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Variation of Young's Modulus with Depletion in Coalbed Methane Reservoirs

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VARIATION OF YOUNG'S MODULUS WITH DEPLETION IN
COALBED METHANE RESERVOIRS

by

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A Research Paper
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TABLE OF CONTENTS

CHAPTER **PAGE**

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 CBM Resource

During the late 1970s, coalbed methane (CBM) emerged as a significant source of clean energy in the United States. Today, CBM production is commercially well established and plays an active role in fulfilling the global energy requirements in several nations, like the US, Canada, Australia, China, and India. Some key factors leading to successful commercial CBM production are favorable geologic conditions, low development and operating costs, and favorable sales market and prices.

Global CBM production from fifteen basins across the US, Australia, Canada, China, and India account for 5.8 billion cubic feet per day (Bcfd) (CBM Asia Corp., 2012). Although the US dominates in CBM production, with approximately 5 Bcfd of current production and nearly 20 Tcf produced to date, this is expected to decline going forward because of CBM resource maturity, not to mention tumbling gas prices. In a few years, Australia may well displace the US as the largest producer, with a projected 6 Bcfd by 2025, once its LNG export plants become fully operational. CBM production is struggling in China (150 MMcfd), India (10 MMcfd), and Indonesia (0.625 MMscfd) due to challenges, such as geologic conditions and low well productivity (EMR, 2014). Other regions, especially Europe, have failed to commercialize production of CBM owing to poor geologic conditions as well as high capital costs.

1.2 Gas Occurrence and Migration

Coalbed Methane (CBM) is natural gas formed by geological processes occurring during formation of coal, the gas content varying for different types of coals and geographical regions. Coalbed reservoirs are uniquely distinct from conventional gas reservoirs since coal serves as both the source and the reservoir rock. The storage characteristics of coal, as well as the gas transport phenomena involved in CBM production, are distinctive and significantly different from those occurring in conventional reservoirs. There are three types of methane storage mechanisms in a CBM reservoir. These are:

a) Adsorbed molecules on organic surfaces,

b) Free gas within pores and cleats, and

c) Dissolved in water within the reservoir (Rightmire et al., 1984)

As compared to conventional reservoirs, gas retention in coalbed reservoirs is significantly higher due to the high methane adsorption capacity by the microporous solid surface of coal.

Gas flow in coalbeds involves three distinct mechanisms, considering the dual porosity characteristic of coal (King, 1985):

1) Desorption of gas from the microporous surface,

2) Diffusion through the coal matrix, usually following the Fick's law, and

3) Darcian flow through the macroscopic cleat system.

Figure 1-1 shows these CBM migration processes occurring in a coalbed.

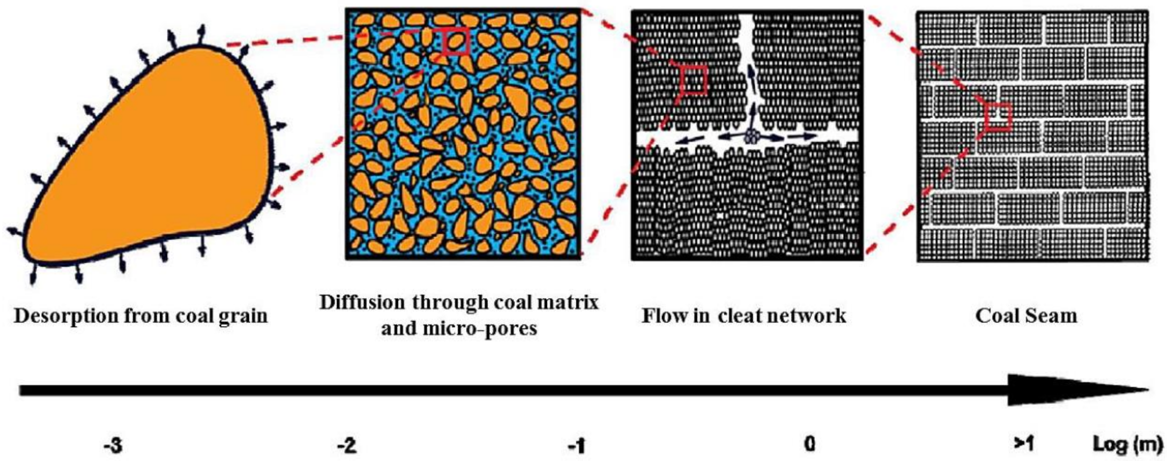

Figure 1-1. Gas transport mechanisms in a coalbed reservoir (Srivastava, 2005)

1.3 Gas Flow in CBM Reservoirs

The majority of CBM operations employ pressure depletion for recovering natural gas initially. This process involves pumping out a large volume of formation water to lower the hydrostatic pressure of the reservoir, which leads to gas desorption from the coal matrix. Continued reduction in water saturation level of the reservoir increases the relative permeability of coal to gas, which permits the desorbed gas to flow towards the wellbore. High initial water production declines with a gradual increase in gas production rate. As water is produced, there is a shift from single phase to two phase (water-gas) flow regime near the wellbore (Sawyer et al., 1987). This can be described as shown below:

a. Single-Phase Water Flow: In this phase, only water flow is observed in the cleat system as reservoir pressure continues to decrease.

b. Unsaturated Single-Phase Water Flow: As reservoir pressure continues to decrease, it leads to desorption of a fraction of the adsorbed gas in the coal matrix. The gas then moves to the cleats and remains immobile as unconnected bubbles of desorbed gas stick to the cleat surface, thereby restricting the relative water permeability.

c. Gas and Water Two-Phase Flow: As reservoir pressure drops further, a considerable amount of gas desorbs in the matrix and moves to the cleat system where gas bubbles are associated. This stage witnesses a significant improvement in gas relative permeability as the water saturation decreases and the flow is now in two distinct phases.

These different production stages are depicted in Figure 1-2. Given the slow pace of the process, gas production can continue up to twenty years and even longer for some wells, as has been observed in the San Juan basin.

