Dynamic impacts on the survivability of shale gas wells piercing longwall panels

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ABSTRACT

Gas wells traversing active longwall panels are susceptible to failure on account of various strata movements induced by mining activities. To reveal the dynamic impacts of longwall mining on the survivability of these shale gas wells, particularly during the mining cycle as the twin flanking panels successively approach and then pass beyond the wells, a three dimensional finite element model is applied to explore the evolution of potential distress to the wells by defining the magnitudes of various well deformations. The results demonstrate that, wellbores undergo accelerated or significant deformation (increase or decrease) when each advancing panel approaches within tens of meters and the deformation stabilizes as the panel passes the well by tens (deep mining, ~300 m) or up to one hundred plus (shallow mining, ~100 m) meters. Wells are more susceptible to instability when each panel, especially the second panel, advances past the well by approximately 50 m in the case of deep mining and more than one hundred meters for shallow mining with the accumulative deformation reaching the maximum. For mining at shallow depths (~100 m), wells deform by axial compaction, longitudinal distortion, lateral compression and tension in the vicinity of the seam, and by shear in layers close to the surface. Conversely, for deep mining (~300 m) the most severe deformations are mainly restricted to the seam and its shallow roof and floor. Locating the well slightly closer to the rib of the second advancing panel (e.g., 7.5 m out from the pillar-center for a 50 m wide three-entry longwall pillar) achieves improved well integrity.

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1. Introduction

Ensuring the stability and security of hydrocarbon wells is a crucial issue in petroleum and natural gas recovery (Aadnoy and Ong, 2003; Al-Ajmi and Zimmerman, 2006; Bradley, 1979a; Santarelli et al., 1986; Zhang et al., 1999). Deformation or instability of wellbores may have significant implications for loss of production and safety (Hale and Mody, 1993; Zeynali, 2012; Zhang et al., 2009). Long-term stability is vital for both energy development and business management. The shale gas boom has resulted from the application of modern technologies of horizontal drilling and hydraulic fracturing (Haluszczak et al., 2013) with shale reservoirs typically overlain by mineable coal seams. Such coal seams within the Appalachian Basin are mainly extracted by longwall mining, which exert significant impacts on the stability of oil and gas wells transiting these mineable coalbeds — due to the deformation of the overlying strata that occurs after the removal of individual panels (Fig. 1). Extensive field practice has indicated that, vertical gas wells in longwall mining areas mainly fail as a result of shear, distortion, compression and tension (Chen et al., 2012; Liang et al., 2014; Liu et al., 2014; Wang et al., 2013), which are principally due to the failure of rock around the borehole, occurring when stresses applied on the wellbore wall exceed the limit strength of the surrounding rock.

Generally, a protective barrier pillar is retained to protect the wellbore as it transits an unmined portion of the seam. However,
the diameter of a gas well is usually 20–40 cm, which is far smaller than that of a vertical shaft (6–10 m) for coal mining. Therefore, gas wells are significantly more sensitive to strata movement than access shafts. Although the pillar can provide certain protection for the well, the effect of significant movements of the overlying strata induced by full extraction (longwall) mining may be damaging.

Numerous studies have explored the stability of oil and gas wells including physical—mechanical or chemical—mechanical interactions between clay minerals and drilling fluids (Hale et al., 1993; Tan et al., 1996; Zeynali, 2012). These explore the influence of mud weights, in situ stresses, rock lithology and other factors on wellbore failure (Aadnøy and Chenevert, 1987; Ajallooeian and Lashkaripour, 2000; Bradley, 1979b; Gough and Bell, 1981; Haimson and Song, 1993; Lee et al., 2012; Niandou et al., 1997; Ong and Roegiers, 1993; Santarelli et al., 1986; Tan et al., 1998; Tan and Willoughby, 1993; Tien et al., 2006). However, fewer investigations have probed the effects of mining-induced deformations. This is particularly relevant in areas such as southwest Pennsylvania, West Virginia, and eastern Ohio, in the United States where active longwall mining recovers seams that overlay the gas reservoirs. Boreholes to extract hydrocarbons penetrate these shallow minable coal seams before reaching the target shale gas horizons. However, the effect of longwall mining on the stability of such wells has not been highlighted until recently (Liang et al., 2014; Rostami et al., 2012; Scovazzo and Russell, 2013; Wang et al., 2013). This issue of instability of gas wells in longwall mining areas has only recently come to the fore since the rapid development of shale gas. Nonetheless, an update is necessary because gas and oil well construction and coal mining have changed considerably since the original requirements for such wells were enacted in 1956. These changes to common practice include well diameter, casing and pipe steel, cementing requirements, mine configurations, seam depths, and extraction thicknesses (Scovazzo and Russell, 2013).

The survivability of gas wells can be informed by parallel studies probing the performance of gob gas vents holes (Karacan, 2009a,b; Karacan and Goodman, 2009; Karacan and Ola, 2013; Whittles et al., 2006, 2007), the three dimensional influence of coal mining on ground-water supplies (Elsworth and Liu, 1995; Liu and Elsworth, 1997, 1999) and on the stability of gate roads underground (Shahanimashcool and Li, 2012). In particular, the relationship between changing reservoir conditions, longwall face position, and surface movement is likely important (Schatzel et al., 2012).

In this work, we extend a two-dimensional modeling study on the stability of gas wells in longwall mining areas (Liang et al., 2014) to explore whether the peak strains are indeed reached in the two-dimensional section or whether these are merely muted relative to the true 3D strains induced around the true 3D mining geometry. This study addresses this issue.

2. Mechanistic model

In this work, a large scale three dimensional model is used to replicate the morphology of interbedded shales and sandstones or limestones adjacent to a coal seam and with the deformability properties of the units and interfaces controlling the response. We examine the distribution and dynamic evolution of shear offsets, bed separation and compression and various strains along vertical well trajectories induced by mining activities, as the twin flanking panels successively approach and pass by these wells. Finally, we evaluate the three dimensional impacts of longwall mining upon the performance and stability of wells.

