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REVISTA FIGEMPA

Stress-strain analysis of works remediation implemented to stabilize the mining subsidence under La Inmaculada School, Zaruma-Ecuador

Análisis tenso-deformacional de las obras de remediación implementadas para estabilizar la subsidencia minera bajo la Escuela La Inmaculada, Zaruma- Ecuador.

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ABSTRACT
Four stress-strain are established that demonstrate the instability process and remediation work, in relation to the subsidence and collapse event of the land where the school the was established "La Inmaculada" (Zaruma-Ecuador). Longitudinal profiles were used in direction of the use "Tres Reyes" vein, where the geological-structural model that serves as basis for strains calculation in the mining galleries around their plastic behavior. The modeling was necessary to determine; the infrastructure dead load, pseudo-static loads, groundwater position, physical -mechanical-elastic parameters of the rock matrix and discontinuities that together define the stress and deformation behavior by the finite elements method numerical (FEM). It designed an optimized mortar with cement (C): two tailings (T) at 1:2 and 0.49 water ratio (W)/cement (C), obtaining a resistance of 18 MPa after fourteen curing days. Finally, it is verified that the fill application in paste inside the galleries surrounding the collapse zone, the strain rock substrate decreases from 1.9 m (scenario two: empty cone) to 0.05 m (scenario four: pulp fill).

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PALABRAS CLAVE
tensión, deformación, subsidencia, relleno, remediación, colapso, mortero, Zaruma.

RESUMEN
En este trabajo se establecen 4 escenarios tenso-defomacionales que evidencian el proceso de inestabilidad y trabajos de remediación, en relación al evento de subsidencia y colapso del terreno donde se establecía la escuela La Imanculada (Zaruma-Ecuador). Se empleo perfiles longitudinales en dirección al aprovechamiento de la veta "Tres Reyes" donde se plasma el modelo geológico-estructural que sirve de base para el cálculo de las deformaciones en las galerías mineras entorno a su comportamiento plástico. Para el modelamiento fue necesario el determinar; la carga muerta de la infraestructura, cargas pseudo-estáticas, posicionamiento del nivel freático, parámetros físico-mecánicos-elásticos de la matriz rocosa y discontinuidades que en conjunto definen el comportamiento de la tensión y deformación mediante la técnica numérica de Método de los Elementos Finitos (MEF). Diseña un mortero optimizado en dosificación 1 cemento (C): 2 relave (R) y 0.49 relación agua (A)/ cemento (C) obteniendo una resistencia de 18 MPa a los 14 días de curado. Finalmente, se comprueba que la aplicación del relleno en pasta dentro de las galerías aledañas a la zona de colapso, disminuyen sustancialmente la deformación del sustrato rocoso de 1.9 m (Escenario 2: Cono vacío) a 0.05 m (Escenario 4: Relleno en pasta).

Introduction

The «Zaruma» canton is part of the most productive gold mining districts in southern Ecuador, its exploitation began to the colony four hundred twenty-four years ago. Industrial mining in «Zaruma-Portovelo» district began with foreign company South American Development Company (SADCO), with fifty-four years' operating period (1896 to 1950), extracting 3,6 million gold ounces, equivalent to USD 4500 million (2014 price); this company implements required national and inter-

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national standards; leaving technically established safety pillars (safety mattress three hundred meters below the «Zaruma» canton surface). After his departure, the Ecuadorian government took over all concession assets and formed the Company Industrial Mining Associated (CIMA), which operated between 1950 and 1976 (twenty-six years). During CIMA's business life, low profitability figures for its shareholders led to closing the company (*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, several groups had obtained legalization (mining concessions and grants) since 80's, and now still anti-technical mining, in addition to poor state control; it had allowed the mineral resource extraction to rise to the surface; causing the substrate rock instability of the «Zaruma» city (see Figure 1); and associated with conditioning factors (lithology, favorable geological structures, weathering) and triggers (static and dynamic loads by blasting and earthquakes, altered tension state, runoff water infiltration), it accelerated the subsidence phenomenon, until collapse chimney below the «La Inmaculada» school occurs (INIGEMM, 2017).

The ground subsidence, that occurred on October 25th, 2016, at «La Inmaculada» school in the «Zaruma» city, was related to rock mass settlement and initial cone formation of 10 m in diameter until increase to 23 m, involve the inhabitant's safety and the architectural stability of surrounding houses (see Figure 2).

The sinking remediation caried out by INIGEMM in 2017, involve two phases, described below:

Phase one (studies), involved the inputs lifting through information diagnosis, «in situ» data processing, direct and indirect research and laboratory research whose scope allow the mitigation works design. Technical work included:

- *Topography,* with surface and underground topographic survey.
- *Geology*, lithology determination, weathering levels and geological structures.
- *Geophysics,* cavity detection based on electrical resistivity and lithological contrast identifications.
- *Hydrogeology*, groundwater level and its chemistry.
- *Mass movements*, typology, susceptibility, speed and displacement vectors.
- *Geotechnics,* rock mass characterization by lifting geomechanically stations.
- *Drilling with witness recovery,* geological-geotechnical model allowing calibration, «in situ» tests, sampling for physical-mechanical laboratory tests.

Phase two (remediation), is based on the twelve caisson type piles construction in situ (280 kg/cm^2 structural concrete with reinforcing steel f'y: 4200 kg/cm^2) with internal diameter de 1,2 m arranged every 3 m embedded in rock to 19 m average depth, they are raised by a mooring beam and screen of armed structure, which together forms a perimeter structure, whose objective was to stabilize the houses near the subsidence zone (see Figure 3).

Subsequently, the interior of the cone is cleaned until reaching the competent rock, where a ±4m x ± 5m plug slab was built with a reinforced structure (0,40 m replanning + electro welded mesh + perimeter beam + 16 anchored micro-piles + double iron grating with diameter: 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 6000 m^3 of compacted till material (sub-base class 3) up to the natural ground profile (see Figure 4) (INIGEMM, 2017).

An important consideration to mention in this remediation plan was that the INIGEMM purpose, 2017, didn't consider fill the mining excavations, which consisted of injecting from surface (drilling) a mortar with mixture cement added, specifically to gallery between the cone base and plugs that built at lower levels. The reason for not proceed with hydraulic landfill was to the insecurity in built plugs mine inside, and by illegal miners worked in the mining exclusion zone, demonstrating; stairs out and supporting elements, explosions and dead people inside the galleries.

