remote sensing

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Article

Generation of stability models and mapping using photogrammetric reconstruction techniques in Chichaca tunnel (Province of Loja).

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Abstract: The Chichaca Tunnel was handcrafted by the residents of Chantaco and Chuquibamba in the Catamayo Canton of Loja Province, Ecuador. Its construction began in 1936, took nearly 20 years, and was completed using only hand tools and blasting techniques. The tunnel spans 62 meters and serves as a crucial route for the region's residents. Despite its stability to date, concerns persist regarding its safety due to the lack of geotechnical investigations. This study addresses these concerns by employing advanced photogrammetric reconstruction techniques, specifically Structure from Motion (SfM), to analyze the tunnel's discontinuities and identify potential structural vulnerabilities. Additionally, a stability analysis will be conducted using Barton's Q-System for geomechanical classification, complemented by wedge failure analysis. By focusing on the tunnel portals and midsection, this research aims to provide a comprehensive assessment of the Chichaca Tunnel's stability and safety.

Keywords: tunnel, photogrammetric reconstruction, discontinuities, stability analysis, geomechanical stations, wedge)

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1. Introduction

In geosciences, digital photogrammetry has traditionally streamlined and enhanced geotechnical operations by allowing for the rapid and accurate evaluation of geometric properties of rock masses.

To model the stability of wedges identified within the tunnel, the digital photogrammetric technique known as Structure from Motion (SfM) [1]will be employed in conjunction with a traditional approach. This method has proven to be an attractive and consistent alternative to traditional techniques, enabling more efficient data collection and allowing for the development of a consistent model of rock mass fabric. Additionally, it provides valuable digital models for educational purposes [2] and will significantly contribute to future research in the field.

This study conducts a geomechanical characterization of the East and West portals of the Chichaca Tunnel and evaluates the rock mass quality using a combination of empirical methods based on geomechanical classification. The East portal has an average height of 5.70 meters, while the West portal reaches a height of 5.80 meters. The widths of the roadways are 4.40 meters and 5.21 meters respectively, each featuring an arched cross-sectional profile. The tunnel extends for 62 meters, with the study focusing particularly on measurements at the portal entrances. The tunnel was selected for this detailed analysis because it was constructed without the benefit of extensive expertise in geomechanics, geology, or tunnel construction engineering techniques.

2.- Location and Geological Background

The Chichaca Tunnel is located on the road connecting Chuquiribamba and Catamayo, about 7 kilometers northeast of Catamayo City, situated at an average elevation of 2605 meters above sea level.

The study area is located in Loja, in the Southern Sierra region of Ecuador, wich is in Catamayo village, it includes the geomorphological domains of the intramontane basin of Gonzanamá, wich mainly consist of green, purple and chestnut colored shales. These contain scattered crystals of selenite; however, layers of tuff and diatomite were also noted [3]. The Gonzanamá Formation rest unconformably on the Sacapalca Formation [4].

In the area, Sacapalca Formation (PcES) from Paleocene age predominates, shaping the geological landscape. It is andesites, tuffaceous breccia, conglomerates, lacustrine shales and scattered dacitic tuffs [5]. Gonzanamá formation is comoposed byred and yellow sandstones, siltstones and shales that unconformably overlie the Sacapalca Formation. Metamorphic rocks (Pzi) are described as metagranodiorite and metaquartzmonzonite. Debris flows and alluvials are also present in the area described as sedimentary deposits [4, 5] (see Figure 1).