2.1. Strata/well deformation

Modes of borehole instability for gas wells transiting coalbeds extracted by longwall mining can be classified into several categories: first, shear failure due to the dissimilarity of rock properties and incongruity of horizontal movement (shear offset) and longitudinal distortion between adjacent layers; second, tensile failure resulting from the incompatibility in vertical displacements (bed separation) between adjacent layers; third, compressional failure resulting from concentrated compressive stresses both in the vertical (penetration/compression occurs within the seam and at weak interfaces between layers, especially at interfaces between the seam and its immediate roof and floor) and horizontal (extrusion/squeeze occurs in the vicinity of the seam) directions; and fourth, combining forms of shear and tension or shear and compression. Among these modes, gas wells are most susceptible to fail by shear and distortion, which has been indicated in practice (Chen et al., 2012; Liang et al., 2014; Liu et al., 2014; Rostami et al., 2012;
Typical deformations of a well within and between layers of alternating soft shale and stiff sandstone as the well is sheared, distorted, stretched and compressed by strata movement induced by coal mining are illustrated in Fig. 2. In this figure, \( \Delta d \) is the relative vertical motion between the upper and lower beds (\( \Delta d > 0 \) corresponds to bed separation and \( \Delta d < 0 \) is for bed penetration/compression) and \( F, T \) and \( \tau \) are respectively the compressive stress, tensile stress and shear stress imposed on the well casing. Magnitudes of well deformation can be calculated from the following expressions.

\[
U_{\text{off}-H} = \sqrt{U_{\text{off}-x}^2 + U_{\text{off}-y}^2}
\]

\[
U_{\text{off}-x/y} = U_{(i,j+1)-x/y} - U_{(i,j)-x/y}
\]

\[
\gamma_{\text{max}} = \sqrt{\gamma_{xz}^2 + \gamma_{yz}^2}
\]

where, \( U_{\text{off}-H}, U_{\text{off}-x} \) and \( U_{\text{off}-y} \) are respectively the total horizontal shear offset on the X-Y plane (horizontal plane) and its two components — the lateral shear offsets in the X and Y directions (Table 1). \( U_{(i,j)-x/y} \) and \( U_{(i,j+1)-x/y} \) are the horizontal displacements of two adjacent nodes at one interface in the X/Y direction. \( \gamma_{xz}, \gamma_{yz} \) and \( \gamma_{\text{max}} \) are respectively shear strains in the X-Z plane, Y-Z plane and the total longitudinal distortion of the vertical well (Table 1). We utilize these relations to calculate the deformations that a well would undergo with the movement of the overlying and underlying strata resulting from longwall mining.

### 2.2. Failure criterion and formulation

In this analysis we neglect any added resistance applied by well casing — as this resistance will be trivial in comparison to the applied deformations. Consequently, we do not mesh the well, but use quantities (displacements and strains) of a series of nodes and zones which correspond to the five candidate vertical well trajectories to demonstrate the specific characteristics of wellbore deformation.

Shear is the primary mode of wellbore instability for gas wells penetrating alternating soft and stiff beds under the effects of longwall mining. We adopt the Mohr–Coulomb strength criterion to determine whether the surrounding rock will yield, with this criterion is defined as

\[
\tau_f = c + \sigma_n \tan \phi
\]

where, \( \tau_f \) is the shear strength, \( c \) is the cohesion, \( \sigma_n \) is the normal stress and \( \phi \) is the angle of internal friction. This can also be expressed in the form

\[
\sigma_1 = \frac{1 + \sin \phi}{1 - \sin \phi} \sigma_3 + \frac{2c \cos \phi}{1 - \sin \phi}
\]

where, \( \sigma_1 \) and \( \sigma_3 \) are respectively the maximum and minimum principal stresses.

### 2.3. Interface characteristics

Within the Appalachian Basin in western Pennsylvania, the Pittsburgh coal seam is the most economically important coalbed, of which the overlying and underlying strata mainly comprise soft shales interbedded with stiff sandstone or limestone. The most common failure mode for gas wells piercing longwall panels is by shear instability, which occurs at weak interfaces between the layered strata. In order to fully replicate the probable response of weak interfaces between layers, interface elements are adopted in our model to represent the weak contact along which slippage, bed separation and compression may occur.

We use the model FLAC3D (Itasca, 2009) with interfaces characterized by Coulomb sliding and tensile and shear bonding. Each interface element is defined by three interface nodes. Generally, interface elements are attached to a surface face. When another grid surface comes into contact with an interface element, the contact is detected at the interface node, and is characterized by normal and shear stiffnesses, and strength. The fundamental contact relation is defined between the interface node and a face (the target face). The constitutive model of the interface element is defined by a linear Coulomb shear-strength criterion which limits

![Fig. 2. Typical deformation of a well within and between layers of alternating soft shale and stiff sandstone as the well is sheared, distorted, stretched and compressed by strata movement induced by coal mining (with slip interfaces between alternating layers) (modified from Liu et al., 2014).](image-url)
The shear force acting at an interface node, the normal shear stiffnesses ($k_n$ and $k_s$), the tensile and shear bond strengths ($\sigma_t$ and $S_a$), and the dilation angle ($\psi$) that causes an increase in effective normal force on the target face after the shear-strength limit is reached (Itasca, 2009). Fig. 3 illustrates the components of the constitutive model acting at the interface node -- P. The relationship between shear stress and shear displacement is illustrated in Fig. 4 where the curve includes two parts: the linear elastic stage and the perfectly plastic stage.

In the linear elastic regime (Fig. 4), the normal and shear forces that describe the elastic interface response at calculation time $(t+\Delta t)$ are determined by Eq. (6):

$$F^{(t+\Delta t)}_n = k_n u_{nt} + \sigma_t A$$
$$F^{(t+\Delta t)}_s = k_s u_{st} + \sigma_s A$$

where, $F^{(t+\Delta t)}_n$ and $F^{(t+\Delta t)}_s$ are separately the normal force and the shear force vector at time $(t + \Delta t)$; $u_{nt}$ is the absolute normal penetration of the interface node into the target face; $k_n$ is the incremental relative shear displacement vector; $\sigma_t$ is the additional normal stress added due to interface stress initialization; $k_s$ is the normal stiffness; $k_s$ is the shear stiffness; $\sigma_s$ is the additional shear stress vector due to stress initialization at the interface; and $A$ is the representative area associated with the interface node.

