The Current Perspective of the Pennsylvania 1957 Gas Well Pillar Study and Its Implications for Longwall Gas Well Pillars

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ABSTRACT

Many states rely upon the Pennsylvania 1957 "Gas Well Pillar Study" to evaluate the coal barrier surrounding gas wells (Commonwealth of Pennsylvania, 1957). The study included 77 gas well failure cases that occurred in the Pittsburgh and Freeport coal seams over a 25-year span. At the time, coal was mined using the room-and-pillar mining method with full or partial pillar recovery, and square or rectangle pillars surrounding the gas wells were left to protect the wells. The study provided guidelines for pillar sizes under different overburden depths up to 700 ft. The 1957 study has also been used to determine gas well pillar sizes in longwall mines since longwall mining began in the 1970s. The original study was developed for room-and-pillar mining and could be applied to gas wells in longwall chain pillars under shallow cover. However, under deep cover, severe deformations in gas wells have occurred in longwall chain pillars. Presently, with a better understanding of coal pillar mechanics, new insight into subsidence movements induced by retreat mining, and advances in numerical modeling, it has become both critically important and feasible to evaluate the adequacy of the 1957 study for longwall gas well pillars.

In this paper, the data from the 1957 study is analyzed from a new perspective by considering various factors, including overburden depth, failure location, failure time, pillar safety factor (SF), and floor pressure. The pillar SF and floor pressure are calculated by considering abutment pressure induced by full pillar recovery. A statistical analysis is performed to find correlations between various factors and helps identify the most significant factors for the stability of gas wells influenced by retreat mining. Through analyzing the data from the 1957 study, the guidelines for gas well pillars in the 1957 study are evaluated for their adequacy for room-and-pillar mining and their applicability to longwall mining. Numerical modeling is used to model the stability of gas wells by quantifying the mining-induced stresses in gas well casings. Results of this study indicate that the guidelines in the 1957 study may be appropriate for pillars protecting conventional gas wells in both room-and-pillar mining and longwall mining under overburden depths up to 700 ft but may not be sufficient for protective pillars under deep cover. The current evaluation of the 1957 study provides not only insights about potential gas well failures caused by retreat mining but also implications for what critical considerations should be considered to protect gas wells in longwall mining.

INTRODUCTION

Coal, oil, and natural gas have coexisted for more than a century in the Northern Appalachian coalfields of Pennsylvania, West Virginia, and Ohio. In 1913, the U.S. Bureau of Mines held a conference on the topic in Pittsburgh, Pennsylvania, with operators from both industries. The *Proceedings* from this conference cited instances of mine explosions attributed to wells that permitted gas migration through the mine floor, well failures in insufficiently supported areas of mining panels, and active and abandoned wells intersected by mine development (Rice and Hood, 1913). U.S. Bureau of Mines Chief Mining Engineer George S. Rice opened an October 1914 discussion on the topic by stating, "Undoubtedly there is a serious problem through the juxtaposition of gas and oil wells and coal mines, not only at the present time, but possibly of far more serious import for the future" (AIME, 1915).

The ensuing decades have no recorded instances and reports of wells causing gas inundations in mines, but coal mining did cause a number of well failures. In 1955, the Commonwealth of Pennsylvania addressed these and other concerns by passing the Gas Operations, Well-Drilling, Petroleum, and Coal Mining Act. The Act required that a pillar of coal be left around any oil or gas well that penetrated an active coal mine. The Act only defined the maximum size of pillar to be left, however, and did not specify the minimum pillar size. Accordingly, the Joint Coal and Gas Committee was formed in 1956 to conduct a cooperative engineering study to develop specific recommendations regarding the size of protective gas well pillars.

THE 1957 GAS WELL FAILURE DATA SET

The Joint Coal and Gas Committee solicited information on well failures from the oil and gas companies and then obtained mining data on each of the case histories from the coal companies. The

Figure 1. Portion of a mine map from southwestern PA during the hand-loading era, showing three gas well pillars completely surrounded by pillar recovery.

data set initially consisted of 77 case histories of gas well failures. Three of the cases were considered "not usable" because they involved a gob well or mining into the well, and two more did not have sufficient data for analysis. The definition of "failure" for the remaining wells was that they stopped producing gas because they were "sheared or pinched off." Presumably, the well blockages were confirmed by attempts to re-enter the well, because the location (depth in the well) of the failure is recorded in each case. The report does not make any mention of gas inundations associated with any of the well failures.

The mining in all but three of the cases occurred between 1925 and 1956. At the start of that period nearly all the coal in the United States was loaded by hand, but by the end of the span of years, loading machines were used for more than 80% of underground production. Even in 1956, however, continuous miners were still in their infancy (Mark, 2002). Well failures occurred at an almost constant rate over the three-decade study period.

Most of the case histories in the study were from the Pittsburgh seam in southwestern PA, with a sprinkling of cases from the Freeport seam. In 1935, the Bureau of Mines published a detailed study of the mining methods used in the Pittsburgh seam. Except for a handful of small mines in Ohio and the West Virginia panhandle, every mine they studied employed one of a large variety of full pillar recovery techniques, and typically recovered more than 80% of the coal (Paul and Plein, 1935). Figure 1 is a portion from a mine map dating from the 1930s that shows three gas wells and the protective pillars left around them. The pillars are essentially islands entirely surrounded by caved gob. Only 13 of the case histories in the 1957 data set were described as partial extraction, apparently development only, with a reported extraction of about 50% of the coal. The others involved pillar recovery, with reported extraction ratios averaging 90%.

The "minimum mining radius" (setback distance) was defined as "the shortest distance from the well on the surface to a mined-out area." Figure 2 plots the setback distance against the depth of cover for the entire data set. It shows that a number of the partial recovery cases fall at the extremes of the data set. Three of these partial recovery cases had the largest setback distances in the data set, another has the smallest, and two had the shallowest depths of cover. It seems likely that atypical failure mechanisms were at work in these case histories. Therefore, the partial pillar cases were excluded from the current re-analysis, leaving 59 cases in the final data set for this analysis.

The mining heights in the remaining case histories ranged from 5 to 8 ft, and the depth of cover was less than 650 ft in all but three cases. As the report noted, "no failures were reported from thinner seams." The floor was described as fireclay in almost all the case histories, though in only 15 cases was it described as both "soft" and "wet." The surface topography was described as a "steep slope" in just one case, and in all the others it was a "gentle slope," the "top of a hill," or "level." The minimum mining radius averaged 38 ft, and it only exceeded 50 ft in a couple of cases. The smallest pillar dimension (width) of the protective pillar was between 50 and 100 ft in 85% of the cases.

The 1957 report's authors noted that they originally expected to find that failures would have "occurred above the coal horizon, [caused] by the action of the draw" (subsidence). However, the great majority of the failures occurred within or below the seam, leading them to conclude that "pillar failure was the cause of the damage." Of the 54 full extraction cases for which data is available, only 10 failures actually occurred in the roof, compared with 24 in the seam and 20 below the seam. All of the failures in the roof occurred within 100 ft of the seam, while the deepest floor failure was 34 ft below the seam.

Of the 46 cases for which data was available, approximately half occurred during or within two years of the completion of mining. Surprisingly, nearly 40% occurred more than five years after mining. Figure 3 plots the time to failure of the case histories against their depth of cover. The figure indicates that while failures seem to occur sooner under deeper cover, the location of the failure is only weakly correlated with the time elapsed.

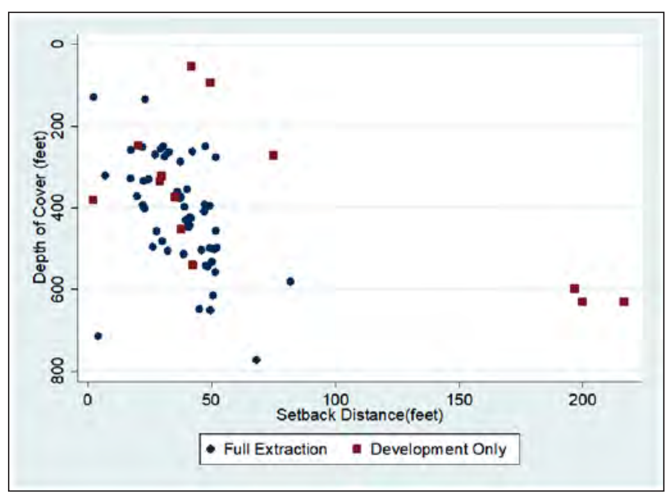

Figure 2. Setback distance and depth of cover for the entire 1957 data set, showing both full and partial extraction (development) case histories.