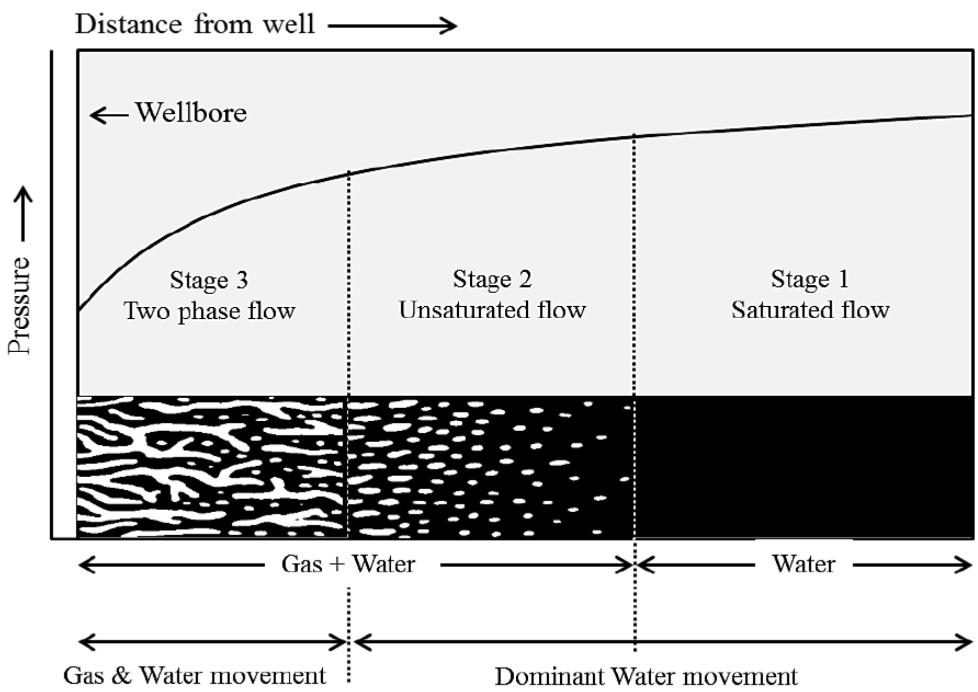

Figure 1-2. Different stages of CBM flow associated with water production (McKee, 1987)

1.4 Modeling CBM Permeability

During the last two decades, tremendous effort has been devoted to modeling of coal permeability and its impact on long-term gas production (Palmer & Mansoori, 1998). Some of these models work fairly well for field operations, although they depend on obtaining input parameters using history matching. The two geomechanical parameters required for modeling are Young's modulus and Poisson's ratio. Typically, these two parameters are assumed to hold constant over the life of producing reservoirs although their values are suspected to vary with continued depletion.

This research paper is aimed at correlating the variation of *in situ* stresses and Young's modulus of a coalbed reservoir with depletion. Both of these factors play an important role in determining the variation of permeability of a CBM reservoir, and hence, the overall gas production. The author believes that Young's modulus of coal, which is an important mechanical property indicative of its strength, is sensitive to pressure depletion. As an important input parameter in most theoretical models for CBM reservoir stresses and permeability, it is essential to determine the characteristics of Young's modulus with respect to gas pressure depletion. This would enable improving the capability to predict permeability variation which, in turn, would improve predictions of long-term gas production.

CHAPTER 2

BACKGROUND

2.1 Stress Variation with Depletion

With depletion and continued gas production, the stress conditions of the reservoir vary continuously, leading to deformation of the reservoir. This deformation is typically categorized into three parts: cleat deformation, linear elastic deformation of coal matrix due to stress variation, and non-linear elastic deformation due to the sorption-induced matrix shrinkage effect (Liu & Harpalani, 2013a). It is well known that coal is a typical porous medium and the volumetric deformations are mainly caused due to variation in effective stresses, defined as the difference between principle stress and pore pressure. Pressure depletion in a CBM reservoir changes the stress in the coalbed and is responsible for matrix shrinkage induced by desorption of gas (Liu et al., 2012). It is well established that reservoir stress variation and behavior of matrix shrinkage in coal are critical factors that influence the permeability which, in turn, impacts long-term gas production from CBM reservoirs (Gray, 1987; Palmer & Mansoori, 1998; Ma et al., 2011; Liu & Harpalani, 2012).

Typically, the flow of water and methane in coal decreases with increasing effective stress before the opening of cleats and generation of fractures within the coal matrix (Wang et al., 2013). Several researchers (Palmer and Mansoori, 1998; Shi and Durucan, 2004) have established links between the permeability of coalbeds and the associated variation in effective stresses during pressure depletion. There is conclusive evidence of this in the literature for permeability measurements conducted under uniaxial strain condition, using methane and helium as pore fluids (Mitra, 2010; Liu 2012; Singh 2014; Soni 2016). This condition, believed to best replicate the *in situ* condition of a coalbed, requires the lateral constraint (i.e., horizontal dimension) to remain constant, allowing coal deformation in the vertical direction only. The vertical stress, caused due to overburden load, remains constant during the depletion process (Mitra, 2010; Liu, 2012).

2.2 Effective Horizontal Stress

Unlike conventional reservoirs, CBM reservoirs experience dynamic variation in permeability during gas production through pressure depletion. It is established that, as the reservoir is depleted, two crucial processes occur with contrasting effects on the flow of gas. First, reduction in pore pressure leads to an increase in the effective stresses. Second, sorption-induced matrix shrinkage results in a reduction in the effective stress (Gray 1987). Gas flow in coalbeds is, therefore, controlled by these two processes, and overall CBM production is determined by their net impact on effective stresses. The effective horizontal stress, defined as the difference between external stress and pore pressure, changes with depletion in reservoir pressure. The typical state of coalbed reservoirs is lateral confinement at depth, where changes in stress or pore pressure can induce strain only in the vertical direction. Therefore, during gas depletion, physical shrinkage of coal as a result of gas desorption does not occur; instead, horizontal stress decreases, ensuring zero horizontal strain as a result of lateral confinement (Liu, 2012).

There have been numerous studies cited in the literature on the effect of stress variation on coal permeability. For San Juan coal, Mitra (2010) attributed the improved gas flow to opening up of cleats due to the desorption-induced shrinkage and loss of horizontal stress. The study reported a decrease in permeability of coal samples that were exposed to helium under the same conditions of pressure and temperature. It has been well established that helium has no sorption effect on coal (Reucroft 1986). In the absence of the shrinkage effect, continuous increase in effective horizontal stress was observed, resulting in a continuous reduction in the flow of helium with pressure depletion.

Liu (2012) performed experiments on San Juan Basin coal, maintaining uniaxial strain condition, and reported an increase in permeability with methane depletion. A direct relationship between methane pressure depletion and a decrease in effective horizontal stress was reported. For helium, a continuous increase in the latter was observed, leading to reduced flow through the coal sample. Singh (2014) conducted similar experiments for San Juan coal, but for higher stress conditions replicating deeper coals. The experimental results performed under uniaxial strain conditions showed a significant decrease in effective horizontal stress with methane depletion. The study also showed weakening of coal due to decrease in the effective horizontal stress with methane depletion, which can ultimately lead to coal failure.

