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Multi-level modelling in block/panel caving mining: A case study at El Teniente mine

F. Celhay[a], D. Bustmante[a], R. Castro[b], L. Arancibia[c], A. Latorre[a] and F. Hidalgo[a]

[a]*Codelco, Chile*

[b]Universidad de Chile, Chile

[c]BCTEC Engineering and Technology, Chile

ABSTRACT

In mines using Block/Panel Caving, more than one extraction level is mined, often by design, with new levels of extraction below previously extracted ones. In those areas interacting with the extraction of a lower level, the characterization of the remaining mineral or broken ore becomes crucial because it should influence both ore extraction in the lower sectors and its recoverable grades. One mine that has faced this issue is El Teniente Division (DET) of Codelco. This mine, located in the high Andes of Chile, has been in operation for over 100 years, and with more than 8 extraction levels, a significant amount of remaining/broken ore has resulted over the years. To characterize the broken ore's remaining grades, a methodology was developed using caving/flow modelling, conciliation with extracted grades at drawpoints, a drilling campaign, and topography measurements. DET used the gravitational flow software FlowSim BC v6.3, which yielded errors of less than 5% when modeling was compared with actual conditions. These findings underscore the efficacy of this modeling approach in providing greater certainty for long-term mining planning in operations utilizing multi-level caving.

1. INTRODUCTION

El Teniente is the largest underground copper mine in the world and the sixth-largest copper mine in terms of reserve size. The mine is located approximately 80 kilometres south of the city of Santiago and 50 kilometres east of the city of Rancagua, between 2,200 and 3,200 meters above sea level.

Division El Teniente (DET) has a long history of underground extraction that began in 1914, with mining methods like sublevel stoping, which have evolved into caving methods. Initially, extraction was done through grizzlies for rock with low fragmentation. As the rock quality improved, ore was extracted using LHDs with more spaced extraction layouts.

As a strategic objective, DET has implemented the extraction of resources from broken ore. The main challenges for this objective include estimating the resources present in the broken ore and finding a methodology that can do so. Currently, DET plans to extract 20% of broken ore in its long-term plan (PND, 2023). To achieve this, DET needed to enhance its methodology for estimating resources in broken ore and optimize the blending model used in its planning processes.

Following the framework established by Laubscher (1994), DET had been using a methodology based on vertical blending for resource estimation. While this methodology has enabled the estimation of broken ore in recent years, it does not account for relevant flow mechanisms in caving mining, such as lateral displacements, fines migration, and rilling.

In this study, the FlowSim BCv6.3 tool was used to estimate resources in broken ore, and the results of the modelling were subsequently compared to actual conditions for accuracy. This FlowSim BCv6.3 tool explicitly simulates gravitational flow through multiple mechanisms such as extraction zone geometry, voids in the ore pile, preferential flow through structures, caving propagation, and surface and internal rilling (Castro et al, 2018; Castro et al, 2020; Castro et al, 2022; Le-Feaux et al, 2022; San Martin et al, 2022).

2. METHODOLOGY

For the resource estimation, an update of the total inventory in DET was conducted covering extraction from 1914 to 2021 using the FlowSim BC v6.3 software to simulate the extraction and mineral blending process of the block/panel caving method. The FlowSim results were then compared with the actual results for accuracy.

2.1 FlowSim BC

FlowSim is based on the numerical method of the Cellular Automata (CA) approach, which is a system of cell objects with the following characteristics:

- Grid/space – The equally sized cells are discretized in blocks having a dimension of 2m × 2m × 2 m or 4m x 4m x 4m.
- State – Each block could have one of three states: granular, solid, or void. In the granular state, blocks can move while their density is equal to the solid density of the rock mass. In the solid state, blocks cannot move even if there is space to fall into. Void blocks have zero density and are generated at the drawpoints by the draw process. The state of a block may change from granular to void and from solid to granular. In FlowSim, a parameter $Cijk$ represents the state of each block placed in a specific location (ijk) within the grid. $Cijk$ may have the value of -1, 0 or 1 which shows the solid, granular or void state, respectively.
- Neighbourhood – This is the basic cell arrangement around a void cell where the transition function is applied (Figure 1).
- Transition function – This local invariant mathematical rule is applied during the simulation for the movement of blocks. FlowSim applies two different transition functions; one for unconfined or surface flow (material at the repose angle outside the drawpoint) and the other for confined or gravity flow (associated with the movement of particles generated by the space created by other in-contact particles). The transition function for gravity flow is defined by the flow probability using the following equation (Castro et al, 2021):

$$P_i = \frac{d_i^{-n} * d_{50,i}^{-m}}{\sum_{k=1}^{9} d_k^{-n} * d_{50,k}^{-m}}$$

where:

$dk =$ distance between the void cell and the cells in the top level,

$d_{50} =$ fragmentation parameter which is related to the flow characteristic of the block. The variable takes the value of d_{50}, which means the size below which 50% of the blocks are found,

$n =$ adjustment constant related to the overall flow behaviour of the caved rock. Increasing this parameter leads to a narrower movement/extraction drawzone, and

$m =$ preferential flow parameter related to the potential for fines migration (blocks with a lower fragmentation measured as d_{50}). The larger the value of m, the larger is the probability of fines migrating to the void.

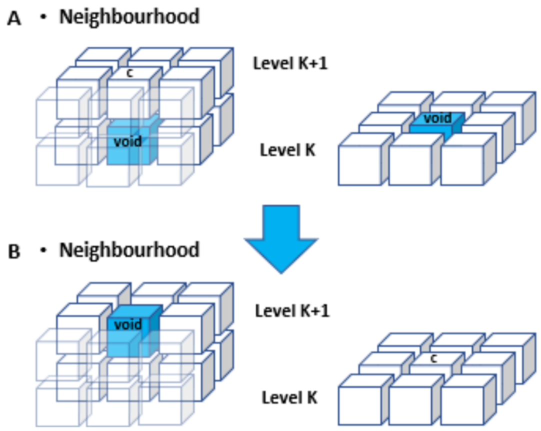

Figure 1 Schematic view of the neighbourhood blocks and upward movement of the void cell; (a) Before extraction; and (b) After extraction.

It should be noted that the transition function is only applied if there is a minimum number of voids (Cv). This parameter restricts the voids' diffusion process and is related to the swell factor. If Cv = 0, then the voids will migrate upwards without restriction, and the swell factor is zero. This mechanism has been demonstrated to replicate the evolution of the movement zone as shown in experiments (Castro 2006).

In Block Cave mining, the rock fragmentation during extraction is mostly generated naturally as the broken ore is extracted from the drawpoints (Laubscher, 2000; Brown, 2007); this process is called secondary fragmentation. FlowSim BC incorporates an internal secondary fragmentation mechanism based on experimental observations (Gomez & Castro, 2022). This secondary fragmentation model considers a reduction rate (R50), which relates vertical stress (σv) to uniaxial compressive strength, as shown in the following equations:

$$R_{50} = \frac{d_{50,i} - d_{50,f}}{d}$$

$$R_{50} = \alpha\left(\frac{\sigma_v}{UCS}\right)^{\beta}$$

where

R_{50}: Reduction rate of d50 in m/m

$d_{50,i}$: Initial d50 size [m]

$d_{50,f}$: Final d50 size [m]

d: Distance travelled by the evaluated block

σ_v: Vertical stress [MPa]

UCS: Uniaxial compressive strength [MPa]

α, β: Adjustment parameters.

This secondary fragmentation mechanism is calibrated through comparisons with mine data (Castro et al., 2024).

2.2 Broken estimation for sector

The sector/mine simulation methodology consists of 4 stages, which are shown below in

Figure 2.

The simulation covers extraction from 1914 to 2021, covering more than 10 levels as shown in Figure 4, Figure 5 and Table 1.

