STUDY OF BOREHOLE STABILITY OF MARCELLUS SHALE WELLS IN LONGWALL MINING AREAS

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by
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ABSTRACT

Gas wells drilled and completed in longwall mining areas face the potential for wellbore instability problems due to substantial ground movements in overburden strata following the mining activity. The ground deformation, caused by caving of the ground behind longwall panel can generate large horizontal displacements and complex stress change in subsurface rock above and to some extent below the coal seam. The deformation and variation of the stresses in subsurface rocks can trigger ground movement which causes casing failure, and thus interruption in operation of the well, need for shutting down the well for repair, or permanent abandonment. Either way, the wellbore failure imposes economic losses to gas well operators while posing a safety risk to miners and mining operations as the gas could be released in underground workings. Thus, it is critical to study the ground movements caused by longwall mining and characterize the parameters related to the mining process to evaluate the changes in ground stresses / strains in different layers to evaluate the wellbore stability under such conditions. The main propose of this study is to develop a general casing design guideline in such areas that can withstand the potential deformations and assure wellbore stability.

To estimate the variation of stresses and strain in the ground surrounding the longwall panel finite element analysis modeling was used. The model included the geometrical design of the longwall panel including the depth, length of the panel, proper size pillars for a three entry system that is comparable to the current and future practice in south west Pennsylvania as well as West Virginia and Ohio. The model simulated the complex ground condition associated with longwall mining areas and quantified the factors affecting the wellbore stability, such as induced stresses and ground movements.

The output of the numerical modeling of the longwall mining and related stress and strain calculation for the pillars and upper strata was used for developing a proper casing design
according to API guidelines. The results indicate that the controlling parameter in wellbore
stability is horizontal strain, and resulting deformation and ground displacement at certain depths
above the coal seam. The modeling of the coal seam at depths of 100, 200, and 300 m shows that
the maximum horizontal stress occur at X, Y, Z m above the coal seam, respectively. The
magnitude of the maximum horizontal strain was estimated to be around $10^{-2}$, corresponding to
displacement of about 100 mm per 10 m long casing. Total deformation of about 250-350 mm
was also estimated based on the modeling but the values used for design purposes was restricted
to 100 mm due the lack of field observation of such high values of horizontal deformation. The
review of literature shows that despite possibility of high horizontal displacement in such
scenarios, the observed values in the field are typically within 150-200 mm even in extreme
conditions and mostly below 100-150 mm.

A casing design model based on spreadsheets was developed to carry out appropriate
combination of casings. The design procedure was based on API guidelines and Pennsylvania
department of environmental protection (PA-DEP). The wellbore completion was then
performed using the values of strain and deformation obtained by the ground modeling. The
output of the program included a wellbore completion design for 5 layer casing design, which
included the collar, water, two layers of protection and the production casing to assure stability of
the wellbore casing after mining activities. The results were compared to the current practice in
wellbore design in south-west PA and the designs proved to be compatible. This study combined
finite element analysis to develop an appropriate completion guide for Marcellus Shale gas wells
in longwall mining areas.
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Chapter 1

Introduction

In the oil and gas industry, wellbore stability is considered to be a critical issue during well drilling and its subsequent completion. Lack of wellbore stability has led to many instances of casing failure and significant economic loss. As such, research into the factors that can lead to this type of casing failure is necessary. Factors and forces that need to be studied that may be applied to the casing are stress and shear that result from an unstable wellbore.

The issue of wellbore stability is a significant problem for wells located in active mining areas. In particular, wells in mining areas where the longwall mining technique is used for the mining of coal could be subject of wellbore casing failures caused by substantial ground movement due to removal of the large panels of coal. With the development of unconventional reservoirs such as the Marcellus shale in active mining areas of Western PA and in general coal reserves in Appalachia that overlays the Marcellus shale, the possibility of wellbore failure due to mining activities needs to be examined. Given the geometric setting of longwall panels and the remaining pillars, factors that are related to long-well mining such as induced stresses and resulting strains and displacements in the ground around the mined out area (gob), pillars of certain size, as well as surface subsidence should be taken into consideration. The stresses, strains and deformations are a function of characteristics of the mining area, geological properties of the formations above and below the workable coal seam, and the wellbore design and completion method used for the drilling of the gas wells tapping into Marcellus shale. This study will focus on the geological settings, geometry of the longwall panel and pillars, and resulting stresses strain and deformation caused by mining activities. The main focus of the study is the stability of the
wellbores that are designed to go through large size barrier pillars. A separate study can look into the possibility of the drilling and wellbore completion in the gob area.

The main objective of the current study is to develop a general model for estimation of the stresses, strain, and ground movement, which can then be used to describe the worst case conditions that may occur near the wellbore in longwall mining areas. With this input, a wellbore can be designed and completed to withstand the anticipated loads. This study allows evaluating the suggested wellbore completion / design to mitigate potential problems that could be caused by excessive ground movement and result in wellbore failures. The suggested design will be compared to what is used in practice by gas well drilling companies to examine their adequacy to assure wellbore stability. The result of this study will facilitate development of the unconventional gas resources in these areas which covers rather sizable land plots in Western PA, WV, OH, and MD.
Chapter 2

Literature Review

An extensive literature review has been performed to look into the issues related to wellbore stability, coal mining using longwall method and its impact on ground movement and induces stresses and strain, and review of various ground modeling methods using empirical and numerical techniques. The ground modeling will be used in estimation of the induced strain and displacements and well design modeling. In this literature review, the stress within the ground caused by the activity of the coal mines are studied, which offers a good understanding of the horizontal strains and displacement that occur in longwall coal mines. Also, the literature regarding ground modeling and the comparison between the empirical subsidence profile and the predicted subsidence by modeling has been studied to provide a reliable means for verification of the estimated strain and displacement by the models.

The casing design is based on the study of casing failure mechanisms and offer criteria for evaluating the possibility of the casing failures.

In-situ and induced stress in longwall mining:

Review of the in situ stresses in the coal mining operation is an important aspect of maintaining the ground stability. The in situ stresses comprise the vertical stresses that are typically gravitational stresses caused by the weight of the overburden, and the horizontal stresses that could be due to the gravitational field or perhaps regional tectonic stresses. The correlation between vertical stresses and the weight of the rock column has been proven in many cases and a general linear relationship exists between the level of vertical stresses in the ground and the depth.
The horizontal stresses could be caused by the weight of the overburden rock as the component of lateral deformation of the material, represented by Poisson’s ratio, causes the lateral stress which can easily be estimated as

\[
\sigma_H = K_0 \cdot \sigma_V, \quad \sigma_V = \gamma \cdot H, \quad \text{and} \quad K_0 = \frac{\nu}{1-\nu}
\]

Where \(\sigma_H\) is the horizontal Stress, \(\sigma_V\) is the vertical stress, \(\gamma\) is the rock density, \(\nu\) is the Poisson’s Ratio, and \(K_0\) is the coefficient of lateral stress. In a perfectly elastic material with no regional stresses, the above formulas can be used to estimate the lateral or horizontal stresses. However, in most cases, the magnitudes of horizontal stresses are higher due to the presence of regional tectonic stresses. In such cases \(K_0\) could be higher than 1, indicating higher horizontal stresses than vertical stresses.

The stresses levels that are used in design or evaluation of the stability of a structure in rock are the induced stresses. Induced stresses are the stresses caused by changing the in situ or virgin stresses due to excavation of an opening. In effect, creation of a structure or a void will change the stresses in the ground and will cause a redistribution of the loads around the opening to compensate for the added feature and to bring the ground stresses into a new equilibrium. Thus for evaluation of stresses for any application, it is important to know the state of virgin stresses and the size and shape of the opening that would determine and control the stress redistribution. The reconfiguration of the stresses in the ground will typically affect areas as far as 2 times the dimension of the longest feature in the structure.

In the case of longwall mining operations, the redistribution of the stresses occurs in much larger scale and reaches much further than the structure, merely because the size of the opening that is excavated is large. Typical longwall mining panel is from 100m to nearly 500 m (300-1500 ft) wide. Therefore, it is natural to assume that the effects could easily reach as far out as about a Km away from the edges of the structure. The width of the subsidence trough
increases with the depth of the seam. There are field observations that confirm this phenomenon. The observations of the subsidence on the ground above the longwall panel shows substantial vertical and horizontal movements, along with zones of tensile / compressive stresses that manifest itself as surface cracks, and heaving of the ground at surface as well as failures in the roof, pillar failures, and floor heave in the mine entries underground.

Meanwhile, in many cases the components of the in-situ stresses show that the magnitude of the horizontal stresses, that are related to tectonic setting within a region, are higher than the vertical stress that is caused by gravitational field. The impact of the higher horizontal stresses does impact the resulting induced stresses and ground deformation.

Under a variety of circumstances, high horizontal stress can have a negative impact on the stability of roof, floor, and ribs of underground mines. The stability of these mine elements is of great importance to mine safety, productivity, and costs and consequently, an analysis of horizontal stress during the study of mining operations is of significant importance. Particular attention should be paid to the horizontal stresses that are located in the proximity of the gob.

Generally, after the mining of a few panels, stress abutment effects may appear in the corner of the gob, which indicate stress concentration. The longwall gob tends to concentrate stress at its corners if the major principal stress passes through virgin ground, thereby creating a horizontal stress abutment effect. These abutment effects may lead to roof failures. It should be noted that the gob serves to relieve the major component of horizontal stress in adjacent areas and at corners where the major principal stress direction intercepts the gob, thereby creating a stress-reducing shadow effect. Vertical stresses in these situations are a function of the gravitational stress and will reach equilibrium after full subsidence has occurred. Figure 2-1 shows a typical layout for longwall panel. Figure 2-2 shows the impact of horizontal stresses on stability of the pillars and mine workings.
Figure 2-1. Typical layout of a longwall panel

Figure 2-2. Impact of Horizontal Stress Abutment and Stress Shadow Concepts for a Typical Longwall Gob
In the past few decades, the intertwined concepts of stress abutments and shadows were considered to be the most significant advancement in terms of predicting stress location(s). The application of these concepts provided a means of predicting where the horizontal stress would occur, or would not occur near a longwall gob. Since the horizontal stress might be a significant cause of instability in many coal mines, this prediction and measuring method should be considered in this study given its impact on the integrity of any wellbore that penetrates it.