STATISTICAL ANALYSIS OF THE 1957 STUDY DATA

Figures 2 and 3 indicate that there are no strong trends that are immediately apparent within the 1957 data set. A detailed statistical evaluation was conducted to test whether subtle trends could be discerned. Prior to the analysis, several new parameters were calculated using the data:

- *Support angle* (calculated as the arctangent of the minimum mining radius divided by the seam depth)
- *Average pillar stress* (calculated assuming full extraction in all directions around the support pillar (see Figure 4)
- *Pillar safety factor* (calculated using the Mark–Bieniawski pillar strength formula and the average pillar stress).

Pairwise correlations were done for the entire data set (Table 1) and then for several subgroups. As expected, the depth of cover, support angle, average pillar stress, and pillar safety factor (SF) all correlated with each other in every analysis. Some more meaningful correlations were as follows:

- Under deeper cover, failures tended to occur rapidly (Figure 3).
- When the floor was reported to be soft (weak and wet), there was some tendency for failures to occur later (Figure 3) and to be located in or below the seam (Figure 5).
- Failures in the roof occurred at shallow and moderate depths, but none occurred when the depth exceeded 550 ft (Figure 2).

Pairwise correlations test only the relationships between two variables at a time. Evaluating the simultaneous relationships between

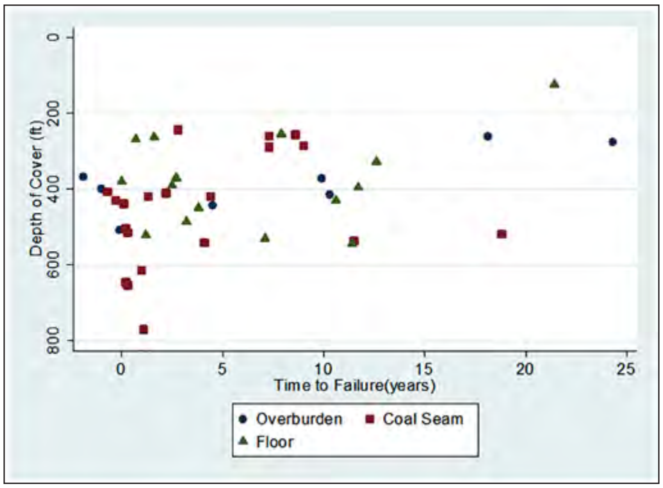

Figure 3. Depth of cover and time to failure of the well failures.

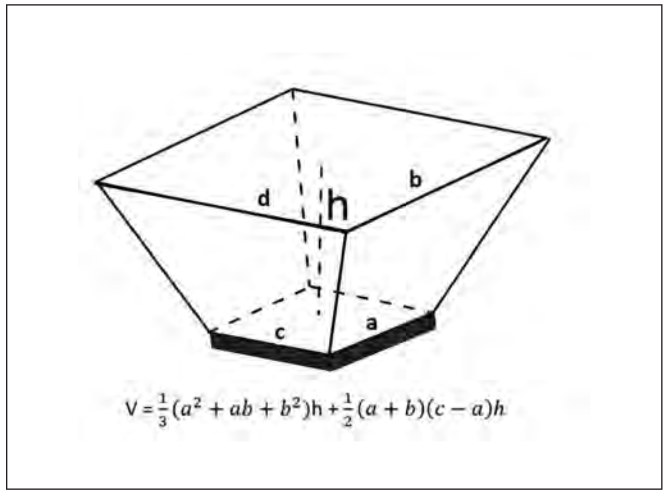

Figure 4. Schematic of the volume of overburden (V) used to calculate the average pillar stress applied to the gas well protective pillars in the data set, where *h* is the depth of cover and *a* and *c* are pillar dimensions. The maximum value of *d* = *c* + 300 ft and of *b* = *a* + 300 ft, to account for the effect of barrier pillars and other unmined remnants.

Table 1. Pairwise correlations obtained for the entire data set. Statistically significant correlations (at about the 90% level or above) are shown in green.

	Depth of cover	Support angle	Pillar stress	Pillar SF	Soft floor	Time of failure	Location of failure
Depth of cover	1.000						
Support angle	–0.363	1.000					
	0.005						
Pillar stress	0.708	–0.689	1.000				
	0.000	0.000					
Pillar SF	–0.479	0.705	–0.706	1.000			
	0.000	0.000	0.000				
Soft floor	0.047	0.195	–0.142	0.0607	1.000		
	0.722	0.143	0.293	0.654			
Time of failure	–0.382	–0.084	–0.226	0.107	0.238	1.000	
	0.009	0.585	0.146	0.493	0.112		
Location of failure	0.089	0.093	0.093	0.156	0.956	0.249	1.000
	0.522	0.512	0.416	0.264	0.000	0.103	

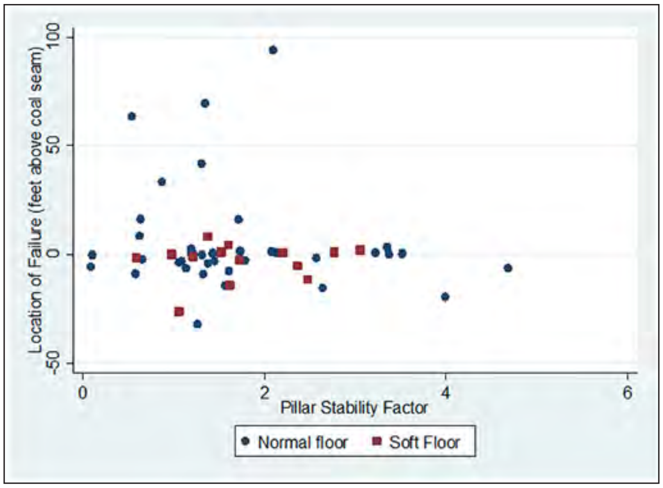

Figure 5. Location of the failures relative to the coal seam and the pillar SFs, for normal and soft floor.

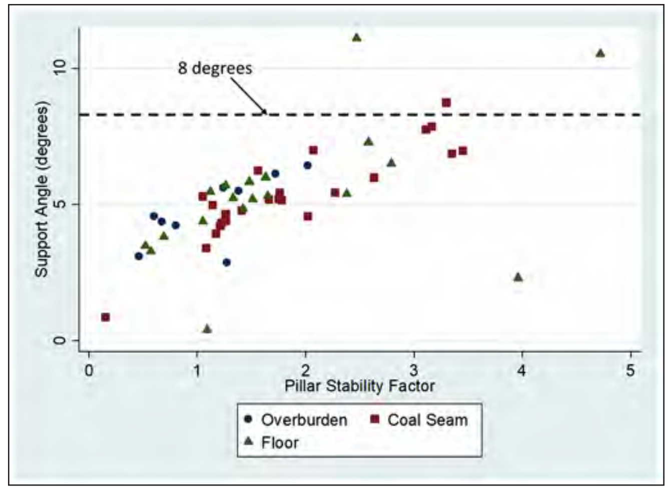

Figure 6. The calculated angle of failure versus the calculated pillar SF, showing the 8-degree support angle identified by the 1957 study.

all the variables requires multivariate techniques. Logistic regression was used in this instance. Logistic regression requires a dichotomous (two-level) outcome variable. However, since all of the cases in the 1957 data set are failures, some other outcome must be analyzed. Two other outcomes are available:

- Location of failure (roof versus coal/floor), and
- Time to failure (failure delayed more than 5 years versus failure during or within 5 years of mining).

Neither of these models resulted in convincing goodness-of-fit values. The best result indicated that delayed failure was associated with shallower depths of cover, but this result was already observed in Figure 3 and in the pairwise evaluations.

In summary, it does not appear that in-depth re-evaluation of the 1957 database via statistics reveals much new information. The 8-degree failure envelope identified by the Committee remains the most useful trend within the data (Figure 6). Another observation, again first noted by the Committee, is the scarcity of overburden failures within this data set. Given the recent insights into unconventional subsidence, the apparent lack of such failures warrants explanation.

EVALUATION OF THE 1957 STUDY FOR ROOM-AND-PILLAR MINING

After the 1957 guidelines were adopted for gas well pillar sizes in room-and-pillar mining, few cases of gas well failures were reported in Pennsylvania. The improvement of gas well stability was largely attributed to larger pillar sizes required by the guidelines. The change in mining practice in room-and-pillar mining after the 1950s may also have contributed to the stability of gas wells. With wide use of continuous miners for coal cutting and roof bolters for roof bolting, standard panels were laid out and barrier pillars and stumps were left in places where pillars were previously fully recovered. Narrower panels and stumps would have helped gas well stability by reducing the amount of subsidence as well as abutment pressure.

On the other hand, it is possible that gas wells were only considered failures if gas production was significantly affected by mining. Mining could still have caused large deformations in gas well casings, but unless the wells were inspected there would have been no way of knowing.

