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Numerical simulation of crown pillar behaviour in transition from open pit to underground mining

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Abstract

Crown pillars provide regional and local support by isolating the ground surface from underground mine workings. Topography above the underground mine may be a relatively flat ground surface or an open-pit structure. Depending on what lies above and design of the underground mine, the crown pillar behaviour will differ. In transitioning setups (open pit to underground), large open pit collapses have taken place as a result of crown pillars located at the transition zone. Hence, this paper focuses on crown pillars between open pit and underground to better understand their behaviour. Taking the Zuuntsagaan Fluorite mine as an example where open pit will transform to underground mining, a remnant ore is to be left as a crown pillar to separate the two mining sections. Through numerical simulation in FLAC3D 7.0, stress distribution and failure mechanisms acting around the crown pillar were monitored as underground mining progresses. Effect of crown pillar geometrical parameters was evaluated, thus crown pillar thickness, span and dip. Further, the open pit geometry influence was also considered on the overall behaviour of the crown pillar. It was found out that in transition from open pit(OP) to underground(UG), slope and stope walls closing in on the crown pillar induce stresses that act as loading from the pillar sides, which in turn influence the failure process.

Keywords: Crown pillar, Open pit to underground mining, Numerical modelling, Underground mining

1 Introduction

During underground mining near the surface, rock mass (often consisting of ore) termed crown pillar is left for protection by separating the ground surface from adjacent underground space. Surface crown pillars serve to prevent water inflow, or mud rushes into the underground workings, heat insulation in cold regions (Sokolov et al. 2013), cave-ins, and ultimately ensure the stability of the surface infrastructure. At times their long term stability is crucial in guaranteeing stability after mine closure (Hutchinson et al. 2002). The surface crown pillar can be categorised into two viz: 1. Surface crown pillar separating a relatively flat ground surface and the underground, 2. Open pit (OP)-underground (UG) crown pillar (positioned between open pit and underground). Failure of surface crown pillars may result in large scale subsidence or even sinkholes in worst case scenarios. Surface crown pillars have been extensively studied after some occurrences of surface settlement and instabilities in the underground space due to crown pillar failure (Carter 1992, 2000; Carter and Miller 1995; Szwedzicki 1999, 2001).

Where OP-UG crown pillar is involved, it can be argued that it presents relatively a new challenge due to its position and the increasing failures in mines worldwide. In mines where there is a transformation from open pit to underground, the crown pillar is positioned in the transition zone (between the pit bottom and stope roof) as shown in Fig. 1. The crown pillar of this setup is often made up of mainly ore, which means ore will be left out permanently and its economic value will not be realised. It may even require large volumes of ore to be left to attain the needed safety value since the stability generally increases with crown pillar thickness. In some instances, the value of the ore left within the crown pillar is so high that an artificial crown pillar is employed for the ore to be mined out completely Xu et al. (2019). On the open pit section during underground mining it is noticed that stresses concentrate on the slope toes (Zhou et al. 2016), and lateral stresses are particularly high at the crown pillar top (Dintwe et al. 2021). Optimum thickness is therefore vital to reduce ore loss and at the same time ensuring enough global stability.

The process of designing crown pillar involves considering some but not limited to geological and mining parameters listed in Table. 1 (Tavakoli 1994), and some critical crown pillar characterising parameters are illustrated in Fig. 2. The design of the crown pillar and its stability assessment are approached through empirical, analytical and numerical methods. Analytical methods put forward to evaluate crown pillar stability are adopted from structural mechanics and tried to fit the crown pillar structure. Xu et al. (2019) did an extensive analysis in determining the crown pillar thickness using various methods including the analytical approach. From the analysis, the analytical methods were found to have limitations and an average value from all the approaches had to be used. The limitation being that the techniques could not account for the heterogeneity of the rock mass. The popular empirical method is the scaled span method developed by Carter, (1992). The scaled span method was aimed at improving the crown pillar design; the charts and the calculations derived in the methods are based on past cases study data, making it a very useful practical tool. The method has since improved over time with more data available from various sites; however, data is still limited to North America and the method cannot be used unanimously with high level confidence for every site. Moreover, OP-UG interaction setup introduces active forces from the slope walls towards the pit bottom, which is one aspect most likely not considered during the empirical formulation.

