Practical considerations and modelling of the sublevel caving exploitation “Tinyag” in Peru

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Abstract

The Iscaycruz mining area, located in Andes in Peru, includes four zinc economic deposits that are being mined. The deposits are sub-vertical seams of poly-metallic ores and the geomechanical country rock conditions vary from bad to good quality. Based on the wide experience of the authors in the development of underground mining methods in this type of zinc seamed deposits, and once pit mined the upper part of Tinyag deposit, it was planned to go on exploiting underground by means of the sub-level caving method. The basics of the mine design are firstly described. An application of a numerical model to estimate the possibility of large circular failures affecting the footwall is presented. An assessment is performed on the subsidence response to two different possibilities of the open pit (with fill or unchanged). Also the caving features are numerically analysed by means of discrete element methods, opening new possibilities of analysis.

1 Introduction

Iscaycruz mining area is located in the western range of the Andes, 320 km NNE Lima, in Peru (Fig 1.a). The owner is the mining company Los Quenuales S.A., belonging to the Glencore Group. The deposits are sub-vertical seams of poly-metallic ores with grades up to 14 % zinc. These seams are located in sedimentary rock formations, formed by pelitic Jurassic sediments followed by Cretaceous sediments, being more clastic on the wall and limier at the top. The intrusion of igneous rocks in these formations originated metallic deposits in meta-somatic and skarn areas (Fig.1 b.).

The company started with the mining of the Limpe Centro orebody by means of underhand cut-and-fill method from sublevels with long-holes and back-filling the stopes with cemented aggregate fill, achieving a production of 1,000 tons per day. In Limpe Centro, the mining strategy has changed to overhand cut-and-fill with cemented aggregate and also paste fill. Presently, three new ore-bodies are under exploitation: Chupa, Tinyag & Rosita, consisting of sub-vertical seams ranging from 8 to 35 m thick (Fig.1.b). In this way, a production of 3,700 tons per day has been recently reached (Cuadros et al., 2007). The Chupa orebody is mined with sublevel open stoping with cemented aggregate fill. The upper parts of the Tinyag and Rosita ore-bodies have been open pit mined (Fig 1.c.). The lower part of Tinyag, which can be described as a lens-shape, skarn-type, 15 to 30 m thick and 8.5% Zn grade deposit (Fig. 1.d.) has just started by sublevel caving. A classic draw point, corresponding to this type of mining, is shown in Fig. 1.e.

In the following a general view of the design and starting of the mine Tinyag, by means of sublevel caving is presented. The first developments of the mining method selection were proposed by the authors, based on the study of classical texts (Kvapil, 1992; Page & Bull, 2000) and on the experience on the geomechanical topics of the method of the first of the authors, who design, started and developed the sublevel caving (SLC) Rosaura mine, located some hundred kilometres away from this area also in the Andean Cordillera. The first design of the mine was also submitted to consideration to a Chilean consultant company, which also proposed a basic design (Krstulovic & Ovalle, 2004). Finally and with the help of some numerical models to contrast particular strategies suggested in the design phase, a final design was proposed and implemented. In what follows the design process of the mine is outlined and some numerical techniques applied are also commented.

