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Stress-Strain Analysis of the Remediation Works Implemented to Stabilize the Mining Subsidence Under the La Inmaculada School, Zaruma-Ecuador

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Abstract: This work establishes 4 stress-deformational scenarios that show the instability process and remediation works, in relation to the subsidence event and collapse of the land where the school La Inmaculada (Zaruma-Ecuador) was established. Longitudinal profiles were used in the direction of the exploitation of the "Tres Reyes" vein where the geological-structural model that serves as a basis for the calculation of the deformations in the mining galleries around their plastic behavior is shown. For the modeling, it was necessary to determine, the dead load of the infrastructure, pseudo-static loads, positioning of the water table, physical-mechanical-elastic parameters of the rock matrix and discontinuities that together define the behavior of stress and deformation by means of the numerical technique of Finite Element Method (FEM). Design an optimized mortar with a dosage of 1 cement (C): 2 tailings (R) and a water (A)/cement (C) ratio of 0.49 to obtain a strength of 18 MPa after 14 days of curing. Finally, it is proved that the application of the backfill with tailings mortar inside the galleries near the collapse zone, substantially decreases the deformation of the rock substrate from 1.9 m (Scenario 2: Empty cone) to 0.05 m (Scenario 4: Backfill with tailings mortar).

Key words: stress; strain; subsidence; fill; remediation; collapse; mortar; Zaruma

1. Introduction

The Zaruma canton is part of one of the most productive vetiform gold mining districts in southern Ecuador, exploitation of which dates back to colonial times, 424 years ago. Industrial mining in the Zaruma - Portovelo district, began with the foreign company South American Development Company (SADCO), with a period of exploitation of 54 years (1896 to 1950), extracting 3.6 million ounces of gold, equivalent to USD 4.5 billion (at 2014 prices). This company implements national and international standards required, leaving technically established safety pillars (safety mattress 300 m below the surface of the Zaruma canton). After its departure, the Ecuadorian government took over all the assets of this concession and formed the Compañía Industrial Minera Asociada (CIMA), which operated between 1950 and 1976 (26 years). CIMA's business life yielded low profitability figures for its shareholders, closing the company for good. (Reyes et al., 2014).

Over the years, illegal mining groups (appropriations) and later legal mining groups (mining companies and mining concessions) have formed, in order to recover the remaining profitable minerals (gold, silver and copper) and invade the security buffer left by SADCO. However, although some of these groups have been legalized since the 1980s (mining concessions and franchises), anti-technical mining operations still persist, compounded by poor state control; it causes the extraction of mineral resources to rise to the surface without discrimination, causing instability of the rock matrix in Zaluma City (Figure 1); in relation to conditional factors (lithology, favorable geological structure, weathering) and triggering factors (static and dynamic loads generated by blasting and earthquakes, changes in tension state, infiltration of runoff water), it accelerated the settlement phenomenon until the collapse of the chimney under the "La Inmaculada" school (INIGEMM, 2017).

Figure 1. a) Mining workings (18 high × 20 long × 10 wide). b) Gallery that caused the subsidence of the ground on the surface. c) Unsafe and non-technical exploitation.

The land subsidence, which occurred on October 25, 2016, at the "La Inmaculada" school in the city of Zaruma, is related to the settlement of the rocky massif and the formation of an initial cone of 10 m in diameter that gradually increased to 23 m, compromising the safety of the inhabitants and the structural stability of the surrounding houses (Fig. 2).

Figure 2. a) Beginning of collapse with a 10 m cone. b) Destabilization of structures. c) Debris (columns, hoses, cables, blocks) inside the gallery that caused the subsidence of the ground at surface.

The remediation of the subsidence executed by INIGEMM in 2017 includes two phases:

Phase 1 (studies), involves the survey of inputs through the diagnosis of information, data processing "IN SITU", direct and indirect and laboratory investigations whose scope allows the design of mitigation works. The technical work included:

- Topography, with surface and subway topographic survey.
- Geology, determination of lithology, weathering levels and geological structures.
- Geophysics, detection of cavities based on electrical resistivity and identification of lithological contrasts.
- Hydrogeology, water table positioning and groundwater chemistry.
- Mass movements, typology, susceptibility, velocity and displacement vectors.
- Geotechnics, characterization of the massif by means of geomechanical stations.

- Drilling with core recovery, allowing the calibration of the geological-geotechnical model, "IN SITU" tests, sampling for physical-mechanical laboratory tests.

Phase 2 (remediation) is based on the construction "IN SITU" of 12 caisson-type piles (structural concrete of 280 kg/cm^2 with steel reinforcement f'y: 4200 kg/cm^2) with an internal diameter of 1.2 m, placed every 3 m, embedded in the rock at an average depth of 19 m, supported by a tie-beam and a reinforced structural screen, which together form a perimeter structure whose objective is to stabilize the houses near the subsidence zone (Fig. 3). Subsequently, the interior of the cone was cleaned until reaching the competent rock, where a ± 4m × ± 5m capping slab was built with a reinforced structure (0.40 m rebar + electrowelded mesh + perimeter beam + 16 anchored micropiles + double iron grillage with Φ: 18 mm @ 0.14 m + HB profiles + 0.40 cm of 350 Kg/cm^2 concrete) and drainage. Finally, the backfilling of the cavity is with 6,000 m^3 of compacted till material (sub-base class 3) up to the natural ground profile (Fig. 4) (INIGEMM, 2017).

Figure 3. a) Spatial distribution of the caisson piles. b) Profile with the location of the piles in soft rock (16.76 MPa). c and d) upward iron reinforcement process. e) 280 kg/cm^2 concrete curing process.

Figure 4. a) Backfill + drains + perimeter beam + iron reinforcement. b) Casting of slab. c) Backfill with compacted material Sub-Base class 3.

An important consideration to mention in this remediation plan indicates that the INIGEMM (2017) proposal does not contemplate the filling phase of mining excavations, which consists of injecting from the surface (drilling) a mortar with a mixture of cement + aggregate; specifically to the gallery located between the base of the cone and plugs previously built at lower levels. The reason for not proceeding with the hydraulic backfill is linked to the insecurity to build the plugs inside the mine, due to illegal miners working inside the mining exclusion zone, evidencing the removal of ladders and support elements, explosions and deaths inside the galleries.

Consequently, the development of this research is based on the realization of 4 geological-geotechnical models. The first model considers the initial state before subsidence occurred due to the presence of mining galleries excavations. The second model considers the morphology of the void cone state. The third model contextualizes the inclusion of the remediation works (piles + slab + backfill) built by INIGEMM (2017) and the fourth model configures the backfill with mortar based on the mixture of cement and tailings. For this, we have information from geotechnical modelling such as: surface and underground topography, 558 m of cores from 8 boreholes, physico-mechanical and deformation parameters of 63 rock samples and 12 mortar cylinders (1 cement and 2 tailings).

