Geotechnical characterization using geophysical tests in areas of high geological complexity and landslides for horizontal directional drilling design.

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ABSTRACT

In August 2021, landslides occurred on the slope of the Cortinas sector over an area of more than three kilometers, which affected electrical towers, a national vehicle highway, an oil pipeline and a gas pipeline. Currently, these infrastructures have limitations in their operation, generating significant economic losses and therefore, in the case of the gas pipeline, the construction of a HDD of two thousand meters in length at depths of up to one hundred meters is proposed, with the purpose of being able to bypass the zones unstable and restore transportation to normal conditions. The design and construction of said work constitutes a challenge, since the project area has very special geological conditions, since the hillside deposits are very susceptible to failure and there is apparently a stress tensor of an active fault that directly affects the stability of the area. The projected HDD crosses a ravine and a slope with steep topography with difficult access, as well as different layers of sedimentary rock with intercalations, which are folded and highly fractured and saturated with water. These special conditions generated difficulties and opposed the completion of several attempts by other HDDs, but taking into account that this alternative constitutes basically the only solution from a technical point of view, it was necessary to carry out some borehole and multiple seismic geophysical tests and geoelectrical that would allow defining a detailed stratigraphic profile to be able to analyze the constructive feasibility and, in such case, the most appropriate method, as well as the geomechanically characterization of the rocks, since according to the numerical modeling they indicate that the stability of the drilling may be affected due to plasticization at its limits, with detachments of rock fragments and jamming of the tools necessary for its construction.

Keywords: Geophysics; oil&gas; horizontal directional drilling; geology; finite element; seismic line, vertical electrical sounding, Electrical resistivity tomography.

1. Introduction

Transportation in a country like Colombia has always been a challenge, taking into account the topography, where there are valleys and savannas as well as moors and snow-capped mountains along the three mountain ranges that cross the country. And not only in terms of transportation of cargo or people, but also in terms of transportation lines within the oil & gas sector. On the eastern mountain range there is a sector in the south of the department of Norte de Santander where different pipelines cross, which from their pre-feasibility phases to their construction and maintenance have gone through great challenges and for years have been able to transport raw materials through these lines from the east of the country to large industries and ports and distribution in general. In August 2021 there were a series of landslides that affected the operation of the pipelines, immediately analysis studies were launched to determine the causes and possible solutions.

The studies concluded that the natural events that occurred are similar in that they have the same geological, geomorphological and hydrogeological conditions, even in that they have been subjected to gradual changes such as the condition of land use and the changes derived from the accumulated geotechnical deterioration over time, whose effect, also gradual, is manifested in the decrease of the mechanical strength parameters of the soil; they were also similar in their magnitude and in the same suddenness in which the ground failure occurred. Additionally, they were under the effects of the triggering factor "rain", which presented rainfall exceeding 200 mm, a behavior that periodically, every four years, had been occurring for the last 16 years.

However, what differentiates these events from others that have occurred in the region is their particular simultaneity. This is explained by the fact that the variation in the magnitude of the conditioning factors in which they were found and the magnitude of the triggering factor, rain, converged to the extent necessary for the risk to reach levels that exceeded the resistance capacity of the terrain and, consequently, the natural phenomenon with the characteristics it presented occurred. The probability of predicting such a confluence is extremely low since it considers a large number of random variables (accumulated volume, number of days of preceding rains, maximum rainfall value in 24 hours, magnitude of the earthquake, among others).

It is very important to take into account that the failures presented in the pipeline rights-of-way did not start in the pipelines themselves, but from the upper part of the slopes and even several hundred meters above and with the increase of the inertia of the material moved under the extreme rains and weakening of the entire slope dragging the pipelines even more than 150 meters in some sectors.

Based on the aforementioned findings, it was concluded that predicting and/or containing situations and events such as those presented is technically and economically unfeasible. However, the objective continues to be the search for solutions to maintain the integrity of the transmission lines and give continuity to their operation.

In one of the most affected sectors, where two important pipelines coincide, different route alternatives were analyzed to avoid the affected areas and relocate the pipeline with the least possible risks. This took into account different variables, both direct and indirect, as well as the fact that it was located near a stream and the existence of protected indigenous areas. The result of the analysis of these alternatives was that the most viable proposal is a horizontal directional drilling (HDD) of approximately 2.0 km in length and due to the variability in the topography, it reaches depths of up to 100 meters with respect to the surface.