The 1957 study showed that gas well failures can be located in the roof, in the pillars, or in the floor. In the following paragraphs, each of those potential locations will be evaluated using the 1957 data and guidelines. In addition, numerical modeling will be used to calculate induced stress in gas well casings for comparison with the strength of the casings.

Figure 7 shows the pillar sizing guidelines presented in the 1957 study. Pillar SF values are calculated for each of the pillar configurations shown, using the loading model illustrated in Figure 4. Figure 8 compares those calculated SF values with the SF of the pillars in the 1957 database. The figure shows that the guidelines result in SF values that are greater than 2.0 when overburden depth is less than 450 ft, but the values reduce to about 1.0 when overburden depth is greater than 550 ft, due to the presence of entries within the pillar bearing area. At these greater depths, the gas well is still surrounded by a 100- by 100-ft-wide solid pillar with a width-to-height ratio of about 15. Such a squat pillar will deform in response to a large load, but it should not collapse.

Minimum distances from the gob can also be calculated from the 1957 data set. The distance to the gob not only affects the induced vertical pressure at the gas well but also the amount of subsurface strata movements at the well. By increasing pillar bearing area and placing gas wells at the center of the pillars, the 1957 guidelines moved gas wells away from the peak abutment pressure zone and also further away from gob. As shown in Figure 9, the gob distances set by the 1957 guidelines exceed those in nearly all the failure cases, especially under deep cover. However, the 1957 study also defined a maximum setback distance of 50 ft from the nearest entry, and a number of the failures did maintain a 50-ft setback.

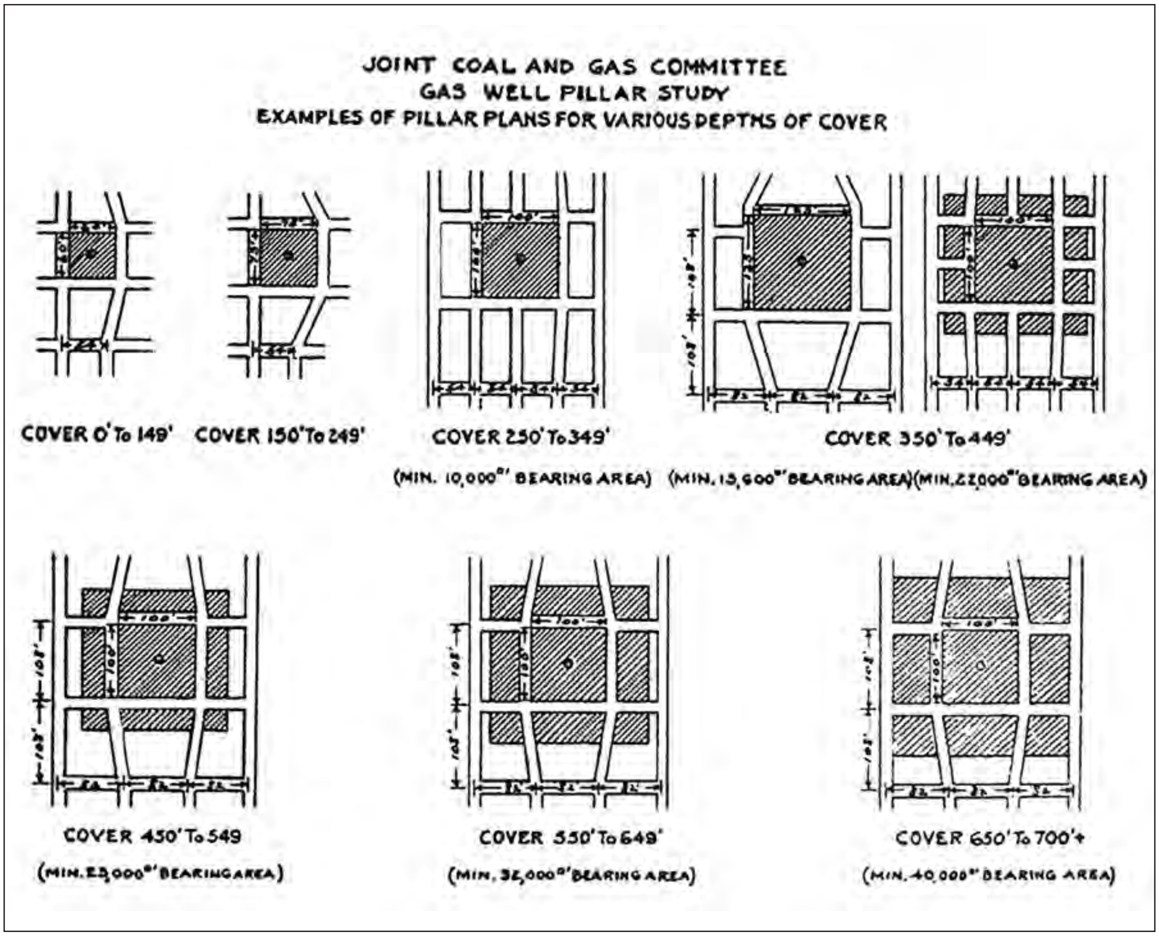

Figure 7. Pillar sizing guidelines presented in the 1957 study.

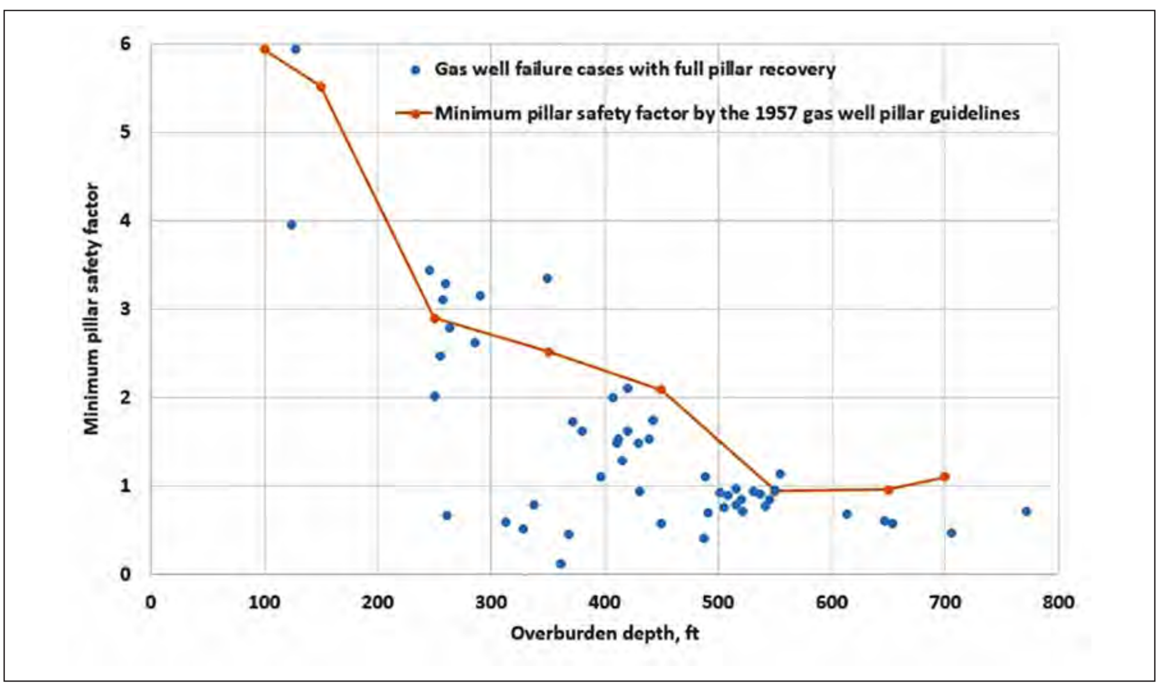

Figure 8. Pillar SF by the 1957 guidelines in comparison with the SF of the pillars in the failure cases.