The main issue in the current study is to identify the stress conditions in the ground which is caused by longwall mining and resulting strain and deformation in the ground. For this purpose several different models for prediction of surface subsidence has been selected and used to verify the result of ground modeling, so that with a good match, the estimated strain and deformations in the ground can be used for design of wellbore completion.
Pillars design

The recommended standards for pillars

The issue of pillar design has been extensively discussed by mine engineers to determine the minimum size of the pillars that can safely carry the load of the upper strata as well as abutments and shadow stresses caused by the in-situ stress conditions. The available models and formulas allows for comparison of the induced stresses with the pillar strength and accounts for the depth, stress levels, slopes, size and shape effects on pillar strength, and finally operational issues. The main objective of this study is to look at pillar design, not so much from the pillar stability viewpoint, rather from the viewpoint of resultant stresses, strain, and deformation in the area surrounding the pillar as well as upper strata, where it is known to experience high shear strains and horizontal displacements.

In 1955, the Joint Coal and Gas Committee and sub-Committee in Pennsylvania issued recommendations concerning standards for pillars where an oil and gas well may penetrate the pillar. Based on their study, they found that the pillar failure is the cause of well damage. So they calculated the angle of support which is the angle of depth of cover against the minimum mining radius. The minimum mining radius is the shortest distance from wellbore at surface to a mined out area. After calculation of the angle of support and development of a frequency curve, it was realized that there were more failures occurring when the angle of support is 5° or 6°. As for 8°, the frequency curve dropped to one well and continued in a straight line relationship for isolated wells (Figure 2-4). The committees mainly studied the damaged wells fell below the 8° curve near the coal mines in various locations in Pennsylvania. And some recommendations are given as follows:

1. The pillars comprising the required pillar plan should be in the form of square,
2. The wells should be centrally located within the required pillar plan,
3. The required pillar plan should conform to specifications that reflect that the pillar area should significantly change with the depth of cover. These specifications are shown on Table 2-1.

![Figure 2-4. Numbers of Well Failures vs. the Angle of Depth of Cover](image)

<table>
<thead>
<tr>
<th>Cover</th>
<th>Req'd Solid Pillar Area</th>
<th>Req'd Additional Pillar Area (Solid or Split)</th>
<th>Total Area Bearing Surface Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 99 ft.</td>
<td>1,600 sq. ft.</td>
<td>-</td>
<td>1,600 sq. ft.</td>
</tr>
<tr>
<td>100 - 149 ft.</td>
<td>3,600 sq. ft.</td>
<td>-</td>
<td>3,600 sq. ft.</td>
</tr>
<tr>
<td>150 - 249 ft.</td>
<td>5,625 sq. ft.</td>
<td>-</td>
<td>5,625 sq. ft.</td>
</tr>
<tr>
<td>250 - 349 ft.</td>
<td>10,000 sq. ft.</td>
<td>-</td>
<td>10,000 sq. ft.</td>
</tr>
<tr>
<td>350 - 449 ft.</td>
<td>10,000 sq. ft.</td>
<td>5,600 sq. ft.</td>
<td>15,600 sq. ft.</td>
</tr>
<tr>
<td>450 - 549 ft.</td>
<td>10,000 sq. ft.</td>
<td>13,000 sq. ft.</td>
<td>23,000 sq. ft.</td>
</tr>
<tr>
<td>550 - 649 ft.</td>
<td>10,000 sq. ft.</td>
<td>22,000 sq. ft.</td>
<td>32,000 sq. ft.</td>
</tr>
<tr>
<td>650 ft. (plus)</td>
<td>10,000 sq. ft.</td>
<td>30,000 sq. ft.</td>
<td>40,000 sq. ft.</td>
</tr>
</tbody>
</table>
The specifications shown on Table 2-1 include additional notes that should be taken into consideration:

1. In most instances, 40,000 square feet of pillar area is the maximum bearing area required. It should be noted that there are exceptions under special conditions.
2. When the additional pillar area is split from the solid form, the excavated areas should not exceed 15 feet in width. And the shortest pillar dimension should not be less than twice the width of the excavated area.

Given that the mining industry is realizing significant and rapid development in terms of technology and methodology, the above listed recommendations and specifications may not satisfy the industries’ requirements. In subsequent years, additional data obtained from mines throughout Pennsylvania might provide additional insights that may be used to update and revise the pillar standards.

Yet, as it stands, it seems like the suggested pillar sizes are very conservative and smaller sizes can be considered and examined to see if there is any possibility to reduce the size of pillars through which a gas well or a series of gas wells could be drilled and completed. Away from the issue of gas wells, the regular pillar size can be selected where the strength is estimated by various pillar strength formulas such as Bieniawski’s pillar strength formula:

$$\sigma_{cp} = \sigma_1 (0.64 + 0.36 \frac{w}{h})$$

Where $\sigma_1 = \frac{k}{\sqrt[3]{36}}$, $\sigma_1$ is the strength of a cubical specimen, $k$ is size effect factor, $w =$ pillar width (ft), and $h =$ pillar height (ft). Stresses in the pillar can be estimated based on the in-situ stresses and the amount of material removed in the mining activities.
An example of Pillar stress formula is:

\[ \sigma_p = 1.1H \left( \frac{w + 1}{w} \right)^2 \]

Where \( H \) is the depth below surface (ft), \( l \) is the roof span (ft). In this formula the vertical stress in “psi” is assumed to be 1.1 times depth in “ft” of the roof.

Figure 2-5. Conditions of pillar in a general design approach

The safety factor (FS) is then applied to determine whether the pillar size satisfies the requirements:

\[ FS = \frac{\sigma_{cp}}{\sigma_p} \text{ (ranges between 1.5 and 2)} \]
The extraction ratio is then applied:

\[ R = \frac{(w + l)^2 - w^2}{(w + l)^2} = 1 - \left(\frac{w}{w + l}\right)^2 \]

If the extraction ratio is not acceptable, pillar width needs to be changed to calibrate the extraction ratio. The formulas mentioned in this section are for room and pillar mining method and not for Longwall mining. In effect, if the stress levels are high and pillar strength is low, which results in low extraction ratios, the use of longwall mining is preferred. Obviously, the downside of longwall mining is the substantial ground subsidence that occurs and the significant disturbance to the upper strata as well as the area adjacent to the longwall panels, as discussed before. One of the consequences of longwall mining is surface subsidence as will be discussed in the following section.

**Surface subsidence prediction**

Longwall mining operations involves removal of the entire seam (coal, or other minerals) within a panel that is 100-500 m (300-1500 ft) wide and could be as long as a few miles, that causes ground deformation to reach a new equilibrium. This deformation is typically referred to as subsidence, which refers to the movement of the ground to fill the large size void left by the mining of the panel. The subsidence results in both vertical and horizontal movement of the layers in the ground, including surface movement (Figure 2-6). These surface movements, if not controlled/mitigated may lead to serious damage to surface and subsurface structures. Also subsidence would affect the stability of wellbore located in the longwall mining areas. Given the focus of this study, the characteristics, attendant to subsidence, need to be considered to permit analysis of its impact on a wellbore. This will be undertaken through the construction of a model.
The amount of strain and deformation occurred in the ground is important for evaluating the stability of the wells to be installed in the longwall mining areas. While there are some methods for estimating the surface subsidence, the estimation of the ground deformation along the well is more difficult due to the geometry of the mining area. Therefore, numerical modeling techniques can be used to model the ground and obtain the stress/strain conditions at various locations in the ground, particularly along the well.

To obtain the correct values of ground deformation, proper values for formation properties should be used in the model. For estimating the realistic rock properties for modeling, the estimated ground subsidence in the models can be calibrated/validated using the predicted surface subsidence profile. The subsidence profile can be calculated using actual field measurement, but this would be too specific to use in modeling, however empirical approaches

Figure 2-6. Types of surface damage due to mine subsidence
that has been developed based on field measurement can be used to observe ground behavior in a more general setting.

To generate a complete subsidence profile, maximum possible subsidence (Sm) needs to be calculated first. The value of Sm cannot exceed the thickness of the extracted seam.

Most likely the maximum Subsidence is:

\[ S_m = A m \]

Where:

A is a subsidence factor which can only be determined from actual field measurement and m is coal seam thickness (ft). Typical value for A in the Pittsburgh area is about 0.6-0.7.

Figure 2-7. Schematic drawing of surface subsidence and ground deformation in longwall mining areas
Examination of the subsidence profile indicates that the subsidence goes way beyond the panel. The area affected by mining and the surfaces that experience subsidence is within the subsidence trough. The easiest way to measure the width of the subsidence trough is to use the angle of draw, which allows for the edge of the surface trough to be determined from the edge of the panel using an angle $\delta_0$. Peng (1995) offered a formula for $\delta_0$ as a function of depth. This angle could be a maximum of 24 and in most cases below 20. If the cover above the coal seam is less than 800 ft (244m), the angle of draw will be constant. And it would increase with greater depths as follows:

$$\delta_0 = 27.96 - 0.02426h + 6.9 \times 10^{-6}h^2$$

Where $h$ is the depth of coal seam.