In the perfectly plastic regime (Fig. 4), the contact states of the interface node can be divided into three types according to the Mohr–Coulomb criteria: (1) the slip while in a bonded state, (2) the Coulomb sliding state, and (3) the separated state. The yield relationships in the shear and normal directions are

$$F_{\text{max}} = cA + \tan\phi(F_n - pA)$$
$$F_n = \sigma_t$$

where $F_{\text{max}}$ is the maximum shear strength, $c$ is the cohesion along the interface, $\phi$ is the friction angle of the interface, $F_n$ is the normal force, $p$ is the pore pressure, and $\sigma_t$ is the normal tensile strength of the interface.

At every calculation time $t$, the normal force $F_n$ and shear force $F_s$ of the interface nodes are compared with the normal tensile strength $\sigma_t$ and the maximum shear strength $F_{\text{max}}$, respectively. If the interface force exceeds the interface strength, the force will be corrected as follows (Itasca, 2009):

1. If $F_n < \sigma_t$ and $F_s < F_{\text{max}}$, then the interface node remains in the elastic regime, failing to slip while bonded. The interface forces are not corrected.
2. If $F_n < \sigma_t$ and $F_s > F_{\text{max}}$, then the interface node falls in the Coulomb sliding regime and the interface forces are corrected. Since we neglect the dilation characteristics of the interface elements, the forces are corrected as follows:

$$F_n = F_{\text{max}}$$

3. If $F_n \geq \sigma_t$, then the interface node falls into the separation regime, and the interface forces are corrected as follows:

$$F_n = 0$$
$$F_s = 0$$
$$\sigma_t = 0$$
3. 3D geomechanical model

A large scale three-dimensional geomechanical model is constructed using the commercial software code FLAC3D (Itasca, 2009). This is an explicit finite-difference program for engineering mechanics with a wide range of constitutive models available to simulate the behavior of rock and soils. It has been widely applied to the modeling of longwall workings in coal measure strata (Mohammad et al., 1997; Whittles et al., 2007; Yavuz and Fowell, 2002).

3.1. Geological condition and parameters

The Pittsburgh coal seam and its overlying and underlying strata within the Appalachian Basin mainly comprise layered strong sandstones or limestones and relatively weak shales. We simplify this model to one comprising a single 2 m thick coalbed with alternating massive shale and sandstone layers each ~10 m thick (Fig. 5). We employ the same rock property parameters in the 3D model as used in a previous 2D study (Liang et al., 2014), which was calibrated against observed and recorded surface subsidence in the Appalachian coalfields (Gutierrez et al., 2010).

3.2. Model geometry and settings

The entire model is 600 m long × 2000 m wide × 142/342 m thick with a flat ground surface. Panels 1 and 2, which have the same dimension (600 m long × 370 m wide × 2 m thick), straddle a 50 m wide central pillar that incorporates a 15 m wide yield pillar, a 5 m wide gate road and a 30 m wide barrier pillar, as illustrated in Figs. 5 and 6. The X, Y, Z axes comprise the panel rib (Y), the transverse direction (X) with the Z axis along the vertical well axis. Extra elements (605 m wide) are added to ensure that the edges of the model along the X and Y axes are fixed for normal displacements. The basal boundary is fixed in the vertical direction and the upper boundary is stress-free.

The model is run to an initial equilibrium by gravity loading to assign the pre-mining stress condition. Then the gate road, followed by panel 1 and then by panel 2 are excavated sequentially. Panel advance is simulated by stepwise excavation — using twenty-eight stages for each panel. Locations of the panels after each excavation stage are indicated in Fig. 6, for the five candidate well trajectories all located at the Y coordinate of 300 m. Each panel advances 10 m in each excavation stage as it approaches and then passes-by the well within a distance of ±100 m in the direction of the Y axis but advances by a greater increment (100 m, 50 m, 30 m and 20 m, sequentially) when the panel is more than 100 m ahead of these wells or when the panel is more than 100 m beyond these wells (20 m, 30 m, 50 m and 100 m, sequentially) (Fig. 6).

We observe that both the cases of a shallow seam (~100 m) and a deeper seam (~300 m) result in larger deformation for gas wells compared to the case of a seam at intermediate depth (~200 m) (Liang et al., 2014). Correspondingly, in this work we explore these two bounding scenarios. We examine the potential performance of five typical well trajectories under the dynamic effects of longwall mining as illustrated in Figs. 5 and 6.

4. Analysis and discussion of model results

We examine the deformation of the overlying layered strata as it is undermined, stretched, tilted, then lowered, and finally recompressed (McNally and Evans, 2007). The overlying beds deform in both vertical and horizontal directions, such that a slow-moving subsidence profile forms across the ground surface (Peng, 1992; Peng and Chiang, 1984). Consequently, mining stresses/strains are induced within the coal seam and its overburden and underburden, especially at panel corners where the mining induced stresses in front of the working face (the front abutment pressure) and along both sides of the gob (the side abutment pressure) superimpose (Fig. 7)(Peng, 1986), and within which wells may be located. Hence, the loading process due to mining-induced stresses on these vertical wells penetrating the pillar is not static but dynamic and changes as the flanking panels proceed in succession. These resulting large strains exert significant deformations on wells, leading to progressive deformation and potentially failure.

We explore this deformation behavior in this analysis. With recovered data of deformations, strains and distortions we evaluate the potential performance of wells under the dynamic impacts of longwall mining to define the potential for failure through the full mining cycle. For clarity, deformations and strains discussed in the following are detailed in Table 1.

