Hydraulic Fill Assessment Model Using Weathered Granitoids Based on Analytical Solutions to Mitigate Rock Mass Instability in Conventional Underground Mining

Cristhian Portocarrero-Urdanivia, Angela Ochoa-Cuentas, Luis Arauzo-Gallardo, and Carlos Raymundo

Abstract This study uses analytical solutions to assess a hydraulic fill model based on weathered granitoid to increase underground opening stability and mitigate rock bursts during mining operations in a conventional underground mining company located in the Coastal Batholiths of the Peruvian Andes. This study assesses the previous geological database provided by the mine, analyzes the on-site strengths produced by the exploitation works that will subsequently be filled, identifies the quality of the material used in the landfill (granitoids) through laboratory tests, and compares compressive strength at different depths, all contemplated within the landfill model used. This study focuses on the applicability of hydraulic fills in conventional underground mine using natural geological material such as granitoid.

Keywords Hydraulic fill · Granitoids · Conventional underground mining · Instability · Analytical solutions · Rock bursts

1 Introduction

The mining industry is one of the economic pillars that drive the development of several countries, such as Canada, Australia, and South Africa, relying on innovative

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technologies in open pit or underground mines [1]. In South America, countries such as Chile, Peru, and Brazil have exploited their mining resources for later commercialization. Although large, medium, and small mining operations are developed in some countries, accidents take place across all the mining operations. Some clear examples of these accidents are rock mass instability produced by the extraction of mineral ore, rockfalls, worker slips, trips, and falls, and poisoning–asphyxiation.

This study selected rock mass caused by mineral ore extraction as a key issue affecting conventional underground mining. Within this analyzed context and due to the different problems identified over time, this particular matter was deemed critical for the mining industry because exploited opening instability generates empty spaces subject to various stress and forces that increase with depth, thereby preventing resource exploitation operations. Hydraulic fill is currently used in Peru with several aggregates, such as cement, in large and medium mining operations. However, it is not yet used in conventional underground mining owing to its high cost and additives that must be added to the landfill to increase its resistance. Therefore, this study proposes adapting hydraulic fills with granitoid in a conventional underground mine. At the Marsa mining company located in the Pataz batholith, hydraulic fills were supplemented with granitoid and rock bursts were successfully controlled and safe operation was ensured [2].

This study aims to demonstrate the application of hydraulic fills with granitoid because it is more affordable and adaptable for conventional underground mining operations than other existing solutions, especially because of its short hardening times.

2 State of the Art

2.1 Hydraulic Fill Method in Underground Mining

Several types of research have investigated the hydraulic fill properties in underground mines and concluded that this type of landfill usually settles at a porosity of approximately 40% and its relative densities are in the range of 40–70% [3]. In addition, when settling as a suspension with 65–75% solid content, these landfills are deposited at a dry density of approximately 0.56 times the specific gravity. Furthermore, the permeability of pulp (10–30 mm/h) is much lower than that desired in the mining industry (100 mm/h) [4, 5].

As a part of their results, some authors agreed that hydraulic fills must ensure good drainage so that the excess water may drain quickly. For achieving a good drainage system, the effective size of the D10 grain must exceed 10 μm. Finally, the literature has shown that when hydraulic fills are mixed as mud with 30% of water content, an extremely dense hydraulic fill is obtained [6, 7].

2.2 Using Granitoids in Hydraulic Fill Models in Conventional Underground Mining

Very few researches have investigated the application of granitoid to hydraulic fills; however, granite exhibits unique properties that provide better reinforcement to hydraulic fills. In previous research, granite rocks were used in landfills, and favorable results from the viewpoint of percolation, sedimentation, and permeability were obtained [8]. These characteristics help us better identify the properties exhibited by granites as an aggregate in hydraulic fills, thereby improving percolation, permeability, resistance, and hardness, among others. [9, 10].

2.3 Using Analytical Solutions in Hydraulic Fills in Conventional Underground Mining

Researchers have considered rock bursts as dynamic disasters that take place when the energy accumulated in the rock mass of the mine is released suddenly, abruptly, and violently. Therefore, these studies used analytical solutions to assess the quality of the rock mass to be filled [10, 11].

Researchers have also claimed that the results obtained using analytical solutions in the landfill, such as the constraining strength and pressures developing in the landfill mass, must be determined according to the geometry of the exploded pits and initial stress conditions [12].