For 2-D ground model, the negative exponential function method is a proper method to predict the subsidence profile. This method is more suitable for sub-critical conditions. Peng & Cheng (1981) offered the following formula for estimation of the subsidence profile $S(x)$:

$$S(x) = S_m * e^{-c \left(\frac{x}{W_s}\right)^d}, W_s = \frac{W}{2} + h * \tan \delta_0$$

Where $S_m$ is the max estimated subsidence (ft), $x$ is the distance from the panel center (ft), $W$ is the panel width (ft), $W_s$ is the half width of the subsidence basin (ft), $h$ is the coal seam depth below surface (ft), $\delta_0$ is angle of draw (rad), $c=8.97$, and $d = 2.03$. 
As noted, the empirical subsidence profile was considered as the validation criteria for numerical modeling. To develop a practical ground model in mining area, the subsidence profile should be sufficiently accurate. In this research, additional prediction methods were studied and used as the basis for validation of the modeling.
Casing failure mechanism

The phenomenon of well casing failure has considerable impact on field productivity and cost of production. These include: inability of workover, pinching of production tubing, de-optimization of artificial lift, loss of zones/well, and porosity and permeability loss.

Reservoir compaction and associated bedding plane slip and overburden shear can induce damage to wells. Usually, casing failure arises through shear owing to displacement of the rock strata along bedding planes or along steeply inclined fault planes. There are certain indicators pointing towards reservoirs which are most likely to suffer casing damage due to reservoir compaction.

Casing failure with compaction

There are usually four main casing damage mechanisms that can be caused by the way compaction loads the casing: column buckling over a short unsupported interval, crushing of the cross section, connection failure, and local buckling.

Column Buckling

As for column buckling, the main issue is about the stiffness of the work string which can easily buckle and lock up due to the drag load supplied by the washpipe. Column buckling of the casing may occur over just a few feet of unsupported length or over a very long section. As the buckle becomes shorter or longer, it becomes easier to push the washpipe through the buckled interval. Once the axial compaction strain exceeds one-half percent, preventing column buckling should rely on effective cement placement and sand control along casing. Adjusting the casing size, weight, or grade would not have a practical effect on preventing this buckling. Recent study
of casing damage mechanisms indicates that column buckling is the most serious casing damage mechanism in terms of compaction: buckling can obstruct a workover at a much lower compaction strain than crushing (E.P.Cernocky 1995).

**Local Buckling**

Local buckling is buckling along the casing wall while the center line of the casing stays straight. This contrasts with column buckling where the center line of the casing bends. It occurs at very short lengths, when the casing is sufficiently well supported to prevent column buckling. Also, it is more likely to occur in the casing body near the connection.

However, if there is a lack of support, critical column buckling would occur and dominate the casing damage prior to any significant local buckling. So local buckling is believed to be not a problem for working through the casing.

**Crushing**

Crushing of the casing cross section is a serious damage mechanism secondary in importance to column buckling. It is stable and is caused by non-uniform mechanical loading among the sand, cement, and casing. Crushing damage can become significant and obstruct working through the casing after large depletion. When the sand is very compactive, or slightly compactive but depletion is very high, concerns for crushing become important and could dominate the choice of the casing size in the pay zone.
**Connection failure**

For the straight part of well, the ground compaction would cause large, plastic and compressive strain in the casing connections in the pay zone. Once the reservoir compacts, the displacement at the top of the reservoir can cause significant tensile strain along the casing above the pay zone. And if the connection between casings is not as strong as the casing body, joint failure can occur in compression in the pay zone. In a reservoir, compressive strain will quickly yield the casing and joints, while the tensile strain in the overburden generally will stay elastic but can exceed the joint strength if the connection is weak in tension. A huge axial load from casing body can also cause the joint failure.

So the joints need to be as good as the casing body in both tension and compression within the pay zone and for a few hundred feet above the pay zone. It is always good to meet this criterion during the casing design to avoid unnecessary risks for the well.

**Casing failure with shear**

Usually, casing failure arises through shear owing to displacement of the rock strata along bedding planes or along steeply inclined fault planes. There are certain indicators pointing towards reservoirs which are most likely to suffer casing damage due to reservoir compaction.

In this study, the most critical form of casing damage results from localized horizontal shear stress induced displacements at weak lithology interfaces within the overburden during compaction or heaving caused by mining of a panel as the ground adjusts to the new conditions and such movements are marked by surface subsidence. The maximum displacement and deformation is often related to weak lithology. Damage is triggered by the compaction-induced shear stresses but the location of damage is generally determined by the position of weak
lithological layers within the overburden. Though the induced shear stresses tend to distribute over relatively large depth intervals, the damage is generally localized. This damage does not exclusively occur at the flanks of the subsidence bowl but is generally observed to be distributed over the field. Other types of shear are associated with the production intervals of the well. For example, reservoir compaction shearing can lead to casing shear. The larger the horizontal shear stress and related strain in the zone, the greater the casing failure potential in the overburden. Casing shear most commonly occurs at the shoulders of the formation structure. This type of mechanism is less important in this study.

**Slip Criterion**

Slippage can be considered to be a representative outcome of overburden shearing. A slip plane can develop along the interface between materials of different stiffness, or in existing discontinuity or weakness planes. In a shale sequence, shear slip occurs more easily, because shale is weaker than sandstone and limestone.

In petroleum geomechanics, it is assumed that the vertical stress ($\sigma_v$) is one of the principal stresses. The other two are the larger and smaller horizontal stresses, $\sigma_H$ & $\sigma_V$. The maximum shear stress, $\tau_{max}$ is defined as $(\sigma_1$-$\sigma_3)/2$ (Figure 2-9).

In Mohr-Coulomb (MC) criterion the effective stress ($\sigma'$) is defined by Terzaghi’s Law (Figure 8), $\sigma'$=$\sigma$-$\sigma$. So higher pore pressures mean lower effective stress.

Linear MC criterion: $\tau_{max}$=$c'+\sigma'_n\cdot\tan (\phi')$

$\sigma'_n$ is the normal effective stress on the slip plane. It can be determined using a finite element numerical model. $c'$ is the cohesion of the rock. $\phi'$ is the internal friction angle.
Often, non-linear failure criteria are used when modeling rock medium. All in all, many failure criteria serve the same function: to relate the maximum permissible shear stress to the effective normal stress in a geomaterial.

Figure 2-9. Some basic stress definitions: principal, in-situ, and triaxial stress conditions

Figure 2-10. Mohr-Coulomb criterion and stresses
Casing failure with in-situ stress:

Associated with complicated geologic structures, casing stresses will vary along the well with in-situ stresses. Non-uniform loads will be applied to the casing when the maximum stress is not equal to the minimum stress. A non-uniform load is one of fundamental reasons that lead to casing failure. If one of the principal stresses is a tensile stress (maximum principal stress) and the other principal stress is a pressure stress (minimum principal stress), the casing failure is more apt to occur.

Also, when the tensile stress strengths of the rocks are large, the rocks tend to more readily fail or crack. This leads to the redistribution of stresses around the well and consequently induces non-uniform loads on the casing.

Casing design

To alleviate or even avoid casing failure issues, proper casings should be selected to be used for well completion. If correct size, type, and amount of casing are used in the well construction, this well is half way to success. In a holistic design process, the integrated casing, cementing, mud, and blowout prevention control program should be taken into consideration.

Types of casing

There are generally four types of casings used in completion: conductor pipe, surface casing, intermediate casing, and production casing. In this research, we need to utilize all the four types of casings.
Conductor pipe

The conductor pipe can also be called “drive pipe”. It is a short length large diameter pipe. A drive pipe can be driven to 250 ft, but in this study the length may just be 50–60 ft. The outside diameter can be 16–24 inches and depends on the depth of the hole. It is used for returning drilling fluid and cuttings back to surface, preventing “cave in”, protecting fresh water sands, supporting the next string of casing, and protecting all the following casings.

Surface casing

Surface casing is the first string of casing immediately after the drive pipe. The size of it can range from 7 5/8 to 20 inch according to the depth of the hole. The length of this casing should depend on depth of fresh water and federal/state regulations. And it also needs to be cemented in its entirety to the surface. A surface casing is used for protecting fresh ground water, isolating unconsolidated formations, and providing primary well control. This type of casing is especially required by regulation for protection of fresh water. Surface casing is also used to support secondary well control equipment, such as diverter and BOP. In this study, we need to mainly consider the water protection issue, and as such, we can refer to it as aquifer casing. According to Pennsylvania regulations, the depth of aquifer casing string should be at least 50 ft below the deepest fresh ground water.

Intermediate casing

The intermediate casing string is located between the surface casing and production casing. It is typically used to seal off weaker zones from high pressure drilling fluid and to protect previous casing strings from higher burst pressure. In this study, intermediate casing is also used
to isolate and protect the coal seam, which consequently is renamed as coal protection casing. This string of pipe is also used to protect the production casing. While the depth of this casing depends on the depth of the coal seam, it can often run to a depth of 1500~3000 ft, and is usually cemented back to surface. However, PA regulations require that the coal protection casing should reach a depth of at least 30 feet but no more than 50 feet deeper than the bottom of the coal seam.

**Production casing**

The production casing is used to control the pressures and fluids associated with hydrocarbon bearing zones. As such, it is set in place prior to the implementation of completion techniques such as hydraulic fracturing and is used to transmit produced fluids (gas and liquids) to the surface. Typically the production casing is cemented from total depth across the pay-zone to a height in the annulus that is sufficient to anchor the casing string and cover any and all zones that may produce extraneous fluids. The production casing is the longest among all strings and its length depends on the depth of hydrocarbon zones. Also, this type of casing should be strong enough to contain the high pressure realized during production process. In this research, we do not need to deeply study the design of this type of casing.

**API casing performance properties**

The loads that act on casing are tension, compression, bending, collapse and burst pressure. The design of casing for all oil-field applications must consider these loads
Pipe body tension

The axial pipe body tension is caused by the weight of the casing body, connectors, and fluid pressure. The highest tension occurs at the top of string. The axial stress (tension or compression) can be expressed as:

\[ \sigma_z = \frac{\sum w_i L_i + \sum P_f}{A} \]

where \( \sigma_z \) is the axial stress (psi), \( L_i \) is the length of tubular section (ft), \( w_i \) is the unit weight of the tubular section in air (lb/ft), \( P_f \) is the pressure force acting on the tubular (psi), and \( A \) is the corresponding cross-sectional area (in\(^2\)).

