Code of Practice

Upstream Polyethylene Gathering Networks – CSG Industry

Companion Paper CP-04-004

Mine Subsidence

Revision 0
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Contents

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Preface

Companion Papers have been developed by the Working Group responsible for the *APGA Code of Practice for Upstream PE Gathering Networks – CSG Industry* (the Code) as a means to document technical information, procedures and guidelines for good industry practice in the CSG industry.

Since 2008 the development of the LNG export industry based in Gladstone, Queensland, with its related requirement for a large upstream CSG supply network of pipelines and related facilities presented the impetus for significant improvements in design and best practice approach.

The principal motivation for the initial development of the APGA Code of Practice was safety and standardisation in design and procedures, and to provide guidance to ensure that (ALARP) risk-based requirements were available to the whole CSG industry. Accordingly, the Code is focused solely on this industry and the gathering networks using locally-manufactured PE100 pipeline. The Code is a statutory document within Queensland.

The incorporation of Companion Papers in the Code is intended to provide information and best practice guidelines to the Industry, allowing the Code to be limited to mandating essential safety, design, construction and operation philosophies and practices.

These documents form part of the suite of documents together with the Code and are intended to be:

1. Used in the design, construction and operation of Upstream PE Gathering Networks;
2. Provide an authoritative source of important principles and practical guidelines for use by responsible and competent persons or organisations.

These documents should be read in conjunction with the requirements of the Code to ensure sound principles and practices are followed.

These documents do not supersede or take precedence over any of the requirements of the Code.

A key role of the Companion Papers is to provide the flexibility to incorporate endorsed industry practices and emerging technologies expeditiously, as/when necessary.

A related benefit is that the Companion Papers can be referenced by the wider resources industry which uses similar PE gathering networks for gas or water handling, including coal bed methane (CBM) in underground coal mines; mine de-watering; or the emerging biogas industries (agricultural, landfill, etc.).

1. Scope

The scope of this Companion Paper is to present measurement, engineering stress review analysis tools and construction techniques to minimize the impact of mine subsidence due to the underground mining of coal directly beneath or adjacent to HDPE infrastructure.

This Companion Paper was introduced to coincide with the release of V6 of the Code, due to increasing instances of underground long wall mining of coal affecting CSG infrastructure.

2. Introduction

2.1 Introduction to Underground Coal Mining

Underground coal mining in Australia mainly occurs in New South Wales and Queensland. In NSW the main coal seams are deepest beneath Sydney and are closer to the surface in the Hunter, Newcastle, Southern and Western Coalfields, where the coal can be extracted at relatively shallow depths.

In Queensland, the main coal seams are typically located in Central Queensland regions, with the active mining within the Bowen Basin around the townships of Moranbah, Emerald and Blackwater. Mining also occurs in the Clarence-Morton and Surat Basins in the south-east and emerging in the Galilee Basin to the west of the Bowen Basin.

There are many ways in which coal is mined underground. The methods depend on the nature, depth and extent of the coal deposit which is to be mined.

There are many underground mining activities that do not result in subsidence because the roof of the underground space is supported to prevent it from collapsing. Some of the oldest methods of mining were conducted in this manner.

One of the drawbacks of mining with roof supports is that a large proportion of the resource must be left behind. However, through advancements in mining technology, it is now possible to safely extract a large proportion of the resource without leaving behind permanent roof supports. Once the roof is allowed to collapse, subsidence may occur at the surface.

In longwall mining, a rectangular panel of coal is totally removed by longwall shearing machinery, which travels back and forth across the coalface. The roof at the coal face is supported by a series of hydraulic roof supports, which temporarily hold up the roof strata, and provide a secure working space at the coal face.

After each slice of coal is removed, the longwall steps forward and the rocks immediately above the coal seam fall behind it to fill the void left by the extraction of the coal. The mechanism progresses upwards through the layers of rock as they fall or sag into the void, resulting in subsidence at the surface.

