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Facultad de Ingeniería en Ciencias de la Tierra

Caracterización geomecánica de los materiales graníticos y metamórficos de Morona Santiago, Ecuador.

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Resumen

La caracterización del subsuelo es un aspecto fundamental en la planificación y diseño de proyectos hidroeléctricos, ya que permite evaluar la viabilidad técnica y geotécnica de las infraestructuras propuestas, garantizando su estabilidad y funcionalidad. Según Hoek y Brown (1997), comprender las propiedades geomecánicas del macizo rocoso es esencial para anticipar su comportamiento frente a cargas estáticas y dinámicas, minimizando riesgos durante la construcción y operación. Este estudio se centra en la caracterización geomecánica de los macizos rocosos en las zonas de "Santa Rosa" y "El Rosario", ubicadas en Morona Santiago, Ecuador, con el objetivo de determinar parámetros clave para el diseño de proyectos hidroeléctricos. Se realizaron ensayos de campo y laboratorio, incluyendo pruebas de compresión uniaxial, tracción brasileña, carga puntual, tilt test y clasificaciones geomecánicas mediante los índices RMR y Q.

Los resultados muestran que las rocas ígneas, como el basalto y la andesita, presentan propiedades mecánicas que varían de moderadas a altas, con resistencias a compresión simple superiores a 120 MPa en el caso del basalto, clasificándose como rocas fuertes. En contraste, las rocas metamórficas, como el chert, presentan menor resistencia, con valores entre 69.69 MPa y 90.63 MPa, clasificándose como moderadamente resistentes. Los valores de los índices RMR y Q reflejan una calidad variable del macizo rocoso, desde excelente en sectores de dioritas y granitos, hasta baja en zonas con discontinuidades y alteraciones significativas. Además, se identificaron variaciones en los ángulos de fricción básicos, con valores entre 18.58° y 38.35°, lo que influye directamente en la estabilidad de las estructuras proyectadas. Estos datos, integrados con modelos numéricos y análisis empíricos, proporcionan una base sólida para el diseño de túneles minimizando riesgos geotécnicos.

En conclusión, este estudio destaca la importancia de la caracterización geomecánica para garantizar la viabilidad técnica de proyectos hidroeléctricos, proporcionando información clave para el diseño y desarrollo de infraestructuras seguras y sostenibles en la región.

Palabras clave: caracterización geomecánica; resistencia de rocas; proyectos hidroeléctricos.

Abstract

Subsoil characterization is a fundamental aspect in the planning and design of hydroelectric projects, as it allows for the evaluation of the technical and geotechnical viability of the proposed infrastructures, ensuring their stability and functionality. According to Hoek and Brown (1997), understanding the geomechanical properties of the rock mass is essential to anticipate its behavior under static and dynamic loads, minimizing risks during construction and operation. This study focuses on the geomechanical characterization of rock masses in the areas of "Santa Rosa" and "El Rosario," located in Morona Santiago, Ecuador, with the aim of determining key parameters for the design of hydroelectric projects. Field and laboratory tests were conducted, including uniaxial compression tests, Brazilian tensile tests, point load tests, tilt tests, and geomechanical classifications using the RMR and Q indices.

The results show that igneous rocks, such as basalt and andesite, exhibit mechanical properties ranging from moderate to high, with unconfined compressive strengths exceeding 120 MPa in the case of basalt, classifying them as strong rocks. In contrast, metamorphic rocks, such as chert, show lower strength, with values between 69.69 MPa and 90.63 MPa, classifying them as moderately resistant. The values of the RMR and Q indices reflect a variable quality of the rock mass, from excellent in areas of diorites and granites to low in zones with significant discontinuities and alterations. Additionally, variations in basic friction angles were identified, with values ranging from 18.58° to 38.35°, which directly influence the stability of the projected structures. These data, integrated with numerical models and empirical analyses, provide a solid foundation for the design of tunnels minimizing geotechnical risks.

In conclusion, this study highlights the importance of geomechanical characterization to ensure the technical viability of hydroelectric projects, providing key information for the design and development of safe and sustainable infrastructures in the region.

Keywords: geomechanical characterization; rock strength; hydroelectric projects.

Chapter 1. Introduction

Ecuador has experienced significant growth in its energy demand, driven by economic development and improvements in the quality of life of its population [1]. Hydroelectric power plants represent a viable and ecological solution to achieve energy and environmental goals, reducing dependence on fossil fuels [2].

The implementation of the hydroelectric projects "El Rosario" and "Santa Rosa", located in the province of Morona Santiago, Ecuador, requires the execution of thorough site investigations to ensure feasibility studies. These investigations help establish the technical, financial, and environmental viability of the proposed infrastructure, particularly the powerhouse, which is designed to generate an approximate total capacity of 49.5 MW each [1]. Field and laboratory tests identify issues and assess the suitability of the sites and materials [2]. The process carefully evaluates the physical and mechanical properties of the site's rock formations. Among the techniques used are in-situ tests, such as the point load test, discontinuity mapping through scanline systems, and permeability tests on rock masses, which determine parameters such as compressive strength, fracture density, and rock mass quality [2-3]. At the laboratory level, uniaxial compression strength (UCS) and triaxial tests are conducted, as well as deformation tests to characterise the material's response to stress. These data are integrated into rock mass classifications such as Rock Mass Rating and the Q-system[4]. Furthermore, the use of numerical models simulates the geomechanical behaviour under different loading and design scenarios, complementing the empirical analyses [5].

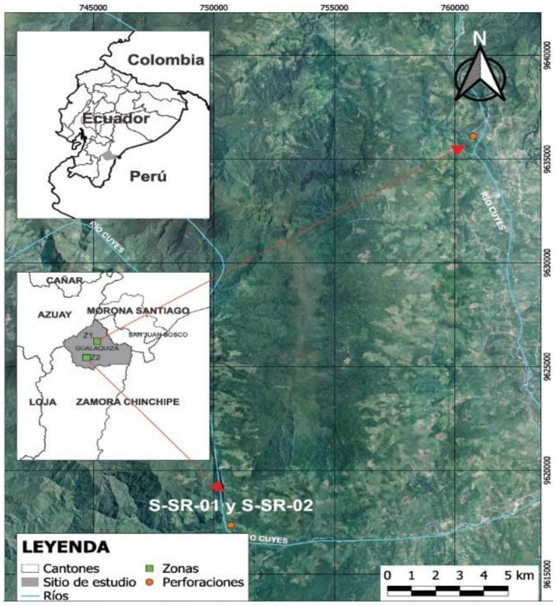
The aim of this research is to characterise the rock mass in order to assign strength and deformability properties to the different sectors analysed, through the collection and analysis of data obtained from two geotechnical field exploration campaigns. The first campaign focuses on the geomechanical characterisation of the rock mass, using core logging techniques and determining parameters such as the RMR (Rock Mass Rating) and the Q index. Complementarily, the second campaign focuses on conducting laboratory tests, including uniaxial compression, Brazilian tensile, tilt tests, and point load tests (PLT). The integration of these results aims to enhance the accuracy of predictions regarding the geotechnical behaviour of the studied area.

Chapter 2. Materials and Methods

2.1 Study Area

The study area is located in the south of the Republic of Ecuador, in the province of Morona Santiago, Gualaquiza canton, in the parishes of El Rosario and Santa Rosa (Fig. 1), defined as Zone 1 and Zone 2, respectively.

Figure 1. *Location of "El Rosario" and "Santa Rosa". (Source: Author's own work)*



The study areas are characterised by varied topography, including steep slopes, narrow valleys, and water bodies that traverse the landscape. This diversity influences the geomorphological processes and the hydrological dynamics of the region [6]. The area is located in the southeastern region of Ecuador, with a predominance of jungle and mountainous terrain, at altitudes ranging from 800 to 3400 meters above sea level. Regarding water resources, the Bomboiza, Chuchumbleza, and Zamora rivers are the main contributors to the Santiago River basin, which is a significant tributary of the Amazon River that flows into the Atlantic Ocean [7].