The experimental studies discussed above indicate that coal permeability, and ultimately CBM production, is essentially dependent on shrinkage of the coal matrix and is governed by effective horizontal stress regimes, which have a prominent effect on variation in geomechanical properties of the coalbed.

2.3 Theoretical Modeling

A good understanding of the permeability variation of CBM reservoirs is essential in order to project long-term gas production with continued depletion. Theoretical models presented a sound solution to describe the permeability variation during depletion as soon as production history in some of the earlier CBM basins became available. The initial permeability models were heuristic in nature. However, some permeability models, based on fundamentals of geomechanics, the assumption of uniaxial strain condition, and concepts of matrix shrinkage have been proposed in the last two decades.

Shi and Durucan (2003) proposed a breakthrough model for permeability variation of a CBM reservoir with pressure depletion assuming coal to be linearly elastic. They derived a relationship where permeability is influenced by effective horizontal stresses which, in turn, can be correlated to mechanical compression of cleats and matrix shrinkage effects, given as:

$$\boldsymbol{\sigma - \sigma_o = -\frac{\nu}{1-\nu}(P - P_o) + \frac{E}{3(1-\nu)}\varepsilon_l\left(\frac{P}{P + P_\varepsilon} - \frac{P_o}{P_o + P_\varepsilon}\right)} \quad (1)$$

where $\boldsymbol{\sigma}$ is the effective horizontal stress, **E** is Young's modulus, $\boldsymbol{\nu}$ is Poisson's ratio, subscript "o" denotes initial values, and, $\boldsymbol{\varepsilon_l}$ and $\mathbf{P_\varepsilon}$ are shrinkage parameters using the Langmuir-type model for shrinkage. Finally, changes in cleat permeability were computed using the McKee equation (1987), given as:

$$\boldsymbol{\frac{k}{k_o} = \exp[-3\,C_f\,(\sigma - \sigma_o)]} \quad (2)$$

where $\mathbf{C_f}$ is cleat compressibility, $\mathbf{k_o}$ is initial permeability, and **k** is permeability at different pressure steps. It should be taken into consideration that equation (1) considers mainly the sorption-induced matrix shrinkage effect, whereas the cleat compression factor comes into play only when the equation is employed to estimate the variation in permeability. The effect is taken into consideration assuming isotropic coal properties and its matrix shrinkage effect due to gas depletion.

In the past, testing of coal core using methane and helium as pore fluid has been performed to measure their effect on permeability with pressure depletion. As expected, helium being non-sorbing, the mechanical decompression of bulk coal and the volume of the coal matrix lead to an increase in effective horizontal stress. For methane, both decompression and shrinkage effects co-exist, but the matrix shrinkage effect plays a prominent role leading to a decrease in the effective horizontal stress with pressure depletion. Thus, in the absence of any matrix shrinkage effect, which is the case during helium depletion, the Shi and Durucan equation for change in horizontal stress can be simplified as follows:

$$\boldsymbol{(\sigma - \sigma_o)_{helium} = -\frac{\nu}{1-\nu}(P - P_o)} \quad (3)$$

2.4 Problem Statement

Interest in the topic of changes in the mechanical strength of coal with gas sorption has received considerable attention by several researchers (Ettinger and Lamba, 1957; Czaplin'ski and Holda, 1982, 1985; Holda, 1986; Aziz and Ming-Li, 1999). These researchers have agreed in their opinion that, during depletion, sorption affects the coal strength due to the variation of coal surface energy which, in turn, weakens the coal.

Apart from the above-stated researchers, there have been a few studies to understand the causes of coal failure in San Juan CBM wells operating in very low-pressure areas in the basin. It has been noted that coal failure triggers at low reservoir pressures (Okotie and Moore, 2010; Moore and Loftin, 2011). Moore and Loftin (2011) associated the permeability variation in CBM wells with coal failure. They further reported Young's modulus to be one of the controlling factors in the variation of coal permeability associated with matrix shrinkage due to gas desorption.

Also, Singh (2014) showed that coal weakens with pressure depletion due to a significant decrease in the effective horizontal stress. Meanwhile, with pressure depletion, the effective vertical stress increases due to the constant overburden on the coalbed. It is believed that, with depletion, coalbed tends to become weak due to its inability to shrink physically in a laterally constrained state. Also, a constant decrease in pore pressure to counter the vertical stress, along with the decreasing confining stress makes it more susceptible to failure. It is due to these conditions that the geomechanical properties of coal representing its mechanical strength, in this instance, Young's modulus, is believed to vary with pressure depletion.

2.5 Objective of Research

The basis of this study is to initiate an effort towards improving the understanding of the correlation between variation of Young's modulus of coal in a CBM reservoir and changes in *in situ* stresses with pressure depletion. The relationship is established by utilizing the Shi and Durucan theoretical model for permeability. It is achieved in two steps. Firstly, the effect of gas depletion on the effective horizontal stress observed during helium depletion is isolated from the Shi and Durucan model, that is, $(\sigma-\sigma_o)_{\text{helium}}$ is presented as equation (3) to model helium depletion results. This is done to establish the Poisson's ratio. Finally, the Shi and Durucan model is utilized to model the methane depletion results by varying Young's modulus, a required input parameter in the Shi and Durucan model for variation in the effective horizontal stress with pressure depletion.

An important outcome of this research paper will be to show that results achieved by varying Young's modulus result in improved modeling of *in situ* stresses with gas depletion. The trend is also believed to improve prediction of permeability variation which, in turn, would improve prediction of overall gas production. The reason for using a variable value of E is justified by achieving an optimum match between experimental and modeled results. As Young's modulus is a direct representation of a material's strength, it was considered an acceptable parameter to vary when replicating the *in situ* conditions.

CHAPTER 3

EXPERIMENTAL DATA

The experimental data utilized for this research paper was obtained from work completed by Shimin Liu (2012). Experiments were conducted to measure the horizontal stress with pressure depletion under uniaxial strain condition. Methane and helium were used as pore fluids of choice. To replicate uniaxial strain condition, the horizontal stress was reduced to compensate for the shrinkage effect in the lateral direction with declining pore pressure. Since the overburden load remains unaltered during gas production, the vertical stress was kept constant throughout the experiment. The experiment was conducted in a triaxial cell, consisting of a circumferential extensometer to monitor change in horizontal strain, a linear variable differential transducer (LVDT) to monitor vertical strain, and a set of gas lines and pressure transducers to monitor and measure the flowrate. The setup was capable of replicating confining and axial stresses initially to simulate the *in-situ* condition. Details of the experimental procedure and setup can be found in Liu (2012).