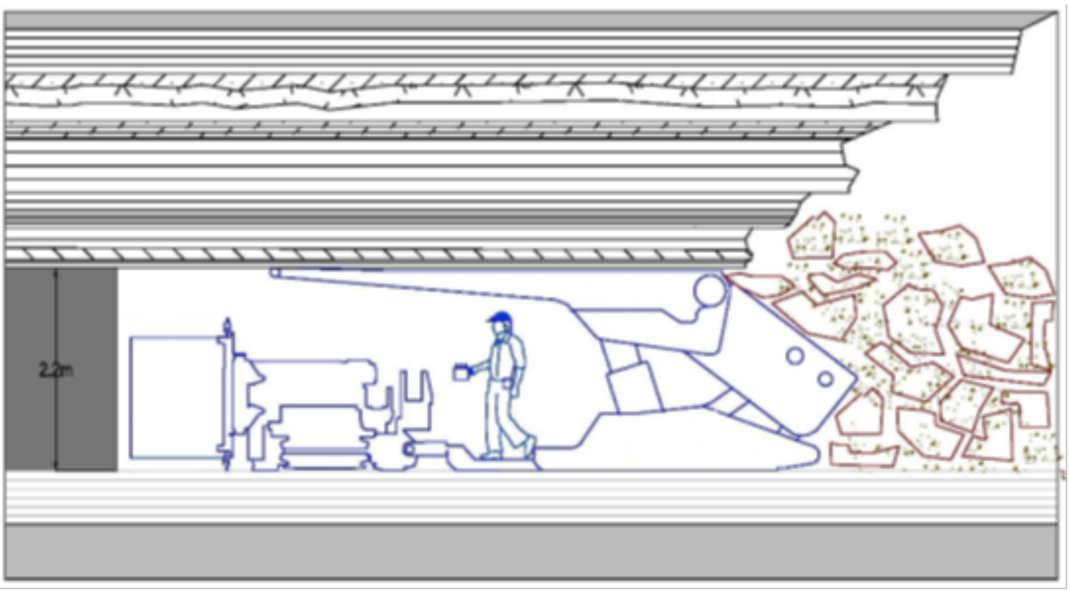

Figure 2.1 - Cross-section showing a typical longwall at the coal face

Longwall coal mining typically occurs at depths from about 50 metres to 700 metres below the surface. The longwall panels are typically 200 metres to 400 metres wide and 1 to 2 kilometres long, extracting from coal seams that are typically between 2 and 4 metres thick, though some mining techniques can extract coal up to 12 metres in thickness. Underground mining can also occur in multiple coal seams beneath the surface.