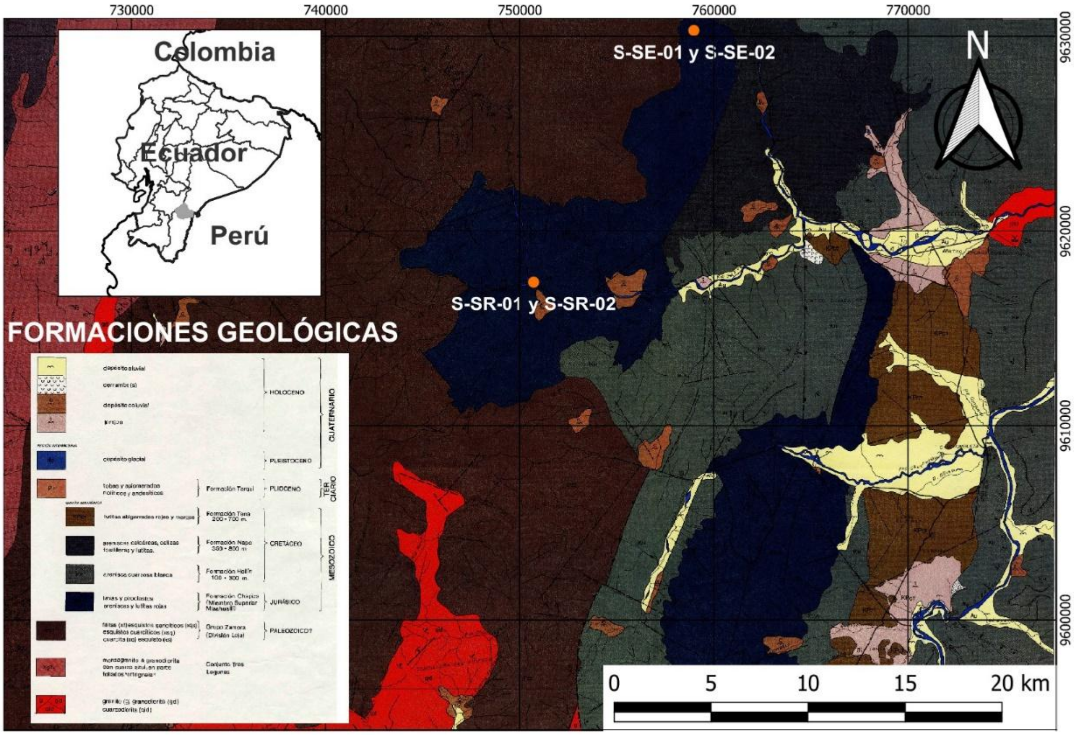
2.2 Geological Background

The region is primarily composed of metamorphic and sedimentary formations (Figure 2) ranging from the Paleozoic to the Quaternary. In the site of "El Rosario," located in Zone 1, rocky outcrops and clayey soils are present, whereas in "Santa Rosa," located in Zone 2, there is a greater presence of alluvial, eluvial, and colluvial soils resulting from erosion and deposition processes [8].

The oldest rocks in the region correspond to the metamorphic rocks of the Zamora Group, of the Paleozoic, considered the most primitive geological units of the area [9]. Subsequently, the post-Paleozoic units include volcanic rocks, such as the lavas of the Chapiza Formation (Misahualli Member), which outcrop in thicknesses exceeding 100 metres. These rocks are composed of lavas, andesites, porphyritic intrusions, red shales, sandstones, and conglomerates. Macroscopically, the andesites and lavas are characterised by being compact rocks with greenish tones, while the lavas exhibit an aphanitic texture with phenocrysts of plagioclase and a grey-green coloration. Additionally, they contain sulphides in veins and disseminated in specific areas [10].

The sedimentary formations from the Mesozoic and Cenozoic, such as the Hollín, Napo, and Tena are mainly composed of white quarzitic sandstones with medium to coarse grains, exhibiting a sugary texture and a whitish-yellow coloration. The sandstones show predominant stratification and a moderate to poor classification, occasionally accompanied by veins of coal. Additionally, black shales are interstratified with these sandstones. The Napo Formation, in particular, consists of a succession of black shales, grey to black limestones, and calcareous sandstones, with a thickness ranging from 200 to over 700 meters [11]. During the Quaternary, the region shows glacial, colluvial, and alluvial deposits, as well as terraces, which reflect active geomorphological processes in the basin [12]. These stratigraphic units are intruded by granodioritic rocks, attributable to an intrusion that occurred during the Cretaceous or Lower Tertiary period. Additionally, the presence of granite rocks belonging to the "Tres Lagunas Unit" is noteworthy. [9].

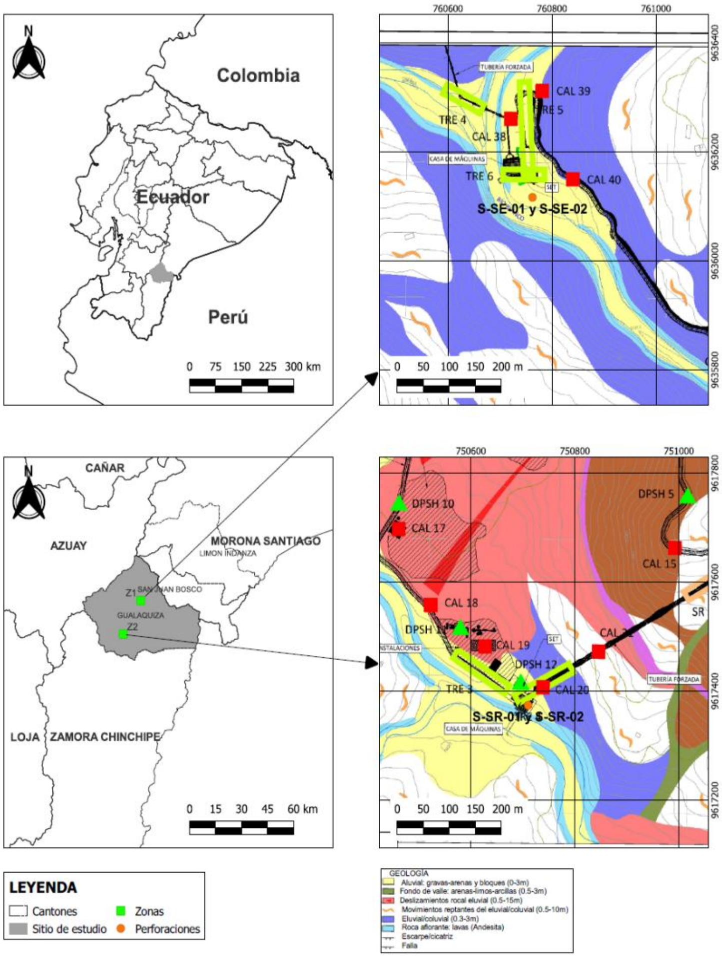
Figure 2. *Regional Geology of "El Rosario" and "Santa Rosa". (Source: Geological Map of Cuenca - Gualaquiza, sheet 75)*



In the study sites (Figure 3), various surface deposits are observed, including glacial deposits in the mountainous regions of the "El Bestion" and "Ortega Alto" ranges to the northeast of Tutupali. All the materials currently eroded in the Real Mountain Range are transported by the powerful eastern drainages. As these drainages lose their carrying capacity in certain sections, they deposit sediments in areas of lower slope, leading to the formation of alluvial deposits [13].

The migration of rivers and changes in base levels have caused the formation of wide alluvial terraces along the banks of the Gualaquiza, Cuchipamba, Cuyes, and Bomboiza rivers, primarily. Additionally, in the slope areas of the valleys, colluvial deposits are found, indicating the movement of material along the slope due to erosion and gravitational processes [14].

Figure 3. *Local Geology of "El Rosario" and "Santa Rosa". (Source: Zonal Geological Map, prepared by Ecoener SA)*



2.3 Sampling

The selected drilling sites (Table 1) are located within the project's area of influence and have been designated as the planned locations for the powerhouse. These study areas are part of the El Bestión mountain range and are situated in the southwest of the Morona Santiago province.

Table 1. *Nomenclature and location of the boreholes.*

Zona	Borehole	Coordinates UTM WGS-84		
		E (m)	N (m)	Z (msnm)
El Rosario	S-SE-01	760762.33	9636116.76	1050.00
El Rosario	S-SE-02	760853.09	9636114.67	1046.00
Santa Rosa	S-SR-01	750696.00	9617391.00	900.00
Santa Rosa	S-SR-02	750710.00	9617374.00	988.50

The boreholes were drilled using HQ drilling pipes with a diamond bit (Figure 4, item a), a technique employed for the continuous recovery of alluvial deposits and granite and metamorphic rock formations. Additionally, a detailed log of the borehole was kept documenting the geological characteristics encountered at each depth (see Figure 4, item c). The HQ pipe allows for the creation of wells with a diameter of 96.1 mm, obtaining cylindrical cores of 63.5 mm in diameter and approximately 1.5 m in length, which are extracted using a steel barrel and stored in plastic boxes of the same diameter (see Figure 4, items b-d). During the process, powdered bentonite and biodegradable polymers were used to optimise the performance of the drilling fluid. The operations were carried out in May 2024.