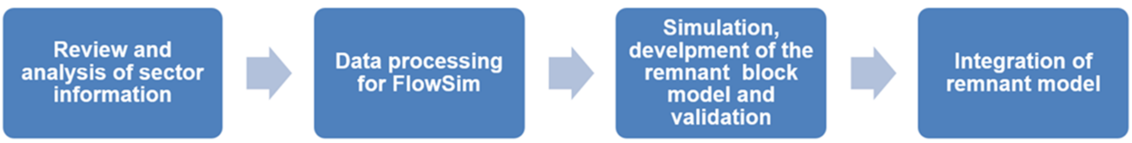

Figure 2 Methodology for estimating broken resources using FlowSim BC.

Stage 1 (Review and analysis of sector information): It is necessary to review the ubication of drawpoints, the geometry of the drawbells, extraction, and daily grade. In both cases, a connection is made between the in-situ block model and the remnant block model.

Stage 2 (Data processing for FlowSim BC): The data provided by DET need to be processed to be simulated in FlowSim BC.

Stage 3 (Simulation, development of the remnant block model, and validation): To obtain the remnant model of each sector, each sector must be calibrated. To do this, various flow models associated with the rock type of each sector are simulated.

Additionally, to validate the remnant/broken block model, comparisons are realized with grades and tonnages extracted for each sector, measured topography, and conducted drillings.

Stage 4 (Integration of the remnant model): FlowSim BC provides a 20x20x20 m³ block model, which is integrated into the in-situ block model to simulate the lower sector, as shown in Figure 3.

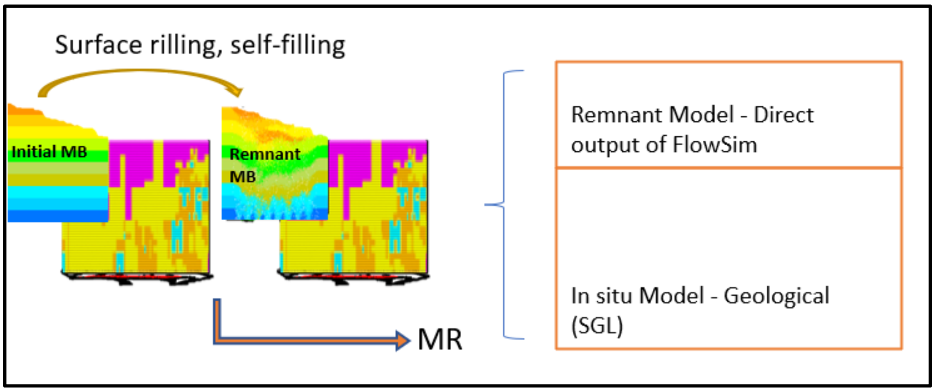

Figure 3 Integration of the remnant/broken model with the in-situ model.