In addition, when studying the axial tension, we should introduce the bending effect into this concern. Bending can occur frequently due to curvature, transverse loads, etc. And bending stresses occur along the tubular section in the same direction as tension. The bending stress can be expressed as:

\[ \sigma_b = \frac{E(D_{op})}{2R} \]

where \( E \) is the modulus of elasticity (psi) of the pipe, \( R \) is the radius of curvature (inch) \((R=1/c, \text{ where } c \text{ is the curvature})\), \( D_{op} \) is the pipe outer diameter (inch).

We can first assume that tubular string is continuous and the effects of couplings are ignored. So the tubular curvature can equal to hole curvature,

\[ c = c_p \]

where \( c_p \) is hole curvature (rad/in), which is also called the dogleg severity and is expressed in deg/100ft.
Collapse strength

In a collapse condition, the stress, $\sigma_{\text{max}}$, will be the maximum in the tangential direction. For this equation,

$$\sigma_i = \frac{r_o^2 r_i^2 (P_i - P_o) \cdot 1}{r_o^2 - r_i^2} + \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2}$$

if we assume that the pipe is subjected only to external pressure $P_o$ and $r=r_i$, we can get

$$\sigma_{i_{\text{max}}} = -\frac{2P_o r_o^2}{r_o^2 - r_i^2}$$

where $P_o$ is the pressure outside the pipe (psi), $r_o$ is the outside diameter of the string (inch), $r_i$ is the inside diameter of the string (inch).

For both pipe body yield strength and collapse strength, we can find the minimum criterion for them in Table 2-2.

Table 2-2. An brief example of minimum Axial yield strength and collapse strength of casing (Bourgoyne, 1986)
Joint strength

After the casing is run, the joints in the upper section of casing are in high tension because of the weight of the suspending casing. These joints should be of sufficient strength to bear the weight of the suspended strings. The axial tension, which can be supported on the casing joints, is called the joint strength. Joint strength of each type of casing can found in the table of minimum performance properties of casing in Applied Drilling Engineering.

Burst strength

When the drilling process is ongoing, the pressure inside the drill string is different from the pressure outside. After the drilling fluid goes down to the bottom of the hole and then goes up to the annular space, the pressure inside will be larger than that outside, and vice versa.

![Diagram](image)

Figure 2-11. An infinite element analysis of unit thickness of casing string

In Figure 2-11, an infinitesimal element of unit thickness is analyzed. And based on the static equilibrium and Hooke’s Law, we can get the Lamé equations:
\[
\sigma_r = \frac{r_o^2 r_i^2 (P_i - P_o)}{r_o^2 - r_i^2} \frac{1}{r^2} + \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2}
\]

\[
\sigma_t = \frac{r_o^2 r_i^2 (P_i - P_o)}{r_o^2 - r_i^2} \frac{1}{r^2} + \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2}
\]

where \(P_i\) is the pressure inside (psi), \(P_o\) is the pressure outside the pipe (psi), \(r_o\) is the outside diameter of the string (inch), \(r_i\) is the inside diameter of the string (inch), \(r\) is the radius of any point on the section (inch), \(\sigma_r\) is the pressure induced stress along the tangent on the casing circle, \(\sigma_t\) is the pressure induced stress perpendicular to \(\sigma_r\).

For both burst strength and joint strength, we can find the minimum criterion for them in Table 2-3.

Table 2-3. An brief example of minimum joint strength and burst strength of casing

(Bourgoynes, 1986)
Casing design process

The design process should include the selection of casing size and length, the definition and calculation of the magnitude of all types of loads, and selection of an appropriate weight and grade of casing. The selection of casing depth is previously discussed, and our focus is on the design process that takes place from this point on.

Casing size and bit size

To determine the casing’s sizes used in a well, we need to begin with the smallest casing diameter to be run into the hole. Once the smallest casing diameter is fixed, other casing sizes and hole sizes are determined. The smallest casing diameter selected is based on well testing and logging tools and production tools to be run into the well. In this case, the production casing, which is the smallest casing, has an outside diameter of 5-1/2 inches. With this in hand, we can then select the bit sizes and other casing sizes according to the recommended tubing and bit selection chart (Figure 2-12). The design process is from the inside out with larger casing-diameters and bit diameters selected until all strings and bits are selected.
There are three types of loads that are considered in this study: collapse, burst, and tension. Burst pressure resistance is assumed to be constant throughout the length of the wellbore and as such, the first consideration should be to exclude all casing that does meet this design criterion. As Figure 2-13 shows, collapse is the dominating load at depths closer to bottomhole. Given this, casing should be selected according to collapse resistance. As the depth decreases, the effect of collapse also decreases while tension stresses are increasing. As a consequence, the
criterion for design is changed to tension. As for the casing near the surface, tension stresses are
the most important factor that should be considered.

Figure 2-13. Stress lines for tension, burst, and collapse along the string

Based on those stresses criteria, we can conclude: joint strength, $F_j$, is a measure of the
resistance of casing to failure in tension at the joints; tensile yield load, $F_a$, is a measure of the
resistance of casing to failure in tension based on the minimum yield strength; collapse pressure,
$P_{cc}$, is a measure of the resistance of casing to failure by collapse under external pressure; internal
yield pressure, $P_i$, is a measure of the resistance of the casing to failure by bursting from internal
pressure. But these criteria are seldom directly used as the maximum allowable stresses for
casings. Hence, we need to introduce safety factor which is the ratio of maximum allowable stress
to actual working stress. The safety factor for each type of load: Joint Load= $F_j/N_j$, Axial Load= $F_a/N_a$, External Pressure= $P_{cc}/N_c$, and Internal Pressure= $P_i/N_i$

API suggestions:

$N_c$: 1.00~1.50,

$N_a$ and $j$: 1.50~2.00,
$N_i$: 1.00~1.75.

So when designing the casing, the strengths must be equal to or larger than the values of loads time safety factors. For example, for tension loads, the maximum tensile load on casing is considered as the body weight of casing. So the casing strength should satisfy these two equations:

$$F_j = WN_j \quad \text{and} \quad F_a = WN_a$$

where $W$ is the weight suspended below the casing under consideration (lb), $F_j$ is the joint strength (lb), $F_a$ is the pipe body strength (lb), $N_j$ is the safety factor for joints, and $N_a$ is the safety factor for pipe body yield strength.

In conclusion, the elements needed for modeling are in place. The rock-mechanics-related knowledge of formation in longwall mining areas will help us to construct the FEA ground model; the failure mechanism and the casing design process can lead us to a practical casing design modeling which produces casings that will meet the purpose of this research. This will be further discussed in Chapter 3 & 4.
Chapter 3

Ground Modeling for Evaluation of Mining Induced Stresses and Deformation

As noted before, the changes in ground stresses due to longwall mining is very complex and while the subsidence is observed and measured at surface, the components of strain and deformation within the ground need to be determined to develop a proper well completion design. For this purpose analytical solutions are often insufficient and numerical modeling seems to be the best option for determination of ground reaction to mining activities. The modeling of the ground was performed by using finite element program Phase2 by Rocscience®, a commercial program. In this model, a single horizontal coal seam was modeled with the assumption that it was located at a depth of 200m (656 ft), with a thickness of 2m (6.5 ft). The extracted panel is 500m (1640 ft) (Figure 3-1). There are two pillars of 15m (49 ft), and 30m (98 ft) in width on each side of the panel, and four gate roads of 5m (15 ft) in width that comprise the access to the panels on each side (Figure 3-2). The model also includes a section of 198m (649 ft) below the coal seam to allow for monitoring the stresses below the coal seam.
Figure 3-1. Body of the elastic ground model in Phase2

Figure 3-2. Panels and pillars after the panels are mined on both sides

In this model, an element length of 3 is used as the mesh size, resulting in 12842 elements in total. The upper boundary is stress-free, and the lateral boundaries are the interface boundaries. Four stages of mining and excavation are simulated in this model, representing virgin ground, after the tailgates are driven, after the headgates are completed, and after mining the center panel.
There are three general different geological units in this model: the upper layer in orange (overburden), coal seam in dark, the extracted panels in white and the lower layer in red. These materials are defined as elastic-plastic solid and the related properties are listed in Table 3-1.

Table 3-1. Rock properties and elastic parameters

<table>
<thead>
<tr>
<th>Layers</th>
<th>Young's Modulus(Mpa/Psi)</th>
<th>Poisson Ratio</th>
<th>Unit Weight(MN/m3/lb/in3)</th>
<th>Failure Criterion</th>
<th>Cohesion(MPa)</th>
<th>Friction angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper layer</td>
<td>4800/6.9e+05</td>
<td>0.2</td>
<td>0.022/0.08</td>
<td>Mohr-Coulomb</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Coal seam</td>
<td>3500/5.0e+05</td>
<td>0.3</td>
<td>0.02/0.073</td>
<td>Generalized Hoek Brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower layer</td>
<td>4500/6.5e+05</td>
<td>0.25</td>
<td>0.024/0.088</td>
<td>Mohr-Coulomb</td>
<td>1</td>
<td>30</td>
</tr>
</tbody>
</table>

Review of modeling result

As stated in Chapter 2, to estimate relatively accurate realistic rock properties for the ground modeling, the estimated ground subsidence in the model needs calibrated by the predicted surface subsidence profile.
Comparison of predicted ground subsidence of the model with empirical models

Two empirical methods of subsidence prediction (Peng, 1992 and Gutierrez, 2010) are used for completing the ground modeling. The results of numerical modeling are calibrated by the change of different elastic properties and parameters within a reasonable range to match the predicted subsidence using the empirical models. The estimated surface subsidence profile by the empirical and numerical models were compared to find the material properties that could result in best match between the estimated subsidence profiles.

