SUBSIDENCE: AN OVERVIEW OF CAUSES, RISKS AND FUTURE DEVELOPMENTS FOR COAL SEAM GAS PRODUCTION

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Summary

In compiling this report, every opportunity has been taken to incorporate measured data and published research. Where this has been insufficient to support the discussion and evaluation, the fundamental principles of geomechanics have been employed to explain the different aspects of ground response to coal seam gas (CSG) exploration and production. Whilst the conclusions are founded on good scientific principles they are necessarily qualitative and contain some degree of speculation.

Coal is a multi-phase porous media in which hydraulic and mechanical processes interact and may cause the compaction of the coal seam during CSG extraction and to some degree affect the entire geological profile. Subsidence does not necessarily represent a prohibitive drawback for CSG production if those processes are properly understood and controlled.

i. Subsidence is caused by the compression of the coal seam as a consequence of the reduction of the pore fluid pressure that increases the effective stress.

ii. Subsidence is a complicated issue in CSG extraction. It can vary in magnitude, from trivial and insignificant to substantial and damaging, depending on the hydro-mechanical properties of the coal seam, the volume of gas extracted, the extraction methods and most importantly the geological settings of the coal seam. Subsidence is expected to increase if additional compaction takes place in overlying and/or underlying strata due to changes in the hydraulic regime (e.g. de-watering).

iii. Subsidence is further complicated by the influence of a stimulation procedure or hydraulic fracturing. Uncontrolled fracturing, caused by high applied fluid pressures during hydraulic fracturing, induces fractures in the coal seam as well as in the adjacent strata (hence degrading their strength). The hydraulic connectivity between different strata may accelerate subsidence.

iv. Different subsidence bowls are expected if vertical or horizontal well configurations are used for gas extraction. The magnitude of the induced-subsidence may not be compared easily as different volumes of coal and different gas production rates are involved in each case.

v. It is expected that multiple wells will enhance the subsidence bowl in both cases. The overlapping of the subsidence bowls will depend not only on the separation

length between wells, but also on the effectiveness of the stimulation and extraction processes.

vi. Permeability is a key factor controlling the performance of the well, irrespective of the extraction method. Changes in permeability by the stimulation and extraction processes will affect the compressibility of the coal seam and thus the amount of subsidence. These changes should be carefully estimated before starting the gas extraction.

vii. The coupled multi-physical processes involved in the CSG extraction are not completely understood. Further research is needed to fully comprehend the process. Of particular interest is the determination of the transport properties of the coal seam and their effects on the mechanical behaviour. A detailed characterization of the cleat system will give clues for the improvements of permeability models and their influence on the coal compressibility which drives the compaction process.

viii. Detailed monitoring through the entire geological profile is crucial for a better understanding of the subsidence phenomenon in CSG extraction. Mitigation techniques developed for each particular case (e.g., water or CO_2 injection) should be based on, and updated according to, the monitoring data. Further research is also required in this field. Monitoring is also required for updating and improving models of subsidence, and will help to develop a solid scientific framework for the production of CSG in Australia.

Contents

1. Introduction

The occurrence of subsidence, either by natural or anthropogenic factors, is of concern in engineering practice due to the potential impacts on infrastructure, natural resources and the environment. Subsidence is a complex phenomenon involving different processes that usually are coupled. Multidisciplinary work involving geology, hydro-geology, geomechanics and environmental engineering is required to understand properly the main mechanisms associated with subsidence. The growing interest in Coal Seam Gas (CSG) as an untapped energy source in Australia means that it is now necessary to evaluate the potential subsidence, as well as the possible mitigation measures, that are available to minimize and/or control subsidence during gas extraction.

The paper discusses the main causes of subsidence with particular emphasis on the effects associated with CSG extraction. An overview of the most common subsidence problems occurring in different engineering scenarios is given in Section 2. The main characteristics of the coal seam gas extraction are described in Section 3, including the most common methods employed for gas extraction, the main mechanisms of subsidence related to CSG extraction, and their potential impacts. The influence of the different extraction configurations, their similarities compared to other mining activities, the potential 'worst' case subsidence scenarios and the risk assessment and management are also discussed in Section 3. The key issues and knowledge gaps regarding subsidence caused by CSG extraction are discussed in Section 4, with emphasis on the further research that is needed to improve current practice as well as subsidence prediction and control.

2. Subsidence

Subsidence is a general term usually applied to downward movements in the ground surface. Subsidence phenomena can be classified in many ways, including:

- Whether it occurs due to natural processes or is anthropogenically induced.
- Whether it is instantaneous or has a time dependency.
- The physical mechanism that caused it.

From a geomechanics perspective, the underlying physical mechanism is of greatest importance.
In general terms, there are four basic origins of subsidence. Subsidence can occur due to:

- A reduction in the volume (shrinkage) of subsurface soils and rocks.
- Compression of subsurface soils and rocks due to a change in stress.
- The filling of a subsurface void by overlying materials.
- Movements in the earth's crust.

Note, that in many cases, it is often difficult to distinguish between shrinkage-induced subsidence and load-induced compression.

A brief discussion about the main cases of subsidence is given in the next sections. For the sake of simplicity, the examples presented below have been divided depending on whether they occur due to natural or anthropogenic processes.

2.1. Natural subsidence

Subsidence may occur naturally as a result of the following processes, for example:

- Relative movements of geological structures, e.g. faults by tectonic actions (tectonic subsidence).
- Induced-consolidation caused by seismic actions.
- Dissolution of geological structures – erosion by water flow.
- Cyclic swelling-shrinkage of clayey materials by changes in the water table.

2.1.1. Tectonic actions (instantaneous or induced-consolidation)

The first two factors are of particular concern in zones of high tectonic activity where large subsidence may be generated in fault systems due to extension, cooling and loading of crustal plates (e.g., Heine et al., 2008; Xie & Heller, 2009). There, sea level is often used as the reference to quantify subsidence at regional scales. At the local scale, tectonic subsidence, in combination with the associated consolidation of the strata, is however difficult to evaluate.

2.1.2. Subsurface erosion and karst collapse (instantaneous or time-dependent)

Dissolution of limestones, salt beds or carbonate rocks by the circulation of water induces important subsidence problems due to the formation of holes and caves. These may cause sinkholes that propagate to the ground surface. If the rock loses support, a sudden collapse may take place. This is a key concern in geotechnical engineering, especially when it occurs in an urban setting. Three main types of natural sinkholes can be identified in nature (U.S. Geological Survey, www.usgs.gov): (i) dissolution sinkholes, (ii) cover-subsidence sinkholes, and (iii) cover-collapse sinkholes. These are schematically depicted in Figure 1. The dissolution sinkholes are caused by the intense dissolution that occurs when a flux of water is directly in contact with the rock, e.g., during periods of heavy rain. Rainfall attacks the rock and flows through fissures and joints, forming depressions and cavities in the ground in a relatively short period of time. Cover-subsidence sinkholes typically require more time because of the presence of a covering layer, frequently sandy soils with high permeability. In some cases, cover-subsidence sinkholes are difficult to identify due to the presence of the thick overburden layer or if some amount of clay is present. The presence of clay delays the creation of the cavity. If the overburden layer is mainly composed of clayey soils it may lead to the development of a cover-collapse sinkhole. The main difference with the preceding type of sinkhole lies in the sudden subsidence or collapse, caused when the arching effect acting on the overburden clay is loosened. Because of their sudden appearance, cover-collapse sinkholes have a more catastrophic impact. Several sinkholes have been reported in Florida (USA) where the geological conditions are suited to their formation (e.g., Sinclair & Stuart, 1985; Rupert & Spencer, 2004). There, sinkholes are common landform features in the central part of the State as indicated by circles in Figure 2. Their impact and severity, however, seems to be strongly dependent on whether they form in an urban setting or not.

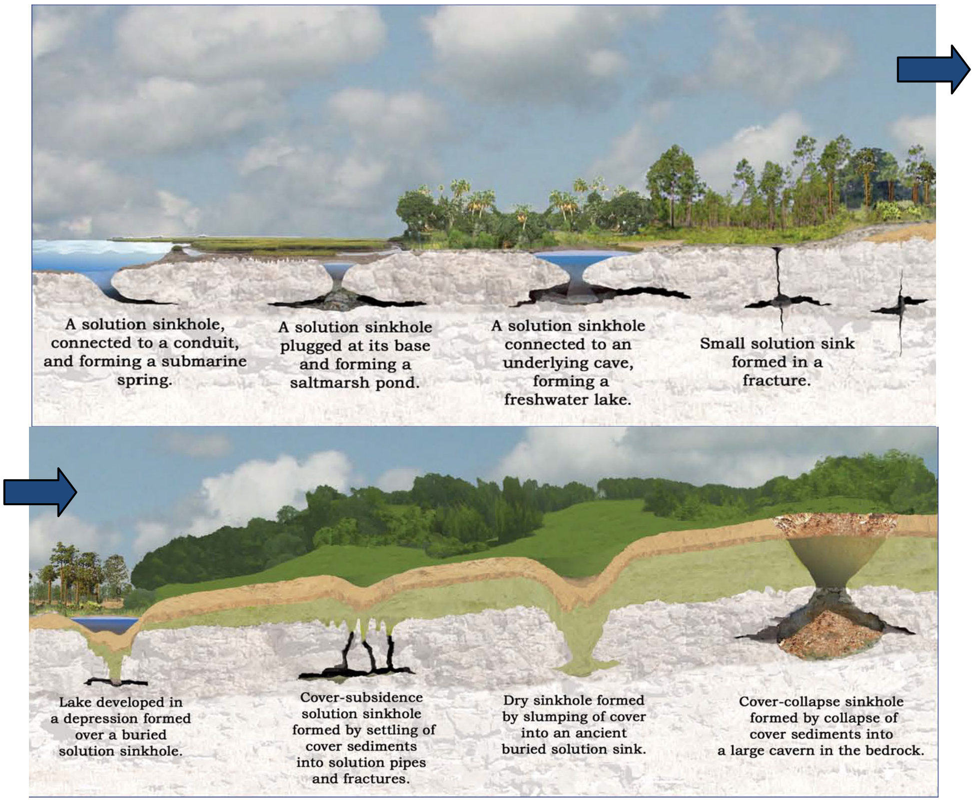


Figure 1.Types of sinkholes (modified from Rupert & Spencer, 2004)

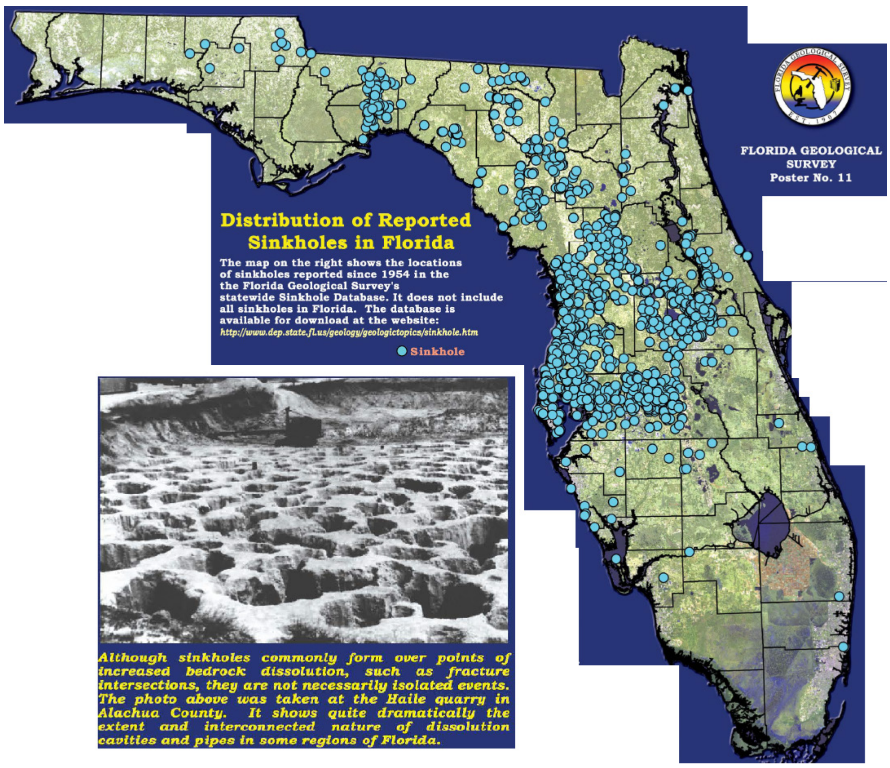


Figure 2.Occurence of sinkholes in Florida-USA (modified from Rupert & Spencer, 2004)

2.1.3. Seasonal subsidence (cyclic effects)

Cyclic fluctuations in water content in the soil due to, for example, seasonal changes may induce volume changes in clayey strata leading to accumulated swelling or shrinkage. The magnitude of the volume change will depend, among other factors, on the mineralogical composition of the clayey fraction which also play a key role on the water retention properties of the soil. Important volume changes are expected if expansive clays are involved, as in the case of many areas of NSW. At shallow depths, subsidence or shrinkage may occur during the lowering of the water table as the soil suction increases. This phenomenon may be irreversible if fissuring takes place as the tensile strength of the soil is exceeded. Several studies has been performed during the last decades due to their relevance on the performance of shallow foundations (e.g., Al-Homoud et al, 1995; Allman et al, 1998; Fityus et al, 2004; Jahangir et al, 2012). Results from a field site in NSW have been reported by Allman et al (1998) and then by Fityus et al (2004). They monitored ground movements, temperature and rainfall at the Maryland field site (Newcastle), where the soil is mainly composed of expansive clays that are frequently associated with stability problems in the Newcastle area. Measurements obtained during seven years of monitoring are presented in Figure 3. The response of ground movements, in particular subsidence movements, showed a clear dependency with accumulated rainfall and temperature variations. After seven years of monitoring, two peaks of subsidence movement developed at shallow depths during the seasons 1993-1994 and 1997-1998. These are indicated in Figure 3 by the dotted ellipses A and B, respectively. It is important to note that the analysis of ground movements, during a specific period of time, should include the recent hydraulic history of the soil. For instance, the maximum subsidence recorded during season the 1997-1998 (≈15mm) took place after a dry winter and a long dry summer. There, the accumulated rainfall was around 380mm and 250mm, measured during winter and summer, respectively. On the other hand, the higher accumulated rainfall recorded during the subsequent season - 515mm during winter and almost 700mm during summer - was consistent with the almost negligible subsidence measured at the end of summer (see Figure 3).

At shallow depths, subsidence caused by changes in the water table is related to changes in soil saturation. There, a rigorous analysis should include the dependency of soil suction (saturation) on both the water retention properties and the associated volume changes. It is not straight forward and requires detailed experimental and theoretical study which, in most cases, is outside the scope of consulting projects. In this particular field, important advances have been made by the Geotechnical Group at The University of Newcastle Australia during last decade (see e.g., Sheng et al, 2003a,b; Fityus et al, 2004; Sheng et al, 2004; Buzzi et al, 2008; Sheng et al, 2008; Buzzi et al, 2009; Zhou et al, 2012a,b,c).

