Deformation due to mining activities

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Council for Geoscience Report number: 2011-065

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1 Introduction

Mining activities in South Africa over the past 120 years have changed the natural environment in several ways. A legacy of many mining areas in South Africa is not only the abandoned mine infrastructure at the surface, but also near surface mined out areas. Current challenges for mining companies lie in rehabilitating the natural environment and preventing further environmental degradation. One particular area of concern is surface deformation associated with mining activities, particularly mining subsidence. Mining subsidence associated with underground coal mining is, in theory, a gentle, gradual settling of the earth’s surface (Perski & Jura 2003). Underground mining cavities can result in a lowering of the earth’s surface (hereafter referred to as surface subsidence) as a result of the collapse of bedrock and the subsequent sinking of unconsolidated surface sediments (Perski & Jura 2003). Some of the primary effects of the collapse of underground cavities include the appearance of tension cracks and crownhole development. The effects of surface subsidence on the built environment are severe and include damage to infrastructure (roads, dams, pipelines and buildings). The effects of surface subsidence on the natural environment include the alteration of hydrological pathways. The ponding of water in subsidence basins results in an increase in groundwater recharge. The groundwater circulating through mining cavities becomes polluted and discharges into the natural environment contaminating wetlands, streams and dams. Two areas of particular concern were surface subsidence is concerned is the undermined areas of the Witwatersrand goldfields as well as underground coalmining in the Witbank Coalfields.

The Witwatersrand goldfields, situated in Johannesburg, East and West Rand areas of Gauteng, are vulnerable to settlement and surface subsidence basin formation. Here surface subsidence poses a potential risk to the safety of many people as well as the structures in which they work and live. One instance of subsidence basin formation (displayed in Figure 1) even lead to the death of a local woman.
Mining activities in the Witbank Coalfields also lead to surface subsidence due to mining activities. Here the expression of subsidence basins at the surface is depended on varying geological conditions including the lithology of the roof strata, the depth of the coal seam, the height of the coal seam and the mining method used. The subsidence associated with mining in this area poses a threat to infrastructure. Additionally, the alteration of hydrological pathways have been reported.

For the mining companies involved, it is necessary to know where subsidence is occurring, how the ground is moving and how fast subsidence is progressing. With this knowledge, informed decisions on current and future infrastructure development can be made and remedial actions and prevention strategies can be formulated for the problems associated with environmental degradation.

2 Mechanisms of surface subsidence basin formation
Subsidesces at surface in undermined areas is caused by collapse of the subsurface mining void. In some areas, linear type failures, along strike, (which have been caused by the failure of underlying stopes) are present (Figure 2). Hill (1981) stated that, during the 1970’s, collapse into old mine workings had not been ‘uncommon’ in the Witwatersrand, with at least 12 such events having being
recorded. He was of the opinion that this type of collapsing of the backfilled void could continue indefinitely as the underlying support weakens until a metastable is reached. Records of subsidence have often not been kept and as indicated by Bell et al (2000) there is no confidence as to whether, or to what degree, settlement has taken place.

Brink (1983) recognized this type of mine related subsidence in the Central Witwatersrand, which he described as sinkholes (Figure 3). In these cases, material i.e backfill that has been deliberately placed in the near surface outcrop of shallow stopes to seal these voids, is progressively washed downwards by infiltrating surface water. By a process of backward erosion a sinkhole develops at surface. Bell et al, (2000) stated that this form of subsidence can be exacerbated by a) the removal of pillars b) the removal of adjacent reefs c) the deterioration of timber props and waste packs etc. They also reported that, in some cases in the Johannesburg area, the sides of outcropping stopes collapsed into the workings below, leading to large subsidence basins (Figure 4). Where a ‘hole’ has been created at surface, “subsidence” is used here to describe any or all of the above type of features.
3 Location of undermining areas in the Witwatersrand goldfields, Gauteng

The extraction of gold ores on the Witwatersrand goldfields has been carried out more or less continuously since the late 1800's. Initially this took place on a basic level as deposits were extracted by hand from the surface (Figure 5). The extraction of deeper ores however required more sophisticated approaches which resulted in the creation of deep mine openings such as shafts, adits etc.

The duration of mining exploitation was dependent on a number of factors such as the size of the ore body, the unit price of the ore etc. When this equation did not favour the continuation of mining, the activities were stopped and the mine site abandoned. On occasions some of these deposits were revisited as mining techniques improved or the value of the ores increased to make mining more profitable, but generally, at some point in time, these sites were just abandoned, leaving behind diggings and/or mine shafts.