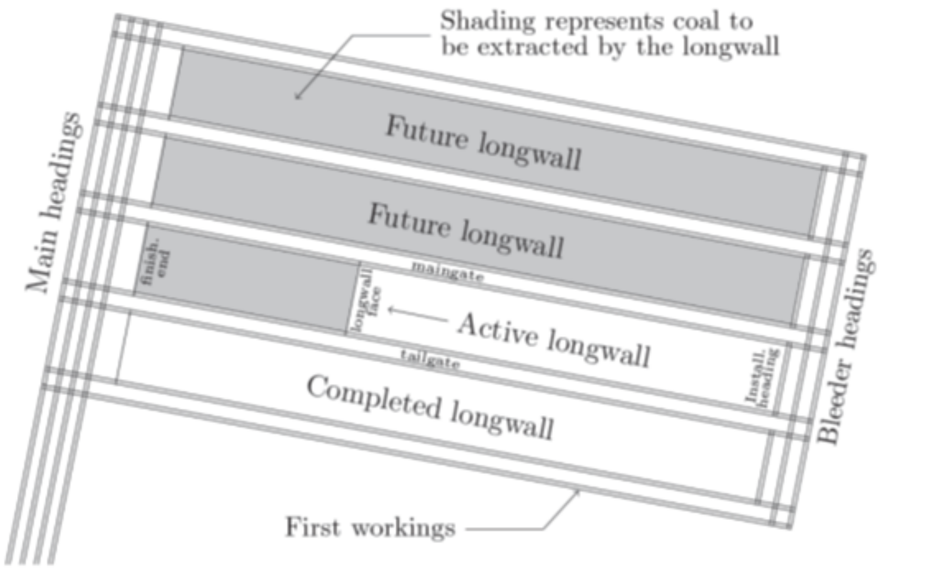

Figure 2.2 - Plan view of typical longwall mine layout

At the surface, the ground subsides vertically as well as moves horizontally towards the centre of the mined goaf area. The maximum subsidence at the surface varies, depending on a number of factors including longwall geometry, depth of cover, extracted seam thickness and overburden geology. The maximum subsidence in single-seam longwall operations in Queensland is generally 65-75 % of the extracted seam thickness.

3. What is Mine Subsidence

3.1. Overview of mine subsidence

Mine subsidence refers to any surface ground movements associated with underground mining. The term “subsidence” can also often refer to a vertical movement at a particular point.

The amount of subsidence varies across the area mined beneath, with greatest subsidence occurring towards the centre of the mined area, and gradually reducing to outside the mined area.

The extent of the subsided area is greater than the extent of the extracted area. As a general guide, the limit of subsidence is typically a distance outside the edge of the extracted area equal to half the depth of cover from the surface to the coal seam. For example, if the depth of cover to the mining horizon is 500 metres, the limit of subsidence would be located approximately 250 metres from the edge of the mined area in plan. At the limit of subsidence, the level of subsidence is generally less than 20 mm. Vertical movements less than 20 mm occur naturally as a result of ground heave and shrinkage caused by changes in moisture content.

Subsidence by itself rarely results in impacts on the surface. If subsidence occurred uniformly across an area, it is unlikely that any impacts would be noticed. However, subsidence does not occur uniformly across an area. Differential subsidence can result in tilting and bending of the ground beneath surface features, and it is these differential movements that can result in mine subsidence related impacts.

Mine subsidence also results in horizontal movements. As a general guide, the rocks above the mined area move into the mined void, both vertically and horizontally. The amount of horizontal movement at each point on the surface varies across the area. Differential horizontal movement results in ground strain. Tensile strains most often occur where hogging curvature develops. Compressive strains most often occur where sagging curvature occurs.

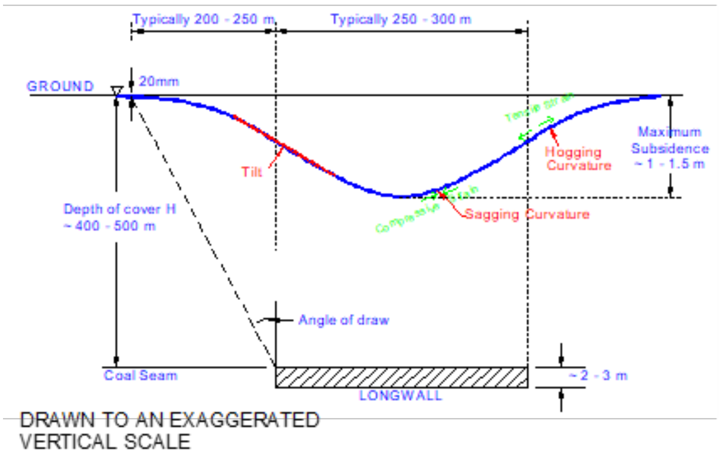

Figure 3.1 – typical Subsidence Profile

The incremental subsidence, tilts, curvatures and strains are the additional parameters which result from the extraction of each longwall. The cumulative or total subsidence, tilts, curvatures and strains are the accumulated parameters which result from the extraction of a series of longwalls.

During the extraction of each longwall, a subsidence wave travels along the surface, following the longwall face as it travels from its starting position at one end of each panel and finishing at the other end. Surface features above the longwall panel will, therefore, experience transient tilts, curvatures and strains as the travelling subsidence wave passes through the site before reaching its final subsided position. Longwalls typically travel between 30 and 150 metres per week depending on underground mining conditions.