4.1. Evolution and magnitudes of horizontal shear offsets

We compare the total horizontal shear offset ($U_{off-H}$) and its two components ($U_{off-x}$ and $U_{off-y}$) occurring at weak interfaces between alternating massive shales and sandstones, for wells penetrating both shallow (100 m) and deep (300 m) seams. The two components of shear offsets are separately in the direction perpendicular to ($U_{off-x}$) and parallel to ($U_{off-y}$) that of panel advance (Fig. 6). Profiles of $U_{off-H}$ and the two components for the five well trajectories passing through the pillar in the two scenarios are shown in Figs. 8–11. Fig. 8 displays the evolution of the largest $U_{off-H}$ of each trajectory along its axis as the twin flanking panels proceed sequentially. Figs. 10 and 11 are for the two components, in which we do not show the negative $U_{off-x}$ and $U_{off-y}$ for wells piercing the shallow seam (100 m), because they are insignificant in comparison to the positive displacements. Fig. 9 illustrates the axial distribution of $U_{off-x}$ as each panel advances far enough beyond these wells which penetrate both shallow and deep seams. The magnitudes of $U_{off-H}$ and its two components for each scenario are listed in Table 2.

4.1.1. Total horizontal shear offsets — $U_{off-H}$

As apparent in Fig. 8, for wells penetrating both the shallow (100 m) and the deep (300 m) seams, evolution of the largest $U_{off-H}$ along well axis in the mining cycles of the twin panels displays similar staged characteristics. All the largest $U_{off-H}$ increase as panel 1 approaches and then passes these wells, but it depends on different wells in the mining cycle of panel 2. When mining the shallow seam (100 m), the development of the largest $U_{off-H}$ may be separated into three stages according to the evolution characteristic as panel 1 proceeds. The greatest $U_{off-H}$ increase slowly until the working face is ~70 m ahead of the well (Stage I, t < ~70 m), $U_{off-H}$ grows no more than 4 mm as panel 1 proceeds each 10 m. Then in Stage II (~70 m to 120 m), the largest $U_{off-H}$ of wells increase rapidly and the peak growth could be ~10 mm for a face advance of 10 m. The peak growth is for path 1 as panel 1 advances 30–40 m after the well. In Stage III (>120 m), $U_{off-H}$ increase gradually again, entering a steady-state with a peak $U_{off-H}$ of 144 mm (path 1). In the excavation cycle of panel 2, the largest $U_{off-H}$ of wells also build rapidly as panel 2 advances ~50 m ahead of and up to ~120 m after these wells have been passed (Stage II). The greatest $U_{off-H}$ of wells 1–3 decrease rapidly, however, the peak $U_{off-H}$ for wells 5 and 4, which are closer to panel 2, switch to increase successively under the increasing influence of mining of panel 2 as it proceeds. The peak growth is ~7 mm with an advance of 10 m, and for path 5 as panel 2 advances 30–40 m after the well. All the $U_{off-H}$ remain constant as panel 2 proceeds sufficiently far (Stage III, >120 m) after wells.

As for wells penetrating the deep seam (300 m), development of
the greatest $U_{\text{eff,Hs}}$ displays similar characteristic to that for wells penetrating the shallow seam as panels 1 and 2 proceed successively. Shear slippage builds as panel 1 approaches within 50 m of the well and advances less than 50 m beyond these wells (Stage II, −50 m to 50 m); the peak growth of $U_{\text{eff,Hs}}$ is 18 mm, and is for path 1 as panel 1 advances 0–10 m after the well. In the mining...
Fig. 8. Dynamic evolution of the largest total horizontal shear offsets ($U_{\text{off-Hs}}$) along well axes occurring at weak interfaces for the five candidate paths of wells piercing both the shallow (100 m) (a, b) and the deep (300 m) (c, d) seams. Panel 1 is extracted first (a, c) and then panel 2 (b, d). The abscissa represents the relative distance (m) between wells and panels. The negative coordinates correspond to locations of the longwall working face ahead of wells which are located at an abscissa of zero, with positive magnitudes corresponding to locations of the working face as it passes-by these wells.

Fig. 9. Longitudinal distribution of the total horizontal shear offsets ($U_{\text{off-Hs}}$) occurring at weak interfaces for the five candidate paths of wells after the single panel 1 (a, c) and then panel 2 (b, d) separately advance sufficiently far (300 m for wells piercing the 100 m deep seam (a, b) and 150 m for wells piercing the 300 m deep seam (c, d)) after these wells.
cycle of panel 2, \( U_{\text{off-HS}} \) changes rapidly as panel 2 advances within 30 m ahead of and less than 40 m after these wells (Stage II, –30 m to 40 m). Thereafter, \( U_{\text{off-HS}} \) of wells 1 and 2 decrease continually, but \( U_{\text{off-HS}} \) of wells 5, 4 and 3, which are closer to panel 2, switch to increase successively under the growing mining influence of panel 2. The peak growth is 20 mm with an advance of 10 m and for path 5 as panel 2 proceeds 0–10 m after the well. All the \( U_{\text{off-HS}} \) tend to be invariant after panel 2 passes these wells by ~60 m.

Clearly in this cycle, shear deformations on wells undergo a repeated cyclic loading as the flanking twin panels successively approach and pass. Shear deformation is maximum when the face approaches within tens of meters and remains for more than one hundred meters after the panels have passed beyond these wells. The specific range where the strong influence of mining endures varies with seam depth and the relative distance between well trajectories and the twin panels. Generally, along the mining direction, the range of strong influence of mining on shear slippage across wells is broader for shallow-mining than for the case of a deeper seam.