The outcropping reefs were initially exploited at surface and as techniques improved, extraction of deeper reserves was targeted. Available records show that some 43 500t of gold have been produced to
date from the area south of central Johannesburg (Wilson and Annhaeusser, 1998). This has resulted in the development of large, east west striking, tabular underground mining voids that intersect the surface in this area. Openings, such as shafts, raizes, winzes and other excavations were created for the various underground activities associated with mining. As the attention of the various mining houses (Figure 6) turned to deeper mining opportunities, scant thought was given to, nor required, for rehabilitating the disturbance caused by the efforts of the previous mining activities. This resulted in a highly disturbed landscape consisting of dangerous, abandoned mine openings of various sizes, depths and origins. The collapse at surface of the near surface mining void also produced numerous mine related openings.

Figure 5: Early mining operations
The most vulnerable areas for settlement and/or subsidence are the areas where the underground mine workings (stopes) are close to the ground surface. In the Witwatersrand goldfields of the project area such areas are related to the presence of the gold bearing reefs, Figure 7. These reefs stretch almost continuously east-west from the West Rand through southern Johannesburg and up to the East Rand areas of Benoni and Boksburg. The northern most reef, the Main Reef, daylights approximately 100m south of Main Reef road, a major arterial road within the central urban area of Johannesburg. The reefs to the south, namely the Kimberley and Bird Reefs, exist in this region over shorter lengths. On the East Rand and West Rand areas these reefs are covered by younger materials and hence are not present at surface.
An example in these areas where subsidence has taken place due to shallow undermining activities is the old Van Rhyn Mine property in Benoni (East Rand) (Figure 8). These mine openings are located at an average distance of ±300m from factories and an informal settlement. A total of 85 holes have been found (Figure 9).

Most of the openings are generally lenticular in shape (3-15m along the long axis) and tend to dip deeply (60-70°) to the south. The openings are aligned in an east-west direction, which appear to follow the strike of the former gold reef outcrop. The majority of the openings (80%) have a depth of over 15m with some of them reaching >100m. Many of the openings are hidden by tall grass. The underlying rock (quartzite) observed in many of these openings is covered by a thin soil cover. The openings are within 10m of foot paths in the area and hence pose a safety threat to local inhabitants.
4  Surface subsidence associated with coal mining activities

The extent of coal seams in South Africa as well as the location both historical and active opencast and underground mining activities are displayed in Figure 10. In the Witbank coalfields in the Mpumalanga
Province of South Africa, coal mining commenced at the turn of the 20th century. The room and pillar (also called bord and pillar) was the extraction technique of choice in the early days. The room and pillar technique is a system in which mined material is extracted across a horizontal plane while leaving pillars of untouched material to support the overburden. The key to successful room and pillar mining is selecting the optimum pillar size. If the pillars are too small the mine will collapse. If the pillars are too large then significant quantities of valuable materials will be left behind reducing the profitability of the mine. Initially, little or no environmental degradation was associated with the mining activities in the coalfields in the Witbank area. However, a pillar-robbing program in the late 1930’s had a marked effect on the environment. In the pillar robbing stages of mining, the pillars were quartered, leaving four smaller pillars at the corners, meaning that approximately 25% of the original pillar was left in tact (Bell et al. 2001). This increased the stress on the remainder of the pillars, eventually leading to pillar collapse. The primary effects of the pillar robbing programme included surface subsidence (several hundreds of square kilometres in extent), the appearance of tension cracks and crownhole development. Secondary effects included the spontaneous combustion of the remaining coal as well as a negative impact on groundwater resources in the area (Bell et al. 2001). The burning of coal accelerated the weakening of the pillars and the collapse of inter-pillar tensional areas resulted in upward void migration through the overlying strata until the weathered zone is reached. In general, the weathered material has subsided by 2 to 3 metres, but in some cases the material collapsed totally into the old workings, leaving voids 15 to 20 m deep. The resultant crownholes at the surface have diameters between 5 and 10 m (Bell et al. 2001). Both gradual subsidence and sudden collapse are accompanied by surface deformation including fractures, crevices, faults, step folds and slides (Perski & Jura 2003). Both primary and secondary effects of the pillar-robbing programmes are visible today. The photographs below (captured on 9 and 10 September 2008) each portrays the effects of the pillar robbing program including surface subsidence (Figure 11), tension cracks (Figure 12) and sinkhole development (Figure 13). The burning of the remaining coal is represented in Figure 14 where smoke is rising from a tension crack on the surface.
Figure 10: The extent of the coal seam and abandoned as well as active coal mines in South Africa.
Figure 11: Pylon affected by subsidence basin formation in the Middelburg area

