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A meta-analysis of coal mining induced subsidence data and implications for their use in the carbon industry

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ABSTRACT

Many emprical subsidence estimation tools exist worldwide but are designed and calibrated for specific coalfields. This paper presents an universal tool for the estimation of maximum subsidence (S_{Max}). The subsidence tool is based on pooling and meta-analysis of empirical data from a number of different countries and coalfields. The key factors influencing S_{Max} are the void dimensions and the mechanical competency of the overburden. These factors are used to estimate subsidence using the empirical equation $S_{Max} = [c/(1 + 10^\wedge(-a((W/D) - b)))] *m$, where W is the width of the void, D the depth, m the effective void thickness, and a, b, c are parameters related to the mechanical competency of the overburden. This universial empirical method was validated against historical data from United Kingdom and Australia. The method also provided S_{Max} estimations for underground coal gasification (UCG) projects, that were inline with those from numerical modelling under certain conditions. This tool would likely be most useful when investigating areas, where there are little or no historical data of subsidence and mining. Such areas are most likely to be targeted by UCG schemes.

1. Introduction

1.1. The challenge of subsidence

Areas with a legacy of coal mining are very familiar with the damaging effects of surface subsidence. Subsidence can cause damage to utilities (e.g. Holla, 1988), structures, water bodies (Booth, 2002a, 2002b, and Dumpleton, 2002), and agricultural land (Darmody et al., 1989). Surface subsidence is caused by the eventual collapse of the roof strata over a mined volume (Fig. 1); filling the mined area with caollapsed material. The beds overlying the collapse flex resulting in a zone of net extension where the beds sag and crack. Higher, there is a zone of net compression (colloquially referred to as the pressure arch), which is typically overlain by another zone of net extension towards the surface (Booth, 2002a, 2002b and Dumpleton, 2002).

Increasing sophistication in the planning and execution of coal mining post second world war resulted in the development of empirical methods to predict (e.g. Marr, 1957) and mitigate the effects of subsidence (Marr, 1965 and Orchard, 1964). The national coal board of the UK (NCB, 1975) is the earliest attempt at a standard prediction method for a specific coal region. NCB (1975) was later followed by empirical methods in Australia (Holla, 1987 and Holla and Barclay, 2000), USA (Dunrud, 1984), India (Saxena et al., 1989), and many other locations. These empirical methods were possible in areas with a history of extensive mining providing sufficient data from which to create robust correlations between mining parameters and the resulting subsidence; and were thus location specific. For example, the UK techniques were applied directly to Australia but often overestimated subsidence (Holla and Barclay, 2000), due to higher mechanical competency of the overburden of Australian coal mines compared to British.

Although developed large economies, such as U.S.A. and China, are increasingly meeting their energy needs from natural gas and renewables rather than coal (Ren et al., 2015), demand for coal and hence coal mining remains resilient. Beyond conventional coal mining, underground coal gasification (UCG) has long been suggested as an answer to safety issues (Liu et al., 2015), how to access unmineable stranded assets, and as a way to directly couple coal exploitation with carbon capture (Younger, 2011). The process of UCG leaves voids underground of similar expanse as shortwall mining, resulting in surface subsidence (Derbin et al., 2015). Potash mining can also result in voids of similar scale to coal mining, i.e. tens of metres wide and hundreds of metres long (Chrzanowski et al., 1997). The UCG and potash examples demonstrate that even if conventional mining declines in the future, the is continued need to better characterise and de-risk estimation of surface subsidence.

The ratio between the width and depth (W:D) of a void left after the coal had been extracted, called a panel, is used as a key parameter for predicting maximum subsidence in many empirical prediction tools,

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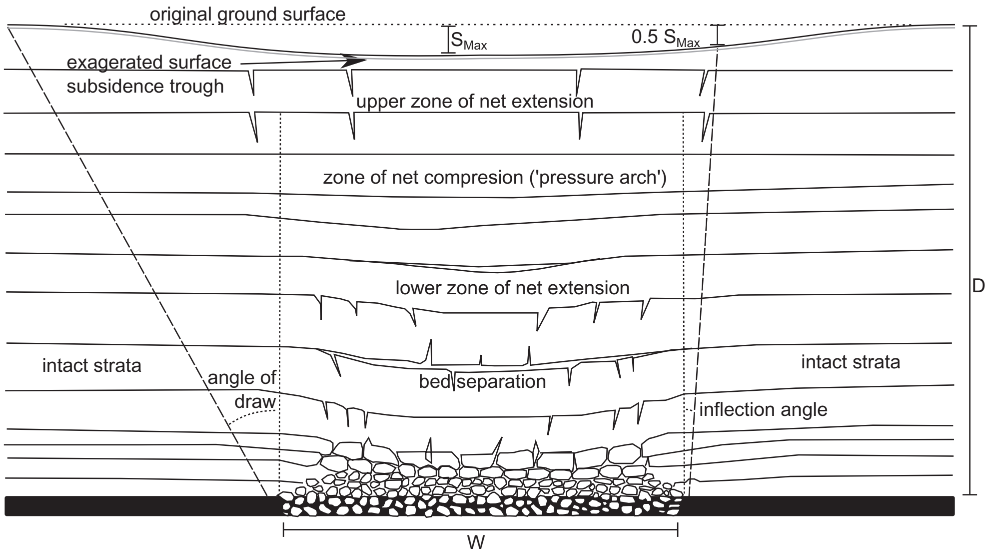