These inputs allow the stress-deformational analysis through finite element models, whose scope is to demonstrate the deformations of the rock mass before and during the formation of the collapse cone and chimney, and after the backfill. Finally, by backfilling with tailings mortar and using tailings sand as fine aggregate, the suggestion of stabilizing the compromise zone in the study area can be supported. In addition, this backfilling proposal contributes to the mitigation and reduction of contaminating elements (tailings leachate) that are emitted into the water tributaries of the upper Puyango river basin.

2. Methodology

In order to develop the stress-strain models evidencing the pre-collapse and post-remediation behavior, we started with the usual state-of-the-art analysis in reference to the subsidence site.

The field work was based on data and samples taken from the geological and geotechnical testing executed during the 2017 remediation. This testing totaled 558 meters of cores from 8 borings in the collapse zone, which were reinterpreted. .Additionally, 63 samples were collected to complement this process, with the objective of guaranteeing the characterization of the rock massif through the laboratory determination of indices, physical-mechanical and deformational properties.

The establishment of the geological-geotechnical model, based on surface information and drilling data collected in field expeditions, as well as the detailed interpretation of lithological logs from exploratory drilling, favors the analysis of the spatial distribution of lithostratigraphy through geological profiles, also allowing 3D modeling. The sectorization of the rock mass quality was carried out according to the basic RMR empirical geomechanical classification (Bieniawski, 1989).

The rock massif samples tested in the laboratory in order to determine the physical-mechanical index parameters involved in the software calculation algorithm, come from the following tests: soil specific weight (20 samples), rock specific weight (20 samples), direct shear (rock and soil, 10 samples), SUCS classification (20 samples), sonic velocity (20 samples), simple compression with elastic modulus/coefficients (20 samples), point load (20 samples).

Tailings sampling was carried out at the "El Tablón" community tailings dam where tailings sands from the gold recovery of 85 operating mills in the Zaruma-Portovelo mining district are deposited. A total of 350 kg (14 bags) of tailings from cyanidation, flotation and gravimetric processes were sampled.

The criteria considered in the preparation of mortar cylinders (cement + tailings) was based on the design of a mortar that meets the conditions of strength and fluidity with the dosage of 1 cement (C) and 2 tailings (R). For its preparation, the analysis was carried out based on ASTM Standards regarding aggregates in concrete and mortar (Table 1, Fig. 5), in order to determine whether the tailings sands are suitable or not.

Table 1. Physical-chemical requirements to be met by fine aggregate (tailings)

Test	Standard
Chemical analysis	ASTM C 114
Fineness, gravel percentage, sand and fines	ASTM C 637
Density, absorption	ASTM D 854
Compressive strength, 50 mm edge cube	ASTM C 109
Organic impurities	ASTM C 40
Material thinner than 75 ums (Sieve n.° 200)	ASTM C 117
Mortar air content	ASTM C 185-02
Flow determination in mortars (slump test)	ASTM C 1437

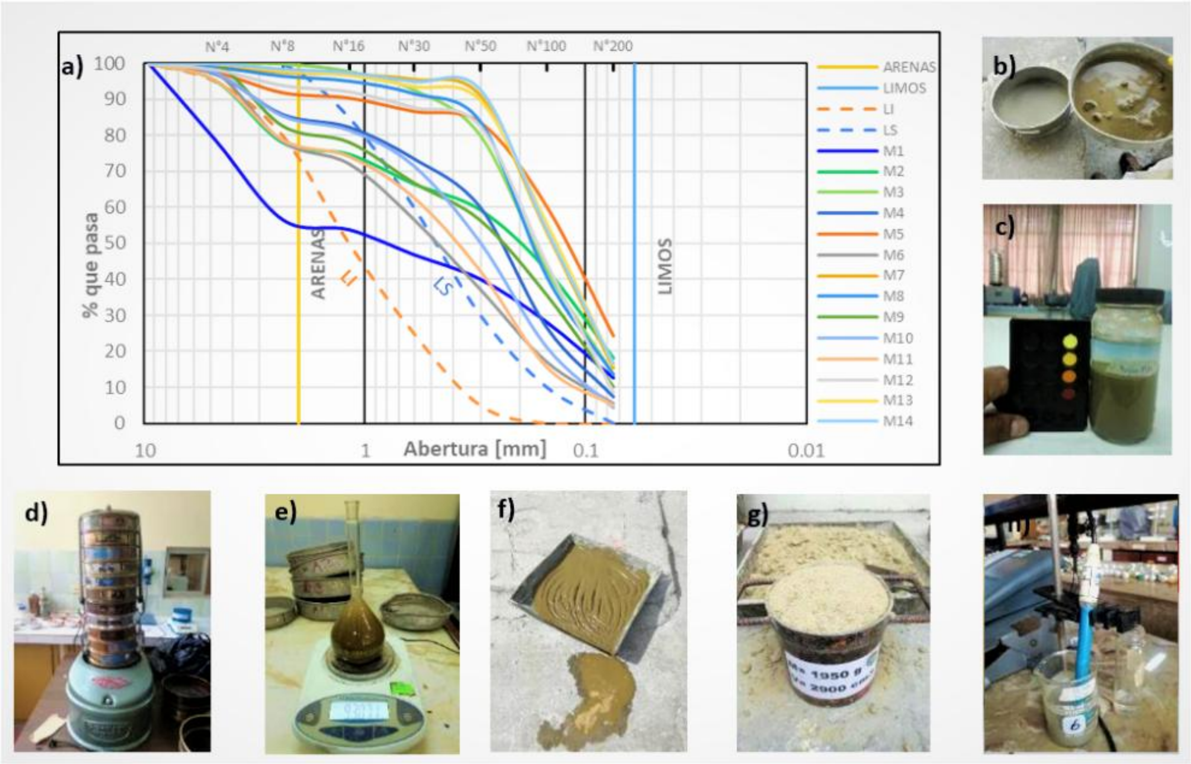


Figure 5. Analysis based on ASTM standards. a) Tailings grain size curves for 14 samples obtained from the "El Tablón" tailings dam. b) Tailings surface saturation for the calculation of material finer than 75 um. c) Organic impurities in the mine tailings, according to the standardized color comparison, it has a value of 1, suitable for use in concrete or mortars. d) Execution of granulometry test. e) Calculation of relative densities; wet, dry and apparent, % of tailings absorption. f) Saturation of 1 kg of mixed tailings of the three processes (cyanidation, flotation and gravimetry). g) Calculation of the average tailings volumetric weight with a value of 1596.12 kg/m^3. h) Measurement of hydrogen potential (pH). in tailings sample.