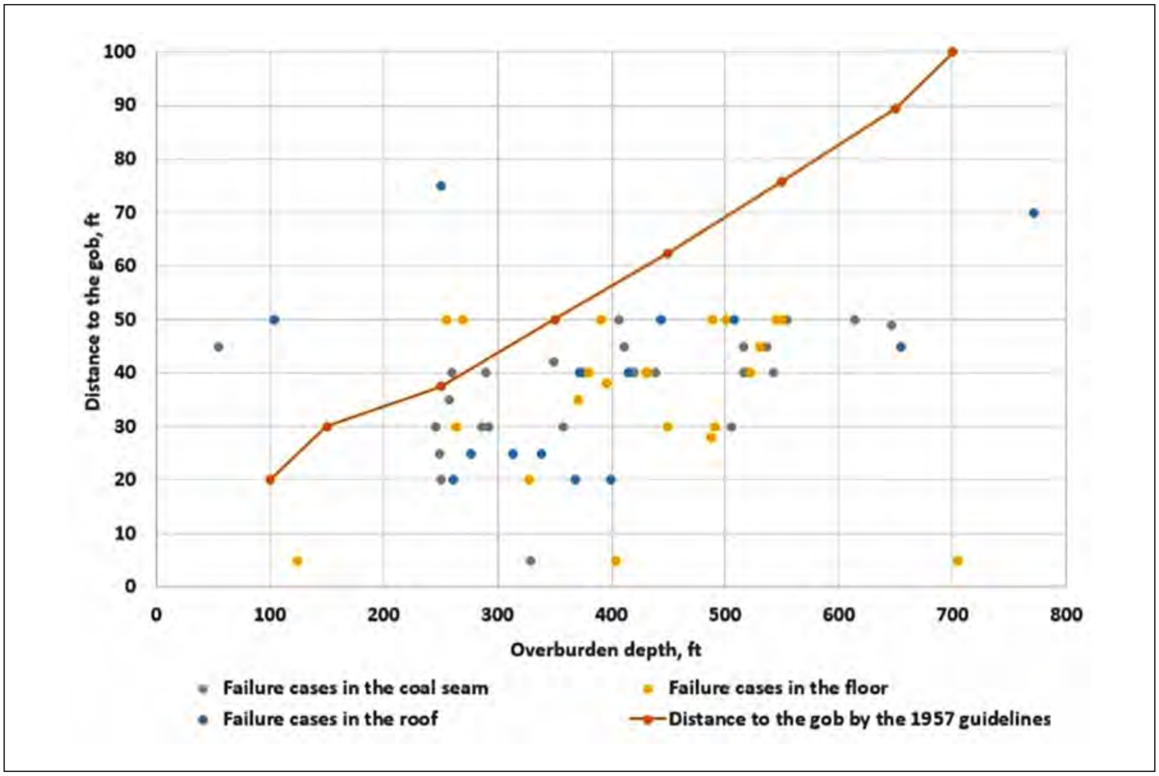

Figure 9. Distance of the gas well to the gob by the 1957 guidelines in comparison with the distance to the gob from the failure cases in the 1957 study.

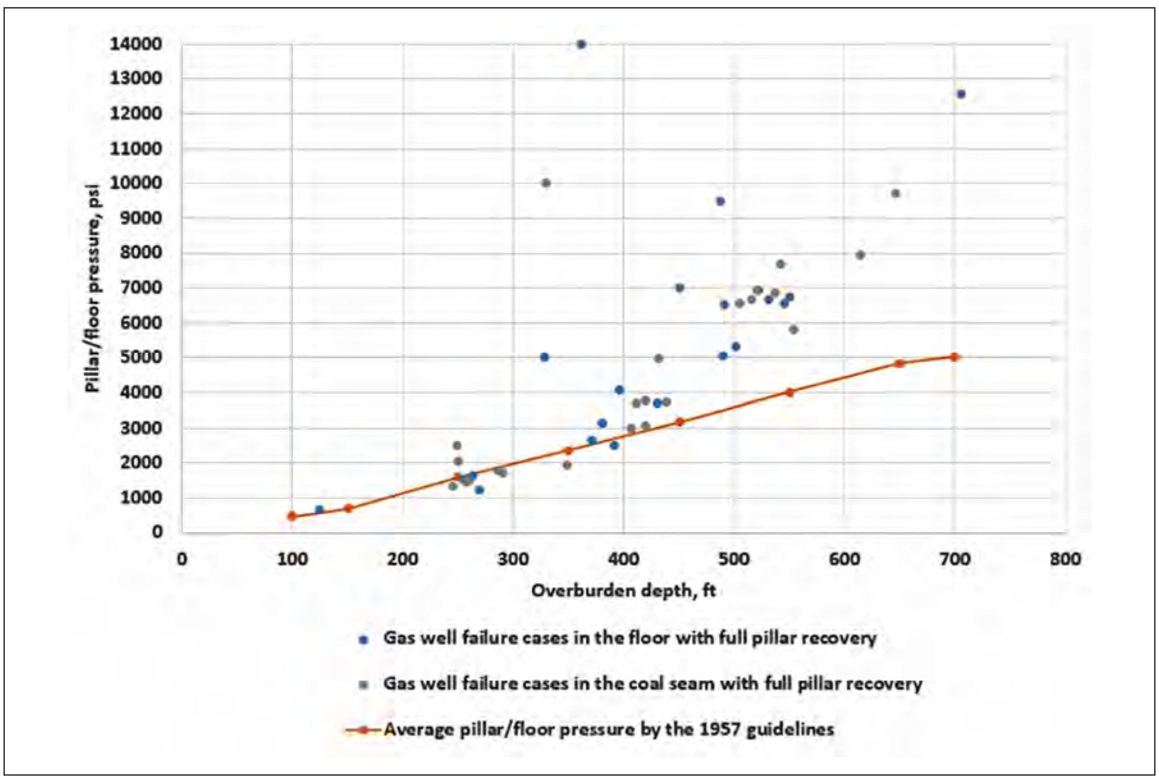

Figure 10. Calculated average pillar/floor pressure for the pillars by the 1957 guidelines in comparison with the calculated pillar/floor pressure for the failure cases in the coal seam and floor.

The 1957 study showed that about 82% of the gas well failures occurred within 20 ft of the coal seam horizon. Those failures are largely associated with high pressure in the coal seam and floor. The 1957 guidelines reduced the possibility of failures around the coal seam horizon by reducing pillar and floor pressure as shown in Figure 10. Following the 1957 guidelines, the average pillar and floor pressures increase linearly with overburden depth. Under deep cover, the average pillar/floor pressure is high in the worst case with gobs on four sides of the pillar, and gas well failures are still possible.

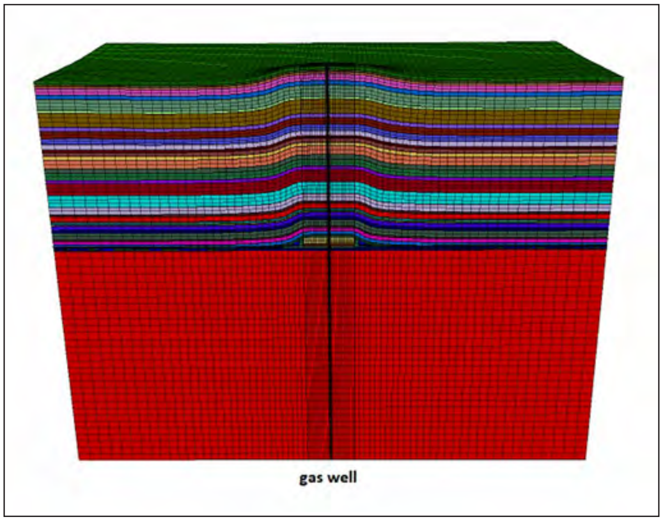

Figure 11. FLAC3D model to calculate induced stresses in gas well casings.

In addition to the evaluation of pillar stability and floor pressure, it is also important to evaluate the response of the gas well casings to the abutment pressure and subsurface movements. To calculate induced stresses in gas well casings utilizing the 1957 guidelines, FLAC3D modeling (Itasca, 2017) is used to model vertical stress distribution over the gas well pillars, as well as response of gas well casings to abutment pressure and overburden movements in room-and-pillar mining with full pillar recovery. Figure 11 shows a three-dimensional (3-D) view of the FLAC3D model. To evaluate the 1957 guidelines, a single squared gas well pillar is modeled for overburden depth up to 450 ft, but a squared pillar surrounded by small pillars is modeled for overburden depth greater than 450 ft. In the 1920s era, typical gas and oil wells intersecting coal seams had three casings, that is, production casing, intermediate casing, and coal protection casing (Draper, 1964). Therefore, three casings are used in the model. The modeling procedure is similar to modeling of gas wells in longwall chain pillars. The model uses typical overburden geology for the Pittsburgh seam. The details of modeling gob material can be found in Tulu et al. (2017), and modeling of gas wells in longwall pillars can be found in Zhang et al. (2019).

Figure 12 shows the vertical stress distribution over a gas well pillar surrounded by gob on two and four sides of the pillar under 700-ft overburden depth. The calculated vertical stress is about 1,500 psi with gob on two sides and about 2,400 psi with gob on four sides. Other cases are also modeled for gas well pillars following the 1957 guidelines for overburden depth from 350 ft to 700 ft.