2. Study Area

The affected area is in the village of Samoré, between the Troya and Cortinas villages in the municipality of Toledo, Norte de Santander. On the western sector, in the lower part of the hillside, is the La China stream with a constant and representative flow of water. The sector is classified as an undulating zone with steep escarpments due to the lithological characteristics of the geological formations. There is evidence of weathering, erosion, and transport by rainfall or gravity (landslides) that transformed, remodeled, and in some cases left traces of pre-existing geoforms.

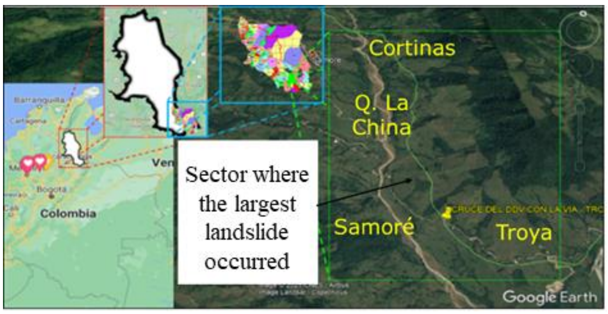


Figure 1. Study Area, Modified from Google Earth.

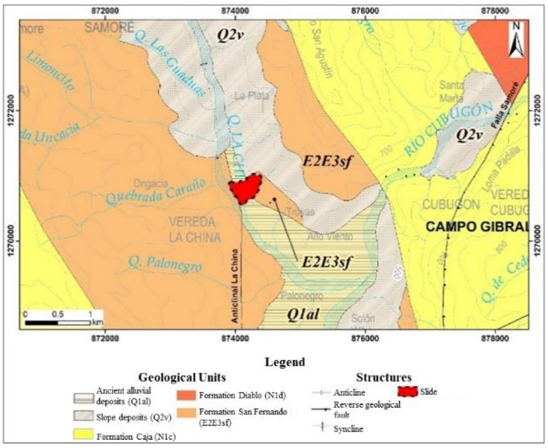
3. Geology

The Colombian territory is located in the northwestern region of the South American plate, in constant interaction with the Nazca, Caribbean, Cocos and other minor plates. The current condition of convergence, especially between the Nazca, South American and Caribbean plates, is responsible for the intensity of the current active tectonic processes, such as the subduction that gave rise to the Andean orogeny during the Cenozoic, the growth of mountain ranges, basins and volcanic chains and the intense seismic activity.

The landslide zone is very regionally located geologically on the northeastern flank of the Eastern Cordillera of Colombia, and is composed of igneous-metamorphic basement rocks of Precambrian to Paleozoic age and overlying the previous ones, sedimentary rocks of Mesozoic to Cenozoic age from the Maracaibo Basin and the Borde Llanero sub-basin, as well as unconsolidated sediments from the Quaternary period.

3.1. Regional geology

Considering the information available from the Colombian Geological Service (SGC), in its geological plates, the landslide zone includes rocks and deposits of the Eastern Cordillera and the Maracaibo basins and the Borde Llanero sub-basin as shown in Figure 2. The sector lithologically presents sedimentary rocks of the San Fernando (E3N3sf), Diablo (N1d) and deposits of slopes (Q2v) and ancient alluvial (Q1al) formations. These formations are deformed forming anticlinal and synclinal structures (La China anticline and Los Deseos syncline), which are fractured by the activity of reverse fault systems, such as the Samoré fault and local faults.



Qlal: Old alluvial deposits: Deposits of streams with terrace geoforms at topographic levels above the present channel, composed of gravels, blocks, poorly selected sands in a sandy silt matrix and in smaller proportion clays and muds. They show apparent reverse gradation in the proximal parts. Age: Holocene

Q2v: Slope deposits: Unconsolidated rock fragments, with heterometric clasts of subangular to angular shapes, poorly transported and accumulated along a slope or in channels with contributions from the slopes, in areas with terrain instability. Age: Holocene

N1c: Caja Formation (Guayabo Formation): Discontinuous layers of fine to medium grained sandstones, quartzose composition, continuous parallel planar tabular structure with laminar stratification and in some sectors wavy, with centimetric layers of mudstones and claystones; occasionally levels of conglomerates. Age: Late Miocene (Montoya et al., 2013).Equivalent in age to the Guayabo Formation.