Incorporating all the aspects of crown pillar design will require a special approach such as numerical modelling. It is capable of handling almost all the aspects, including the heterogeneity of the rock mass, even in 3 dimensions. Numerical modelling offers the use of distinct element modelling (DEM) for capturing the presence and effects of discrete blocks within the crown pillar, or continuum modelling as finite element method (FEM) (Kumar and Deb 2016) and finite difference method (FDM) for modelling less jointed rock masses (Nguyen and Niedbalski 2019). The use of numerical modelling in crown pillar design, particularly in OP-UG interaction, has a good success record in determining the pillar thickness. Nguyen and Niedbalski, (2019) employed FLAC3D to estimate the crown pillar thickness in an OP-UG transitioning coal mine. The suggested thickness was considered enough to prevent water inflow. Xu et al. (2019) used FLAC3D to make forward predictions to estimate the natural pillar thickness in the transition zone of a gold mine that had transitioned to underground. The same thickness was adopted for the artificial crown pillar construction during the replacement of the natural one. Yardimci et al. (2016) carried out the factor of safety analysis of a crown pillar located between an open pit and underground using FEM based software (Phase2). Zhao et al. (2012) validated pillar performance by numerical simulation in RFPA^{2D} code, and the results assured that the pillar size is adequate for the desired stability. In Agnico-Eagle mines, forward predictions performed in FLAC3D assisted in selecting the mining method as well as stope designs in extracting a crown pillar positioned in the transition zone (Kalenchuk et al. 2019).

All the above mentioned studies involving the crown pillar have, however focused on the specific case studies with parameters limited to those areas. Also, little literature has covered the general behaviour and failure mechanisms of crown pillars located in the transition zones of open pit to underground. For that reason, this study uses numerical simulation in FLAC3D software to investigate the behavioural mechanisms of the OP-UG crown pillars during underground mining.

Zuuntsaagan Del fluorite mine is currently transitioning from open pit to underground sublevel open stoping (SLOS). The selected underground method necessitates a crown pillar in the transition zone before the underground mining could start. As part of the study, adequate pillar thickness has to be determined. Further, effects of pit geometry (slope angle and height), stope dip and finally, the span were investigated on the stability of the crown pillar.

Table. 1 Parameters affecting the stability of the crown pillar (Tavakoli 1994)

Geological parameters	Mining parameters
• Rock type; hangingwall, footwall and orebody	• Geometry of crown pillar and surrounding stopes
• Dip of the orebody	• Supporting methods
• Strength and deformation characteristics of the rock mass	• Mining sequence
• Virgin stress conditions	• Stress distributions caused by mining
• Properties of contact zones between ore and host rock	

2 Overview of the Zuuntsagaan mine (Engineering and Geology)

The Zuuntsagaan Del fluorite mine is located in south eastern part of Mongolia, 150 km north of Sainshand city and 280 m south-east of Ulaanbaatar city. The orebody consists of quartz and calcite fluorite veins hosted within the basaltic andesite. Orebody thickness is about 10 m on average and varies along the 200 m strike length. The orebody extends approximately 200 m downwards at a sub-vertical dip of 70°. The closed open-pit extends 200 m on the long axis, and pit limit was reached at 100 m depth with an overall slope angle of 45°. The remaining ore reserves are estimated to be over 150 million tons. The decision on the underground mining method was based on the competency of the rock mass, ore geometry and availability of fill material; hence SLOS was pertinent in this instance.

3 Pillar failure mechanisms

Pillars such as those in room and pillar mines undergo stress loadings in the underground space as they carry the overburden load directly above them and that of the void space. Suppose the stress loading is more than the pillar carrying capacity or it happens that the pillar deteriorates over time. In that case, the fracture process will start from the free pillar surfaces and progress inwards to its core to have the actual pillar shear failure. The process is highlighted in Fig 3 and it is typical for hard rock pillars (Mortazavi et al. 2009). According to Rafiei Renani and Martin (2018), Fig. 3 shows the failure initiation process from 70% of peak stress. Figure 3a-d represent 70%, 85%, 95% and post-peak stresses respectively. The imminent fractures on the corners of the pillar at 70% signify initial spalling failure. Fractures propagated and coalesced to reach the core at about 95% of the peak stress and at this stage it may be referred to as partially failed. Thereafter, failed or post failure is when all confinement is lost and fractures are internal into the core.