Figure 3-3. Contour for vertical displacement of the virgin ground
Once the material properties were selected based on the calibration of the numerical model with empirical subsidence model (Figure 3-5), the calculated values of stresses, strain, and deformation along the vertical well trajectory passing through a barrier pillar (located at left-hand side of the extracted panel) was used to represent the ground conditions along the wellbore. This was done by using a query function within the Phases program. Through this query line, the profiles of stresses and strains in a certain geology column could be obtained.

When matching the numerical result with the empirical one, the finite element modeling could predict the maximum subsidence with reasonable degree of accuracy, but the subsidence trough of numerical model was wider than the empirical model. This is possibly because the nature of the FEA modeling, Phase2, which is unable to perfectly simulate super-critical span in this area. After the coals is mined out, the position of the roof strata part of the overburden above the target panel seem to move below the coal seam, which is physically impossible. Thus the FEA model seems to overestimate the vertical and horizontal subsidence, as well as shear stress and strains around the upper strata. Even though, these issues need to be resolved, these modeling
results could be useful for analysis of the stress and strain in overburden layers in this project. The mismatch of the subsidence trough could very well be due to the assumption of elasticity and continuity of the ground over the panel and near surface which in reality, the ground is broken and the subsidence trough I smaller and slopes are indeed sharper. This means that the reach of the subsidence area is smaller and so are the horizontal stresses (shear and tensile) and similarly the strains and the horizontal displacement is anticipated to be lower than predicted by FEA program.

Figure 3-5. Subsidence profiles for a panel width of 500m
**Horizontal displacement in modeling**

The horizontal displacement reaches maximum at the inflexion point of the subsidence trough, where the curvature changes from convex to concave and the slope is also at its maximum. A traditional approach to estimate horizontal displacements is by linear correlation of the displacement profile to slope of the subsidence trough at the surface. According to the ground modeling result from Phase2, we found that the maximum horizontal displacement could be a maximum value of 15 inches along the well trajectory (Figure 3-6). This result could be a little excessive and is possibly caused by the FEA modeling’s overestimation, as stated above. In fact, this large displacement has been measured in some cases in Australia where peculiar surface topography exists. And also, a huge horizontal displacement as 18 inches was measured in a Cumberland mine panel in Pennsylvania (Gutierrez, 2010), which is, though, may not be an exemplary case. Therefore, we can conclude that the horizontal displacement measured in our FEA model is credible. However, to conduct generic recommendations for the casings, we limited the maximum horizontal shear strain to 100 mm per 10 ft pipe (4 inches per 30 ft) section, which is also based on the data of some actual ground subsidence measurements (Rostami et. al. 2012). This result is closer to the actual subsidence measurements made in the field, so the maximum shear strain of 10-2 or 10 cm per 10 m of pipe was used in the following casing design process.
Vertical stress

For virgin ground, the vertical stress is proportional to the depth. For this study, following empirical equation was used to express this relationship:

$$\sigma_V = 1.1H$$

where $\sigma_V$ is the vertical stress along the well trajectory.

After the deformation, the vertical stress for multi-layered ground is also related to the unit weight of each type of rocks. The total vertical stress will be:

$$\sigma_V = H_1\gamma_1 + H_2\gamma_2 + H_3\gamma_3$$

where $H_x$ is the depth of layer $x$, $\gamma_x$ is the unit weight of layer $x$.

However, in this FEA modeling, the lower layer is not included in the calculation automatically, so the modeling only displays right stress distribution for the upper layer and the
coal seam, which are fortunately the main target layers that we need to study. Figure 3-9 illustrates that the vertical stress is natural gravitational field.

![Figure 3-7 Contour for vertical stress of the virgin ground](image)

The vertical stress estimated in the numerical model is the maximum principle stress since the gravitational stress field is considered and no regional horizontal stresses were included for modeling. Vertical stresses start from 0 and goes to a high value of 14.52 MPa (2105 psi) at coal seam level after mining of the panel (Figure 3-9). Then it decreases a little and goes up with depth again. But the vertical stresses are not the controlling factor in casing design and can be ignored as will be discussed later.

![Figure 3-8. Contour for vertical stress after mining the center panel](image)
Horizontal stress in modeling

In this FEA modeling, the horizontal stress acting on an element of rock is much more difficult to estimate than the vertical stress. So in general, the ratio of horizontal stress and vertical stress was used to obtain the horizontal stress:

\[ \sigma_H = \sigma_V K_0 \]

where \( \sigma_H \) is the horizontal stress along the well trajectory, \( K_0 \) is the ratio of horizontal stress and vertical stress (normally 0.7–0.8 in PA).
Therefore, the distribution of horizontal stress from ground surface to a depth of 1400 ft could be similar to the vertical stress distribution. Since the well is located at one of the subsidence troughs around surface, it would suffer from high horizontal stress along with the horizontal displacement (Figure 3-12). The direction of the surface stress would be opposite to the center of subsidence. And then, when the depth exceeds the coal seam to the lower layer, the horizontal stress gets closer to the trend in virgin ground, just as the vertical stress does.

Figure 3-12 shows the horizontal stresses (x-direction) in virgin ground and the induced stresses that could reach 5.86 MPa (850 psi), caused by mining of the coal in the longwall panel. The horizontal stresses reach a maximum value of 12.73 MPa (1846 psi) at the coal seam level and decreases to a depth of 274 m (900 ft). The stresses will then increase with depth as anticipated in virgin ground since the effect of mining does not extend far below the coal seam. Examination of the estimated stresses and strains along the projected well location allows for quantifying the values needed for casing design.

![Figure 3-10. Contour for horizontal stress of the virgin ground](image-url)
Figure 3-11. Contour for horizontal Stress after mining the center of panel

Figure 3-12. Horizontal stress vs. Depth
Shear stress in modeling

For virgin ground, there will be nearly no shear stress along the well trajectory, because no deformation and stress change in this situation.

The result of numerical modeling shows that the shear stress starts from a small value around surface and increases to a maximum of 2.47 MPa (358 psi) and 4.72 MPa (685 psi) at depth of about 130 m (380 ft) and immediately below the coal seam, respectively. These values can be taken into consideration in well design. Basically, the shear stress in this case is smaller than horizontal stress.

Figure 3-13. Contour for shear stress after mining the center panel
To better calibrate the model and evaluate the impact of elastic properties and strength parameters on the results of modeling, a sensitivity analysis was performed. For this purpose, all the parameters of the model were kept constant and only one parameter was changed to see the variations relative to that particular parameter. The purpose of the sensitivity analysis was to see the potential errors caused by use of incorrect rock strength parameters in the modeling as well as the possibility of matching the empirical surface subsidence by varying the material properties in overburden layers within a reasonable range.

Figure 3-14. Shear Stress vs. Depth

**Sensitivity analysis**
Figure 3-15. Subsidence profile with different Young’s Modulus

When E=4800 MPa is used as elastic modulus of the overburden strata, the maximum subsidence is about 1.4, which is equal to the estimated subsidence by empirical model (Figure 3-15). As the Young’s Modulus decreases, the maximum subsidence increases with an increasing rate. Generally, when the Young’s Modulus changes within a proper range, it contributes a significant difference in modeling results. Similarly, sensitivity analysis was also performed relative to the variation of the Poisson’s ratio in upper strata.
Poission ratio

![Sensitivity Analysis for Poisson Ratio](image)

Figure 3-16. Subsidence profile with different Poisson Ratio

According to Figure 3-16, when the Poisson’s Ratio increases, the maximum subsidence decreases. But the range of estimated values of subsidence does not change the estimated ground subsidence result by much.
Among all the sensitivity results given by numerical modeling, Unit Weight of the overburden was found to be the most influential factor which is able to impact the subsidence result quite a lot. When the Unit Weight increases, not only the maximum subsidence will be larger, but also the subsidence trough on both sides is wider. Generally in shale formation, the unit weight of overburden could be in a range of 0.02~0.03 MN/m3. This range was used in the sensitivity analysis and the results are shown in Figure 3-17.
In Phase 2, Element Length is used to define the size of finite elements for modeling. Generally, an Element length of 3m seems appropriate for this application. As shown in Figure 3-18, the variation in maximum subsidence between different element sizes was about 0.1m, for an element size ranging from EL=0.3 to EL=10. So the size of elements would not affect the subsidence result significantly.

As for the change of failure criterion and both cohesion and friction angle for Mohr-coulomb criterion, they would not make any difference in subsidence profile, because they are just used for determining the ground stresses and strains in Phase 2.
The results of sensitivity analysis show that the selected parameters for modeling are reasonable and that minor variation in the input parameters (as result of errors in measurement of material properties in the field or laboratory, as well as using such properties in the model) is not going to change the end results drastically. In other words, the obtained results can be used in design of the well completion with reasonable degree of reliability.

It should be mentioned that numerical modeling of the ground subsidence was also performed using finite difference method by using FLAC commercial program. The results of the finite difference modeling of the upper strata was more realistic, due to the nature of the program that allows for higher ground displacement, compared to FEA method. The results of modeling which is reflected in a separate report (Rostami et. al. 2012) was compared to the FEA modeling of this thesis and the results in magnitude of the surface subsidence were very similar, while the projected subsidence profile by FLAC modeling offered a better match to empirical subsidence models.

The estimated horizontal strain and especially the magnitude of the shear strain by FLAC model was more realistic than estimated values by FEA model, thus the result of FLAC modeling was used for the subsequent wellbore casing design process. The main controlling parameter that was used is the maximum shear strain of $10^{-2}$ along the wellbore at a location above the coal seam which happens to coincide with the location of the maximum shear strain by FEA model. The magnitude of the maximum horizontal slip or displacement used in casing design for a 10 m (30 ft) section of the pipe was then selected to be 100 mm (4 inch), as noted before. This value should be examined further by field measurements and surveying of the wellbore in active mining areas as recommended by the Rostami et al. (2012) report.
Chapter 4
Casing Design for the Gas Wells in Mining Areas with Induced Stresses and Deformation

In this section, a casing design model will be introduced to design casing-strings for a gas well in longwall mining area for undergoing production from the Marcellus Shale. The stress/strain data are obtained using numerical modeling of ground.

