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Numerical modelling of shallow abandoned mine working subsidence affecting transport infrastructure

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ABSTRACT

This work presents details of a shallow mining subsidence event that occurred in the summer of 2001 causing the formation of crown-holes at the surface which affected the East Coast Main Railway line in the UK. This subsidence event caused significant disruption and the remediation effort required the construction of a 1.8 km long diversion built on a piled, reinforced concrete raft. Details of the ground investigation are summarised along with a large parametric numerical modelling study undertaken in FLAC 3D into the potential causes of the instability, including the role of variations of the level of the groundwater table, the influence of the structure of the rock mass and also the potential geometry of the abandoned workings. Ultimately the modelling allowed constraints to be placed on the likely excavation width of the workings at the site along with bedding spacing and strength of the overlying rock mass. The modelling also suggests that the increase in the ground water table may also have been a factor in the occurrence of instability on the site.

1. Introduction

Coal mining has played a significant role in shaping the economic development of the United Kingdom (UK), most significantly during the industrial revolution. Although vital to the economic development of the UK in the past, there are negative impacts of mining and of concern is the threat to safety posed by the collapse of subsurface voids. As such the legacy of past mining is an increasingly important issue, where the threat of mining subsidence is recognised to be of concern not just in the UK but globally (Bell, 1992; Jones et al., 2005).

Mining began on a significant scale in the UK in the 13th century (Bell and De Bruyn, 1999). By the 15th and 16th centuries the pillar and stall method of extraction became common (Bell and De Bruyn, 1999; Healy and Head, 2002). In this process, a mineral is extracted, commonly in a regular pattern, while pillars of the mineral deposit (in this case coal) are left in place to support the roof of the mine (Attewell and Taylor, 1984). Pillar and stall mining has largely been replaced in the UK by longwall mining where the roof of the workings is allowed to collapse in a controlled manner as mining progresses. As such any subsidence due to pillar and stall workings within the UK is likely to be associated with mine workings abandoned over a century ago (Attewell and Taylor, 1984; Waltham, 1989). Due to the large number of abandoned mine workings in the UK (with estimates as high as 70,000 (Deb and Choi, 2006)) where the structural integrity/stability of the workings is unknown it is clear that these pose a significant engineering and safety issue.

Best practice in assessing the subsidence hazard posed by shallow mine workings is currently based on the empirical evidence available from previous failures (Bell, 1975; Attewell and Taylor, 1984; Waltham, 1989; Whittaker and Reddish, 1989; Healy and Head, 2002). These may be useful tools where data is limited, but do not easily provide a rigorous assessment of collapse hazards at a particular site. Where increased site investigation data is available it is possible to undertake more detailed analysis and, as demonstrated in this work, this can better constrain the hazard posed by abandoned workings. In this paper an example of shallow abandoned mining subsidence that had a significant impact on transport infrastructure in Scotland, is investigated through a numerical modelling study in order to better understand the causal mechanisms and significant factors in this event. The findings of this work are used to inform wider applicability to practising engineers when considering the stability of shallow abandoned mine workings, and the modelling, monitoring and site investigation of such phenomena, and in identifying the key factors and triggers of void migration, subsidence and collapse.

2. Shallow abandoned colliery working subsidence

The typical geometry of Scottish pillar and stall (or stoop and room) workings can be seen in Fig. 1 where the stoops (coal pillars) supporting the roof are square in plan and the rooms are of a regular repeating pattern (Healy and Head, 2002).

There are three main mechanisms of deterioration and collapse of abandoned mine workings (floor heave, pillar crushing and roof collapse) and of these, roof collapse due to the disintegration and deformation of roof strata is the primary closure mechanism in shallow

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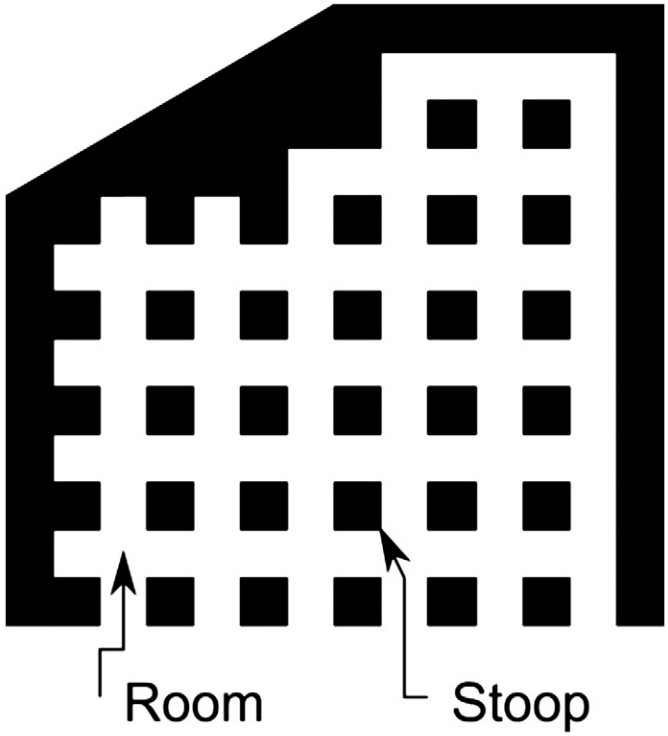

Fig. 1. Typical geometry of Scottish pillar and stall/stoop and room workings.

workings, and is considered the greatest problem in subsidence engineering practice (Healy and Head, 2002).