A similar process could be deduced for crown pillars in the open pit to the underground mine, however, few modifications ought to be made. The difference comes from the loading direction, which in turn determines the failure mechanism of the pillar. It can be agreed that OP-UG crown pillar receives loading from the sides, and free surfaces could only be possible from the top and bottom. Consequently, failure will probably emanate from the two ends as confinement is lost. Unlike the normal surface pillar (without an open pit), the OP-UG crown pillar is under stress generated by the slope walls, potentially increasing pillar failure chances. Herein, an attempt is made to explain this crown pillar behavioural process by numerical simulation.

4 Numerical model development

4.1 Model geometry

A 3D model was built in the FLAC3D based on the simplified geometry of the mine. Figure 4 illustrates the geometry of the open pit and underground sections separated by the crown pillar. The model length is 1200 m long and 600 m wide, with a total height of 300 m. The crown pillar is assumed to be made up of ore completely. Therefore, as mining progresses either upwards or downwards, there should be a considerable remnant ore to protect the two sections. The planned excavation zone is 100 m by 200 m, and the suitable size of the crown pillar has to be determined, as shown in Fig. 5. While determining the crown pillar thickness, underground support was disregarded, thus backfilling. Therefore, this study has conservative outputs and focuses only on the crown pillar.

Crown pillar geometry differ according to the ore deposit; orebodies could vary from flat laying at 0° dip to vertical at 90° dip. To cover most of the ore body dips that are likely to be mined by SLOS, six cases were investigated, with dip ranges of 40°-90° respectively. The crown pillar span was varied from 5-25 m for the selected dip case, and thus at a certain dip angle, the crown pillar span was adjusted from 5-25 m to determine the crown pillar thickness. Further, four cases of slope heights are considered. However, the slope and height cases were varied only for 70° ore dip.

The model side boundary limits are set considerably farther away from excavation zones and the crown to avoid boundary effects within the model. Roller boundaries are applied on the sides to permit vertical movement, whereas, at the model bottom, movement is restricted in all directions by fixed boundaries. From the top end of the model, gravity is applied and varies according to depth.

4.2 Rock mass properties and governing models

In rock mechanics and rock engineering, there are several rock classifications. The classification systems are developed to categorise rock based on properties exhibited by the rock mass. The quantitative classifications are Rock Mass Rating (RMR) (Bieniawski 1973), Q system by Barton and Rock Mass Quality Rating (RMQR) (Aydan et al. 2013). In addition, Hoek proposed a classification system like termed Geological Strength Index GSI. The system is qualitative and based on a visual assessment of the rock mass to estimate its strength. Nevertheless, here a generic approach was preferred to evaluate the rock mass condition utilising three rock mass classification systems RMR, RMQR and GSI.

Field survey was carried out in the open pit to assess the rock mass state and then evaluated using RMQR and RMR. In addition, some attempts were made to identify the GSI number. The values of parameters for RMQR and RMR are given in respective Tables 1 and 2. To estimate or relate classification values, the following relations may be used.

Hoek suggested GSI should be related to RMR as follows

$$GSI = RMR - 5 \quad (1)$$

Aydan et al (2013) relates RMQR to RMR as follows

$$RMQR = 100\left(\frac{RMR}{RMR + 1.1(100 - RMR)}\right) \quad (2)$$

Table 1. RMQR rock classification

Parameter	DD	DSN	DS/RQD	DC	GWSC	GWAC	TOTAL
Value	12	8	12	22	7	5	66

DD: Degradation degree, *DSN:* Discontinuity Set number, *DS:* Discontinuity spacing, *DC:* Discontinuity condition, *GWSC:* Groundwater seepage condition, *GWAC:* Groundwater absorption condition

Table 2. RMR classification

Parameter	UCS	RQD	DS	DC	GWS	TOTAL
Value	12	13	15	20	7	67

UCS: Uniaxial compressive strength, *RQD:* Rock quality designation, *DS:* Discontinuity spacing, *DC:* Discontinuity condition, *GWS:* Groundwater state

Model parameters are attained from laboratory experiments performed on the samples collected from the core. All the physical parameters of the rock units in the model are tabulated in Table 2. To characterise the rock mass, Geological Strength Index (GSI) was employed. Field investigations mainly based on mapping and core logging reveal an estimation of 67 RMR and 62 on GSI scale according to Eq (1). To estimate strength parameters of the rock mass based on the Hoek and Brown criterion; uniaxial compressive strength (UCS), the value of the Hoek and Brown constant (m_i) and the GSI value have to be utilised.

