan area has led to a need to adequately evaluate the feasibility of developing lands that have been historically undermined.

GEOLOGY OF BOULDER AND WELD COUNTIES

Outcropping Units

Outcropping units within Boulder and Weld Counties are the Pierre Shale, the Fox Hills Sandstone, the Laramie Formation and Quaternary gravels and soils. The Pierre Shale is a lead gray to brown and black shale of marine origin (Figure 4). Total thickness in the area is greater than 7,000 feet (Blair 1951), with the majority of the formation made up of shale. Near the top, the Pierre Shale becomes increasingly sandy and contains beds of fine sandstones and

approximately 600 feet and is made up of mostly clay shales, very fine sandy shales, and lenticular beds of sandstone. The shales are largely carbonaceous and in places become lignitic. The Laramie Formation lies comfortably on the Fox Hills Sandstone.

Structure

Boulder and Weld Counties lie on the western edge of the Denver-Julesberg Basin against the Front Range Uplift of the Rocky Mountains. This basin contains up to 13,000 feet of sediments derived from the ancestral Rockies, which laid to the west. Two kinds of faulting occur in this portion of the basin. A basement-controlled late Cretaceous Laramide faulting is the most prevalent and is the result of deformation associated with uplift. The second basin has been described by Davis and Weimer (1976) as growth faulting as a result of differential loading of the deltaic sequence at the time of deposition.

Growth faulting is the major structural feature seen in the area. A zone is present with dominant faults trending in a northeasterly direction. This system is ten miles wide and thirty miles long. These faults are high-angle, normal structures near the surface, but seismic work has shown that they tend to flatten and die out at depth. Work by Davis and Weimer (1976) shows that these listric normal faults do not continue below the Hygiene Member of the Pierre Shale. Antithetic faults resulting from tension then form horst and grabens. This effect had resulted in the increased thickness of sediments in the graben areas. The Fox Hills Sandstone has been reported to have a thickness near a growth fault of 484 feet (Spencer, 1961). The Laramie Formation also has increased thickness in these zones and this is believed to be the reason for the increased thickness of the coal seams in the Boulder-Weld coalfield (Figure 5).

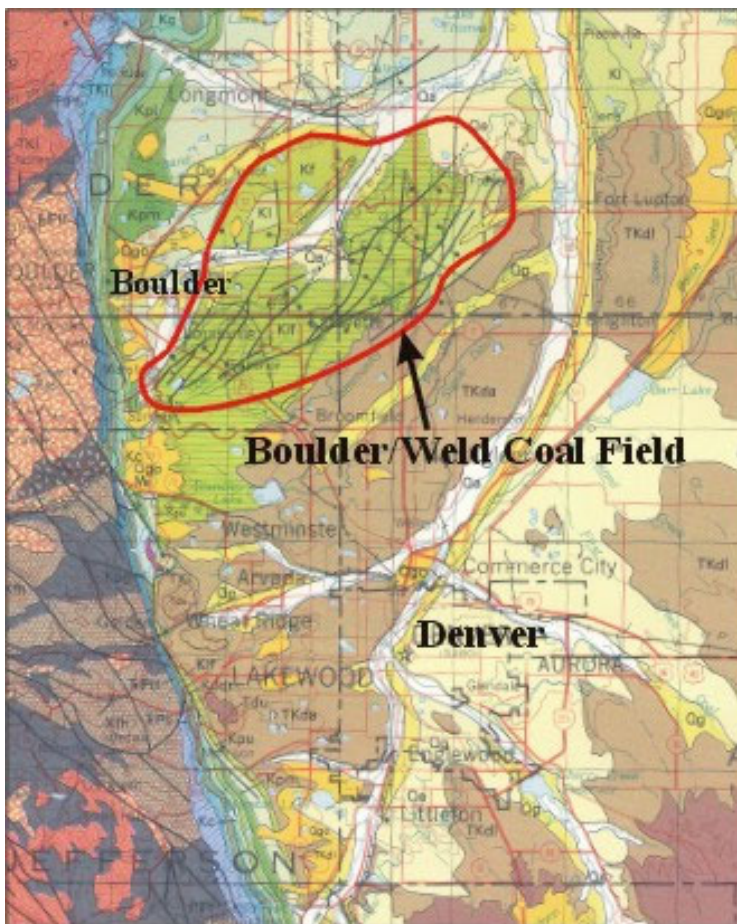


Figure 4. Front Range Geology and the Boulder/Weld Coalfield, from Tweto, 1979.