Nld: Diablo Formation (Guayabo Formation): Yellowish-white, medium to coarse-grained quartz-sandstones, in very thick layers, with lenses of conglomerates with quartz cobbles, and intercalations of gray claystones and siliceous siltstones in thin layers, sporadically decimetric layers of coal are found. Age: Early Miocene (Plate 154 - Hato Corozal, González et al., 2015). Equivalent in age to the Guayabo Formation.

E2E3sf: San Fernando Formation (León Formation): Gray claystones and medium- to coarse-grained quartzoarenites, in medium- to thick-bedded, cross-stratified strata. In the lower and middle part, sporadic coal lenses are present. Age: Upper Eocene to Lower Oligocene. Equivalent in age to the Guayabo Formation (Plate 154 - Hato Corozal, González et al., 2015).

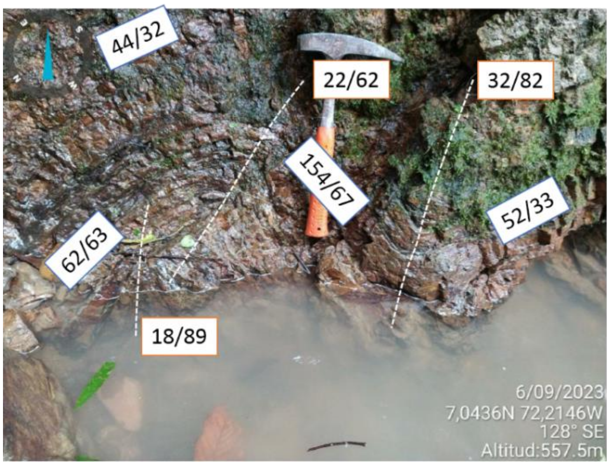
Figure 2. Regional geological map, Taken and modified from (SGC, 2015a).

3.2. Structural geology

The project area is located in the foothills of the Eastern Cordillera, where Paleogene and Neogene sedimentary rocks outcrop with lithologies that vary between claystones, siltstones and sandstones, in addition to colluvial and alluvial deposits of the Quaternary. The geological units correspond to the San Fernando, Diablo and Caja formations. From the deformation point of view, these sedimentary rocks are affected with folds and faults, in a thin-skinned structural style under a compressive stress regime.

3.2.1. Folds and faults

Based on reference information, field visits by geological specialists, description of samples taken in the field and analysis of 13 stations in nearby areas, the geological structures present in the study area were described. These include the La China anticline, the Los Deseos syncline, the Samoré fault, the Loma de San José fault and diaclases - stress tensor.



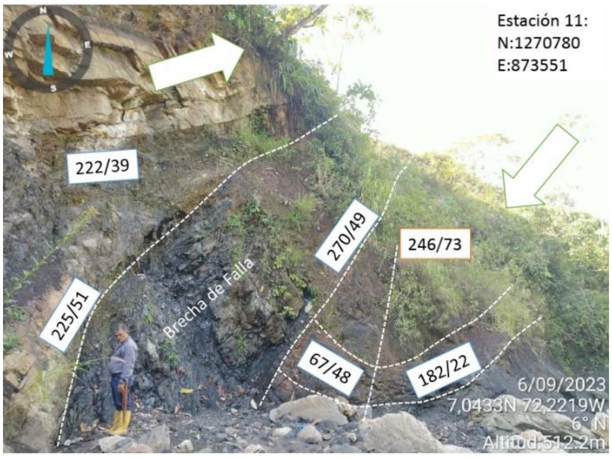


Figure 3. Second-order folds on the eastern flank of the La China Anticline / Fault planes and fault gap affecting the San Fernando Formation.

3.2.2. Diaclases - stress tensor

The fracture planes measured in the field stations are projected on the stereographic network to see their direction and inclinations (Figure 3). From this diagram it is possible to identify four families of joints, with SW-NE, NW-SE, SSE-NNW and W-E directions. This projection highlights the relationship of conjugate fractures of the first two families (separated approximately 60°) so they are classified as shear fractures, with an approximate bisector in W-E direction, which can be related to a maximum horizontal stress or stress tensor, which in this case corresponds to σ1, considering the type of structures that predominate in the area: folds and reverse faults. In addition to the conjugate joints, fractures parallel to the tensor (W-E) and others almost perpendicular (SSE-NNW) can be distinguished, which may correspond to cleavage planes.