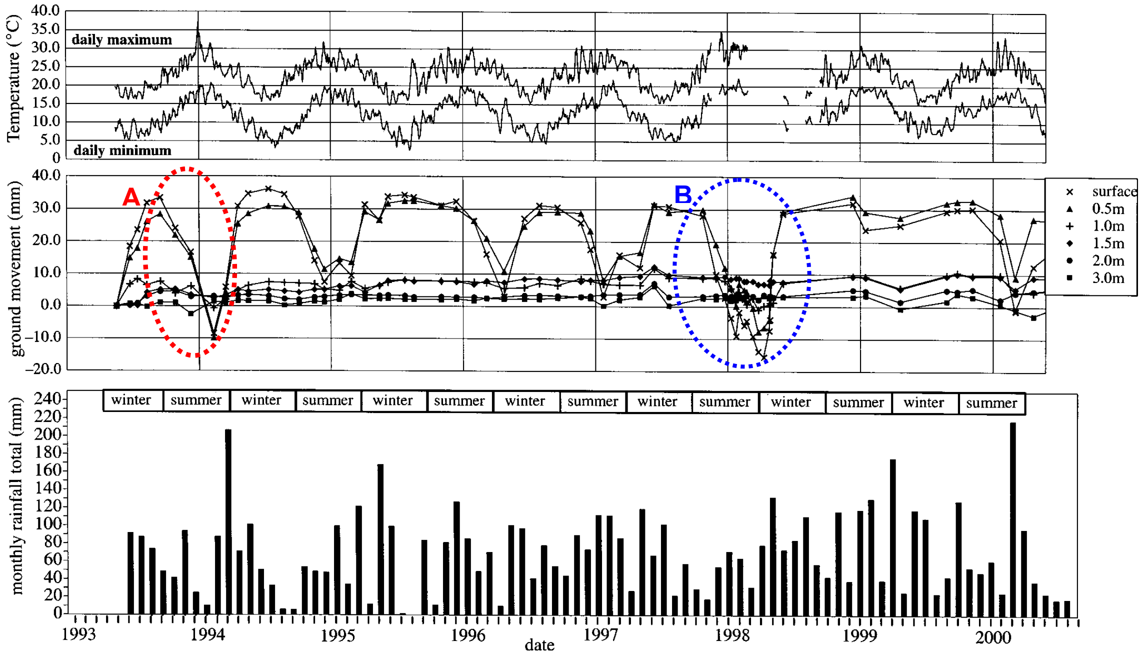


Figure 3.Data from Maryland field site, NSW, registered between 1993 and 2000. (a) Temperature (b) ground movements, (c) monthly rainfall (from Fityus et al, 2004)

2.2. Subsidence by anthropic factors

Subsidence may also occur as a result of various human activities. The main causes related to engineering works can be summarized as follows:

- Excavations: tied-back excavations, tunnelling, mining, etc.
- Withdrawal of ground fluids: geothermal fluid extraction, water, oil and gas production.
- Indirect factors: induced sinkholes by mining activities, leaks of water in underground pipes, induced earthquakes by mining activities, induced compaction by changes in the hydraulic regime, due to mining or withdrawal of pore fluid in underlying strata.

2.2.1. Excavation related (instantaneous or time-dependent)

Any type of excavation causes ground movements. Their magnitude will depend on the soil/rock properties as well as on the stress path applied. In most cases, ground movements display some qualitative similarities, irrespective of the excavation method. Ground settlements or subsidence are always accompanied by lateral movements. Profiles of the ground movements, in a direction orthogonal to the excavation front, tend to display some degree of symmetry. Finno & Roboski (2005) studied the three-dimensional ground movements caused by a 12.8m deep tied-back excavation through a mixed soil profile in Chicago (USA). The soil profile ranged from granular soils (z<5m) to soft to medium stiff clays. The excavation was supported by a sheet pile wall and three levels of tie-backs. Of particular interest was the quantification of both the vertical and horizontal displacements caused by the excavation due to the potential damage on neighboring buildings. Figure 4a shows the construction stages and the vertical movements measured at the West Wall of the excavation. In addition, Figure 4(b) compares the maximum vertical settlements and horizontal displacements measured at different excavation stages. Maximum vertical movements of around 70mm were recorded. Vertical settlements were higher than the horizontal displacements until Stage 4. This ratio, however, decreased to around 0.80 in Stage 6. Finno & Roboski attributed this behaviour to the volumetric response of the granular soils which experienced compression at the initial stages of the excavation, but then dilated as the ground movements become larger.

Different excavation methods cause different ground movements in a soil/rock mass. In tunnelling, for instance, different excavation methods have been employed in the past, depending the soil type and geological-geotechnical conditions. The tunnel geometry plays a key role in both the short-term and long-term ground movements. Traditional excavation methods for tunnelling in soils and rocks (e.g., cut-and-cover, New Austrian Tunnelling Method, NATM) create a non-circular cavity in which stress concentrations at the tunnel wall may cause stability problems. This problem is overcome in new tunnelling techniques (Tunnelling Boring Machine: TBM, Earth Pressure Balance: EPB) where the circular geometry minimizes the stress concentration around the tunnel wall. In both cases, stability of the tunnel front is a key concern, especially for shallow tunnels. Face stability analysis provides the most probable failure mechanism, as well as the parameters that must be taken into consideration when predicting the ground movements caused by tunnelling (ITA-AITES, 2007). Two main collapse mechanisms may take place (see Figure 5). Large volumes of soil are involved in front stability problems for clays. There, a sinkhole with a width larger than one tunnel diameter may be formed (see Figure 5a). On the other hand, chimneys are the common collapse mechanism in cohesionless soils (see Figure 5b).

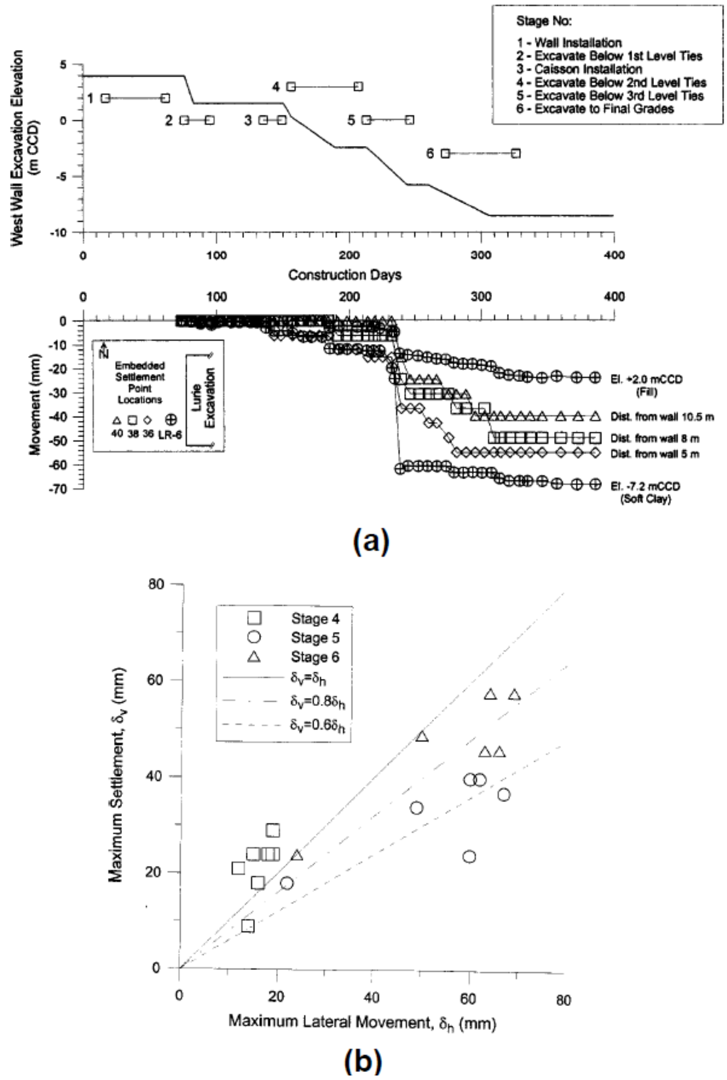
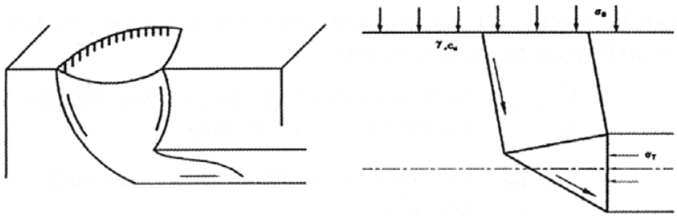
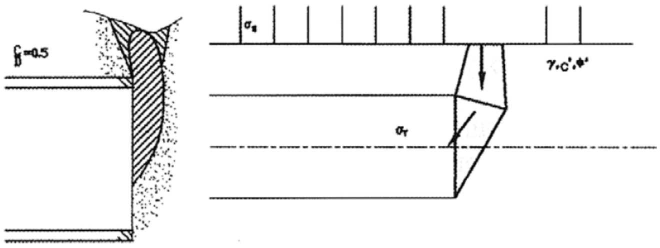


Figure 4.Excavation of a tied-back in Chicago. (a) Excavation stages and vertical movements. (b) Maximum vertical and horizontal movements (Finno & Roboski, 2005)



(a)

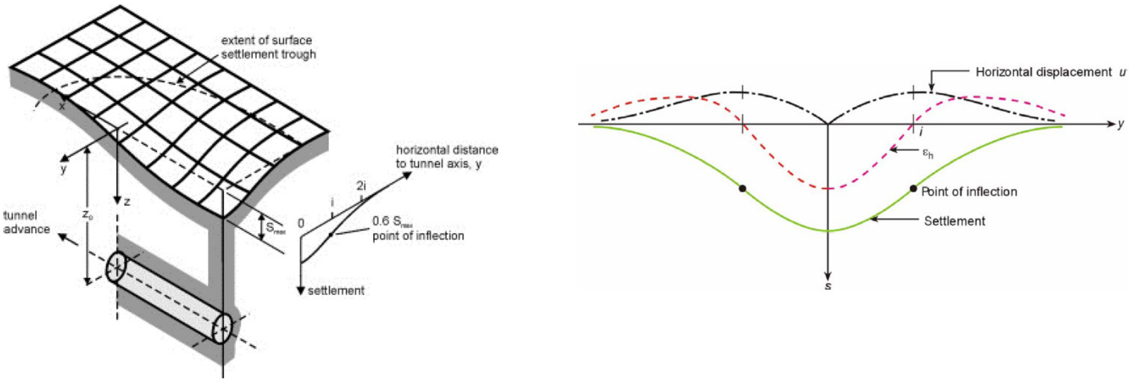


(b)

Figure 5.Face stability problems during tunnelling in soft ground (ITA-AITES, 2007)

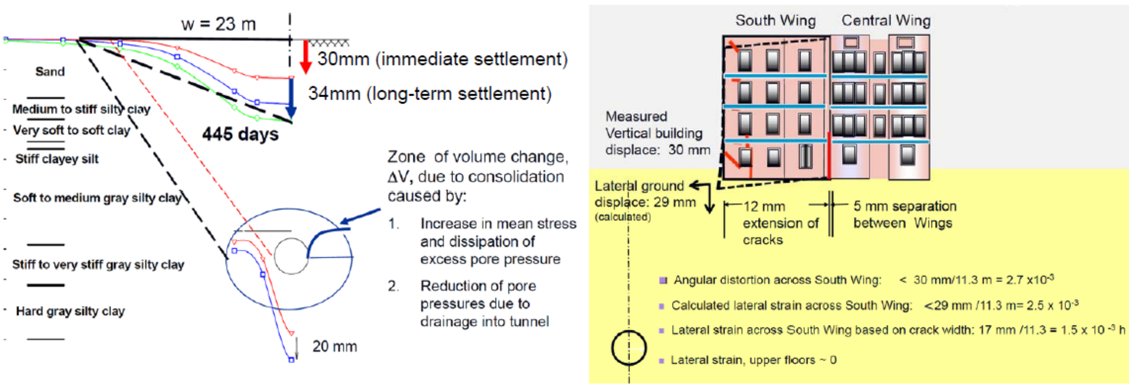
The three-dimensional ‘settlement trough’ – as it is usually called - caused by tunnelling is shown schematically in Figure 6. As the tunnel front advances, both longitudinal and orthogonal ground movements take place. Based on in-situ data, it was pointed out several decades ago that ground movements developed behind the tunnel front display a symmetric settlement trough (see Figure 6b) which, in the case of soils and soft rocks, can be associated with a Gaussian-type distribution as suggested by Peck (1969). As far as horizontal displacements are concerned, two deformation mechanisms are involved that are divided, geometrically, by the inflection point “i”. At this point, the horizontal displacements are a maximum. Compressive horizontal strains take place between i>y>-i, whereas tensile strains are developed for i<y<-i. This method is the most common procedure used to compute settlements and volume losses induced by tunnelling in soils, and various examples are available in the literature.

Cording et al (2008) described the irreversible settlement and associated distortion induced by a tunnel excavation (3.6m in diameter and located at 17m depth in soft clay) that caused significant damage to a brick-walled structure with concrete floors in Evanston-Illinois (USA). Figure 7(a) summarizes the settlement history. At the ground surface, the tunnel excavation caused an immediate settlement equal to 30mm. It created a subsidence zone extending about 19m measured from the centreline, i.e., the point of maximum subsidence. An additional subsidence of around 34mm was measured during the next 445 days, as a consequence of the consolidation experienced by the clay (see Figure 7a). The consolidation process experienced by the clay is characterised by the volume change zone around the tunnel (the ellipse). The extent of the subsidence zone increased up to 23m due to the long-term subsidence. The South Wing of the building under consideration was located in the tension zone of the settlement trough (Figure 7b). The measured vertical building displacement at the South bearing wall was equal to 30mm, whereas the lateral ground displacement at the edge of the building was computed to be 29mm. This caused diagonal shear cracks at ground level but also above the windows close to the South wall. The maximum opening of cracks observed was around 17mm, whereas the South and Central Wings separated by around 5mm (see Figure 7b).



(a) (b)

Figure 6.Tunnelling in soils. (a) Settlement trough (b) vertical and horizontal movements



(a) (b)

Figure 7.Consequences of tunnelling on buildings in Evanston. (a) Settlement trough. (b) Damage on a neighbour building (Cording et al, 2008).