CHAPTER 4

RESULTS AND ANALYSIS

In this section, the variation in effective horizontal stress with changes in pore pressure under-replicated *in situ* condition is discussed. To simulate the initial *in situ* stress condition, the sample was stressed vertically/horizontally to ~2100/1400 psi. Next, helium gas was injected into the coal sample at ~1100 psi, replicating the initial pore pressure condition. After strain equilibrium, the pore pressure was then reduced gradually from ~1100 to 100 psi in a step-wise manner and the stress/strain experimental data for pressure depletion were recorded at each step. For each pressure step, the horizontal stress was adjusted to ensure zero horizontal strain. The vertical stress was kept constant throughout the experiment.

After completion of the helium cycle, the coal sample was flushed with methane to expel the residual helium. Following this, the sample was saturated with methane at ~1100 psi and was left until strain equilibrium was achieved. After attaining strain equilibrium, the cycle was repeated and, at each pressure step, the horizontal stress was measured. Hence, values of horizontal stress at each pressure step were established for helium and methane depletion.

4.1 Variation in Horizontal Stress with Pore Pressure Reduction

The changes in horizontal stress with pressure depletion for helium and methane are presented in Figures 4-1 and 4-2, respectively.

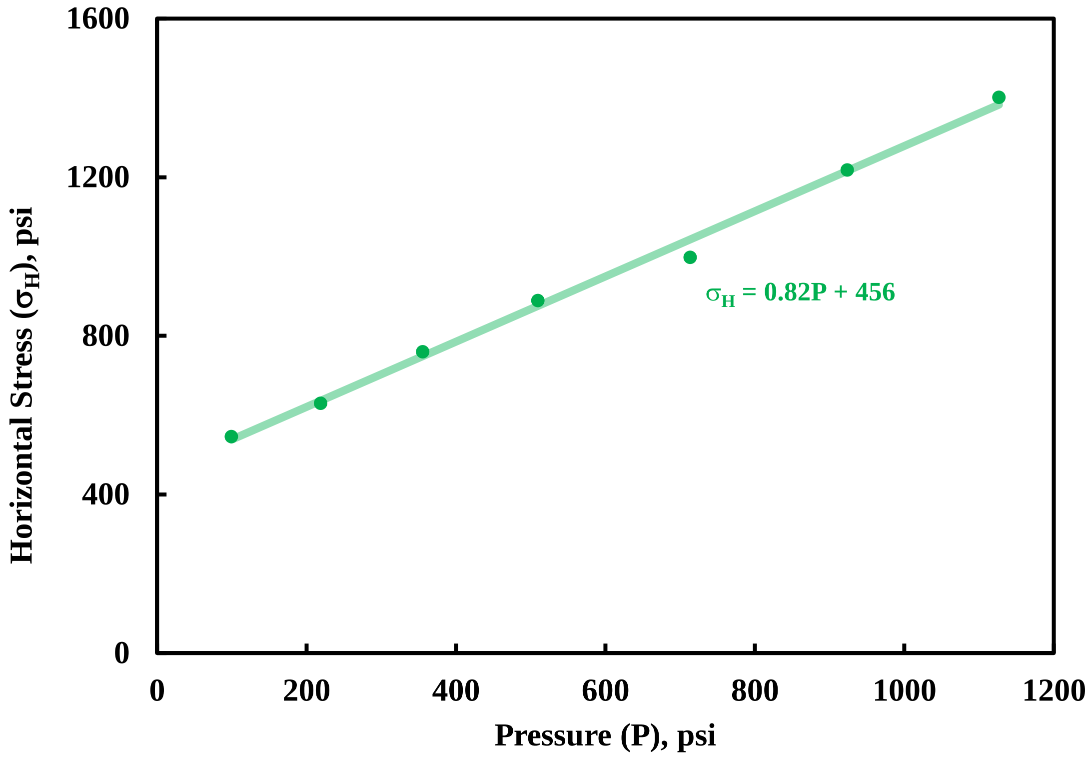

Figure 4-1: Variation in horizontal stress with helium depletion

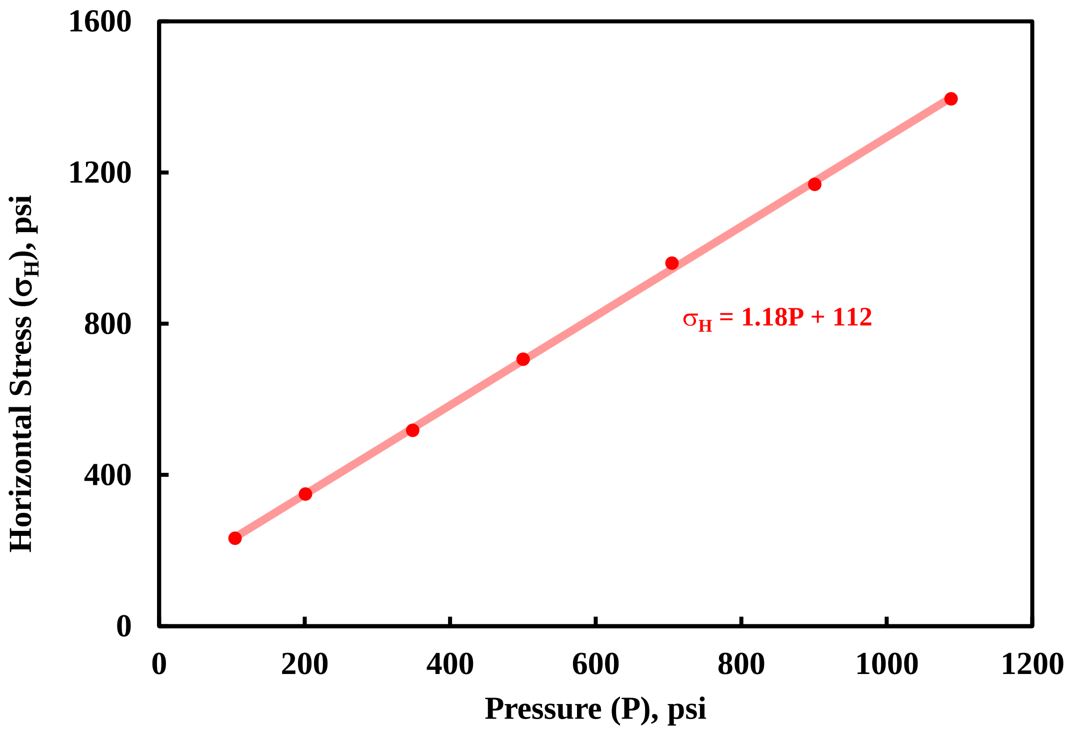

Figure 4-2: Variation in horizontal stress with methane depletion

The figures show that, at complete depletion, the horizontal stress decreased to ~456 psi for helium depletion and ~112 psi for methane depletion. With the sorption phenomenon induced by methane depletion, there was a significant reduction in the horizontal stress compared to helium. This is in agreement with the experimental results reported by previous researchers (Mitra, 2010; Singh, 2008). The effective horizontal stress, which is the difference between horizontal stress and pore pressure, is presented for helium and methane in Figures 4-3 and 4-4, respectively.