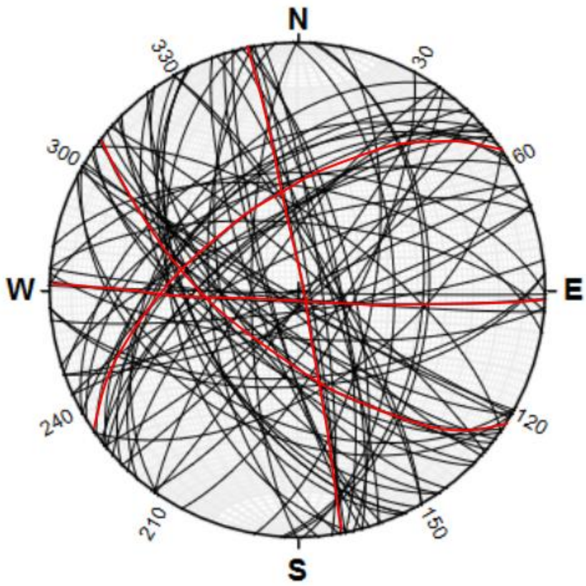


Figure 4. Stereographic projection of the joint planes measured in sandstones of the Diablo Formation and in mudstones and sandstones of the San Fernando Formation.

To confirm the geometric relationship of the fractures and the orientation of the stress tensor, the planes measured in sandstones of the Diablo Formation are selected because this lithology deforms in brittle under a stress field, expressing more clearly the Andersonian principles of fracture (Anderson's Law).

By processing only the data from stations 5 and 6, located in the lying block of the fault, the two conjugate families are exposed, with which it is possible to confirm the W-E stress tensor. This tensor explains the W-E joints as tension or open fractures and the NNW planes as closed planes with a slight sinistral strike component.

3.3. Local geology

Considering the regional geology, geomorphology, exploration tests and field and secondary information, the surface geology is described, which refers to both exposed and subsurface soil and rock classified from an engineering point of view. Taking into account the above mentioned, mainly colluvial transported soils were found and recognized in the area. Additionally, alluvial transported soils, fluvial-torrential transported soils and poor-quality rocks of the shales and sandstones of the San Fernando Formation were found in the vicinity.

The rock shows different degrees of weathering and little lithological variety, it is a monotonous sequence of mudstones with dark gray tonality, in some drillings some medium to thick layers of light gray siltstone are reported from 65m depth. The presence of discontinuities is common, the RQD is less than 50% in almost all of the direct geotechnical exploration in rock, then there is a slight increase in RQD up to 100m depth. This indicates that the quality of the rock mass investigated is poor to fair.

The most relevant geological feature from the lithological description of the cores is the presence of fault planes that were identified along the deepest drill holes, from 38m to 99m and from 34m to 94m. These planes have a characteristic luster so they are also called fault mirrors and are the product of the formation of new minerals by the high shearing that develops on these surfaces. In several of these planes, friction striations are observed that form very thin parallel lines or crevices that are formed by the friction between the rock blocks when they move. In addition, some shear steps were identified, which are small jumps or dips also associated with tectonism. Figure 5 shows some examples of fault surfaces.

Figure 5. Cutting surfaces cores found.

4. Geotechnical exploration

Since 2021, when the landslides and pipeline failures occurred, several exploration campaigns have been carried out to characterize and analyze the viability of the different alternatives for reconnection variants.

4.1. Direct geotechnical exploration

Figure 6 shows the SPT boreholes that have been drilled in the study area.

