Characterization and empirical analysis of block caving induced surface subsidence and macro deformations

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ABSTRACT: The increasing move to block cave mining methods (including sublevel and panel caving) to access deeper and lower grade ore deposits as near surface sources become exhausted raises questions as to the extent and magnitudes of caving-induced subsidence as it may affect strain-sensitive infrastructure on surface. Predicting these surface deformations is difficult as they tend to be discontinuous and asymmetric due to large movements around the cave controlled by geologic structures, rock mass heterogeneity and topographic effects. Of further impediment is the sparse number of case histories available, in which actual subsidence measurements are reported to provide guidance and empirical constraints for subsidence calculations. This study reports the development of an exhaustive and comprehensive database of available (i.e. public domain) subsidence data from block cave mining operations from around the world.

1 INTRODUCTION

With the increasing exhaustion of near surface ore deposits accessible through open pit mining, block cave mining methods (including sublevel and panel caving) to extract massive low grade orebodies are gaining increasing attention from the mining industry given their merits in terms of safety, tonnages produced and mining costs that can match those of open pit operations. The mining method involves the undercutting and bulk extraction of ore through caving (see Kendorski 1978, Brown 2003), which in turn leads to the development of surface subsidence above the propagating cave (Flores & Karzulovic 2003). The damage, destruction or replacement of surface and underground infrastructure due to the subsidence is often the cause for additional capital expenditures of block caving operations as well as for environmental degradation. Therefore, it is critical to predict the extent and magnitudes of this subsidence with reasonable accuracy so as to be able to protect mine infrastructure and minimize environmental impacts (e.g. Moss et al. 2006).

Much of the work on the topic of mining-induced subsidence has been directed towards longwall coal mining and continuous subsidence, for which empirical procedures and guidelines are relatively well established (e.g. Whittaker & Reddish 1989). However, block cave mining produces discontinuous subsidence due to large movements around the cave controlled by geologic structures, rock mass heterogeneity, etc. Vyazmensky (2008) demonstrated this effect using a hybrid finite-element/discrete-element modelling approach that simulates brittle fracturing within a network of discontinuities. Their work highlights the importance of joint set orientation on controlling cave propagation and the development of discontinuous and asymmetrical surface subsidence. Still, prediction of discontinuous subsidence and the use of sophisticated numerical models require understanding of the site conditions and constraints with respect to the representation of the geology and material properties used. An impediment to this is the sparse number of case histories available to provide general guidance for subsidence analysis in which actual subsidence measurements are reported.

Given that such data is essential to better understanding discontinuous subsidence and its controls, this paper reports the development of a comprehensive database of available (i.e. public domain) in-situ subsidence information from block cave mining operations from around the world. The objectives of the database are to lay the foundation for more effective empirical and numerical analysis of surface subsidence induced by block cave mining. Based on the database, empirical relationships can be drawn to demonstrate the limitations of analysis techniques that do not explicitly incorporate geological structures and rock mass anisotropy. In addition, preliminary guidelines are provided that contribute to improving the accuracy of subsidence prediction based on correlations between different geological factors influencing subsidence and characteristics of the subsidence patterns measured.

2 BLOCK CAVING SUBSIDENCE DATABASE

The database compiled in this study is populated by more than ninety cave mining operations throughout the world including both historical mines that have ceased to operate and those still producing. Figure 1 shows the breakdown of the database by continent, mining method and mineral produced. The majority of operations are North American based (42%), while an increasing number of mining operations in Asia are adopting cave mining methods (Fig. 1a). When it comes to mining method, 67 percent of the cases involve block caving with 16 percent using sublevel caving to adapt to the local topography and/or orebody type (Fig. 1b). The integrated use of two methods in tandem – block caving plus sublevel caving or block caving plus panel caving – is increasing to facilitate excavation as well as mine management. As for minerals produced by these mines (Fig. 1c), copper and gold form the majority with 60 percent followed by asbestos (11%) and diamond (10%). In terms of activity, 65 percent of the cases involve mines that are currently operating (Fig. 1d).