Figure 4. *Geotechnical exploration campaign and field sampling: (a) Drilling on site using the wire-line system; (b) HQ pipe with a diameter of 96.1 mm; (c) Detailed on-site logging of the borehole; (d) Storage and documentation of field samples for transportation to the laboratory. (Source: Author's own work).*

	
(a)	(b)

(c)

(d)

To obtain a complete lithological sequence and reach the bedrock of the site, four boreholes were strategically distributed: two in the Santa Rosa area and two in El Rosario (see Table 1). These boreholes facilitated the geological characterisation by revealing the different lithologies present at each location (see Table 2), providing essential data for the geotechnical analysis of the area.

2.4 Rock Mass Rating (RMR)

The following analysis is based on the 1989 version of the classification [15]. In order to classify rock masses using the RMR system, the following six parameters are used:

1. Uniaxial compressive strength of the rock material.

2. Rock Quality Designation (RQD).

3. Discontinuity spacing.

4. Condition of the discontinuities.

5. Groundwater conditions.

6. Orientation of the discontinuities.

For each of the six parameters considered, five values are presented, depending on the specific conditions associated with those parameters. The Rock Mass Rating (RMR) classification index is calculated as the sum of the values assigned to each of these parameters, varying linearly within a range from 0 to 100. This index increases proportionally to the quality of the rock, reaching higher values in materials with better geomechanically characteristics. [16].

2.5 Q Index

Barton (1974) proposed a Tunnel Quality Index (Q) based on the evaluation of historical cases of underground excavations, which is used to determine the characteristics of the rock mass and the construction requirements for tunnels. [17].

The Q index presents a logarithmic scale variation, with values ranging from 0.001, corresponding to rock masses of very low quality, up to a maximum of 1000, characteristic of rock masses with excellent geomechanically properties. This index is defined by the following expression: $Q = \frac{RQD}{Jn} * (\frac{Jr}{Ja}) * \frac{Jw}{SRF}$

Where:

$RQD = Rock\ Quality\ Designation.$

$J_n = Joint\ number.$

$J_r = Joint\ roughness\ number.$

$J_a = Joint\ alteration\ number.$

$J_w = Joint\ water\ reduction\ factor.$

$SRF = Stress\ Reduction\ Factor.$

2.6 Uniaxial compressive Strenght (UCS)

The uniaxial compressive strenght test is performed on cylindrical rock cores to determine the uniaxial compressive strength (σc), modulus of elasticity (Ei) and the axial deformation (ϵ). These data evaluate the load-bearing capacity and the mechanical behaviour of rocks under compression. This test must follow the guidelines outlined in the ASTM D7012-04 standard [18]. The standard indicates that the most suitable length-to-diameter ratio for the sample is 2.00:1.00 (L/D = 2.00), corresponding to intact samples obtained from the boreholes (see Figure 5, item b).

Figure 5. *Uniaxial compression test. (a): Rock samples tested for uniaxial compression from the El Rosario sector; (b): Sample from borehole "Santa Rosa" S-SR-02 placed in the uniaxial compression equipment for the test. (Source: Author's own work)*

	
(a)	**(b)**

The maximum compressive strenght is described as the stress required for the cylindrical core to generate a fracture in its structure. When conducting the test, the fracture will occur at the moment when there is a sudden drop in the applied load. The compressive force produced is in accordance with the ASTM D7012-04 standard [19]. , corresponds to:

$$\sigma_c = \frac{\sigma}{(0.88 + 0.222\left(\frac{d}{t}\right))}$$

Where:

$\sigma_c = corrected\ rupture\ stress.$

$\sigma = failure\ stress.$

$d = sample\ diameter.$

$t = sample\ lenght.$

2.7 Indirect tensile test or "Brazilian test"

The indirect tensile test (also known as the Brazilian test) allows for the determination of the tensile strength of cylindrical rock samples indirectly through diametral tension. The main parameter obtained in this test is the tensile strength (σt), which helps to understand the resistance of the rock material to tensile stresses. The test is conducted in accordance with the ASTM D3967 – 95 standard [20], (Figure 6).

Figure 6. *Indirect tensile test or Brazilian test. (a): S-SR-02 cores, samples obtained after conducting the Brazilian test; (b): S-SR-02 core, placed in equipment.*

	
(a)	**(b)**

The test samples will be circular discs-cores with a thickness-to-diameter (t/D) ratio between 0.2 and 0.75. The diameter of the sample must be at least 10 times greater than the largest mineral grain component. A diameter of 50 mm (NX) will generally meet this criterion (see figure 7). According to ASTM D3967 – 95 standard [20] The tensile strength of the specimen must be calculated as follows:

$$\sigma_t = \frac{2P}{\pi LD}$$

Where:

$\sigma_t = Tensile\ strength\ , MPa\ (psi).$

$P = Max.load\ applied\ as\ indicated\ by\ the\ testing\ machine, N\ (o\ lbf).$

$L = Thickness\ of\ the\ sample, mm\ or\ inches.$

$D = Diameter\ of\ the\ sample, mm.$

2.8 Point Load Test (PLT) – "Franklin Test"

This test is used to determine the load-bearing capacity of a soil by applying a load through a circular plate placed on the surface of the soil. The parameters that will be obtained include the ultimate load capacity. (qu) This test is conducted by applying a load in a point and uniaxial manner, which gradually increases to measure the strength of the rock specimens (see Figure 7, item b).

Figure 7. *Point Load Test. (a): Placement of specimen in the machine; (b): Rock specimen tested with point load. (Source: Author's own work).*

(a)	**(b)**

After recording the force applied by the piston on the rock sample to break it, the point load index is calculated using the following equation.

$$I_s = \frac{P}{D_e^2}$$

Where:

$I_s = Uncorrected\ point\ load\ strength.$

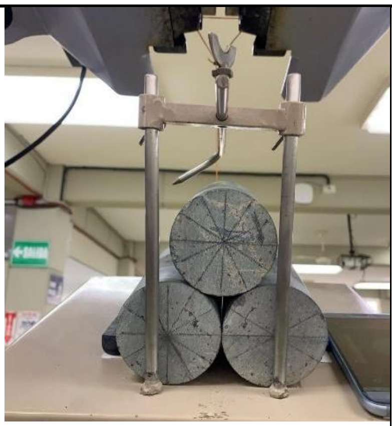
$P = Maximum\ load\ applied\ to\ break\ the\ sample.$

$D_e = Equivalent\ diameter\ of\ the\ sample.$

2.9 Tilt Test

This test provides the basic friction angle (ϕb) of a material, a key parameter for evaluating the stability of rock slopes and other geotechnical structures. The tilt test, according to ASTM C1444 – 00 standards [21] ,where the contact of the sample must rotate to obtain further data on the failure angle (see Figure 8, item a).

Figure 8. *Tilt test. (a): Samples marked to alternate the contact faces between the rocks; (b): Inclination of the equipment during the execution of the test. (Source: Author's own work.)*

	
(a)	**(b)**

Chapter 3. Resultas

3.1 Stratigraphy

For the characterisation of the obtained drilling cores, a geotechnical logging of the sample boxes was conducted, which allowed for the identification of the lithological and structural characteristics of the materials. In the El Rosario area, intrusive igneous rocks were identified, classified them as diorites and granites, while the second borehole predominantly featured volcanic igneous rock, represented by basalt, andesite, and diorite/granite. In the Santa Rosa area, the first borehole revealed a volcanic igneous composition with andesite, diorite/granite, and basalt, followed by a metamorphic rock from the chert subgroup, subsequently accompanied by volcanic igneous rock composed of andesite and basalt, as summarised in Table 2.

Table 2. *Lithologies present at each location.*

Zone	Borehole	Depth	Lithology	
			Group	**Subgroup**
El Rosario	S-SE-01	1.70 - 2.00	Intrusive Igneous	Diorite/ Granite
		5.00 - 8.00		
		9.70 - 11.20		
		16.75 - 18.10	Volcanic igneous	Basalt
		24.40 - 28.50		Andesite
	S-SE-02	23.40 - 30.00		Andesite
Santa Rosa	S-SR-01	5.00 - 6.20		Diorite/ Granite
		7.00 - 8.40		Andesite
		12.60 - 23.50		Basalt/ Andesite
	S-SR-02	10.00 - 10.50		Andesite
		15.20 - 17.00	Metamorphic rock	Chert
		22.20 - 24.30	Volcanic igneous	Basalt/ Andesite
		34.30 - 35.90		Andesite

Additionally, the samples for laboratory tests were prepared following the procedures established in specific technical standards. For the unconfined compressive strength test, ASTM D7012-14 standards were followed [22], which establishes the methods for determining the uniaxial compressive strength and the modulus of elasticity of rocks. In the case of the indirect tensile test or Brazilian test, the ASTM D3967-16 standard was employed [23], which defines the procedures for measuring tensile strength by applying diametral load. Meanwhile, the point load test was conducted following the guidelines of the ASTM D5731-16 standard [24], which regulates the determination of the strength of rocks through point loads. Finally, the Tilt Test, used to determine the basic friction angle between the contact surfaces of the rocks, was conducted in accordance with the ASTM C1444-00 standard [25].