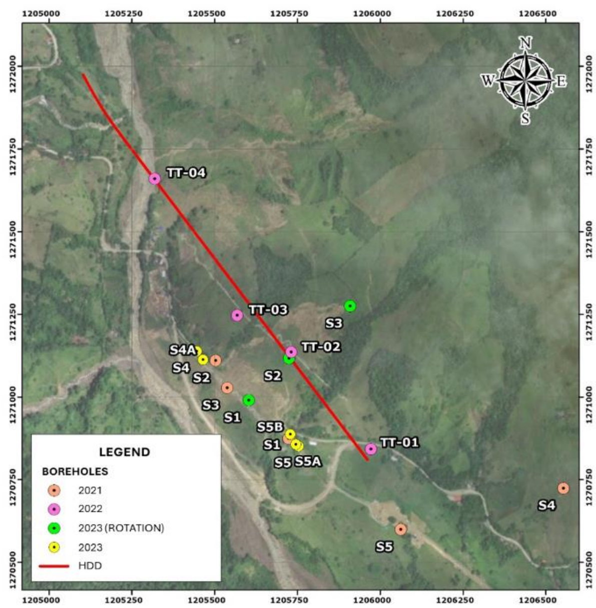


Figure 6. Soundings carried out in the study area, 2021 - 2023.

The following table shows a brief summary of the description of the materials encountered in the deepest boreholes.

Table 1. Summary of some drill holes.

Bore holes	Depth From (m)	Depth To (m)	Description
TT-02	0.0	34.5	Slope deposit (Q2v): Heterometric sandstone blocks, subangular and angular, with diameters between 8 to 50 cm, in a sandy clay matrix with gravels between 5 mm to 5 cm in size.
	34.5	59.0	Very fractured and brittle gray to black mobilized mudstone.
	59.0	100.0	Fractured gray and black mudstone with some intercalations of more competent siltstone (E2E3sf).
TT-03	0.0	7.0	Slope deposit (Q2v): Heterometric sandstone blocks, subangular and angular, with diameters between 8 to 50 cm, in a sandy clay matrix with gravels between 5 mm to 5 cm in size.
	7.0	9.0	Residual soil of the San Fernando formation.
	9.0	56.0	Very fractured and brittle gray to black mobilized mudstone.
	56.4	100.0	Fractured gray and black mudstone with some intercalations of more competent siltstone (E2E3sf)..

4.2. Indirect geotechnical exploration

Likewise, the importance of indirect geotechnical exploration was fundamental to complement the studies, some of the geophysical studies carried out are shown in the following figure.

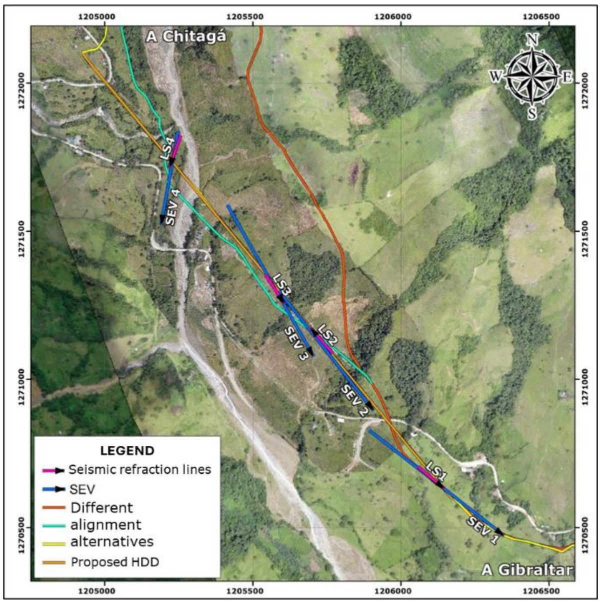


Figure 7. Geophysics performed in study area.

4.2.1. Seismic refraction lines

Refraction seismic is one of the most traditional surveying methods in geophysics. Its fundamental principle is based on the measurement of travel times of seismic waves generated by an impulsive source at (or near) the subsurface surface and refracted at interfaces between media (refractors) with different physical properties (i.e. acoustic impedances). The analysis of these travel times, under certain defined hypotheses and following the laws of wave propagation, allows in principle to obtain an in-depth profile of the geometrical distribution of the different refractors, with the corresponding velocities at which the seismic wave propagates through them (Redpath, 1973).

The following image shows the result of one of the seismic lines executed, showing the different stratigraphic zones and their respective descriptions.