The pseudo-static stress-strain analysis based on the geological-geotechnical model, index, strength and elastic parameters of the rock mass and the mortar specimens (1C:2R), will help determine the occurrence of subsidence phenomena under 4 scenarios: before collapse, during, after the mitigation works and proposed backfilling with tailings mortar.

3. Discussion of Results

3.1 Geological-geotechnical model

In the regional geological context, the La Inmaculada school is located in a geological transition zone south of the equator, where the geodynamic environments involve metamorphic rocks (Paleozoic-Mesozoic) of the Amotape-Tahuín Block (BAT) and volcanoclastic sequences of continental volcanic arc origin known as Portovelo Unit (Oligocene), whose tectonic boundary at the southern end is configured by the Piñas-Portovelo fault and at the northern end by the Palestine Fault. Within the mining context, the study area is located in the Zaruma-Portovelo gold district, where there is a system of quartz veins (Riedel system) with high contents of economically profitable minerals (Au, Ag, Cu), reaching lengths between 2.5-3.5 km with variable strengths between 0.3 to 3 m. These veins maintain a preferential N-S strike and variable dips to the E. (Bonilla, 2009).

In the collapse chimney and galleries of the sector, there are volcano-sedimentary sequences formed by andesitic tuffs, crystal tuffs and andesites. The rock mass is moderately fractured with incipient mineralization and the development of different degrees of weathering, with residual soil cover (clay) outcropping on the surface. The delimitation of the weathering levels allowed the zoning of 5 geotechnical units, differentiated by their behavior in relation to their resistance (Table 2).

Table 2. Geotechnical zones in relation to simple compressive strength behaviour (laboratory data)

U. Geotec.	Weath. Rock	Description	Resistance	
			Class	Lab (MPa)
UG-I H: 4-15 m	Residual ground	Dark orange clay soil, with high plasticity, soft consistency and high natural humidity.	S2-S3	0.08
UG-II H: 6-15 m	Complete	Grey in colour, with high plasticity, soft consistency and high natural humidity, rock fragments up to 2 cm.	S4-S5	0.14
UG-III H: 8-18 m	High	Light grey with dark shades, silty-sandy, of moderate plasticity and consistency, it is common to find andesites and resistant tuffs with natural humidity.	S5-S6	0.38
UG-IV H: 8-15 m	Moderate	Dark gray rocks with some green, the aphanitic texture is all rock. Its strength degree increases with depth.	R1-R2	16.76
UG-V H: >25 m	Fresh-light	Dark gray, with some green on fresh surfaces, closed and open joins, filled with hard minerals. The tuffs are aphanitic and the andesites present mineral paragenesis of: plagioclase volcanic glass amphibole chlorite +- epidota	R3-R4	30.70

Note: S2 (weak ground), S3 (firm ground), S4 (rigid ground), S5 (very strong ground), S6(hard ground), R1 (very soft rock), R2 (soft rock), R3 (reasonable hard rock), R4 (hard rock).

Figure 6 represents the geological model integrating the spatial distribution of the galleries that exploited the "Tres Reyes" vein (blue solid) from the so-called Chorillos L1/3 level (elevation: ±1050 m.a.s.l.), ascending through multiple mining excavations (baul-irregular sections between ±5 and ±45 m^2) inclined at 45° (stopes). The gallery located at elevation ±1158 m.a.s.l. m (magenta solid) was the cause of the instability of the rock mass under the La Inmaculada school, where the conditioning factors (low lithostatic load, intense weathering, unfavorable geological structures, minimal geomechanical properties) and triggers (high rainfall, static load of the classrooms, dynamic load due to blasting, change in the geomechanical properties of the school, change in the rock mass, etc.) were the cause of the instability of the rock mass, dynamic load due to blasting, change of the tensional state due to mining excavations) had an impact on the loss of resistance of the rock mass, initially producing an accelerated phenomenon of subsidence of the terrain, followed by subsidence with the formation of a cone of up to 23 m in diameter (elevation ± 1206 m. s.n.m.) and a collapse chimney of ± 40 m in length (red solid), (INIGEMM, 2017).

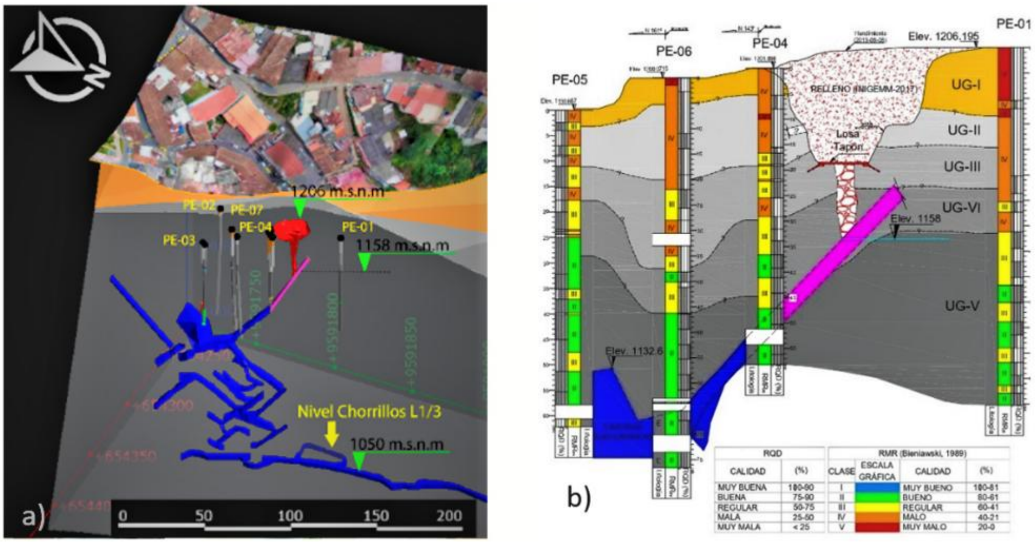


Figure 6. a) 3D geological-geotechnical model. b) Section between exploratory drillings PE-01, PE-04, PE-06, PE-05, showing 5 levels of weathering, RQD and the quality of the rock mass according to Bieniawski (1989). Source: Modified INIGEMM (2017) and Rivadeneira, A. (2021).

3.2 Physico-mechanical parameters of rock mass, backfill material and tailings mortar backfill

Table 3 summarizes the physico-mechanical and elastic parameters described below:

Rock mass refers to the sampling of 63 drill cores (different elevations), taking as reference the weathering levels (UG-I, II, III, III, IV, V), which were subjected to direct shear and simple compressive strength tests with elastic moduli. In the predominant discontinuity systems (D1 and D2), cohesion and friction angle were calculated using the empirical breakage criterion of Barton-Bandis (1990).