4. Techniques to measure

4.1 Predicting mine subsidence

Whilst the prediction of subsidence is not an exact science, mining companies engage specialist mine subsidence engineering consultants to predict mine subsidence movements.

Subsidence has been measured extensively across NSW and Queensland. These observations provide a large database of information that has been used to develop many methods for predicting subsidence.

The simplest methods provide an estimate of the extent of the surface area that might experience subsidence and a prediction of the maximum subsidence that might develop. More advanced methods are able to provide robust predictions of vertical subsidence, tilt, curvature and ground strain at any point within the subsided area and at any stage of mining. The predicted movements can be provided in a manner that allows pipeline engineers to input displacements into numerical model for the purposes of conducting impact assessments.

The large database of information can also be used to provide probabilities of exceeding subsidence parameters (e.g. compressive or tensile ground strain).

4.2 Monitoring for mine subsidence

Mine subsidence is traditionally monitored by placing rows of survey pegs on the surface. The pegs are then surveyed before, during and after mining. The extent, timing and frequency of monitoring is typically advised by specialist mine subsidence engineering consultants in consultation with pipeline engineers.

The surveys are typically surveyed in either 3D (easting, northing and height), or 2D (height and horizontal distances between adjacent survey pegs). There are a variety of alternative methods for conducting surveys. The choice of appropriate survey method is influenced by survey accuracy required. Cheaper surveying methods are typically less accurate and can provide information that may provide information that is too blunt for assessing potential impacts on pipeline infrastructure.

Recent advances in (Global Navigation Satellite System (GNSS) technology have introduced cost effective continuous monitoring of position of a point or points on the surface.

Structural condition monitoring equipment can also be used to monitor changes in condition of surface infrastructure. These include tiltmeters, strain gauges and displacement sensors.

4.3 Managing potential mine subsidence on PE pipelines

In most cases, subsidence and its impacts on PE pipelines can be managed. Subsidence predictions and impacts assessments, as discussed in this paper, provide a sound reference point.

Impact estimates and contingencies are usually developed in case subsidence predictions are exceeded. Mining companies consult with stakeholders to identify and assess the risks of subsidence impacts. Mitigation measures and monitoring systems are used to manage these risks.

A subsidence management plan is typically developed to describe the measures that are planned to be implemented to ensure that pipelines remain safe and serviceable during and after mining. The plan is typically developed by a technical team of specialists that have been assembled by either the mining company, the pipeline operator, or both. This Companion Paper provides a guide that can be used by pipeline engineers when conducting their role within the overall subsidence management strategy.

5. Construction Considerations

5.1. Pipeline Alignment

Consideration should be given to aligning pipeline sections to reduce the impact of subsidence upon the pipeline. This could be achieved by aligning the pipeline outside or towards the outside of the zone of expected subsidence and/or parallel to the direction of the longwall panels.

If crossing of subsidence areas cannot be avoided, consideration should be given to allowing lineal expansion such as but not limited to, zig-zagging the pipeline across these areas to reduce the maximum pipe stress at any one point.

5.2 Burial

For buried pipelines that are to be mined underneath, one method that can be employed to reduce pipe stresses is to excavate the material above and around the pipe before subsidence occurs. This allows pipe strain to be more evenly distributed over the excavated zone, thereby reducing the risk of overstressing the pipe at any one point. This also improves the effectiveness of any additional pipeline monitoring efforts being employed. It is recommended that this practice be employed for any known electrofusion joints, tapping saddles, risers and offtake tees on buried pipelines within the subsidence zone.

For new pipelines that are typically buried, consideration should be given to installing these pipelines above-ground or shallow buried with appropriate physical controls, in the peak subsidence zones.

5.3 Jointing Methods

For buried pipelines in areas where subsidence is expected, electrofusion joints, tapping saddles, risers and offtake tees should be avoided as much as possible, as these have been found to be more susceptible to leakage in subsidence conditions.

In general, the number of pipe joints within subsidence zones should be minimised as much as possible.

5.4 Pipeline SDR

Where stress review techniques indicate that the chosen pipe SDR may be overstressed from the expected subsidence, consideration should be given to increasing the pipe SDR to reduce the risk of overstress.