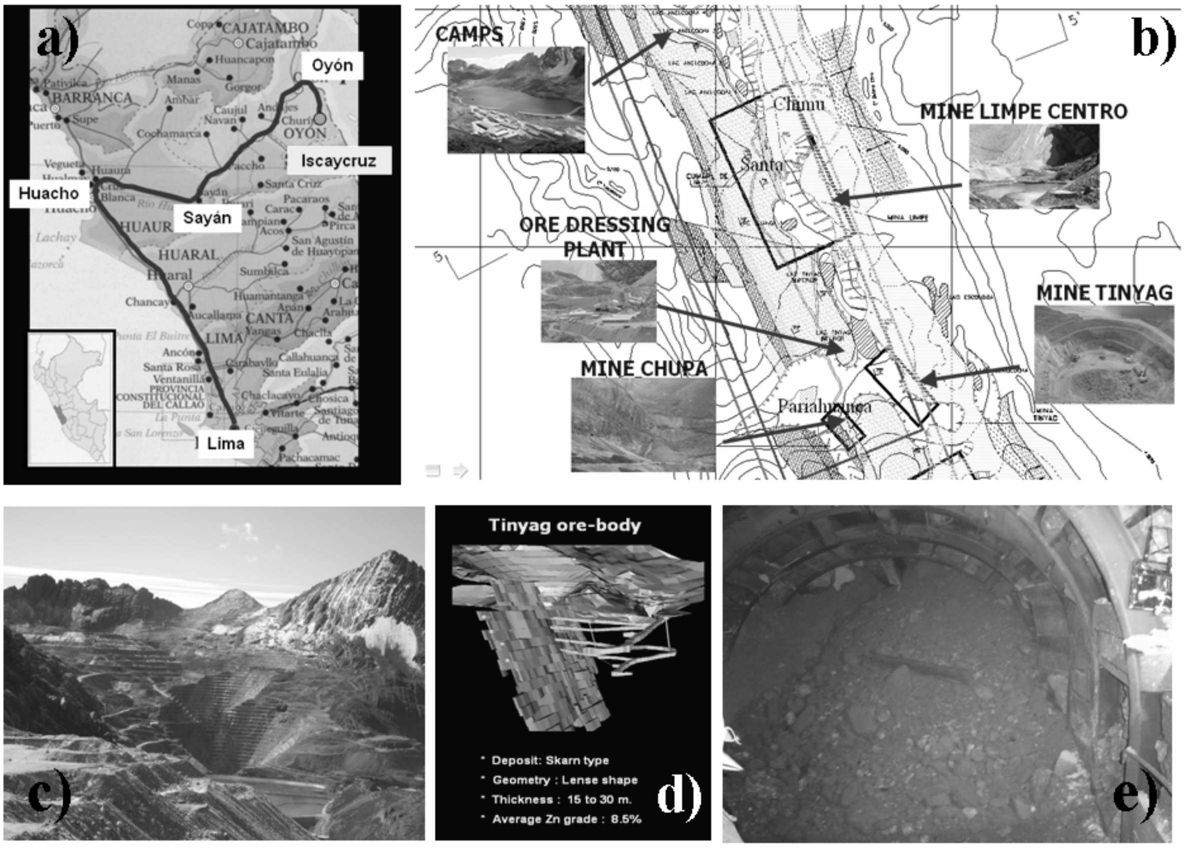

Figure 1 Information on Iscaycruz mining area. a) Location of the Iscaycruz area on a map of Peru, b) General geological arrangement and location of the different mines and mine premises, c) General view of the Tinyag (lower) and Rosita (upper) open pit mines, d) Tinyag ore-body 3-D view and e) Typical draw-point on a sublevel caving zinc mine.

2 Geology and rock mass characterization

2.1. Regional Geological setting

The Iscaycruz area is found in a sedimentary environment, belonging to the Andean cretaceous basin. This basin is structurally characterized by a series of folds and thrusts very representative of the western range of the Peruvian Andes. The Cretaceous rock series are composed in their lower parts by clastic rocks including sandstone, siliceous sandstone and limestone, belonging to the formations Oyón, Chimú, Carhuáz and Farrat. The upper part consists of a sequence of limy rocks together with some bituminous shale corresponding to the formations Pariahuanca, Chulec, Pariatambo y Jumasha. Igneous rocks, including tonalite, dacite and granite porphyry, have intruded these sedimentary rocks formations. Finally, tertiary age volcanic rocks, corresponding to the Calipuy formation, have discordantly covered the sedimentary formations.

During the Andean orogeny, the sedimentary sequence was intensely folded, mainly in the direction N-20º-W. In the Iscaycruz area the dip of bedding is 70 to 80 º NE. The anticlines and synclines extend for various tens of miles, intertwined with thrust areas parallel to the principal strain axis. Various sets of faults –in directions parallel and normal to the ore bodies- complete this complex geological picture of the mine area.

2.2. Geology of Tinyag deposit

Tinyag deposit is lens-like orebody of N-35º-W direction and dipping between 65 and 70º NE. It is in average 17 m thick, varying from 3 to 29 m, with 210 m length and it has been studied up to a depth of 160 m. The ore is disseminated within a skarn formation, where massive bodies of sphalerite, pyrite, chalcopyrite and magnetite appear. Zinc grades up to 29 % have been observed within the body, but the average grade is around 8 % Zn. The complete sedimentary series appearing in the zone of Tinyag is shown in the schematic cross-cut of Figure 2. It includes the formation Carhuáz in the foot-wall, basically formed by mudstone, the formation Santa –initially formed by limestone and sandstone, and where in the Tinyag area the skarn intruded forming the ore deposit and some Skarn an pyritic areas- and the formation Chimú in the hanging-wall, comprehending a thick pack of quartzite of average size grain, massive texture, and whitish colour. This last quartzite is bedded and forms the highest peaks in this mountain area. In a first glimpse, the geomechanical quality of the ore is average to bad, and that of the hanging wall is very bad. The footwall presents average rock mass quality.