Along the longitudinal direction, when mining is shallow (100 m), the largest \( U_{\text{off-HS}} \) (144 mm) arises in the shallow roof (20/30 m above the seam) for candidate path 1, but elevates to interfaces close to the ground surface (90 m) for paths 2–5 after panel 1 is extracted. Then these \( U_{\text{off-HS}} \) migrate to interfaces at an elevation around the half depth of the seam, and the peak \( U_{\text{off-HS}} \) changes to be 111 mm. When mining is deep (300 m), \( U_{\text{off-HS}} \) of wells all peak on weak interfaces within the shallow roof (10–30 m) either after panel 1 (121 mm) is, or both panels (114 mm) are extracted. The \( U_{\text{off-HS}} \) on interfaces within shallower layers are much smaller. \( U_{\text{off-HS}} \) occur on weak interfaces more than 60 m above the seam are all less than 15 mm when the twin panels are both mined (Fig. 9d). Referring to these longitudinal distributions of \( U_{\text{off-HS}} \), the length of protective casing or grouting of the surrounding rock can be designed. Besides, along the well axis, \( U_{\text{off-HS}} \) fluctuates as the strength of overlying beds varies. The \( U_{\text{off-HS}} \) on one weak interface with a stiffer layer above and a soft layer below is generally larger than as occurs on the interface with a softer layer above and a stiffer one below, which is even more apparent when mining is shallow.

In this study, we still define the threshold for well instability by

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Fig. 10. Dynamic evolution of the largest (both positive and negative) lateral shear offsets – \( U_{\text{off}} \) (the component along the direction parallel to the face) along well axes occurring at weak interfaces for the five candidate paths of wells, which penetrate both the shallow (100 m, a, b) and deep seams (300 m, c–f), as the twin flanking panels sequentially advance. Panel 1 is first extracted (a, c, e), followed by panel 2 (b, d, f).
shear as 100 mm (Liang et al., 2014), which corresponds to the maximum allowable horizontal shear offset, as indicated by the dashed lines in Figs. 8 and 9. For shallow mining (100 m) (Fig. 8a, b), path 1 shears first as panel 1 advances ~60 m after the well, and the accumulated $U_{off-H}$ of paths 2 and 3 exceed the threshold as panel 1 advances 150 and 200 m separately after the wells. Only the remainder $U_{off-H}$ of path 1 is still greater than 100 mm as panel 2 is sufficiently extracted (>120 m). For deep mining (300 m) (Fig. 8c, d), path 1 shears first as panel 1 advances ~60 m after the well, and the accumulated $U_{off-H}$ of paths 2 and 3 exceed the threshold as panel 1 advances 150 and 200 m separately after the wells. Only the remainder $U_{off-H}$ of path 1 is still greater than 100 mm as panel 2 is sufficiently extracted (>120 m).

Table 2

<table>
<thead>
<tr>
<th>Seam depth</th>
<th>Relative motion between adjacent layers/mm</th>
<th>Panel 1 Hazardous locations/m</th>
<th>Panel 1 Height</th>
<th>Panel 1 Advancement</th>
<th>Panel 2 Hazardous locations/m</th>
<th>Panel 2 Height</th>
<th>Panel 2 Advancement</th>
<th>Percentage change</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m</td>
<td>$U_{off-H}$</td>
<td>144</td>
<td>+30/-90</td>
<td>&gt;200</td>
<td>111</td>
<td>+40</td>
<td>&gt;150</td>
<td>-23%</td>
</tr>
<tr>
<td></td>
<td>$U_{off-x}$</td>
<td>−31 to 144</td>
<td></td>
<td>−9 to 111</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>187%/-23%</td>
</tr>
<tr>
<td></td>
<td>$U_{off-y}$</td>
<td>−3 to 44</td>
<td></td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>$\Delta d$</td>
<td>2</td>
<td>−0</td>
<td>&gt;120</td>
<td>0.4</td>
<td>+90</td>
<td>&gt;120</td>
<td>61%/-31%</td>
</tr>
<tr>
<td>300 m</td>
<td>$U_{off-H}$</td>
<td>121</td>
<td>+10</td>
<td>&gt;60</td>
<td>114</td>
<td>±10</td>
<td>≥&gt;50</td>
<td>-6%</td>
</tr>
<tr>
<td></td>
<td>$U_{off-x}$</td>
<td>−71 to 121</td>
<td></td>
<td>−141 to 105</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>61%/-13%</td>
</tr>
<tr>
<td></td>
<td>$U_{off-y}$</td>
<td>−15 to 37</td>
<td></td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>$\Delta d$</td>
<td>23</td>
<td>+30</td>
<td>≥&gt;50</td>
<td>9</td>
<td>+110</td>
<td>+100</td>
<td>22%</td>
</tr>
</tbody>
</table>

Note: Hazardous height refers to an elevation (m) above (positive) or below (negative) the coal seam where shear offset reaches the peak and the well is most likely to fail by shear; and heights “±0” refer to the interfaces between the seam and its immediately roof and floor.
d), $U_{\text{off-H}}$ of path 1 reaches the threshold as panel 1 advances ~30 m after the well and it is ~40 m for path 5 as panel 2 passes by the well. $U_{\text{off-H}}$s of paths 2–4 are always less than 100 mm in the entire mining cycle of the twin panels. Thus, wells piercing a 100 m deep seam are more susceptible to shear than those piercing a 300 m deep seam. The unfavorable influence resulting from the mining of panel 2 is more severe for paths 5 and 4 across the pillar and is mainly manifest in the vicinity of the seam (Fig. 8b, d and Fig. 9b, d).

From the foregoing analyses, it is apparent that the rock movement and deformation within the thinner overlying strata of a shallow seam (100 m) are more severe, and the range of strong influence induced by shallow mining is relatively broad along both the transverse and mining directions. While for deep mining, strata movement (and associated deformation of wells) is mainly restricted to the shallow roof, and engenders a smaller influence along the mining direction. In the cross-section of the pillar, it is advisable to locate the well slightly closer to the second advancing panel (e.g., along candidate path 3, which is 7.5 m from the pillar center on the side of panel 2) irrespective of seam depth in order to minimize shear slippage during the entire mining cycle of panels 1 and 2.