2.2.2. *Mining subsidence (instantaneous or time-dependent)*

Another excavation process causing important subsidence problems is due to mining activities, e.g., longwall or room and pillar methods. This is of major interest in Australia due to our long history of large-scale coal mining. Longwall coal mining involves cutting panels around 150-400m wide, 1000-4000m long and 2-5m thick. The roof of the excavation front is temporarily supported but is then allowed to collapse causing subsidence. The coal that is allowed to collapse once the temporary support is removed is defined as the goaf. Longwall mining operations are defined by the *extraction width*, the *panel length* and the *pillar width*. All these affect the mine subsidence, as the particular geological and geomechanical properties of the overlying strata. The mechanisms of subsidence in longwall mining show some similarities with those described previously for tunnelling, though the overburden is normally much thicker. Some authors have described the "general scenario" for subsidence in longwall mining (e.g., Bai & Kendorski, 1995; Holla & Barclay, 2000) (see Figure 8a). Subsidence in longwall mining involves the development of a fully damaged zone above the excavation width. Larger values of permeability are expected there due to the high degree of fracturing. The thickness of the damaged zone may range between 10m to 20m (Seedsman Geotechnics Pty Ltd, 2012). The disturbed zone, i.e. the soil/rock mass directly involved in the subsidence phenomenon, includes a thick layer - 6 to 30 times the excavated thickness according to Bai & Kendorski (1995) - overlying the damage area. The points of maximum distortion - indicated by a dashed line in Figure 8 - define the boundaries of the disturbed area. Small deformations, mainly in the horizontal direction, take places in materials beside the disturbed zone so that surface subsidence is caused by compaction of the shallow strata overlying the disturbed zone. Dilation may also occur in intermediate strata (see, Bai & Kendorski, 1995) as a consequence of the large downward movement of the disturbed area, compared with the small compaction of the underlying strata. As observed in Figure 8(b), a similar settlement trough or settlement bowl (as described previously in Figure 6b) is caused by subsidence in longwall mining. The extent of the subsidence, defined by the angle of draw, is delimited by a minimum vertical subsidence of 20mm (not zero as indicated in Figure 8a).

Seedsman Geotechnics Pty Ltd (2012) discuss the additional factors causing subsidence in longwall operations which can be summarized as follows:

- ✓ *The presence of adjacent panels*: for shallow panels subsidence is the sum of the subsidence of independent panels; for deeper longwall panels subsidence is controlled by the response of the chain pillars.

- ✓ *Multiple seams*: despite little available data, the common practice is to add the subsidence of each seam and update the predictions once additional data is obtained.
- ✓ *Disordered movements*: buckling and cracking of rock bars may occur when the longwall passes under drainage courses.
- ✓ *Subsurface model*: related to the local hydro-geologic model (e.g., Figure 8a).

Several examples of subsidence in longwall mining have been published in the past (e.g., Kapp, 1984; Kapp & Kennerley, 1986; Li et al, 2007; Seedsman Geotechnics Pty Ltd, 2011,2012; MSEC-Mine Subsidence Engineering Consultants, 2012). Seedsman Geotechnics Pty Ltd (2011) described the subsidence registered in the Balgwonie Seam longwall, which overlies the Bulli Seam, mined around 70-80 years ago. The Balgownie longwall, around 1.35m thick, was mined between 1970 and 1980 and subsidence records are available. Panel widths ranged from 144 metres to 186 metres and the pillar widths were initially 25 metres increasing to 40 metres. The interburden thickness between the Bulli and Balgownie Seams ranged from 8 -16m. Three cross lines covering the overall panels were used to monitor the subsidence during extraction (see Figure 9). The influence of adjacent panels on the subsidence trough may be clearly identified in Figure 9. The depth of cover ranged from 240-280m which suggests an important influence of the chain pillars on the induced subsidence. The subsidence pattern showed a settlement around 0.55m above the chain pillars and additional sag between them of 0.2-0.8m. The maximum subsidence was 1.4m.

In regard to the horizontal movements caused in longwall mining, Li et al (2011a,b) evaluated the current methodologies used to relate horizontal movements with vertical subsidence and their implications for risk management. They used data obtained in NSW Coalfields and found that the characteristics of the horizontal movements do not match well with data reported in the subsidence literature. They suggested that the methodologies for predicting horizontal movements, used in currently in Australian engineering practice, should be revised.

Large values of subsidence are common in mining activities. Commonly, the analysis of subsidence compares the ratio of the maximum subsidence to the thickness of the seam (S_{max}/T) against the ratio of the panel width to the cover depth (W/H). In the case of coalfields in NSW, the ratio S_{max}/T tends to a maximum value around 0.6-0.65 (see e.g., Seedsman Geotechnics Pty Ltd, 2012; MSEC-Mine Subsidence Engineering Consultants, 2012). Table 1 summarizes values of maximum subsidence reported in the literature for coalfields in NSW. Extreme care is required to avoid damaging effects on urban settings and neighbouring structures (e.g., dams, highways, bridges, underground pipes). Due to the complexity of each scenario, the impact of subsidence is commonly evaluated individually.

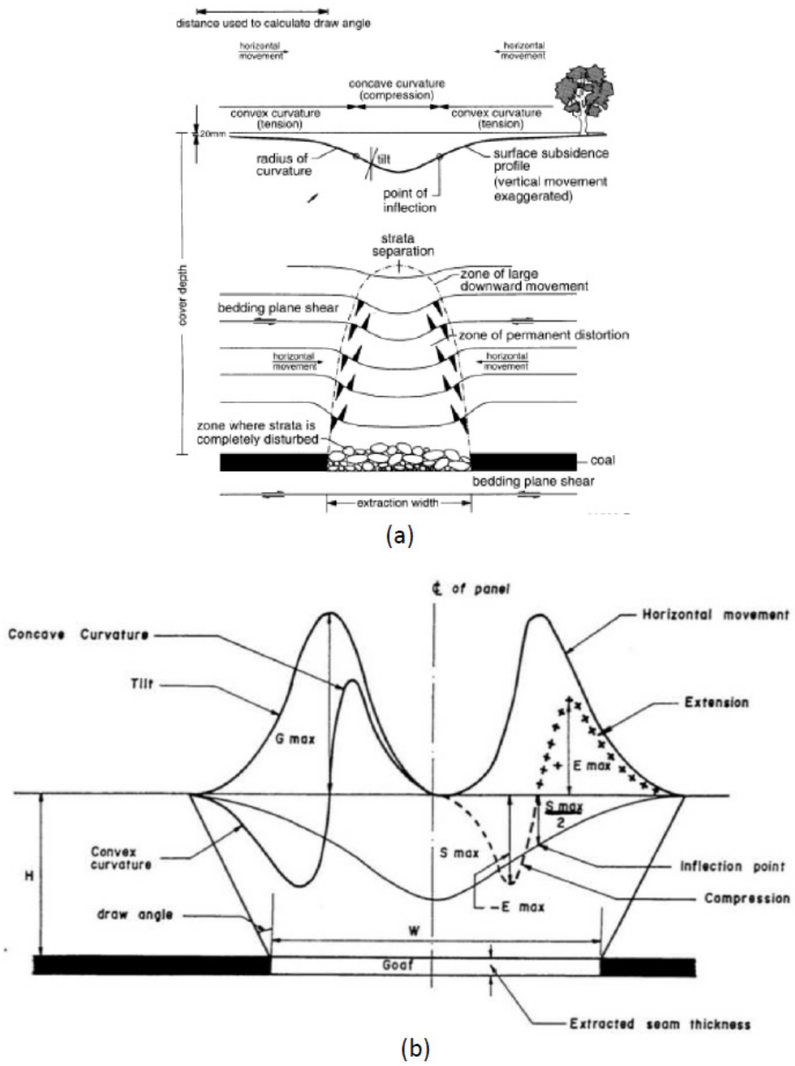


Figure 8.Subsidence in longwall mining.(a) Subsidence model (Hall & Barclay, 2000). (b) Development of vertical and horizontal displacements

Table 1.Some published data of maximum subsidence in NSW coalfields

Location	Panel	T (m)	W (m)	H (m)	S_{max} (m)	Source
Newstan Colliery	LW 6	3.4	155	60	2.03	Holla & Thompson (1992)
	LW 8	3.2	210	75	3.03	
Liddell Colliery	LW 1	2.4	180	160	1.55	Li et al (2007)
	LW 3	2.0	180	200	2.10	
Cumnock Colliery	LW 17	2.2	210	90	1.72	
	LW 3	2.5	205	133	1.25	

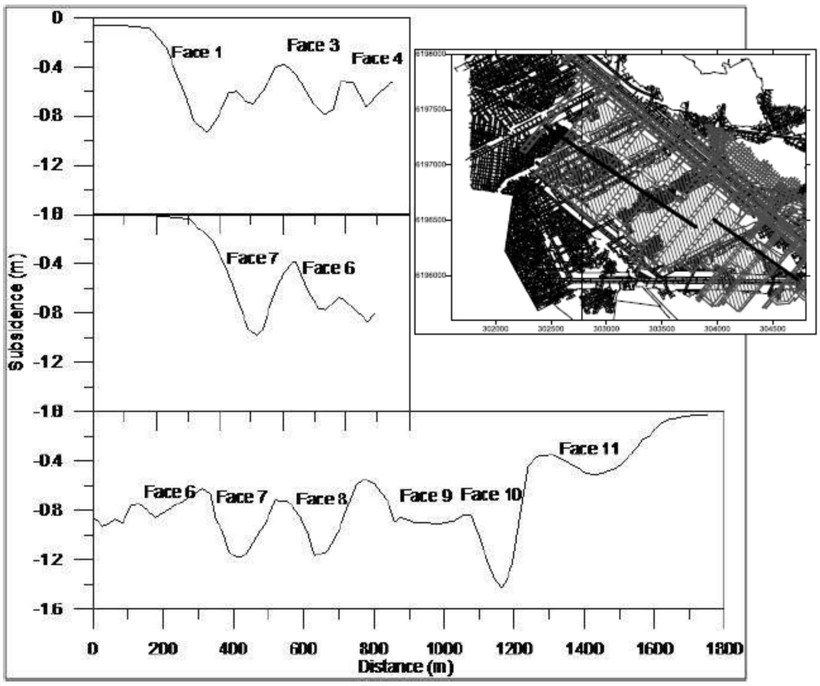


Figure 9.Subsidence registered in Balgownie seam longwall (from Seedsman Geotechnics Pty Ltd, 2011)

2.2.3. Subsurface erosion and karst collapse (instantaneous and time-dependent)

Another type of subsidence related to mining activities is the creation of sinkholes or caverns, mainly due to shallow overburden, poor mechanical properties of the overburden material, geological conditions (such as discontinuities), and the presence of soluble rocks. This problem is usually studied as a face stability problem as previously described for tunnelling. Some examples of sinkhole formations due to mining activities have been discussed by Singh & Dhar (1997).

2.2.4. Withdrawal of ground pore fluid (time-dependent)

One of the most common activities causing subsidence is related to the withdrawal of ground fluids such as geothermal water or steam, ground water, and oil and gas. Each of these has caused a maximum subsidence of the same order or magnitude (Poland, 1984). In general terms, subsidence occurs as a result of two mechanisms during ground fluid withdrawal: (i) local compaction due to the reduction of the pore pressure that increases the effective stress according to consolidation theory, and (ii) lateral shrinkage of strata where the water table was lowered. The subsidence bowl tends to be approximately symmetric, even if the compacted volume is not. Due to the complex geological profiles found in nature, the withdrawal of ground fluids does not only affect the specific strata under consideration, but also layers located above and below. Thus, the subsidence bowl is a result of the superposition of subsidence from each compacted strata. Although compaction and subsidence are related, it is not easy to observe compaction of an underground reservoir. Surface subsidence, however, may be detected easily. In fact, subsidence has been recognized as the first indicator of compaction over hydrocarbon fields since the first case studies were published (e.g., Pratt & Johnson, 1926).

Doornhof et al (2006) divided the formations involved in subsidence as follows: (i) compacting volume, (ii) overburden, (iii) sideburden – materials laterally connected to the compacting formation, and (iv) underburden – materials beneath the compacting formation and the sideburden. The last two terms are frequently taken into account in geomechanical analysis. The compacting volume does not only include the hydrocarbon-bearing formation, but also the aquifers above or below that can be compacted and act as drains. On the other hand, the sideburden material does not experience compaction and, on the contrary, it helps to sustain some of the overburden weight that had been supported by the compaction formation via arching effect. The importance of the arching effect will depend on the properties of both the overburden and sideburden materials, the lateral extent of the compacting zone, and the amount of compaction (Doornhof et al, 2006). Some examples are described below, which comment on the particular aspects involved with the removal of ground water and oil and gas, respectively.

Figure 10 shows the general scenario that can be found during ground-water extraction (Poland, 1984). Two cases are analysed in this figure. Case 1 (left) includes only one confined aquifer system whereas in Case 2 (right) there are two. Confined beds and aquitards (fine-grained compressible interbeds) are also included in both cases to describe the most general cases encountered in practice. Aquitards play a key role in the subsidence potential due to their high susceptibility to compaction (because of its fine-grained nature) compared to the sand or gravel composing the aquifer during an increase in stress. Based on 13 years of continuous monitoring, Poland et al (1975) published the response of an aquifer system (101m thickness) at the Pixley site in the southern part of the San Joaquin Valley-California (USA) (see also Poland, 1984). There, around 60 aquitards with different thickness ranging from 0.6 to 15m has been reported. Figure 11 shows the monitored data – water level and compaction - as well as the changes in applied stresses computed by Poland et al (1975). The changes in stresses within the depth interval (B in Figure 11) were computed from hydrographs (A) of wells 16N4 (water table) and 16N3 (confined system). Measurements from extensometers located at different depths (C) were used to compute the compaction of the aquifer system (D). The stress-strain response at that interval is also included (E). From the inspection of Figure 11, the following aspects deserve comment. A cyclic change in the depth of the water below the land surface was observed during 13 years. This was attributed to the characteristic seasonal pumping for irrigation (A). A reduction in the rate of compaction (C) was observed during 1962-1963 as indicated by the dashed ellipse. This was consistent with the smaller reduction in the depth of water as indicated by the dotted circles (see A and B). A similar behaviour was observed in 1967 and 1969. A small expansion took place during winter periods, due to a recovery of the water-level in the aquifer system, as indicated by the arrows. The stress-strain response showed a cyclic behaviour which was consistent with the cyclic response of the water level. The strata analysed experienced a maximum stress change of 40kPa (40m of water), whereas the maximum compaction of the aquifer system after 13 years was around 0.85m.

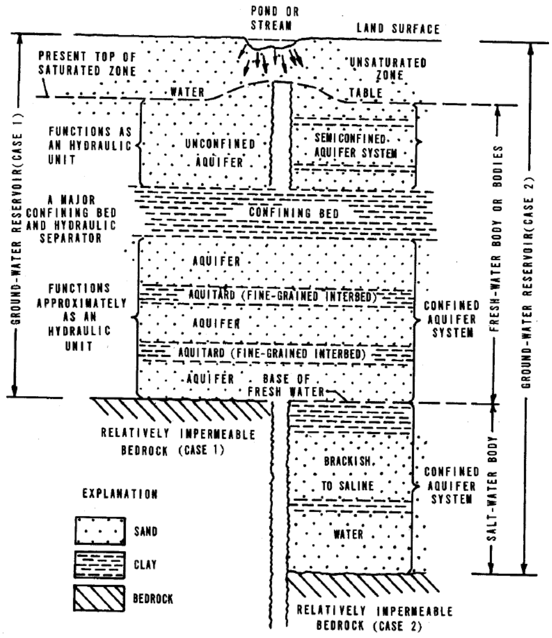


Figure 10.Schematic model for ground-water extraction (Poland, 1984)

Subsidence caused by ground-water extraction may also affect large areas. Such is the case of two of the most historical cities in the world: Mexico City (Mexico) and Venice (Italy). Mexico City rests on very soft lacustrine clays – with a void ratio up to 12 - and sands from Lake Texcoco. Values of subsidence around 9m have been measured as a consequence mainly of the compaction of two silty clay strata (25-30m and 5-10m thick) located in the top 50m below the ground surface. Figueroa-Vega (1984) established that about 75% of the overall subsidence was caused by the compaction of the shallow clayey strata and the remainder subsidence was due to compression of the underlying aquifer which are hundreds of meters thick. Venice, on the other hand, has suffered major subsidence since the last century due mainly to two causes: (i) ground-water extraction that increased dramatically after World War II due to the increase in population, and (ii) natural gas extraction in a zone across the lagoon. This caused an increase in the rate of subsidence of up to 1.4-1.7cm/yr, measured between 1968-1969 (Brighenti et al, 1995). After a heavy flooding event in 1966, the extraction of water and gas was essentially halted to control subsidence. This lead to a small rebound of the surface once the aquifer level rose. Despite this, the city is still experiencing subsidence, although under a lower rate. As for subsidence caused by geothermal ground fluid withdrawal, the reader is referred to the review published by Narasimham & Goyal (1984). There, subsidence is attributed to the volume changes during depletion of geothermal fluid in addition to geothermal contraction.