The data used in the completion design are obtained by using a query function, which lists the calculated parameters along a vertical line representing the gas well. The stress/strain data obtained from modeling are used in the background spreadsheet for casing design and are not accessible by users who are using the spreadsheet for gas well design. Meanwhile, the horizontal displacement observed from the FEA model needs to be considered in the casing design modeling, too. This is expressly for the bending effect discussed when the section for casing strength starts. For mining geometries other than the one set forth, background stress and strain data need to be added to the spreadsheet prior to undertaking casing design.

There are 5 types of casing in the base model: drive pipe, aquifer casing, coal protection casing, intermediate casing and production casing. The model is built into a spreadsheet and allows an interactive design by changing the input parameters and will show the resulting casing and well completion design parameters (Table 4-1).
Table 4-1. The input and output parameters in casing design model

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of aquifer</td>
<td>OD and ID for the drive pipe</td>
</tr>
<tr>
<td>Depth of coal seam</td>
<td>OD and ID for the aquifer casing</td>
</tr>
<tr>
<td>4 safety factors (NA, NJ, NC, NL)</td>
<td>OD and ID for the coal protection casing</td>
</tr>
<tr>
<td></td>
<td>OD and ID for the intermediate casing</td>
</tr>
<tr>
<td></td>
<td>5 bits sizes for 5 types of casings</td>
</tr>
<tr>
<td></td>
<td>A schematic drawing of the casing size results</td>
</tr>
<tr>
<td></td>
<td>All available casings with proper properties for the intermediate casing</td>
</tr>
<tr>
<td></td>
<td>All available casings with proper properties for the coal protection casing</td>
</tr>
<tr>
<td></td>
<td>All available casings with proper properties for the aquifer casing</td>
</tr>
<tr>
<td></td>
<td>All available casings with proper properties for the drive pipe</td>
</tr>
</tbody>
</table>

In the case considered in this study, the coal seam depth is fixed to a depth of 200 m (660-670 ft). The depth of ground water can be varied to a depth of between 60 and 120 m (200-400 ft). Through the input interface in this model, users are also allowed to input safety factors, which are used to quantify the minimum strength of all casings. And then by selecting the “read safety factors” and “feasible casing” buttons, the user can see the results for various casing sizes. The yellow “feasible casing” button is for the coal protection casing; the light blue area is for the aquifer casing; the black colored cells are for the drive pipe; and the brown color section is for the intermediate casing information and specifications. Users are able to click the “start over” button to erase all input data and calculated results, and retype other groups of data as needed (Figure 4-1).
For the selection of casing, 4 tables of casings with various minimum performance properties were put at the right side of the “feasible casing” buttons. The properties that included in the tables are shown in Figure 4-2 to 4-5. Each type of the casing with certain properties was numbered in order. After the initial setting and data entry, the model will automatically select proper casing size and grade for the aquifer casing, coal protection casing, intermediate casing, and drive pipe. And then, the numbers of available casings will appear in the “Target” column at the left side of the input data for manual selection of feasible casings for the given geometric and ground conditions (Figure 5-2).
Figure 4-2 The minimum performance properties of the intermediate casing

<table>
<thead>
<tr>
<th>Target</th>
<th>Coal Protection Casing</th>
<th>Diameter (in)</th>
<th>Diameter (mm)</th>
<th>Collapse Resistance (psi)</th>
<th>Grade</th>
<th>Body Yield Strength (psi)</th>
<th>Joint Strength (psi)</th>
<th>Internal Pressure Resistance (psig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.75</td>
<td>10.722</td>
<td>260</td>
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<td>10500</td>
</tr>
<tr>
<td>2</td>
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<td>15.20</td>
<td>260</td>
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<td>3500</td>
<td>10500</td>
<td>10500</td>
<td>10500</td>
</tr>
<tr>
<td>3</td>
<td>16.25</td>
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<td>260</td>
<td>355</td>
<td>3500</td>
<td>10500</td>
<td>10500</td>
<td>10500</td>
</tr>
<tr>
<td>4</td>
<td>16.25</td>
<td>15.20</td>
<td>260</td>
<td>355</td>
<td>3500</td>
<td>10500</td>
<td>10500</td>
<td>10500</td>
</tr>
<tr>
<td>5</td>
<td>16.25</td>
<td>15.20</td>
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<td>355</td>
<td>3500</td>
<td>10500</td>
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<td>3500</td>
<td>10500</td>
<td>10500</td>
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</tr>
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<td>10500</td>
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<td>10500</td>
<td>10500</td>
<td>10500</td>
</tr>
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<td>10</td>
<td>16.25</td>
<td>15.20</td>
<td>260</td>
<td>355</td>
<td>3500</td>
<td>10500</td>
<td>10500</td>
<td>10500</td>
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<tr>
<td>11</td>
<td>16.25</td>
<td>15.20</td>
<td>260</td>
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<td>10500</td>
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<td>12</td>
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<td>10500</td>
<td>10500</td>
<td>10500</td>
</tr>
</tbody>
</table>

Figure 4-3 The minimum performance properties of the coal protection casing

<table>
<thead>
<tr>
<th>Target</th>
<th>Aquifer Casing</th>
<th>Diameter (in)</th>
<th>Diameter (mm)</th>
<th>Collapse Resistance (psi)</th>
<th>Grade</th>
<th>Body Yield Strength (psi)</th>
<th>Joint Strength (psi)</th>
<th>Internal Pressure Resistance (psig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>15.029</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>20000</td>
<td>20000</td>
<td>20000</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>15.029</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>20000</td>
<td>20000</td>
<td>20000</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>15.029</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>20000</td>
<td>20000</td>
<td>20000</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>15.029</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>20000</td>
<td>20000</td>
<td>20000</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>15.029</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>20000</td>
<td>20000</td>
<td>20000</td>
</tr>
</tbody>
</table>

Figure 4-4 The minimum performance properties of the aquifer casing

<table>
<thead>
<tr>
<th>Target</th>
<th>Drive Pipe</th>
<th>Diameter (in)</th>
<th>Diameter (mm)</th>
<th>Collapse Resistance (psi)</th>
<th>Grade</th>
<th>Body Yield Strength (psi)</th>
<th>Joint Strength (psi)</th>
<th>Internal Pressure Resistance (psig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>19.060</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>16500</td>
<td>16500</td>
<td>16500</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>19.060</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>16500</td>
<td>16500</td>
<td>16500</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>19.060</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>16500</td>
<td>16500</td>
<td>16500</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>19.060</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>16500</td>
<td>16500</td>
<td>16500</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>19.060</td>
<td>480</td>
<td>380</td>
<td>355</td>
<td>16500</td>
<td>16500</td>
<td>16500</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>19.060</td>
<td>480</td>
<td>380</td>
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<td>16500</td>
<td>16500</td>
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<tr>
<td>7</td>
<td>20</td>
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<td>380</td>
<td>355</td>
<td>16500</td>
<td>16500</td>
<td>16500</td>
</tr>
</tbody>
</table>

Figure 4-5 The minimum performance properties of the drive pipe
The selection of casing diameter and bit size

First item in the design steps is to determine the outside diameter of production casing. This parameter is fixed to 5.5 inches. The sizes of the 4 other casings can be determined based on the size of the production casing. The outside diameter of the coupling used on production casing is 6.05 inches. Here it should be stated that the surface subsidence in coal mine area can cause large horizontal ground displacement. In this case, the horizontal displacement would also cause the bending effect on the casings, which will be discussed below. As for other casing’s annular space, the Pennsylvania Code requires that all permanent casing shall be surrounded by a minimum of 25 mm (1 inch) of grout the entire length of casing. Therefore according to the cementing tables of Halliburton and design code of wellbores in Pennsylvania, we can determine the sizes of other casings and couplings (Figure 4-6). After the casing size is determined, the corresponding bit size can be selected using the bit size table in Figure 2-11.
The selection of casing length

The Pennsylvania gas well design Code requires the following design parameters for length of various casings:

1. For aquifer casing, the operator shall drill 50 feet below the deepest fresh groundwater or at least 50 feet into consolidated rock, whichever is deeper, and immediately set a string of surface casing to that depth.

2. For coal protection casing, when a well is drilled through a coal seam at a location where the coal has been removed or when a well is drilled through a coal pillar, the operator...
shall drill to a depth of at least 30 feet but no more than 50 feet deeper than the bottom of the coal seam. The operator shall set and cement a coal protection string of casing to this depth.

Since the production casing length should depend on different requirements of companies, we focus on the other 3 casing strings. With the input of the depths of fresh ground water and coal seam, the model will generate the appropriate lengths of corresponding casing. The length of drive pipe is set to 50 ft. After calculation, the model will generate a general view of the casing strings (Figure 4-7).

Figure 4-7 A sample of casing general view generated in casing design model
The selection of casing strength

During the selection of the grade of casing, designer should pay attention to its strength to see whether this casing can bear the possible maximal stress and tension. In this model, we are looking into 4 main strengths corresponding to 4 types of failures. Those strengths are: Collapse Resistance, Pipe Body Yield Strength, Joint Strength, and Internal Pressure Resistance (Burst Strength). After the casing size is selected, a series of casing grade and strength can also be examined. Those grade and strength data are put into the model in terms of the charts corresponding to different types of casing (Figure 4-2~5).

Collapse design

For collapse design, it is assumed that the casing is empty inside. The horizontal stress and shear stress in the ground model are discussed previously. To select appropriate casings that can bear the maximum stresses along the well trajectory, we use safety factor for collapse ($N_c$) to compare the collapse resistance of casings,

$$P_{cc} = P_c \times N_c$$

where $P_c$ (psi) is the maximum external pressure along the casing.