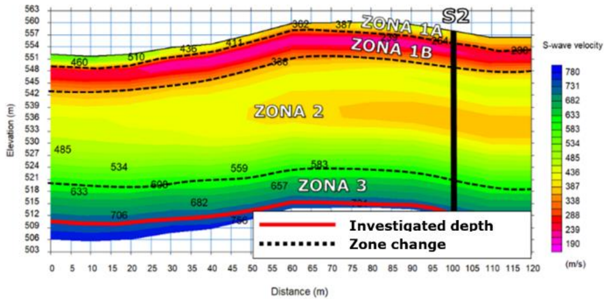


Figure 8. Example of seismic line result.

Zone 1 shows shear wave velocities (Vs) between 200 and 510 m/s, and compressional wave velocities (Vp) between 400 and 600 m/s; of low to medium stiffness with an approximate thickness of 10.0 meters, the lower middle layer possibly with a higher degree of humidity (orange to red colors). **Zone 1A** shows velocity increases associated with rock fragments or blocks of the recent colluvial. **Zone 1B** is associated with colluvial materials composed of sandy clays with gravels and block fragments.

Zone 2 has shear wave velocities (Vs) between 400 and 600 m/s, and compressional wave velocities (Vp) between 600 and 1400 m/s; it is associated with intercalations of highly fractured sandstones, shales and siltstones with residual soils of the San Fernando formation, composed of clays and sandy clays with gravels and fragments of blocks.

Zone 3 has shear (Vs) and compressional (Vp) wave velocities greater than 600 and 1400, respectively, of undetermined thickness and whose stiffness increases with depth. It is associated with healthier rock strata of the San Fernando formation with variable RQD.

4.2.2. Electrical resistivity tomography

The electrical tomography or "Electrical Imaging" test is one of the most traditional geophysical prospecting methods (Arias, 2011). Its main principle is based on the measurement of currents and voltages generated by a current injection initially at the surface and subsequently into the ground. From a geometric factor generated by the array or device used, added to the measured current and voltage values, it is possible to establish the apparent resistivity values at depth and laterally of the line.

With the acquired measurements, a two-dimensional (2D) section is constructed to show a first approximation of the changes in the subsurface. Subsequently, an inversion algorithm is applied to obtain the real distribution of resistivities or electrical image. This image will be an interpretable result from a physical and geological point of view and will give information about the physical characteristics of the subsurface.

It is characterized as a multi-electronic resistivity technique, whose geometric arrangement varies depending on the object of study.

The following image shows the result of one of the tomographies performed, showing the different areas and their respective descriptions.

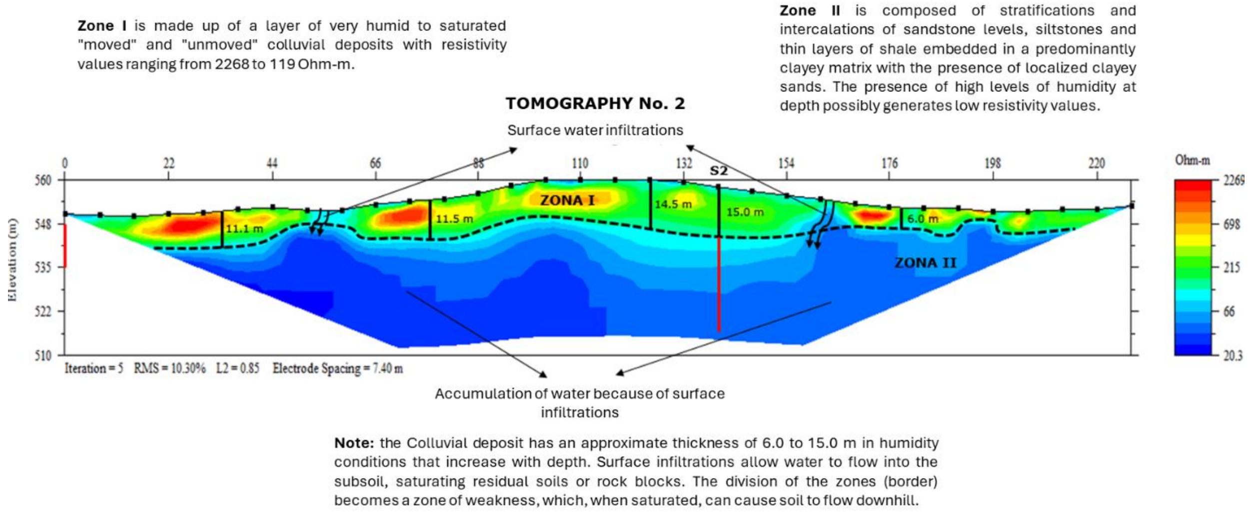


Figure 9. Example of an electrical tomography result.