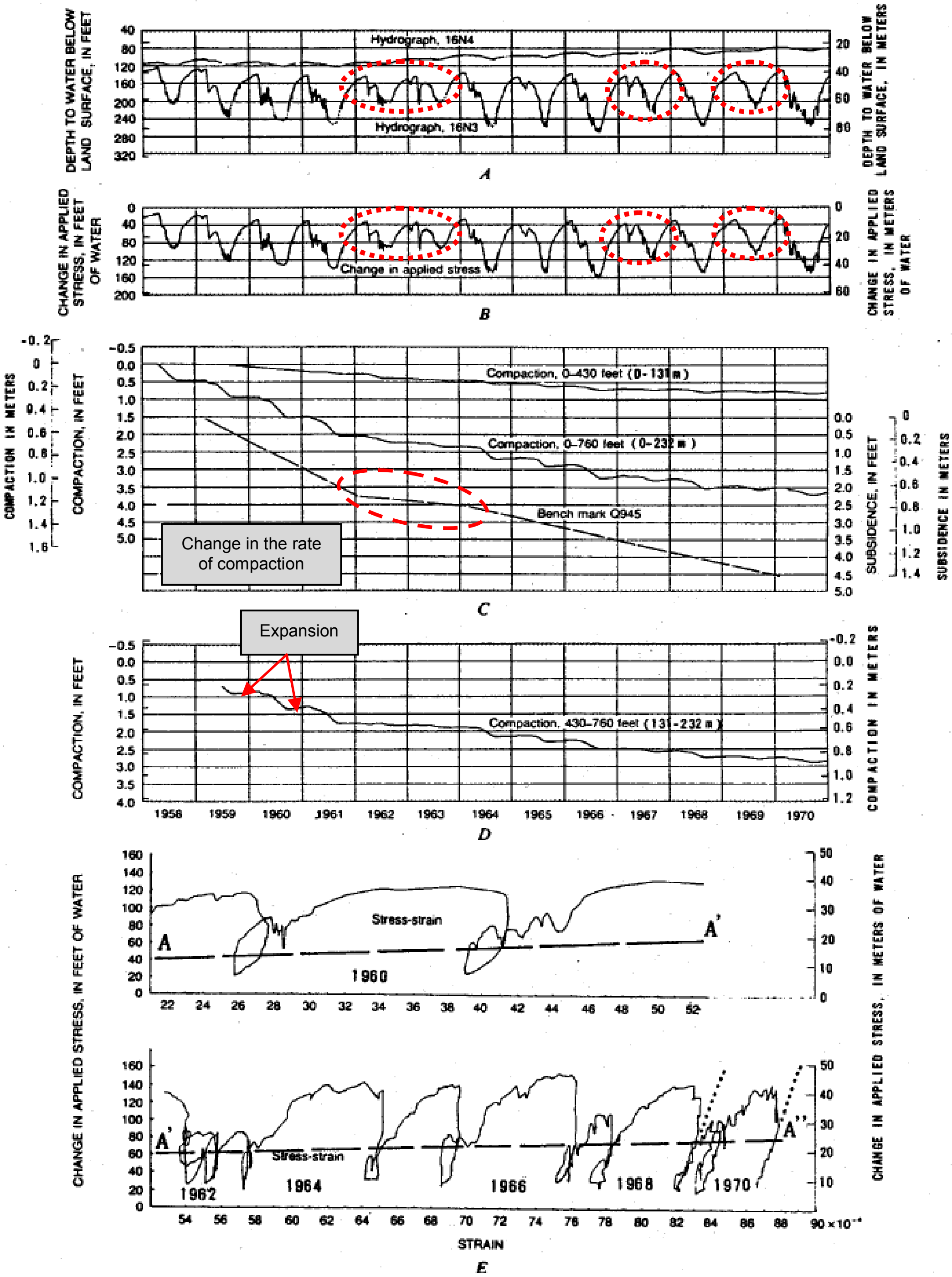
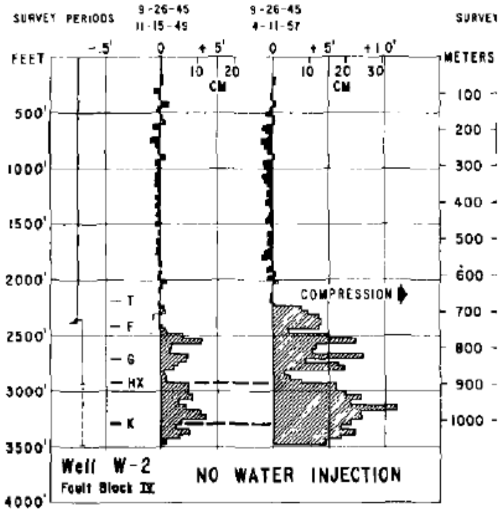
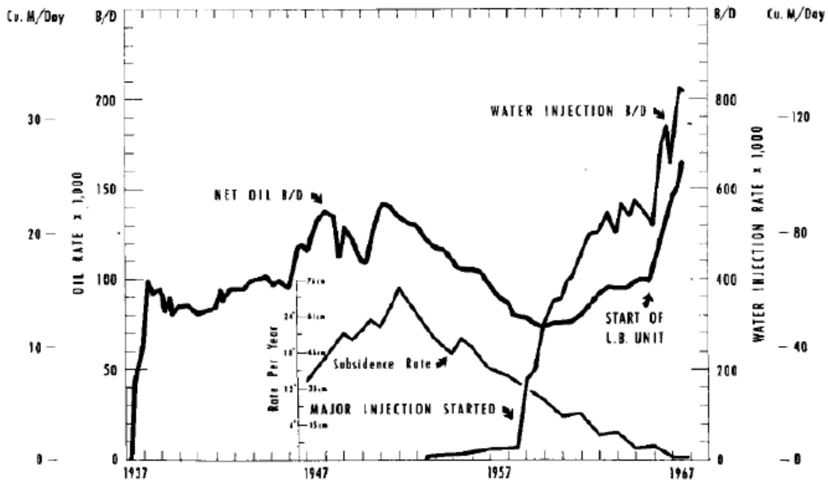


Figure 11.Ground water extraction in San Joaquin Valley. (a) Hygrographs. (b) Changes in applied stresses. (c) Compaction in different levels. (d) Compaction in 131-232m depth interval. (e) Stress changes vs strain (from Poland et al, 1975)

In general terms, oil and gas extraction follow the same physical mechanisms controlling ground-water and geothermal fluid extraction: oil/gas withdrawal decreases the pore pressure which causes compaction and finally surface subsidence. The chief difference is that oil/gas reservoirs generally do not show the seasonal depletion-refilling process as observed in aquifers (see A in Figure 11). Some of the most important oil fields in the USA were established in the early 19^{th} century. After a few years, strong subsidence problems were observed in some oil fields. As a consequence, important advances in monitoring techniques were made. Subsidence at the Wilmington oil field - Long Beach, California - was one of the first well-documented cases reported in the literature (e.g., Mayuga and Allen, 1969). The Wilmington oil field rests on an asymmetrical anticline broken by transverse normal faults. The productive zone spans a vertical section of about 1500m, mainly composed of sands with a porosity ranging from 25 to 45% and interbedded with shales and siltstones. Oil extraction started in 1936 and caused a maximum subsidence of around 9m, evaluated between 1926 and 1968. The subsidence bowl covered an area of about $50km^2$ during that period. Because of the limited water encroachment, the pressure decline in the reservoirs (oil and gas) was relatively rapid (Mayuga and Allen, 1969). The horizontal movements caused extreme damage to several surface and subsurface structures. Many oil wells were destroyed by subsurface shearing associated with subsidence. Some controversy emerged from the first two comprehensive studies performed in 1945 because of the different hypotheses used to explain the causes of the subsidence. One of them concluded that subsidence was caused by compaction occurring within the fluid producing sands, whereas the second study attributed the subsidence to the compaction of the shale layer. Because of the doubts regarding the compaction strata and the mechanisms of compaction, an important improvement in monitoring techniques, called collar counting, was used to measure relative displacements at different depths (Law, 1950). The comparison of the measurements obtained between 1945 and 1947 and from 1945 to 1957 allowed the evaluation of the compression taking place at different depths. As observed in Figure 12(a), it is clear that compaction was localized between 650-1100m depth, which corresponds to the four uppermost oil producing zones. From these observations, subsidence can be explained by the substantial decrease in the reservoir pressures, which causes compaction within the oil producing zones. The most successful remediation technique applied in the Wilmington oil field was a re-pressurization program started in 1958 to inject sea water into the productive strata. Until 1961, a full scale injection operated in the Long Beach harbour area which injected 174,900 m^3/day of water (Mayuga and Allen, 1969). Using this technique, the rate of subsidence reduced from 71 cm/yr (1951) to 0 cm/yr (1968) (see Figure 12b). One of the more important lessons learned from the Wilmington oil field subsidence was the development of water injection as a remediation technique to control the rate of subsidence.



(a)



(b)

Figure 12.Subsidence in Wilmington oil field-California. (a) Compaction of the deeper strata – sands- obtained using the collar counting (Allen & Mayuga, 1969) (b).Variation of the oil production, subsidence and water injection from 1937 to 1967 (Mayuga & Allen, 1969)

A similar problem has been observed in the Ekofisk field, a massive chalk structure draped over a salt dome located in the North Sea. The Ekofisk field has experienced important subsidence during the last decades as a consequence of extraction of hydrocarbons (oil and gas). Due to the high porosity of the chalk (25-40%) compaction is a main concern. The registered subsidence rate in the late 80's was around 30 cm/yr, so that water injection was studied as a remediation measure (Doornhof et al, 2006). Water injection started in 1987, but the subsidence still increased until 1998. In fact, a maximum value of 42 cm/yr was measured during that period as shown in Figure 13. The production was halted in 1998, due to the installation of a new complex of platforms, but water injection continued. The subsidence rate dropped to 15 cm/yr during this period while the pressure in the reservoirs increased due to the past water injection. As in the case of the Wilmington oil field, water injection was successfully used to control the rate of subsidence due to the withdrawal of ground fluids.

The previous examples have demonstrated that the rate of subsidence caused by withdrawal of ground fluid can, at least to some degree, be "controlled" by raising the pressure inside the reservoirs, i.e., limiting the fluid extraction within a production/settlement balance. This requires high-quality monitoring along the profile with the aim of computing deformations, and also changes the stresses that are used for geomechanical analyses.

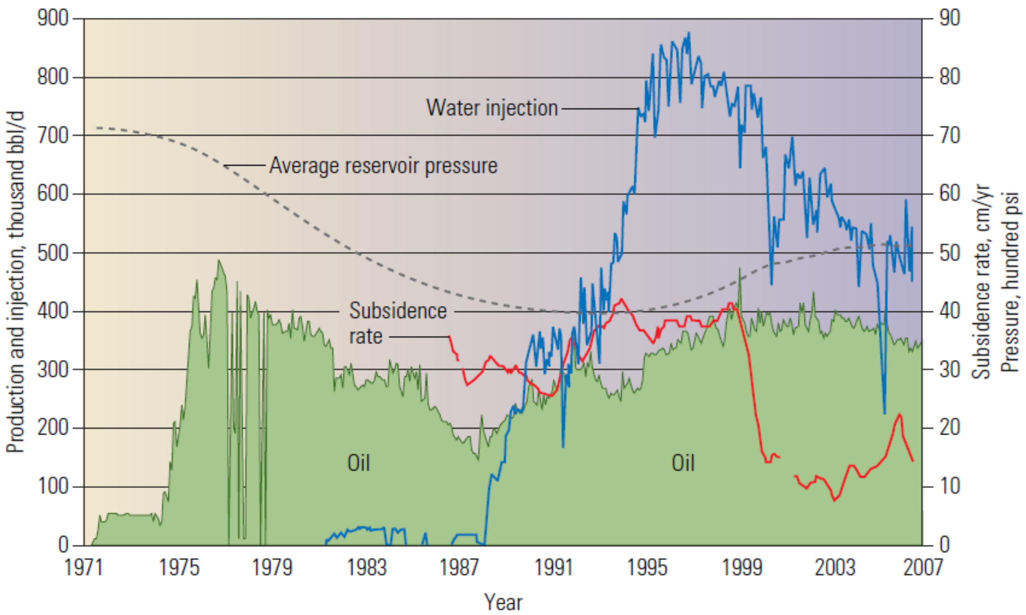


Figure 13. Variation of the reservoir pressure, subsidence rate and water-injected pressure at Ekofisk field-North Sea (from Doornhof et al, 2006)

2.3. Final remarks

The examples described above have been intended to outline the general features of subsidence phenomena observed in different geomechanical environments. The main causes, as well as the typical scenarios in which subsidence is prone to occur, have been described. As a summary, subsidence can be defined as a time-dependent vertical settlement of the ground surface. It may be caused by either natural or human activities, many of which involve geotechnical engineering such as mining, tunnelling, the behaviour of expansive soil/rocks, and the withdrawal of ground fluids.

In most of the scenarios described above, subsidence was caused by:

- Loss of a volume of soil/rock and associated consolidation due to tunnelling, or mining activities.
- Compaction of some strata due to the dissipation of pore pressure, which is often associated with the withdrawal of ground fluids.
- Collapse of a soil/rock mass due to tunnelling or the formation of sinkholes.

The analysis of subsidence shows some similarities in these scenarios. Consolidation theory, as used in soil mechanics, is employed to quantify the compaction of strata due to changes in water table and the withdrawal of ground fluid, but is also used to predict the settlement of clayey layers induced by other processes. Although Coal Seam Gas (CSG) production involves the same physical processes described above, and is now discussed in the following sections.

3. Coal seam gas (CGS) extraction

Coal seam gas (CSG) is a ‘natural gas’ comprised of around 97% methane. It is formed from the compression of organic matter under pressure, thermal changes (thermogenic processes) and also, although to a lesser degree, by biological reactions. Coal seam gas is usually referred to as ‘unconventional’ gas because it occurs in unconventional deposits – coal beds - located typically at between 300-1000m depth (www.csiro.au). For instance, in the Camden Gas Project in south-western Sydney, coal seams are located at between 600-1000m depth. There, the two upper seams - Bulli and Balgownie - are the major CSG targets.