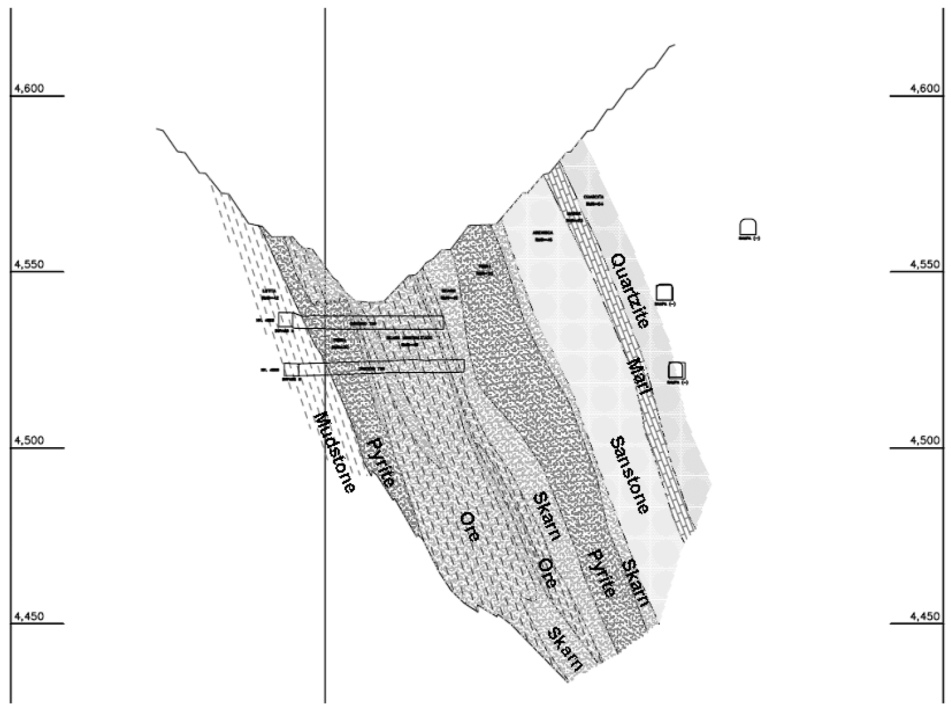

Figure 2 Detail of the Iscaycruz mining area geology. Cross-cut geology of Tinyag.

2.3 Rock mass characterization of the materials affecting Tinyag mine

Iscaycruz manages an updated geomechanical data-base. As part of the routine work the Department of geology performs geotechnical mapping of the underground and open mine works, as well as in the drill cores obtained for mining investigations. Information is formatted according to ISRM suggested methods (Brown, 1981). The basic information of the geotechnical mapping includes type of rock, rock mass quality and joint sets. It includes geomechanical features, weathering and water level for every joint set identified.

2.3.1. Rock masses structure

More than 500 discontinuities have been measured in the zone of the deposit, which once analysed have shown to belong to three joint sets, the first of which can be considered parallel to bedding (057º/70º), being the two other ones normal to this one and dipping around 70º (152º/68º & 321º/69º) (Figure3.a). These two last joint sets can be considered as cross-joints to the general bedding dividing the strata in rhombus-like shaped elements, This structure is considered to be highly convenient in what concerns the cavability of the ore rock mass (Figure 3.b).

The ore and skarn, and the sandstone, marls, mudstones and quartzite present average spacing from 6 to 60 cm, apertures from 0.1 to 1 mm, continuities from 3 to 10 meters, lightly rough surfaces with weak fills, moderated weathering, and water conditions between wet and dripping. The rock mass quality of every rock mass is controlled by its compressive strength. The pyrite is structurally different from the rest of materials, for it present a soil aspect in which no joints can be identified.

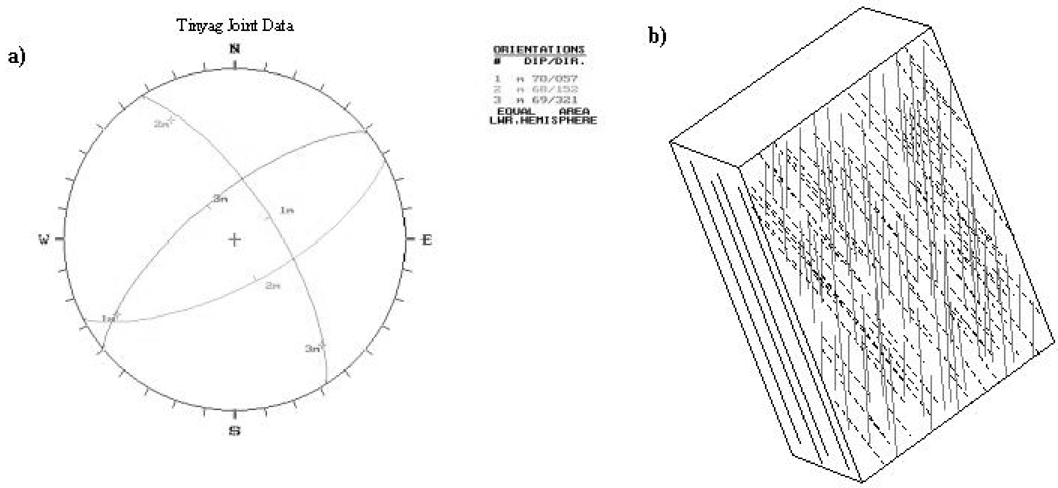

Figure 3 Major planes of the ore and walls rock masses and b) scheme of the rock mass structure.