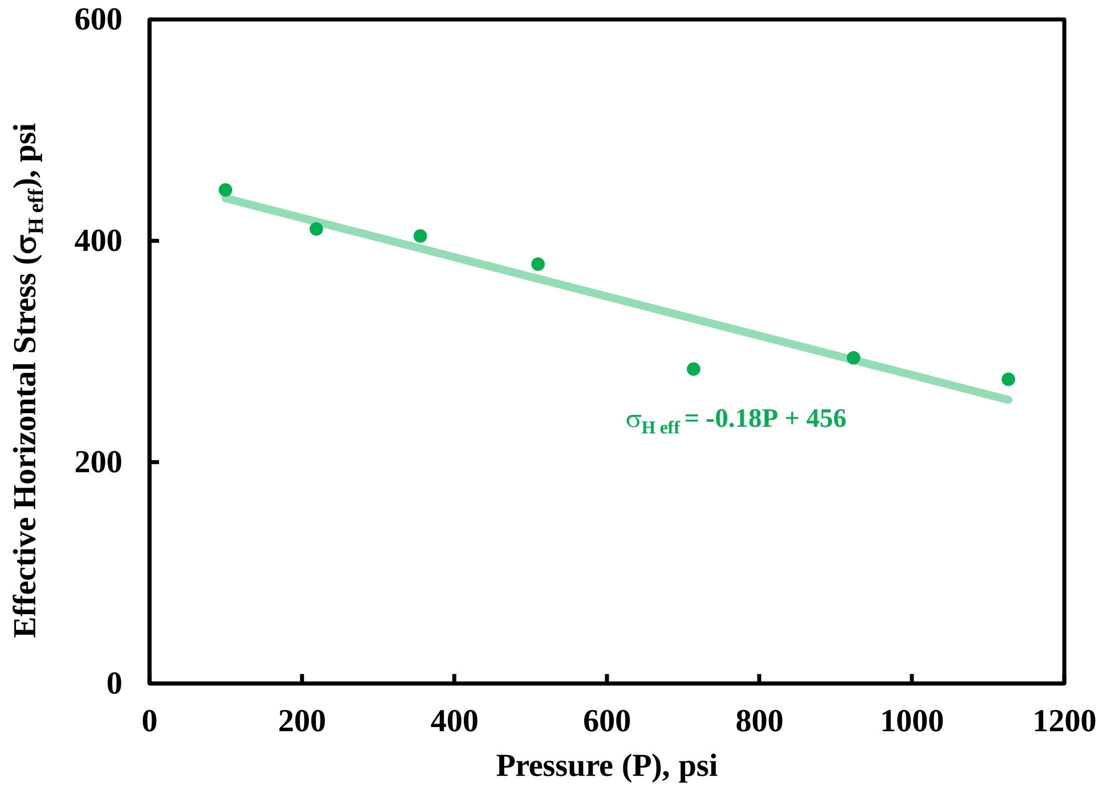

Figure 4-3: Variation in effective horizontal stress with helium depletion

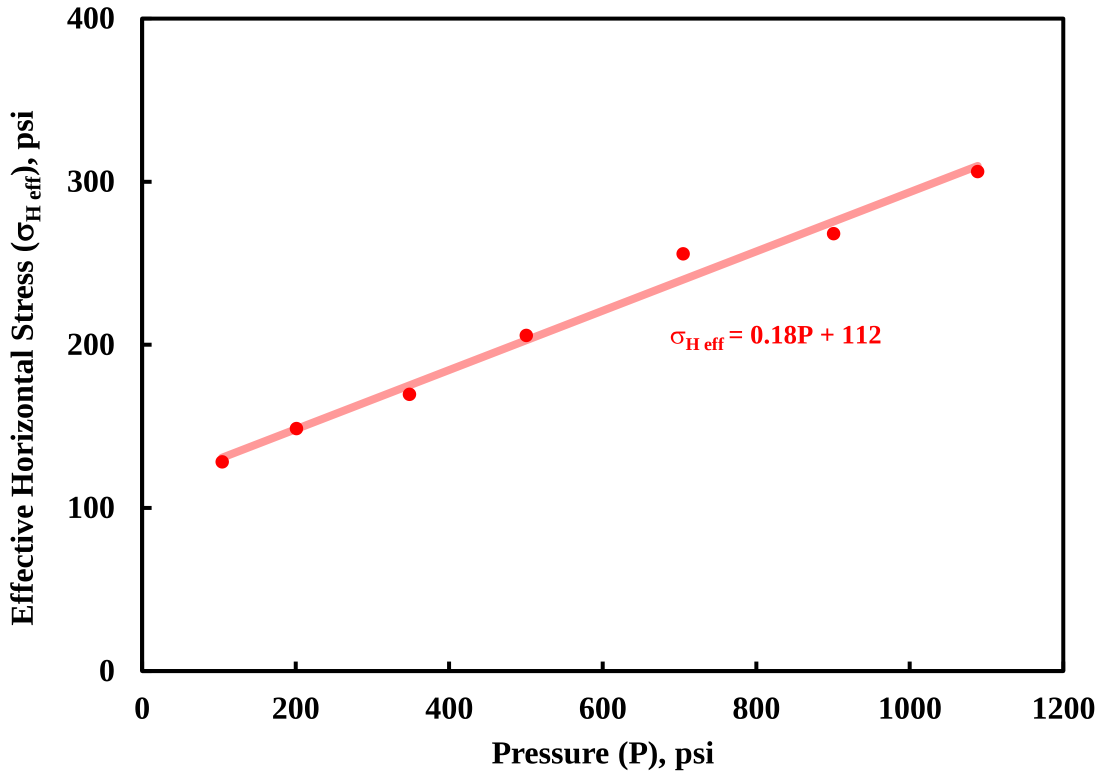

Figure 4-4: Variation in effective horizontal stress with methane depletion

It is evident from the two figures that the effective horizontal stress for helium increases with depletion, attaining a value of ~456 psi at complete depletion. The reason for this is the decompression of the coal sample. For methane, the dominant presence of matrix shrinkage effect leads to a continuous decrease in the effective horizontal stress, reaching a value of ~112 psi at complete depletion. This reduction in the effective horizontal stress is one of the major factors due to which the coal weakens as a result of being in laterally constrained conditions. On complete depletion, the weakening may, or may not, result in coal failure during later stages of pressure depletion (Singh 2014; Soni 2016).

4.2 Shi and Durucan Modeling

This section presents a comparison between experimental and modeled results using the Shi and Durucan model for the variation in effective horizontal stress as a result of depletion. The modeling results were first obtained using a