The development of this research is based to do four geological-geotechnical models; first model, considers the initial state before the subsidence existence by the mining gallery excavations presence, the second model, is the state cone empty morphology, the third model, is the works remediation inclusion (slab, piles and fill) built by INIGEMM, 2017 and the fourth model, is about filling in paste based on the cement and tailings mixture. For this purpose, we have geotechnical modeling information, such as; surface and underground topography, 558 m of witnesses of eight probes, sixty-three rock samples strain and twelve mortar cylinder's physical-mechanical (cement and tailings ratio 1:2).

These materials allow strain-strain analysis by finite elements models, whose is to show the rock mass deformations before and during cone and chimney collapse conformation after filling. Finally, it makes possible that the areas committed in the study area stabilization, by paste filling; using fine aggregate; tail sands. In addition, this landfill purpose pollutants mitigation and reduction (tailings leaching) that are thrown to the Puyango river.

METHODOLOGY

In order to develop stress-strain models that show the

Figure 1. a) mining work (18 high x 20 length x 10 width), b) gallery that causing the land subsidence on the surface, c) anti-technical and unsafe exploitation

Figure 2. a) collapse start with 10 m cone, b) unstable structures, c) rubble (columns, hoses, cables, blocks) inside the gallery that caused the ground subsidence on the surface

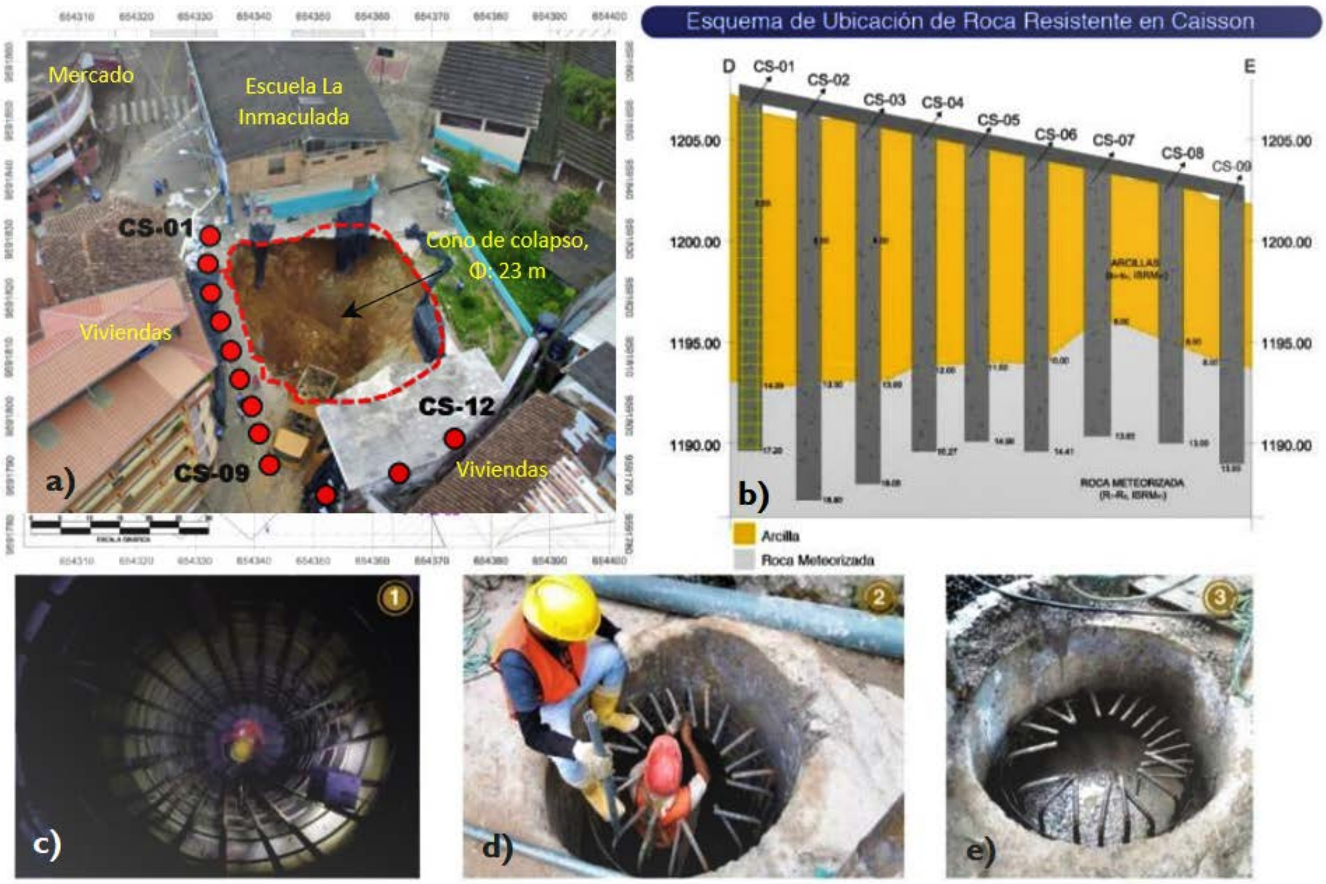


Figure 3. Location (plant and profile) and caisson-type stilt construction process (CS-#)

behavior before collapse and after remediation, it's began with the sinking analysis.

The field work was based with data and samples taken from the geological-geotechnical core rocks carried out during the 2017 remediation, which were interpreted, with core rocks 558 m from eight test tube rock located in the collapse zone; this process was collected sisxty three samples, where its purpose is guarantee rock mass characterization with the indices' laboratory determination, physical-mechanical and strain properties.

The geological-geotechnical model, based on data surface information and drilling collected in field expeditions; and exploratory surveys lithological interpretation; it is important to know the lito-stratigraphy spatial distribution analysis by profiles geological, also modeling in 3D. the quality rock mass was carried out according to the empirical geo-mechanical classification RMR basic (Bieniaswski, 1989).

The mass rock samples were analyzed in the laboratory in order to determinate the physical-mechanical parameters, involved in the software with algorithm to calculate, that come from the tests; Specific weight (twenty samples), specific rock weight (twenty samples), Direct shear (rock and ground, ten samples), SUCS classification (twenty samples), Sonic velocity (twenty samples), Single compression with elastic coefficients/modules (twenty samples), Point load (twenty samples).

The tailings sampling was carried out at the «El Tablon» Community tailing where the tailings sands are deposited as gold recovery result of the eighty-five-process mineral operational plants of «Zaruma-Portovelo» mining district. 350 kg were sampled for cyanidation tailings, flotation and gravimetry processes.