Figure 1. Cave mining by: (a) continent; (b) mining method (BC = block cave, PC = panel cave, SC = sublevel cave), (c) resource mined, and (d) activity. Total number of cases is reported in brackets below the percentage.

A tabular format adopted for the database is designed to systematically display diverse basic information on a mine including the name, location, and major factors that affect subsidence. Only 5 percent of the surveyed mines report detailed subsidence measurement data. Due to this limited availability of surface subsidence profiles, the majority of subsidence information is qualitative, focusing on large-scale deformations and outlines of collapse structures (i.e. glory holes). Still, the database represents an important undertaking and forms a solid framework for continued data collection. Updating of the database is continuous with ongoing efforts seeking to incorporate in-house data not available in the public domain. Mining operations interested in sharing their data may do so by contacting the authors (kwoo@eos.ubc.ca).

3 FACTORS AFFECTING BLOCK CAVING SUBSIDENCE

Factors that affect block caving subsidence and their relative importance are summarized in Figure 2a (Flores & Karzulovic 2003), with topography and structural geology ranked as factors of high importance. Topography is critical because the scope of surface deformation induced by block cave mining can be expanded and the shapes are more likely to be irregular due to the terrain's ruggedness. Structural geology is important as faults, foliation, and/or the discontinuity network create paths of weakness that may influence cave propagation and the development of discontinuous surface deformations. Again, typically symmetry is assumed when predicting mining induced subsidence. Those mines that do report measured surface subsidence profiles confirm that subsidence above block cave mines is largely asymmetric, meaning that the angle of break from the hangingwall and footwall differs in relation to the structural geology. Structural geology is the overriding factor that governs the asymmetry of subsidence.



Figure 2. (a) Factors affecting block caving subsidence and relative importance, (b) relationship between break angle and rock mass rating (RMR), and (c) relative frequency of block heights mined showing a shift towards increasing block heights in the past 20 years. After Flores & Karzulovic (2003).

Figure 3a shows the detailed information compiled in the database with respect to initial undercut area, production rate and draw rate. The area of the undercut is a key parameter used for subsidence prediction. By observing caving propagation starting from the undercut, the extent of surface subsidence can be projected and estimated based on the rock mass quality (Fig. 2b) and depth of the undercut or block height (Fig. 2c). Typically, the initial undercut is controlled by the type of orebody. The undercut area for a kimberlite pipe being mined for diamonds (e.g. Kimberly: undercut area = 1688 m^2) is relatively small compared to that of a porphyry copper-gold deposit (e.g. Northparkes: undercut area = $35,280 \text{ m}^2$). In terms of tonnage, only 30 percent of the mining operations populating the database have production rates greater than 20,000 tonnes/day (Fig. 3b). However, this trend has an upward projection due to technological advances and growing investment in large-scale mining projects (Brown 2004). Typical draw rates for a block caving operation are 0.3 m/day or lower (78%), with an average rate of 0.2m/day (Fig. 3c). Typically, below-average draw rates are used in the early stages of caving, shifting to above-average rates when over 30 percent of the block height has been extracted.



Figure 3. Distribution of: (a) area of initial undercut, (b) production rate, and (c) draw rate.

Also included in the database is geological information of each surveyed mine. Such details provide the basis for correlating surface subsidence characteristics to geological elements. Butcher (2002) demonstrated the importance of performing a geological structural survey to determine the presence of any major structures that intersected the expected zone of subsidence above a proposed block cave operation. According to Stacey & Swart (2001), such structures could modify or enlarge the glory hole perimeter of a daylighting cave through further break back. Where possible, angles of subsidence were added to the database. The analysis of the rela-

tions between undercut area, undercut depth and angle of subsidence make it possible to estimate the extent of subsidence affecting the surface.