3 Contribution

This hydraulic fill assessment model is based on two concepts: granitoid, i.e., the material used as input, and analytical solutions, which will be a determining factor in terms of design and implementation. The proposed model displays the developed methodological approach and different steps used for predicting hydraulic fill performance properties and streamline its mixing. The methodology includes three main phases: experimental, modeling, and optimization, as presented in Fig. 1.

3.1 Model Components

Phase 1 This phase includes the experimental process of the pulp formed by water and granitoid in laboratory tests based on the main parameters and analysis that may affect its strength and consistency. This phase aims to generate inputs, such as granulometry and percolation, through experimental and analytical assessments aligned with the theoretical model.

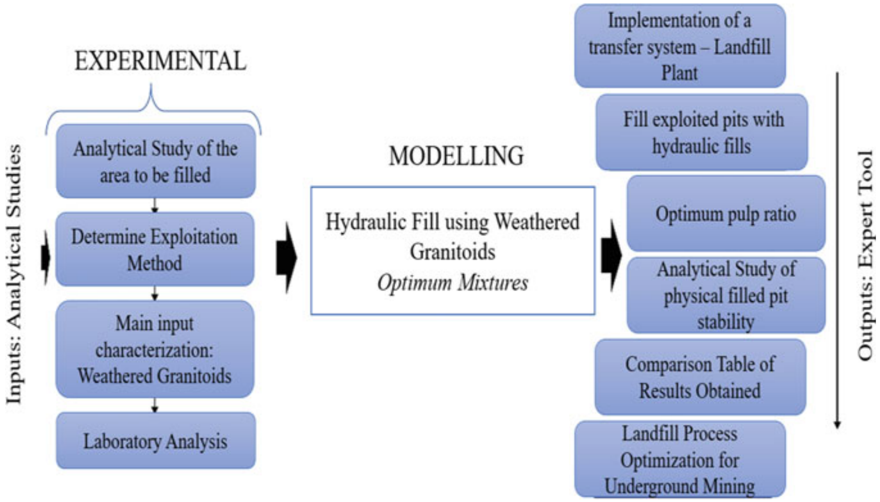

Fig. 1 Applied methodology

Phase 2 This phase includes simulation of the hydraulic fill model based on analytical solutions and laboratory tests in the established domains and parameters.

Phase 3 Proposed model validation process: For this purpose, the results obtained are assessed in terms of the following three basic factors: uniaxial compressive strength, slump test, and the costs incurred for its subsequent application. The aim is to optimize landfill improvements by creating optimum mixtures, thereby providing a tool focused on landfills.

3.2 Process View

As a first step in the implementation of this type of landfill, the current situation must be analyzed to gather information on the mining site conditions through studies focusing on the rock mass and exploited area that will subsequently be filled. Gathering information regarding the exploitation method and rock mass parameters will provide the basic knowledge related to the compressive strength for which the hydraulic fill is subjected.

The geometric dimensions of the pits to be filled must be established according to theoretical values of the arc, whose width can determine as follows:

$$Wt = (0.15D + 18.3)^{3/4} \tag{1}$$

where: Wt =Pit width, D =Pit depth from the surface.

Any value between these parameters will allow the internal pit to withstand a load equivalent to half the width of the pit. However, if the operational requirements are exceeded, the safety factor of 2.5 will have to be used instead of 2.

If the room and pillar mining method are considered, the hydraulic fill using granitoid will recover the alternate pillars by acting as ultimate active support that facilitates the exploitation of the adjacent pit. For structures exceeding 4 meters, mining operations must be performed by level or using another mining method, such as a sublevel stopping method. To determine the volume to be filled, determining the dimensions of an exploded and empty front would be ideal (Fig. 2).