SUBSIDENCE/STRAIN PREDICTION

With no empirical and only very limited geo-technical data, an easily applied and defensible strain and subsidence prediction method was required to provide planners and land owners a process to evaluate and potentially develop undermined property. The surface strain analysis and subsidence prediction method chosen by Western Environment in 1981 is an adaptation of the United Kingdom National Coal Board's graphical strain profiling system. This method of strain prediction was developed for on-going long wall mining operations. To make the method applicable to abandoned pillar retreat mines, several modifications and assumptions were made.

The first modification is to define the thickness of the void space. The standard method is to use the actual mineable thickness of coal. However, geophysical logging of drill holes indicate that collapse is complete in

approximately 95% of the borings. Therefore, to proceed with a “worst case” theoretical analysis, the following assumption was made: any increase in hole diameter greater 50% of the original boring diameter will be treated as an open void. The amount of “theoretical” void for all holes intercepting the mine was then averaged. The average depth to top of the mined interval is also used.

The width of the extraction is critical to the analysis, and several options are available for use. They include a proportional distance between drill holes, actual width (length) of the workings interpreted as room length, or arbitrary values to produce the maximum amount of subsidence. The maximum strain and/or subsidence value produced along the profile is then reported as the maximum strain and/or subsidence possible throughout the project. This method has been successfully used on hundreds of projects since 1981. The aggregate value of these projects is estimated to be in excess of 4 billion dollars. Recently, Western Environment has been questioned regarding the applicability of the NCB system in the Boulder/Weld Field. No one has doubted the conservative values reported using the NCB method. However, due to the pressure to develop property, every effort is being made to lessen or eliminate subsidence related development restrictions. Some have approached this issue by searching literature for strain or subsidence prediction methods that allow unrestricted development in areas previously not recommended for construction. As a result, Western Environment has evaluated the very limited research and records regarding subsidence in the Boulder/Weld Field. The majority of this data has come from indirect sources including original mine maps, photographs, and newspaper accounts.

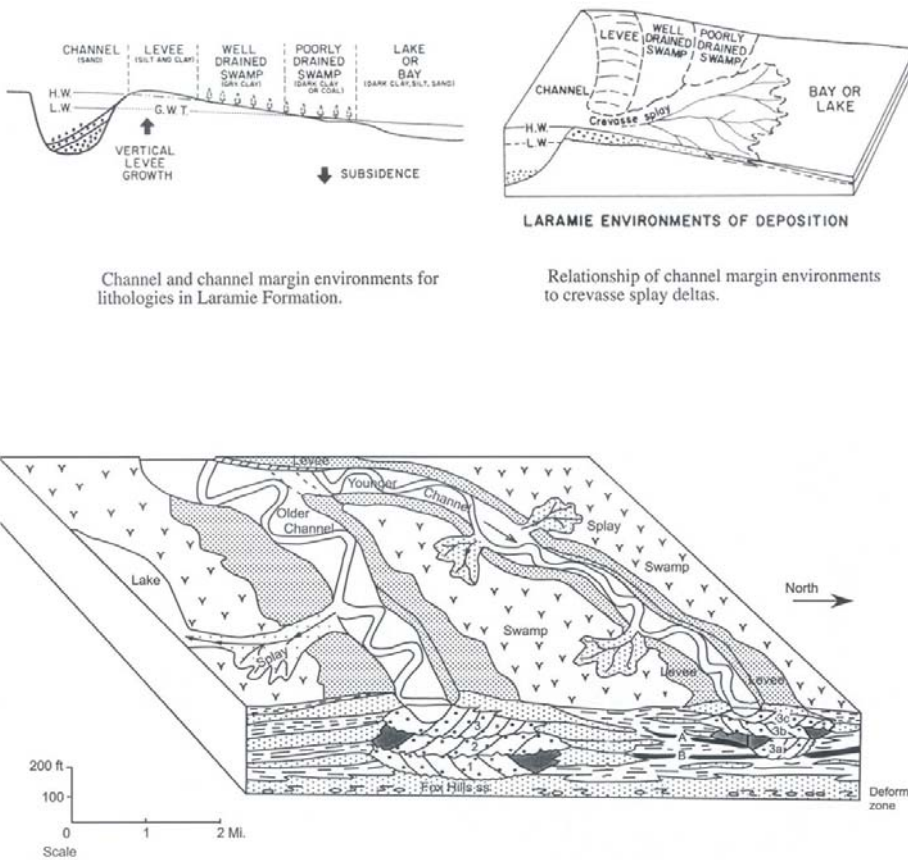


Figure 5. Generalized Stratigraphic Model of the Laramie Formation, from Weimer, 1973

With what is unquestionably a lack of geo-technical data, Western Environment has begun to acquire core samples from projects throughout the Boulder/Weld Coal Field. In two recent projects completed during 2004, thirty samples of claystone, sandstone and coal were submitted to geotechnical laboratories for analysis. These samples were selected for unconfined compression testing and moisture/density analysis. A total of twenty-two of the samples were chosen for unconfined compression testing.