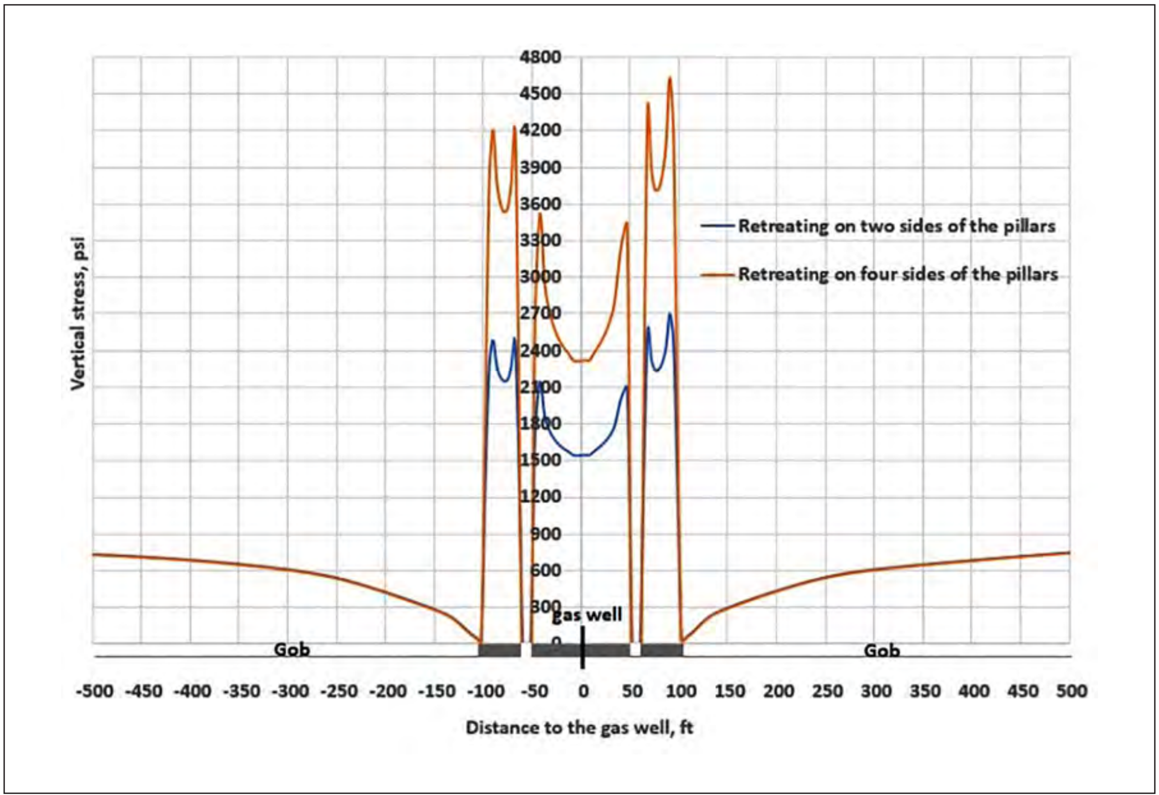

Figure 12. Vertical stress distribution after pillar retreating on two and four sides of the pillar.

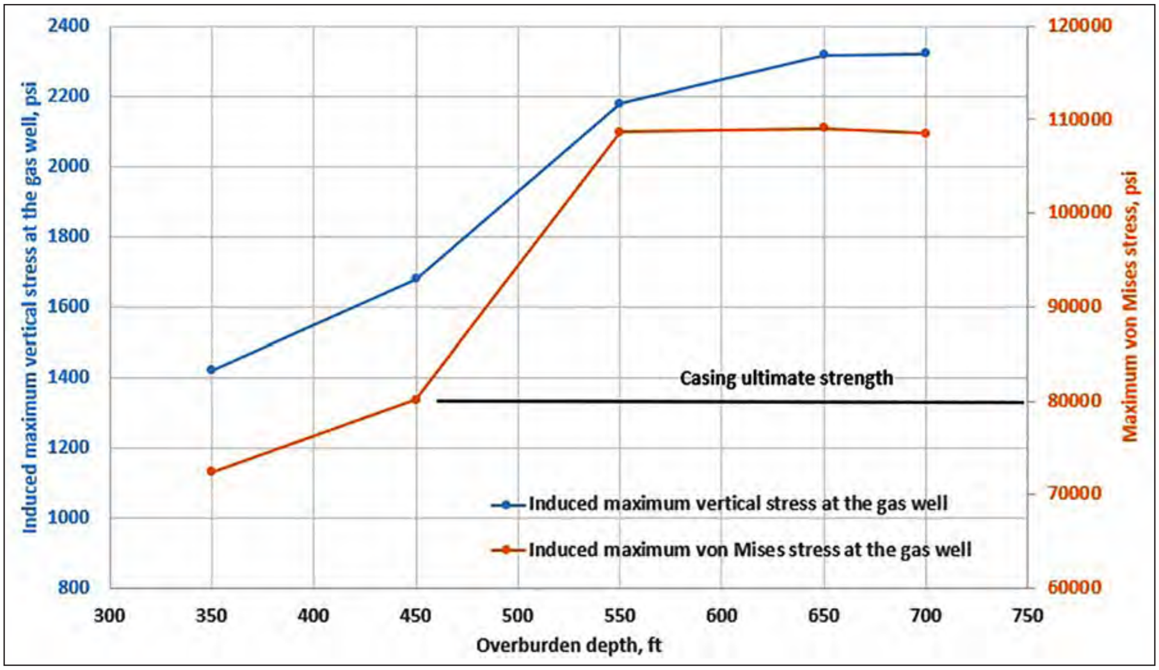

Figure 13. Induced vertical stress in the pillar at the gas well and induced maximum von Mises stress in the gas well casings under different overburden depths.

Von Mises stress is a widely used criterion for steel failure, and an equivalent von Mises stress calculated in FLAC3D is used for casing yielding. Figure 13 shows the predicted induced vertical stress in the pillars at the gas well and the predicted induced maximum von Mises stress in the coal protection casing under different overburden depths. The pillar sizes under different overburden depths follow the 1957 guidelines. The induced vertical stress in the pillar at the gas well increases with overburden depth, with a predicted maximum induced vertical stress of 2,350 psi when overburden depth is 700 ft. The induced von Mises stress also increases with overburden depth, such that when overburden depth is greater than 450 ft, the predicted induced von Mises stress in the coal protection casing could exceed the ultimate strength of the casing, in which case large casing deformation could occur. The amount of the induced stress in the coal protection casing demonstrates that even though the gas well pillar sizes follow the 1957 guidelines, casing yielding and large deformation could still occur when full pillar recovery is performed on four sides of the gas well pillars.

In summary, the 1957 guidelines greatly helped prevent gas well failures in room-and-pillar retreat mining under overburden depth less than 700 ft by ensuring large pillars and maintaining appropriate setback distance to the gob as well as sufficiently low floor pressure. However, the guidelines are not conservative under worst case scenarios, and gas well casing failure can still occur following the guidelines under certain high stress conditions if the gas well pillars are surrounded by retreat gobs on three or four sides.

EVALUATION OF THE 1957 STUDY FOR LONGWALL MINING

To evaluate the applicability of the 1957 study to longwall mining, it is important to understand that the mining parameters and mining process in the cases of the 1957 study are different than in longwall mining. A comparison of mining parameters of the 1957 cases with those in longwall mining in the Pittsburgh seam is shown in Table 2. Mining depths in the 1920s−1950s were typically much shallower than depths of current longwall mining in the Pittsburgh seam. As much of the mining was done by drilling, blasting, and hand loading, the mining height was also restricted to only the Pittsburgh coal thickness. Because of equipment size and production demands, modern longwall typically cuts higher than selective mining methods of years past. The mining panels in room-and-pillar mining were generally narrower, though some retreat

Table 2. Mining parameters in the 1957 case history compared with with tyipcal current Pittsburgh seam longwall.

Mining Parameter	1957 Cases	Typical Current Longwall Mining
Overburden depth	Less than 700 ft	700−1,300 ft
Mining height	6−7 ft	6.5−8.5 ft
Entry width	12−15 ft	16 ft
Panel width	300−500 ft	1,200−1,500 ft
Development	Drilling and blasting	Continuous bolter miner
Mining direction	on all sides	Parallel to chain pillars
Time for mining by a gas well	Six months to one year	One to two months
Coal extraction ratio	80%−100%	100%
Surface subsidence	Less than 2.0−3.0 ft	3.5−5.5 ft
Subsidence period	Could be several years	About one year

panels had long break lines. The coal extraction ratio in room-and-pillar mining with full recovery is less than in longwall mining. Room-and-pillar mining generally left coal stumps at pillar corners during pillar recovery, and it is difficult to achieve a 100% coal extraction ratio. Therefore, the surface subsidence caused by pillar recovery under shallow cover was small.