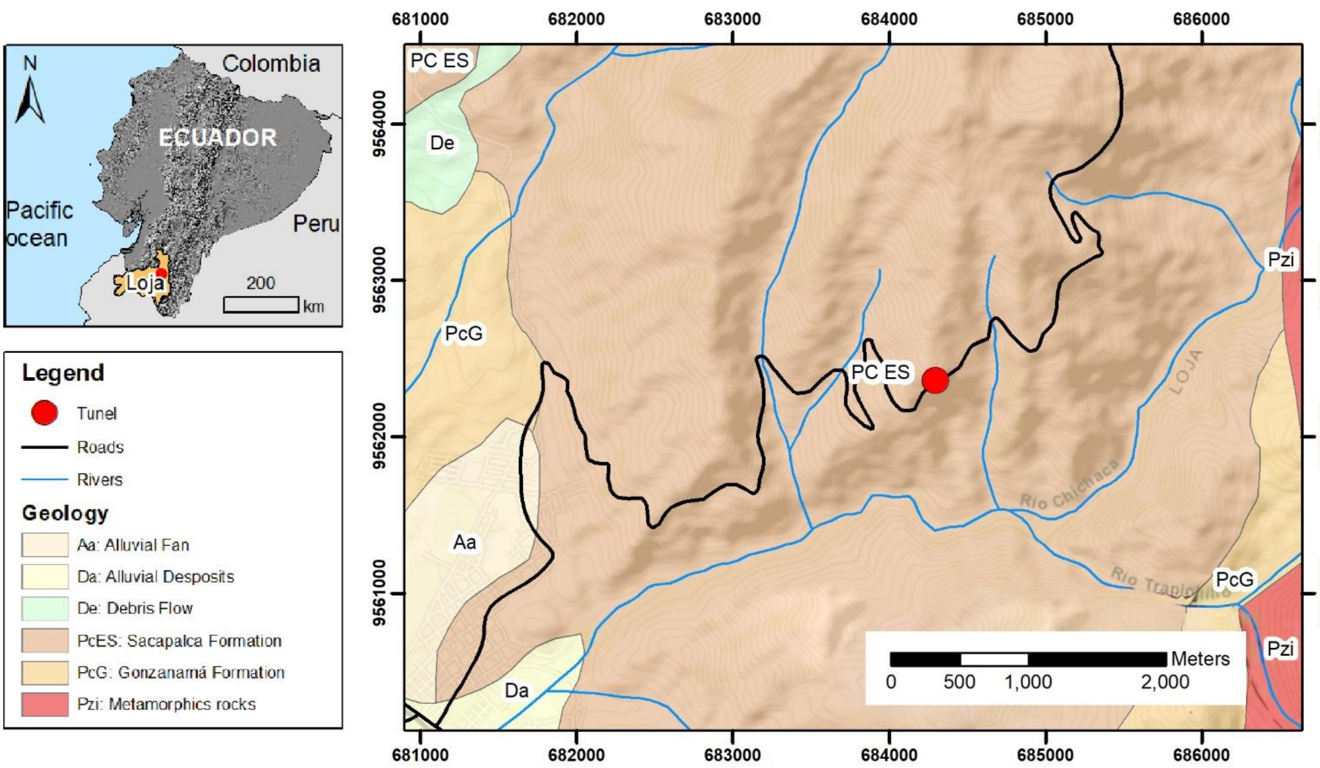

Figure 1. Study area location and geological map.

3. Materials and Methods

3.1.- Photogrammetry

Photogrammetry employs parallax, which refers to the differences in the apparent position of an object due to the varying perspectives provided by overlapping images taken from different viewpoints, to obtain volumetric information that accurately describes surface structures. This method is particularly effective for images with significant overlap that capture the complete three-dimensional structure of a scene from different viewpoints, or as suggested by its name, from images derived from a moving sensor [6].

The SfM technique has many advantages over traditional short-range photogrammetry method. These include greater efficiency, flexible workflows, and the absence of the need for expert supervision [7]. Additionally, the SfM technique simplifies the acquisition of XYZ coordinates for rock masses, resulting in a 3D point cloud. The 3D model database created with SfM was built using a standard mobile device (iPhone 12), with an average photo size of 4.25 MB. The digital reconstruction was processed on a laptop computer Core i7 processor and 16 GB of RAM memory. The specific geometric and optical information can be used to remotely identify shape changes or to determine typical parameters of a rock [6]. Consequently, issues of inaccessibility and bias are mitigated when collecting large amounts of data, leading to more representative and accurate outcomes [8].

3.2.- Geomechanical Classification

To assess the rock mass quality of the tunnel, two geomechanical classification systems, the Rock Mass Rating (RMR) and the Q-System method [9] were applied.

To apply the RMR classification [10], the rock mass along a tunnel route is divided into distinct structural regions, i.e. zones in which certain geological feature are relatively uniform. For each structural unit, the following six parameters are used to classify a rock mass using the RMR system:

- Uniaxial compressive strength of the intact rock material
- Rock Quality Designation (RQD)
- Joint or discontinuity spacing
- Joint conditions
- Groundwater conditions
- Orientation of fractures in relation to the tunnel

The Q-System, developed in Norway by Barton, Lien, and Lunde [11], is used to determine the need and/or amount of reinforcement in a tunnel according to its size and the quality of the rock mass. The Q-System assigns a value to each type of rock proportionate to better quality.

$$Q = \frac{RQD}{Jn} * \frac{Jr}{Ja} * \frac{Jw}{SRF} \quad (1)$$

RQD stands for Rock Quality Designation index (i.e. The relationship between the sum of core lengths from a drill exceeding 10 cm and the total length of 1 meter, shown in percentages). Jn is based on the number of joint families in the rock mass and ranges from 0.5 to 20. The value of Jr varies according to the roughness of the discontinuity and ranges from 1 to 4. Ja varies from 0.75 to 20 according to the degree of alteration of the dike walls. Jw is based on the presence of water in the rock mass and varies from 0.05 to 1. SRF stands for Stress Reduction Factor and relies on the state of stress of the rock crossing the tunnel.

For the estimation of sustainment to be applied during excavation, a two-entry chart [11] where the Q-System index of the rock is on the x-axis and the tunnel width is on the y-axis was used. It was then modified by applying a correction factor to obtain a value referred to as the tunnel’s Equivalent Diameter (De), as illustrated in the following equation:

$$De = \frac{Span\ or\ high\ (m)}{ESR} \quad (2)$$

Here, an ESR value of 1.3 will be used for minor road, railway, access, and collector tunnels, as well as balance shafts.

To estimate the RMR, Barton's Q-System index, and other joint parameters in the rock mass, the methodology for analysis with geomechanical stations was employed [12] [13]. The number of stations and their location depend on the favorable conditions and representativeness of the terrain (accessibility and existing outcrops). Data was recorded at each station, allowing for the characterization of both tunnel portals, their discontinuities and geomechanical parameters.

The stability analysis of wedges was performed using the UnWedge software from Rocscience [14] through a deterministic type of analysis. The shear strength of the rock was modeled using the Mohr-Coulomb criterion. The residual friction angle was calculated in the laboratory using Barton and Choubey's proposal [15], as indicated in the following relationship:

$$\phi_r = (\phi_b + 20°) - 20\,\frac{r}{R} \quad (3)$$

Where fb = basic friction angle, R = Schmidt rebound on dry unweathered sawn surfaces and r = Schmidt rebound on wet joint surfaces. The basic friction angle used for Andesite was 40° [16].

4. Results

4.1.- Tunnel Geometry with Photogrammetry

This investigation assessed the results of the wedge stability analysis based on geomechanical stations and three-dimensional models developed with photogrammetric reconstruction. Additionally, the stability of the tunnel portal and the center of the tunnel were evaluated empirically.