constant value of Young's Modulus (**E**) and were compared to the experimental results. Using the constant input parameters listed in Table 4.1, the variation in effective horizontal stress for decreasing pressure for both helium and methane was estimated using the Shi and Durucan model shown as equations (1) and (3). The shrinkage parameters and Young's modulus value are taken from the Ph.D. dissertation of Dr. Shimin Liu (2012). The value of Poisson's ratio is determined using the helium experimental data and the Shi and Durucan model as presented in equation (3). This is done because equation (3) does not utilize Young's modulus as an input parameter, which is a given value for use in Shi and Durucan model for methane depletion modeling.

Table 4.1: Input parameters required for Shi and Durucan Model (Constant E Value)

Input Parameters for Shi and Durucan Model				
Coal Type	**E (psi)**	**ν**	**ε_∞**	**P_ε (psi)**
San Juan	330000	0.15	0.009	1077

Experimental data and modeling results are shown in Figures 4-5 and 4-6 for helium and methane, respectively.

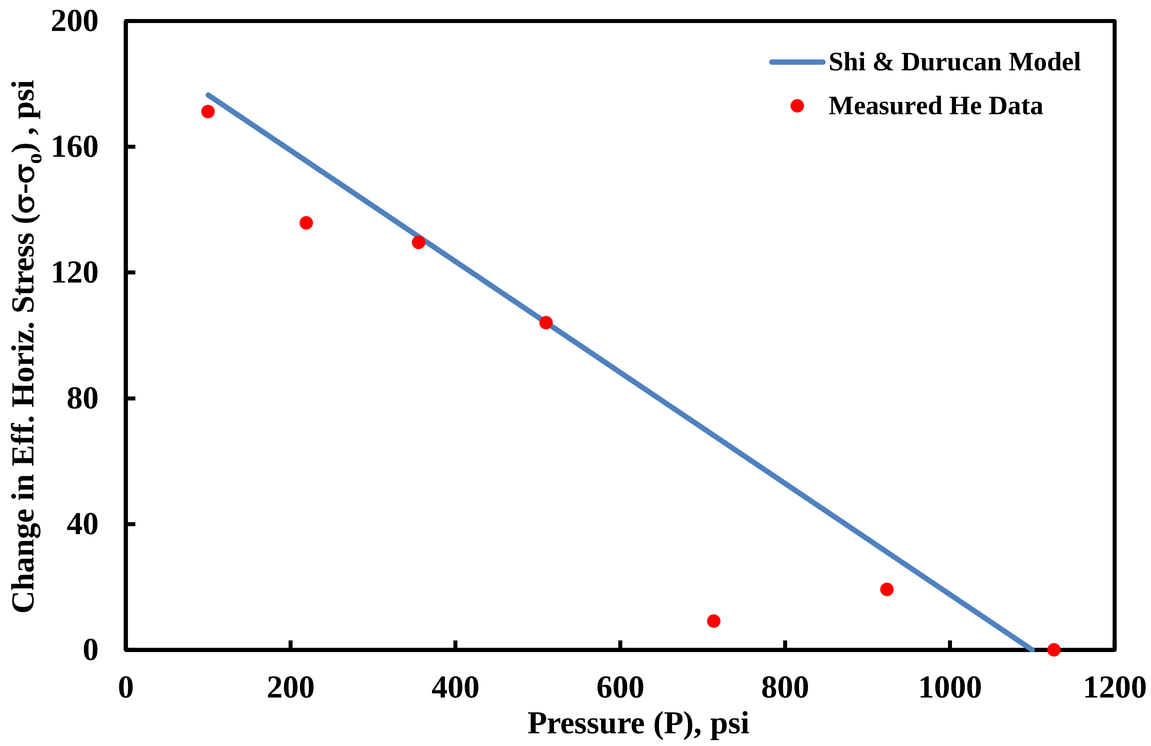

Figure 4-5: Measured and modeled change in effective horizontal stress with helium depletion