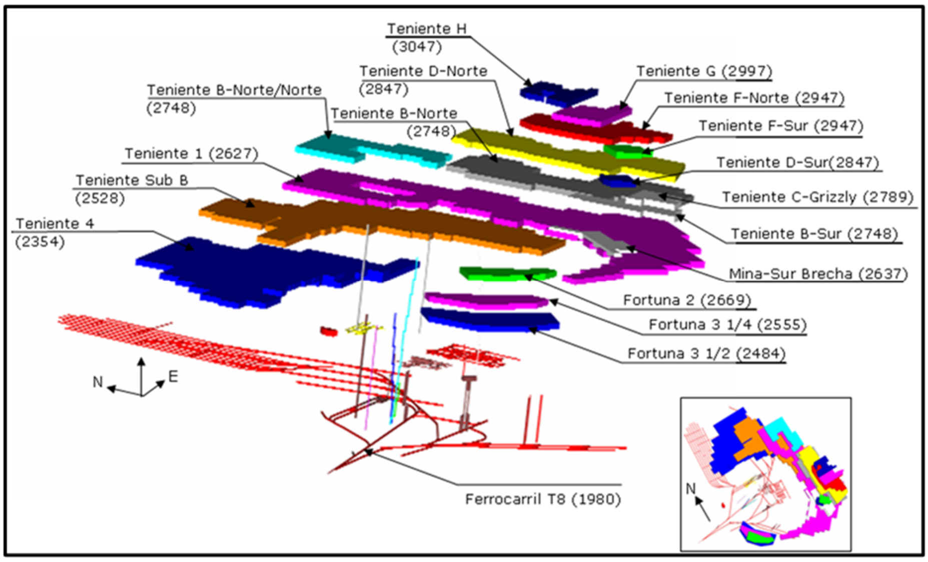

Figure 4 Sectors simulated up to 1994.

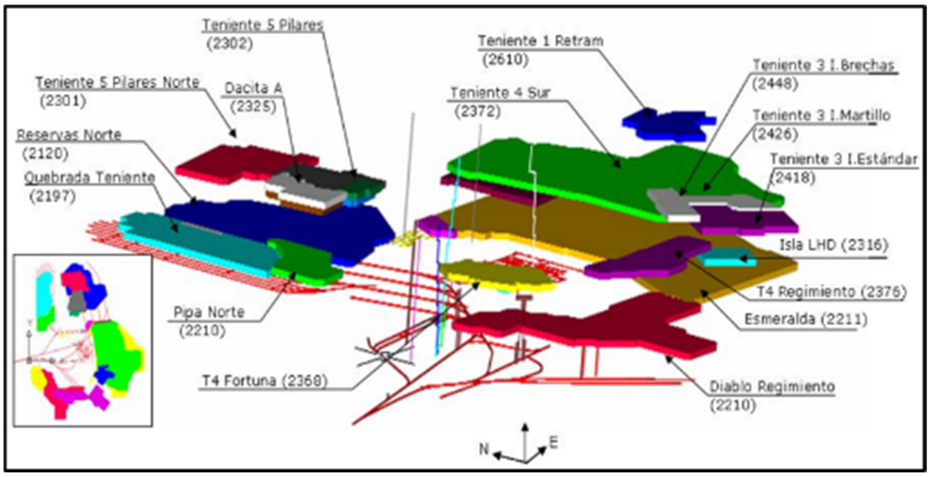

Figure 5 Sectors simulated from 1994 to 2021.

Table 1 Sectors simulated in DET

Sector	Elevation UCL	Extraction start year	Reported tonnage (t)
Fortuna 2	2669	1914	717,000
Fortuna 4 Sector Bornita	2361	1919	292,834
Fortuna 3 1/4	2555	1920	7,080,721
Fortuna 3 1/2	2484	1921	2,589,642
Teniente H	3047	1926	7,758,537
Teniente G	2997	1927	6,640,011
Teniente F	2947	1935	17,552,355
Teniente D	2847	1941	23,313,380
Teniente B	2749	1949	83,477,872
Teniente C	2789	1959	6,820,525
Teniente 1	2627	1971	190,133,010
Teniente TSB	2534	1981	125,945,950
Teniente 4 Sur	2372	1984	301,106,527
Rajaduras 4 Sur	2372	1984	8,445,895
Fortuna and Puente	2369	1986	51,181,882
Sur Brecha	2637	1989	1,860,123
Teniente 5 and Dacita C	2301	1989	29,623,901
Reservas Norte and Dacita	2126	1989	238,312,139
Paneles 4 Sur	2341	1991	27,577,754
Regimiento	2376	1992	56,084,445
Teniente 4 Norte	2354	1994	221,670,512
Islas Martillo and Estandar	2426	1994	55,822,555
Fortuna Subnivel	2323	1994	1,041,985
Dacita A and Dacita B	2301	1994	2,751,070
Quebrada Teniente, Pacifico and Andes	2198	1994	75,766,457
Isla Brecha	2448	1995	18,938,056
Esmeralda Convencional and extensions	2211	1997	140,957,387
Isla LHD	2316	2002	5,909,596
Sur Andes Pipa	2207	2003	13,244,667
Diablo Regimiento	2211	2005	115,555,123
Panel Reno	2088	2005	10,273,109
Pipa Norte	2207	2009	39,506,524
Pilar Norte	2120	2010	8,553,240
Esmeralda Bloque 1 and 2	2211	2011	89,251,387
Panel Esmeralda	2179	2012	15,470,775

Pacifico Superior	2265	2016	11,995,105

3. RESULTS

Three types of comparisons were conducted to validate the broken resource model. These were tonnages and grades by sector, drillings, and topography.