In February 2024, photographs with a horizontally leveled plane set up facing North were taken during a field campaign. The reference planes' locations at each portal were configured by placing 3 marks for the orientation and scaling of the model. Whit this arrangement, relative measurements can be taken, and point 2 was set as initial reference (0,0,0 coordinates) to generate the 3d models of portal (see figure 3). An iPhone 12 was used get a set of 303 photographs at the tunnel portals to create 3D models (see Figure 4) [17]. Specifically, 158 photographs were taken on the East side and 145 on the West side. Later, 3D models of each tunnel portal were build using Agisoft Metashape software version 1.7.0 [18], producing dense point clouds that were then exported to CloudCompare software version 2.12.4.

Figure 2. Chichaca Tunnel, length=62 m, plunge 72°, Agisoft Metashape model.

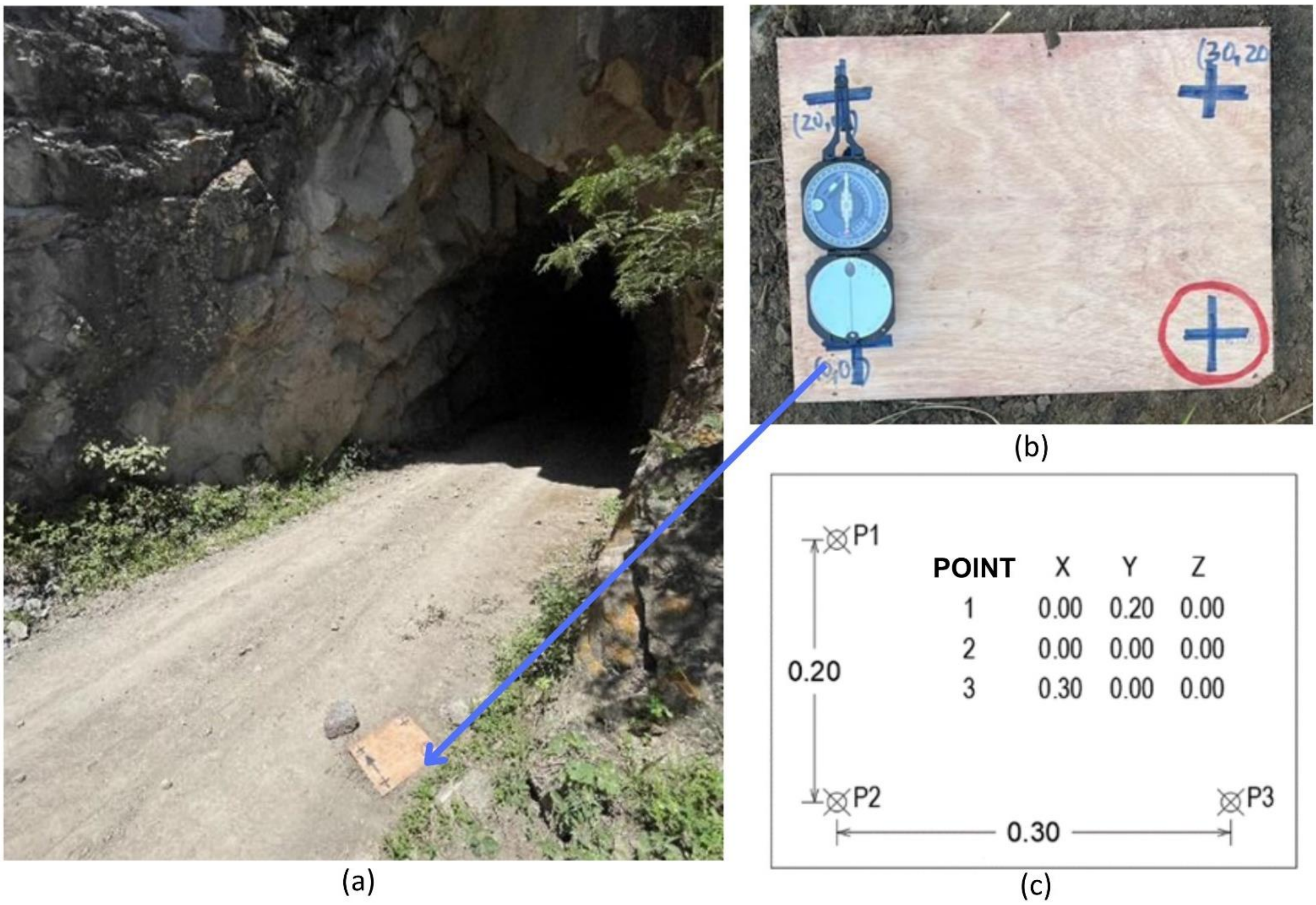

Figure 3. West Portal (a), board with coordinate points and facing north (b, c)

Figure 4.- Model of tunnel view in West (a) and East portal (b) from Agisoft Metashape.