2.3.2. Rock mass quality and rock strength

RMR has been used to characterize the quality of the rock masses affecting the mine, starting from the data of the Department of geology. A verification process was carried out by comparing these data with in-situ data from Tinyag open pit. In Table 1 the average values of the RMR for the different rock masses are presented. Also the average compressive strength (U.C.S.) of every rock as estimated from Schmidt hammer rebounds, geologist hammer response and some laboratory tests –when possible- are included in Table 1. Finally average values from the Hoek parameter m_i are given as obtained form laboratory triaxial testing –if possible- or assessed from literature. Once considered all this topics and possible presence of joints, every rock is assigned a material behaviour model (Mohr-coulomb, ubiquitous joint or strain-softening) and the basic parameters are calculated according to standard techniques (Rocscience, 2002) and shown on Table 2.

Table 1 Rock mass quality, compressive strength and m_i value of the different rocks encountered.

Rock Mass	RMR	U.C.S (MPa)	m_i
Pyrite	26	5	10
Sandstone	30	15	15
Marl	32	20	40
Quartzite	45	55	20
Ore	38	20	12
Skarn	40	25	15
Mudstone	43	50	6

Table 2 Basic geomechanical information for the different material involved in Tinyag mine.

									JOINTS	JOINTS	MODEL
	RMR	density	E	Poisson	bulk	shear	cohesion	friction	cohesion	friction	
		kg/m^3	MPa	-	MPa	MPa	kPa	°	kPa	°	
pyrite	26	2600	285	0,3	237,50	109,62	80	24			mohr
sandstone	30	2400	1500	0,28	1136,36	585,94	120	28	53	30	ubiqu
shale	32	2000	620	0,28	469,70	242,19	100	24			mohr
quartzite	45	2500	2500	0,25	1666,67	1000,00	180	31	66	30	ss
ore	38	3400	1010	0,28	765,15	394,53	130	31	63	32	ss
skarn	40	2500	1600	0,28	1212,12	625,00	130	31	74	30	ss
mudstone	43	2400	1800	0,26	1250,00	714,29	140	29	3	27	ubiqu

3 Mine design

Tinyag orebody represents the continuation towards south of the Limpe Centro deposit. This body is around 200 m long. Tinyag is 15 to 25 m thick. The ore is disseminated in a skarn and it forms massive sulphide bodies. The grades are 7.7 % zinc for Tinyag. In what concerns the country rocks: pyrite, oxides and silica horizons with quartzite and marl appear sequentially in the hanging-wall. Beds of pyrite, mudstone, altered mudstone and shaly sandstone appear sequentially in the footwall.

Since the body was almost outcropping, its mining was performed by means of open pit mining, representing around 20 % of the ore entering the plant. The rock mechanics program focused on the design and on the control of open pit slopes. Final general slopes varied between 42 to 49º dip, with 6 m high benches inclined between 55 and 60º. In the western walls of the Tinyag pit, it has been necessary to use cable-bolts in order to reinforce the stratified rock dipping toward the slope. The Tinyag pit has already been mined out up to its economic bottom (Figure 1.c).

3.1 Mining method selection

Since there is still ore below the pit, the underground mining of the lower part of this ore-body was decided. The mine method selection could be based in the method by Nicholas & Marek (1981) to find that sublevel caving is a suitable option. If we take also into account the average operational costs we would find that after block and panel caving (unsuitable for seamed deposits), room and pillar (not reasonable for sub-vertical deposits) and sublevel stoping (inconvenient for low strength rocks); the cheapest mining method would be typically sublevel caving (Krstulovic & Ovalle, 2004).

3.2 Sublevel Caving Design

3.2.1. Basics

The experience of the authors is that in deposits such as Tinyag orebody, and due to the bad quality of the hanging wall, the sublevel caving (SLC) method is probably the cheaper underground method.

To define the geometrical features of the SLC method to be applied, the size of drifts is a good starting point. Since in the Iscaycruz mining unit, Tinyag is the third underground mine opened, it has been considered convenient to keep constant size of drifts, drift advance equipment and other characteristics; to facilitate changeability of workers and machines. Therefore 3.5 m wide and 3 m high drifts will be used. This size is compatible with the use of standard load (4 yd^3 scoop-trams) and perforation (SIMBA-H281) equipment. This size will be increased up 4 m x 4 m high in straight ramp zones and 5 m wide x 4 m high in ramp curves.

Together with classical literature (Kvapil, 1992; Bull & Page, 2000; Laubscher, 1994; Rustan, 2000) and in order to define the most suitable geometrical design for Tinyag SLC, the experience of the authors basically comes from the design of Rosaura Mine (Córdova, 2004). This is a mine with a similar ore type where physical models of the behaviour of ore were performed (Figure 4.a), suggesting the following widths and heights of the extraction ellipsoids –later in-place confirmed-, which are compared to classical Kvapil (1992) results in Table 3.