6. HDPE ANALYSIS AND LIFE ASSESSMENT

6.1 PE Pipes Structural and Life Consideration in Mine Subsidence Area

The structural performance of buried PE pipes is to ensure pressure containment is maintained during the pipe design life. The standard dimension ratio and the minimum required strength with the appropriate design factors are used to calculate the hoop stress so the pipe would not fail under the design operating pressure and temperature for the given design life. This approach is adequate if the pipeline is not subject to other actions such as bending and longitudinal strains.

In a mine subsidence region, the ground movement can cause a buried pipeline to experience additional longitudinal and potentially, hoop stress due to ground movement. Due to the buried pipe being constrained by the soil, when the ground subsides, the pipeline will follow the deformation profile of the ground although there could be some slippage between the pipe and the trench fill depending on the depth of cover and the nature of the fill material. The pipe stress due to the mining-induced ground movement should be determined.

It can be estimated by applying structural mechanics principles by assuming the pipe deforms with the ground without slippage, or by using suitable numerical analysis methods that accounts for soil-pipe interaction and time dependent material behaviour of the polyethylene. The former approach can provide a first-pass assessment of the pipeline subject to mine subsidence.

6.2 Pipe stress – von Mises stress

When a longitudinal stress is induced by the combined action of bending and stretching/compression, a complex stress state will result in the affected section of the pipeline. The appropriate stress parameter for assessment should be the combined stress (i.e. von Mises stress) which accounts for hoop, longitudinal and radial stress components. In determining the stress state of the pipe when subjected subsidence, the following stress components should be considered:

- Hoop stress caused by internal pressure
- Hoop stress caused by ring action due to dead and live loads although this may not be significant unless the depth of cover is very large and/or a high live load is applied
- Longitudinal tension caused by the Poisson's effect in a buried pipe
- Longitudinal stress by thermal effect. When the operating temperature is higher than the reference temperature, a compressive longitudinal stress will result
- Longitudinal bending stress caused by ground sagging or hogging. Tensile and compressive stresses will be induced by the radius of curvature of the ground deformation
- Longitudinal stress caused by tensile and compressive ground strains. It is conservative to assume no pipe slippage in the soil. Compressive ground strain will normally result in a high longitudinal pipe stress and thus a high von Mises stress.
- Radial stress predominantly caused by internal pressure. The soil load may also contribute to the radial stress if the depth of cover is high

By considering the total longitudinal stress, s_L, hoop stress, s_h, and radial stress, s_r, and assuming they are the principal stress components, the von Mises stress can be calculated by:

$s_{vm} = \sqrt{1/2\,[(s_h - s_L)^2 + (s_L - s_r)^2 + (s_r - s_h)^2]}$ Equation 1

6.3 Pipe stiffness

The PE100 material apparent stiffness reduces rapidly when it was first manufactured. It then decreases slowly after about 5 to 10 years. The appropriate short-term stiffness should be used for calculating pipe stress when the pipe is subject to sudden or gradual perturbation such as mine subsidence that can occur within weeks of the longwall face passing under the pipeline.

6.4 Equivalent von Mises strength

Normally the minimum required strength (MRS) together with the design factor (C) is used to assess against the design hoop stress. When the pipeline is subject to deformation, an equivalent von Mises strength should be used for the assessment of the peak von Mises stress calculated in Equation 1.

The equivalent von Mises strength can be derived from the MRS. Note that how the time to failure testing of the pipe (ISO 9080:2012) was carried out must be considered. Type A (i.e., with end thrust) used for determination of long-term hydrostatic strength (ISO 1167-1:2006) will induce longitudinal stress in the pipe in addition to the hoop stress in the laboratory test. Therefore, the equivalent von Mises strength must include the longitudinal stress component in the back-calculation. The equivalent von Mises strength with end cap is about 13% less than the one without end cap. Note that without the end cap, the equivalent von Mises strength is the same as the MRS. Using logarithmic interpolation, it is possible to obtain the equivalent von Mises strength for different temperature and time to failure. The operating temperature factor, f_1, can also be applied for this purpose. The pipe stress assessment can be performed by:

Design von Mises stress $\leq$ Equivalent von Mises strength/C   Equation 2
where $C = f_0\ f_1\ f_2\ f_3$

6.5 Mitigations

If the design von Mises stress exceeds the equivalent von Mises strength, then mitigation measures should be considered to reduce the pipe stress to within the acceptable limit such that it can continue to operate to its design life post-mining.