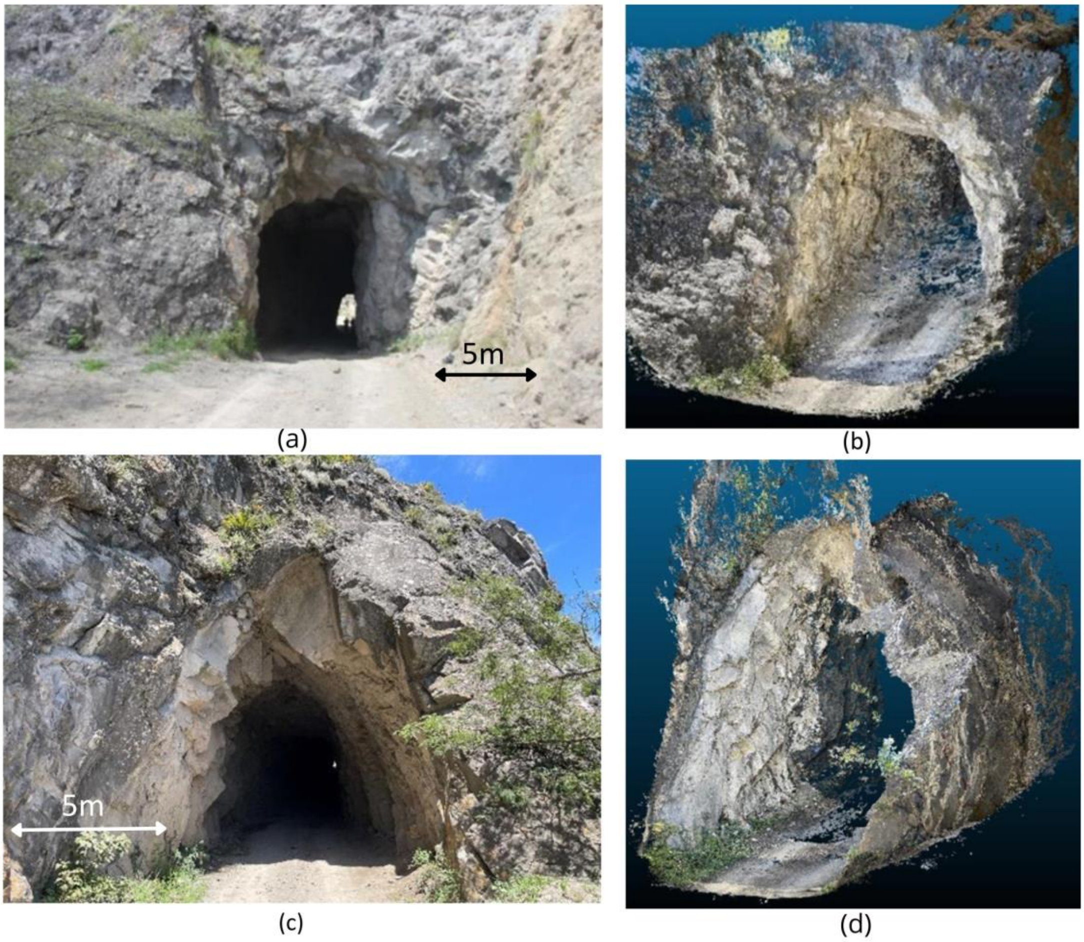

Figure 5.- East (a and b) and West (c and d) tunnel and point cloud portals, (c) and (d) belongs to CloudCompare 3D model.

Field work recollected Dip Dir and Dip in 6 geomechanicals stations, using compass (Table 1). On the other hand, the same information was extracted in both of three-dimensional CoudCompare model (Table 2)[17]. Field work data represented and average of 50% from digital model data. Dip Dir and Dip measurements were extracted from CloudCompare models produced in high and medium, quality without significantly varying data.

Table 1.- Dip Direction and Dip measured with compass at geomechanical stations.

West Portal

Joint	**J0**	**J11**	**J12**	**J13**	**J14**	**J15**	**J21**	**J22**	**J23**	**J3**	**J4**	**J51**	**J52**	**J53**
Dip. Dir.	54	79	61	69	40	43	289	322	285	144	243	57	49	65
Dip.	58	59	53	53	46	49	58	51	56	43	45	48	50	47

East Portal

Joint	**J61**	**J62**	**J7**	**J8**	**J91**	**J92**	**J93**	**J11**	**J12**	**J131**	**J132**	**J133**
Dip. Dir.	55	65	266	322	299	297	293	83	67	291	302	293
Dip.	70	58	37	38	72	48	69	74	57	47	42	39

Table 2.- Dip Direction and Dip measured with ClouCompare software.

West Portal

No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Dip Dir	293	328	311	326	27	47	128	168	168	186	113	183	155	303	183	161
Dip	63	69	45	70	59	57	89	86	54	74	58	83	75	66	76	84

No.	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
Dip Dir	163	192	319	148	168	164	332	191	184	150	43	184	331	343	57	35
Dip	74	41	83	72	85	72	46	64	89	87	58	58	89	87	71	60

East Portal

No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Dip Dir	182	37	51	0	359	125	17	29	186	357	276	292	169	45	23	329
Dip	87	46	58	53	87	78	73	75	44	72	48	63	87	44	69	75

No.	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Dip Dir	175	319	355	30	270	164	266
Dip	88	47	43	44	50	88	54

A comparative representation of the joint families was obtained using stereographic networks, and they was plotted using Dips V7 software from Rocsience [19], which allowed to identify the discontinuities families and to determine differences between field survey and SfM technique (see Figures 6 and 7). Measurements of joint orientations (manual and remote) drawn in Dips show a concentration of poles identifying two principal discontinuities families called J1 and J2 in each portal ,