4.1.2. Shear offsets – $U_{\text{off-x}}$ and $U_{\text{off-y}}$

Figs. 10 and 11 show the evolution of the two components ($U_{\text{off-x}}$ and $U_{\text{off-y}}$) of the total horizontal shear offset ($U_{\text{off-H}}$) along the well axis for wells penetrating both shallow and deep seams as the twin flanking panels advance sequentially, where the small negative $U_{\text{off-x}}$s and $U_{\text{off-y}}$s for wells piercing the shallow seam (100 m) are not presented (they are much smaller than the positive magnitudes). As apparent in Fig. 10, evolution of the component $-U_{\text{off-x}}$ as the twin panels advance sequentially displays similar characteristics and magnitudes to that of $U_{\text{off-H}}$ (Table 2). In terms of the contribution to the $U_{\text{off-H}}$ between $U_{\text{off-x}}$ and $U_{\text{off-y}}$, the former contributes the largest. Nevertheless, development of the component $U_{\text{off-y}}$ shows a different feature. $U_{\text{off-y}}$s are considerably smaller in magnitude (the peak $U_{\text{off-y}}$ is approximately one third of the peak $U_{\text{off-x}}$), whose evolution is approximately symmetrical as each panel advances. The symmetry plane lags behind the wells by ~35 m for shallow mining and abreast of the wells for deep mining. $U_{\text{off-y}}$s increase slightly first, then grow rapidly to a peak before declining rapidly to a residual displacement (Fig. 11). Along the transverse direction, both the positive and negative $U_{\text{off-y}}$s are greatest for path 1 (~40 mm) in the mining cycle of panel 1 and for

Fig. 12. Dynamic evolution of the largest bed separation ($\Delta d > 0$) and compression ($\Delta d < 0$) along well axes occurring at weak interfaces for the five candidate paths of wells piercing both shallow (100 m, a, b) and deep (300 m, c–f) seams. $\Delta d$ are induced above and below a longwall pillar flanked by twin panels as they advance sequentially. Panel 1 is first extracted (a, c, e) followed by panel 2 (b, d, f).
path 5 (−40 mm) when mining panel 2, irrespective of mining depth.

4.1.3. Bed separation and compression − Δd

We record the vertical relative motion of two adjacent layers (Δd), in extension (separation) (Δd > 0) and in compression (Δd < 0) (Fig. 2 and Table 2) separately represent the tensile and compressive deformation occurring between alternating layers. Evolution of these bed separations and compressions as the twin panels sequentially advance are shown in Fig. 12 for mining at a depth of 100 m and 300 m. Since the largest bed separation for shallow mining (100 m) only accounts for 2 mm in the entire mining cycle, they are not displayed in Fig. 12.

As the working face moves progressively forward, the roof above the pillar edge begins to rotate and to sag, resulting in considerable compression between alternating hard and soft layers, especially between the seam and its immediate roof and floor. For shallow mining (100 m), the largest bed separation is −2 mm for path 2 which occurs on an interface close to the surface (Table 2), where it is compressed and switches to compression as panel 1 advances. Bed separations for other wells are all less than 2 mm and ultimately switch to bed compressions. In the mining cycle of panel 2, the largest bed separation is 0.4 mm (path 1), which also occurs on the top interface. As for bed compression, they all increase gradually as the twin panels advance. The largest bed compressions at wells are separately −209 mm and −274 mm after single panel 1 and then both panels are extracted (Table 2). Bed compression is much larger for paths 1 and 5 which are closest to the flanking panels after both panels are mined, and path 2, which is closest to the pillar center, suffers the smallest bed compression. Along the longitudinal direction, bed compressions at interfaces between the seam and its immediate roof and floor are greatest (Fig. 13 and Table 2).

For deep mining (300 m), the greatest bed separation accounts for −23 mm in the mining cycle of panel 1, which is for path 1 and occurs at an elevation 30 m above the seam when panel 1 advances 50 m beyond the well (Fig. 12 and Table 2). Bed separations of other wells do not exceed 10 mm. Bed separations increase as panel 2 approaches then passes these wells by −100 m when they become invariant with a permanent set (−7 mm). Bed compressions increase progressively as the twin panels advance in succession. In the mining cycle of panel 1, the peak bed compression of path 1 (−279 mm) is much larger compared with that for paths 2−5 (−102 mm). In the mining cycle of panel 2, inter-lamellar compressions increase continuously, and increase faster as panel 2 advances 10 m ahead of and 30 m beyond the wells. As panel 2 proceeds sufficiently far after these wells, paths 1 and 5 have the greatest cumulative inter-lamellar compressions, which are each −340 mm, occurring in the vicinity of the seam (Fig. 13 and Table 2). Excessive bed separation and compression would induce tensile and compressive failure for wells along their axes requiring ductile or reinforced well casings to resist longitudinal compression.

4.2. Evolution of longitudinal well distortions, lateral and vertical strains

Beside bed slippage, separation and compression between alternating soft and stiff layers can result in shear, tensile and compressive failure. For wells subject to the influence of longwall mining, the high mining-induced strains at corners of the working face, where the front and the side abutment pressure superimpose (Fig. 7) are also destructive to the integrity of wells located within the pillar. Consequently, evolution and magnitudes of strains in mining cycles of the twin flanking panels are critical and need to be

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**Fig. 13.** Longitudinal distribution of bed separation (Δd > 0) and compression (Δd < 0) occurring at weak interfaces for the five candidate paths of wells after the single panel 1 (a, c) and then panel 2 (b, d) separately advance sufficiently far (300 m for wells piercing the 100 m deep seam (a, b) and 150 m for wells piercing the 300 m deep seam (c, d)) after these wells.
investigated. We analyze the total longitudinal well distortion ($g_{\text{max}}$) and its two components ($g_{xz}$, $g_{yz}$) that develop for wells piercing both the shallow (100 m) and the deep (300 m) seams. These distortions are equivalent to changes in lateral displacement with depth. We also analyze the horizontal strains ($\varepsilon_{xx}$, $\varepsilon_{yy}$) and vertical strain ($\varepsilon_{zz}$) along wells which might engender tensile and compressive failure in the casings. Model results are shown in Figs. 14–19 and Table 3.