Mitigation measures may involve:

- Reducing the internal pressure – this is by far the most cost-effect measure if it can be done
- Reducing the depth of cover to reduce the longitudinal restraint
- Exposing the pipe in a trench to decouple the pipe from the ground movement
- Exposing the pipe in a trench with adjustable supports to keep the pipe in its undeformed configuration while the surround ground subsides. The pipe can be reburied once the subsidence has ceased.

Besides the pressure reduction measure, the above-mentioned mitigations can be costly and potentially causing operational/business disruption. Exposing the pipe will also be subjected to other environmental risk factors.

The pressure reduction strategy will reduce the pipe stress while subsidence occurs. Depending on the pipe deformation once the ground has stablised post-mining, the internal pressure can return to a higher pressure or back to the design pressure and temperature. However, the remaining life could be shortened due to the occurrence of high pipe stress in the deformed pipe. A life assessment should be performed to determine which mitigation measures to adopt.

6.6 Life Assessment

The peak von Mises stress of the pipe at various times can be used to estimate the life used or consumed. This approach is like the Miner's rule (Miner, 1945) in estimating fatigue life for a metal. This methodology has been provided in ISO 13760:1998, however, it considers hoop stress only.

It is possible to use von Mises stress and strength to estimate the life consumed. The equation below is one suggested method:

$$T_{consumed} = \sum_{i=1}^{k} \frac{T(\sigma_{vm},\theta)_i}{T_{all}(\sigma_{vm},\theta)_i} \qquad \text{Equation 3}$$

where $T_{consumed}$ = the proportion of the life consumed over the total life

$T(s_{vm}, \theta)$ = the duration at which the pipe experiences the von Mises stress, s_{vm} at temperature, θ

$T_{all}(s_{vm}, \theta$ = the allowable duration at s_{vm} and temperature, θ

and k = the different stages of s_{vm}, and θ the pipe is under.

The life consumed prior to mine subsidence is estimated based on the internal pressure and temperature experienced by the pipe during this period. When the ground subsides due to coal extraction, lower internal pressure and temperature can be used and the corresponding von Mises stress can be estimated.

Post-mining, the final ground strain and the operating pressure and temperature can be used to estimate the von Mises stress. Equation 3 can be used to estimate the life consumed in the above stages and the remaining design life can be determined to check if it is acceptable. Different scenarios can be examined until a suitable mitigation is found.

6.7 Uncertainties – long-term material performance

Currently there is insufficient published information regarding how creep and stress relaxation could affect the performance of a deformed PE pipeline. Anecdotal evidence suggested there would be a reduction of stress in the pipe material with time. However, there is no guidance on how the stress components would behave quantitively in the long-term especially when the pipeline has been held in the deformed configuration in the ground post-mining. Engineering judgement could be made considering the material stiffness when determining the stress components in the pipe.

Further laboratory tests may be required to provide quantitative guidance on this subject.

7 REFERENCES

ISO 1167-1:2006 Thermoplastics pipes, fittings and assemblies for the conveyance of fluids – Determination of the resistance to internal pressure – Part 1: General method.

ISO 13760:1998 Plastic pipes for the conveyance of fluids under pressure – Miner's rule – Calculation method for cumulative damage.

ISO 9080:2012 Plastic piping and ducting systems – Determination of the long-term hydrostatic strength of thermoplastics materials in pipe form by extrapolation.

Miner M.A. 1945 Cumulative damage in fatigue. Journal of Applied Mechanics 12: 149-164.