Lastly, high resolution satellite images of some 30 mining operations were captured using the Google Earth image database. These satellite images provide a source of information on the development of large-scale deformations (referred to as macro-deformations) particularly, by phase. Satellite imagery technology, including satellite radar interferometry (InSAR), is already showing potential for providing a valuable new source of caving associated subsidence 2-D and 3-D data (Eberhardt et al. 2007).

Based on the above considerations, the database was analyzed to serve the following objectives:

- i). To provide relationships correlating geological information to subsidence observations as a means of guiding and constraining future numerical analyses;
- ii). To provide a framework on which to base the selection and integration of investigation, monitoring and analytical techniques to be used to analyze the effects of geology in promoting asymmetry and discontinuous caving-induced subsidence; and ultimately;
- iii). To develop empirical characterization tools based on the diverse information compiled in the database to aid in the projection of expected subsidence patterns during the planning stages of future new mining projects.

4 EMPIRICAL ANALYSIS USING HIGH RESOLUTION SATTELLITE IMAGERY DATA

Subsidence above block caving operations can be divided into micro- and macro deformations (Butcher 2005). Micro deformations include those detected as tilting ground, small strains and/or vertical and horizontal displacements detectable through deformation monitoring. Although relatively small compared to macro deformations, they can still be significant in causing differential displacements of several centimeters, which in turn can affect the structural integrity of strain sensitive materials (e.g. concrete). Lupo (1998) reported that micro deformations have been observed up to 250m from the perimeter of a glory hole, the large surface cavity that forms when a cave breaks through to surface. Macro deformations involve those ground movements that are visually detectable such as the opening of tension cracks, development of scarps, fracturing and break back of the surface above and around the cave's footprint, and breakthrough of the cave itself to form a large crater. Figure 3 illustrates the extent of micro deformations (extent of subsidence) and the caved zone and fractured zone that make up the extent of macro deformations as defined by Van As (2003).



Figure 4. Definition of block caving subsidence zones and its quantification with respect to angles extending from the undercut (after Van As 2003).

Understanding zones of macro deformation around or above a caving operation can have serious implications in terms of safety, damage to surface infrastructure and environmental concerns. Based on experiences from caving operations in Australia and Southern Africa, Butcher (2002) suggested that the ground immediately above the cave footprint will subside, cave and collapse, and thus any excavations or surface infrastructure situated within the footprint will ultimately be destroyed. Predicting the zone of macro deformation with fair precision is also critical in terms of project viability as macro deformations and ground collapse into the cave can result in dilution of the ore being extracted. Dilution is one of many challenges confronting mining operations requiring extra expenditures to deal with waste material that can transform valuable ore into waste below the cutoff grade.

To examine the characteristics of macro deformations above block cave operations, high resolution satellite images, where available, were examined. In total, images were found for just over 30 mine sites in the database. The different patterns identified in these images were first grouped according to three visually distinct topographic controls: operations below relatively flat surface topography (40%), operations under mountainous topography (25%), and operations beneath open pit mines (35%). The distinct patterns seen in these groupings confirm that topography, both natural and anthropogenic (i.e. open pit), is a key factor that affects the extent and shape of the subsidence profile.

Figures 5 and 6 present several examples of the satellite images analyzed, grouped according to a classification system devised based on the macro deformation patterns observed.



Figure 5. Macro deformation patterns observed in which topographic effects are minor: Type-A: circular, Type-B: elliptical, Type- C_1 : irregular with scarps but without a distinct collapse structure/glory hole, and Type- C_2 : irregular with a distinct collapse structure/glory hole.