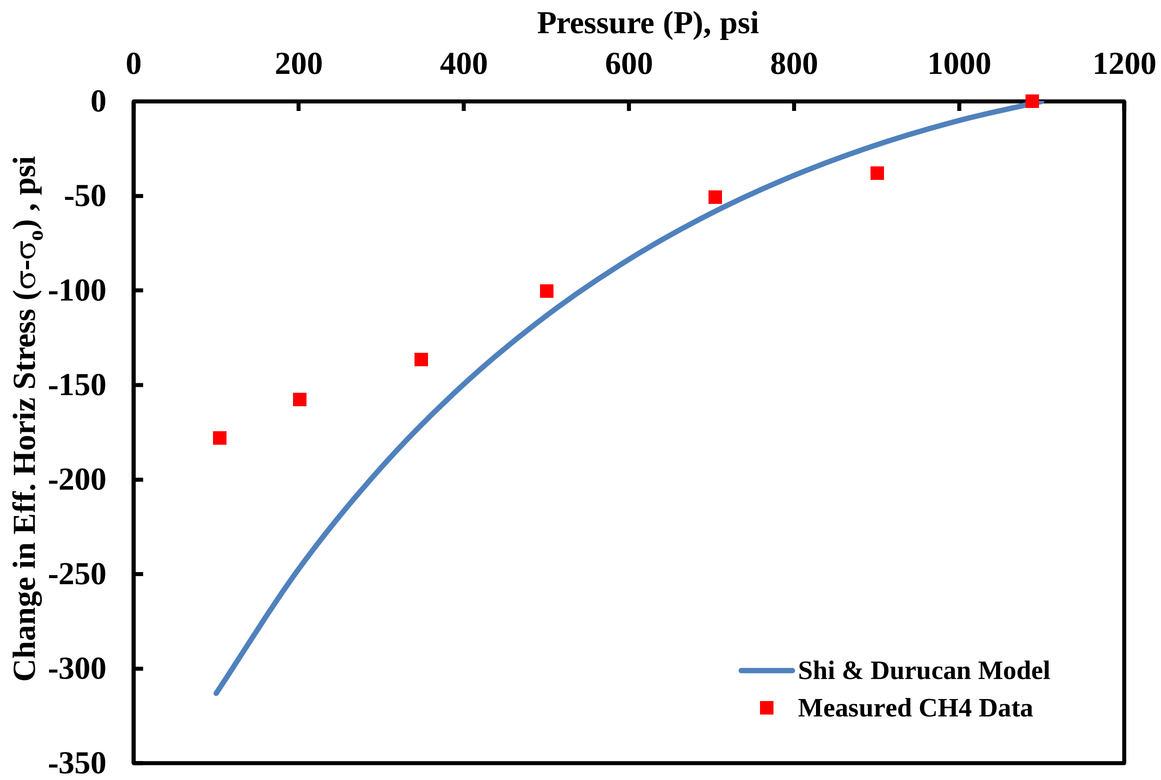

Figure 4-6: Measured and modeled change in eff. horizontal stress with methane depletion (Constant E)

A good match was achieved between the experimental results and the Shi and Durucan model for helium depletion. Apart from one experimental data point, at ~700 psi, the rest of the experimental data was close to the modeled results. The odd data point may be the result of experimental error. In the case of methane depletion, experimental results for change in effective horizontal stress matched modeling results reasonably well for pressure values higher than ~500 psi. Below this, the match was unacceptable.

The value of the geomechanical parameter, **E**, was then varied for the remaining data points to improve the match with the experimental results. Using different and continuously decreasing values of Young's modulus (**E**) during different pressure regions of the depletion, the variation in effective horizontal stress for methane was estimated using the Shi and Durucan model. Experimental data and modeled results are shown in Figure 4-7.

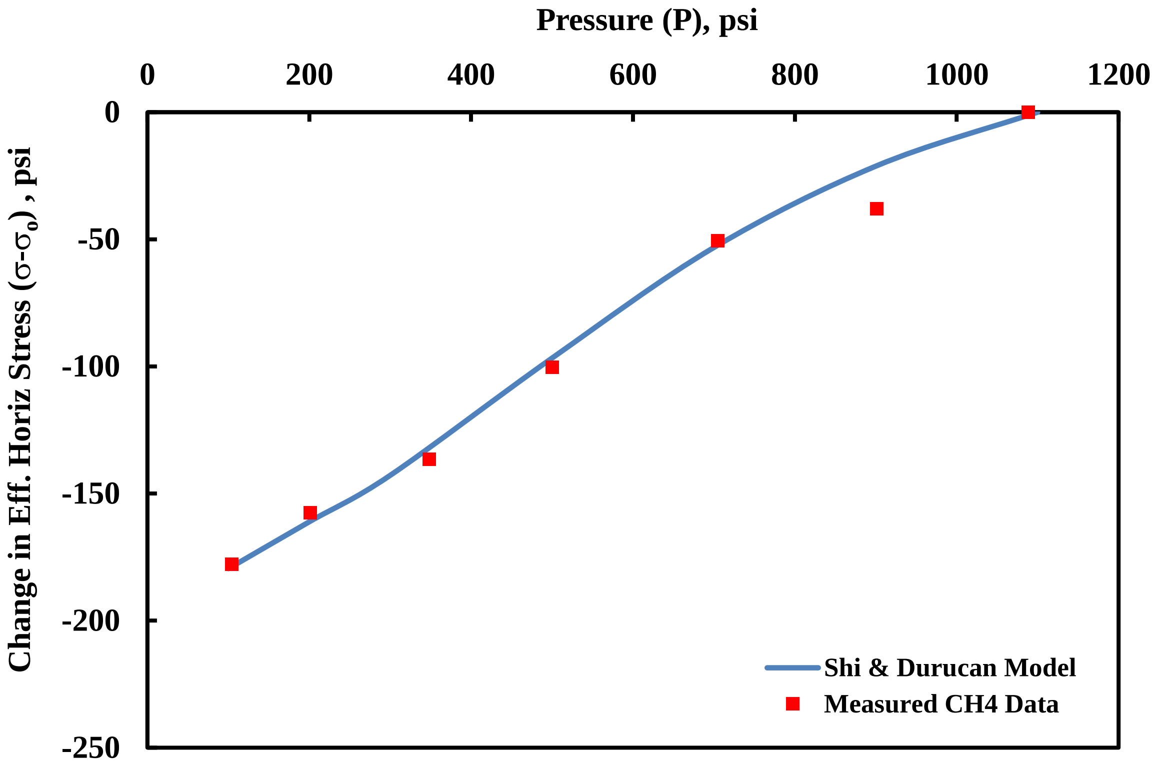

Figure 4-7: Measured and modeled change in eff. horizontal stress with methane depletion (Variable E)

The different values of **E** used for different pressure regimes as input parameters are listed in Table 4.2. The plot of variation in the value of E is shown in Figure 4.8.

Table 4.2: Input parameters required for Shi and Durucan Model (Varying E Value)

Input Parameters for Shi and Durucan Model				
Pressure (psi)	**E (psi)**	**ν**	**ε_∞**	**P_ε (psi)**
1100	330000	0.15	0.009	1077
900	320000			
700	315000			
500	305000			
300	280000			
200	260000			
100	240000			

It is evident from Figure 4.7 that the match improved significantly using a variable Young's modulus (**E**). The value of **E** is decreased continuously with depletion while keeping the other parameters constant. The experimental data for variation in the horizontal stress in a laterally constrained environment could be conveniently modeled using the hypothesis that the mechanical behavior of coal is changing with pressure depletion.

Another property representing the geomechanical behavior, Poisson's ratio, was not varied as it was unable to model the experimental data for changes in effective horizontal stress with depletion. The values of Langmuir-based shrinkage parameters were kept constant given that these remain unaffected with gas depletion.