The preparation of the samples included cutting and conditioning the specimens to ensure their compatibility with the geometric and physical requirements of each test. This process maximised the reliability of the obtained results, providing accurate and consistent data for subsequent geotechnical analysis. Compliance with these standards ensures the standardisation of procedures and contributes to the quality and precision of the studies conducted.

3.2 RMR and Q index

Based on the geomechanically classifications RMR and Q index, the following main characteristics of the evaluated rocks were identified. The diorite/granite at a depth of 11.20 m showed an RMR of 96 and a Q index of 96, classifying it as an excellent quality rock. Meanwhile, the basalt at 17.35 m achieved an RMR of 60 and a Q index of 5.00, indicating good rock quality. In the case of andesite, at a depth of 26.90 m, an RMR of 83 and a Q index of 190.00 were recorded, also classifying it as excellent quality. Finally, the samples of diorite/granite at 8.90 m exhibited significantly lower values, with an RMR of 23 and a Q index of 0.03, indicating low quality due to the presence of discontinuities and alterations.

The results obtained for the El Rosario area are presented in Table 3.

Tabla 3. *Factors for obtaining the RMR and Q Index in the El Rosario area.*

ZONA	SONDEO	LITOLOGÍA		PROFUNDIDAD MUESTRA	PARAMETROS RMR										INDICE Q						
		GRUPO	SUBGRUPO		1. RESISTENCIA DE LA ROCA SANA (Mpa)	2. RATING RQD	3. SEPARACION DE JUNTAS	4. DIACLASAS: 4.1 PERSISTENCIA	4. DIACLASAS: 4.2 APERTURA	4. DIACLASAS: 4.3 RUGOSIDAD	4. DIACLASAS: 4.4 RELLENO	4. DIACLASAS: 4.5 ALTERACION	5. PRESENCIA DE AGUA	RMR básico	1. RQD - ROCK QUALITY DESIGNATION	2. JN - INDICE DE DIACLASADO	3. JR - INDICE DE RUGOSIDAD DE	4. JA- INDICE DE ALTERACION DE	5. JW - FACTOR DE REDUCCION POR AGUA	6. SRF - STRESS REDUCTION FACTOR	INDICE Q
EL	S-SE-01	Ígnea Instrusiva	Diorita/ Granito	5.30	15	13	0	0	1	3	6	5	0	43	50	2	2	1	1	1	37.50

	Ígnea Instrusiva	Diorita/ Granito	8.00	15	8	0	0	0	0	0	0	0	23	35	1	1	1	1	3	14.00
	Ígnea Instrusiva	Diorita/ Granito	8.90	15	3	5	0	0	3	0	0	0	26	10	15	1	4	1	5	0.03
	Ígnea Instrusiva	Diorita/ Granito	9.70	15	3	8	0	0	3	0	3	0	32	20	15	1	4	1	5	0.07
	Ígnea Instrusiva	Diorita/ Granito	11.20	15	20	15	0	5	5	6	6	0	72	90	1	2	1	1	5	96.00
	Ígnea Instrusiva	Diorita/ Granito	12.50	15	13	8	0	0	3	0	3	0	42	50	4	1	4	1	8	0.40
	Ígnea Volcanica	Basalto	17.35	15	17	10	0	4	3	6	5	0	60	75	2	2	1	1	5	5.00
	Ígnea Volcanica	Basalto	18.10	15	13	10	0	4	3	6	5	0	56	50	2	2	1	1	5	3.00
	Ígnea Volcanica	Basalto	19.00	15	3	8	0	0	3	0	1	0	30	20	20	1	4	1	5	0.05
	Ígnea Volcanica	Basalto	22.00	15	8	10	0	4	5	6	5	7	60	40	3	2	1	1	4	6.67
	Ígnea Volcanica	Andesita	24.40	15	8	8	0	1	5	6	5	10	58	31	4	2	1	1	3	5.00
	Ígnea Volcanica	Andesita	26.00	15	13	10	0	4	3	6	5	15	71	64	3	3	1	1	3	26.00
	Ígnea Volcanica	Andesita	26.90	15	20	15	0	4	3	6	5	15	83	95	1	3	1	1	3	95.00
S-SE-02	Ígnea Volcanica	Andesita	23.40	15	8	5	0	1	5	4	3	10	51	31	15	2	8	1	3	0.16
	Ígnea Volcanica	Andesita	24.40	15	13	10	0	1	5	4	5	15	68	61	3	2	1	1	3	10.20
	Ígnea Volcanica	Andesita	26.00	15	8	8	0	1	3	4	5	15	59	35	4	2	3	1	3	1.50
	Ígnea Volcanica	Andesita	27.60	15	8	8	0	1	3	6	5	15	61	32	4	2	2	1	3	2.00
	Ígnea Volcanica	Andesita	29.20	15	13	8	0	1	3	4	5	15	64	52	4	2	2	1	3	3.20

Santa Rosa, the following results were obtained, as shown in Table 4.

In the analysis of the obtained samples, different quality levels were identified according to the RMR and Q Index values. The samples with excellent quality, those with a Q Index above 10 or an RMR greater than 80, include cases such as sample S-SR-02 at a depth of 20.20 m, which presented a Q Index of 12.17 and an unspecified RMR, classifying it as good quality. At the same point, another measurement yielded an RMR of 73 with a similarly high Q Index of 12.17, placing it in the excellent quality category. Additionally, sample S-SR-01 at a depth of 24.30 m showed a Q Index of 7.78, which also indicates very high quality.

Regarding igneous rocks, such as diorite/granite and andesite, high RMR and Q Index values were observed, as in the case of granite at 11.20 m, with an RMR of 96 and a Q Index of 190. These characteristics reflect high strength and low fracturing, classifying them as excellent quality rocks. On the other hand, igneous rocks like basalt and andesite, with RMR values between 50 and 80 and Q Indices between 1 and 10, are considered of good quality. A representative example is sample S-SE-02 at 26.00 m, which presented a Q Index of 26.00, confirming its good mechanical behaviour.

Finally, metamorphic rocks, such as chert, exhibited the lowest values of RMR and Q Index, as seen in the sample at 15.20 m, which recorded an RMR of 4.56 and a Q Index of 0.74. This indicates lower strength and greater susceptibility to fracturing, classifying them as low-quality rocks.

Tabla 4. *Factors for obtaining the RMR and Q Index in the Santa Rosa area.*

					PARAMETROS RMR										INDICE Q						
ZONA	SONDEO	LITOLOGÍA		PROFUNDIDAD MUESTRA	1. RESISTENCIA DE LA ROCA SANA (Mpa)	2. RATING RQD	3. SEPARACION DE JUNTAS	4. DIACLASAS					5. PRESENCIA DE AGUA	RMR básico	1. RQD - ROCK QUALITY DESIGNATION	2. JN - INDICE DE DIACLASADO	3. JR - INDICE DE RUGOSIDAD DE DISCONTINUIDADES	4. JA- INDICE DE ALTERACION DE DISCONTINUIDADES	5. JW - FACTOR DE REDUCCION POR AGUA EN DISCONTINUIDADES	6. SRF - STRESS REDUCTION FACTOR	INDICE Q
		GRUPO	SUBGRUPO					4.1 PERSISTENCIA	4.2 APERTURA	4.3 RUGOSIDAD	4.4 RELLENO	4.5 ALTERACION									
SANTA ROSA	S-SR-01	Ígnea Volcanica	Basalto/ Andesita	12.60	7	3	8	0	1	3	6	6	10	44	16	6	1	2	1	3	0.44
		Ígnea Volcanica	Basalto/ Andesita	13.70	12	13	10	0	1	3	6	6	10	61	51	3	2	1	1	3	8.50
		Ígnea Volcanica	Basalto/ Andesita	14.70	12	8	8	0	1	3	6	6	10	54	30	4	2	1	1	3	3.75
		Ígnea Volcanica	Basalto/ Andesita	15.60	12	13	10	0	1	3	6	6	10	61	63	4	2	1	1	3	10.50
		Ígnea Volcanica	Basalto/ Andesita	17.10	7	3	5	0	1	3	6	3	10	38	18	15	2	4	1	3	0.15
		Ígnea Volcanica	Basalto/ Andesita	18.20	4	3	5	0	1	3	4	3	10	33	10	9	2	2	1	3	0.28