Table 3 Experimental curves of the extraction ellipsoid. Width (W) versus Height (H)

Kvapil (1992) - standard		Rosaura results – physical modelling	
W	H	W	H
5	18.6	5	22.3
5,5	19,3	5,5	23,2
6	20	6	24
6,5	20,9	6,5	25
7	21,2	7	26

To introduce a numerical approach to the topic of the estimate of the extraction ellipsoid accounting for the orientation of discontinuities in the rock mass, the discrete element method UDEC (Itasca, 2005) is used to model a cross section of a draw point where the ore is extracted by blasting and gravity flow. The model was built considering three joint sets that regularly divide the rock mass into blocks. Blasting is simulated setting the cohesion of the material joints to zero, letting the blocks to slide freely into the opening. After blasting, the material flows by due to gravity it is extracted periodically from the opening. The geometrical features of the ellipsoids are reasonably recovered (Figure 4. b). This opens a research line to study the role of spacing and dilation of joints and the interactive draw. Obviously more advanced modelling techniques have been applied to this problem (DeGagné & McKinon, 2005; Pine et al., 2006) but some of them do not account specifically for discontinuities, which the authors believe, may play a non-negligible role.

3.2.2. Initial design. Longitudinal SLC

Since the tabular orebody was not particularly thick, but its continuity was quite good, in a first approach (Krstulovic & Ovalle, 2004) the longitudinal SLC method was considered flexible enough to mine Tinyag. The longitudinal version of the SLC was also able to suit the irregularities and discontinuities of the mass. The hanging wall in Tinyag is very weak. This contributes to a good caving behaviour of the rock but increases dilution, which should be controlled at all times.

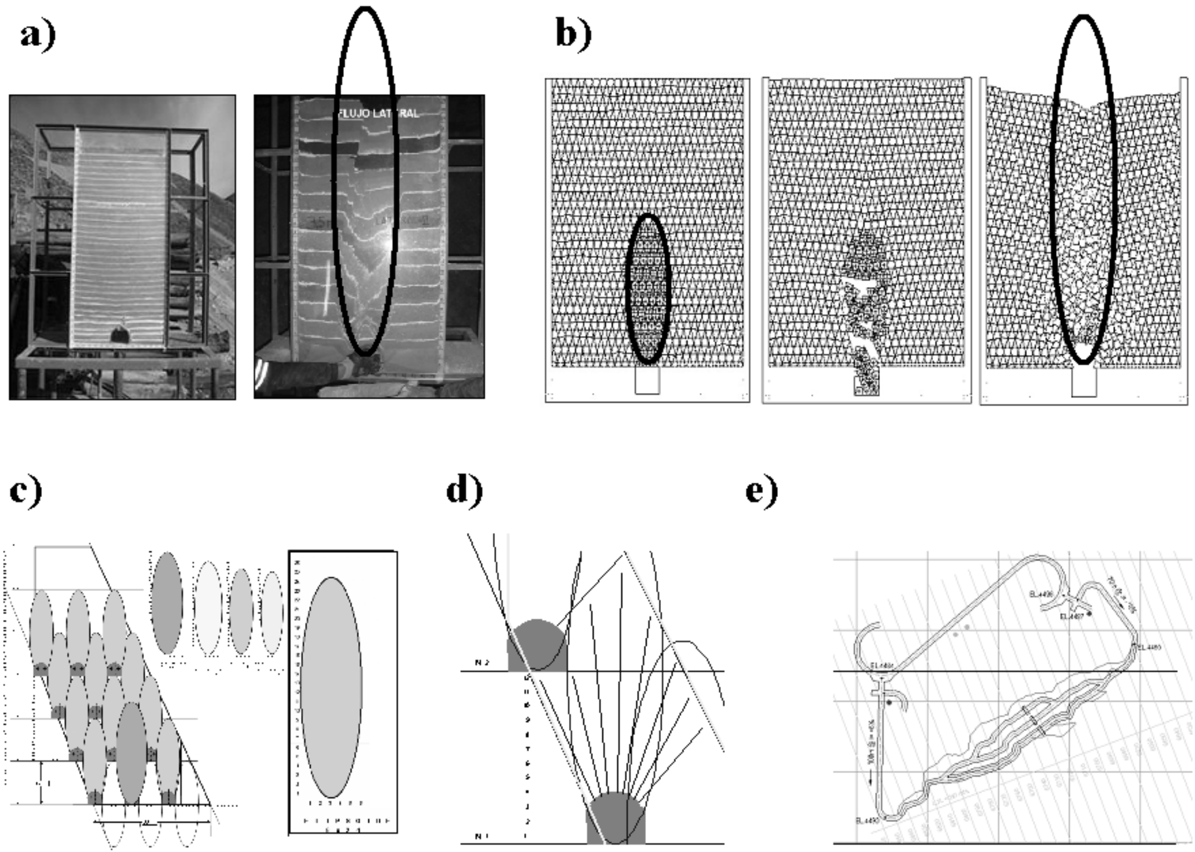

Figure 4 a) Physical modelling of the extraction and loosening ellipsoids for Rosaura mine. b) UDEC verification of the extraction ellipsoid for Tinyag. c) Estimate of the extraction ellipsoid for the thicker part of Tinyag for longitudinal SLC. d) Drill ring scheme in a narrow zone of Tinyag seam e) Plan view of the longitudinal SLC design for Tinyag in an particular level.