Coal is a low porosity sedimentary rock composed of two constituents (see Figure 14): (i) the coal matrix, which displays a very low porosity, and (ii) a system of orthogonal fractures (cleats) that divide the coal matrix into ‘blocks’. The fractured or cleated nature, and the unique storage mechanism of methane through adsorption, are the two distinguishing features that control the extraction process (taken here to include both the exploration methods and subsurface operation in CSG production (Loftin, 2009)). Methane is adsorbed by the micro-pores within the coal matrix, at a near-liquid state, due to the large internal surface area of the coal matrix. Methane is also stored inside the cleats, although it represents only around 5-9% of the total volume in the coal seam (Close, 1993). Due to the high efficiency of the adsorption mechanism, methane extraction from coal is more complex compared with conventional gas reservoirs. Methane adsorption is maintained by pressure, e.g. hydrostatic water pressure. If the pressure decreases the methane is able to ‘de-sorb’ from the coal and become mobile. The release of methane from the coal is analysed using the Langmuir isotherm which is unique for each coal formation. The isotherm describes the gas storage capacity (e.g., scf/ton) as a function of the pore fluid pressure (see Figure 15). In other words, it represents the maximum storage capacity of a coal in a formation at given pressure. Thus, coal is saturated if its current gas content is equal to the storage capacity as described by points located on the isotherm. If the current gas content is lower than the maximum storage capacity at a given pressure, the coal is under-saturated and the current state locates below the isotherm. A coal seam may reduce its gas content but remain saturated by following a path along the isotherm (path 1-2), as could happen in a geological uplift. If the coal is reloaded, the released gas is not re-stored (path 2-3) and the under-saturated state is maintained. At point 3 (see Figure 15) the coal contains less gas than could be expected under the current pressure. In addition, methane will not be released until the pressure reduces and reaches the isotherm. During this process, only water is extracted from the well (Loftin, 2009).

'De-watering' of the cleat system is the first stage of a gas extraction process. A large volume of water is usually extracted to reduce the water pressure until the methane is released from the coal matrix. Over time, gas production increases as the cleat system is saturated with 'de-sorbed' gas, as in shown schematically in Figure 14. The low gas rate observed during early extraction is contrary to the common observation in conventional reservoirs, where high gas production rates are achieved from the beginning of the extraction process. This behaviour adds another unique feature to coal seam gas. Loftin (2009) remarked that both the water-filled cleat system, as well as the shape of the isotherm curve, impacts on every aspect of the field development (both subsurface and surface).

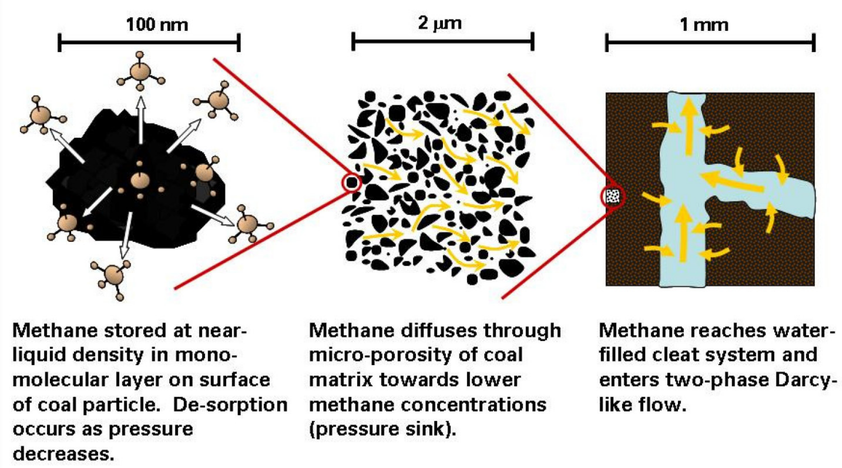


Figure 14.Movement of methane in coal (from Loftin, 2009).

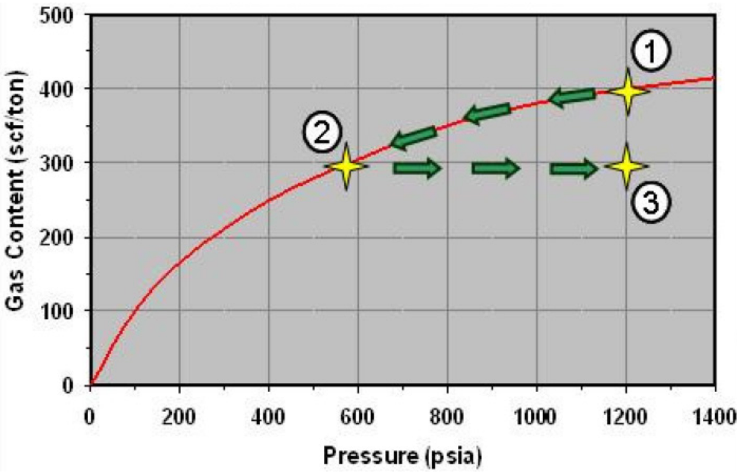


Figure 15.Langmuir isotherm for coal (from Loftin, 2009).

3.1. Extraction methods in Coal Seam Gas (CSG)

In CSG production, gas is extracted through wells drilled to pump out the ground water-gas mixture. Due to the very low permeability of the coal matrix, non-conventional drilling techniques are required to promote the creation of new pathways for gas extraction. Two main configurations, involving two drilling techniques, are usually employed in CSG production: (i) vertical wells (vertical drilling), and (ii) horizontal boreholes (directional drilling) connected to a main vertical well.

Gas extraction from a single vertical well (see Figure 16(a)) is generally inefficient. To achieve the desired production from vertical wells, many closely spaced wells are required, but this is often uneconomic. For this reason, stimulation techniques are required. Hydraulic fracturing or so-called "fracking" is frequently employed to increase the permeability of the medium around the wells. Alternatively, the combination of a vertical well with directional drilling techniques can be employed in CSG practice to reduce the need for hydraulic fracturing (see Figure 14(b)), although in very low porosity shale gas extraction, both horizontal drilling and fracturing are combined. A mandatory requirement in all cases is the proper casing (insulation) of the vertical well to avoid the contamination of aquifers in strata overlying and underlying the coal seam. Depending on the permeability of the coal and the drilling method employed, hydraulic fracturing requirements may be minimal or massive.

Hydraulic fracturing involves the injection of fluid under pressure (water+sand+proppants) into the well to enhance the fracturing pattern of the coal seam (Figure 16a). The fluid pressure is increased quickly, reaching values above the minor in-situ stress and tensile strength of the coal. This induces the propagation of cleats but also creates new fractures. According to linear fracture mechanics, pre-existing fractures or cleats propagate until the stress-intensity at the fracture tip is lower than a critical stress-intensity of the rock (e.g., Savalli & Engelder, 2005). Once the injection of fluid has finished, the ground pore fluid is pumped out to the surface. During this process, methane is released from the coal micro-pores and flows through the cleats, as the pressure decreases according to the isotherm. The initiation and propagation of hydraulic fractures are, however, not well understood from the standpoint of physics and mechanics. In fact, highly experienced practitioners recognize that the optimization of the hydraulic fracturing process in coal seams is, in most cases, a trial-and-error exercise (e.g., Loftin, 2009). Two main factors are considered to influence the fracture behaviour in CSG production. First, hydraulic fractures may extend far from the target formation into overlying and underlying strata.

Secondly, fractures may connect with natural fracture systems and permeable formations, facilitating the unintended movement of fracturing fluids. During the hydraulic fracturing process, the propagation of fractures is affected by the following site-specific factors (Ketelaar, 2009):

- ✓ *Properties of the coal seam and surrounding geologic formations*: horizontal fractures more commonly occur at shallow depths as they propagate perpendicular to the direction of the minor stress. Vertical fractures are expected to occur in deeper coal seams.
- ✓ *Natural fracture (cleat) systems*: hydraulic fracturing enhances natural cleating. The preferential fracture direction of the cleats is exploited to some degree.
- ✓ *In-situ stress state and stress changes*: the magnitude and direction of the principal stresses control the pressure required and the propagation of fractures.
- ✓ *Operator's influence*: fracture dimensions will be affected by the different approaches adopted by different drilling operators.

Despite being common practice, hydraulic fracturing techniques in CSG production are by no means standardized. Each coal seam is different so that the effects of using different fracturing techniques cannot be quantified easily. The outcomes of fracturing processes depend to a high degree on the expertise and experience of the operator who, in some cases, may have a financial incentive to keep the hydraulically-induced fracture within the target coal zone (Ketelaar, 2009).

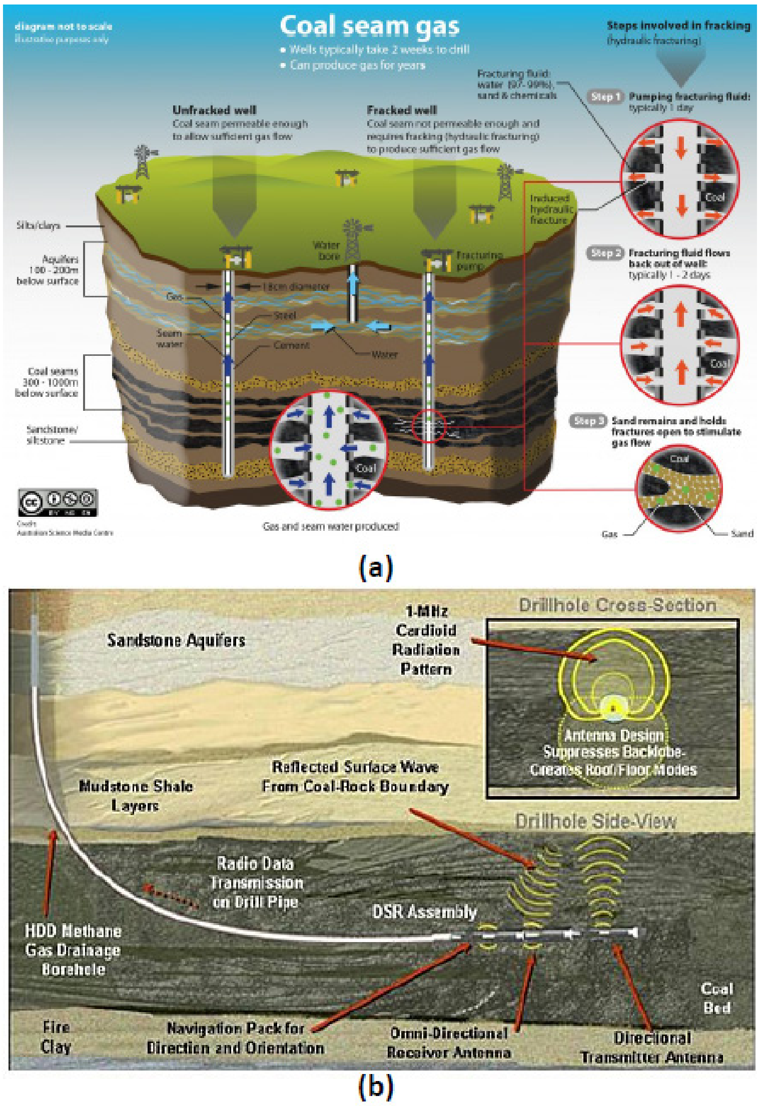


Figure 16.CSG extraction. (a) vertical wells (www.smc.org.au). (b) horizontal –multidirectional-wells (www.netl.doe.gov)

Because of the uncertainties and issues related to the use of hydraulic fracturing techniques in coal, directional drilling has emerged during recent decades as an alternative procedure in CSG production. Horizontal or directional drilling refers to the practice of intentionally deviating a wellbore in a controlled way from its initial path. Under ideal conditions, directional drilling can provide some advantages (Maricic et al, 2008; Loftin, 2009) including: (i) a high drainage area per well and reduced environmental impact, (ii) convenient exposure to the overall gas reservoir, (iii) optimal access to the orientation of the cleat system, and (iv) the ability to tap into lower permeability areas. In horizontal wells, the gas flow peaks early compared with vertical wells due to the larger drainage area (see Figure 17(a)). Different horizontal well-configurations can be employed in-situ. The most common arrangements are the single-lateral, dual-lateral, trilateral, quadrilateral, and fishbone (pinnate) configurations as shown in Figure 17(b). In most cases, a single vertical well is used to pump out the water-gas mixture. A parametric study performed by Maricic et al (2008) analyzed the influence of well configuration, spacing between laterals (BBL), and length on the efficiency of coal seam methane extraction. Using a specific set of reservoir properties, they showed that a quadrilateral well configuration achieved the optimum production rate. This result is in agreement with the experience of other authors, although some problems related to wellbore collapse and de-watering of the laterals has also been reported to occur (see e.g., Loftin, 2009).

The main problems reported with horizontal wells seem to occur at shallow depths where high-angle directional wells are required. High-angle wells sometimes cause several complications when crossing through naturally-cleated coal. The interaction between the hole-angle, the well azimuth and the hydraulic fracture azimuth defines the good or poor alignments in regard to the plane of hydraulic fracture (see Figure 18). Poor alignment may lead to premature screen-out and ineffective flow recovery of the fracturing fluid. In most vertical wells, in horizontal seams, good results are obtained from hydraulic fracturing as the wellbore is (by default) typically aligned with the plane of fracturing (Figure 18) since cleats are typically developed perpendicular to the coal bed thickness. In directional wells, two additional factors have to be taken into consideration: (i) the well azimuth and (ii) the azimuth of the face cleats. Satisfactory results are obtained if the well azimuth tends to be parallel to the azimuth of the face cleats. However, if the well azimuth deviates from the azimuth of the cleats by more than about 10º, systematic problems may appear. Transverse fractures may form along the wellbore. This may limit the propagation of the fractures in the well bore, if the transverse fractures interfere with each other creating tortuous flow paths. An increase in the hole-angle as well as the difference between azimuths will magnify the problems discussed above (Loftin, 2009).