	Ígnea Volcanica	Basalto/ Andesita	19.10	12	13	10	0	1	3	6	5	10	60	62	3	2	2	1	3	6.89
	Ígnea Volcanica	Basalto/ Andesita	20.40	7	13	8	0	1	3	6	5	10	53	30	4	2	2	1	3	1.88
	Ígnea Volcanica	Basalto/ Andesita	21.40	4	3	5	0	1	3	4	5	10	35	10	3	2	2	1	3	0.83
	Ígnea Volcanica	Basalto/ Andesita	21.70	4	3	5	0	1	3	4	6	10	36	10	3	2	2	1	3	0.83
	Ígnea Volcanica	Basalto/ Andesita	22.00	7	13	8	0	1	3	6	5	10	53	50	4	2	2	1	3	3.13
	Ígnea Volcanica	Basalto/ Andesita	23.50	7	3	8	0	1	3	6	5	10	43	12	6	2	2	1	3	0.50
	Ígnea Volcanica	Basalto/ Andesita	24.80	7	3	4	0	1	3	4	3	10	35	10	9	2	2	1	3	0.28
	Ígnea Volcanica	Basalto/ Andesita	25.70	7	3	4	0	1	3	4	3	10	35	10	9	2	2	1	3	0.28
	Ígnea Volcanica	Basalto/ Andesita	26.80	7	3	4	0	1	3	4	3	10	35	10	9	2	2	1	3	0.28
	Ígnea Volcanica	Basalto/ Andesita	27.70	7	8	5	0	1	3	6	3	10	43	37	12	2	3	1	3	0.51
	Ígnea Volcanica	Basalto/ Andesita	28.70	7	3	4	0	1	3	4	3	10	35	10	9	2	2	1	3	0.28
	Ígnea Volcanica	Basalto/ Andesita	29.80	7	3	4	0	1	3	4	3	10	35	10	9	2	2	1	3	0.28
S-SR-02	Ígnea Volcanica	Basalto/ Andesita	20.20	7	13	10	0	1	3	6	5	15	60	73	4	2	1	1	3	12.17
	Ígnea Volcanica	Basalto/ Andesita	21.80	4	3	5	0	1	3	6	5	15	42	13	15	2	1	1	3	0.58
	Ígnea Volcanica	Basalto/ Andesita	22.70	7	8	8	0	1	3	6	5	15	53	39	6	2	1	1	3	4.33
	Ígnea Volcanica	Basalto/ Andesita	24.30	4	3	5	0	1	3	6	5	15	42	10	9	2	1	1	3	0.74
	Ígnea Volcanica	Andesita	25.40	4	3	5	0	1	3	6	5	15	42	10	9	2	1	1	3	0.74
	Ígnea Volcanica	Andesita	27.00	4	3	5	0	1	3	6	3	10	35	10	12	2	4	1	3	0.14
	Ígnea Volcanica	Andesita	27.80	2	3	5	0	1	3	6	1	10	31	10	9	2	2	1	3	0.37
	Ígnea Volcanica	Andesita	28.70	4	3	5	0	1	3	6	3	10	35	10	9	2	1	1	3	0.74
	Ígnea Volcanica	Andesita	29.70	4	8	5	0	1	3	6	5	15	47	33	9	2	1	1	3	2.44
	Ígnea Volcanica	Andesita	30.00	4	3	5	0	1	3	6	5	15	42	10	9	2	2	1	3	0.37
	Ígnea Volcanica	Andesita	30.70	4	3	5	0	1	3	6	5	15	42	10	9	2	2	1	3	0.37
	Ígnea Volcanica	Andesita	31.70	2	3	5	0	1	3	6	3	10	33	10	12	2	3	1	3	0.19
	Ígnea Volcanica	Andesita	32.80	4	13	10	0	1	3	6	5	15	57	7	2	2	3	1	3	7.78

Ígnea Volcanica	Andesita	33.30	4	13	8	0	1	3	6	3	15	53	51	4	2	3	1	3	2.83
Ígnea Volcanica	Andesita	34.30	4	8	8	0	1	3	6	5	15	50	41	6	2	3	1	3	1.52

3.3 Uncofined Compression

The unconfined compression test was conducted to determine the uniaxial compressive strength (UCS) of different lithologies in the study areas "El Rosario" and "Santa Rosa."

The results, organised in Table 5, show that the intrusive rocks of diorite/granite exhibited a strength that varied between 89.38 MPa and 125.80 MPa, indicating that they are strong rocks, with average applied loads ranging from 279.87 kN to 393.00 kN. On the other hand, basalt, with a strength exceeding 120 MPa and an average of 131.70 MPa, is classified as a high-strength rock, demonstrating consistency in the quality of the samples with an average load of 412.03 kN. Andesite exhibited a more variable strength, fluctuating between 41.43 MPa and 90.46 MPa, which classifies it as moderately resistant, with average applied loads reaching up to 250.00 kN. Finally, the metamorphic rock chert had an average compressive strength of 80.16 MPa, with an average load of 251.70 kN, reflecting moderate strength compared to igneous rocks.

In this case igneous rocks, especially basalt and diorite/granite, are suitable for structural applications in hydropower projects, while andesite and chert exhibit lower strengths, suggesting the need to consider their behaviour in the design of geotechnical infrastructures, thereby ensuring the stability and viability of projects in the aforementioned areas.

Table 5. *Average results and standard deviation of the unconfined compression test by lithology.*

Group	Subgroup	Borehole	Depth (m)	Lithology	Average Load (kN)	Standard Deviation Load (kN)	Average UCS (MPa)	Standard Deviation UCS (MPa)
Igneus Rock	Intrusive	S-SE-01	9.70 - 11.20	Diorite/Granite	279.87	46.12	89.38	16.80

		S-SR-01	5.00 - 6.20	Diorite/Granite	393.00	39.14	125.80	12.28
	Volcanic	S-SE-01	16.75 - 17.35	Basalt	412.03	23.00	131.70	7.78
		S-SE-01	26.90 - 28.50	Andesite	130.07	29.89	41.43	9.11
		S-SE-02	24.00 - 30.00	Andesite	138.13	38.70	45.53	13.82
		S-SR-01	7.00 - 8.40	Andesite	341.07	53.06	108.80	16.49
		S-SR-01	12.60 - 14.70	Basalt/Andesite	292.43	31.43	90.46	10.26
		S-SR-02	10.00 - 10.50	Andesite	250.00	26.85	79.70	3.44
		S-SR-02	20.20 - 21.80	Basalt/Andesite	264.94	51.52	84.83	17.96
		S-SR-02	34.30 - 35.90	Andesite	56.30	0.40	17.03	1.72
Metamorphic Rocks	Chert	S-SR-02	15.20 - 17.00	Chert	251.70	32.13	80.16	10.43

3.4 Brazilian indirect Traction

The indirect tensile test, known as the Brazilian test, was conducted to assess the tensile strength of various lithologies in the study areas 'El Rosario' and 'Santa Rosa'. The results obtained are described below. For diorite/granite, which is an intrusive igneous rock, an average load of 30.5 kN was recorded, with a standard deviation of 4.33 kN. The average stress obtained was 10.99 kPa, with a standard deviation of 1.22 kPa, indicating an average tensile strength. In the case of basalt, a volcanic igneous rock, a significantly higher average load was observed, reaching 57.35 kN, with a standard deviation of 13.92 kN. The average stress was 21.73 kPa, with a standard deviation of 4.88 kPa, suggesting a high tensile strength. Andesite, also a volcanic igneous rock, exhibited an average load of 31.35 kN with a standard deviation of 6.23 kN. Its average stress was 10.51 kPa, with a standard deviation of 2.02 kPa, reflecting a lower tensile strength compared to basalt. Chert, a metamorphic rock, recorded an average load of 34.81 kN with a standard deviation of 12.34 kN. Its average stress was 11.82 kPa, with a standard deviation of 4.91 kPa, indicating a moderate tensile strength. The results of the Brazilian test show that basalt has the highest tensile strength, followed by chert, diorite/granite, and finally andesite, which has the lowest stress values.