3.1 Tonnages and grades by sector

For each sector, DET reports the amount of extracted tonnage and the extracted copper grade. Each sector was simulated using FlowSim BC v6.3 to minimize the error in copper grade, taking into account the specific characteristics of each sector.

The results of comparing grades in the simulated sectors are presented below in Table 2.

Table 2 Summary of grade comparison by sector

Sector	Real tonnage (t)	Simulated tonnage (t)	Real Fine Cu [%]	Simulated Fine Cu [%]	Copper grade error [%]
Teniente H	7,758,537	7,794,932	183,102	184,139	+0.1
Teniente G	6,640,011	6,675,093	148,697	153,335	+3.0
Teniente F	17,552,355	17,639,575	397,616	390,440	-2.3
Teniente D	23,313,380	23,467,172	467,187	459,580	-2.3
Teniente C	6,820,525	6,840,334	111,655	101,234	-9.6
Teniente B	83,477,872	83,828,180	1,744,688	1,737,269	-0.8
Fortuna 2	717,000	722,989	16,491	12,511	-24.5
Sur Brecha	1,860,123	1,880,920	34,851	36,626	+3.9
Teniente 1	190,133,010	191,133,010	3,645,336	3,458,887	-5.3
Fortuna 3 ¼	7,080,721	7,127,426	153,645	115,367	-25.4
Teniente TSB	125,945,950	127,814,217	2,328,692	2,285,709	-1.2
Fortuna 3 ½	2,589,642	2,605,219	54,534	45,652	-16.5
Teniente 4 Norte	221,670,512	223,329,019	3,566,901	3,572,943	-0.1
Teniente 4 Sur	301,106,527	302,205,632	3,262,444	3,319,636	1.0
Isla Brecha	18,938,056	18,986,128	273,347	283,500	3.7
Fortuna and Puente	51,181,882	51,336,800	469,119	402,821	-6.7
Regimiento	56,084,445	56,268,734	486,413	465,839	-5.3
Fortuna 4 Sector	292,834	296,261	6,445	5,417	-17.0
Islas Martillo and	55,822,555	56,051,331	789,009	677,047	-14.2
Pacifico Superior	11,995,105	12,033,696	124,065	127,329	2.4
Fortuna Subnivel	1,041,985	1,043,911	12,389	6,748	-45.3
Dacita A and Dacita B	2,751,070	2,751,078	40,476	40,764	0.7
Teniente 5 and Dacita	29,623,901	29,781,139	389,887	386,022	1.0
Paneles 4 Sur	27,577,754	27,626,970	265,796	284,968	7.0
Quebrada Teniente,	75,766,457	76,488,614	928,458	923,314	-0.6
Rajaduras 4 Sur	8,445,895	8,492,102	106,580	121,479	13.1
Pipa Norte	39,506,524	39,656,814	375,722	364,276	-3.0
Sur Andes Pipa	13,244,667	13,283,735	155,880	153,709	-1.4
Reservas Norte and	238,312,139	239,076,887	2,668,207	2,662,666	-0.2
Isla LHD	5,909,596	5,939,178	67,721	64,273	-5.1

Esmeralda Bloque 1	89,251,387	89,583,539	866,679	873,265	0.8
Esmeralda	140,957,387	141,381,245	1,550,920	1,542,140	-0.6
Diablo Regimiento	115,555,123	115,914,387	975,954	981,002	0.2
Panel Esmeralda	15,470,775	15,517,486	160,858	169,887	5.2
Panel Reno	10,273,109	10,300,665	98,519	90,468	-8.2
Pilar Norte	8,553,240	8,580,872	94,786	101,330	6.5
Total	2,013,222,051	2,023,455,290	27,023,069	26,601,592	-1.6

Most sectors have an error below 5% in comparison with the copper grade, except for the Fortuna sectors. When comparing globally, there is a 1.6% error in the copper grade.