4.2.3. SEV: Vertical electrical sounding

The specific purpose of vertical electrical soundings is to determine the apparent distribution of the electrical resistivity of the subsoil in a certain depth range along a measurement profile obtained by conventional direct current measurements; by interpreting the apparent resistivity data, information is obtained on the subsoil structures and their physicochemical characteristics, defining the conditions of the geological environment. The interpretation methods can be divided into qualitative or empirical and quantitative. The final result of this type of study is a distance-depth section with the distribution of the resistivity of the subsoil, easily understandable in geological or geotechnical terms.

Soil resistivity values are determined primarily by the porosity and salinity of the water they contain, rather than by their mineralogical composition. The electrical resistivity of materials varies from 10-8 Ohm-m in native metals to 1015 Ohm-m in micas (formation perpendiculars), which implies a wide range of values that characterize the materials. It is important to indicate that in detrital materials the resistivity increases with the grain size, the mentioned factors make that the resistivity of each type of soil presents great variability.

The following table shows a brief summary of the description of the materials associated with the data obtained in one of the SEVs.

Table 2. Summary of vertical electrical sounding.

Depth (m)	Und Geo	Resist (Ohm -m)	Description
0 – 0.64	Q2v moved	178	Unconsolidated colluvial deposit with the presence of large blocks (sandstones) with dry characteristics.
0.64–1.59	Q2v moved	1358	Unconsolidated colluvial deposit with a greater presence of fine soils (clays).
1.59-3.94	Q2v moved	273	Unconsolidated colluvial deposit composed of clays and medium wet sandstone blocks.
3.94-15.23	Q2v	119	Inactive "dormant" colluvial deposit composed of medium wet clays and sandstone blocks.
15.23-25.97	E2E3sf	74	Residual soils of the San Fernando formation, formed by gray claystones and dark gray shales, very fractured and slightly humid.
25.97-53.51	E2E3sf	33	Dark gray claystones, consolidated, highly fractured and deformed, with medium

			weathering index and consistency.
53.51-79.89	E2E3sf	139	Dark gray shales, laminated with presence of coal layers, low fracturing.
79.89-165.0	E2E3sf	1874	Lutites with presence of thin layers or lenses of sandstones, of high rigidity.

4.3. Geotechnical exploration results

In addition to the raw information from boreholes with results of number of hits, description, RQD and seismic lines, tomography and vertical seismic lines, tomographies and vertical electrical soundings in terms of wave velocities and resistivities, different laboratory tests were carried out on the extracted samples:

- Classification (limits, granulometry, humidity).
- Unit weight.
- Specific gravity.
- Direct shear.
- Unit weight
- Static triaxial.
- Unconfined compression in soil.
- Simple compression in rock.
- Point load.
- Tilt test in rock.

Based on the large amount of information or "big data" that was available, a complete perspective of the terrain, stratigraphy and engineering properties was obtained.

5. Design inputs

Once the information was organized, graphic columns were generated taking into account different essential values for the feeding and calibration of the stratigraphy and the parameters for the models that were planned to be carried out. As shown in Figure 10.