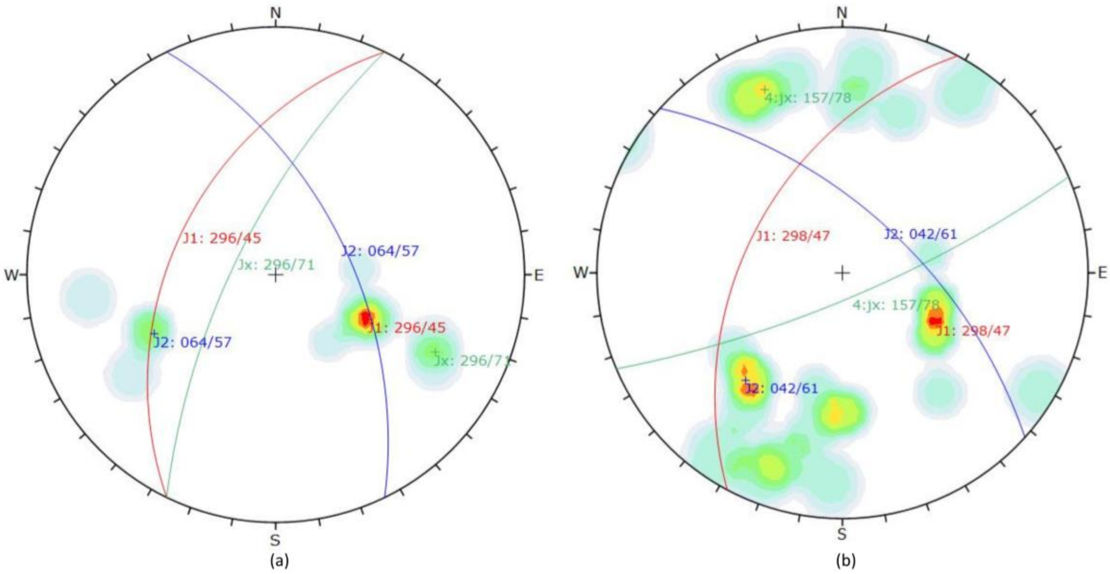

Figure 6.- East portal, stereograms, Manual Data (a) vs CloudCompare (b).

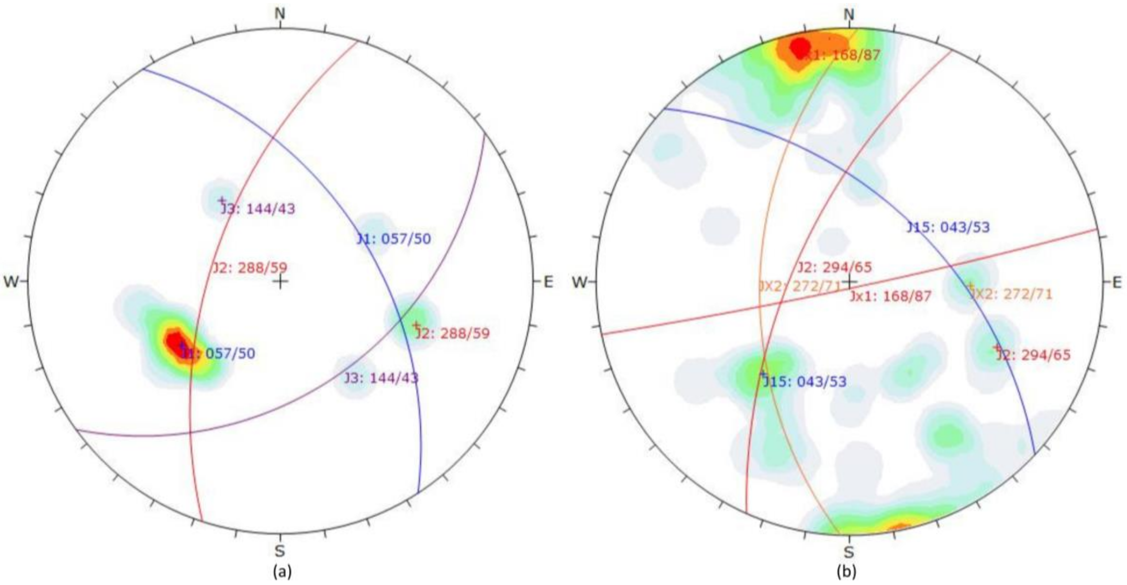

Figure 7.- West portal, stereograms, Manual Data (a) vs CloudCompare (b).

Table 3 summarizes the families of discontinuities registered manually and remotely with SFM, indicating differences of 2° in Dip Dir and Dip at the J1 joint and 22°/4° at the J2 joint for East portal, while at West portal, difference is greater 14°/3° at J1 and 4°/6°. This suggests similarity of data in both methods, with errors in remote data collection that can vary by up to 30%.

Table 3.- Joints, manual and remote data.

Joint	Geomechanical Station		CloudCompare		Difference	
	Dip. Dir.	**Dip**	**Dip. Dir.**	**Dip**	**Dip. Dir.**	**Dip**
J1-East	296	45	298	47	2	2
J2-East	64	57	42	61	22	4
J1-Oste	57	50	43	53	14	3
J2-Oste	298	59	294	65	4	6

4.2.- Stability assessment using Geomechanical Classifications

In addition to the photographs, geotechnical data were collected at both tunnel portals for rock mass characterization using geomechanical stations. The collected parameters were the discontinuity orientations, compressive strength of the rock matrix and discontinuities, roughness profiles, joint length and spacing, discontinuity conditions, infill material, and water presences. The data were used for the RMR calculation and Q Index geomechanical classifications.

The geotechnical characterization with geomechanical stations collected the orientation of the joints and properties of the discontinuities in the rock matrix in the walls of the tunnel portals. The recorded data are synthesized in 5 geomechanical stations (3 on East side and 2 on the West side), which the calculations were performed in laboratory to determine the RMR and Q index as well shear strength parameters of the discontinuities.

According to Bieniawski's criteria, the RMR shown in Table 4 indicates good quality rock, whereas Barton's Q Index classification rates the rock quality as poor to medium (Table 5).

By having a geological formation along the tunnel, it is possible to apply the RMR classification.

Table 4.- RMR index defined from Geomechanical station data.