A study by GAI Consultants in 1977 reported that in western Pennsylvania, total extraction mining of the Pittsburgh coal resulted in long-term subsidence amounting to 2–3 ft maximum for gob areas equaling or exceeding the critical width. The critical width was estimated in western Pennsylvania to be 1.5–1.6 times the overburden depth. The surface subsidence caused by pillar recovery also took a longer time to develop. In comparison, modern longwall panels are much wider, and the longwall face advances at a much faster rate than room-and-pillar retreat mining, making the subsidence basin supercritical and subsidence period shorter. With wider panels and 100% coal extraction in longwall mining, caving and fracturing in the overburden are also developed higher than in room-and-pillar mining. Therefore, potential gas well failure could occur at higher horizons above the coal seam in longwall mining than in the cases of the 1957 study.

The comparison of room-and-pillar mining and longwall mining shows that both mining methods influence gas well stability by inducing abutment pressure and subsurface movements over gas well pillars, although the magnitude and extent of abutment pressure and subsurface movements are different. As longwall chain pillars have gob on either one or two sides, the gas well pillars and casings are subjected to less influence by the abutment pressure than in full extraction room-and-pillar mining. But, larger mining heights and wider panels in longwall mining may increase the horizontal movement in the overburden. As the influence factors to gas wells in longwall mining are similar to room-and-pillar mining, the potential gas well failures in longwall mining also occur in the coal seam, in the floor, and in the roof or overburden. The failure cases of the 1957 study imply that potential gas well failures are more likely to occur around the coal seam horizon in longwall mining, especially under deep cover. To evaluate the applicability of the 1957 study to longwall mining, the next step is to understand how the chain pillar sizes following the 1957 guidelines affect the stability of gas well casings in the coal seam horizon.

FLAC3D modeling was conducted using typical Pittsburgh seam overburden geology to calculate the induced stress in the pillars and gas well casings. The modeling focused on gas well stability around the coal seam horizon. The chain pillars are developed with a three-entry system with gas wells located around the center of the chain pillars. The chain pillars have a minimum ACPS pillar safety factor greater than 1.62 under overburden depth of 1,000 ft with isolated loading. Table 3 shows the numerical modeling results for longwall chain pillars following the 1957 guidelines under different overburden depths up to 1,000 ft.

The numerical model, developed by researchers at the National Institute for Occupational Safety and Health (NIOSH), has been calibrated with several cases for gas well pillars in the Pittsburgh coal seam (Su, 2016; Su et al., 2018, 2019; Zhang et al., 2019). To validate the model for prediction of vertical deformation, the predicted surface subsidence is compared with the measured surface subsidence above the center of the chain pillars in the Pittsburgh coal seam as shown in Figure 14. The subsidence above the chain pillars was measured under similar mining conditions in the Pittsburgh seam (Luo, Peng, and Chen, 1997; Su et al., 2018). The surface subsidence at the gas well indicates the amount of overburden deformation and chain pillar/floor squeezing caused by abutment pressure. The higher the surface subsidence is at the gas well, the higher the induced compressive and shear stresses within and adjacent to the pillar; and thus higher the induced stresses in the gas well casings.

The vertical stress in the coal seam at the gas wells is determined based on the vertical stress distributions over the chain pillars. Figure 15 shows the vertical stress distribution over the chain pillars

Table 3. Modeling results for longwall chain pillars following the 1957 guidelines under different overburden depth.

Overburden depth, ft	**350**	**450**	**550**	**650**	**700**	**800**	**900**	**1,000**
Total chain pillar width (rib-to-rib), ft	116	148	152	179	200	200	200	200
Chain pillar width (rib-to-rib), ft	76, 24	100, 32	104, 32	119, 44	140, 44’	140, 44	140, 44	140, 44
Setback distance of the gas well to the gob, ft	40	50	54	79	100	100	100	100
ACPS pillar SF (isolated loading)*	3.78	3.84	2.86	2.70	2.87	2.33	1.93	1.62
Predicted pillar/floor vertical stress at the gas well after mining on both sides of the chain pillars, psi	844	1,020	1,242	1,395	1,500	1,743	2,010	2,315
Induced vertical stress in the coal pillar at the gas well after mining on both sides of the chain pillars, psi	459	525	637	680	730	863	1,020	1,215
Induced maximum von Mises stress in the production casing after first panel mining, psi	10,388	13,953	18,506	21,000	23,383	25,991	29,147	33,751
Induced maximum von Mises stress in the production gas well casing after second panel mining, psi	32,212	34,8964	47,006	49,014	47,717	59,878	72,736	81,917
Predicted surface subsidence at the gas well, inches	1.12	1.61	2.40	2.79	3.11	4.56	6.14	7.44

*The pillar SF is calculated by ACPS, Analysis of Coal Pillar Stability software (Mark and Agioutantis, 2018).

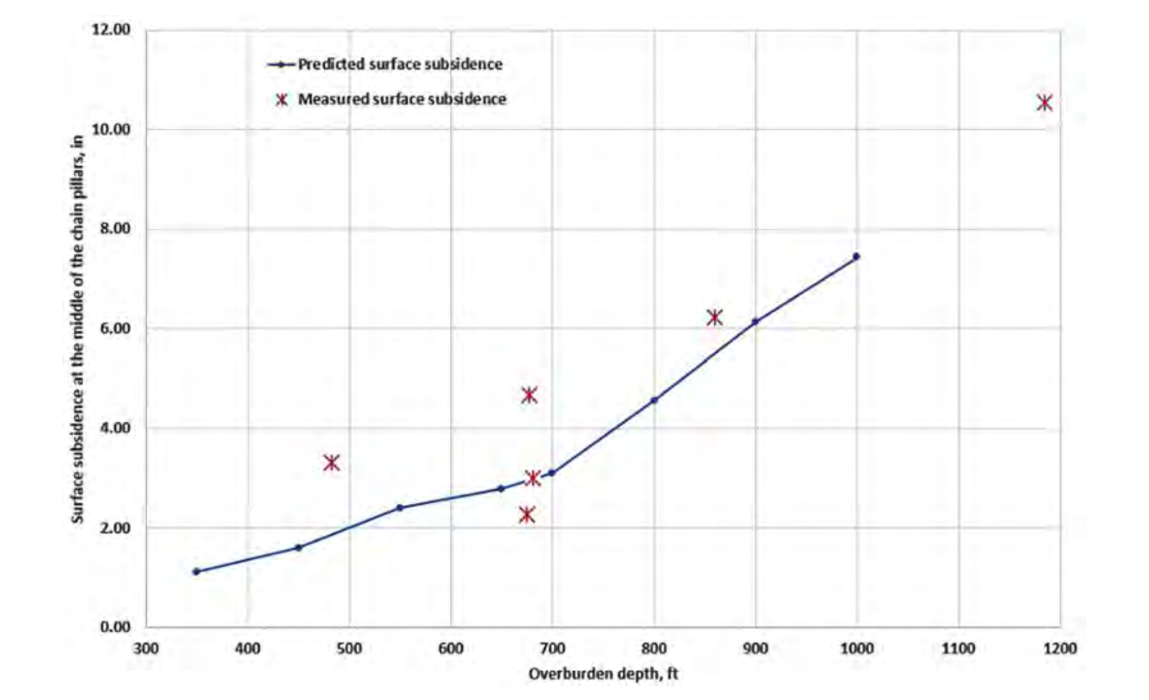

Figure 14. Surface subsidence at the gas well under different overburden depths.