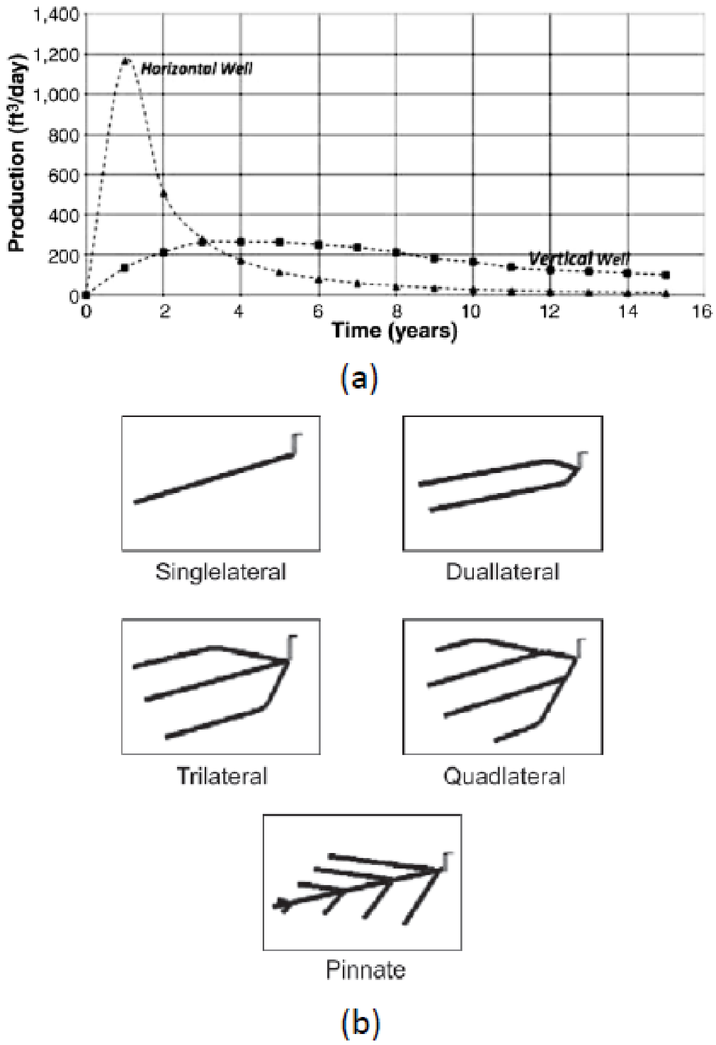


Figure 17.Horizontal wells. (a) Comparison between vertical and horizontal wells. (b) Types of horizontal wells configurations (from Maricic et al, 2008)

Coal seams are multi-phase porous media (i.e. composed by solids, liquid and gas). As such, coal seam gas (CSG) extraction should be studied as a multi-phase porous medium problem. A proper understanding of the coupled mechanisms controlling the response of the medium (i.e., thermo-hydro-mechanical processes), under particular hydro-geological conditions, is required to develop a framework of behaviour and improve current practice. Multidisciplinary research is essential to improve the current state of knowledge and current practice in coal seams, as highlighted by different experts (e.g., John Williams Scientific Services Pty Ltd, 2012a). In the specific case of subsidence problems, and despite the difficulties for a detailed quantification, the extraction method plays an important role. This is discussed in the following section.

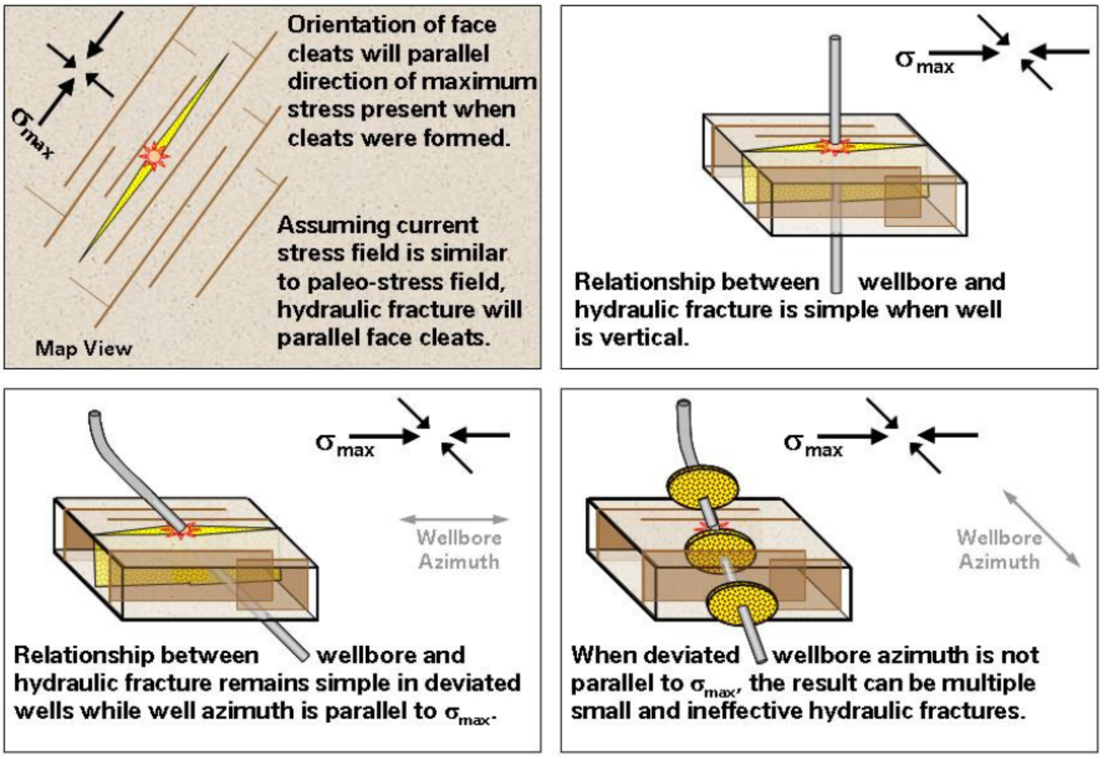


Figure 18.Relationship between the drilling procedure and the characteristics of the coal seam (from Loftin, 2009)

3.2. Subsidence associated with Coal Seam Gas production

The study of the subsidence caused by Coal Seam Gas (CSG) production is even more complex than the subsidence associated with mining or civil engineering activity, due to the special interrelationship between the different phases (gas, liquid and solid) inside a naturally fractured system such as coal seam. Some of these couplings are not well-understood. The main problem lies in the fact that the coal in each seam is different and behaves according its own isotherm and the characteristics of its cleat system (which is further modified during the ‘stimulation’ process). Even under the guidance of a highly qualified operator, drilling and ‘stimulation’ processes induce a certain level of disturbance, not only in the coal seam itself but also through the entire geological profile. Under ideal conditions, if the disturbance is properly quantified, which includes reliable prediction of stresses and fluid pressures in different strata, it would be possible to analyse changes in the mechanical behaviour during gas extraction with a high degree of confidence. In the particular case of subsidence associated with gas extraction, the marketing requirements of high production rates speeds up the compaction of geological strata, which may in turn cause unexpected surface settlements.

Subsidence occurs due to the response of the whole profile to the gas extraction, although the main contribution is the compaction (compression) of the coal seam. The process of gas extraction inside the coal seam can be represented, in a simple way, using the phase-diagram shown in Figure 19. There, the subscripts “i” refer to the specific stage analysed. The three main stages of the gas extraction process are identified: (i) the initial state with subscript 0, (ii) the post-fracturing state with subscript 1, and (iii) the final state with subscript 2. The final state represents a late stage of the extraction process. A unit total volume (V_T) of coal seam is assumed in the analysis. As a multiphase medium, the coal seam is composed of the volume of solids (V_S) plus the volume of voids (V_V) which can be subdivided into micro-pores (V_m, containing most of the available methane) and macro-pores (V_M, defining the cleats system):

$$V_T = V_s + V_V = V_s + (V_M + V_m) \quad (1)$$

The ‘stimulation’ processes, hydraulic fracturing or horizontal wells, induce an increase in the volume of voids (ΔV_V), but also a small reduction in the volume of solids (V_S) caused by the drilling of the wells. Hydraulic fracturing adds additional volume of fluid to the system that could induce a small volumetric expansion. However, this stage is carried out quickly so that the expansion may not be noticed at surface. As ground fluid is pumped out, the pore fluid pressure decreases and leads to the compaction of the coal seam. The compaction is due to the release of the methane from the micro-pores and the associated drainage of water from the cleat system (macro-porosity).

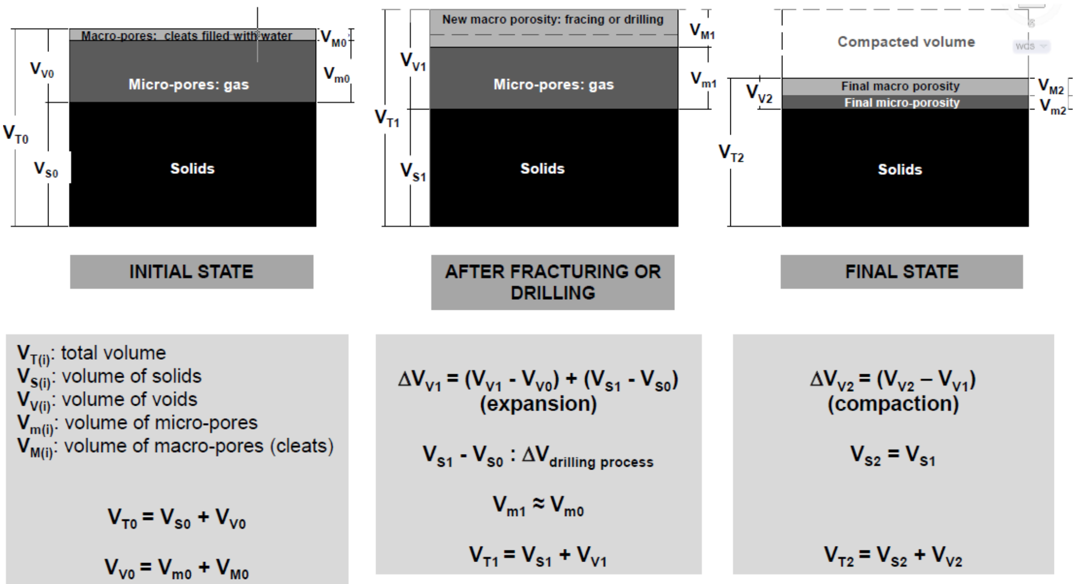


Figure 19.Phase diagrams for the coal seam compaction

As the external forces remain constant during gas production, the compaction of the coal seam is due to the dissipation of the pore fluid pressure (Δu_{fluid}). The factor that plays a key role in the degree of compaction is the compressibility of the coal seam. Figure 20 shows a schematic compression curve in the space of porosity vs effective stress for a natural coal seam. λ_{nat} defines the compressibility index of the natural coal seam developed along its geological history. As known in geomechanics, λ_{nat} remains more or less constant, if the coal seam maintains a normally-consolidated state. Thus, the point O defines the in-situ stress state at the time of development. Drilling and 'stimulation' procedures cause a small reduction in the effective stress, represented by the path OA. If the disturbance induced during the 'stimulation' process is negligible, the stress state should move along the compression curve for the natural coal until its reaches the point B' (path AOB'), as the pore fluid pressure dissipates. However, the disturbance caused by fracturing allows the stress state to move along the path AB that, as observed in Figure 20, displays a higher compressibility index, λ_{frac}. A higher compaction should be expected in this case. If the lateral dimension of the coal seam is large compared to its thickness, the compaction is assumed to be mainly vertical and the maximum compaction can be quantified from conventional consolidation theory (Terzaghi, 1925) in terms of the compressibility modulus ($m_v=\Delta\varepsilon_v/\Delta p'$; $\Delta\varepsilon_v\rightarrow$change in vertical strain, $\Delta p'\rightarrow$change in effective stress), pressure change (Δu_{fluid}) and reservoir thickness (H): $S_{max}=m_v.\Delta u_{fluid}.H$. The compressibility of the coal seam in the horizontal direction depends also on Poisson's ratio, ν, which defines the ratio between the horizontal and vertical strains. The magnitude of ν and m_v in the coal seam are influenced by the stimulation process, in particular by their effectiveness. There is a direct relationship between commercial requirements for high production rates (intense fracturing and increasing m_v) and subsidence issues. In this sense, a rigorous control of the stimulation processes and gas production, including the continuous monitoring of pressures and relative displacements along the entire profile, will have at least two important benefits: (i) a better estimation of compressibility m_v and Poisson's ratio of different strata, and (ii) a proper estimation of the induced compaction.

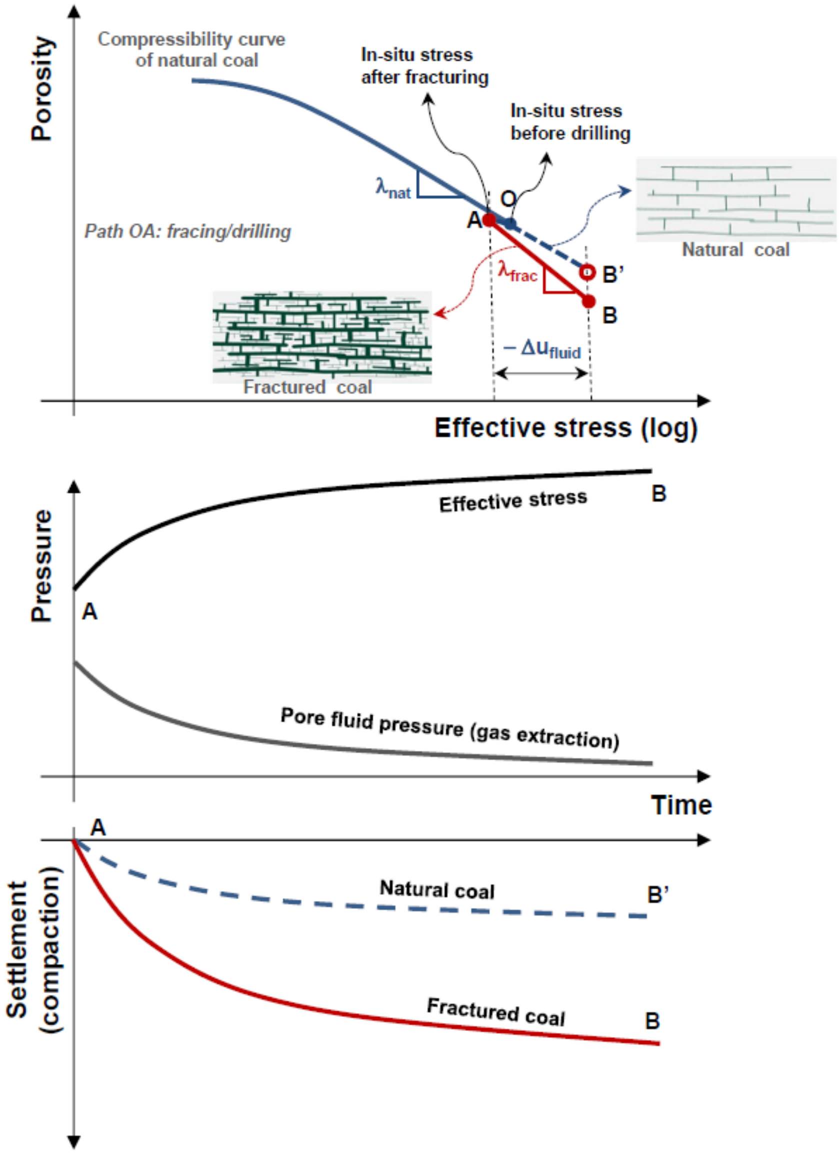


Figure 20. Schematic view of the coal seam compaction

Surface subsidence can also result from indirect subsidence: the compaction of underlying and overlying strata. Additional compaction will take place if the hydraulic regime within the entire profile is modified, e.g. in the aquifer system. Thus, the maximum surface subsidence can be estimated as the compaction of each stratum as follows:

$$S_{\max} = S_{direct(coal-seam)} + S_{indirect(other-strata)} = \sum_{i=1}^{n} m_{v(i)} \cdot \Delta u_{fluid(i)} \cdot H_{(i)} \qquad (2)$$

For instance, Figure 21 shows the geological profiles at the Camden Gas Project in south-western Sydney, where the coal seam targets for CSG production – Bulli and Balgownie - are located at a depth of around 770m. In these cases, the maximum subsidence should be the result of compaction of the two coal seams plus the additional compaction due to the ‘de-watering’ caused in the overlying strata (such as the claystone located at the top of the Bulli seam).