With the corresponding sizes of the extraction ellipsoids and in Figure 4.c (Krstulovic & Ovalle, 2004) it is graphically shown the interacting of the extraction ellipsoids, with the geometry of the seam (in its thickest part), in order to define the sublevel height. Most of the ellipsoids correspond to 24 m high and 6 m wide case, as shown in table 2. Based on this geometrical approach, with extraction ellipsoids as defined in Table 3, the nominal quantity of ore and the dilution was calculated for various sublevel heights to find that to minimise dilution 11 to 12 meter high sublevels would be in order.

Balancing mining cost and recovery-dilution, it was decided to choose the 12 m height. This figure also coincides with the sublevel height of the contiguous cut & fill 'Limpe-Centro' mine and permits to keep the longest drill under 15 m, operational features very helpful for the overall mining company daily work.

This low figure of sublevel height for the improved SLC design (Bull & Page, 2000) is a geometric result due to the low dip and moderate thickness of the seam, and the low geomechanical quality of the hanging-wall. The gravitational flow of the material close to the hanging-wall will produce in little time high dilution, so reduced sublevel height is a must. In the case of the Rosaura mine, 20 m high sublevels were used. This figure applied to Tinyag would result in low recovery and high dilution.

For the longitudinal SLC strategy, the first drift should be located 1.5 m towards and inside the foot-wall (measured in the floor) to maximize the ore extraction and to allow the last drill of the ring to be parallel to the seam dip (Fig. 4.d). Once fixed the location of the first production drift (draw-point) and in order to minimize dilution the free distance between drifts must be in the range of the extraction ellipsoid width (namely 6 m). This distance should be reduced to produce a small overlap between ellipsoids to ensure full recovery, so it is suppose to be equal to 5.5 m. Therefore the distance between drifts is fixed in (5.5 + 3.5 =) 9 metres. The typical blast ring will be made by 8 2.5'' drills completing 82 metres drilled per ring (Fig. 4.d). A two metre slice will be mined for every ring and the vertical and longer drill will be 15 meter. In one blast ring 1700 tons are to be recovered meaning 20.6 ton/drilled m. It was also shown that it was not interesting locate a drift closer than 3 m to the hanging-wall for it will only serve to recover waste. Therefore for the Tinyag seam the number of production drifts was set to 1 (for seam thickness between 3 and 15 m), to 2 (for seam thickness between 15 and 24 m) and to 3 for thicker areas and up to maximum observed (around 30 m). A plan view of the location of the extraction drifts in a particular level of the mine is shown in Figure 4.e for this possible initial design of longitudinal sublevel caving.

3.2.3. Final mine design. Transversal SLC

With the previous report in mind (Krstulovic & Ovalle, 2004), and before starting the underground operation in Tinyag it was reassessed the possibility of use the transversal SLC instead of the longitudinal one. Eve if it was clear that the preparation costs were much lower (around 30 %) for the longitudinal SLC, the flexibility of this last method was very low in such a way that three sublevels should be always opened if the production was to be assured at all times, as it was required. Therefore, it was decided that although the costs were higher it was preferred to opt for the transversal sublevel caving method. The distance between draw-point was kept to 9 m, and the rest of basic design parameters were also kept (Fig. 5.a). This transversal version also permits to interactively draw as suggested by Page & Bull (2000), which helps to improve the recovery levels. A final view of the mine method design is presented in Fig. 5 b. With the presented geometrical values and the transversal SLC, the mining of Tinyag started in 2006. Even if in the first levels the degree of dilution was extremely high, now satisfactory results are obtained. So far, 85 % recovery of the ore has been achieved with dilution, not yet well determined, but in the range of 18 to 22 %, which is a reasonable figure for SLC.

3.3. Critical points on sublevel caving design

There are a series of critical topics of much interest which should be addresses if one ones to ensure the future mining in Tinyag, which are also important for any SLC exploitation. These topics includes the subsidence effects, the possibility of occurrence of a circular or similar failure typically in the hanging wall of the seam and finally possible problems derived form the incorrect location of the infrastructure of the mine (ramps, ventilation shafts, skip if existing), which can be affected by rock mass movements in the advanced mining stages. These aspects are addressed under the following subheadings.