	Geomechanical Station				
Parameter	**1**	**2**	**3**	**4**	**5**
RCS	7	7	7	7	7
RQD	18	18	16	18	15
Spacing	10	13	14	17	8
Continuity (persistence)	4	4	2	2	2
Aperture	1	1	1	1	1
Ruoghness	1	1	3	3	3
Filling	4	4	2	2	2
Alteration	5	5	3	3	5
Water	15	15	15	15	15
RMR_b	**65**	**68**	**63**	**68**	**58**

The data from geomechanical stations 1 to 4 were taken at the portals. Geomechanical Station 5 data (located 15 m from the East portal), were used to perform the model in center cross section. For the calculations of the Q index in the portal, Jn x 2 was used for EG 1 to EG4, and Jn x 1 was used in EG 5.

Table 5.- Q index defined from Geomechanical station data.

	Geomechanical Station				
Parameter	**1**	**2**	**3**	**4**	**5**
RQD	90	90	75	90	70
Jn	6	6	6	3	3
Jr	3	3	3	2	3
Ja	4	4	3	3	3
Jw	1	1	1	1	1
SRF	2,50	2,50	2,50	2,50	2,50
Q	**2,25**	**2,25**	**2,50**	**4,00**	**9,33**

The results of the geomechanical stations were plotted on the permanent support recommendation chart based on Q values and Width/ESR [11] (Table 6). They indicate that stations 3, 4 and 5 did not require support; while in station 1 and 2, support must be applied in the tunnel section with systematic bolting spaced 1.2 m apart and sprayed concrete for 5-6 cm of thickness plus fibre reinforced.

Table 6.- Summary of rock quality according to RMR y Q.

Location	Geomechanical Station	RMR_b	Classification	Q	Score	Span (m)	ESR	Span/ESR
West	1	65	Good	2,25	Bad	5.00	1.30	**3.85**
West	2	68	Good	2,25	Bad	5.00	1.30	**3.85**
East	3	63	Good	2,50	Bad	4.00	1.30	**3.05**
East	4	68	Good	4,00	Medium	4.00	1.30	**3.05**
Center	5	58	Medium	9.33	Medium	5.00	1.30	**3.85**

To conduct the numerical stability analysis using Unwedge software, residual friction angle and tensile strength values were calculated for each geomechanical station (see Table 7).

Table 7.- Residual friction angle **ϕr** and tensile strength **σ_n**.

Geomechanical Station	r	R	ϕ basic	ϕ r	σ_n
1	55,80	63,40	40,00	37,60	0,078
2	48,40	59,40	40,00	36,30	0,078
3	37,80	53,80	40,00	34,05	0,078
4	25,60	51,00	40,00	30,04	0,078
5	43,80	57,80	40,00	35,16	0,078

4.3.- Unwedge Wedge Analysis.

The tunnel cross-sections obtained through surveying were delineated in AutoCAD and imported to UnWedge for analysis. The joints families orientation (fieldwork and digital data acquisition) provides specific information for each tunnel stability model, while the common data include alignment, inclination, friction angle, tensile strength, and cohesion. The numerical analysis was conducted using the Mohr-Coulomb failure criterion. For the stability analysis using UnWedge, the alignment (72°) and inclination of the tunnel (4°) data were taken from the topography survey. The cohesion considered for the Mohr-Coulomb model was C=0. The results of models show safety factors greater than one, as indicated in Figures 8, 9 and 10.

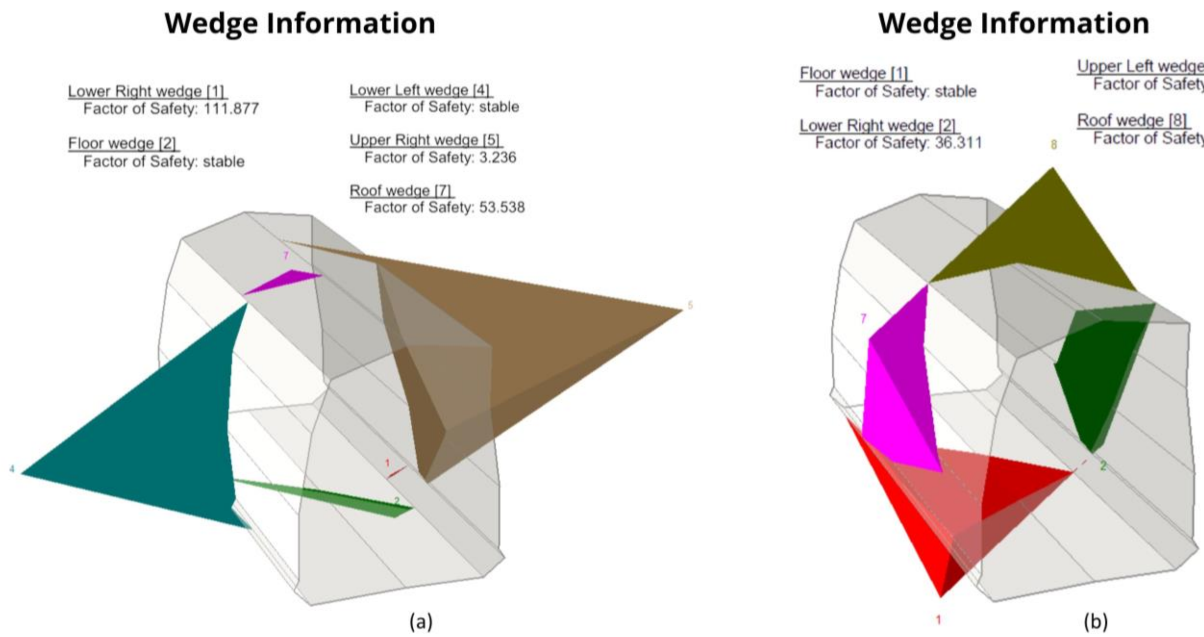

Figure 8.- East Portal, Geomechanical station (a) and tridimensional model. (b)