The criteria considered in the mortar cylinders elaboration (cement and tailings) was based a mortar design that the resistance conditions and fluidity with cement and tailings ratio 1:2. For their preparation, analyzes were carried out with ASTM standards for arid in concrete and mortar (see Table 1, Figure 5), in order to could be used tailings sands or not.

The pseudo-static tenso-strain analysis based on the geological-geotechnical model, index parameters resistant, rock mass elastic parameters and mortar cylinders (1C:2T ratio), the occurrence determination of the subsidence phenomena occurrence under four scenarios; before collapse, during, post mitigation works and filling with tailings.

Results discussion

Geological-geotechnical model

In the regional geological context, «La Inmaculada» school is located in a geological change zone to the south «Ecuador», where the geodynamic environments involve metamorphic rocks (Paleozoic-Mesozoic) of the Block Amotape Tahin (BAT) and the volcano-clastic continental volcanic sequences called «Portovelo» Unit (Oligocene), the tectonic limit in the south end is set by the «Pinas-Portovelo» fault and in the north end by the «Palestine» fault. The study area is located in «Zaruma-Portovelo» gold district, where quartz filons system (Riedel system) with high profitable mineral content (Au, Ag, Cu) is located, lengths between 2,5-3,5 km with variable powers between 0,3 and 3 m, these veins have a preferential N-S course and variable dips to the E. (Bonilla, 2009).

In the collapse chimney and sector galleries outcrop volcano-sedimentary sequences formed by andesitic tuff, crystal tuff and andesites. The rock mass is fractured where it was found minerals inside and different grades weathering, the grade weathering levels allowed to show five geotechnical units where it's possible differentiate is by ratio their behavior in relation to resistance (see Table 2).

Figure 6 represents the geological model with the galleries spatial distribution that took advantage of the «Tres Reyes» vein (blue solid), from the level «Chorillos» L1/3 level (dimension: +- 1050 m. s. n)., up by multiple mining excavations (trunk-irregular sections between +- 5 and +- 45 m^2) inclined to 45° (recess) (see Figure 6). The gallery located in the dimension +- 1158 m. s. n. (magenta solid) was the cause of instability of the rock mass under the «La Inmaculada» school, where the conditioning factors (low lithostatic load, intense weathering, unfavorable geological structures, minimal geomechanically properties) and triggers (high precipitation, classrooms static load, dynamic blasting load, tension state by mining excavations) affected the resistance rock mass loss, producing an subsidence accelerated phenomenon of soil to consecutively occur the sinking with cone conformation up to 23 m in diameter (dimension +- 1206 m. s. n.) and collapse chimney +- 40 length (red solid) (INIGEMM, 2017).

Rock mass physical-mechanical parameters, filling material and pulp

Table 3. summarizes the physical-mechanical and elastic parameters described to:

- *Rock mass*, refers with sixty-three drilling cores sampling (different levels) taking as reference weathering levels (UG-I, II, III, IV, V), they were subjected to direct cutting and simple strength compression tests with elastics modules. In the discontinuities systems (D1 and D2), cohesion and friction angle were calculated using Barton-Bandis breakage criterion (1990).
- *Rockfill material*, refers to andesitic composition angular rock blocks with diameters between 0.70 to 1.20 m, which are arranged locked inside the cavity of the collapse chimney. Cohesion is zero by the rock mass washing in winter times. The strength and

Figure 4. a) mortal level + drains + viga perimetral + armed with iron, b) slab cast, c) fill with class three sub-base compacted material

Table 1. Physical-chemical requirements that the fine arid must be (tailings)

Test	Norma
Chemical analysis	ASTME 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