Table 7. *Average results and standard deviation of the Brazilian tensile test.*

Group	Subgroup	Borehole	Depth (m)	Diameter (mm)	Lithology	Average Load (kN)	Load Deviation (kN)	Average Stress (kPa)	Stress Deviation (kPa)
Igneous Rocks	Intrusive	S-SE-01	9.70 - 11.20	63.3	Diorite/Granite	30.52	4.33	10.99	1.22
	Volcanic	S-SE-01	16.75 - 17.35	63.3	Basalt	57.35	13.92	19.73	4.88
		S-SE-01	24.40 - 26.00	63.3	Andesite	31.35	6.23	10.51	2.02
		S-SE-02	24.00 - 26.00	63.3	Andesite	33.73	6.37	11.24	2.16
		S-SE-02	26.00 - 30.00	63.3	Andesite	40.88	9.59	13.63	3.18
	Intrusive	S-SR-01	5.00 - 6.20	63.3	Diorite/Granite	45.67	8.96	15.16	3.22
	Volcanic	S-SR-01	7.00 - 8.40	63.3	Andesite	68.54	12.34	22.25	4.56
		S-SR-01	12.60 - 14.70	63.3	Basalt/Andesite	61.53	10.23	20.48	4.12
		S-SR-02	10.00 - 10.50	63.3	Andesite	53.85	11.34	17.37	4.23
Metamorphic Rocks	Metamorphic	S-SR-02	15.20 - 17.00	63.3	Chert	34.81	12.34	11.82	4.91
Igneous Rocks	Volcanic	S-SR-02	34.30 - 35.90	63.3	Andesite	7.87	2.36	2.64	0.87

3.5. Point Load Test (PLT)

The Point Load Test was conducted on various rock samples to determine their compressive strength. The results are expressed in terms of Is (point load strength) in megapascals (MPa) and the corrected strength Is(50) at a standard load of 50 mm. For the Diorite/Granite samples, two depths were recorded in borehole S-SE-01. At a depth of 5.30 m, the Is value was 9.19 MPa, with a correction factor of 1.11, resulting in a corrected strength Is(50) of 225.22 MPa. At 6.20 m, an increase in strength was observed, with Is reaching 18.10 MPa and Is(50) attaining 443.35 MPa. For Basalt, also in borehole S-SE-01, two depths were recorded. At 7.60 m, the Is value was 10.75 MPa, which, with the same correction factor of 1.11, resulted in an Is(50) of 263.36 MPa. At 8.00 m, the Is value increased to 11.02 MPa, yielding an Is(50) of 300.18 MPa. Regarding Andesite, in borehole S-SE-02, at a depth of 5.30 m, the Is value was 4.23 MPa, with a corresponding Is(50) of 103.64 MPa, using the same correction factor. At 10.50 m, the Is value increased to 11.52 MPa, resulting in an Is(50) of 285.21 MPa. For Chert, in borehole S-SE-02, at a depth of 15.20 m, an Is value of 9.73 MPa was recorded, which, with the correction factor of 1.11, resulted in an Is(50) of 238.42 MPa. The Diorite/Granite samples exhibited high compressive strength, with Is values ranging between 9.19 MPa and 18.10 MPa, and corrected strengths reaching up to 443.35 MPa. Basalt also demonstrated a good load-bearing capacity, with Is values between 10.75 MPa and 11.02 MPa. Andesite showed Is values from 4.23 MPa to 11.52 MPa, indicating moderate strength. Chert exhibited relatively lower strength compared to the igneous rocks, with an Is of 9.73 MPa.

These results highlight variations in the compressive strength of the different lithologies analysed, providing valuable information for the geotechnical assessment of the rocks in the study areas.

Table 8. *Results obtained from the Point Load Test.*

Group	Subgroup	Borehole	Depth (m)	Average Is (MPa)	Correction Factor	Average Is(50) (MPa)
Intrusive Igneous	Diorite/Granite	S-SE-01	5.00 - 5.30	9.19	1.11	225.22
	Diorite/Granite	S-SR-01	5.00 - 6.20	18.10	1.11	443.35
Volcanic Igneous	Basalt	S-SE-01	7.60 - 8.00	10.75	1.11	263.36
	Andesite	S-SE-02	4.00 - 5.30	4.23	1.11	103.64
	Andesite	S-SR-02	10.00 - 10.50	11.52	1.11	285.21
	Basalt/Andesite	S-SR-02	20.20 - 21.80	11.52	1.11	285.21
Metamorphic Rocks	Chert	S-SR-02	15.20 - 17.00	9.73	1.11	238.42

3.6. Tilt Test

The Tilt Test results table presents the basic friction angle (φb°) obtained for various rock samples, with measurements taken at six different inclinations for each sample (1 to 6), along with the final average for each case.

Intrusive Igneous (Diorite/Granite):

- The friction angles range between 32° and 36°, with an average of 33.4°.

- This rock exhibits a relatively high basic friction, indicating good stability under inclined conditions.

Intrusive Igneous (Diorite/Granite):

- The friction angles range between 32° and 36°, with an average of 33.4°.
- This rock exhibits a relatively high basic friction, indicating good stability under inclined conditions.

Volcanic Igneous (Basalt):

- The friction angles range from 30° to 33°, with an average of 31.7°.
- Although the friction is slightly lower than that of diorite/granite, it remains stable for structural applications.

Andesite:

- In the first sample (26.90 - 28.50 m), the friction values range from 26° to 32°, with an average of 30.4°.
- In the second sample (24.00 - 26.00 m), the friction angle remained constant at 35°, indicating good stability.
- In the third sample (28.00 - 30.00 m), friction was also constant at 35º.

Metamorphic Rock (Chert):

- Friction values range from 29° to 34°, with an average of 31.07°.
- This rock exhibits moderate friction, suggesting reasonable but not exceptional stability.

The most critical value corresponds to the Diorite/Granite sample (S-SR-01, 5.00 - 6.20 m), where the friction angle drops to 13° - 21°, with an average of 18.58°, and a minimum value as low as

13°. This result suggests that the rock has low frictional resistance, which could lead to potential stability issues.

Table 9. *Results of the tilt test with their characteristics.*

Borehole	Depth (m)	Lithology		Tilt Test						Basic Friction Angle (º)
		Group	Subgroup	1	2	3	4	5	6	
S-SE-01	9.70 - 11.20	Intrusive Igneous	Diorite/ Granite	36	31	35	34	33	32	33.4
	16.75 - 18.10	Volcanic Igneous	Basalt	33	31	31	30	32	33	31.7
	26.90 - 28.50		Andesite	30	26	32	32	32	31	30.4
S-SE-02	24.00 - 26.00	Volcanic Igneous	Andesite	35	35	35	35	35	35	35.0
	26.00 - 28.00			42	43	40	35	39	41	40.2
	28.00 - 30.00			35	35	36	35	35	35	35.0
S-SR-01	5.00 - 6.20	Intrusive Igneous	Diorite/ Granite	21	22	22	16	13	17	18.58
	12.60 - 14.70	Volcanic Igneous	Basalt/ Andesite	25	25	28	30	30	32	28.22
	19.10 - 20.40			26	27	28	31	27	29	27.93
	22.00 - 26.50			30	32	28	29	30	26	29.13
S-SR-02	10.00 - 10.50	Volcanic Igneous	Andesite	33	30	30	31	30	29	30.68
	15.20 - 17.00	Metamorphic	Chert	29	34	30	31	32	30	31.07
	20.20 - 21.80	Volcanic Igneous	Basalt/ Andesite	34	36	36	31	34	28	33.20
	22.70 - 24.30	Volcanic Igneous	Basalt/ Andesite	35	38	38	39	37	32	36.65
	34.30 - 35.90	Volcanic Igneous	Andesite	38	39	39	40	37	37	38.35

Chapter 4. Discussion

The results obtained in this study allow for the interpretation of the geomechanical properties of the rocks in the El Rosario and Santa Rosa areas, providing key information to assess the quality of the rock mass and its behaviour under different geotechnical conditions. The most relevant results are discussed below:

4.1 Persistence of Discontinuities

Table 4, a persistence value of 0 (continuity greater than 20 m) was assigned to all samples as a conservative measure, given the lack of precise data on the actual extent of the discontinuities. This decision follows the recommendations of Bieniawski (1989), who suggests that, in the absence of detailed information, it is preferable to avoid overestimating the quality of the rock mass [15]. Persistence is a key factor in the RMR classification, as greater continuity of fractures can significantly reduce the overall strength of the rock mass. This conservative approach ensures a more realistic assessment and facilitates the design of appropriate support measures for potentially unfavorable conditions.

4.2 Tensile Strength

Table 6 presents the average values and standard deviations of the tensile strength obtained through the Brazilian test. Below is a simplified summary:

Table 9. *Average values and standard deviation of the Brazilian tensile test.*

Lithology	Average Load (kN)	Desviación Carga (kN)	Average Stress (kPa)	Stress Deviation (kPa)	Observations
Diorite/Granite	30.52	4.33	10.99	1.22	Average tensile strength.
Basalt	57.35	13.92	21.73	4.88	High tensile strength, the most consistent.
Andesite	31.35	6.23	10.51	2.02	Moderate tensile strength, with lower variability.
Chert	34.81	12.34	11.82	4.91	Low tensile strength, high variability.

The results indicate that basalt exhibits the highest tensile strength, which aligns with its classification as a strong rock. In contrast, andesite and chert show lower values, representing moderate strength. When compared to previous studies, such as those by Hoek and Brown (1980), who reported tensile strengths for basalts ranging between 15 and 25 kPa and for granites between 10 and 15 kPa, the values obtained in this study are consistent with the expected ranges. This reinforces the reliability of the tests conducted (Brown & Hoek, 1980).