$$F(x) = -\frac{x^2}{1.30} \tag{2}$$

$$S_3 = \int_{-1.25}^{1.25} \frac{x^2}{1.30}\mathrm{d}x$$
$$S_3 = 1\,\mathrm{m}^2 \tag{3}$$

$$S_2 = 2.5 \times 1.20 - S_3$$
$$S_2 = 2\,\mathrm{m}^2 \tag{4}$$

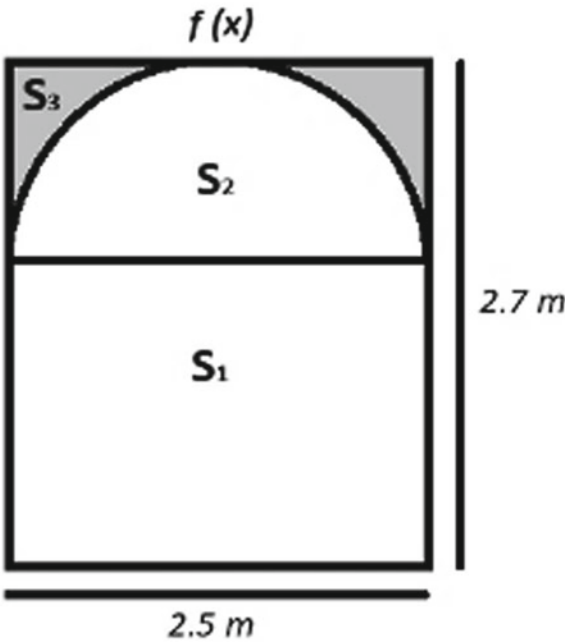

Fig. 2 Section pending of filling

		Vein		Roof Cavity		Floor Cavity	
Item	BASIC CLASSICATION PARAMETERS	DESCRIPTION	VALUE	DESCRIPTION	VALUE	DESCRIPTION	VALUE
1	Undisturbed Rock Strength	0.33	7	100-250 Mpa	12	100-250 Mpa	12
2	Rock Quality Designation	50-75%	13	50-75%	13	75-90%	17
3	Fracture Span	Under 60 mm	4	Under 60 mm	20	Over 2 m	20
4	Fracture Status	Hard Surface Under 5 mm	4	None	6	Soft Surface Over 5 mm	0
5	Underground Water Conditions	Dry	15	Dry	15	Dry	15
6	Effect from Crack Direction and Dip	Regular	-5	Favorable	-2	Favorable	-2
	Rock Mass Rating	RMR(Vein)	38	RMR(Roof)	64	RMR(Floor)	62
Correlation with Q	Bieniaswki RMR=9lnQ+44	Q(Vein)	0.51	Q(Roof)	9.23	Q(Floor)	7.39
	Barton RMR=15logQ+50	Q(Vein)	0.16	Q(Roof)	8.58	Q(Floor)	6.31
	Unsupported Roof Span (m)		0.3		0.9		0.9

Fig. 3 Rock mass assessment

$$S_1 = 2.5 \times 1.5$$
$$S_1 = 3.75\,\mathrm{m}^2 \quad (5)$$

In addition, a detailed geomechanical assessment was conducted. All the relevant parameters for a conventional underground mine are listed in Fig. 3.

The optimum particle size distribution for the landfill to reach a maximum on-site density that may guarantee the design uniaxial compressive strength value is determined by the Talbot curve because it provides the maximum density required for landfill optimization.

Furthermore, other laboratory calculations were also made, as shown below:

- Specific gravity: To calculate the specific gravity or bulk density, two samples of previously standardized and quartered weatherized granodiorite was extracted. After assessing both samples, an average specific gravity of 2.58 was obtained.
- Material hardness: According to the MOHS scale of mineral hardness, the hardness of weathered granitoid is 4.0. The critical speed of the pulp was 2.59 m/s.
- Pore ratio: It is defined as the ratio between the volume occupied by pores (V_p) and that occupied by solids (V_s). In a granular mass, the pore ratio is generally 30%.
- Porosity: It was calculated as 64.89%, revealing an excellent porosity rate, which is positive for hydraulic fills since water is quickly percolated. This means that water will flow out of the landfill in less time; therefore, the pulp will also dry faster.
- Solid percentage: The number of solids present in the landfill was 75% of the total weight.
- Sedimentation rate (slump test): First, the granodiorite and water must be mixed in a ratio of 3:1 to form the pulp. Then, the pulp will be gradually filled in the slump at a height of 19 cm, as per the requirements for the slump test. After standing for 3 min, the final height was 18 cm.