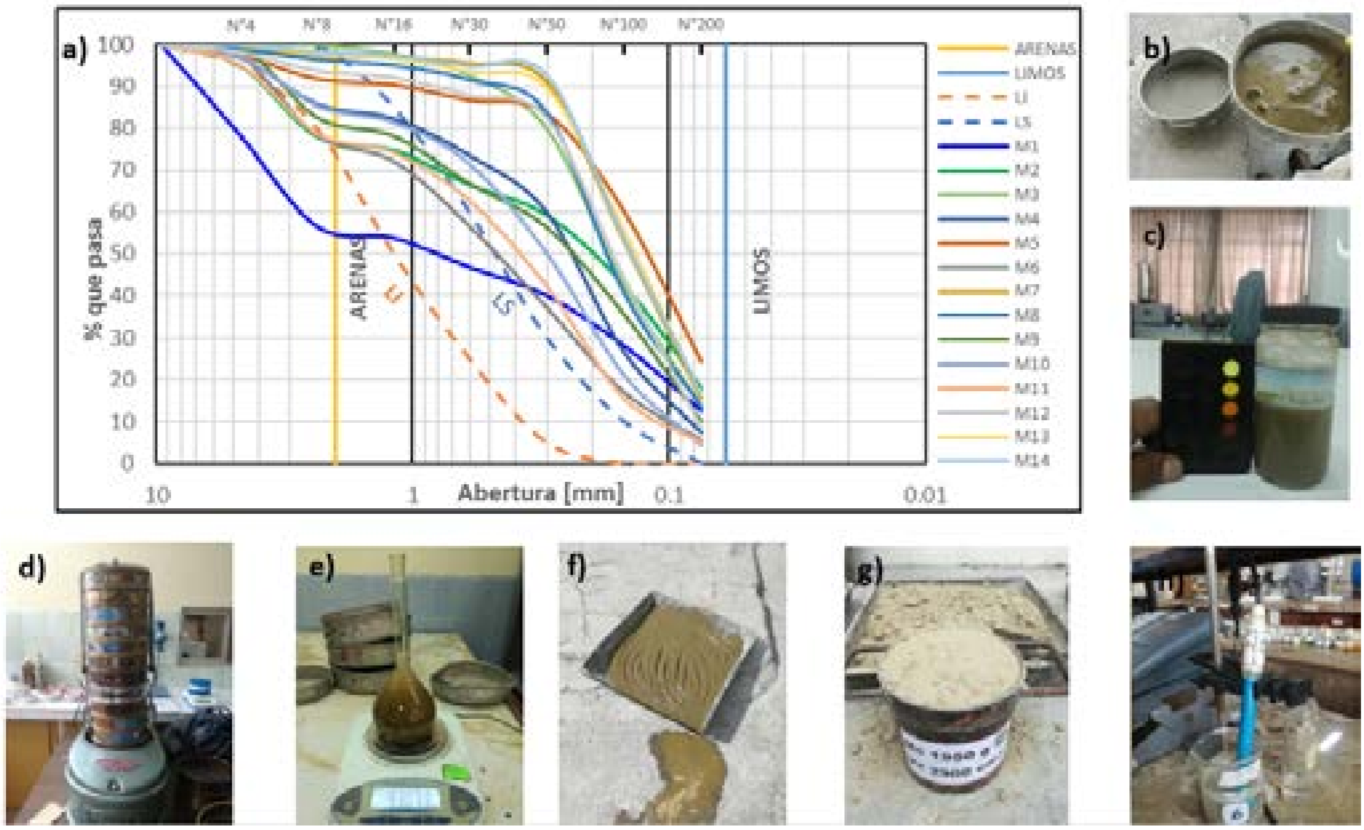


Figure 5 a) Granulometric curves of the relay compared to fourteen simples obtained from tailing "El Tablon" b) Surface saturation of the tailing for the material thinner than 75 um calculation c) Organic impurities in the mining tailing, according with the normalized data, it is one, suitable for use in concretes or mortars. d) Granulometry test e) Density relative calculation; wet, dry and tailing percentage absorption f) 1 Kg of the three process mixed tailings (cyanuration, flotation and gravimetry) g) Weight volumetric calculation of tailing average with 1596.12 kg/m3 h) Hydrogen potential measurement (pH) in tailing sample.

- elastic parameters are determinated from rockfill guide (2009) and Perucho, A. (2004).
- *Sub-base compacted material class three*, it is andesitic waste rock, that mining companies out. The filling design was calculated to 2 mm compaction in with 90% with 10.74% humidity and 2.0 kg/m^3 density. The strength parameters are based to Lambe, t et al, (2010). The elastic module was calculated to empirical correlations exposed in Rondon, H. (2013), using 3% CBR laboratory obtained.
- *Pulp filling,* it refers a mortar design based on the Rivera, G., 2013 methodology, based cement absolute volumes calculation, tailings (T) and water (A), with an optimal ratio 1C: 2T: 0.49 W/C for the briquettes manufacture (see Figure 7) and cylinders. The aggregate fine analysis obtained from analysis meet in 95% the characteristics required for mortars built and desired strength. The 5% percent in relation to finesse module with a value less than 2.3, show it that more cement should be added to the mixture and change the final mixture (Rivadeneira, A., 2021).

The fluidity percent is related for smooth-consistency mortar (self-leveling mortars), and its use could be manual or injection. It is important apply the strength requirements, equation 1 was applied:

$$\mathbf{R'mm} = 1.35 \times R'm \qquad \text{Ec. (1)}$$

Donde:

R´mm (MPa): Compression strength mortar after twenty-eight days.
R´m: Mortar compression strength after twenty-eight days, according a type M mortar (RCS 17.5 MPa)
If the type M mortar needs to be check by the standard strength (17.5 MPa), we could have a condition:

$$1{,}20 \times F'm \leq R'm \leq 1.50 \times F'm$$

Donde:

F´m (kg/cm^2): Design strength compression is 21MPa.

Finally, the briquettes were found to have resistance of 18 MPa at fourteen days of curing with water and cement ratio 0.49. the cement amount in relation to the finesse's module is given to 602.10 kg/m^3 of mixture, water quantity 295.03 kg/m^3 and 1136.14 kg/m^3 for cement and tailing ratio 1:2. Once the mortar was designed, mortar cylinders were developed to determine; resistant and elastic parameters that were obtained by triaxial tests and simple compression applied to twelve samples. It's important that the rupture was at fourteen curing days, time where the mortar reaches 90% of its maximum strength (see Table 3).

Stress-strain analysis

The geological-geotechnical environment, physical-mechanical-elastic properties, distributed loads and pseudo-static conditions, four scenarios were represented by longitudinal profiles that are parallel to the «Tres Reyes» vein, by the stress-strain analysis by finite elements.

The numerical modeling allowed to know the rock mass behavior, which the graphic outputs isolines (cold and warm colors scale) and vectors; displacements, tensions and deformations in reference to the mining excavations; allowing demonstrate areas with instability risk (plasticized areas) and breakage mechanisms.

The analysis has two scenarios, which cone and collapse chimneys were subjected in "La Inmaculada" school, before cone conformation, during cone conformation and collapse chimney, and after remediation by INIGEMM (2017). The fourth scenarios are the purposed surface-filling pulp using cement mortar with tailings sands.

Scenario 1: Model before cone formation and collapse chimney (October, 25th 2016)

Geological model: Figure 8a, showed the spatial distribution of weathering levels with the join systems (D1 and D2). With the color white represents the mining excavation's location that up from the «Chirillos» gallery L1/3. With red color represent the school «La Inmaculada» dead load and the water ground level position (FN) with blue line (see Figure 8a).

*Stress-strain Model***:** Figure 8b, showed the total strain behavior, with values of 20 mm in the area where the school «La Inmaculada» was located (see Figure 8b). It showed from south gallery (level: 1166 m. s. n. m.) to the north gallery (level: 1163 m. s. n.) with maximum strains up to 30 mm above the central gallery (28 m x 18 m). In the central lower, it's possible it's to strain increase happened in the center, this is to the geometric configuration of galleries excavated in anti-technical way, and taking advantage of the pillars that provide safety.

Scenario 2: Model during cone formation and collapse chimney. (Zaruma, 21st February 2017).

Stress-strain model: Figure 9d, the strain behavior showed in the collapse chimney sector, where occurred movement of 1.90 m. the strain isolines shows the rock mass relax inside of the cone (see Figure 9). This model represents the instability cone and chimney collapse behavior. That's occurred developed seven instability events; beginning on October 25th, 2016 with 10 m cone until on February 20, 2017 where the cone reached 31 m diameter. The stress modification generated an imbalance, at the moment ground sinking, causing the chimney walls collapse. (circular break).

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

U. Geotec.	Weath. Rock	Description	Resistence Class	Resistence Lab (MPa)
UG-I H: 4-15m	Residual ground	Dark Orange clay soil, with high plasticity with soft consistency and high natural humidity.	S2-S3	0,08
UG-II H: 6-15m	Complete	Grey coloration, that have clay-slime with high plasticity of soft consistency and high natural humidity, rock fragments up to 2 cm	S4-S5	0,14
UG-III H: 8-18m	High	Light gray with dark shades, that have silt-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: 8-15m	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: >25m	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).