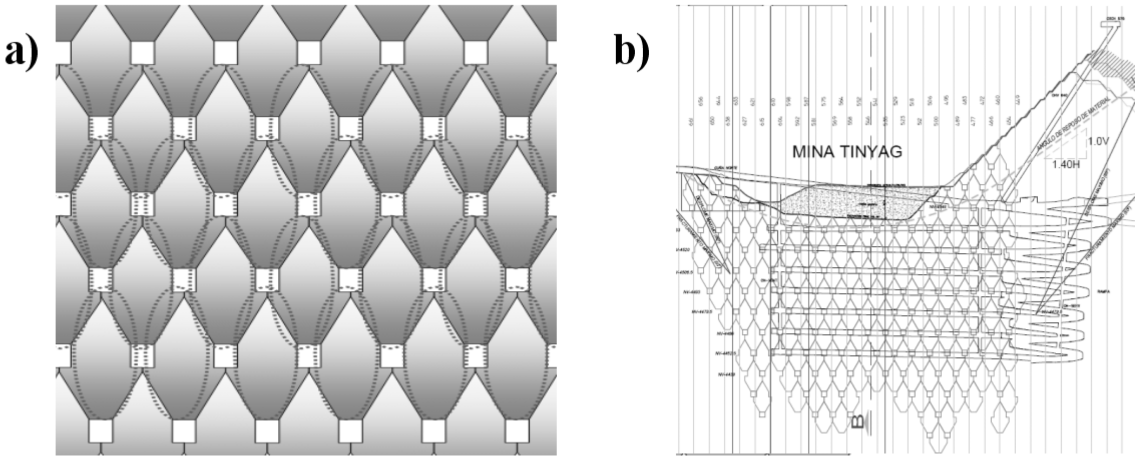

Figure 5 a) Basic "improved" SLC design for Tinyag mine and following Bull and Page (2000) and b) General view of the mine design for Tinyag transversal SLC.

3.1. Subsidence

In not very thick ore seams with tabular shape the propagation of subsidence use to be controlled by the dilation of the caved material, which fills the shape created by mining. A consideration of the subsidence topic is a must when planning a SLC mine. This topic has been studied form the early seventies (Hoek, 1974) and many references can be found on the topic. Typically a fracture and falling limit angles are considered to estimate the area of surface affection. These angles have been studied in a number of Chilean mines (Karzulovic, 1990), where these values are correlated with the basic RMR of the affected rock masses (Figure 6.a). This was estimated for the case of the Tinyag open pit as shown in Figure 6.b.

The affected area was considered as reasonable initially. Nevertheless, and in the early development of the SLC mining, various problems were identified in the old Tinyag pit, including early funnelling or chimney caving (Figure 7.a) and a trend to tensile cracking and toppling in the quartzite east slope. (Figure 7.b & c)

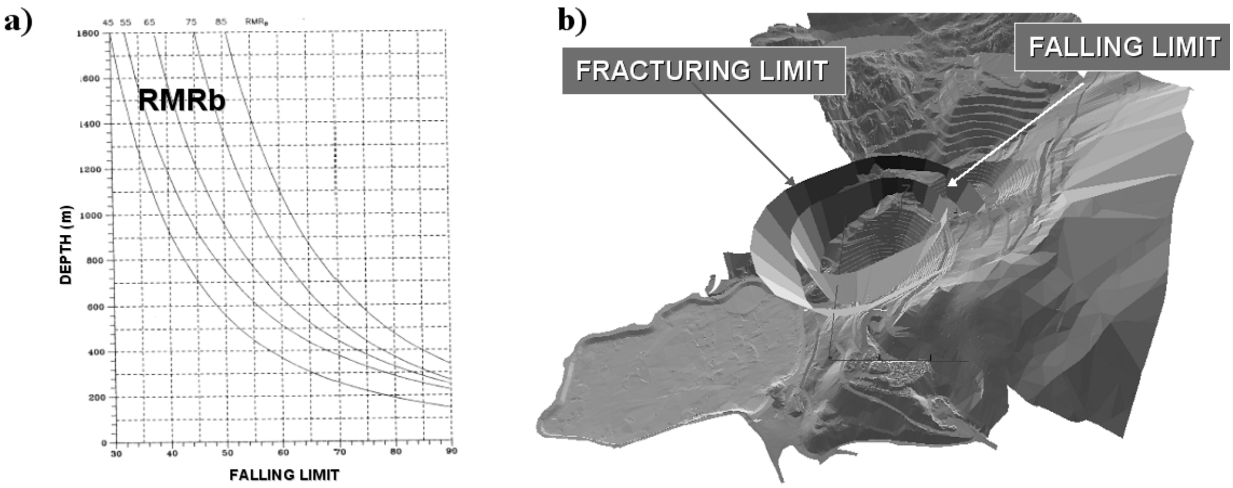

Figure 6 a) Estimate of the falling angle limit as developed by Chilean researchers and b) estimate of falling and fracturing affection for the case of Tinyag SLC.

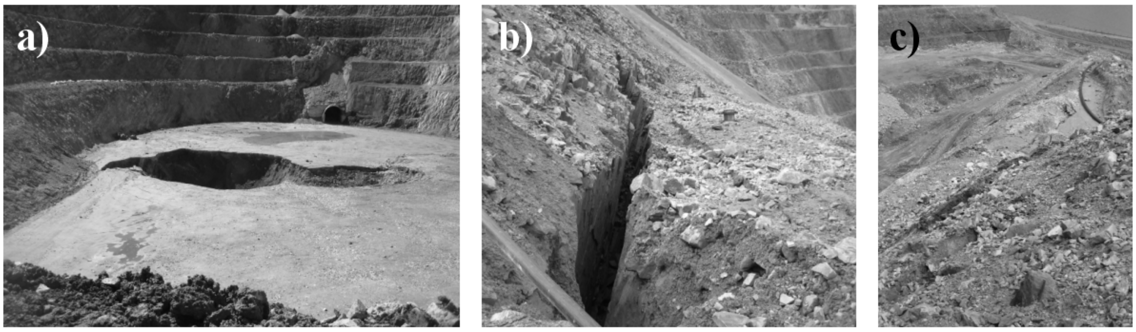

Figure 7 Early affections of subsidence in Tinyag: a) Chimney caving in the floor of the Tinyag pit a few weeks after underground mining SLC started, b) Tensile opening of bedding planes in quartzite due to toppling in the east slope and c) detail of toppling in the east open pit wall.