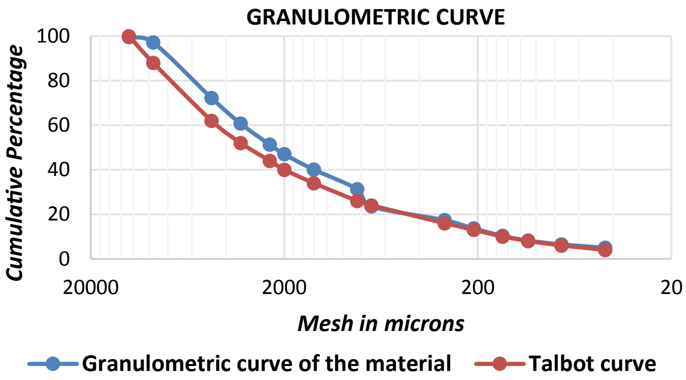

Fig. 4 Comparison against the talbot curve

3.3 Indicator View

The function that indicates the amount of strength exhibited by the landfill with granitoid for each meter of the height of the self-established slope was obtained (Fig. 4).

Since the excellent quality of the granitoid exceeds in the Talbot curve, the strength of the proposed models exceeds the required strength, thereby validating the proposed model.

4 Validation

4.1 Scenario Description

The hydraulic fill system model supplemented by granitoid will be implemented at the San Marcelo Mining project geographically located in the Paucartambo batholith in the Eastern Andes. The study area covers an approximate area of 600 hectares of weathered granitoid from the Quaternary age.

Current conditions of the San Marcelo Mining Landfill The required landfill volume is determined based on the current production volume reported by the company, listed as (Table 1).

Based on these results, an approximate landfill volume was determined for a production level of 24,000 t/month with a specific gravity of 3 t/m^3.

We also identified the volume of the different landfill types currently used, listed as (Table 2).

Table 1 Monthly production

Method	T.C.S.	Percentage
Overhand cut and fill	16,468.00	76.26
Shrinkage	3154.00	14.61
Advances	1973.00	9.14
Monthly production	21,595.00	100

Table 2 Landfill progress in meters

Landfill type	m^3	Percentage
Hydraulic fill	5745.00	77.65
Conventional fill	1654.00	22.35
Total	7399.00	100

5 Discussions

The main contribution of this study is that we are using a material that is not common for use in hydraulic fillings, however, its use would bring operational benefits. A detritic filling and a hydraulic filling with granitoid, the difference is that the detritic filling is a mechanical filling, while the hydraulic filling with granitoid is a pulp that will be transported by pipes providing more consistency in the empty spaces (interstitium) of the exploited pits. The hydraulic filling with granitoid is a filler specifically suitable for the method of exploitation cut and ascending filler where it will not be necessary to use a lot of cement (cemented hydraulic filler), since the weathering granodiorite in contact with water has a welding effect (clay repellent, plagioclase), which after 5 h percolates all the water creating a consistent platform that allows entering the next guard to continue the programmed exploitation, bringing productivity improvements, reducing operational times and costs. This type of hydraulic filling can be implemented in other types of deposits located exclusively in batoliths (precambrian rocks) since it is a place where granitoid can be found. This type of hydraulic filling is beneficial in gold deposits since many gold companies started with the recovery of the ore (gold) that goes to the tailings, and it would not be feasible to use that same tailing for their mine filling, so they use the hydraulic filling with granitoid, because even this filling allows the recovery of pillars.

6 Conclusions

The applicability of hydraulic fill conditions using weathered granitoid is governed by the physical characteristics of the rock mass and exploitation method. Some of the variables applied in this model are the presence of an incompetent roof cavity, subhorizontal veins, variable vein shoot, continuous mineralized structures, and mineral recovery close to 100%. The recovery exhibited by this hydraulic fill model exceeds

95%. Results obtained for this type of landfill using granitoid were the exposure of filled pits exceeding 5 m without requiring cement because a uniaxial compressive strength close to 0.8 kg/cm^2 was achieved. The proposed hydraulic fill with granitoid would eventually reach the pit; however, considering a case in which the work conducted at a level higher than that at the plant, we hereby propose a pumping system. Different scenarios can be identified to assimilate the on-site stress that the hydraulic fill may withstand. At the depth of 740 m, the horizontal stress considered is at 19.98 and vertical stress is at 28.02 MPa.

We propose the expansion of this research as a contribution to the study of hydraulic fillings in underground mining since its application would imply the improvement of the company as an organization compared to the competition.

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