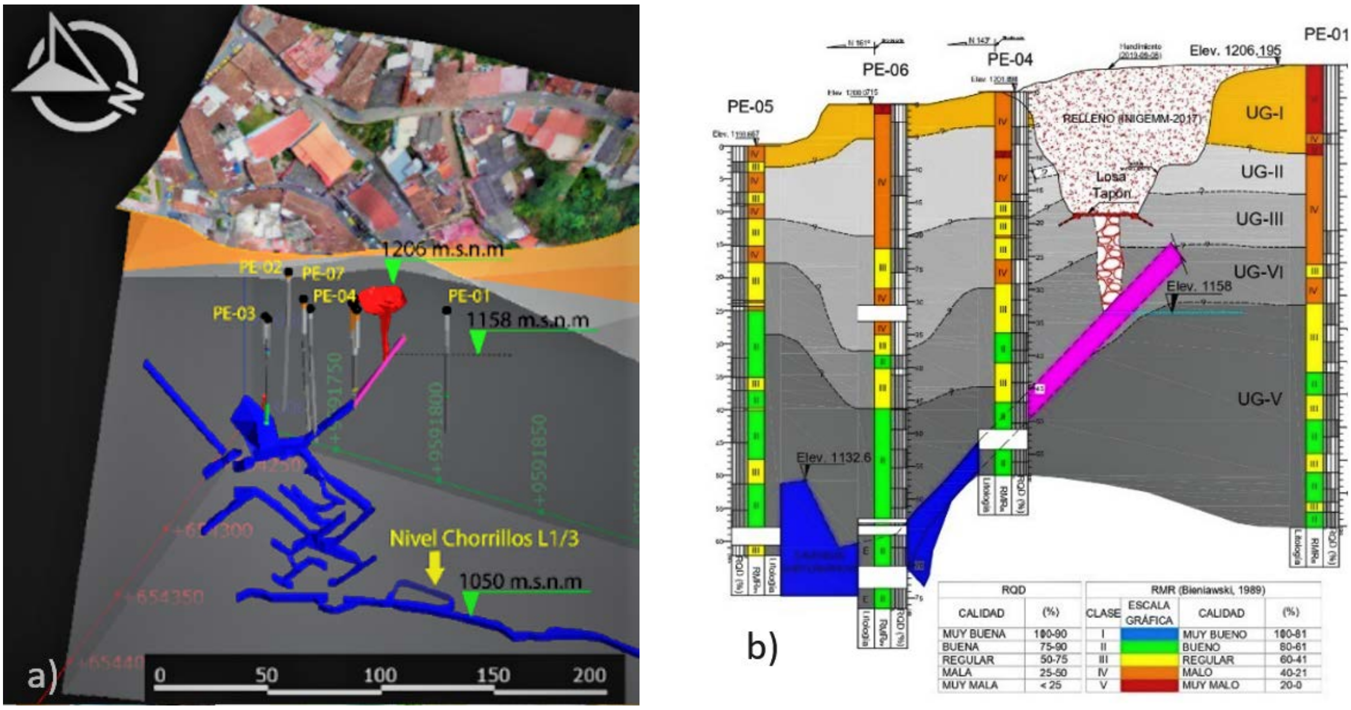


Figure 6: a) 3D Geological-geotechnic model b) Areas between exploration probes PE-01, PE-04, PE-06, PE-05, where it is showed; five levels of weathering, RQD and mass rock quality according to Bieniaswski, 1985. Source: Modify INIGEMM, 2017 y Rivadeneira, A.,2021.

SCENARIO 3: MODEL-REMEDIATION INIGEMM, (2017) (PILES, SLAB, FILLED)

Geological Model: Figure 10a, shows the geological part described before and remediation works that finished on October, 2017, where it is inlcuded; twelve caisson-type piles construction of 1.20 m diameter and average length of 19 m, 32 m perimeter screen of support in the reinforced concrete, slab stopperconstruction in beams moved and theses supported in sixteen micropiles (see Figure 10a).

Finally, the work is completed with the compacted landfill to rebuild the natural surface topograpghical conditions. In adition to, the rockfill material inside the collapse chimney is showed, this filling was part of the emergency solution, made by GADM Zaruma on February 2017 with the advice of the Risk Management Secretary

Stress-strain model: Figure 10b, the total deformation behavior, after the remediation works, is showed reaching values of 5 mm in the area where the piles work was carried out (see Figure 10b). Evidence that the stabilization proposal implemented by INIGEMM (2017) was effective. It is important knew that the plasticizing from the south gallery to the north gallery strains of up to 30 mm above the central gallery, the area where the school is located

Table 3. Parameters index summary, resistant and deformations, obtained from specific weight test, direct cut, SUCS classification, sonic velocity, strength simple and point load

Code	Material/ structure	Description	Analysis Type	N.º	ɣ [KN/m³]	ϕ [°]	C [MPa]	E [MPa]	ɣ́
UG-I	Ground	MH	Laboratory- Hoek & Brown (2002)	7M	27,08	29,00	0,091	37,72*	0,1**
UG-II		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), ɣ́ (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).