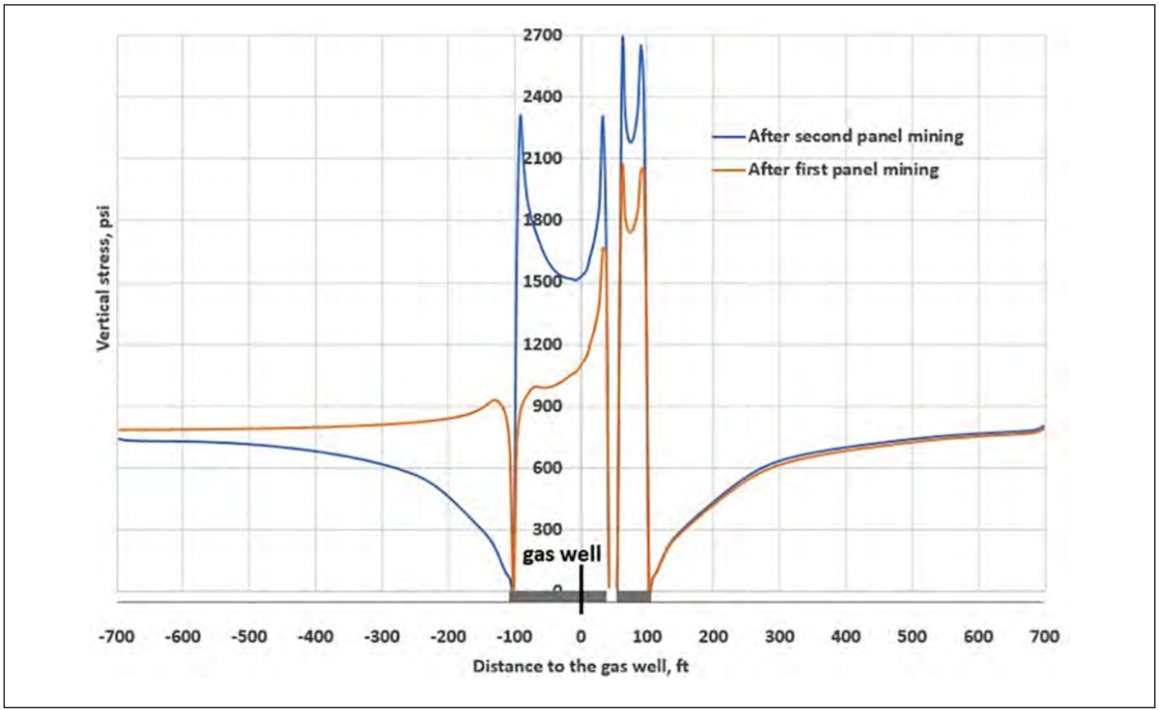

Figure 15. Vertical stress distribution over chain pillars under an overburden depth of 700 ft.

under overburden depth of 700 ft. The predicted vertical stress at the gas well after mining on both sides of the chain pillars is 1,500 psi. The induced vertical stress in the pillar at the gas well, which is the total vertical stress minus the overburden pressure, is 730 psi. Figure 16 shows the induced von Mises stress along the coal protection casing after mining on both sides of the chain pillars under overburden depth of 700 ft. With typical overburden geology in the Pittsburgh seam, the maximum von Mises stress occurs at the coal seam horizon, and its value is 51,181 psi, slightly less than the typical casing yield strength of 55,000 psi.

Figure 17 shows the predicted pillar and floor pressure and induced vertical stress at the gas well under different overburden depths. The pillar and floor pressure at the gas well increases almost linearly with overburden depth. When overburden depth is less than 700 ft, the pillar and floor pressure is less than 1,500 psi and the possibility of floor heave is low if the floor is dry. When overburden depth is 900 ft, the pillar and floor pressure increase to 2,000 psi, which increases the potential for floor heave. When the overburden depth is greater than 900 ft, the induced vertical stress is greater than 1,000 psi. Large deformations in gas well casings have occurred when induced vertical stress at the gas well is greater than 1,000 psi. The pillar and floor pressure are also calculated for chain pillar sizes following an 8-degree support angle as shown in Figure 17. It can be seen that with pillar sizes following an 8-degree support angle, the induced vertical stress at the gas well only increases slightly with overburden depth.

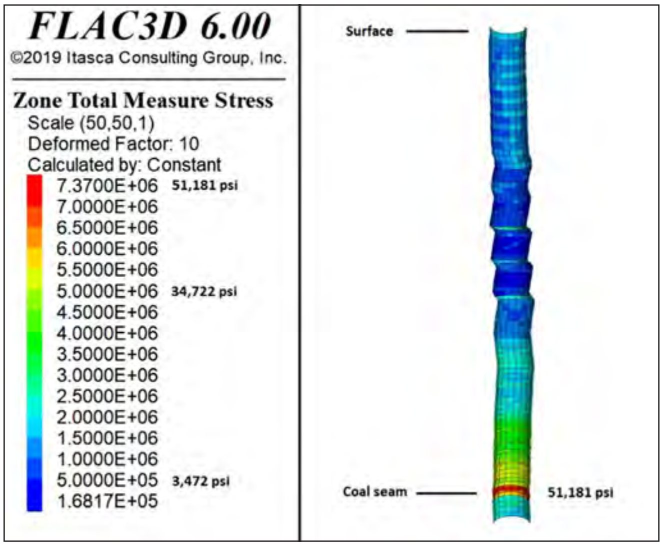

Figure 16. Induced von Mises stress along coal protection casing with an overburden depth of 700 ft.

Figure 18 shows predicted induced maximum von Mises stress in the coal protection casing under different overburden depth after mining of the first panel and second panel. The maximum induced von Mises stress is 32,000 psi up to an overburden depth of 1,000 ft after mining of the first panel, which is significantly less than the yield strength of gas well casings. The induced von Mises stress in coal protection casing increases greatly after mining of the second panel. When overburden depth is less than 750 ft, the induced von Mises stress in the coal protection casing is less than the yield strength of the casing. When overburden depth is 1,000 ft, the induced von Mises stress is over the ultimate strength of the casing. Casing yielding could occur when overburden depth is greater than 750 ft, but large casing deformations are likely to be observed when the induced von Mises stress is close to the ultimate strength of the casing.

Two cases of large casing deformation have been documented under overburden depth of 800–1,000 ft as shown in Table 4 (Scovazzo

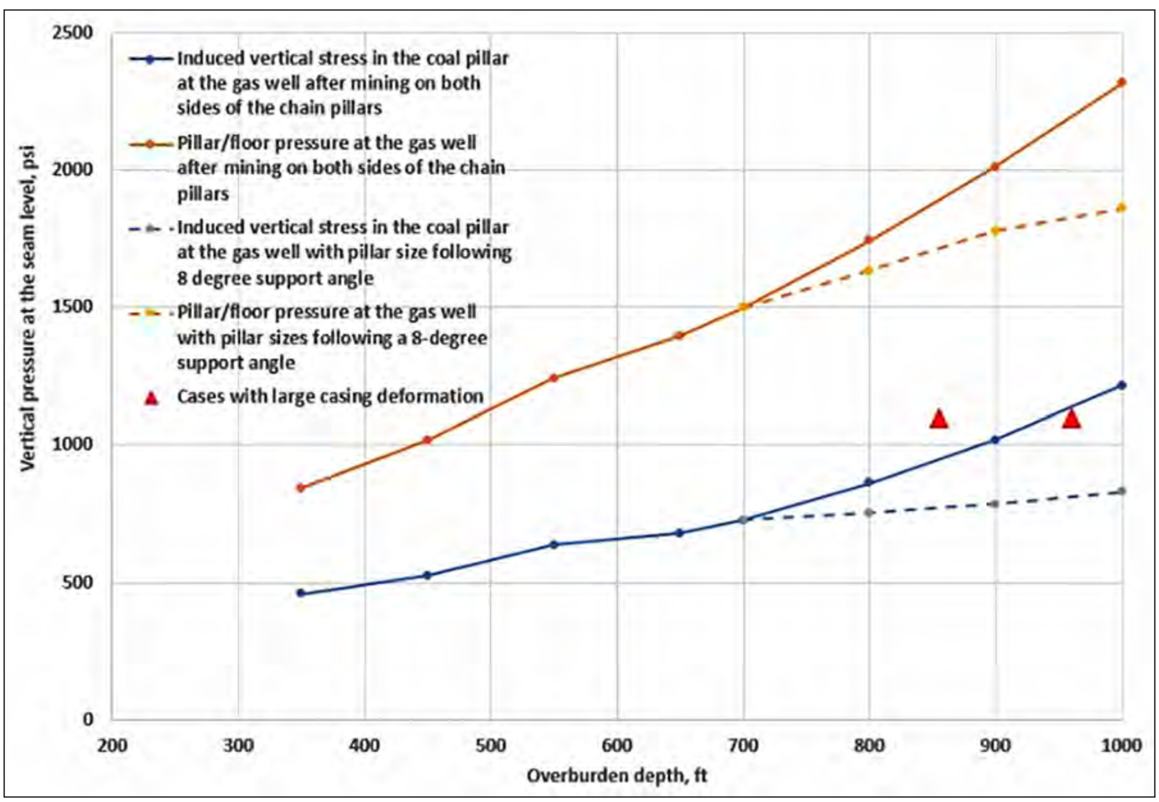

Figure 17. Predicted pillar and floor pressure and induced vertical stress at the gas well under different overburden depths.

and Moran, 2016; Zhang et al., 2019), both of which are included in Figures 17 and 18. Though the chain pillar sizes in those two cases were not compliant with the 1957 guidelines, the comparison is still valid because the casing stability is based on the induced von Mises stress. The maximum von Mises stress in the coal protection casing is also calculated for the chain pillars following an 8-degree support angle as shown by the dotted line in Figure 18. The maximum von Mises stress is slightly above the yield strength but much less than the ultimate strength of the casing when the overburden depth is 800–1,000 ft. Therefore, with chain pillars following the 1957 guidelines, casing yielding could occur at deeper cover, but casing deformation would likely be very small.