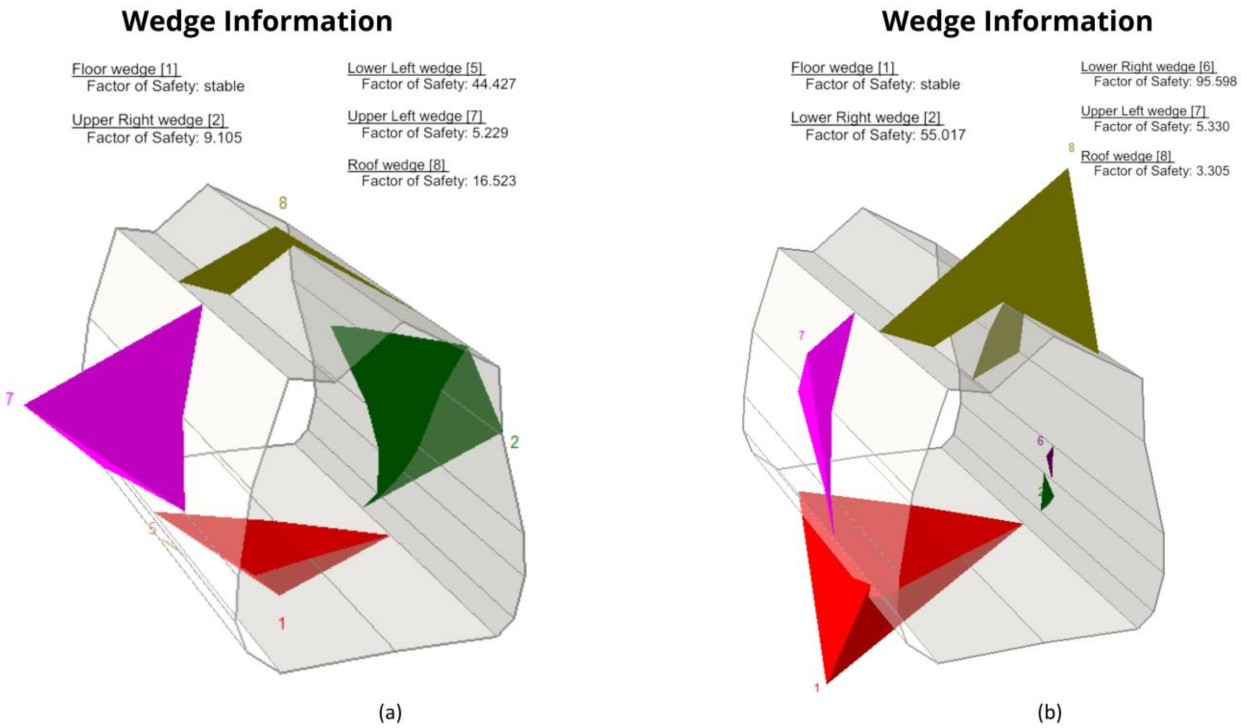

Figure 9.- West Portal, Geomechanical station (a) and tridimensional model. (b)

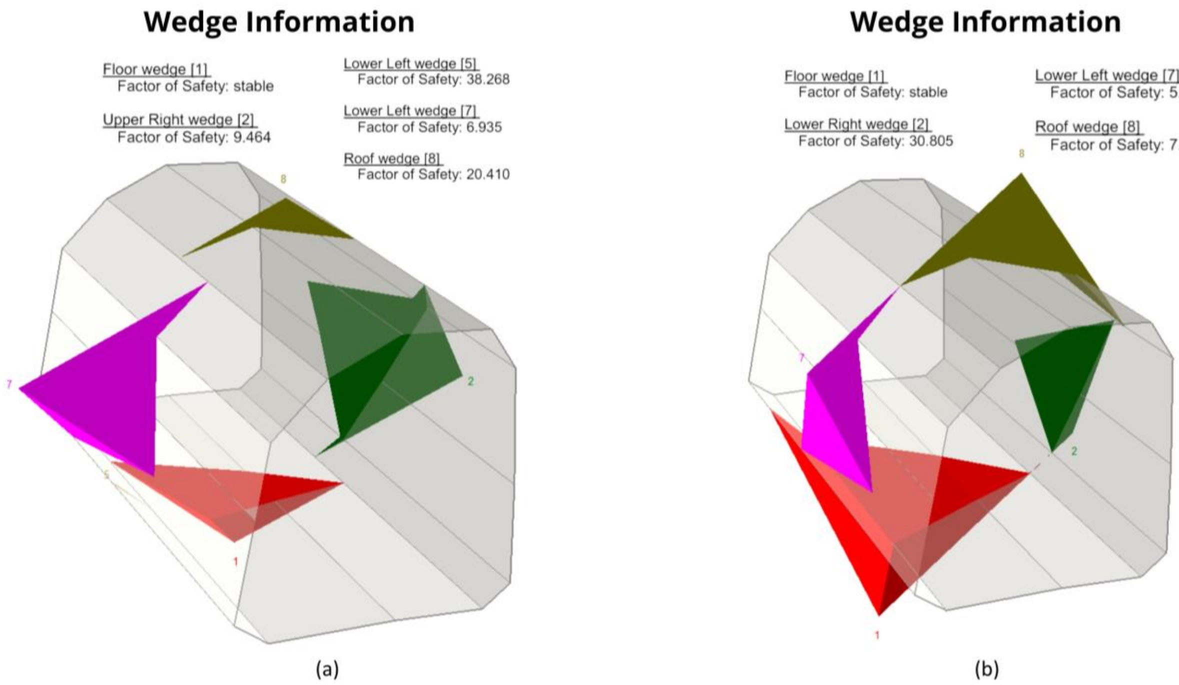

Figure 10.- Central cross tunnel, Geomechanical station (a) and tridimensional model. (b)

5.- Discussions

The remote sensing technique with SFM allowed the acquisition of joint orientation data at any location within the study area without the need for fieldwork. In photogrammetric reconstruction, it was evident that with blurred photographs and poor capture positioning, it is not possible to construct a 3D model that would be useful for the user. When converting photos into point clouds, unrealistic random points can be generated on the discontinuity planes, altering the true inclination of the measured plane. A limitation of this technique is observed in spaces lacking interior lighting, as the resulting modeling does not provide researchers with usable data (Figure 2).