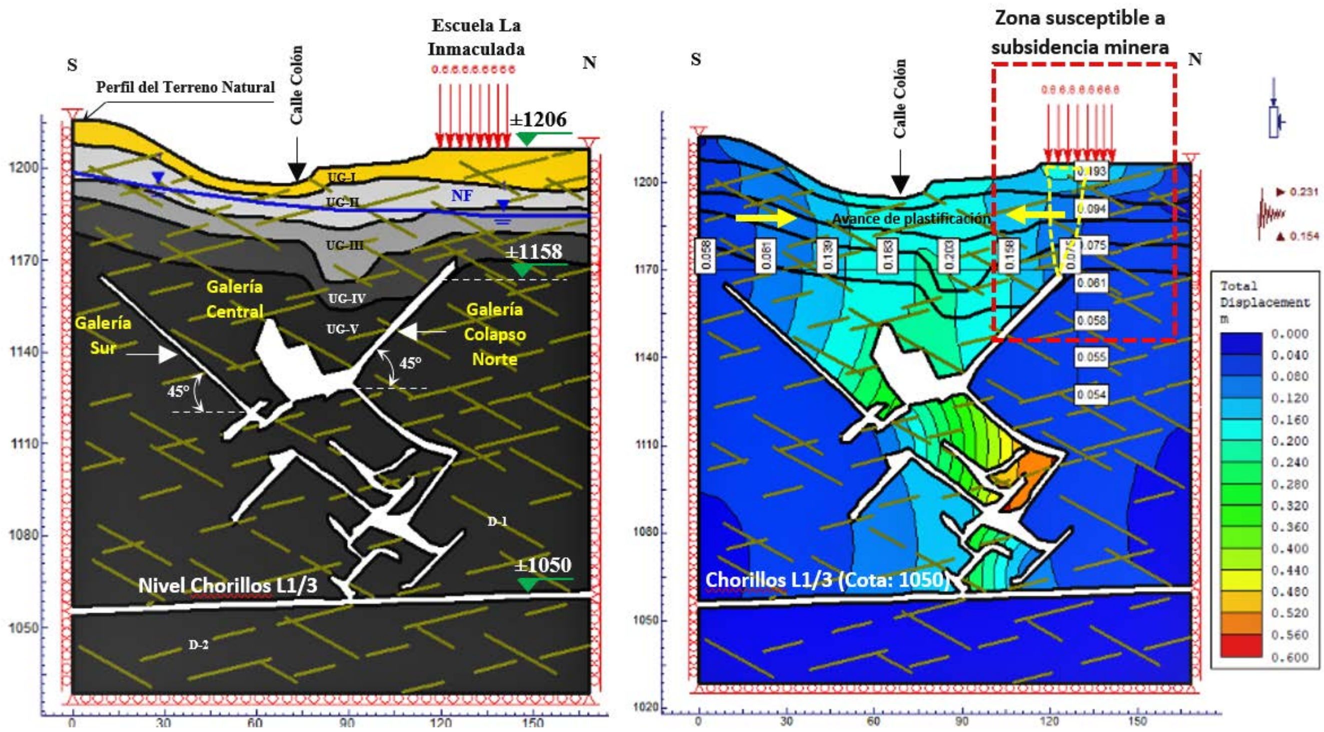


Figure 8. a) pre-collapse geological model, b) stress-strain model with areas plasticized development. «La Inmaculada» school there is evidence of disturbed zone. The isolines show the cone configuration and tendency of the collapse chimney (yellow line).

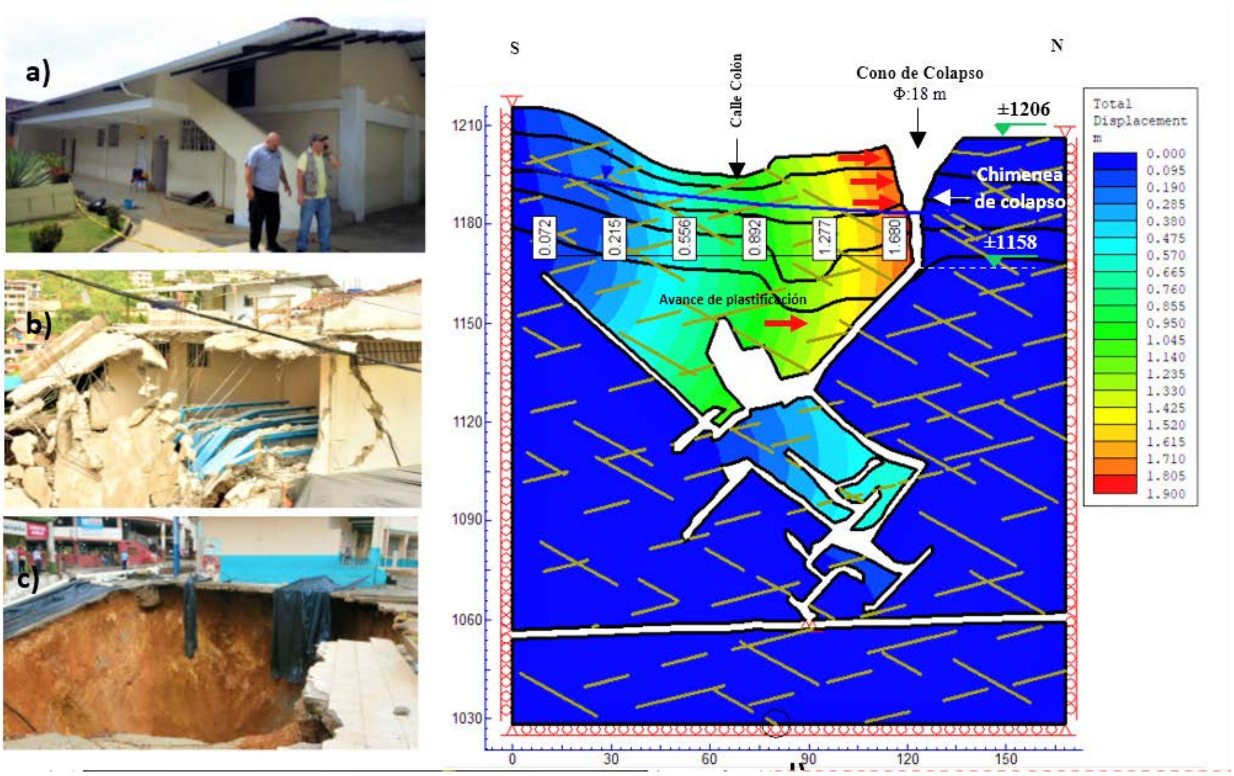


Figure 9. a) «La Inmaculada» school classroom (oct-2016), b) classroom collapse, c) cone (Φ:18 m) and chimney (L:34 m), d) stress-strain model where the strain develops parallel to walls of chimney reached displacements of up to 1,90 m