A combination of GSI value, UCS and m_i values of intact rock are used to estimate the rock mass strength constants using equation (3)-(5). The values obtained from Hoek-Brown were then converted to Mohr coulomb equivalent using Roc Lab software. The Hoek-Brown and Mohr Coulomb corresponding values are presented in Table 3. An elasto-plastic model was assigned to all rock mass elements. The Mohr-Coulomb criterion is set to govern both the ore body (crown pillar) and the host rock (hangingwall and footwall).

$$m_b = m_i exp\left(\frac{GSI - 100}{28}\right) \quad (3)$$

$$s = exp\left(\frac{GSI - 100}{9 - 3D}\right) \quad (4)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/_{15} - {}^{-20}/_{3}}\right) \quad (5)$$

where D characterises the degree of damage in the rock mass due to excavation, and depends on the blasting and excavation technique. m_b together with s and a are Hoek and Brown constants required in estimating the rock mass strength

4.3 In situ stress estimation

Prior to excavation of both surface and underground mining, field stress conditions have to be introduced into the model. Stress varies in three dimensions within the crust, and generally, field measurements are carried out to estimate the variation with depth. Thereafter, major, intermediate and minor principal stresses are identified and prescribed accordingly into the numerical model. To estimate the stress in vertical direction, equation (6) was used. Since no in situ stress measurements were carried out in the site or in neighbouring localities for horizontal stresses, by using Aydan's method it is possible to estimate in situ stress by considering geological features such as the striations, folding, and faults. This study used striations rake angle and vein orientation information to estimate horizontal stresses using Aydan's method (Aydan 2000, 2016). For underground development, the horizontal stress was estimated to be 0.7 times the vertical stress, see (Fig. 6), and vertical stress is determined by equation (6)

$$\sigma = \gamma H \quad (6)$$

where, σ is the vertical stress, γ is the rock unit weight, H is the depth below the ground surface

Table. 3 Rock mass strength parameters

Parameters	Footwall	Hangingwall	Vein
GSI	62	62	62
(mi)	25	20	25
(mb)	3.17	2.14	3.17
(s)	0.004	0.004	0.004
Mohr-Coulomb equivalent estimated rock mass values			
(E_{rm}) (GPa)	13.35	12.3	13.35
(σ_{cm}) (MPa)	13.2	9.8	9.06
(c) (MPa)	2.1	1.77	1.72
(σ_t) (MPa)	0.277	0.277	0.19
(ϕ) (°)	58.6	54.5	56.2

Notes: GSI = Geological Strength Index; σ_{ci} = uniaxial compressive of intact rock material; mi, mb, s = Hoek-Brown parameters; Erm = young modulus of rock mass; σ_{cm} = uniaxial compressive of rock mass; c = cohesion, σ_t = tensile strength of rock mass; ϕ = friction angle.

5 Results of crown pillar modelling

The results in this paper are assessed in terms of the stability indicators or mechanical parameters within the constructed model. Results present response on the rock mass during underground mining. Stress distribution around the pillar is monitored and the resulting displacements are also recorded to have a comprehensive evaluation. In addition, yielding zones are observed for visual assessments of failure propagation in the rock mass.

5.1 Determination of the crown pillar thickness

Thickness of the crown pillar is critical for safe operation in the mine. Therefore, before underground mining, the crown pillar thickness must be determined based on the apparent rock mass properties and the average geometry values of the ore, 10 m span and 70° dip angle. To assess the performance, monitoring points are positioned at M1 (footwall-orebody contact), M2 (crown pillar centre), M3 (hangingwall-orebody contact), and lastly, M4 (pit bottom) as shown in Fig.7. Figure 8 depicts the maximum horizontal and vertical displacements respectively of the selected monitoring points. From the plotted displacements graphs, it is observed that as the crown pillar thickness increases, the displacements decrease until 15 m thickness. Beyond 15 m thickness, displacement tends to stabilise, indicating that no further deformation is taking place. The least horizontal displacement occurs at the pit bottom (top of the crown pillar) and highest horizontal displacement is recorded at the hangingwall-orebody contact, while the highest vertical displacement occurs at the crown pillar top and the least vertical displacement occurs at the hangingwall-orebody contact. At 15 m thickness, lateral and vertical displacements at the hanging-orebody contact reduced from -40 mm and -7 mm to about -10 mm and 5 mm, respectively. On the footwall side, lateral displacement reduced from 22 mm to about 0 mm. For the crown pillar top, vertical displacement has decreased from 27 mm to 9 mm.