Fig. 14. Dynamic evolution of the largest total longitudinal well distortions ($g_{\text{max}}$) for the five candidate paths of wells piercing both the shallow (100 m) (a, b) and the deep (300 m) (c, d) seams as the twin flanking panels advance sequentially. Panel 1 is first extracted (a, c) followed by panel 2 (b, d).

Fig. 15. Distribution of the total longitudinal well distortions ($g_{\text{max}}$) for the five candidate paths of wells after the single panel 1 (a, c) and then panel 2 (b, d) separately advance sufficiently far (300 m for wells piercing the 100 m deep seam (a, b) and 150 m for wells piercing the 300 m deep seam (c, d)) after these wells.
4.2.1. Total longitudinal well distortions $- \gamma_{\text{max}}$

Evolution of the largest total longitudinal well distortions ($\gamma_{\text{max}}$) (Fig. 14) for the five wells bears an analogy to that of the largest total horizontal shear offsets ($U_{\text{off}}$) (Fig. 8) during the entire mining cycle of the twin panels. That is, irrespective of seam depth, $\gamma_{\text{max}}$ of wells augment progressively when panel 1 approaches and passes these wells and increase relatively faster than when panel 1 advances tens of meters (deep mining) and about one hundred meters (shallow mining) beyond the wells. In the mining cycle of panel 2, the development of $\gamma_{\text{max}}$ also undergoes a cycling through minor to severe deformations and then returning to minor deformations.

When mining is shallow (100 m), the largest $\gamma_{\text{max}}$ (1.3 milli-strain) is for path 1 and occurs in the shallow roof (8 m above the roof)}
Figure 17. Longitudinal distribution of horizontal strains ($\epsilon_{xx}$) for the five candidate paths of wells after single panel 1 (a, c) and then panel 2 (b, d) separately proceed sufficiently far (300 m for wells piercing the 100 m deep seam (a, b) and 150 m for wells piercing the 300 m deep seam (c, d)) after these wells.

For shallow mining (100 m), the influence of mining on well distortion along the mining direction is more extensive. Longitudinal distortions ($\gamma_{max}$) for wells closer to the twin panels begin to develop rapidly (increase or decrease) as panel 1 advances and panel 2 (paths 5 and 4) pass alongside these wells, and asymptote after each panel advances more than one hundred meters beyond these wells. While for deep mining (300 m), the largest $\gamma_{max}$ of $\epsilon_{xx}$ is maintained at ~2 millistrain, which is for path 5 and also evolves in the shallow roof. When mining is deep (300 m), the largest $\gamma_{max}$ of each path are all smaller to those in the case of shallow mining as either the single panel 1 or both panels are extracted. Irrespective of seam depth, paths 2 and 3 have smaller $\gamma_{max}$ on the twin panels are mined, both of which do not exceed 0.3 millistrain.

Regardless of mining depth, the largest $\gamma_{max}$ along the well axes all arise in the shallow roof (8 m above the seam), where the well is distressed by distortion. Also, wells closer to panels (paths 1 and 5) have the larger distortions as panel 1 and then panel 2 are sequentially extracted.

Evolution of the two components ($\gamma_{xz}$ and $\gamma_{yz}$) of the total longitudinal distortion ($\gamma_{max}$) is not presented here. The pattern and magnitude of evolution of $\gamma_{xz}$ is similar to that of $\gamma_{max}$ as the twin panels approach and then pass the wells. $\gamma_{xz}$ contributes most to $\gamma_{max}$. For shallow mining, the component $-\gamma_{xz}$, are respectively ~0.3 to 1.3 millistrain and ~2.0 to 1.3 millistrain after first panel 1 has passed and then after panel 2 is extracted; and for deep mining, they are ~0.8 to 1.2 millistrain and ~1.0 to 1.2 millistrain respectively (Table 3). The other component $-\gamma_{yz}$, is much smaller (<±0.4 millistrain). Evolution of $\gamma_{xz}$ displays approximate symmetry as each panel advances, the symmetry plane lags behind the wells by 10 m for shallow mining and abreast of the wells for deep mining. $\gamma_{xz}$ increases first as the panel approaches the well and reaches a peak when the panel advances to the plane of symmetry thereafter $\gamma_{yz}$ decreases progressively.
Fig. 18. Dynamic evolution of the largest vertical strains ($\varepsilon_{zz}$) (both the positive and negative) along well axes for the five candidate paths of wells piercing both the shallow (100 m, a–d) and the deep (300 m, e–h) seams as the twin flanking panels advance sequentially. Panel 1 is extracted first (a, c, e, g) and then panel 2 (b, d, f, h).
first panel 1 and then panel 2 are sequentially extracted for wells piercing the shallow seam (100 m). They change to be 1.8 to 4.4 millistrain and 2.8 to 4.4 millistrain respectively when mining is deep (300 m). Wells deform more severely by tension or compression in the horizontal plane in the vicinity of the seam (Fig. 17) especially as the second panel advances within tens (deep mining) and more than a hundred (shallow mining) meters beyond these wells (Fig. 16).

4.2.3. Vertical strains - 3zz

As apparent in Fig. 18 there is a strong influence of the second advancing panel on the evolution of vertical strains (50–100 m ahead of wells) compared to those resulting from the first-mined panel (20–50 m ahead of wells). This is because plastic deformations developed during the mining of panel 1 contribute additively to those developed during the mining of panel 2. The development of vertical strains both ahead of and after the passing of the face is broader when mining is shallow. Irrespective of mining depth, 3zz are principally extensional along most of the length of the wells (Fig. 19). Peak vertical extensile strains all arise in the shallow roof (at an elevation of 13 m and 1.5 m above the seam for the shallow and deep mining cases, respectively), and the peak vertical compressive strains all arise within the seam.