The subsidence bowl, or ‘settlement trough’ as it is called in tunneling engineering, depends on the geometry of the problem, as well as the mechanical properties of the soil/rocks involved. For instance, the subsidence associated with oil/gas extraction in a circular or axisymmetric reservoir, can be computed using the analytical solutions derived by Geertsma (1973). Assuming the overburden is uniform and elastic, the vertical displacement, u_z, taking place in a point located at a distance r from the vertical axis of the well is given by:

$$u_z(r,0) = -\frac{m_v(1-\nu)}{\pi}\frac{D}{\left(r^2+D^2\right)^{3/2}}\Delta u_{fluid}\cdot V \quad (3)$$

where ν is the Poisson’s ratio, D is the depth of burial and V is the volume of the reservoir. Negative values in Eq. (3) imply subsidence; and positive values indicate uplift. The following analytical solution for the horizontal displacement was also derived by Geertsma (1973):

$$u_r(r,0) = +\frac{m_v(1-\nu)}{\pi}\frac{r}{\left(r^2+D^2\right)^{3/2}}\Delta u_{fluid}\cdot V \quad (4)$$

From the above, the ratio between the horizontal and vertical displacements is r/D. The maximum subsidence can be computed by assuming the reservoir is disc-shaped of thickness H, radius R and located at depth D, as follows:

$$u_z(0,0) = -2m_v(1-\nu)\Delta u_{fluid}\cdot H\left(1-\frac{D/R}{\sqrt{1+(D/R)^2}}\right) \quad (5)$$

These analytical expressions include some simplifications which may be more or less valid, according to the particular problem analyzed. Additional methods including semi-analytical models (e.g., Fokker, 2002; Fokker & Orlic, 2006) and numerical methods (Sroka & Hejmanowki, 2006; Geertsma & van Opstal, 1973; Fredrich et al, 2000; among others) have also been developed for this purpose.

The important aspect to note here is the dependency of the induced subsidence on the two key parameters mentioned previously: (i) the compressibility modulus m_v of coal seam, and (ii) the Poisson's ratio. Both are affected by the mechanical ´stimulation´ procedure and the extraction process itself.

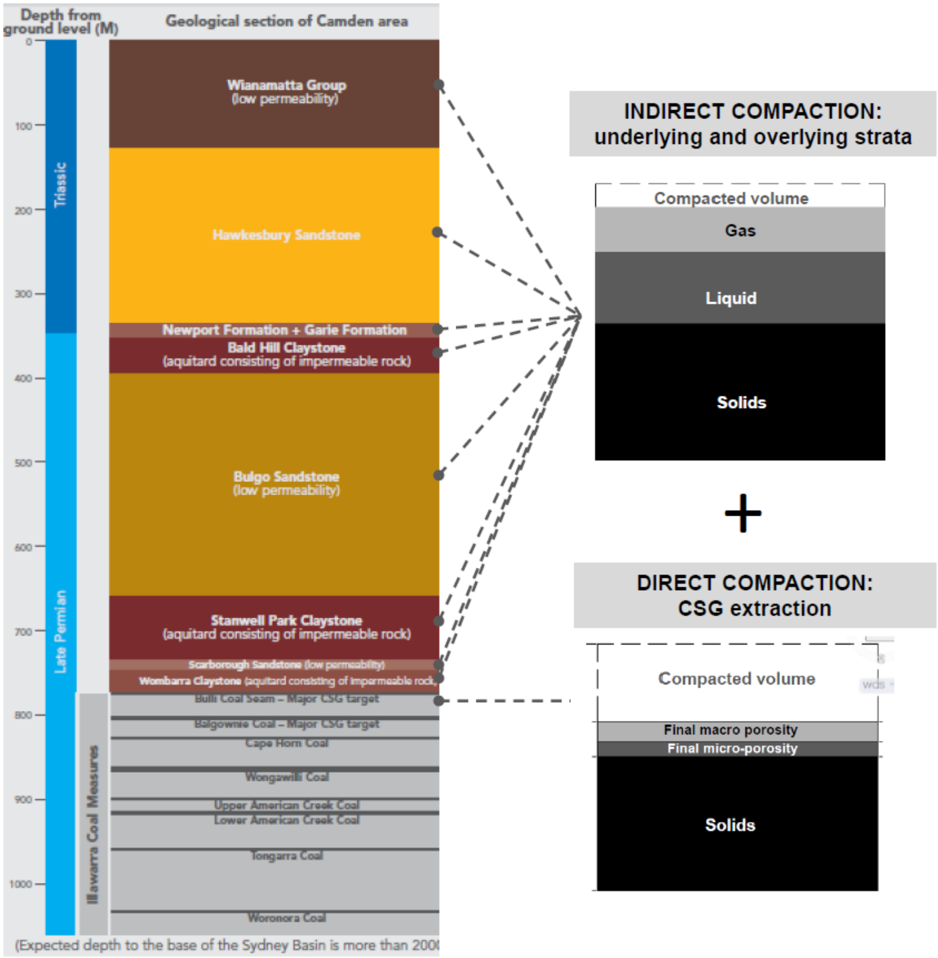


Figure 21.Geological profile at Camden Gas Project (www.nsw.gov.au). Compaction process

3.2.1. Potential subsidence impacts from Coal Seam Gas production

As pointed out by CSIRO (2012), the prediction of the potential long-term subsidence from CSG production and the severity of its impacts is a difficult task, due to the potential superposition of region-specific impacts of multiple developments. In general terms, subsidence caused by CSG production may have two main types of impact:

- Impacts on infrastructure: the well itself, access roads, houses, buildings, pipelines, bridges, water supply, sewage systems, dams, connection to nearby underground workings.

- Impacts on natural resources: aquifers, streams, rivers, lakes, cliff lines, rock formations, archaeological sites, micro-tremors in fault systems.

It is worth noting that the impacts and severity of subsidence in CSG production depends mostly on proximity to the well, but also on the vulnerability of the infrastructure under study. Therefore, damage criteria have to be developed to evaluate severity and to be able to implement mitigation measures in each particular case.

A major concern about CSG production is the potential impact on natural resources (e.g., U.S.E.P.A., 2004; John Williams Scientific Services Pty Ltd, 2012a,b; Pells & Pells, 2012). Underground excavations, e.g. by conventional mining, withdrawal of pore fluid and gas extraction, cause changes in the natural water regime. CSG production is typically located at between 200-1000m depth, so that shallow aquifers and natural hydraulic structures can be affected. Subsidence may change the natural connection between aquifers, but it may also induce new connections between geological structures as a consequence of an uncontrolled fracturing process. Changes in the ground water table may cause additional and unexpected compaction, or even collapse, if old underground workings or natural sinkholes are present in the area of influence.

3.2.2. Potential subsidence from vertical and horizontal wells in CSG production

The use of vertical or horizontal wells has associated advantages and drawbacks. A direct comparison is sometimes difficult because the volumes of coal affected are not equivalent in both cases. Differences would not be exclusively due to different geometries between vertical and horizontal wells, but also due to the different perforation and stimulation techniques. The following three scenarios are analysed here by assuming the same volume of coal:

- ✓ Effectiveness of the stimulation procedure.
- ✓ Single vertical vs horizontal well.
- ✓ Multiple wells.

In the first case, the subsidence potential is highly dependent on how effective the stimulation of the coal seam is controlled. As discussed above, the performance of hydraulic fracturing and multidirectional drilling processes in coal seams is site-dependent, so that a general quantification of their effectiveness is not possible. For the same volume of coal to be ‘affected’, horizontal drilling seems to give, at least in theory, more satisfactory results if no issues are encountered during the drilling of the horizontal wells. In both vertical and horizontal wells the subsidence bowl is expected to be aligned according to the direction of the cleat system which controls the permeability of the coal seam. A detailed geophysical characterization should be employed to define the direction of the ‘stimulation’ technique and, in this way, to predict the preferential alignment of the subsidence bowl.

A proper comparison of the potential subsidence between a single vertical and a horizontal well should be made based on the assumption of a constant pumping rate in both wells. Due to the lack of data on this, two possible scenarios are evaluated here in terms of the expected changes in permeability obtained at the end of the ‘stimulation’ process. If the same increase in permeability is obtained after the stimulation process, a similar compressibility could be expected as well. A comparison of the cumulative production (see Figure 22) obtained from the numerical analysis performed by Maricic et al (2008) shows that a horizontal well allows higher rates of production due to its large surface area in contact with the coal seam (assuming the same volume of coal in both cases). Therefore, a horizontal well will tend to reach the maximum settlement early. However, different shapes of the subsidence bowl could be expected. An enlarged subsidence bowl, symmetric about the horizontal well axis, similar to the one observed in tunnels, could be expected in horizontal wells (see Figure 6) compared to the axisymmetric type of bowl that is commonly observed in conventional vertical wells. On the other hand, if different permeabilities are induced after the ‘stimulation’ procedure, larger subsidence could be expected for the material with higher permeability (or larger compressibility as shown in Figure 20).

There are differences between the effects of short-term and long-term subsidence on infrastructure. In the short-term, larger horizontal displacements (leading to cracking) may be developed in infrastructure located near the inflexion point of the subsidence bowl. In the long-term, the rate of horizontal displacement at the same location will be lower due to the expansion of the subsidence bowl. Of course, the rate of expansion of the subsidence bowl will depend on the rate of gas extraction.

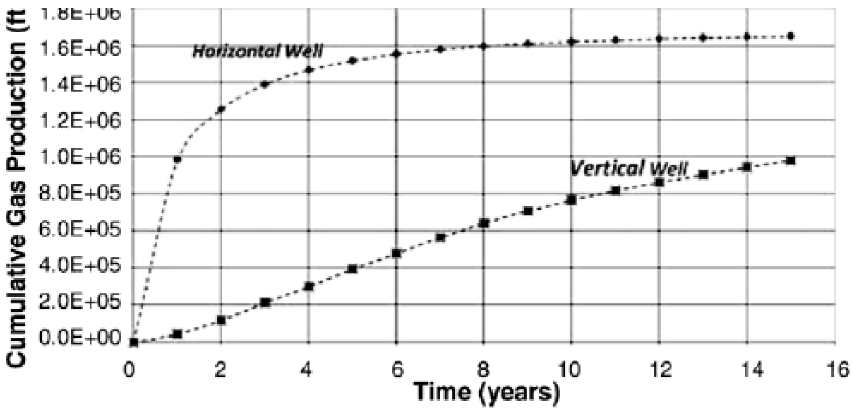


Figure 22.Cumulative gas production in vertical and horizontal wells (from Maricic et al, 2008)

The adoption of multiple wells, in both vertical and horizontal configurations, will enlarge the volume of soil prone to settlement. Thus, the impacts on natural resources, such as aquifers and rivers, as well as infrastructure will increase. A complex and possibly non-symmetrical subsidence bowl could be expected if multiple wells are involved. The magnitude of the subsidence caused by multiple wells and their impact on natural resources and infrastructure will depend on their configuration, including the possible overlapping (separation) between subsidence bowls, as previously described for longwall mining (see Figure 9). Despite the economic benefit of multiple wells, a careful design is required to maximize gas production while at the same time minimizing the subsidence which may affect other economic activities.

3.2.3. Similarities between subsidence from CSG with other mining and gas extraction activities

Coal seam gas (CSG) and shale gas production includes the same exploration and extraction procedures (vertical and horizontal drilling) so that similar subsidence patterns, at least from a qualitative viewpoint, should be expected. The main differences are: (i) hydraulic fracturing is always used in both vertical and horizontal shale gas wells, (ii) the thickness of shale gas seams is commonly greater, and (iii) shale gas seams are frequently found much deeper than coal seams. Similar subsidence phenomena are expected to occur, and the particular impact on surface subsidence will depend on the specific hydrogeological profile.

CSG production also has many similarities to conventional oil/gas extraction, and with the withdrawal of ground fluids in general. In these cases, the change in the volume of solids is negligible compared with the volume of fluid extracted. Compaction and surface subsidence is a consequence of the reduction in the pore fluid pressure leading to an increase in effective stress. Similar shapes of the subsidence bowl could be expected in these cases, particularly if compared with vertical wells.

The subsidence pattern observed in horizontal wells during CSG extraction is similar to the subsidence bowl obtained during tunnelling operations, while the order of magnitudes may differ. There, a symmetric settlement trough or subsidence bowl about the tunnel axis is frequently observed. Multiple horizontal wells will display a similar subsidence bowl as observed when two tunnels are drilled close to each other. Subsidence bowls are superposed in a similar way as also observed in longwall mining with multiple chain pillars (see Figure 9).

3.2.4. What are the potential 'worst case scenarios' for subsidence associated to CSG production

The definition of a potential 'worst' subsidence scenario is not straightforward, even less if a detailed description of the site-conditions is not available. Such a scenario will depend on the occurrence of different events, not necessarily taking place at the same time, which are associated with particular hydro-geological circumstances. In terms of subsidence the 'worst' scenario is perhaps the one leading to large settlements affecting infrastructure and natural resources, as well as the gas production itself.

Based on geomechanics principles and some degree of speculation, the following scenarios could develop:

- Intense cracking may develop at the boundaries of the subsidence bowl if large settlements occur. This may reduce the pressure of the pore fluid inside the coal seam as it is connected with overlying strata. Intense cracking may cause important stability problems on neighbouring infrastructure, depending on its proximity regarding the well.
- Another possible scenario involves the differential settlement caused by overlapping of the subsidence bowls in cases of multiple wells. The time-dependent evolution of the subsidence bowl means that the deformations experienced by infrastructure are also evolving with time during CSG production. Depending on its location, the deformations produced in the short-term may cause more damage to buildings than those associated with long-term subsidence.
- In the case of horizontal wells, drilling through fault systems or highly fractured zones may also induce instability of the surrounding mass leading to sudden volume changes.

- Probably the 'worst' scenario of all possibilities (but also the rarest to take place in CSG production) is the one that causes a collapse mechanism in the coal seam itself or along the geological profile. Such collapse may occur if the ground contains voids or cavities from old mine workings, chemical dissolution of carbonate rocks, or suffusion in sandstone. Collapse failure occurs when the material (rock or soil) loses strength and support. Uncontrolled hydraulic fracturing, at high fluid pressures, enhances existing fractures/joints and may also induce new fractures in the coal seam as well as in the underlying and overlying strata (thus degrading their strength). Fractures and joints may also lead to new connections between existing voids or cavities. The hydraulic connectivity between different strata may speed up the formation of a collapse mechanism.

In all cases, the likelihood of problems during CSG will depend on many factors. Detailed geophysical, geological and geotechnical characterization of the site has to be carried out. A careful control of the hydraulic fracturing practice as well as a continuous monitoring of the extraction process will be needed to minimize any dangerous consequences.