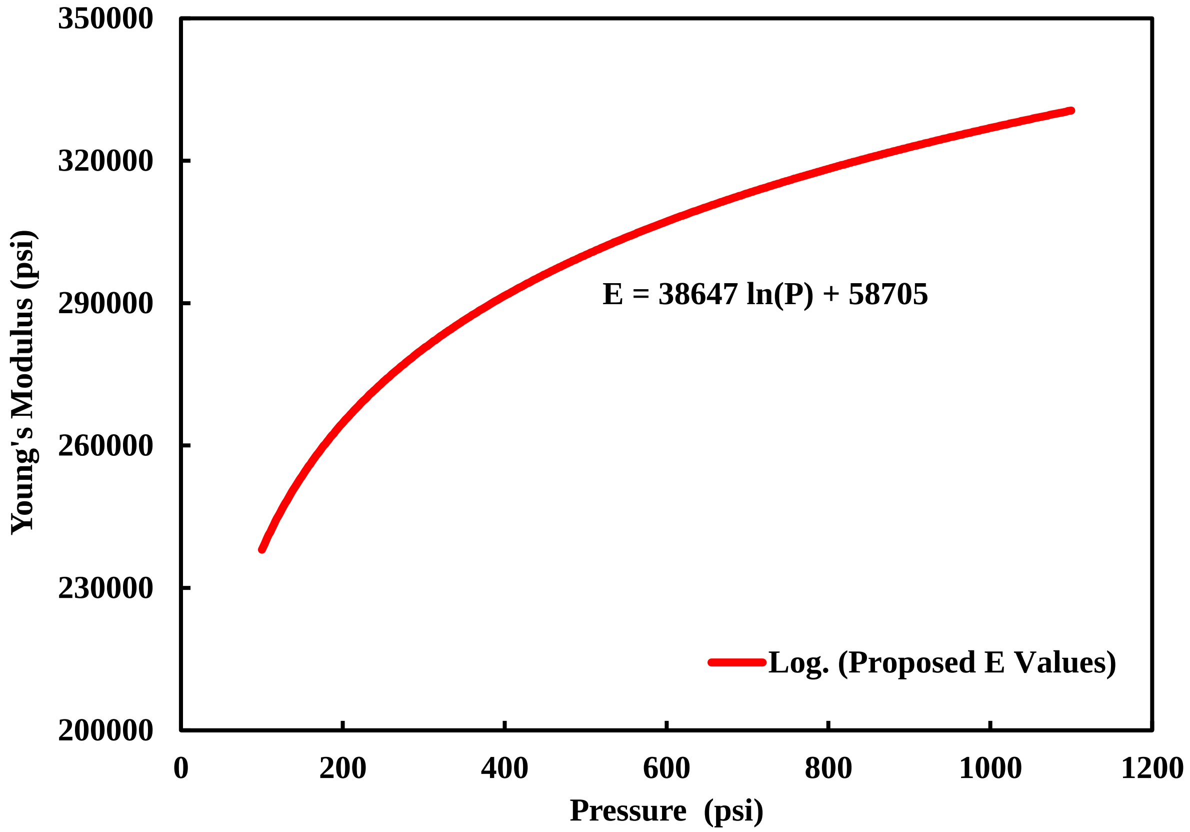

Figure 4-8: Variation in Young's modulus with methane depletion

The magnitude of Young's modulus in Figure 4.8 decreases continuously in a logarithmic manner. This is an outcome of this modeling study in which the mechanical strength of coal is continuously decreasing along with pressure depletion in the CBM reservoir. Assuming the hypothesis is correct supports the fact that theoretical modeling of San Juan type coal could be improved if varying Young's modulus values are used as input to model the changes in effective horizontal stress.

The author believes that Young's modulus of coalbed with pore pressure is different from that of a depleted reservoir. With continuous inner matrix shrinkage occurring during depletion, the coalbed tends to lose its mechanical strength due to its inability to shrink physically in a laterally constrained condition. As depletion occurs, the inner matrix structure continues to shrink, thus creating a void volume which gradually increases with continued gas production. Also, the hydrostatic pore pressure countering the vertical load lowers as depletion occurs. Along with it, a decrease in effective horizontal stress confining the coalbed reservoir makes it more susceptible to failure. Young’s modulus is a fundamental parameter representing the mechanical behavior of a coalbed. Hence, for this study, reduction in the mechanical strength of the coalbed is represented by decreasing Young’s Modulus with pressure depletion. The experimental data for *in situ* stress changes could be explained effectively using the hypothesis that Young’s modulus of coalbed is sensitive to pressure depletion in a CBM reservoir.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Based on the knowledge acquired in this study, the conclusions are summarized below:

1. With continued depletion of helium and methane, horizontal stress decreases. In laboratory conditions, horizontal stress is decreased manually to simulate the uniaxial strain condition during the pressure depletion of a laterally constrained CBM reservoir.
2. Effective horizontal stress increases during helium depletion, whereas, it decreases for methane depletion. This is due to the matrix shrinkage phenomenon coming into play during methane depletion as compared to helium which has no sorption effect on coal.
3. Using continuously decreasing values of Young's modulus (**E**) during different pressure regions of the depletion, the variation in effective horizontal stress for methane was estimated using the Shi and Durucan model. Varying the **E** value leads to a better fit between the modeled and experimental data when compared to using a constant **E** value.
4. Based on the reasoning for the hypothesis and the excellent results obtained based on it, it is concluded that the mechanical strength of coal weakens with continued depletion of the CBM reservoir. This is represented in this study by varying Young's modulus (**E**) of coal, which is an important parameter included in theoretical models to predict permeability or stresses with depletion. The modeled results are a better fit to the experimental data using the hypothesis where the value of **E** is varied with depletion.

Based on the knowledge acquired in this study, the recommendations for future research are stated below:

1. It is not clear whether, under a laterally constrained environment, only Young's modulus among other geomechanical parameters, can be used to represent the variation in mechanical behavior of coal. This requires further investigation.

2. The study validates the hypothesis based on the experimental data for the sample from the San Juan basin. To have a definitive understanding of weakening characteristics of coals from a region, and to understand the variation of Young's modulus for them, more coal samples should be tested from a basin. Furthermore, a better understanding could be achieved by testing samples from different basins across the world.
3. Effort should be devoted to model the experimental data for coals using different theoretical models utilizing geomechanical parameters. For instance, modeling based on a permeability variation model (Palmer et al., 2005) could be done to understand the behavior of all types of geomechanical input parameters used in the model.

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