Figure 5 includes those patterns in which topographic effects are minimal. The Type-A pattern involves those cases in which a circular glory hole (i.e. symmetric macro deformation) develops, davlighting into a flat topographic surface. In these cases, the geometry of the cave collapse structure mimics that of the orebody and undercut. The Type-B patterns are those involving the development of an elliptical collapse structure daylighting into a flat topography. In most cases, this reflects the geometry of the undercut or the mining method (e.g. sub-level caving along an inclined orebody). In some cases though, the elliptical shape may be suggesting that some form of rock mass heterogeneity or systematic set of geological structures are a governing factor affecting subsidence. Surface fractures for Types A and B form a relatively regular pattern around the perimeter of the collapse structure. Types C_1 and C_2 include those patterns that are irregular in shape without and with the development of a glory hole, respectively. The absence of a glory hole may be simply related to the maturity of the block cave and may eventually develop as mining progresses. In some cases though, sites that fall into the C_1 type category involve operations where mining has finished, perhaps suggesting that higher rock mass strengths may be the reason why a glory hole did not develop. Again, given that these cases (Types C_1 and C_2) involve relatively level topography, the irregular nature of these patterns suggest the controlling influence of one or more discrete geological structures (e.g. major faults), perhaps oriented in different directions.



Figure 6. Macro deformation patterns where topography has a controlling influence: Type-E: open pit with collapse structure/glory hole contained within pit, Type-F: open pit with collapse structure/glory hole extending outside of pit, and Type-G: collapse structures in mountainous topography.

The Type-D patterns, shown in Figure 6, are representative of those cases in which the block cave daylights into an open pit, but in which the collapse structure/glory hole is contained within the pit, often appearing as a circular hole in the bottom of the pit. In some cases, the shape of the collapse structure depends on the shape of the open pit. The Type-E patterns likewise involve a cave daylighting into an open pit cave, however in these cases, the collapse structure and scarps extend outside the outline of the pit. Here, both the influence of topography and the geology interact with the propagating cave to affect the subsidence pattern. Lastly, the F-type patterns involve those cases of macro deformation that develop in a mountainous topographic setting. Generally speaking, scarps develop in the higher altitudes while moderately sloped subsidence appears at lower altitudes.

Table 1 summarizes the empirical indexation of subsidence based on the presence of visual indicators in the high resolution satellite images. Index 1 denotes cases where subsidence indicators are not visible but does not discount the possibility of micro deformations. An Index 2 subsidence is a ground deformation whose characteristics stand somewhere between those of continuous and discontinuous deformation. An Index 3 subsidence is a macro deformation that occurs in the intermediate stages of caving and is easily observed in satellite images. An Index 4 subsidence involves a fully developed collapse structure forming a glory hole. This stage is typically observed in the final phase of block cave mining. Accordingly, the development of subsidence evolves with the caving process and therefore the visual indicators are partly a function of the temporal maturity of the caving operations.

Table 2 shows the indexation of subsidence shapes derived from the image analysis. The most frequently observed shapes where topography was relatively flat were circular and elliptical, although irregular shapes are also observed often. For cases where caving was initiated below an open pit mine or mountainous topography, the subsidence shapes are largely affected by the topography. What is interesting to note from the image analysis is that except for the Type-A cases of a circular collapse structure, the majority of deformation patterns are asymmetric.

Table 1. Subsidence classification by visibility.						
Visible Deformation	Index					
Non visible	1					

Non visible	1
Minor cracking	2
Scarps	3
Glory hole	4
n	

Table 2.	Subsidence	classifi	ication	by	shape

Туре	Sha	Index	
	Cincular	Centered	A _C
A	Circular	Eccentric	A_E
р	Elliptical	Centered	B _C
В	Emptical	Eccentric	\mathbf{B}_{E}
C	Impossion	Centered	C _C
C	Integular	Eccentric	C_{E}
D	Anthropogenic	Pit Contained	D
Е	(Open Pit)	Pit Extended	Е
F	Mountain Topography		F

The results of the image analysis for each mine site are summarized in Table 3. The dimensions of the collapse structures were scaled off of the satellite images, and are reported in Table 3 as X, which represents the maximum length/extent of the collapse, and Y, which measures the length perpendicular to X. Cases that do not have a clear X and Y were not measured. Furthermore, because the images were not taken exactly at vertical angles to each surface, values may be slightly distorted. However, as an approximation, the dimensions provide a generally reliable measure of the extent of macroscopic deformation for each case.