Understanding the need to develop a comprehensive set of geotechnical results, Western Environment chose to present additional information documented in Dr. Gordon Matheson’s paper *Observations on the Location of Chimney Subsidence Sinkhole Development Along the Colorado Front Range* (1986), with the results of core sample analysis recently completed. The following tables present a list of the results from the three referenced investigations.

Table 1. Average Rock (Wet) Density Comparison

Rock Type Tested	Matheson (1986)	Project A (2004)	Project B (2004)
Claystone	141 pcf	134 pcf	135 pcf
Sandstone	144 pcf	166 pcf	135 pcf
Coal	83 pcf	83 pcf	91 pcf

Table 2. Average Unconfined Compressive Strength

Rock Type Tested	Matheson (1986)	Project A (2004)	Project B (2004)
Claystone	775 psi	1093 psi	696 psi
Sandstone	1450 psi	not tested	2111 psi
Coal	2640 psi	greater than 1377 psi*	1670 psi

* The sample strength exceeded the compression frame capacity

Unconfined compressive strength data varies somewhat between projects. However, qualitative observations of the data confirm that coal and sandstone have the highest compressive strength of the three rock units, followed by claystone. This relationship has significant implications when evaluating long-term pillar stability. In his paper entitled "Pillar Design and Coal Strength" (Mark and Barton, 1997), Dr. Christopher Mark compared the results of over 4000 unconfined (uniaxial) compressive strength test results to case studies of coal mine pillar performance. This investigation included the analysis of pillar performance utilizing widely accepted pillar strength formulas (Bieniawski 1968) that incorporate uniaxial strength data from laboratory samples. In his conclusions Dr. Mark states, "laboratory testing should not be used to determine coal pillar strength." This conclusion is made because coal is "notoriously difficult to test due to micro-fractures, cleats, bedding planes, partings shears and small faults." Furthermore, even though the range of compressive strengths vary greatly (Salamon 1991, Galvin 1995, and Mark 1990), the back calculated in-situ coal strength falls between the very narrow range of 780 psi and 1,070 psi, resulting in an average or default value of 900 psi (Mark and Barton 1997). Western Environment agrees that the default value of 900 psi for in-situ compressive strength is at least conservative for Laramie Formation coals in the Boulder/Weld Field.

The estimation of rock mass (pillar) strength is not a straightforward comparison of unconfined compressive strength data and cross sectional pillar dimension. Matheson (1986) chose to "back calculate" a range of rock mass strengths from recorded roof and floor failures of varying rock types. This method is further described by Terzaghi and Peck (1948) and Vesic (1970). The results of Boulder/Weld data reported by Matheson conclude, "roof failure is the most critical failure mode followed by floor failure". Dr. Matheson continues, "The mine pillars should be the most stable... which is consistent with verbal descriptions provided by miners" (Tomlinson, 1933).

To provide an estimation of pillar stability, Western Environment choose to utilize the Pittsburgh Research Center of the US National Institute for Occupational Safety and Health Analysis of Retreat Mining Pillar Stability (ARMPS) computer program. This program was specifically developed to aid in planning for retreat methods of coal production similar to that used in the majority of the larger mines in the Boulder/Weld Field. Simple input values are required to calculate "stub" pillar size maintaining a safety factor of 1.5 while utilizing a default uniaxial strength value of 900 psi.

To utilize this program in determining pillar and roof stability, Western Environment first determined the average room pillar width and length from measurements of the original mine maps. The average room pillar length and width varies greatly based upon depth. However, the two mines evaluated during the 2004 Western Environment investigations were similar in depth, resulting in Mine A having an average room pillar size of 18' X 190' while the average pillar size in Mine B was 18' X 210'

To determine the size of the "stubs" occurring following retreat mining, Western Environment sequentially reduced the cross cut spacing input for the ARMPS from the average room length until a safety factor of approximately 1.5 was achieved. The other documented input values, including seam thickness (7.0'), depth of cover (114.5') and overburden load (135 pcf), were used. This resulted in the dimension of the stubs (the smallest pillars left in-place) being 10' X 18' for both mines.

Unfortunately no records exist as to the dimensions of the "stubs" produced during retreat mining of these or any other mines within the Boulder/Weld Field. However, Tomlinson (1933) indicates that in active Boulder/Weld mines, room widths ranged from 14 to 18 feet and stub size varies from 5' X 15' to 15' X 36' for extraction ratios of 82% to 76%, respectively. The calculated stub dimensions from the ARMPS program appear consistent with this contemporary record. The resulting extraction ratios produced are 84 % for both mines.