On the whole, regardless of seam depth, both the compressive and extensional vertical strains grow progressively as panels 1 and 2 advance sequentially, and grow faster as each panel proceeds around these wells. Ranges of vertical strains, in the case of shallow

![Fig. 19. Longitudinal distribution of vertical strains (3zz) for the five candidate paths of wells after single panel 1 (a, c) and then panel 2 (b, d) separately proceed sufficiently far (300 m for wells piercing the 100 m deep seam (a, b) and 150 m for wells piercing the 300 m deep seam (c, d)) after these wells.](image)

### Table 3

<table>
<thead>
<tr>
<th>Seam depth</th>
<th>Strain/E-4</th>
<th>Panel 1 Hazardous locations/m</th>
<th>Panels 1 and 2 Hazardous locations/m</th>
<th>Percentage change</th>
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<tr>
<td>100 m</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>γmax</td>
<td>13 8 &gt;120</td>
<td>20 8 &gt;120</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>γxx</td>
<td>−3 to 13 −1 to 2 −20 to 41 1.5/8 &gt;150</td>
<td>−20 to 13 −1 to 3 −28 to 78 1.5/8 &gt;150</td>
<td>40%–90%</td>
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<tr>
<td></td>
<td>γyy</td>
<td>−3 to 4 −8 to 8 0/13 &gt;170 12 8 &gt;120</td>
<td>−3 to 5 4 40 10 to 9 0/13 &gt;120 8 &gt;120</td>
<td>25%–13%</td>
</tr>
<tr>
<td>300 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>γmax</td>
<td>12 8 &gt;120</td>
<td>12 8 &gt;120</td>
<td>56%</td>
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<tr>
<td></td>
<td>γxx</td>
<td>−2 to 3 −18 to 44 1.5/8 &gt;50 15/8 &gt;50</td>
<td>−2 to 3 15/8 &gt;24 15/8 &gt;50</td>
<td>56%–0</td>
</tr>
<tr>
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<td>γyy</td>
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<td>0 &gt;22 to 3 0/15 &gt;50</td>
<td>29%–0</td>
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Note: Hazardous height refers to an elevation (m) above the coal seam where various strains reach the peak and the well is most likely to fail; and the height “0” represents vertical compressive strains are largest within the seam.
mining, are ~0.8 to 0.8 millistrain and ~1 to 0.9 millistrain after first panel 1 and then panel 2 are extracted successively, and they change to ~1.7 to 0.3 millistrain and ~2.2 to 0.3 millistrain correspondingly when mining is deep (Table 3). Consequently, wells are more likely to crush by compression along their axes in the seam especially as the second panel advances tens (deep mining) and more than a hundred (shallow mining) meters beyond these wells (Figs. 18 and 19).

5. Conclusions

The redistribution and concentration of strains induced by the movement of overlying strata resulting from full extraction mining are a fundamental threat to the stability of gas wells piercing active longwall panels. We explore and define the anticipated distribution and magnitudes of deformations likely to potential wells and their dynamic evolution during the mining cycle by means of a stepwise excavation through a large scale three dimensional finite element model. This model represents a realistic representation of the evolving mining geometry and in situ conditions to return anticipated strains as they evolve around the multiple panel geometry. Through this study, the following conclusions are drawn:

(1) The effects of longwall mining on the stability of gas wells piercing a longwall pillar display staged characteristics as the twin flanking panels first approach then pass by these wells, first on one side (panel 1) and then the other (panel 2). Evolution of various well deformations may be cyclic and peak as the panel face passes closest to the well and then wane — only to repeat as the panel passes on the other side of the pillar. The severity of the maximum effects varies with seam depth and the relative distances between wells and ribs of the twin flanking panels. Wells begin to undergo accelerated or significant deformation (increase or decrease) when each advancing panel is tens of meters away and the deformation stabilizes as each panel passes the well by tens (deep mining, ~300 m) or more than a hundred (shallow mining, ~100 m) meters. Wells are more susceptible to instability after each panel, especially the second panel, advances approximately 50 m past the well in the case of deep mining and more than a hundred meters in that of shallow mining with the accumulative deformation reaching the maximum.

Both the total horizontal shear offsets \((U_{\text{hf}})\) and the total longitudinal distortions \((v_{\text{max}})\) of wells increase progressively during the advance of the first panel. However, it depends on different wells in the mining cycle of the second panel, \(U_{\text{hf}}\) and \(v_{\text{max}}\) for wells closer to the first advancing panel decrease gradually or remain constant, but for wells closer to the second mined panel, they evolve from slow decline to fleet increase. Respective components of \(U_{\text{lf}}\) and \(v_{\text{lf}}\) associated with the direction parallel to the working face — \(U_{\text{lf}}\) and \(v_{\text{lf}}\), also display similar evolutionary characteristics and magnitudes to those of them \(U_{\text{lf}}\) and \(v_{\text{lf}}\). While for components associated with the advancing direction \((U_{\text{lf}})\) and \(U_{\text{lf}}\), they are far smaller and show approximate symmetry as each panel proceeds. As regards bed compression, horizontal and vertical strains, substantially, they all increase monotonously as each panel approaches and passes by these wells, and tend to be invariant as each panel advances tens (deep mining) and more than one hundred (shallow mining) meters beyond these wells.

(2) Along the longitudinal direction, wells are prone to shear on weak interfaces both in the shallow roof (irrespective of seam depth) and close to the surface (only for shallow mining), especially on weak interfaces with a stiff layer above and a soft one below. Irrespective of mining depth, wells might fail by the combined impacts of distortion, tension and compression in the vicinity of the seam. Through a comprehensive evaluation of various well deformations in the whole mining cycle of longwall panels around the well, it is advisable to locate the well slightly closer to the rib of the second advancing panel, in which case, improved well integrity can be achieved.

(3) For mining at shallow depths (~100 m), rock movement and deformation within the thinner overlying strata of the seam are more severe, and the range of strong influence induced by shallow mining is relatively broad along both the transverse and mining directions. While for deep mining (~300 m), strata movement (and associated deformation of wells) is mainly restricted to the shallow roof, and engenders a smaller influence along the mining direction.

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