The results from the dimensioning analysis indicate that the zone of macro deformation for cases with mountainous topography tends to be larger compared to those for the other cases, with maximum surface dimensions (X) ranging from 700 to 2000m. This suggests that topography has an amplifying influence on subsidence. In comparison, the X length of glory holes daylighting into flat topography range from 400 to 800m.

Table 3. Summary of image analysis results for each mine site, including other mine specific data for comparison. X and Y are dimensioning parameters where X is the maximum length/extent of the macro deformation feature, and Y the dimension perpendicular to it.

	Mine	Caving Method	Mineral	Production Rate (ton/day)	Draw Rate (m/day)	Initial Undercut Area(m2)	X(m)	Y(m)	Shape	Visibility
1	Ekati 🏼 🏓	SC	Diamond	-	-	-	-	-	D	1
2	Northparkes 🗮	BC	Copper, gold	12000	0.2	35280	359	299.2	Ac	3
3	Sunrise	BC	Iron	3350	-	5000	587.1	362.5	BE	4
4	Kimberly	BC	Diamond	17400	-	1688	397.7	364.9	Be	4
5	Creighton	BC	Nickel	-	-	-	703.2	562.6	Ce	2
6	San manuel	BC	Copper	50000	0.53	-	-	-	Ce	3
7	Big bell 🗮	SC	Gold	4750	-	-	704	230.4	Ce	3
8	Stobie 🏼 🌞	SC	Copper	9050	-	-	-	-	Ce	3
9	Kiruna	SC	Iron	-	0.051	-	-	-	Ce	3
10	Wesselton	BC	Diamond	12000	0.4	4320	484.6	464.9	Ce	4
11	Bultfontein	BC	Diamond	-	-		695.3	497.4	Ce	4
12	Cullinan 🔀	BC	Diamond	-	-	3600	806.4	359.1	Ce	4
13	Du toi's pan 🔀	BC	Diamond	-	-	-	702.8	384.5	Ce	4
14	Nchanga	BC	Copper, Cobalt	-	-	-	468	131	Е	3
15	De Beers 🔀	BC	Diamond	-	-	-	403.8	239	Е	3
16	Palabora 🔀	BC/PC	Copper	30000	0.2	19600	-	-	Е	3
17	Perseverance	SC	Gold	-	-	-	-	-	Е	3
18	Lakeshore	BC	Copper	6000	-	-	444	222	Е	4
19	Ray	BC	Copper	9000	-	1855	678.9	232.5	D	4
20	Koffiefontein 🔀	BC	Diamond	12000	0.4	4320	402.5	389.1	D	4
21	Insperation	BC	Copper	17000	-	900	-	-	Е	4
22	Finsch	BC/PC	Diamond	17000	0.2	5500	367.9	316	D	4
23	Ridgeway	SC	Gold, Silver	-	0.138	-	125.3	75.2	D	4
24	Mt Lyell 🗮	BC	Copper, Gold	6900	-	-	721.9	605.7	F	3
25	Santo Tomas 🛛 🚬	BC	Copper	24000	-	-	-	-	F	3
26	Andina	BC/PC	Copper	14000	0.14	14400	-	-	F	3
27	Salvador	BC/PC	Copper	18000	0.104	11440	2064	1345.5	F	3
28	El Teniente	BC/PC	Copper	95000	0.333	10000	-	-	F	3
29	Henderson	PC	Molybdenum	36000	0.67	10000	705	527.5	F	3
30	Climax	PC	Molybdenum	44000	-	14884	1960	1092	F	3
*	\star : Canada 🛛 🎫 : Aus	tralia	USA 🚬 So	outh Africa	: Sweder	n T : Zar	nbia ≽	: Philippi	nes	: Chile