In summary, when chain pillar sizes meet the 1957 guidelines, gas well casings are likely to be stable in the coal seam horizon under overburden depth less than 700 ft. When overburden depth is over 750 ft, casing yielding or large deformation is likely to occur around the coal seam horizon. If the chain pillar sizes follow an 8-degree support angle, the casings are not likely to experience large deformations under deep cover, but casing yielding could still occur.

RISKS IN APPLYING THE 1957 GUIDELINES TO LONGWALL GAS WELL PILLARS

The past 60 years has led to both a better understanding of nonconventional subsidence as well as the role played by horizontal slip along weak bedding planes, and the impacts they may have on sensitive imbedded ground structures. Such mechanisms were not well discussed or even considered during the development of the 1957 guidelines, which focused on pillar and floor stability. Even if gas wells are stable near the coal seam horizon, there is still a risk that they could be damaged by overburden movements

Table 4. Cases with large casing deformation in longwall chain pillars.

Overburden Depth	Total Pillar Width (rib-to-rib) ft	Pillar SF	Distance to the gob, ft	Induced Vertical Stress at the Well, psi	Induced Maximum von Mises stress, psi	Failure Location
855	169	1.3	61	1,099	59,587	17 ft above coal
960	184	1.25	52	1,100	80,000	15 ft below coal

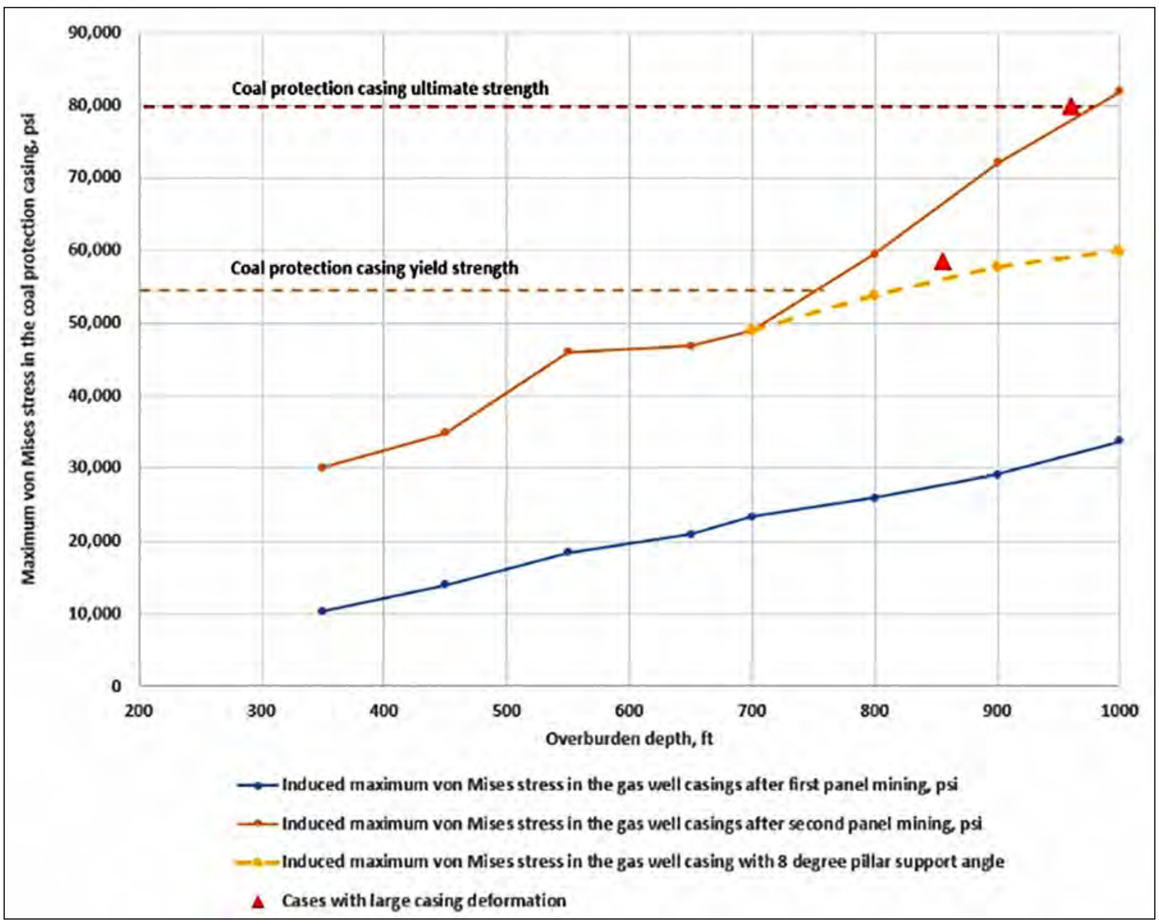

Figure 18. Induced maximum von Mises stress in the coal protection casing under different overburden depths after mining of the first panel and second panel.

beyond the setback distances given by the 1957 guidelines. When the Pittsburgh coal seam is shallower than about 600 ft, gas well stability is potentially influenced more by horizontal strata movements above the pillars, and larger setback distance from the gob may be needed to reduce shear failure in gas well casings. In that case, a risk assessment and additional evaluation has to be conducted based on site-specific geology and mining conditions even though the pillar sizes meet the 1957 guidelines. A risk assessment approach has been proposed by Mark and Rumbaugh (2019) to evaluate the risk of gas well failures for longwall mining.

This study focuses on conventional gas wells, but it should be pointed out that the new development of unconventional shale gas wells has changed the risk of gas well failures. Although longwall-induced stresses and deformations are similar for both types of wells, high consequences of unconventional gas well failure would have different requirements for protective pillars and construction of gas well casings.

Natural gas well extraction methods in Pennsylvania have undergone dramatic change since development of the 1957 guidelines. Prior to 2004, gas extraction was achieved through conventional wells. Conventional wells are vertical boreholes drilled into traditional gas reservoirs such as sandstone or limestone formations with a high porosity and permeability. In the bituminous coalfields of Pennsylvania, these formations tend to be slightly undercharged or have reservoir pressures slightly less than hydrostatic pore pressure.

The first unconventional well was successfully drilled into the Marcellus Shale formation in 2004. "Unconventional" refers to wells drilled into shale formations below the base of the conventional oil and gas formations and are stimulated using hydraulic fracturing. A typical well pad contains clusters of multiple wells, each with horizontal laterals extending through the target formation for up to 20,000 ft. In addition to being deeper, often at depths greater than 6,000 ft, pore pressures in the northern zones of the Marcellus Shale play are overcharged. In 2010, conventional and unconventional gas well permit applications in Pennsylvania were approximately equal. By 2018, six out of seven well permit applications were for unconventional gas wells.

Changes in technology and the geologic conditions have altered the risks associated with the interaction between coal mines and gas wells in the Pennsylvania coalfields. First, unconventional wells are now the prevailing method of gas extraction and produce significantly higher volumes of gas from deeper, overcharged horizons with much higher pressures. Second, unconventional well pads require significant capital investment and produce high volumes of gas over longer periods. Mine operators historically elected to purchase and permanently plug conventional oil and gas wells that obstructed longwall panels and gateroad pillars. Unconventional wells are far more valuable, so permanently plugging clusters of them in advance of mining is not an attractive option. Finally, a recent event during well-drilling activities in southwestern Pennsylvania indicates that ruptures of the production string and protective casings can occur during hydraulic fracturing, and gas can migrate into and through the rock strata for thousands of feet vertically and laterally. Underground mines in close proximity to unconventional wells would be susceptible to an inundation of gas if safety precautions were not in place to control the risks associated with well completion activities.

CONCLUSIONS

Based on the analysis of gas well failure cases from the 1957 gas well pillar study and numerical modeling of gas well stability in longwall chain pillars, the following conclusions are made:

- The great majority of the conventional well failures in the 1957 study occurred within or just beneath the coal seam.
- The 1957 guidelines greatly helped prevent gas well failures in room-and-pillar retreat mining under overburden depth less than 700 ft by ensuring large pillars and maintaining appropriate setback distance to the gob as well as sufficiently low floor pressure.
- The 1957 guidelines for gas well pillars in room-and-pillar mining are not conservative in all cases. Under covers deeper than 700 ft, with pillared gob on three or four sides, gas well failures could still occur.
- When the 1957 guidelines are applied to longwall chain pillars, gas wells are generally predicted to be stable in the coal seam horizon if overburden depth is less than 750 ft, but the risk of gas well failure still exists in the overburden due to potential horizontal strata movements over the chain pillars.
- When overburden depth is greater than 750 ft, gas wells in chain pillars could be damaged even if the chain pillars around gas wells meet the 1957 guidelines.

DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention (NIOSH) or Mine Safety and Health Administration (MSHA). Mention of any company or product does not constitute endorsement by NIOSH or MSHA.

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