4.3 Basic Friction Angle

Barton y Choubey (1977) established typical ranges for the basic friction angle (ϕb) in different rock types, depending on roughness and discontinuity characteristics (*The Shear Strength of Rock Joints in Theory and Practice*, s. f.). The most typical values are:

- Igneous rocks (granites, basalts, andesites): 30°-40°

These rocks exhibit rougher surfaces and greater shear strength, which explains their high friction angles.

- Metamorphic rocks (schists, chert): 25°-35°

In these rocks, the roughness of the discontinuities is moderate, which slightly reduces the friction angle.

- Sedimentary rocks (sandstones, limestones): 20°-30°

These rocks typically have smoother and less resistant discontinuities, leading to lower basic friction angles.

4.4 Comparison with study results

In this study, the basic friction angle values obtained (Table 8) range from 18.58° (Diorite/Granite in Santa Rosa) to 38.35° (Andesite in Santa Rosa). When compared with the typical ranges:

- The values for basalt (31.7°) and andesite (30.4°–38.35°) fall within the expected range for igneous rocks (30°-40°), indicating favorable shear strength conditions.
- However, the lowest value obtained for diorite/granite (18.58º) falls below the typical range for igneous rocks. This could be attributed to highly polished discontinuity surfaces or unfavorable local conditions, reducing shear strength.

In general, higher basic friction angle values (such as those for basalt and andesite) suggest better stability conditions for slopes and underground structures, whereas lower values (such as in diorite/granite) may require additional support measures.

4.5 Implications for hydroelectric projects and future research

Considering these findings, it can be concluded that the geomechanical characterisation conducted is essential for the planning of hydroelectric projects in the region. The data obtained on the compressive and tensile strength of different lithologies, as well as the basic friction angle, are crucial for assessing the feasibility of constructing infrastructures such as dams and powerhouse facilities in the El Rosario and Santa Rosa areas. The high UCS of basalt (exceeding 120 MPa) and diorite/granite (ranging between 89.38 MPa and 125.80 MPa) suggest that these rock types are suitable for supporting the structural loads associated with a dam. Additionally, the relatively high basic friction angle observed in these lithologies indicates favorable stability conditions for slopes and underground structures, which is critical for ensuring the safe construction of dams.

However, attention must be given to areas where weaker rock types, such as andesite and chert, have been identified. These may require more careful engineering design and the implementation of additional support measures. Overall, the results of this study provide a robust foundation for the planning and design of hydroelectric projects in Morona Santiago, ensuring their technical and geotechnical feasibility.

The conservative assignment of discontinuity persistence, based on Bieniawski approach (1989), ensures a cautious assessment of the rock mass but may lead to overly conservative and costly designs. To reduce this uncertainty, it is recommended that additional studies be conducted, such as advanced geological mapping using laser scanners or digital photogrammetry, along with in situ tests to more accurately measure the actual extent of discontinuities. These measures would optimize geotechnical designs, balancing safety and cost-effectiveness in future projects.

This study has characterised the geomechanical properties of the rock masses in Santa Rosa and El Rosario, revealing that igneous rocks such as basalt and diorite/granite exhibit high compressive strength, making them suitable for hydroelectric projects. The uniaxial compressive strength (UCS) of these rock's ranges between 89.38 MPa and 125.80 MPa, with basalt exceeding 120 MPa. The data obtained is crucial for assessing the technical and geotechnical feasibility of the proposed infrastructure, ensuring its long-term stability. Additionally, the basic friction angles indicate favorable stability characteristics in the igneous rocks. However, some diorite/granite samples exhibited lower values, suggesting that additional support measures may be required to enhance structural integrity.

Chapter 5. Conclusions

This study has characterized the geomechanical properties of the rock masses in Santa Rosa and El Rosario, revealing that igneous rocks such as basalt and diorite/granite exhibit high compressive strength, making them suitable for hydroelectric projects. The uniaxial compressive strength (UCS) of these rock's ranges between 89.38 MPa and 125.80 MPa, with basalt exceeding 120 MPa. The data obtained is crucial for assessing the technical and geotechnical feasibility of the proposed infrastructure, ensuring its long-term stability. Additionally, the basic friction angles indicate favorable stability characteristics in the igneous rocks. However, some diorite/granite samples exhibited lower values, suggesting that additional support measures may be required to enhance structural integrity

Supplementary Materials

Table A. Results obtained from the uniaxial compression test measurements.

Sondeo	**Profundidad (m)**	**No. Muestra**	**Litología**		**Carga (kN)**	**RCS(Mpa)**
			Grupo	**Subgrupo**		
S-SE-01	9.70 - 11.20	2	Ígnea Intrusiva	Diorita/ Granito	344.40	109.78
	9.70 - 11.20	4			237.80	76.29
	9.70 - 11.20	5			255.80	82.06

	16.75 - 17.35	1	Ígnea Volcánica	Basalto	388.20	123.36
	16.75 - 17.35	2	Ígnea Volcánica	Basalto	413.80	131.91
	17.35 - 18.10	1	Ígnea Volcánica	Basalto	434.10	138.82
	26.90 - 28.50	1	Ígnea Volcánica	Andesita	95.90	30.28
	26.90 - 28.50	2	Ígnea Volcánica	Andesita	147.10	46.74
	26.90 - 28.50	3	Ígnea Volcánica	Andesita	149.20	47.26
S-SE-02	24.00 - 26.00	2	Ígnea Volcánica	Andesita	129.40	41.64
S-SE-02	24.00 - 26.00	3	Ígnea Volcánica	Andesita	96.40	31.12
S-SE-02	24.00 - 26.00	4	Ígnea Volcánica	Andesita	112.20	36.34
S-SE-02	26.00 - 30.00	2	Ígnea Volcánica	Andesita	100.30	31.97
S-SE-02	26.00 - 30.00	3	Ígnea Volcánica	Andesita	180.90	58.03
S-SE-02	26.00 - 30.00	4	Ígnea Volcánica	Andesita	145.10	46.55
S-SE-02	26.00 - 30.00	7	Ígnea Volcánica	Andesita	205.00	65.97
S-SE-02	26.00 - 30.00	8	Ígnea Volcánica	Andesita	99.70	32.09
S-SE-02	26.00 - 30.00	9	Ígnea Volcánica	Andesita	110.60	35.71
S-SR-01	5.00 - 6.20	1	Ígnea Intrusiva	Diorita/ Granito	399.40	126.91
S-SR-01	5.00 - 6.20	2	Ígnea Intrusiva	Diorita/ Granito	428.30	136.53
S-SR-01	5.00 - 6.20	3	Ígnea Intrusiva	Diorita/ Granito	351.30	111.98
S-SR-01	7.00 - 8.40	1	Ígnea Volcánica	Andesita	286.80	91.42
S-SR-01	7.00 - 8.40	2	Ígnea Volcánica	Andesita	345.80	110.23
S-SR-01	7.00 - 8.40	3	Ígnea Volcánica	Andesita	392.60	124.75
S-SR-01	12.60 - 14.70	1	Ígnea Volcánica	Basalto/ Andesita	316.80	100.67
S-SR-01	12.60 - 14.70	2	Ígnea Volcánica	Basalto/ Andesita	252.50	80.24
S-SR-01	19.10 - 20.40	1	Ígnea Volcánica	Basalto/ Andesita	272.50	86.59
S-SR-01	19.10 - 20.40	5	Ígnea Volcánica	Basalto/ Andesita	308.00	97.26

	10.00 - 10.50	1	Ígnea Volcánica	Andesita	259.30	82.14
	10.00 - 10.50	3			243.90	77.26
S-SR-02	15.20 - 17.00	1	Roca metamórfica	Chert	283.40	90.63
	15.20 - 17.00	3			220.00	69.69
	20.20 -21.80	1			357.70	114.02
	20.20 -21.80	2			261.60	83.39
	20.20 -21.80	3		Basalto/ Andesita	239.40	76.31
	20.20 -21.80	4			246.00	78.42
	20.20 -21.80	5	Ígnea Volcánica		217.00	68.95
	22.70 - 24.30	1			189.90	60.73
	34.30 -35.90	1			56.90	18.43
	34.30 -35.90	2		Andesita	56.10	18.05
	34.30 -35.90	3			45.80	14.60

Table B. Results obtained from the measurements of the Brazilian tensible strength test.