In order for void migration to occur, the roof of the workings must fail. Prior to the formation of any cavity, the stresses in the earth will reach an equilibrium state. Formation of a void causes the overburden load to be taken by the pillars causing tensile stresses to develop in the immediate roof, and compressive stresses to build at the upper corners of the workings (Attewell and Taylor, 1984; Twiss and Moores, 1992; Dyne, 1998). This can cause the overlying strata to become fractured. This fractured material may be made stable by the confining stress; however any disturbance in the *in-situ* stress at this point can then lead to further roof failure (Thigpen, 1984). It is the potential changes in these conditions that led to a disturbance in the initially stable excavations at Dolphingstone that are investigated herein.

Typically once void migration/roof failure has commenced it will continue unless arrested by natural arching, choking of the void by collapse debris or encountering a high strength layer capable of spanning the void (Bell, 1992).

The geometry of the failure is controlled by the presence and orientation of joints in the rock mass, particularly bedding spacing and the presence of sub-horizontal steeply dipping joints. If steeply dipping joints are present with an unfavourable orientation, then roof failure may occur by shearing along these discontinuity surfaces (see Whittles et al., 2007 for a summary of differing roof failure mechanisms). In situations where steeply dipping discontinuities are not present then the failure mechanism is dominated by snap through or buckling failure and occurs because as a roof layer fails, it flexes downwards due to yielding (the degree of actual deformation is dependent on the thickness and stiffness properties of the roof beam). This leads to the development of cracks at the point where the roof strata meets the pillar (Goodman, 1989). Fractures also develop at the roof centreline on the base of the layer forming the roof. The initial yielding and sagging of the strata can be seen in Fig. 2 and due to the nature of the stress field at the ends of the roof layers, these cracks propagate diagonally away from the pillars into the strata above the excavation (Goodman, 1989). Ultimate collapse of a roof beam leaves a pair of cantilevers as abutments for the overlying roof strata, effectively reducing the span of the excavation. This progression can be seen in Fig. 3.

Continued failure and roof collapse will naturally lead to a stable, conical void assuming sufficient height to rock head (Goodman, 1989) and that choking by bulking of collapse debris or bridging of the void by high strength strata in the overlying rock mass do not occur. Where there is insufficient height to rock head (normally considered to be cases where the rock mass overlying the void is less than 30 m thick or 10 times the worked seam thickness) and where neither bridging or bulking occur then the void may migrate to surface forming a crown-hole. This mode of failure has been observed in the field (Healy and Head, 2002) and has also been successfully demonstrated in laboratory physical modelling (Bieniawski, 1984).

3. Subsidence at Dolphingstone

During May and June 2001 a pair of crown-holes of approximate diameter 1.5–2 m were found adjacent to the East Coast Main Line (ECML) track at a site near Dolphingstone between Prestonpans station and Wallyford Cutting (Dolphingstone is a village located approximately 4 km East of Edinburgh in East Lothian in Scotland, Ordnance Survey Grid Reference NT 381732). The location can be seen in more detail in Fig. 4.

The presence of these crown-holes prompted the commissioning of a site investigation in order to better understand the causes of the subsidence on site.

During the desk study phase of the site investigation, it was found that historical mining had taken place on or adjacent to the site. The presence of crown-holes and the confirmation of historical mining activity and subsidence at the site, coupled with the risk of further subsidence,

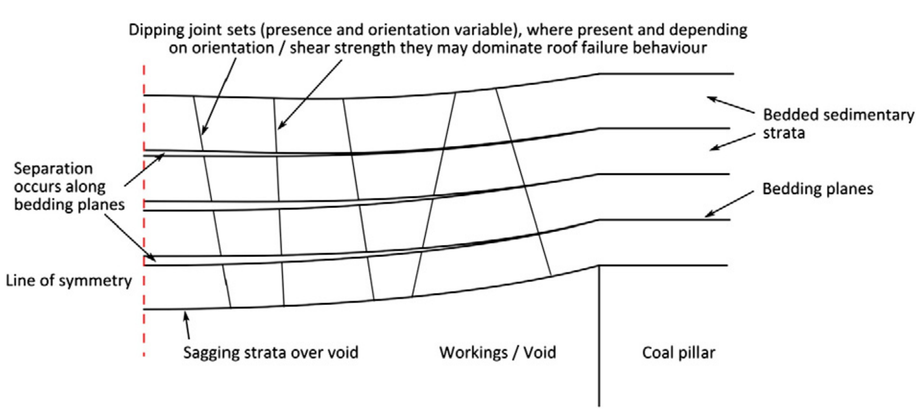

Fig. 2. Yielding of roof strata over an excavation.