The difficulty in discerning data in CloudCompare models at the tunnel portals led to the division of the 3D models into sectors (walls and vault). CloudCompare allowed for the extraction of joint orientations throughout the digital model environment.

For the purposes of this research, tunnel stability analyses were conducted using the empirical Q System method, combining manually measured (compass) orientation data with data extracted from the CloudCompare 3D model. From the processed manual and remote information, two families of joints called J1 and J2 governing the stability of the wedges at each portal were synthesized (Figures 6, 7, and Table 3). The differences in plane inclination range from 2° to 22° in the dip direction and from 2° to 6° in dip. Dip Dir and Dip measurements in digital models were compared with data from control points of geomechanical stations, noting that measurement differences may also result from a larger measurement surface in UnWedge compared to the support surface of a geological compass.

The results of the empirical analysis based on the Q index indicate that support for the East and central sections of the portal is unnecessary, while the West portal requires support with bolts and shotcrete. The six stability analyses conducted in UnWedge (2 in the East portal, 2 in the West portal, and 2 in the center) determined safety factors greater than unity (Figures 8, 9, and 10).

Table 8.- Summary of stability analysis in the Chichaca tunnel.

Location	Geomechanical Station	Measurement of discontinuities	Empirical analysis	Numerical analysis
West Portal	EG 01	Manual	Requires sustainment	Stable
West Portal	EG 01	Remote	Requires sustainment	Stable
East Portal	EG 03	Manual	No Sustaining Required	Stable
East Portal	EG 04	Remote	No Sustaining Required	Stable
Center	EG 05	Manual	No Sustaining Required	Stable
Center	EG 05	Remote	No Sustaining Required	Stable

6.- Conclusions

The basis of this research lies in the utilization of remote techniques for inaccessible sites and wedge stability analysis in tunnels. The study conducted allowed for the definition of tunnel stability and safety conditions, employing geomechanical classifications (RMR and Q) and numerical analyses, in combination with manual data and photogrammetric techniques (SfM).

The creation of 3D models enabled a more comprehensive visualization of wedges throughout the studied area, from which more plane orientation data can be obtained compared to manual measurements, which are typically recorded at accessible heights ($h<2m$). This advantage favored numerical models with UnWedge, which more accurately represented the wedges in the tunnel sector under analysis.

The empirical evaluation and remote method confirmed the stability of the East portal and central section of the tunnel. In the West portal, results differed between both methods, concluding the need for support in the empirical method, while stability of the system was indicated by the numerical evaluation. Given this difference in results, it is recommended to conduct a future research campaign with finer geotechnical parameters.

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Conflicts of interest: The authors declare that they have no conflict of interest.

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CERTIFICACIÓN DE REVISIÓN DE PROYECTO DE TITULACIÓN

Por medio de la presente, Yo Davide Besenzon Venegas, Coordinador del Programa de Maestría en Geotecnia de la Escuela Superior Politécnica del Litoral (ESPOL), certifico que:

Con fecha 10 de abril de 2024, los estudiantes Francisco Javier Coello Monar y Andrés Fernando Cedeño Oviedo con números de identificación 0919640581 y 0916556897, de la Cohorte 2 y 4, respectivamente, presentaron la propuesta de su tema de titulación al Comité Académico del programa. Posteriormente, con fecha 31 de mayo 2024, el Comité revisó y aprobó la propuesta mediante la resolución FICT-CA-GEOTEC-011-2024, cumpliendo con los requisitos establecidos para la aprobación del tema.

A partir de dicha aprobación, los estudiantes mantuvieron reuniones periódicas con el tutor designado, Daniel Omar Garcés León, para la elaboración y desarrollo de su proyecto de titulación, siguiendo los lineamientos establecidos por el programa. Con fecha 12 de junio 2024, los estudiantes presentaron y sustentaron su proyecto de titulación ante el tribunal evaluador asignado, cumpliendo con el proceso formal de evaluación académica.

Por lo tanto, en calidad de Coordinador del Programa de Maestría en Geotecnia, certifico que el trabajo de titulación denominado **"Generación de modelos de estabilidad y mapeo utilizando técnicas de reconstrucción fotogramétricas en el túnel Chichaca (Provincia de Loja)"**, realizado por los estudiantes Francisco Javier Coello Monar y Andrés Fernando Cedeño Oviedo con números de identificación 0919640581 y 0916556897, respectivamente, ha sido revisado y evaluado conforme a los lineamientos y estándares establecidos por el programa.

Debido a circunstancias externas, no ha sido posible obtener las firmas de los involucrados (estudiante, tutor(es) y/o evaluadores). No obstante, en calidad de Coordinador del Programa, certifico que el proyecto cumple con los requisitos académicos y ha sido revisado para su presentación y archivo institucional.

Atentamente,

Firmado electrónicamente por:
DAVIDE BESENZON VENEGAS

M. Sc. Davide Besenzon Venegas
Coordinador de la Maestría en Geotecnia