The estimated horizontal and shear stresses in the ground obtained from numerical modeling are used in casing design. If the depth of the ground water and the coal seam are fixed, they can be inputted into the interface of the casing design model. Then the model will compare the stress values from results generated in the FEA model, with a depths limited by the depths of the aquifer and the coal seam, and pick up the maximum stresses. After that, the casing design model will compare the maximum stresses to the collapse resistance/strength of the selected
casing. If the collapse resistance of casing is larger than the calculated maximum load on casing, this type of casing will be considered sufficient for well completion.

The collapse design in this project uses the external stress from the formation surrounding the casings, so the ground modeling results have a significant impact in selection of the casing grade and estimated casing stresses. If the ground deformation in mining area leads to considerable horizontal stress or shear stress acting on the casings, the casings may experience the risk of collapse failure. Therefore, the reliability of the ground modeling results needs to be taken into consideration.

**Burst design**

For burst design, it is assumed that there is no “back up” fluid outside the casing. Then expected pore pressure is used to measure the maximum internal pressure. The pore pressure gradient and fraction gradient data are inputted and used in the calculation (Figure 4-7).
For burst consideration, we assume that any gas kick is composed of methane with molecular weight of 16 and ideal gas behavior. Formation temperature is equal to \(520 + 0.012H\), where \(H\) is the depth of casing. To obtain the maximum burst pressure along the well trajectory, the injection pressure \(p_i\) is firstly needed.

\[
p_i = 0.052 \times \rho_m \times H
\]

where \(\rho_m\) is the mud density read from Figure 4-7.

We can then calculate the gas gradient for the calculation of casing internal pressure.

Here, the real gas equation is introduced:

\[
\rho_g = \frac{pM}{zRT} \text{ (in consistent units)} = \frac{pM}{80.3zT} \text{ (in field units)}
\]
where $\rho_g$ is the gas density, $p$ (psi) is absolute pressure, $T$ (R) is absolute temperature, $z$ is gas deviation factor, $R$ is universal gas constant, and $M$ is gas molecular weight.

Since the gas gradient $= 0.052\rho_g$, the casing internal pressure $P_{in}$ (psig) will be

$$P_{in} = p_t - 0.052\rho_g H$$

Then the safety factor for burst ($N_i$) is used to compare the internal pressure resistance of casings with the burst-design load as,

$$P_i = P_{in} * N_i$$

If the estimated internal pressure resistance of casing is larger than the calculated maximum internal pressure inside the casing, this type of casing selected is considered to be sufficient.

As to the burst design, the depth of casing can influence the internal pressure significantly. Since the mud density is essentially constant during calculating the injection pressure, the internal pressure tends to be a function of depth. Increased internal pressure requires casing with a higher internal pressure resistance. Thus, more attention should therefore be paid to the depth of casing.

### Tension design

For tension design, both the body yield strength and the coupling strength of casing are taken into consideration. From the casing design data, which are input parameters for the spreadsheet, the model can use the density of each casing to calculate the axial tension on body of the casing for various depths of casing. And as we discussed in Chapter 2 and earlier in this Chapter, the bending effect is also considered in this part of model. In this model, we assumed that the maximum horizontal displacement can be 100 mm (4 inches), which causes a curvature
on the well and an increase on the axial tension. To quantify the axial force caused by bending effect, the following equation can be utilized:

\[ F_{ab} = 64 \alpha d_n w \]

where \( F_{ab} \) is the axial force caused by the effect of bending (lbf), \( \alpha \) is the dogleg-severity angle (the change in angle, in degrees, per 100 ft of borehole length), \( d_n \) is the outside diameter of casing (in), and \( w \) is the casing weight per foot (lbf/ft).

If both the body yield strength and the coupling strength exceed the maximal axial tension, the casing selected can be an option. The minimum tensile yield strength and the minimum joint strength would then be,

\[ F_a = (W+F_{ab}) \times N_a \]
\[ F_j = (W+F_{ab}) \times N_j \]

Both conditions need to be satisfied, for the selected casing to be included in the design.

In the case of tension, the pipe body weight is not a factor that may lead to the failure of design. The casing lengths do not need to be significantly long, so the pipe body weight would not cause a tremendous axial load. However, the load caused by bending effect needs to be thoroughly analyzed and considered in selection of the proper casing. Since there is a horizontal displacement around the surface, which could result in casing deformation, all the casings may realize an extra axial load that is generated by bending. So we should consider the bending effect along with the pipe body weight in tension design in order to prevent the casing from being damaged by unexpected axial loads.

All the casings are selected by checking the three performance properties as noted above to assure that they meet the regulatory and design requirements. The user will provide the input parameters including depth of coal seam and the fresh ground water and the model will generate the results including: a schematic view of the casings, the outside and inside diameter of aquifer casing, the grade and type of aquifer casing, coal protection casing, and drive pipe.
Chapter 5
Casing Design Modeling Results

Input data

As shown in Figure 5-1, values for six input parameters were provided for the casing design model. The example values are shown in Figure 5-1.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Safety Factor (Na)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Safety Factor (Nj)</td>
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<td></td>
</tr>
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<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td><strong>Depth of Coal Seam</strong></td>
<td><strong>Feasible casing</strong></td>
</tr>
<tr>
<td>45</td>
<td></td>
<td>660 ft</td>
<td><strong>Range: 660~670</strong></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Read Safety Factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>54</td>
<td></td>
<td></td>
<td><strong>Depth of Aquifer</strong></td>
<td><strong>Feasible casing</strong></td>
</tr>
<tr>
<td>55</td>
<td>Start Over</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>57</td>
<td></td>
<td>200 ft</td>
<td><strong>Range: 200~400</strong></td>
<td><strong>Feasible casing</strong></td>
</tr>
</tbody>
</table>

Figure 5-1 The input data for casing design
The output data of casing/bit size and casing length

Since we already determined the OD (5.5 in) and OD (6.05 in) for the production casing and its couplings, the results start with the ID of coal protection casing. Based on the criteria mentioned in Chapter 4 and Figure 2-11, the size of all the casings and bits are output in Figure 5-2. The ID and OD of the coal protection casing are colored with yellow; the ID and OD of the intermediate casing are colored brown; the ID and OD of the aquifer casing are in light blue; and the ID and OD of the drive pipe are colored black. And all the casing lengths are applied for the same assigned color.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD of production casing (inch)</td>
<td>5.5</td>
</tr>
<tr>
<td>Length of production casing (ft)</td>
<td>2000</td>
</tr>
<tr>
<td>OD of coupling for production casing (inch)</td>
<td>6.05</td>
</tr>
<tr>
<td>Max stress for drive pipe (Psi)</td>
<td>850.3406</td>
</tr>
<tr>
<td>Max stress for aquifer casing (Psi)</td>
<td>850.3486</td>
</tr>
<tr>
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<td>1345.14</td>
</tr>
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<td>Max stress for intermediate casing (Psi)</td>
<td>2410.8377</td>
</tr>
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</tr>
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<td>OD of drive pipe (inch)</td>
<td>20</td>
</tr>
<tr>
<td>ID of drive pipe (inch)</td>
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</tr>
<tr>
<td>OD of coal protection casing (inch)</td>
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</tr>
<tr>
<td>OD of coal protection casing (inch)</td>
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</tr>
<tr>
<td>Length of coal protection casing (ft)</td>
<td>700</td>
</tr>
<tr>
<td>Length of aquifer casing (ft) (250-450)</td>
<td>250</td>
</tr>
<tr>
<td>OD of coupling for coal protection casing (inch)</td>
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</tr>
<tr>
<td>Length of intermediate casing (ft)</td>
<td>2000</td>
</tr>
<tr>
<td>OD of intermediate casing (inch)</td>
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</tr>
<tr>
<td>ID of intermediate casing (inch)</td>
<td>3.579</td>
</tr>
<tr>
<td>OD of coupling for coal intermediate casing (inch)</td>
<td>10.625</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD of aquifer casing (inch)</td>
<td>16</td>
</tr>
<tr>
<td>ID of aquifer casing (inch)</td>
<td>15.01</td>
</tr>
<tr>
<td>Bit Size (production)</td>
<td>7.385</td>
</tr>
<tr>
<td>Bit Size (Intermediate Casing)</td>
<td>10.625</td>
</tr>
<tr>
<td>Bit Size (aquifer)</td>
<td>17.5</td>
</tr>
<tr>
<td>Bit Size (drive)</td>
<td>24</td>
</tr>
</tbody>
</table>
The results of size and length design of casings are determined by the program and a 2-D schematic drawing is generated to show the extent of the casing (as represented by depth and casing diameter) in the model (Figure 5-3).

Figure 5-3 The 2-D schematic drawing of proposed design by the program.
The results of pipe strengths selection

Collapse strength selection results

As noted in Chapter 3, the results of shear stress and horizontal stress along the wellbore from surface to a depth of 398m (1306 ft) are calculated. And in the casing design model, for each type of casing, the maximum stress between shear stress and horizontal stress along the pipe is selected and put in the background spreadsheet containing “constants” or data from the numerical modeling of the upper strata to evaluate stress and strain (Figure 5-2). For the drive pipe, the maximum stress on its body is the shear stress of 5.86MPa (850 psi); for the aquifer casing, the maximum stress on its body is also the shear stress of 5.86MPa (850 psi); for the coal protection casing, the maximum stress on its body is the horizontal stress of 12.72MPa (1846 psi).

Based on the criteria in Chapter 4, the maximum external pressure for the drive pipe and the aquifer casing is 850*1.125=956.6 (psi), and the maximum external pressure for the coal protection casing is 1846*1.125=2076.9 (psi). Casing, with collapse resistance (Figure 4-2~5) larger than the maximum external pressure, can pass the collapse strength selection.