In the same monitoring points where displacements are obtained, the stress values were also extracted. The recorded lateral and vertical stress values are plotted and presented in Figs. 9a and b, respectively. The lateral stress data shows that vertical stress vary significantly at low crown pillar thicknesses, and from 15 m pillar thickness and beyond stress does not change much. On the other hand, on the vertical stress distribution, a similar observation may be made that stress fluctuate more at crown pillar thicknesses below 15 m. As the thickness increases from 15 m, stress change is almost constant on all monitoring points. In both the horizontal and vertical distributions, footwall-orebody experiences the greatest stress concentration at 5 m thickness and drops from 27 MPa to 8 MPa in lateral direction and decrease from 10.5 MPa to 2.5 MPa in the vertical direction. This change takes place as the thickness increases from 5 m to 15 m crown pillar thickness.

The analysis on Figs. 8 and 9 convincingly suggest that crown thickness of 15 m will be adequate to provide local support for the two mining sections.

5.2 Failure zones analysis

Failure patterns for each set crown pillar thickness was assessed through yielding zone identification and corresponding principal stresses, as shown in Fig. 10. Failure initially propagates from stope roof (crown pillar bottom) towards the pillar core followed by slightly smaller failure zones on the pit bottom (crown pillar top). The figure shows that yielding zones increase as the crown pillar thickness is reduced. At larger crown pillar thickness (25 m) yielding zone area is quite small and will not threaten the pillar stability. While when the thickness is reduced up to 5 m, the yielding zone coalescence occurs and the core of the crown pillar will completely fail.

The failure around the stope and slope foot increase with thickness reduction. Slope walls next to the pit bottom indicate an almost complete failure at 5 m thickness. Stope wall failure propagates towards the slope wall signifying collapse in both sections of the mine; therefore, the overall stability may be compromised. The process of failure observed here, can be likened to the mechanism explained in section 2. As loading increases from the slope and stope walls when the thickness is reduced, the failure pattern observed is similar to the one stated in section 2 of this paper. The difference is only that the loading direction is different. Although the crown pillar bottom is more affected than the top part, deformation at the top should be anticipated to occur either by uplift or subsidence in OP-UG crown pillar. Deformation at the top is attributed to the slope walls exerting stress from the pillar sides. The slope and stope closure induce stress loadings on to the pillar.

The corresponding total stress distribution is indicated in Fig. 11. Stress concentration is generally high at the crown pillar corners. When the thickness reduces, the concentration tends to shift or rather spread towards the pillar core where there was low stress concentration. At 25 m thickness, it is observed that the core is relatively under low stress of about 7 to 9 MPa compared to the corners and edges of the pillar. Meanwhile, the 5 m thickness pillar, stress at its core is about 25 MPa and the whole pillar is highly stressed.

5.3 Relationship between crown pillar span and thickness

The crown pillar span represents the horizontal extension of the ore from the footwall-orebody contact to the hangingwall-orebody contact. Along the strike, the orebody geometry is bound to change, including the span and for a given span, the crown pillar thickness has to be determined. For instance, in Zuuntsagaan, the average span value is 10 m, however, it has lower and upper values of 0.5 m and 20 m. Therefore, this prompts an investigation on determining the crown pillar for a given span. In order to efficiently assess the performance of the crown pillar at different spans, in the parametric study, five span cases were considered 5, 10, 15, 20 and 25 m. Displacements of each cases were plotted against the corresponding spans and the crown pillar thick was varied from 5 to 25 m at 5m interval, as depicted in Fig. 12.

Figure 12a shows that generally, displacement increases with a decrease in crown pillar thickness. The lateral displacement increases at any given span as the thickness reduces. However, for a constant thickness, the span has the allowance of adjusting with no significant change in the displacement, except when the thickness is set at 5 m and 10 m, an obvious change in the in the displacement is observed. Here, the displacement rises when the span is increased. Whereas, at 15 m or more thickness, the span may vary from 5 to 25 m and displacements tends to have stabilised. Vertical deformation in Fig. 12b indicates that displacements fluctuate more at low crown pillar thickness, thus 5 m and 10 m thickness. The displacements show to be more stable when the thickness increases.

5.4 Effect of stope dip on the stability of crown pillar

Geometry of the crown pillar should also consider the inclination of the crown pillar from a horizontal plane, thus the dip angle. As aforementioned, the dip angle may vary and 40°-90° dip angles were selected for this study at 10° intervals to investigate potential effects on crown pillar behaviour resulting from change in dip angle. The model geometry and orientation were held constant but only the dip was varied. When adjusting the dip angle, it was assumed to be consistent throughout the strike length of the ore body.