Breakwater material refers to angular rock blocks of andesitic composition with variable diameters between 0.70 to 1.20 m, which are arranged locked (remoulded) inside the cavity of the collapse chimney. Cohesion is assumed to be zero due to the washing of the matrix in winter. The strength and elastic parameters are determined from the bibliographic diagnosis of the Guide for breakwaters (2009) and Perucho (2004).

Compacted sub-base material, class 3, refers to box material (waste rock) of andesitic composition, which mining companies dispose of, in waste dumps. The design of this fill was calculated for a compaction of 2 mm penetration at 95% with an optimum moisture content of 10.74% and density of 2.0 kg/m^3. The strength parameters are based on Lambe et al. (2010). The calculation of elastic modulus was by means of empirical correlations exposed in the work of Rondón et al. (2013), using the value of 3% CBR obtained from laboratory.

Filling with tailings mortar refers to the design of a mortar based on the methodology of Rivera (2013), based on the calculation of absolute volumes of cement (C), tailings (R) and water (A), with an optimum ratio of 1C: 2R: 0.49 A/C for the manufacture of briquettes (Fig. 7) and cylinders. The data obtained from the analysis of the fine aggregate (mining tailings) meet 95% of the characteristics required for the formation of mortars of desired fluidity and resistance. The 5% related to the fineness modulus with a value lower than 2.3, indicating that a greater amount of cement should be added to the mixture and the final dosage should be modified (Rivadeneira, 2021).

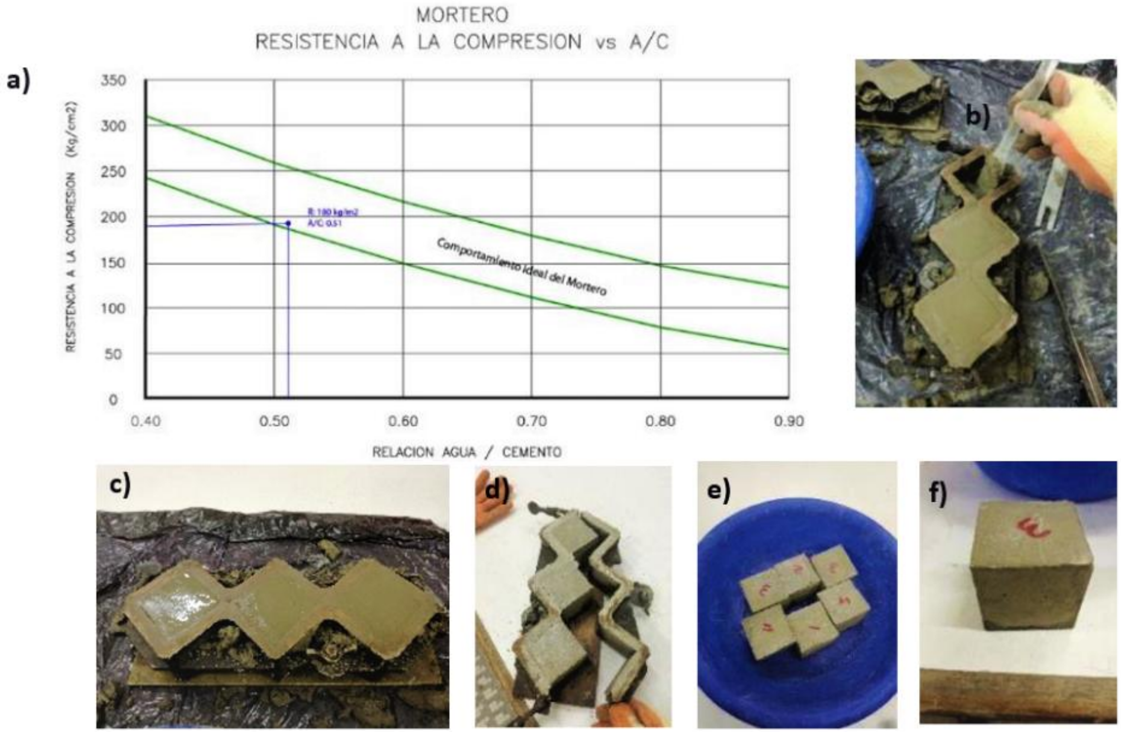


Figure 7. a) Strength obtained at 28 days in 50 mm edge briquettes: The green colored curve delimits the water/cement ratio as a function of the ideal RCS. b) tamping of the mixture in layers (25 times) inside bronze molds. c) final screeding of the mortar cubes. d) removal of the bronze molds after approximately 24 hours of setting. e) mortar cubes numbered and taken to the curing room. f) mortar cube to be tested after 14 days of curing. Source: Modified from Rivera, (2013).

The percentage of fluidity is related to a mortar of fluid consistency (self-leveling mortars), whose workability can be manual or by injection. Equation 1 was applied to meet the strength requirements:

$$R'mm = 1.35 \times R'm \quad \text{Equation 1}$$

Where:

R'mm (MPa): compressive strength of the dosage mortar at 28 days (cubes of edge).

R'm: compressive strength of the mortar at 28 days, according to Type M mortar (RCS = 17.5 MPa).

To verify if the Type M mortar complies with the standard strength (17.5 MPa), the following condition is established:

$$1.20 \times F'm \leq R'm \leq 1.50 \times F'm$$

Where:

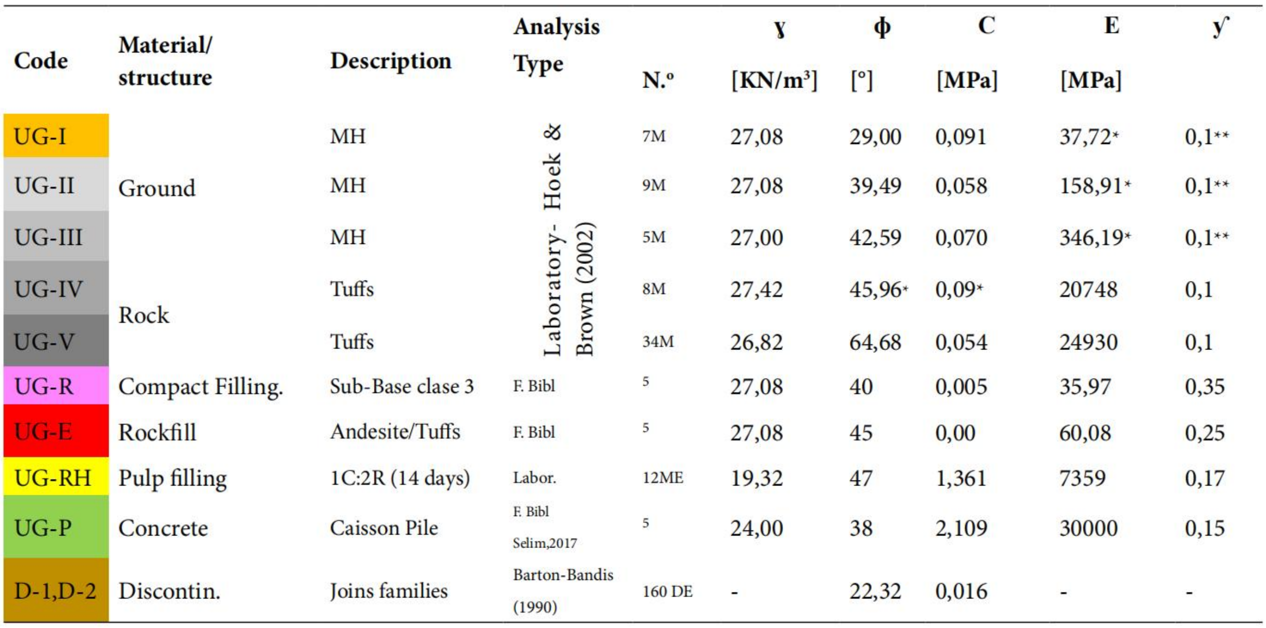
F'm (kg/cm^2): required design compressive strength is 21 MPa.