Figure 12: Tension cracks representing secondary features of surface subsidence
Present day mining activities are also associated with surface subsidence features although these features are less pronounced than those associated with the abandoned mines. Currently primarily two
mining techniques are employed including the room and pillar technique, as well as a technique known as longwalling. The longwall mining technique is a form of underground mining where a longwall of coal is mined in a single slice. The longwall panel (the block of coal being removed) is typically 3 to 4 km long and 250 to 400 m wide. The roof strata between the remaining roof support structures are subject to sagging leading to surface subsidence at the surface. This may cause a characteristic wave-like appearance of subsidence features on the surface. The advantages of longwall mining compared to the room and pillar method includes the fact that there is a greater resource recovery (80% compared with 60% for the room and pillar method). Additionally, less roof support consumables are needed and surface subsidence is largely immediate allowing for better planning. The surface subsidence associated with longwall mining is referred to as controlled subsidence with mining companies anticipating the deformation.

The severity of the impact of coal mining depends on various parameters including the mining methods used the local geological conditions and whether the mine is working or abandoned (Bell et al. 2001). In particular, the composition of the roof strata will influence the expression of surface subsidence on the surface. These statements are supported by the fact that varying conditions between the Witbank/Middleburg area and the Standerton area leads to different expression of surface subsidence being observed. The Witbank/Middelburg areas of the coalfields are coincident with roof strata composed of shale while in the Standerton area, roof strata are composed of sandstones. The sandstones, being more competent will be less susceptible to deformation while the less competent shale will be more susceptible to gradual movements. Additionally, the coal seam in the Witbank area is between 0 and 80 m below the surface with the thickness of the coal seam ranging between 4 and 4.5m. On the other hand, mining at the Standerton area takes place approximately 200 m below the surface while the thickness of the coal seam is between 2 and 2.5 m. In addition to these geological conditions, the mining method also influences the expression of surface subsidence with the room and pillar method being employed in the Witbank/Middelburg area whilst the longwall method is used in the Standerton area. These factors combine to produce different patterns of surface subsidence. The Witbank/Middelburg area is prone to subsidence basins of larger surface area (approximately 3.3 Ha for the largest subsidence basin recorded between November 2007 and September 2008) compared to the Standerton area where the largest recently recorded subsidence basin is 2.8 Ha in extent. Additionally, the surface in the Witbank/Middleburg area is known to subside by between 2 to 3 metres (Figure 15) while deformation in the Standerton area is less pronounced with subsidence reaching a maximum vertical deformation of between 0.4 and 0.8 m (Figure 16). The secondary effects of surface subsidence such as the appearance of tension cracks are also more pronounced in the Witbank/Middleburg area (Figure 17) while they remain virtually underdeveloped in the Standerton area.
Figure 15: Subsidence basin observed in an agricultural field in the Witbank area

Figure 16: Subsidence basin observed in an agricultural field in the Standerton area
5 Cost of remediation
The cost of remediation is difficult to determine as it is dependent on the number of events that may occur and the number of people and structures that may be affected. What is more easily understood is the value of land affected where development should be avoided or would require costly engineering measures to overcome this problem.

The area affected by shallow undermining in the Witwatersrand goldfields of southern Gauteng is approximately 40km long and 50m wide. It stretches from Randfontein (in the West Rand) to Boksburg (in the East Rand) and is located immediately south of Main Reef Road in central Johannesburg. Parallel areas, associated with the Kimberley and Bird reefs may also be present though their lateral extension appears to be broken in places. This area has historically been avoided for development because of this risk. As sometimes there are no obvious signs, such as settlement or subsidence, some structures may have inadvertently been placed across these features and may thus be vulnerable. The vacant areas
along this zone are probably the most vulnerable since little or no control is being exercised and informal settlements are developing.

Areas affected by shallow undermining in the Witbank Coalfields are known to be affected by surface subsidence. Mining companies involve continuously monitor surface subsidence basins once their existence become known. In areas where longwall mining is taking place, the subsidence is planned for which effectively decreases the vulnerability associated with the resulting subsidence.

6 References