In order to control these affections it was thought that if the waste of final excavations in the open pit Rosita was used to fill the bottom of Tinyag mine eventually the deformation and caving expected can be mitigated. The interest of this possibility was numerically analysed. Starting form the experience of the authors in numerical modelling of subsidence (Alejano et al., 1999), various models were run with the material models and parameters as shown in Table 2. In particular Phase-2D comparing also the cases with and without fill were run, where it was shown that the filling of the bottom of the pit highly reduce the displacement in the upper parts and therefore the deformation (Figure 8.a). For the case of code Flac-2D, even if the results must be yet refined and new behavioural characteristics should be yet included (for instance the role of dilatancy of rock masses should be taken into account), some of the observed instability mechanism have been observed (Figure 8.b). Even if these numerical models should be interpreted qualitatively so far, they indicate that a great deformation should be expected. However this deformation is mitigated when filling the pit. This was done with the waste from Rosita open pit in its final excavation stages.

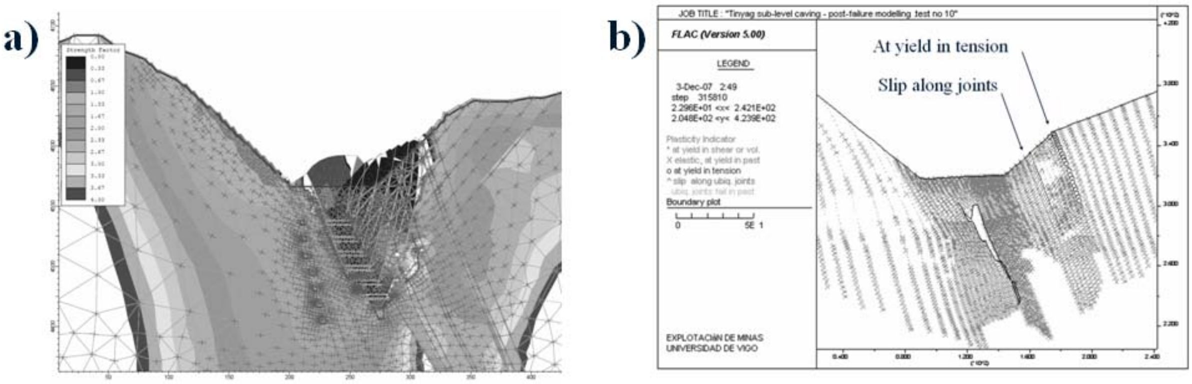

Figure 8 Longitudinal numerical modelling of Tinyag: a) Phase-2D detail model in 8 stages of mining, substituting ore by caved and fractured material and b) Flac-2D simulation of the process of caving where the main instability mechanisms are identified, a further refinement of the model is needed to interpret it in a quantitative way.

3.2. Circular slip failures

Another critical topic is the possible occurrence of circular slip failures of the slopes of the mountains and pits and attaining the underground works. In a Flac model, the shear strength of the materials was reduced , in order to find out that the safety factor of such a possibility is over one, however a topographical control of some points in the east and west slopes was recommended, specially for advanced stages of mining.

3.3. Infrastructure

The main access (ramp) and ventilation shafts must be located in the best possible rock. The quartzite rock mass is the most suitable one due to its bets geomechanical quality and unconfined strength characteristic.

4 Conclusions

We have highlighted the different topics of the rock mechanics and mining work leading to the design and starting of the operation of Tinyag mine in Iscaycruz by means of the transversal version of the sublevel caving underground mining method.

Geomechanics has been and is of paramount interest to design and fine-tune the mining method. A series of open questions have been adequately solved to start to run the mine. Subsidence, circular slip and infrastructure location are critical points for sublevel caving, that have been addressed with standard but strongly rock mechanically based approaches to find out that the applied design methods, though limited if compare to high developed techniques (Brown, 2003), can yield good results in the general mining operation. A wide experience has been gained in the difficult task of appropriate mining method selection for Andean sub-vertical metallic seams, according to the country rock geomechanical conditions. In Tinyag mine, so far, 85 % recovery of the ore has been achieved with dilution, not yet well determined, but in the range of 18 to 22 %, which is a reasonable figure for SLC.

Future work includes the refinement of the presented numerical models (including extraction ellipsoids with UDEC), more detailed dilution control in place and the establishment of dilution policies, and the monitoring and control of surface displacements, with the aim of controlling the numerical models applied.

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