The plots of each dip case against the maximum displacements are indicated in Fig. 13. The deformation behaviour was determined by monitoring the displacement after setting the dip and then observing the displacements at various thicknesses. Lateral displacements indicate that displacement is high at low dip and angles (40° and 50°). The effect of the dip on the pillar thickness grows as the dip angles decrease. As the dip angle increases from 50° to 90° the impact gradually reduces. At the vertical dip, it is observed that basically dip angle has a minor effect on the lateral displacement. The maximum displacement of 25 mm is recorded at the 50° dip. The dip angle also shows to have an effect on the crown pillar thickness. From the plot, crown pillar thickness reduces as the dip angle increases. For instance, at 50° dip, 25 m pillar thickness records the smallest displacement and highest at 5 m thickness. However, at 90° dip angle the displacement for all the pillar thickness is almost the same and close to 0 mm. In terms of displacement, the gap between the 25 and 5 m thickness gradually decreases as the dip and angle increases from 50° to 90°. The results imply that at steep dips, less crown pillar thickness may be required to attain stability of the crown pillar in comparison to gentle dipping orebodies.

Figure 13b shows the vertical displacement plot of the varied dip angles. Results here indicate that the displacement slightly increases as the dip angle increases from 40° to 90°. The thickness of the crown pillar depicts the same observation; the displacement generally increases at each thickness for a given dip angle. Thus, the thickness of, say 25 m will always record high vertical displacements at 80° dip than at 50° dip. Nonetheless, vertical displacements still show that as the thickness increases the displacement reduces despite the dip angle. The 5 m thickness experienced subsidence of 10 mm to 16 mm for all dip cases. The 10 to 25 m crown pillar thickness undergo an uplift, indicated by positive vertical displacement values. The uplifting of the crown pillar is not unforeseen; it has been proven with field monitoring in Longshou mine (Ma et al. 2012; Zhao et al. 2013) and physical experiments (Ding-bang et al. 2014; Zhou et al. 2016).

5.5 Effect of open-pit geometry on the crown pillar behaviour

The open-pit limit is subject to the economic feasibilities for a specific mine site. This means open pit limit can be reached at very shallow or deep depths depending on the site specifications. When the limit is realised, the slope walls will be at certain heights and angles. The depth of the pit together with the slope angle may have influence on the buffer zone, thus the crown pillar behaviour. Understanding the effects of having different pit geometry requires testing possible pit geometries and observing the crown pillar performance. A parametric study was carried out for four cases of bench heights and four cases of slope angles. The bench heights are set at 12 m, 14 m, 16 m, 18 m and 20m, while the slope angles are 41°, 45°, 48° and 52°.

Figure 14 presents the results for parametric study of the bench height. For each bench height, the crown pillar thickness was adjusted and performance was evaluated in terms of displacement as shown in Fig. 14a. Results show two phases where the displacements are low at lower bench heights and then increase as the height increases. Second, the displacements show slight increment, almost negligible, as the bench height is increased from 14 m to 20 m. The lateral displacements are all negative, indicating that the movement within the pillar centre is towards the footwall. It implies that higher stresses are induced from the hanging wall, and these stresses tend to increase with the increasing bench height.

Vertical displacements of the crown pillar at various slope heights are plotted in Fig. 14b. When crown pillar thickness is above 5 m the crown pillar movement indicates to be independent of the bench height; there is a slight gradual decrease in displacement as the bench height increase. Also the vertical displacements here are positive showing that there is an uplift of the crown pillar rock mass. In contrast, when the crown pillar thickness is 5 m, it is observed that displacement increases with the bench height. The displacement at 20 m bench height is twice the displacement at 12 m bench height. In both vertical and lateral displacements, it is obvious that as crown thickness increases, displacement is reduced. It can be concluded that as the bench height or overall slope height has influence on the crown pillar deformation. The effect (high displacement) is noticed mostly on the lateral movement as at heights beyond 14 m bench. Whereas, at 20 m bench height, the effect is noticed on the vertical movement, particularly at 5 m crown pillar thickness.