3.3. Risk assessment and management of subsidence in CSG production

In simple terms, risk is defined as the expected consequences associated with a given event. Considering the CSG extraction as the event to occur, the risk of subsidence, R_{sub}, is defined as the likelihood of CSG extraction, $P_{CSG\text{-}extraction}$, multiplied by the induced-consequences, $C_{(i)}$:

$$R_{sub} = P_{CSG-extraction} \cdot C_{(i)} \qquad (6)$$

where the subscript "i" refers to any factor (such as a structure, activity, etc) that is prone to being affected by CSG extraction including infrastructure (access roads, houses, building, etc) and natural resources (aquifers, rivers, lakes, etc) as discussed above. In addition, $C_{(i)}$ depends mainly on two factors (see Figure 23): (i) the site-conditions, and (ii) the particular features of the structure analysed. Site-conditions include the hydro-mechanical properties of the coal seam and each geological stratum within the entire profile involved in the CSG extraction. It is important to note that site-conditions are highly influenced by the stimulation process as explained above. On the other hand, the characteristics of the structure under consideration include the type of structure (access road, building, house, aquifer, river), location relative to the well and also the damage criteria developed according to the particular structural/geological features. According to Eq. (6) there are two possibilities for $P_{CSG\text{-}extraction}$: 0 if there is no extraction or 1 during stimulation and gas production.

The risk assessment is site-dependent, but also depends on the 'structure' evaluated. For this reason, particular risk management strategies should be developed in each case. The approach used for risk management should include, at least, three levels of risk as follows: (i) a lower limit below which risk is considered acceptable and no significant action is required, (ii) an upper limit above which risk becomes unacceptable, requiring significant actions, (iii) an intermediate value where risk is considered to be reduced 'as low as reasonably practicable'. This approach is being used in the UK for shale gas exploration as described in a report recently published by Climate Principles (2013).

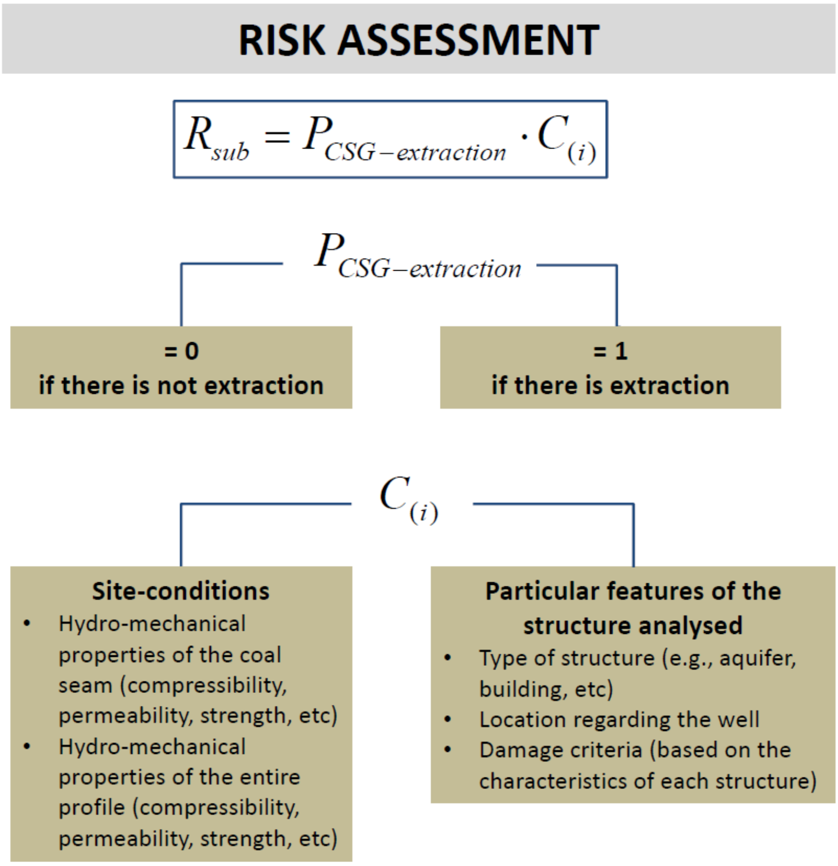


Figure 23. Risk assessment of the subsidence associated with CGS extraction

Monitoring is crucial for risk assessment and for the development of risk management strategies to control and mitigate subsidence. Because of the similarities between CSG extraction and conventional oil/gas production, a possible 'remediation' procedure to minimize subsidence could be the reinjection of fluid (e.g. water) into the coal seam as successfully employed to reduce the rate of subsidence in conventional oil/gas reservoirs. A proper seal of the wells would be required to keep the reservoir pressurized.

As explained in Section 2, reinjection of salt water into oil reservoirs reduced the rate of subsidence almost completely at the Wilmington oil field (see Figure 12). At the Ekofisk oil-field (see Figure 13) reinjection of water reduced substantially the rate of subsidence from 42cm/yr to 15cm/yr. It is worth noting that gas is only released from the coal once the pore fluid pressure reduces. This means that a modified protocol should be implemented to avoid the premature cessation of gas extraction. A controlled re-injection protocol, in which both gas pressure and injected fluid are carefully manipulated, could be an alternative to control subsidence. The key point is to find the equilibrium between extraction pressure and the injected fluid pressure. Some problems could appear in cases where hydraulic fracturing was uncontrolled and extended to the ground surface.

Another option to control subsidence and, at the same time, to extract gas from coal seams is the re-injection of anthropogenic CO_2. The sequestration of CO_2 into the coal seam represents, *a priori*, and additional environmental benefit. The injection of CO_2 into the coal seam allows an easy displacement of the methane from the coal micro-pores by changing their polymer-like structure. CO_2 diffuses into the coal micro-pores in the same way as the methane was stored (Reucroft & Patel, 1986). Despite their *a priori* benefits, there are some issues regarding the interaction between coal, CO_2 and methane, which are not well-understood. The changes in the polymer-like structure of the coal seam, when exposed to CO_2, reduces its strength and stiffness and induces swelling of the coal matrix (Reucroft & Patel, 1986; Walker et al, 1988; Masoudian et al, 2011,2012). This causes irreversible changes in the coal permeability (e.g., Palmer & Mansoori, 1986; Masoudian et al, 2011). Further research is required in this regard.

Continuous monitoring is fundamental during and after the implementation of any mitigation measure. This will allow the process to be updates as the extraction proceeds, with the aim of minimizing the subsidence potential.

4. Issues and knowledge gaps regarding subsidence caused by CSG production

Subsidence associated with CSG extraction is a coupled hydro-mechanical phenomenon caused by the reduction of the pore fluid pressure when extracting the methane from the coal seam. As schematically represented in Figure 24, the unique characteristics of the coal, in combination with the exploration techniques used to extract the gas, makes the subsidence a complex multi-phase and site-dependent problem. Despite the experience acquired during recent decades in CSG engineering, the phenomenon is not completely understood. Additional efforts should be made to improve our engineering knowledge. The following aspects particularly deserve further study:

a) **Detailed hydro-mechanical characterization:** both in-situ and laboratory techniques have to be combined to obtain a detailed characterization of the coal seam as well as the soil/rocks composing the entire geological profile. Measurements of the hydromechanical properties (permeability, diffusivity, adsorption isotherm, compressibility, stiffness and the in-situ stress) will provide a proper reference, not only for design purposes but also for evaluating changes during the lifespan of the well. In-situ (e.g., pre-fracture) well tests and laboratory tests should be combined to reduce uncertainties caused by scale effects. It has been recognized by several authors (see e.g., Loftin, 2009; Liu et al, 2011; Clarkson et al, 2012) that the fluid storage and transport mechanisms in CSG production are not fully understood. One of the main reasons for this is the lack of information about the cleat system, a natural open-mode fracture system, which controls both the hydraulic and mechanical properties of the coal seam. Their influence should be thoroughly determined as the cleat system displays a natural-preferential alignment which seems to be essential for a successful exploration and gas production (Laubach et al, 1998) and for determining a possible preferred alignment of the subsidence bowl. Compressibility and strength measurements along the entire profile will be useful in subsequent settlement analysis of different strata and also in stability estimations. The localization of weak strata or fault systems along the well alignment (vertical or horizontal) should be also detected and properly characterized.

b) **Stimulation techniques and evaluation of hydraulic properties:** stimulation techniques have to be controlled carefully to avoid impacts on underlying and/or overlying strata. Further study is required for a better understanding on the real impacts of hydraulic fracturing within the coal seam including its effectiveness and the formation of preferential paths. To do that, the study of the cleat system and its relation to fracture propagation is crucial (e.g., Laubach et al, 1998; Loftin, 2009; Liu & Rutqvist, 2010; Liu et al, 2011). The cleat system plays a key role during gas extraction. However, their evolution/response during stimulation and gas extraction has not been analysed in detail. A detailed characterization of the in-situ stress field should help to improve the practice of hydraulic fracturing by limiting the injection pressures to values just above the minor principal stress when “fracking”. The influence of hydraulic fracturing on the permeability and compressibility require additional experimental and theoretical analysis. Quantitative models for characterising these influences will lead to refinements in the analysis of subsidence. Experience gained in pre- and post-fracture well test analyses in shale gas extraction may help to evaluate the effectiveness of the stimulation procedures used in CSG extraction (Clarkson et al, 2012), but taking into account the particular features of the coal seam.

c) **Detailed monitoring:** monitoring is possibly the most important factor, not only to improve subsidence analysis but also in the control of gas production. Detailed monitoring of pressures and relative displacements inside the coal seam will allow a proper quantification, in almost real time, of the compaction process of the coal seam. In addition, monitoring in overlying and underlying strata can be used to detect changes in the hydraulic regime and to estimate the induced-compaction. Monitoring can also be used for the development of subsidence contours and subsidence bowls. From this, mitigation measures and risk maps could be implemented for each particular case. Some examples of the benefits of a detailed monitoring were given in Section 2 (see Figures 11, 12 and 13). A detailed monitoring program seems to be a convenient option to improve and update current models used for subsidence analysis.

d) **Multi-phase models:** the former three aspects should be used to improve and/or develop new constitutive models including the particular characteristics of the coal seams. A multi-phase approach seems to be the best option to include the different coupling mechanisms that act naturally in the coal seam and control their hydraulic and mechanical responses such as the induced-subsidence.

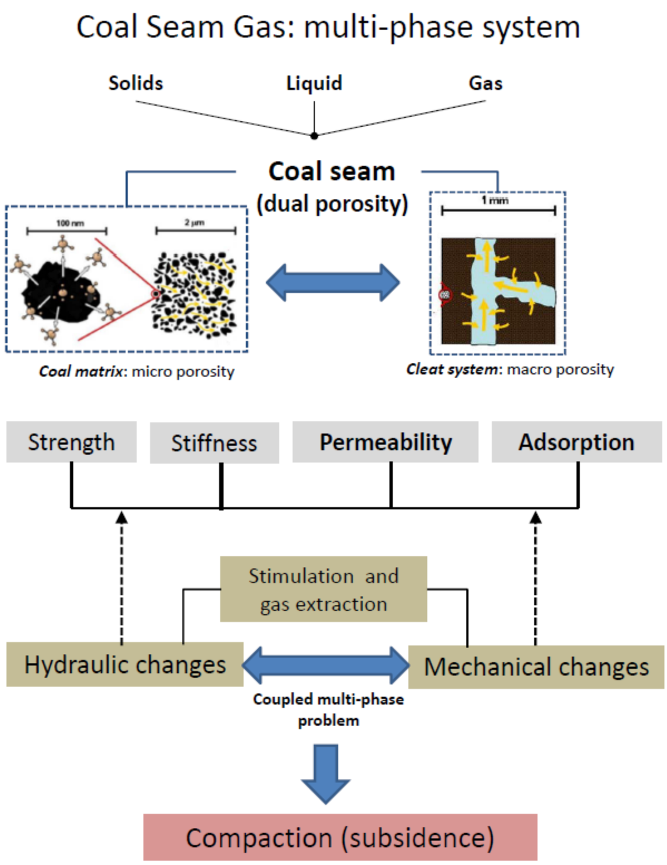


Figure 24.Schematic representation of subsidence in CSG extraction

5. Final remarks

A review of the main causes of subsidence is presented in this paper, with particular emphasis on the subsidence caused by coal seam gas extraction. CSG extraction is gaining more interest as an untapped energy source in Australia. In a recent study, John Williams Scientific Services Pty Ltd (2012a) pointed out the necessity for a new focus in research and academic leadership to support the development of CSG production in Australia. A holistic perspective in teaching and research involving multidisciplinary scenarios is required to study coal seam gas energy production. New scientific and engineering knowledge will provide essential tools to manage CSG production and to evaluate its effects on natural resources and infrastructures.

CSG production involves several processes affecting not only the properties of the coal seam itself but also the entire geological profile. It does not necessarily represent a drawback for CSG extraction if those processes, many of them acting in a coupled way, are properly understood and 'controlled'. CSG extraction is a multi-phase problem in which multidisciplinary work is the best option to improve current practice and also to develop a framework of behaviour for CSG extraction, including improvements to evaluate subsidence. Based on the discussion presented in the previous sections, the following remarks related to subsidence caused by CSG extraction can be made:

i. Subsidence is caused by the compression of the coal seam as a consequence of the reduction of the pore fluid pressure (by gas extraction) that increases the effective stress.
ii. Subsidence is a complicated issue in CSG extraction. It can vary in magnitude, from trivial and insignificant to substantial and damaging, depending on the mechanical properties of the coal seam, the volume of gas extracted, the extraction methods and most importantly the geological setting of the coal seam. Subsidence is expected to increase if additional compaction takes place in overlying and/or underlying strata due to changes in the hydraulic regime (e.g. de-watering).
iii. Subsidence is further complicated by the influence of a stimulation procedure or hydraulic fracturing. Uncontrolled hydraulic fracturing with high fluid pressures may induce fractures in the coal seam as well as in underlying and overlying strata, and hence degrade their strength. The hydraulic connectivity between different strata may accelerate subsidence.

iv. Different subsidence bowls are expected if vertical or horizontal well configurations are used for gas extraction. The magnitude of the induced-subsidence may not be compared easily, as different volumes of coal and different gas production rates are involved in each case.

v. It is expected that multiple wells will enhance and complicate the subsidence bowl in both cases. The overlapping of the subsidence bowls will depend on the separation length between wells but also on the effectiveness of the stimulation and extraction processes.

vi. Permeability is a key factor controlling the performance of the well, irrespective of the extraction method. Changes in permeability caused by the stimulation process will affect the compressibility of the coal seam and thus the amount of subsidence. These changes should be carefully estimated before starting the gas extraction.

vii. Many of the coupled multi-physical processes involved in CSG extraction are not completely understood. Further research is needed to answer unsolved questions. Of particular interest is the determination of the transport properties and their effects on the mechanical behaviour of the coal. A detailed characterization of the cleat system will give clues for the improvements of permeability models and their influence on the coal compressibility which drives the compaction process.

viii. Detailed monitoring throughout the entire profile is crucial for a better understanding of the subsidence phenomenon in CSG extraction. Mitigation techniques developed for each particular case (e.g., water or CO_2 injection) should be updated according to the monitoring data. Further research is also required in this field. Monitoring is also required for updating and improving models of subsidence, which will help to develop a solid framework for the production of CSG in Australia.

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