Table 4 summarizes the results according to each of the classification groupings. Included in this comparative analysis is an estimation of how centered the collapse structure is with respect to the undercut. If the glory hole forms directly over the undercut footprint, it is classified as

centered (Table 2). If the glory hole is offset from the footprint of the undercut, the collapse structure is classified as eccentric. Although the number of cases in which both satellite imagery and geo-referenced mine schematics were available is limited, Table 4 shows that a number of these cases involve caves that did not daylight directly over the undercut. In several of these cases, this migration was a function of the orebody geometry (e.g. inclined orebodies). However in other cases, the eccentricity observed speaks to the influence of geology on the subsidence pattern.

	No visible	Minor		Scraps	Glory hole
	[1]*	[2]		[3]	[4]
Circular		C** [C]	-	C [C] 2	С[С] -
[A]	-	E*** [E]	-	E [E] -	E [E] -
Elliptical	_	C [C]	-	С[С] -	C [C] -
[B]	-	E [E]	-	E [E] -	E [E] 3, 4
Irregular		C [C]	-	С[С] -	C [C] -
[C]	-	E [E]	5	E [E] 6, 7, 8, 9	E [E] 10, 11,12,13
Pit Contained [D]	1	-		-	19, 20, 22, 23
Pit Extended [E]				14, 15, 16, 17	18,21
Mountain Topography [F]	-	-		24, 25, 26, 27, 28, 29 30	9, _

Table 4. Comparative analysis showing mine case histories that fall into each classification grouping. The numbers listed correspond to the case numbers reported in Table 3.

* [] : Indice defined in Table 2 and Table 3 **C: Center ***E: Eccentric

The results from the comparative analysis in Table 4 highlight the asymmetric nature of block cave mining-induced subsidence and the influence that topography and geology have on it. These findings are constrained though by limitations in the data available in the public domain. Of the ninety block caving operations that populate the database, satellite imagery was only found for thirty cases. This limited availability is due to the short history of the Google Image service which became available just a few years ago. Furthermore, some of the released satellite images are out of date and do not necessarily show the current state of the mining operations. Despite these drawbacks, the significance of the databased images lies in the quick and visual information they provide on characteristics of mining-induced macro deformations.

As more data is acquired, refinement of the classification system will continue. One key additional data set that will be incorporated into this study is that from high resolution satellite imagery. Differential interferometric analysis of these images (DInSAR) will allow for the additional characterization of the micro-deformation component of block cave mining-induced subsidence.

5 CONCLUSION

Block cave mining methods are increasingly being utilized by the mining industry to economically and safely mine lower grade and deeper ore deposits. Accordingly, the importance of understanding block cave mining-induced subsidence in terms of its magnitudes, extent and potentially negative effect on strain sensitive surface infrastructure is likewise increasing. To build on existing treatments of surface subsidence prediction, and provide guidance and constraints for sophisticated numerical models, this study represents efforts to develop an empirical understanding of the complex subsidence patterns induced by block caving and the parameters that control it. The database represents an exhaustive and detailed collection of data available in the published literature and public domain involving over 90 block, panel and sublevel caving operations.

Included in the database are a number of satellite images. Comparative analyses of these images were used to develop a preliminary classification system for macro deformations and block caving-induced collapse structures. The results highlight the degree of asymmetry in the subsidence profiles and the inferred influence of topography, orebody type and structural geology in controlling it. Efforts will continue to update this database with additional geological, topographical, operational and surface deformation information, with the next phase of development to focus on including mine data not available in the public domain.

Overall, the results show that rarely do these subsidence patterns fit the idealized symmetric patterns inherently assumed in conventional subsidence analyses. For accurate subsidence prediction, these findings point to the need to utilize analytical techniques that can explicitly account for the effects of structural geology, topography, and rock mass heterogeneity are required.

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