Finally, a briquette strength at 14 days of curing of 18 MPa with a water-cement ratio of 0.49 was obtained. The amount of cement in relation to the fineness modulus is given by 602.10 kg/m^3 of mixture, an initial amount of water 295.03 kg/m^3 and 1136.14 kg/m^3 for an initial ratio of 1(Cement): 2(Ratio). Once the mortar dosage was designed, mortar cylinders were elaborated to determine; resistant and elastic parameters that were obtained through triaxial and simple compression tests applied to twelve samples. It should be noted that the breakage was after 14 days of curing, time in which the mortar theoretically reaches 90% of its maximum strength.

3.3 Stress-strain analysis

Based on the geological-geotechnical environment, physical-mechanical-elastic properties, distributed loads and pseudo-static conditions, 4 scenarios represented through longitudinal profiles running parallel to the "Tres Reyes" vein were processed by means of stress-strain analysis by finite elements.

Table 3. Summary of index, strength and deformation parameters obtained from specific gravity, direct shear, SUCS classification, sonic velocity, simple compression and point load tests



Code	Material/ structure	Description	Analysis Type	N.º	ɣ [KN/m^3]	ϕ [°]	C [MPa]	E [MPa]	ƴ
UG-I		MH	Laboratory- Hoek & Brown (2002)	7M	27,08	29,00	0,091	37,72*	0,1**
UG-II	Ground	MH		9M	27,08	39,49	0,058	158,91*	0,1**
UG-III		MH		5M	27,00	42,59	0,070	346,19*	0,1**
UG-IV	Rock	Tuffs		8M	27,42	45,96*	0,09*	20748	0,1
UG-V		Tuffs		34M	26,82	64,68	0,054	24930	0,1
UG-R	Compact Filling.	Sub-Base clase 3	F. Bibl	5	27,08	40	0,005	35,97	0,35
UG-E	Rockfill	Andesite/Tuffs	F. Bibl	5	27,08	45	0,00	60,08	0,25
UG-RH	Pulp filling	1C:2R (14 days)	Labor.	12ME	19,32	47	1,361	7359	0,17
UG-P	Concrete	Caisson Pile	F. Bibl Selim,2017	5	24,00	38	2,109	30000	0,15
D-1,D-2	Discontin.	Joins families	Barton-Bandis (1990)	160 DE	-	22,32	0,016	-	-

Note: ɣ (specific weight), ϕ (friction angle), C (cohesion), E (strain module), ƴ (Poisson coefficient); #M (sample number), F Bibl. (reference). #DE (structural data numbers). With an asterisk (*), resistance parameters and strains calculated using the Hoek-Brown empirical break criterion (2002) are identified and with double asterisk (**) the assumed Poisson's ratio values for lithology equality. Source: INIGEMM (2017).

The numerical modeling allowed to know the behavior of the rock massif, in which the graphic outputs outline isolines (scale of warm and cold colors) and vectors of: displacements, tensions and deformations in reference to the mining excavations, allowing to deduce zones with risks of instability (highly plasticized zones) and rupture mechanisms.

The analysis focuses on two initial scenarios, to which the cone and collapse chimney at La Inmaculada school was subjected, i.e. before the formation of the cone, during the formation of the cone and collapse chimney, and after remediation by INIGEMM (2017). The fourth scenario is the proposed backfilling with mortar from the surface using a cement mortar with tailings sands.

Scenario 1: Model before the formation of the collapse cone and chimney (25/Oct/2016)

Geological model: Figure 8a shows the spatial distribution of the weathering levels together with the main diaclasis systems (D1 and D2). The location of mining excavations (stopes) ascending from the horizontal gallery "Chorillos L1/3" is shown in white. The dead load of the La Inmaculada school is represented with red colored vectors and the position of the water table (NF) is represented with blue line.

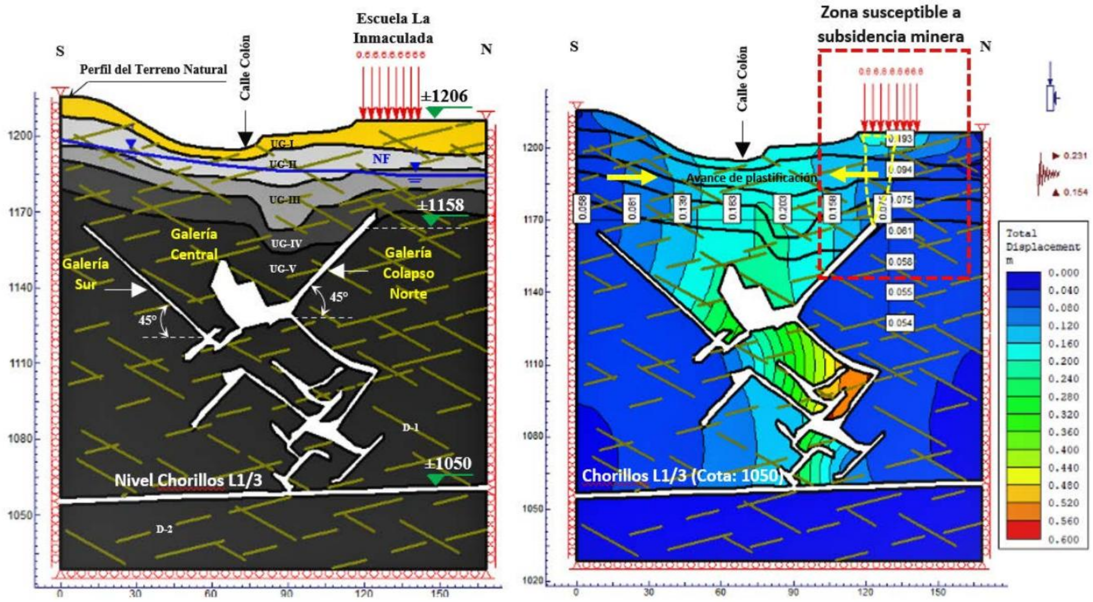


Figure 8. a) Geologic model prior to collapse. b) Stress-strain model with development of plasticized zones. In the sector of the La Inmaculada school, a disturbed zone is evident, the isolines demarcate the cone configuration and tendency of the collapse chimney (yellow line).