Therefore, assuming that the smallest pillar left in place is stable and that pillar failure is both geo-technically (Matheson, 1986) and empirically (Tomlinson, 1933) unlikely, the most plausible remaining failure mode would be roof falls. Again, Matheson (1987) indicates that with "assumed tensile strengths," roof spans for safety factors of near 1.0 would be approximately 12.0'. In his 1998 publication *The Role of Overburden Integrity in Pillar Failure*, Dr. van der Merwe states, "overburden in sedimentary rocks is vertically jointed and therefore tensile strength can be

ignored.” Additionally, he concludes, “roof failure will occur when horizontal compressive stress exceeds the unconfined compressive strength of the rock.”

To determine potential maximum stable roof spans, Western Environment back calculated widths until the safety factor approached 0.5. The 0.5 safety factor was chosen because we assumed that roof failure would be imminent when the safety factor was near 50%. By simplistically vectoring the vertical load from 114.1 feet of overburden, at a density of 135 pcf, the resulting compressional stress of 1,702 psi at a safety factor of 50% produces a span width of 16.0 feet. This roof span is consistent with predications in the Matheson study, 12.0 feet and the 14.0 to 18.0 foot room widths reported by Tomlinson (1933).

As previously discussed, some of our colleagues have concluded that construction is feasible in areas that Western Environment has indicated as developable only with building restrictions. However, the difference in the conclusions are that some investigators place “No restrictions or special building requirements” while the NCB developed recommendations utilized by Western Environment propose structure type, length and height restrictions.

To reconcile this difference of opinion, Western Environment researched and evaluated the subsidence mechanisms referenced in the reports recommending no restrictions. The competing investigators references Piggot and Eynon (1977) that states “subsidence will not propagate to the ground surface over room and pillar workings where the overburden to extraction thickness ratio (H/h) exceeds 10.” Additionally, these studies quote Piggot and Eynon (1977) indicating that “Caving of the roof above a mine can continue until the extraction and collapse area is filled with broken and bulked rock or caving reaches the surface” using a bulking factor of 40%. This conclusion results in recommendation that “residential or commercial construction is feasible in areas where the mine is greater than 90 feet in depth.” However, the acceptance of this conclusion requires that no records of significant effects of subsidence has ever occurred in the Boulder/Weld Field when the mine is greater than 90 feet in depth.

In a paper presented at the 1985 Conference on Coal Mine Subsidence in the Rocky Mountain Region, Sherman (1986) inventoried structural damage to over 100 buildings in the Louisville and Lafayette (Boulder/Weld) area constructed prior to mining. The results of this study were used to confirm, if not the validity, the conservatism of using the British National Coal Boards (NCB) Graphical Strain Profiling Method. Subsequently, the study also determined that “no two-story brick buildings constructed prior to mining survived through the late 1920's.” This investigation, together with other studies (Amuedo and Ivey, 1975) and reports of damage to buildings and roads in local newspapers, indicate that surface subsidence as a result of coal mining has occurred throughout the Boulder/Weld area at mining depths much greater than 90 feet.

Oravec (1977), in a paper entitled *Measurement of Surface Displacement Caused by Extraction of Coal Pillars* states “From the point of view of the induced displacement field, the method of pillar extraction (pillar retreat) lies somewhere between the methods of board and pillar (room and pillar) and longwalling. In the development stage it is equivalent to board and pillar mining, when already a considerable proportion of the seam has been extracted without disturbing the roof strata significantly. In the stage when the pillars are extracted the roof strata are induced to cave just as in longwall faces.” This conclusion is consistent with Sherman (1984) that states “ V_z (percentage of maximum possible subsidence, S_{max}) for the Boulder/Weld field would be on the order of 20% of the NCB predicted value.”

The subsidence prediction method employed by Western Environment, the NCB Graphical Strain Prediction method, was developed for long wall mining methods. As previously stated, it is our contention that the pillar retreat method used in the larger more complex mines more closely resembles the long wall method in recovery percentage and surface subsidence (Oravec, 1977) and (Sherman, 1986) then the classical room and pillar method evaluated by Piggot and Eynon (1977) and used by some of our colleagues. However, the use of the Piggot and Eynon (1977) research regarding collapse and bulking is valid when mining techniques or mine geometry is similar to room and pillar extraction methods or following the post-extraction collapse of mines that utilize the pillar retreat method.

Nonetheless, we feel that with the inherent and irreconcilable uncertainties associated with abandoned mine subsidence prediction, additional conservatism must be incorporated in all proposed development. The proven conservatism inherent in the NCB method meets this requirement, and its results are within the range of values of predicted and observed subsidence events.

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