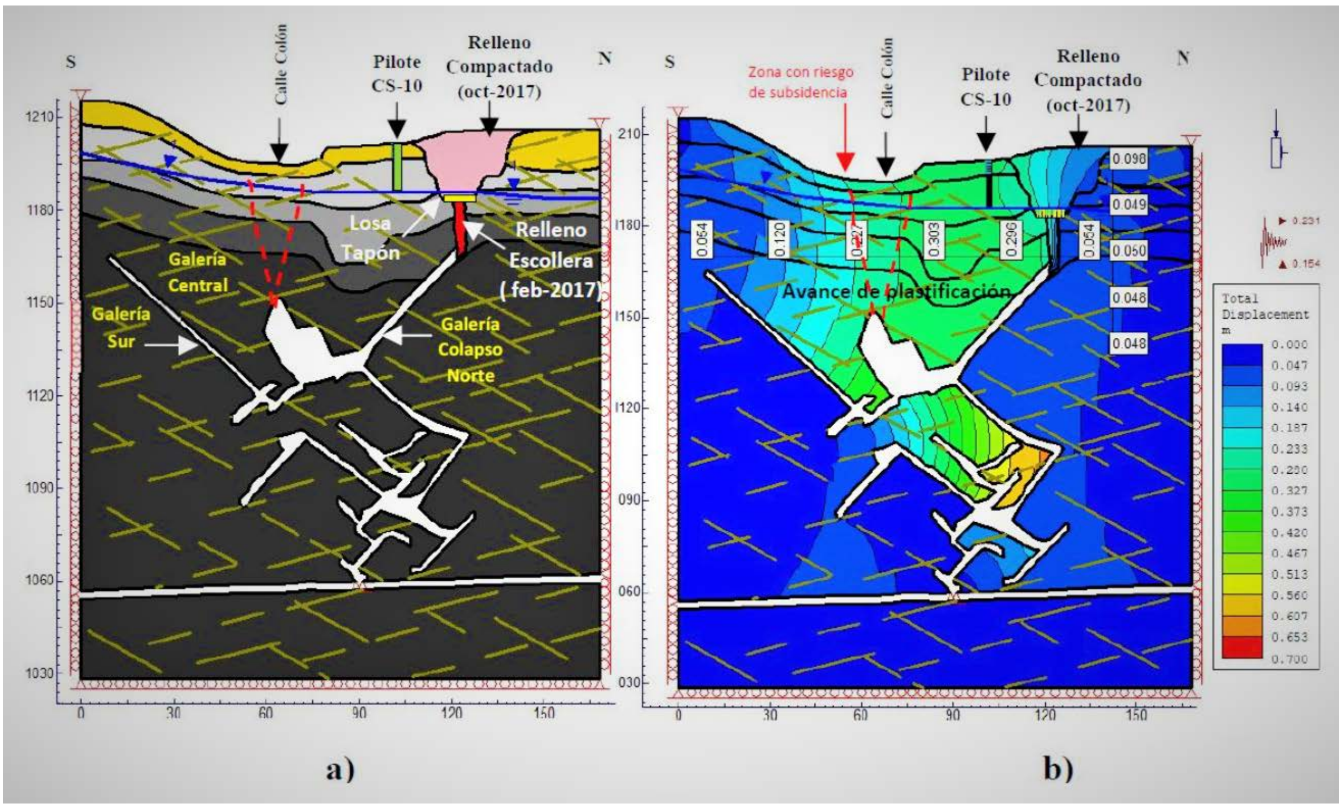


Figure 10. a) geological model with the mitigation works location; piles, sly plug and compacted filling, b) remediation works post-implementation strain behavior

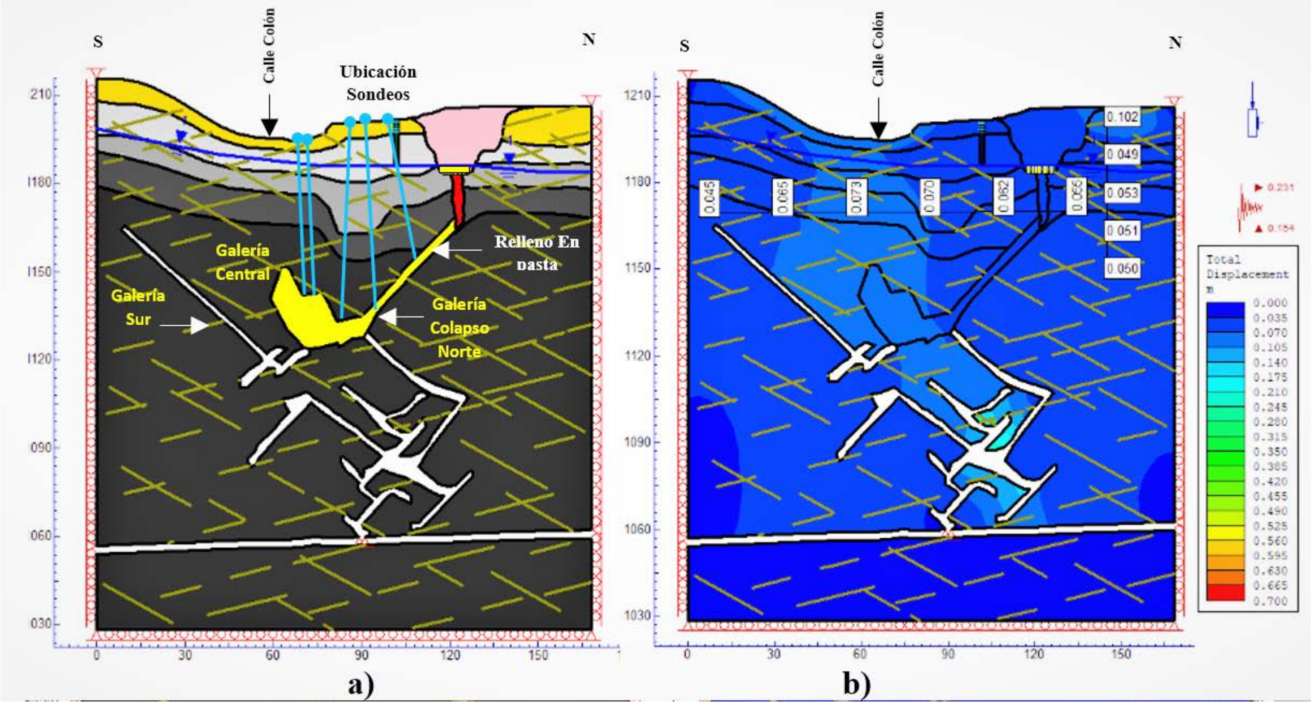
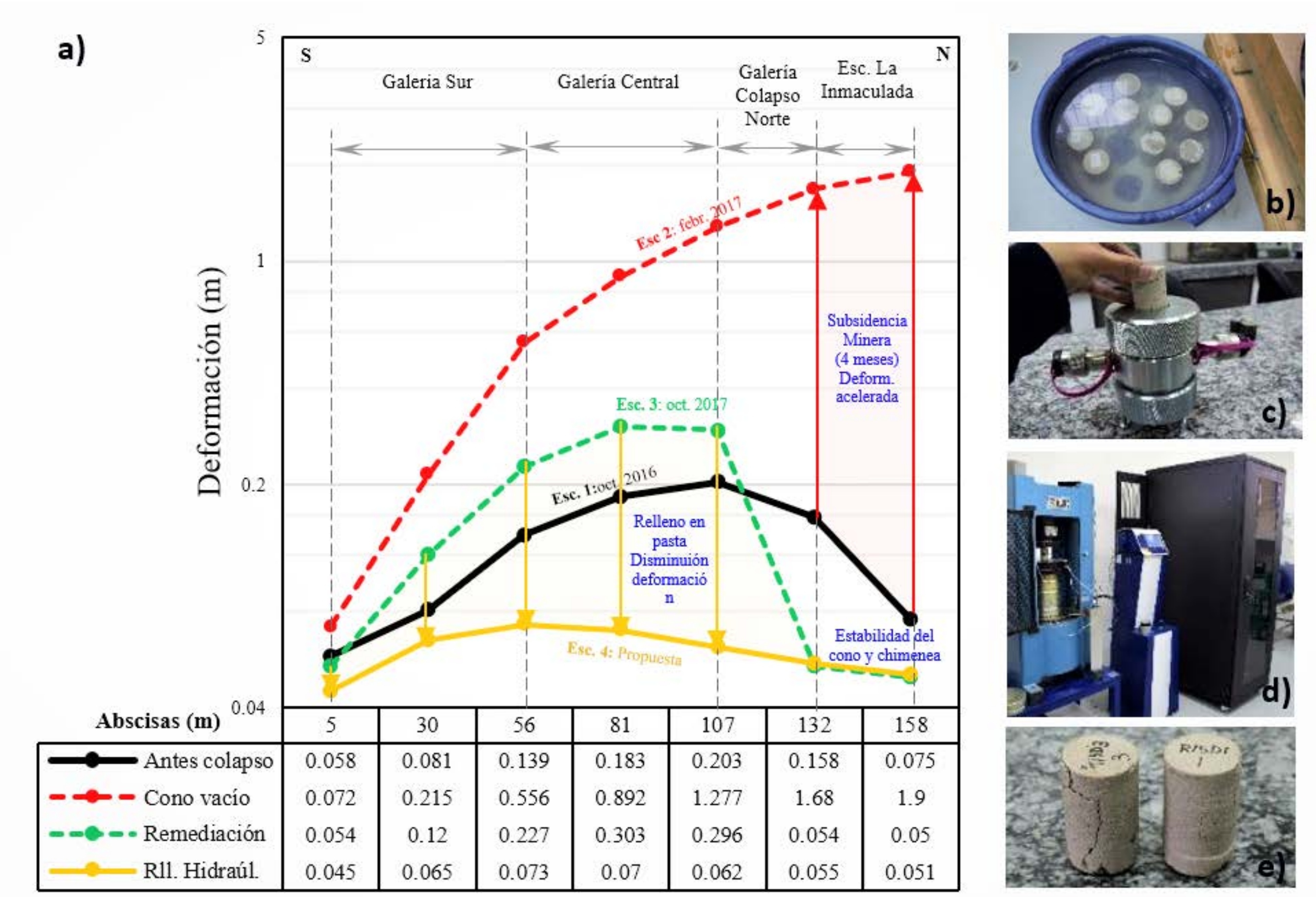