Tensile-deformational model: Figure 8b shows the behavior of the total deformation, reaching values of 20 mm in the area where the La Inmaculada school was located. An advance of plasticization (L: 90 m) is observed from the south gallery (elevation: 1,166 m) to the north gallery (elevation: 1,163 m) with maximum deformations of up to 30 mm in the central gallery (28 m × 18 m). In the lower central part, there is a tendency to increase the deformation, which responds to the geometric configuration of the galleries excavated in an antitechnical way, even taking advantage of the pillars that provide security.

Scenario 2: Model during cone formation and collapse chimney (21/Feb/2017)

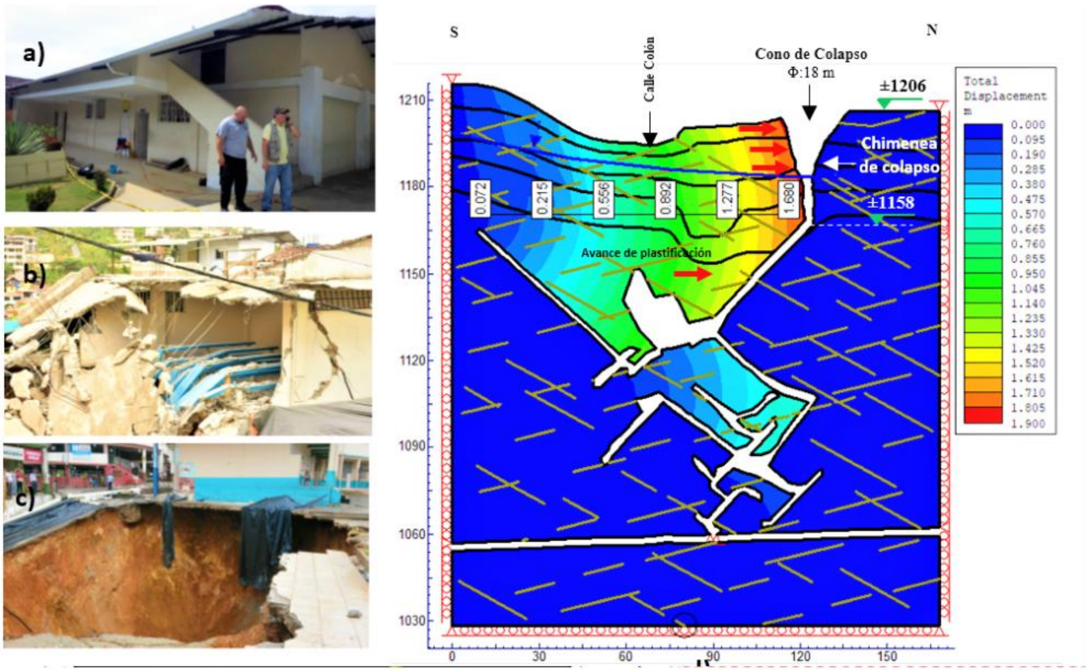


Figure 9. a) Classroom of La Inmaculada school (Oct-2016). b) Classroom collapse. c) Cone (Φ: 18 m) and chimney (L: 34m). d) Tensile-deformational model where deformation develops parallel to collapse chimney walls reaching displacements up to 1.90 m.

Tensile-deformational model: Figure 9d shows the deformation behavior in the collapse chimney sector, where the plasticization shows displacements of 1.90 m. The deformation isolines show the relaxation of the rock mass towards the interior of the cone. This model represents the instability behavior of the collapse cone and chimney, which, since its formation, has developed seven instability events, starting on October 25, 2016 with a 10 m cone until February 20, 2017, where the cone reached 31 m in diameter. The modification of the stress state generated an imbalance at the time of land subsidence, causing the collapse of the chimney walls (circular breaks).

Scenario 3: Model - INIGEMM Remediation (2017) (Piles+Slab+Compacted fill)

Geological model: Figure 10a shows the geological environment described above and the remediation works that were completed in October 2017, including the construction of 12 caisson piles of 1.20 m in diameter and an average length of 19 m, 32 m of reinforced concrete perimeter support screen, construction of a capping slab supported on continuous beams and these in turn, supported by 16 micropiles. Finally, the works are concluded with the compacted backfill to reconstitute the topographic conditions of the natural terrain. In addition, the breakwater material inside the collapse chimney is schematized, and this filling was part of the emergency solution, executed by GADM of Zaruma in February 2017 with advice from the Secretariat of Risk Management.