3.2 *Drillings*

Between 1993 and 2014, a total of 16,043 meters of drilling were carried out in the Broken Material unit from both surface and underground locations. Sampling support was predominantly conducted at 2-meter intervals. The estimation was carried out using only drilling samples from the broken material with a search radius of 100 meters and a minimum of 4 samples. The model was restricted to the location of the drillings, for which a volume was created for each group of drillings using the polygon and floor and ceiling elevations, as shown in Figure 6.

Comparisons were realized between the drill hole block models developed by the DET and the FlowSim BC´s broken block models. Table 3 shows the results of the comparison between the drillings and the remnant grades from the broken models.

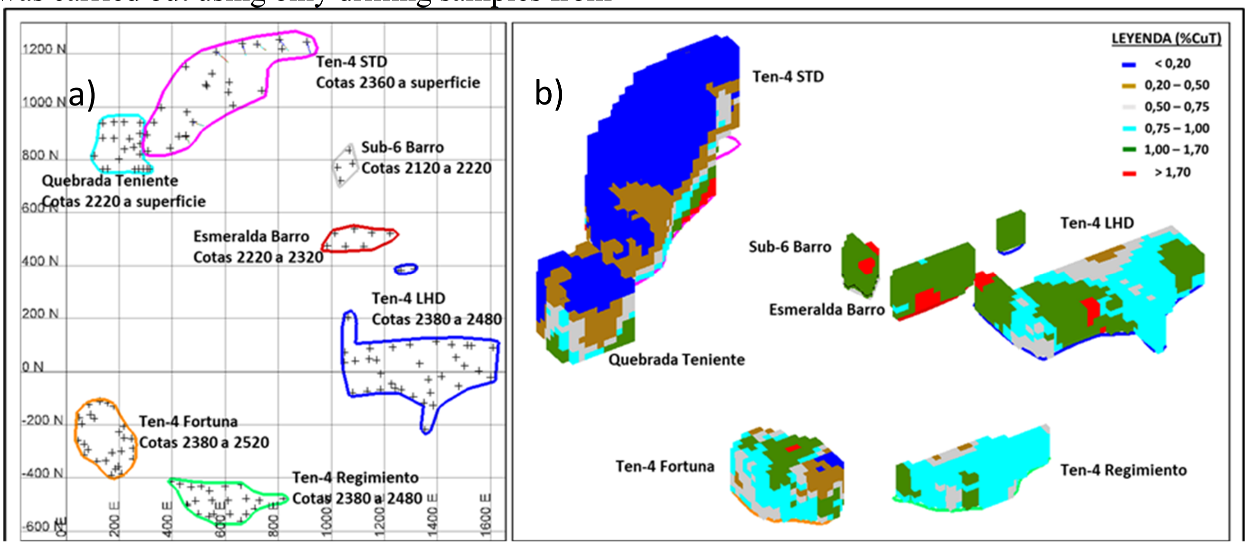

Figure 6 a) Consolidated model's limit; b) Drill hole block model.

Table 3 Summary of drilling results

Zone	Mean copper grade error [%]	Mean molybdenum grade error [%]	Mean arsenic grade error [%]
Teniente 4 Sur	1.0	-10.5	-19.7
Teniente 4	-16.3	-12.5	-56.0
Teniente 4 Norte	-24.4	-12.5	-71.0
Teniente 4 Fortuna	-31.9	42.9	-63.8
Esmeralda Barro	-33.3	-66.1	-45.0
QT Biolix	-35.6	-	-

Sub-6 Barro	-61.0	-68.3	-

In the Teniente 4 Fortuna, Teniente 4 Norte, and QT Biolix sectors, the broken block model underestimates copper grade, which could be because the in-situ model underestimated the grade in the upper parts. In Esmeralda Barro and Sub-6 Barro, there is a greater difference, which may be due to a focused draw strategy that occurred.