The plots in Fig. 15 present the results of different slope angles against the displacement recorded at the crown pillar center. Lateral displacements in Fig. 15b are almost the same in all slope angle cases except when the angle is changed to 48° at 5 m crown pillar thickness. At 48°, an insignificant increase in displacement occurs and then dropped when the slope angle is increased to 52°. All lateral displacements are negative, suggesting that the crown pillar undergoes shifting from the hangingwall towards the footwall. Displacements here still reduce with the increasing crown pillar thickness; lowest displacement record is 2.8 mm at 25 m thick pillar and highest at 5 m thickness with 14.3 mm.

Figure 15b depict the vertical displacements of the crown pillar at varied slope angles. As the slope angle increases, the displacements gradually decrease for crown pillar thicknesses beyond 5 m. Additionally, the displacements are positive, showing that there is uplift. At 5 m, crown pillar settlement is observed, demonstrated by the negative displacement values. Further, as the slope angle rise, the subsidence increase. The minimum subsidence is 11.3 mm, and maximum is 16.4 mm and are recorded at 41° and 52° respectively.

6 Discussion

Carter (2014) investigated failure types of surface crown pillars and identified five principal failure mechanisms. The suggested failure mechanisms are realised considering the geometry effects of the crown pillar with a relatively flat cover on top. As far as the OP-UG crown pillar is concerned, the cover effect is complex, and the failure mechanism is bound to differ from the traditional set mechanisms. It is evident that the OP-UG crown pillars experience an uplift deformation (Zhao et al. 2013; Zhang et al. 2017), a pattern not observed in surface crown pillars. Therefore, it is required that cover issues from the overlaying structure must also be considered.

During underground mining below a crown pillar, removal of ore creates voids and loading is then generated from the stope walls towards the crown pillar. The generated loadings will be greatly felt at the crown pillar bottom, and that is probably where the failure will emanate. However, in the OP-UG crown, loading is not only from the bottom end, but also from the top. Loading at the top is induced by the closure movement of the slope walls, consequently resulting in high lateral stress concentrations at the slope toes. It is this stress from the slope toes that cause deformation from the top end of the crown pillar. The possible deformation outcome at the top will be either uplift or subsidence depending mostly on the pillar orientation (dip angle) and crown pillar thickness see Figs. 8b and 13b. The dip is the main factor because it will determine the stress distribution around the crown pillar along the contacts with the hangingwall and footwall. Whereas, the crown pillar thickness is crucial for the obvious reason that stability increases with an increase in thickness.

7 Conclusion

Crown pillars positioned between the open pit and underground mining sections have become more important as most open pit mines are transitioning to underground mining. Stability and their performance is till yet to be fully understood. In this paper, a study was carried out to investigate the OP-UG crown pillar behaviour by numerical simulation to add to body of knowledge of OP-UG crown pillars. Zuutsaagan Del Flourite mine in Mongolia was used for the investigation. First, the optimum crown pillar thickness was determined by predicting performance through stress distribution assessment and movement around the pillar. A parametric study followed this to evaluate the effects of crown pillar span, dip and the open pit geometry. The main points taken from this study are as discussed in subsequent paragraphs.

The numerical simulation revealed that a crown pillar thickness of 15 m will be appropriate to give sufficient support for both mining sections. This selected thickness comes about after stability in displacement and stress is realised at this thickness. The yielding zone area is also indicated to have reduced well enough to ensure stability when the pillar thickness is at 15 m. The coalescence of the yielding zones at the slope and stope was impossible at this thickness.

Crown pillar span influences the crown pillar performance and the effect is generally pronounced at low crown pillar thickness. Stability of the crown pillar is compromised when the span is increased and will therefore require higher crown pillar thickness to stabilise.

Generally, the crown pillar dip impacts more at sub-horizontal dips. At low dips from 40° to 60°, the crown pillar is most likely to collapse than in other cases. The critical dip being 50°, this is where maximum displacement was observed. The lateral movement is almost null at a vertical orientation, and only vertical movements are to be expected. Moreover, the influence of the crown pillar dip is more obvious at low crown pillar thickness and tends to reduce with the increasing thickness.

In terms of open-pit geometry, bench heights appear to influence the crown pillar performance when the height is increased from 12 m to 14 m, and thereafter it is negligible. Likewise, the bench height beyond 12 m will threaten the crown pillar stability at low crown pillar thickness of 5 m. Slope angle tends to affect the vertical movement of the crown pillar more than the lateral movement. Change in the slope angle is almost insignificant for lateral deformation, while vertical deformation changes with adjustment of the slope angle.

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