Figure 11. a) geological model, mitigation works and pulp filling, b) post-filling deformation behavior in pulp



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) relation between on x-axis (scenarios 1-4) and maximum strain for events: before collapse (October, 2016), cone and collapse chimney gradual expansion (February, 2017), remediation works implementation, b) mortar cylinders (1C:2R), c) Hoek for triaxial test, d) simple compression test with modules, e) tailings and cement cylinders after breakage

«La Inmaculada» has an apparent stability which has a relation to the strain of galleries that had no treatment.

SCENARIO 4: MODEL WITH PULP FILLING PROPOSAL (CEMENT + TAIL)

Geological Model: Figure 11a, shows the geological part, mitigation works and the proposed pulp filling with a mortar design (cement and tailings ratio 1:2) (see Figure 11a). The mining excavations injection was proposed from the surface by five soundings (did in 2017: SE-3, SE-4, SE-5, SE-6, SE-7). Before filling, its built reinforced concrete topons that block the mining galleries for the closing the injection system.

Stress-strain model: Figure 11b, it showed the filling effectivity using tailings sands how fine aggregate, the mortar designed after fourteen days had a simple strength compression of 10 MPa (see Figure 11b). The stress-strain model in the filling zone indicated lower values than 6 mm. the deformation behavior in relation to other galleries decrease, and plasticized areas low when the excavations were stabilized.

Conclusions

The four stress-strains models show plasticizing rock mass state, by the mining galleries that were under school surrounding «La Inmaculada». Figure 12a shows the investigation results, in order to have a relation with strain and gallery's location in the longitudinal section with north-south direction:

- *Scenario 1, before collapse (October, 2016):* the strain curve is maximum in the area between the central and north gallery; reaching displacements values between 10 mm and 20 mm, the development and advancement of these galleries disturbed the tensorial state, leading to the rock mass plasticizing between 0+50 and 0+132.
- *Scenario 2, empty cone (February, 2017):* when the first instability event, the cone and chimney collapse increased their diameter by the rock changes and efforts modification, conditional factors (lithology, favorable geological structures, weathering) and triggers (static and dynamic loads by blasting and earthquakes, stress disruption, runoff water infiltration), allowed a decrease in the rock mass resistance, causing surface subsidence to occur the sinking.
- Scenario 3, Remediation (October, 2017): the mitigation works designed by INIGEMM, 2017 in the area under «La Inmaculada» school minimized the strain up to 5 mm, achieve the sector stability, in the other hand, the strain between the central gallery and the north gallery (0+50 and 0+132) showed values of up to 30 mm. it is important that the authorities consider the following suggestions:
    - A periodic geodetic monitoring implementation of the area between «La Inmaculada» school grounds and the «Ernesto A. Castro» and «Bolivar» intersection streets, as a susceptible area.
    - Discard the traffic and prevent the new buildings construction on the landfill area and the «Ernesto A. Castro» street surrounding until implement a remediation work that offers stability.
    - Build a Surface drainage system to cause runoff water, with avoid the fines washing and reduce differential settlement phenomena in the fill area.
- Scenario 4, Pulp filing (proposed): the strain curve shows values less than 7 mm, showing the pulp filing possibility with cement and tailings mortar (Figures 12b, c, d, e), with a favorable mechanical rock mass behavior by back the stress state lost, disappearing subsidence effects. Which shows that the filling in pulp in the other galleries existing under the «Zaruma» city, taken as reference the ideal dimension to locate plugs, about 1110 asl. In the other hand, it is an effective proposal to the problem of environmental pollution in the «Puyango» river caused by leachates in the tailings.

This preliminary investigation demonstrates that the proposed cement and tailings injection mixture, decreases the plasticizing of rock around mining excavations. No having the necessary studies to design the ideal cement and tailings ratio to have a good material (pulp filling), which have variables such as: physical-mechanical parameters, heavy metals inert, costs and operational processes.

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