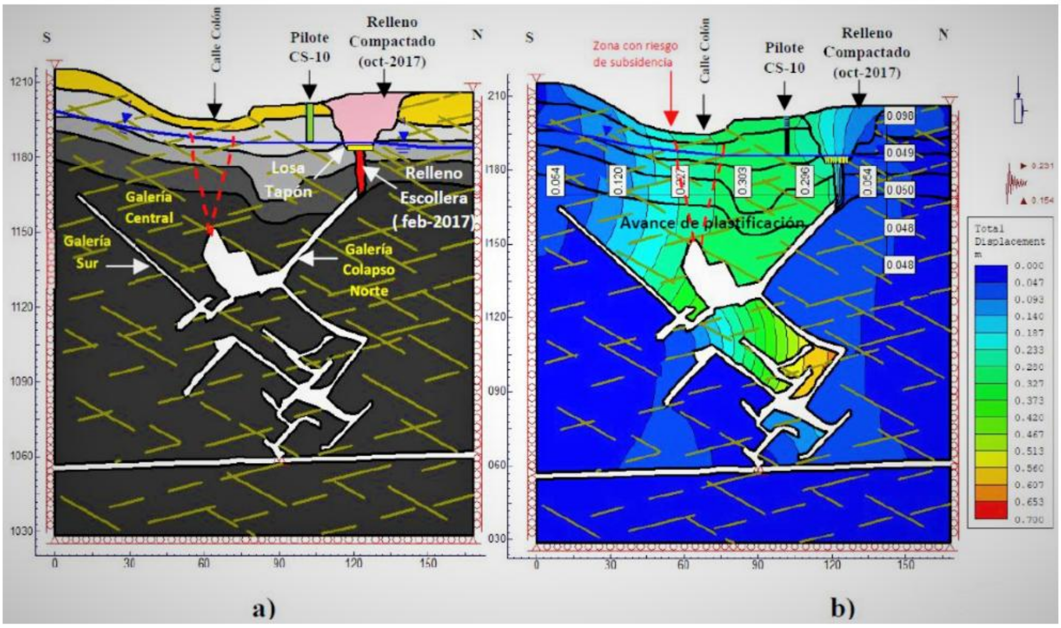


Figure 10. a) Geological model with the location of mitigation works: pile, capping slab and compacted backfill, b) Deformation behavior after the implementation of remediation works, shows a plasticized area where the rock mass can accelerate a subsidence phenomenon due to large cavities (Av. Colón and Ernesto A. Castro).

Tensile-deformational model: Figure 10b shows the behavior of the total deformation after the implementation of the remediation works, reaching values of 5 mm in the area where the piling + capping slab + backfill works were carried out, showing that the stabilization proposal implemented by INIGEMM (2017) was effective. It should be noted that the plasticization advance from the south gallery to the north gallery maintains maximum deformations of up to 30 mm over the central gallery, i.e., the area where La Inmaculada school is located maintains an apparent stability, which is linked to the deformation of the galleries that did not have any treatment.

Scenario 4: Model with proposed backfill with mortar (cement+reclave)

Geological model: Figure 11a shows the geological environment, the mitigation works and the backfill proposal with a mortar design (1 cement: 2 tailings). The injection of mining excavations is proposed from the surface using 5 boreholes (executed in 2017: SE-3, SE-4, SE-5, SE-6, SE-7). Prior to backfilling, reinforced concrete toppings must be built to block the mining galleries in order to close the injection system.

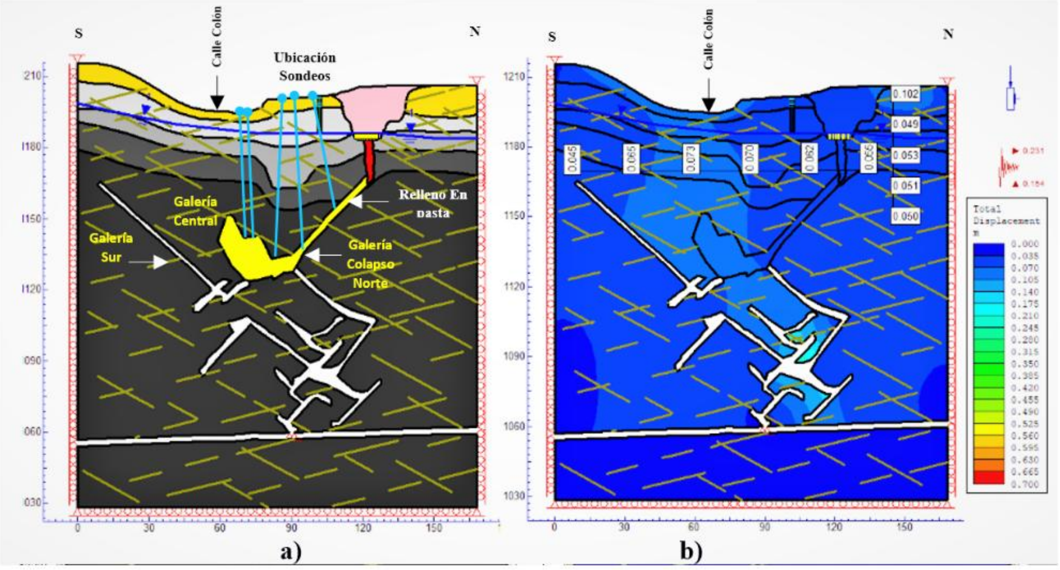
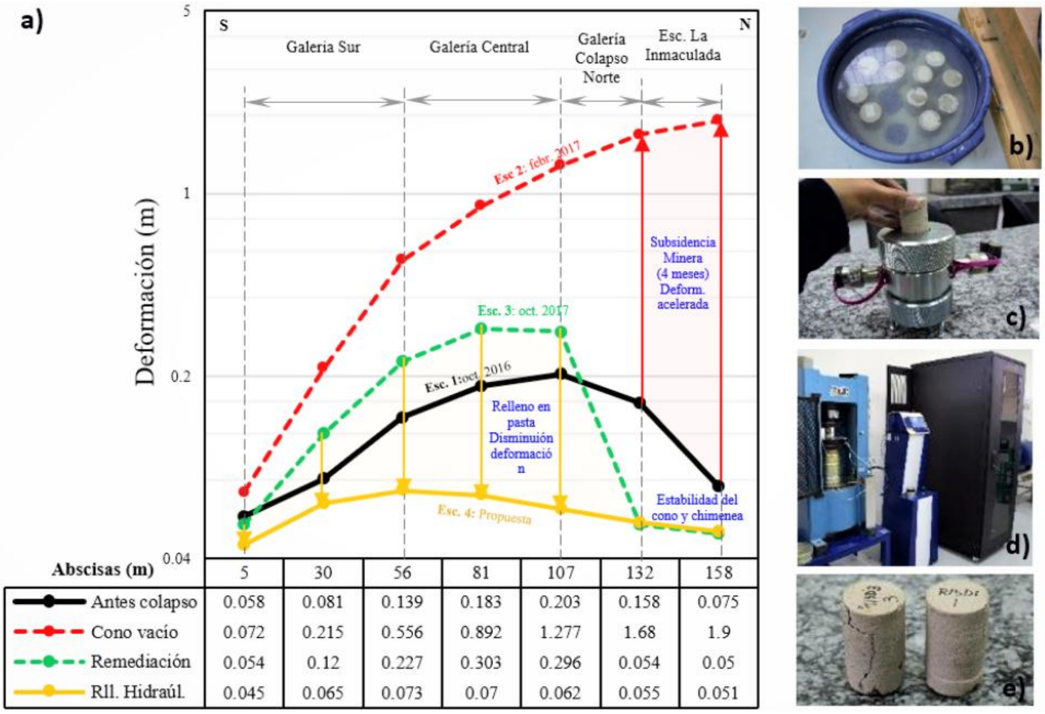


Figure 11. a) Geological model, mitigation works and mortar backfill. b) Deformation behavior after backfilling with mortar.