As an example, we take the first casing from the listed coal protection casings in Figure 4-3. Its collapse resistance is 2660 (psi), which is larger than 2076.9 (psi). So this casing is qualified for the collapse design.

Burst strength selection results

Another area of focus is the upper sections of coal protection casing. Using the criteria for burst design in Chapter 4, the injection pressure ($p_i$) is:

$$p_i = 0.052 \times \rho_m \times H = 0.052 \times 11.7 \times 700 = 425.88 \text{ psi}$$
For the given value of $\rho_m$, we can read the following from Figure 5-7.

The gas density is:

$$\rho_g = \frac{pM}{80.3zT} = \frac{(425.88 + 14.7) \times 16}{80.3 \times 1 \times (520 + 0.012 \times 700)} = 0.166 \text{ lbm/gal}$$

Thus, the casing internal pressure $P_{in}$ (psig) will be:

$$P_{in} = p_i - 0.052\rho_g H = 425.88 - 0.052 \times 0.166 \times 700 = 419.84 \text{ psig}$$

And the minimum burst strength is estimated at:

$$P_i = P_{in} \times N_i = 419.84 \times 1.1 = 461.82 \text{ psig}$$

Based on minimum performance table, the internal pressure resistance of the sample casing is 4010 (psi) (Figure 4-2), which is greater than 461.82 (psi), so this casing is qualified to meet the burst design criteria.

**Tension design results**

According to the discussions in Chapter 4, to obtain the maximum axial tension stresses, we need to calculate both the pipe body weight and the force caused by bending effect. We can get the density of the sample casing from Figure 4-3, and then calculate the body weight of this casing:

$$W = w \times H = 60 \times 700 = 42000 \text{ (lbf)}$$

To consider the bending effect, the axial force caused by bending needs to be added to the estimated axial tensile stresses and hence:

$$F_{ab} = 64 \times \alpha \times 11.75 \times 60$$

Since in this design, the maximum horizontal displacement is assumed 100 mm per 10 ft pipe (4 inches per 30 ft) section, then $\alpha = \arctan(4/((30 \times 12)))/30 \times 100 = 0.037 \text{ (deg/100ft)}$.

And consequently
\[ F_{ab} = 64 \times 0.037 \times 11.75 \times 60 = 1669.44 \text{ (lbf)} \]

So the minimum body yield strength will be

\[ F_a = (W+F_{ab}) \times N_a = (42000+1669.44) \times 1.8 = 78604.99 \text{ (lbf)} \]

And the minimum joint strength will be

\[ F_j = (W+F_{ab}) \times N_j = (42000+1669.44) \times 1.8 = 78604.99 \text{ (lbf)} \]

Then the result will be checked by the model. Since both the body yield strength and the joint strength (Figure 4-2) are larger than the maximum axial tension, this casing fits the requirement of tension design, and thus, is qualified to meet the strength criteria of this model. So in this example, this casing can be used in the condition in this study.

After the selection of all the casings, there are 13 qualified casings that can be used as the intermediate casing (Figure 5-4), 8 qualified casings can be used as the coal protection casing (Figure 5-5), 4 as the aquifer casing (Figure 5-6), and 2 for the drive pipe in total (Figure 5-7).
Figure 5-5 The selection results of the coal protection casing

<table>
<thead>
<tr>
<th>Target</th>
<th>Coal Protection Casing</th>
<th>OD(inch)</th>
<th>ID(inch)</th>
<th>Density(lbm/ft)</th>
<th>Collapse Resistance(lb)</th>
<th>Grade</th>
<th>Body Yield Strength(lb/in²)</th>
<th>Joint Strength(lb)</th>
<th>Internal Pressure Resistance(lb)</th>
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Figure 5-6 The selection results of the aquifer casing

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<th>Target</th>
<th>Aquifer Casing</th>
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<th>ID(inch)</th>
<th>Density(lbm/ft)</th>
<th>Collapse Resistance(lb)</th>
<th>Grade</th>
<th>Body Yield Strength(lb/in²)</th>
<th>Joint Strength(lb)</th>
<th>Internal Pressure Resistance(lb)</th>
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Figure 5-7 The selection results of the drive pipe

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<th>Drive Pipe</th>
<th>OD(inch)</th>
<th>ID(inch)</th>
<th>Density(lbm/ft)</th>
<th>Collapse Resistance(lb)</th>
<th>Grade</th>
<th>Body Yield Strength(lb/in²)</th>
<th>Joint Strength(lb)</th>
<th>Internal Pressure Resistance(lb)</th>
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Chapter 6

Conclusions

The main focus of this study is the evaluation of the performance of the gas well casing in the longwall mining areas and possibility of failure of these wells due to induced stresses and strains caused in the upper strata and overburden layers by the mining activities. In particular, in-situ stress and induced stress in longwall mining areas are analyzed to examine the possibility of damages to the wellbore casing. A precise ground modeling was carried out to better estimate and to quantify the stresses and strain and resulting deformation in the ground that would determine the stress distribution in the ground and along the well trajectory in longwall mining areas. For this analysis, the gas wells are assumed to be placed in the middle of the abutment pillars in the head/tail gate in a three entry development system, which is the typical of longwall mining operations in southwest Pennsylvania. A parametric study was performed using the pertinent parameters to see the impact of variation in these parameters on the stresses and strains due to mining. The sensitivity analysis in this parametric study was performed on variables including Young’s Modulus, Poisson’s Ratio, Unit Weight and Element Length. The results of the parametric study show that the variation of these parameters within a limited range is not going to change the estimated strain and deformation values drastically and the outcome of the numerical analysis is valid over a reasonable range of these parameters. The highest sensitivity of the numerical modeling seems to be relative to unit weight of the overburden rock.

The calculated stresses and strains were in turn used in a casing model, to offer a safe casing design based on the depth to the aquifer and coal seam. The model is capable of offering the casing design based on recommended guidelines by API and PA regulations and the basic input value of the production casing size and depth to aquifer and coal seam and anticipated ground deformation for a given depth of coal seam.
The analysis of the numerical modeling and the casing design model yields the following conclusions:

1. The critical location for casing failure is near surface, where the magnitude of maximum horizontal displacement seems to be the highest. Also in the interval along the casings around the coal seam, where largest stresses have been observed there is a possibility of wellbore failure.

2. The maximum horizontal displacement based on Finite Element Analysis (FEA) modeling is extremely large close to the ground surface. Unusual high values of displacement have been estimated in the modeling, which has not been observed in the field except for some cases in Australia where peculiar surface topography exists. The mismatch between the estimated surface subsidence and that of the empirical formulas suggest that the numerical modeling shows much wider area of subsidence and extended subsidence trough that is not realistic or typical of southwest PA.

3. The result of a parallel analysis using finite deference modeling shows smaller subsidence trough and is more realistic and the modeling suggest the maximum shear strain of $10^2$ which corresponds to displacement of about 100 mm (4 inch) in a casing section of 10 m (33 ft). The total displacement of the wellhead could be higher but to use a value for design, field measurement is needed.

4. There are 5 types of casings to be used in design including: the drive pipe, aquifer casing, coal protection casing, intermediate casing and production casing. The design comprises casing lengths, casing sizes and bit sizes can be concluded in the following table:

Table 6-1 The design result of casing depths, casing sizes and casing bit sizes

<table>
<thead>
<tr>
<th>ITEM</th>
<th>MODELING RESULT</th>
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<tbody>
<tr>
<td>Drive Pipe Depth (ft):</td>
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<td>Dive Pipe Diam. OD,ID (in):</td>
<td>$20''/19''$</td>
</tr>
<tr>
<td>Drive Pipe Bit Size (in):</td>
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<td>Aquifer Casing Depth (ft):</td>
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<td>Aquifer Casing Diam. OD/ID (in):</td>
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<tr>
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<td>------------</td>
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<tr>
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<td>Coal Protective Casing Bit Size (in):</td>
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<td>Production Casing Depth (ft):</td>
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<td>Production Casing Diam. OD/ID (in):</td>
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<td>Production Casing Bit Size (in):</td>
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</table>

5. Based on the casing design model which used the estimated stress and strains from the numerical modeling, various casings were identified to be applicable for given mine and geometrical setting: 13 intermediate casings, 8 coal protection casing, 4 aquifer casings and 2 drive pipe.

6. The methodology of the research could be applied to other case studies, where casing stability in area prone to experience subsidence from longwall mining of coal in a close proximity, where the wellbore happens to be in the abutment pillars. The results are diverse for different mine design and seam depth and the given scenario should be modeled using the numerical analysis and casing design program to see the suitability of various set of casing for each specific project.
Recommendations

Following recommendations are offered for the follow up studies on this subject:

1. Field instrumentation of a wellbore in the vicinity of a longwall panel should be performed to offer realistic values for rock properties, stresses and strains, displacement, and displacement and slippage of the beds and layers.

2. Elaborate shale layers and diverse formation patterns in longwall mining area should be introduced into the FEA modeling, to collect more credible formation data of rock properties, stresses and strains, etc.

3. Additional study using finite difference methods should be performed to evaluate the stresses and strains or use of hybrid FEA method with different material properties and constitutive models should be considered to evaluate the possibility of ground modeling which could result in closer match with field observation.

4. Development of an expert system and a computer program that can simulate the impact of the rock properties, coal seam depth, etc., using a database of API recommended casing that can meet PA (or proper regulatory agency) and offer a full casing design.

5. Continuous comparison of the result of simulation with field practice to update the design model and closer evaluation of the wellbore failures to allow for understanding of the mode of failure in the casing.
Reference

Bell, J. S.1996. Petro Geoscience 1. IN SITU STRESSES IN SEDIMENTARY ROCKS (PART 1): MEASUREMENT TECHNIQUES.


Peng, “Coal Mine Ground Control”, Dept. of Mining Engineering, West Virginia University, 2008.