Fig. 1. Schematic cross-section showing the impacts of void collapse around a gasification borehole, forming goaf and overlying zones of extensional and compressional deformation. The angle of draw delimits the outer edge of the zone of strata deformation and the inflection angle the locations of half maximum subsidence on the surface. Figure edited after Younger, 2011. S_{Max} is defined as the point of maximum surface subsidence, *W* as the width of the excavated zone, D as the depth of the excavated zone.

including the UK (NCB, 1975), Australia (Holla, 1987 and Holla and Barclay, 2000), and U.S.A. (Karmis et al., 1984). These empirical methods converged on a sigmoidal relationship between maximum subsidence and *W:D*, which were presented graphically by NCB (1975) and Holla and Barclay (2000). Alternativaly Karmis et al. (1987) presented an upper bound of maximum subsidence with the following equation.

$$S_{Max} = [0.61 - (0.05/(W/h - 0.07))]*m \qquad 1$$

These sigmoidal relationships offer the conceptual model, that below *W:D* of 0.5 there is initially little increase in subsidence associated with wider panel. Then as *W:D* ratio increases there is a significant increase in subsidence (usually between 0.5 and 1.0 but varies by coal basin or region), these *W:D* ratios are know as sub-critical extraction widths. With increasing width, there comes a point where subsidence maxes out and no longer increases, known as the critical extraction width and typically found in *W:D* values of 1.5 to 2.0. Increases in *W:D* ratio beyond the critical width (known as supercritical extraction) does not results in higher magnitudes of subsidence. The magnitude of subsidence at this critical width varies significantly between coal basins, resulting in an S_{Max} of 90% of extraction thickness in the UK compared with only around 60% in Australia.

Numerical modelling of coal mining related subsidence had used a variety of different approaches, such as elastic or rigid block (O'Connor and Dowding, 1990; Choi and Coulthard, 1990). As computational power and experience progressed numerical models showed good agreement with empirical data and models (Coulthard, 1995; Alejano et al., 1999) but with specific limitations for each approach. Numerical modelling supports risk assessment for site specific issues such as effects of faults (Otto et al., 2016). However numerical models can be time consuming to set up and require sufficient data to properly calibrate material properties. The advantage of empirical models remains in initial characterisation and subsidence risk assessment, as they are able to quickly and simply provide subsidence estimates. Influence function methods can offer prediction of subsidence curves and zone of influence on the surface (Karmis et al., 1990) and can be tuned to site specific conditions (Ren et al., 2010). Probability-integral method has been used for mining subsidence estimations (Jianjun et al., 2012; Zhang et al., 2009). But the influence function methods require known subsidence data such as S_{Max} to create the subsidence influence profiles (Karmis et al., 1990), and probability-integral methods are also dependent on reliability of input parameters (Zhang et al., 2009). In the U.S.A., Karmis et al., 1987 proposed using a factor realted to the competency of the overburden, to allow tuning of empirical predictions to different coal basins. However, despite the wealth of data available on a global basis, such methods have maily been used for subsidence prediction at the region they were developed. A subsidence prediction method that can be applied without dependence on the region of interest, would be of particular importance for potential future coal exploitation techniques, such as underground coal gasification, where lack of experience means there is not sufficient data for any area, around which an empirical subsidence method could be based.

Here, we investigate the development and formation of a universal empirical subsidence (S_{Max}) prediction model based on the collection of representative regional data across the world and using a novel analytical approach. In particular, a meta-analytical approach is used for the initial treatment of the collected data, followed by a statistical optimal fitting approach to extract useful trends between the interconnected parameters and allow for quantification of the subsidence predictions.

2. Methods and results

2.1. Data pooling and meta-analysis

Meta-analysis techniques have been used to compare collated subsidence studies and data, such techniques were originally developed and widely used in fields such as medical research and social science (Schmidt and Hunter, 2014). In these disciplines, meta analysis techniques systematic protocols to compare tens to hundreds of studies and data, e.g. Biondi-Zoccai et al. (2006) began by investigating 612 studies but eventually usedjust of these six for use in a meta-analysis investigating the effect of aspirin use for risk of coronary artery disease. Another need was for systematic merging of studies with thousands of data, e.g. Bischoff-Ferrari et al. (2005) investigating 19,114 data on bone fracture prevention with vitamin D supplement. In the geosciences, attempts at meta-analysis have been rarely employed but for some issues such as salt marshes (Shepard et al., 2011) and soil carbon storage (Guo and Gifford, 2002) or high level comparisons of life cycle analysis of carbon capture and storage (Schreiber et al., 2012).

To implement this method, an extended literature search for regional subsidence data, with a wide geographical span, has been conducted. 59 publications were identified which could have data, of which 23 publications contained some subsidence data (these publications are listed in supporting material). Publications were not used if they did not contain the raw data which would be required for further analysis. Orchard and Allen (1970), and Aynsley and Hewitt (1961), and Orchard (1964) presented tables from which data were extracted,