Abscisas (m)	5	30	56	81	107	132	158
Antes colapso	0.058	0.081	0.139	0.183	0.203	0.158	0.075
Cono vacío	0.072	0.215	0.556	0.892	1.277	1.68	1.9
Remediación	0.054	0.12	0.227	0.303	0.296	0.054	0.05
Rll. Hidraúl.	0.045	0.065	0.073	0.07	0.062	0.055	0.051

Figure 12. a) Relationship between x-axis distance (Scenarios 1-4) and maximum deformation for the events: before collapse (October 2016), gradual enlargement of the collapse cone and chimney (February 2017), implementation of remediation works (October 2017). b) Mortar cylinders (1C:2R) c) Hoek cell for triaxial test d) Execution of simple compression test with moduli e) Tailings and cement cylinders after rupture.

Stress-strain model: Figure 11b shows the effectiveness of the backfilling with mortar using tailings sand as fine aggregate, and the mortar designed after 14 days reached a simple compressive strength of 10 MPa. The stress-strain model specifically in the backfill zone shows values of less than 6 mm. The general behavior of the deformation in relation to other galleries decreases substantially, i.e., the advance of the plasticized zones is attenuated once the upper excavations are stabilized.

4. Conclusions

The four stress-strain models show the state of plastification of the rock massif, due to the presence of the mining galleries under the vicinity of La Inmaculada school. Figure 12a shows the results of the investigation, relating the deformation for each event with the location of the galleries in the longitudinal section with north-south direction:

Scenario 1, Before collapse (October 2016): The deformation curve is maximum in the area between the central gallery and northern gallery; it reaches displacement values between 10 mm to 20 mm, i.e. the development and advance of these galleries disturbed the tensor state, resulting in the plasticization of the rock mass between abscissae 0 + 50 and 0 + 132.

Scenario 2, Empty cone (February 2017): From the first instability event, the collapse cone and chimney increased its diameter due to rock distension and stress state modification, conditioning factors (lithology, favorable geological structures, weathering) and triggers (static and dynamic loads due to blasting and earthquakes, alteration of the stress state, infiltration of runoff water), allowed a decrease in the resistance of the rock massif, causing subsidence of the terrain to consequently produce subsidence of the same.

Scenario 3, Remediation (October 2017): The mitigation works designed by INIGEMM (2017) in the area under La Inmaculada school, minimized the deformation up to 5 mm, achieving the stability of this sector. On the other hand, the deformation between the central and northern galleries (abscissae 0 + 50 and 0 + 132) present values of up to 30 mm, demarcating an area susceptible to mining subsidence. It is imperative that the competent authorities consider the following suggestions:

- The implementation of a periodic geodetic monitoring of the area between the La Inmaculada school grounds and the intersection of Ernesto A. Castro and Colon Avenue (UTM: 654366.6088E, 9591776.6322N), as it is considered a zone susceptible to the development of subsidence (risk of collapse).
- Prevent vehicular traffic and the construction of new buildings on the infill area and in the vicinity of Ernesto A. Castro Street until the implementation of a new road system and a remediation project to provide stability are possible.
- Construct a surface drainage system to channel runoff water, in order to prevent the washout of fines and thus reduce differential settlement phenomena in the fill area.

Scenario 4, Backfilling with tailings mortar (proposed): The deformation curve shows values less than 7 mm, revealing the possibility of backfilling based on cement mortar with tailings (Fig. 12 b, c, d, e), with a favorable mechanical behavior of the rock mass by returning the lost tensional state, disappearing the subsidence effects. This confirms the replicability of mortar backfilling in other existing tunnels under the city of Zaruma, using the ideal elevation for plug placement of over 1110 m above sea level as a reference. On the other hand, it is an effective proposal to solve the problem of environmental contamination of the upper Puyango river basin caused by leachate from the tailings dams.

It should be noted that this preliminary research demonstrates the feasibility that the proposed injection of the cement and tailings mixture minimizes the plasticization of the rock around the mining excavations. The studies necessary to design the ideal dosage of cement with tailings (backfilling with mortar), which is subject to the knowledge of variables such as; physical-mechanical parameters, inertization of heavy metals, costs and operational processes, are still pending.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Barton, N.R. and Bandis, S., 1990. Review of predictive capabilities of JRC-JCS model in engineering practice. In rock joints, proc. int. symp. on rock joints, Loen, Norway, (eds N. Barton and O. Stephansson), pp. 603-610. Rotterdam: Balkema.

[2] Bieniawski, Z.T., 1989. Engineering rock mass classifications. John Wiley, New York, 251.

[3] Bonilla W., 2009. Metalogénica del Distrito Minero Zaruma-Portovelo República del Ecuador, Tesis Doctoral, pp. 219.

[4] Guía de escolleras, 2009. Guía para el proyecto y la ejecución de muros de escollera en obras de carretera, 3ª edición: 36 pp.

[5] Hoek, E., Carranza-Torres, C. and Corkum, B., 2002. Hoek-Brown Failure Criterion – 2002 Edition. 5th North American Rock Mechanics Symposium and 17th Tunneling Association of Canada Conference: NARMS-TAC, pp. 267-271.

[6] Instituto Nacional de Investigación Geológico, Minero, Metalúrgico – INIGEMM, 2017. Estudio multidisciplinario para la estabilidad del cono y chimenea de colapso de la Unidad Educativa "La Inmaculada Fe Y Alegría" – Cantón Zaruma: pp. 546.

[7] Lambe, T. W., y Whitman, R. V., 2010. Mecánica de suelos. 1a ed. México, D.F.: Limusa: pp. 163.

[8] Perucho, Á., 2004. Estudio de deformabilidad de escolleras. Tesis (Doctoral), E.T.S.I. Caminos, Canales y Puertos (UPM): pp. 69-72.

[9] Reyes, A., Valverde, E., Ordóñez, J., Romero, M., 2014. Historia del Cantón Zaruma. Colección: Historia de la Provincia de El Oro. Machala – Ecuador: pp. 267.

[10] Rivadeneira, A., 2021. Relleno pasta aplicando un modelo de estabilidad en excavaciones subterráneas, mediante caracterización química y geotécnica del relave, bajo el hundimiento de la unidad educativa "fe y alegría", en la ciudad de Zaruma, provincia de El Oro. Universidad Central del Ecuador, Quito.

[11] Rivera G., 2013. Concreto Simple. Universidad del Cauca-Cap 9: pp. 203.

[12] Rondón, H., Fernández W. y Hernández J., 2013. Influence of Subgrade and Unbound Granular Layers Stiffness on Fatigue Life of Hot Mix Asphalts – HMA. Tecnológicas: pp. 57-59.

[13] Selim P., Amir G., Ertekin O., Metin H., y Serhat D., 2017. Experimental Determination of Cohesion and Internal Friction Angle on Conventional Concretes. ACI Materials Journal: pp. 407.