Sondeo	Profundidad (m)	No. Muestra	Diámetro (mm)	Litología		Carga (kN)	Esfuerzo (kPa)
				Grupo	Subgrupo		
S-SE-01	9.70 - 11.20	1	63.3	Ígnea Intrusiva	Diorita/ Granito	33.37	11.19
	9.70 - 11.20	1	63.3			37.39	12.54
	9.70 - 11.20	1	63.3			26.83	8.99
	9.70 - 11.20	1	63.3			27.54	9.23
	16.75 - 17.35	2	63.3	Ígnea Volcánica	Basalto	54.10	18.14
	16.75 - 17.35	2	63.3			48.11	16.13
	16.75 - 17.35	2	63.3			47.39	15.89
	16.75 - 17.35	2	63.3			79.82	26.76
	24.40 - 26.00	1	63.3		Andesita	39.36	13.19
	24.40 - 26.00	1	63.3			33.00	11.06
	24.40 - 26.00	1	63.3			28.37	9.51
	24.40 - 26.00	1	63.3			24.67	8.27
S-SE-02	24.00 - 26.00	2	63.3	Ígnea Volcánica	Andesita	31.76	10.65
	24.00 - 26.00	2	63.3			29.64	9.94
	24.00 - 26.00	2	63.3			37.85	12.69

	24.00 - 26.00	2	63.3			28.03	9.40
	24.00 - 26.00	4	63.3			43.22	14.49
	24.00 - 26.00	4	63.3			20.39	6.83
	24.00 - 26.00	4	63.3			27.96	9.37
	24.00 - 26.00	4	63.3			32.19	10.79
	26.00 - 30.00	3	63.3			35.84	12.01
	26.00 - 30.00	3	63.3			46.19	15.49
	26.00 - 30.00	3	63.3			26.55	8.90
	26.00 - 30.00	3	63.3			52.90	17.73
S-SR-01	5.00 - 6.20	1	63.3	Ígnea Intrusiva	Diorita/ Granito	45.22	15.16
	5.00 - 6.20	1	63.3			35.20	11.80
	5.00 - 6.20	1	63.3			44.32	14.86
	5.00 - 6.20	1	63.3			57.94	19.42
	7.00 - 8.40	2	63.3		Andesita	61.29	20.55
	7.00 - 8.40	2	63.3			73.20	24.54
	7.00 - 8.40	2	63.3			71.46	23.96
	7.00 - 8.41	2	63.3			66.17	22.18
	12.60 - 14.70	2	63.3		Basalto/ Andesita	59.04	19.79
	12.60 - 14.70	2	63.3			86.34	28.95
	12.60 - 14.70	2	63.3			69.65	23.35
	12.60 - 14.70	2	63.3			29.40	9.86
	19.10 - 20.40	3	63.3			35.31	11.84
	19.10 - 20.40	3	63.3			42.95	14.40
	19.10 - 20.40	3	63.3			73.12	24.51
	19.10 - 20.40	3	63.3			57.06	19.13
S-SR-02	10.00 - 10.50	1	63.3	Ígnea Volcánica	Andesita	66.76	21.66
	10.00 - 10.50	1	63.3			52.65	19.61
	10.00 - 10.50	1	63.3			49.77	18.54
	10.00 - 10.50	1	63.3			44.21	14.34
	15.20 - 17.00	3	63.3	Roca metamórfica	Chert	14.05	4.56
	15.20 - 17.00	3	63.3			38.14	14.21
	15.20 - 17.00	3	63.3			43.36	16.77

15.20 - 17.00	3	63.3			43.69	13.73
34.30 -35.90	1	63.3	Ígnea Volcánica	Andesita	10.07	2.99
34.30 -35.90	1	63.3			4.55	1.91
34.30 -35.90	1	63.3			7.85	2.93
34.30 -35.90	1	63.3			6.21	2.08

Table C. Results obtained from measurements of the Point Load Test.

Sondeo	Profundidad (m)	No. Muestra	Litología		Is (MPa)	F(factor de corrección	Is(50) (Mpa)	σ_c
			Grupo	Subgrupo				
S-SE-01	5.00 - 5.30	1	Ígnea Intrusiva	Diorita/ Granito	8.27	1.11	9.19	225.22
	7.60 - 8.00	1			13.45	1.11	14.95	366.30
	7.60 - 8.00	2			11.60	1.11	12.89	315.89
	9.70 - 11.20	1			8.25	1.11	9.18	224.85
	9.70 - 11.20	2			10.83	1.11	12.04	295.06
	9.70 - 11.20	3			8.35	1.11	9.29	227.50
	16.75 - 17.35	1	Ígnea Volcánica	Basalto	9.67	1.11	10.75	263.36
	16.75 - 17.35	2			11.02	1.11	12.25	300.18
	17.35 - 18.10	1			9.22	1.11	10.26	251.30
	24.40 - 26.00	1		Andesita	4.86	1.11	5.41	132.47
	26.00 - 26.90	1			5.76	1.11	6.40	156.88
	26.00 - 26.90	2			3.80	1.11	4.23	103.64
S-SE-02	24.00 - 26.00	1	Ígnea Volcánica	Andesita	3.80	1.11	4.23	103.64
	24.00 - 26.00	2			6.84	1.11	7.61	186.38
	24.00 - 26.00	3			4.67	1.11	5.19	127.23
	24.00 - 26.00	7			7.26	1.11	8.07	197.72
	26.00 - 30.00	1			7.70	1.11	8.57	209.87
S-SR-01	5.00 - 6.20	1	Ígnea Intrusiva	Diorita/ Granito	16.27	1.11	18.10	443.35
	5.00 - 6.20	2			20.02	1.11	22.27	545.50
	5.00 - 6.20	3			16.41	1.11	18.25	447.05
	7.00 - 8.40	1	Ígnea Volcánica	Andesita	16.81	1.11	18.69	457.93

	7.00 - 8.40	2			1.66	1.11	1.85	45.35
	7.00 - 8.40	3			16.52	1.11	18.37	450.12
	12.60 - 14.70	3		Basalto/ Andesita	13.74	1.11	15.27	374.21
	19.10 - 20.40	1			7.32	1.11	8.14	199.50
	19.10 - 20.40	3			8.65	1.11	9.62	235.64
	19.10 - 20.40	5			7.68	1.11	8.54	209.18
	22.00 - 23.50	2			5.42	1.11	6.02	147.55
S-SR-02	10.00 - 10.50	1	Ígnea Volcánica	Andesita	4.17	1.11	4.64	113.72
	10.00 - 10.50	2			3.89	1.11	4.33	105.97
	10.00 - 10.50	3			2.97	1.05	3.12	76.55
	10.00 - 10.51	4			6.81	1.11	7.57	185.50
	15.20 - 17.00	1	Roca metamórfica	Chert	8.75	1.11	9.73	238.42
	15.20 - 17.00	2			10.58	1.11	11.76	288.21
	15.20 - 17.00	3			7.52	1.11	8.36	204.80
	20.20 -21.80	1	Ígnea Volcánica	Basalto/ Andesita	10.36	1.11	11.52	282.14
	20.20 -21.80	2			3.73	1.11	4.15	101.65
	20.20 -21.80	3			9.86	1.11	10.96	268.51
	20.20 -21.80	4			8.54	1.11	9.50	232.77
	34.30 -35.90	1		Andesita	1.44	1.11	1.61	39.35
	34.30 -35.90	2			1.45	1.11	1.61	39.43
	34.30 -35.90	3			0.87	1.11	0.97	23.80
	34.30 -35.90	4			1.57	1.11	1.75	42.81

Conflict of interest: The authors declare that they have no conflicts of interest regarding this study. No personal, financial, or institutional interests have influenced the design, execution, interpretation, or reporting of the research findings. Furthermore, the funding entities played no role in the study design, data collection, analysis, or interpretation, nor in the preparation of the manuscript or the decision to publish the results.

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CERTIFICACIÓN DE APROBACIÓN DE PROYECTO DE TITULACIÓN

Madrid, 19 de marzo de 2025

M. Sc.

Davide Besenzon Venegas

Coordinador del Programa

Maestría en Geotecnia

En su Despacho

De mi consideración:

Yo, **Luis Jordá Bordehore**, de nacionalidad **española**, portador del pasaporte No. **PAT561314**, en mi calidad de Tutor del Proyecto de Titulación correspondiente a la **Maestría en Geotecnia**, **VI Cohorte**, de la Escuela Superior Politécnica del Litoral (ESPOL), certifico lo siguiente:

Con fecha **20/06/2024**, acepté la tutoría de los estudiantes **Walter David Becerra Moreira y Antonella Zulema Tupac Yupanqui Rodríguez, con cédula de identidad No. 0104683081 y 0954062139**, respectivamente, para el desarrollo del proyecto de titulación denominado: *"Caracterización geomecánica de los materiales graníticos y metamórficos de Morona Santiago, Ecuador"*.

Certifico que este trabajo de titulación fue supervisado de manera continua durante todo su desarrollo, revisado en cada una de sus etapas y, finalmente, aprobado por mi persona en su versión final, entregada el día 18/02/2025.

Particular que pongo en su conocimiento para los fines pertinentes.

Firmado por JORDA BORDEHORE LUIS - ***2787** el día 19/03/2025 con un certificado emitido por AC FNMT Usuarios

Atentamente,

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