In the sectors with higher tonnage (Teniente 4 Sur, Teniente 4 Regimiento, Teniente 4 Norte, Teniente 4 Fortuna), there is a good overall reconciliation for molybdenum. In Esmeralda Barro and Sub 6 Barro, the grade from drillings is three times higher than the grade from the broken model, which could also be due to focused draw strategies in that sector.

For arsenic grade, the results are acceptable (error under 50%) in Teniente 4 Sur and Esmeralda Barro. The sectors Teniente 4 Fortuna, Teniente 4 Regimiento, and Teniente 4 Sur show a significant underestimation of the broken model compared to the drillings. This difference is explained because the in-situ model, i.e. the input for gravity flow simulation, was likely underestimated. Then, the simulations contain an error stemming from the underestimated input.

3.3 *Topography*

FlowSim BC incorporates mechanisms of horizontal blending and surface rilling, which allows for a realistic topography. The differences do not exceed a maximum of 60m, with an average between 10m and 20m. Figure 7 shows the comparison realized for Pacifico Superior.

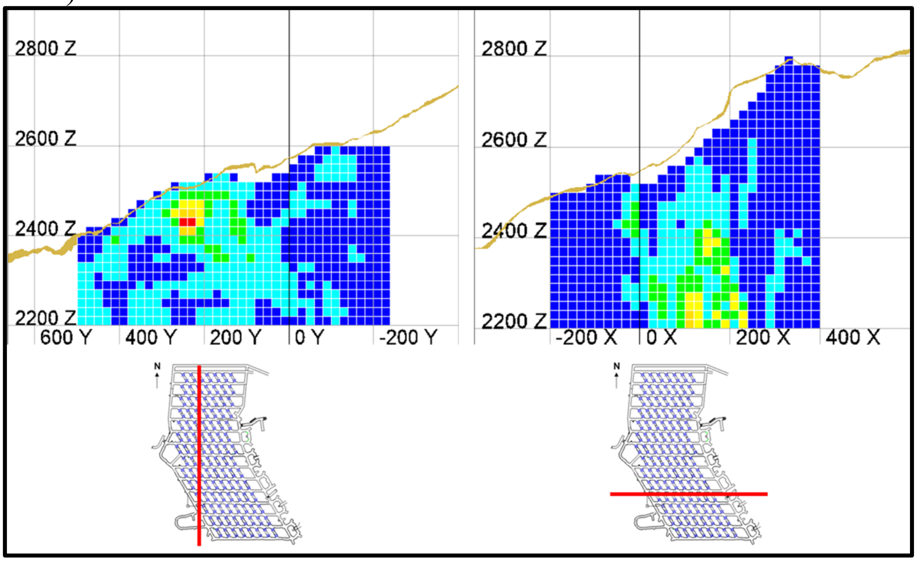

Figure 7 Comparison of topography for Pacifico Superior (BCTEC, 2022).

4. CONCLUSIONS

DET has been using a methodology to estimate resources in broken ore that considers vertical flow exclusively, neglecting other flow/caving mechanisms such as the progression of extraction zones, lateral movements, fines migration, and rilling. The new methodology using FlowSim BC v6.3 for estimating resources in broken ore considers multiple flow/caving mechanisms, resulting in a more robust outcome and enabling the incorporation of a greater amount of broken ore extraction. This methodology has been validated in collaboration with DET, as it has been compared with reported grades in each sector, grades in drillings, and topography, with errors of less than 5% in the simulated sectors. The methodology proposed in this work can be incorporated into other Block/Panel Caving operations that extract at multiple levels to improve estimations for long-term mining planning.

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