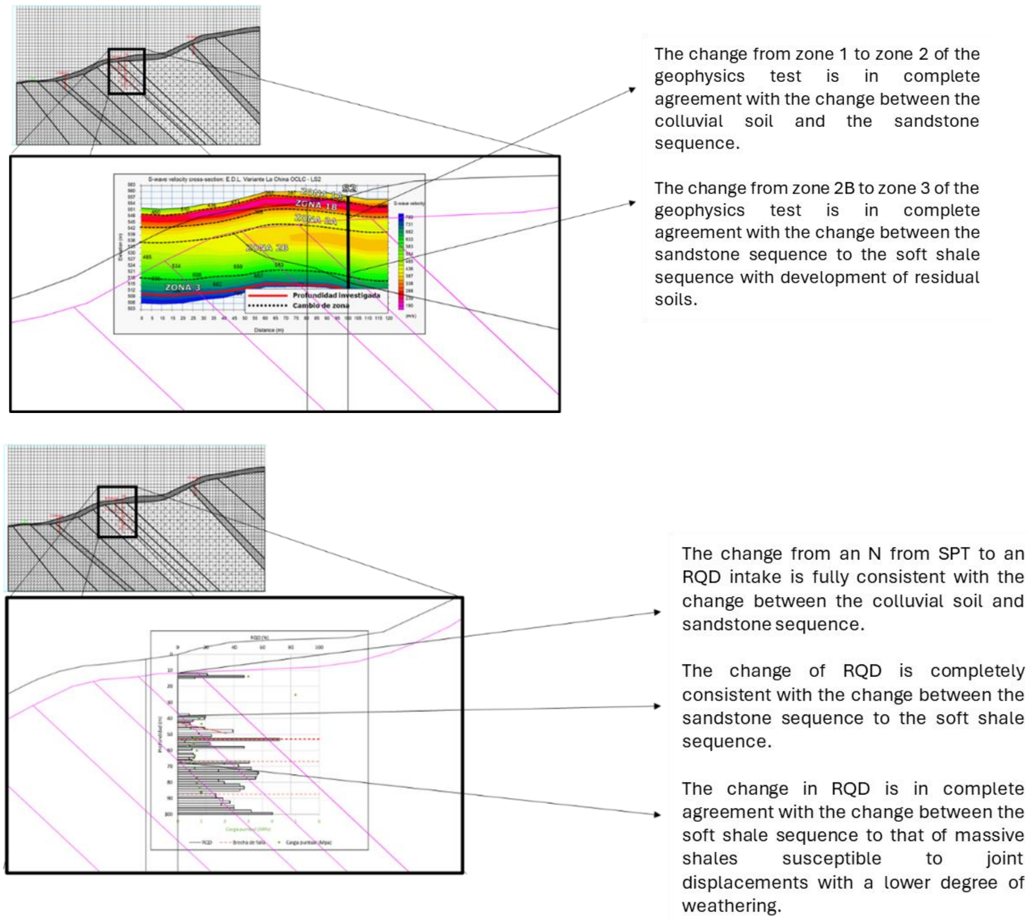


Figure 10. Linking of geotechnical information for verification of stratigraphy and parameters in profiles for models.

Another primary input taken into account was the inclusion of discontinuities in the rock strata that were characterized in the geology from drilling, field visits, secondary information and sample descriptions.

6. Numerical modeling with finite elements

For the correct modeling of the global failure surfaces of the terrain and a correct estimation of the plasticization points resulting from the execution of the HDD excavation, the use of the Hoek Brown constitutive model for weathered rocks is chosen. Its greatest advantage over other models is that a single set of massif calibration parameters correctly reproduces the resistant stress at 4 points either in slope or in excavation without having to modify the resistance parameters, this allows us to correctly analyze probable sliding or convergence failures of the excavation. This model adopts a Mohr-Coulomb yield surface with curved generatrix.

6.1. Importance of geophysics for model input

A fundamental data that allowed feeding the parameters for the models and that was taken from the results of geophysical tests was the shear wave velocity (vs), as can be seen in Figure 11. defined for each material change together with the different properties selected according to the totality of the characterization and discontinuities found in the rock strata.

Lithology	RQD	PLI (MPa)	GSI	USC (MPa)	mi	Vs (m/s)	γ (kN/m3)	Go (MPa)	v	Eo (MPa)
Sequence of fine to very fine-grained sandstones, locally weathered. Sandy-clayey soils and sandy clays, towards the base fine-grained sandstones	13	5	14	90	13	420	25	450	0	1080
Sequence of fine to very fine-grained sandstones, locally weathered. Sandy-clayey soils and sandy clays, towards the base fine-grained sandstones. (Highly weathered)	0	3	10	54	13	340	25	295	0	708
Intercalations of soft shales with development of residual soils, with levels of fine-grained sandstones, locally conglomeratic. Towards the base soft weathered shales	7	0.65	12	8.19	4	500	25	637	0	1529
Intercalations of soft shales with development of residual soils, with levels of fine-grained sandstones, locally conglomeratic. Towards the base soft weathered shales (Highly weathered)	0	0.65	10	8.19	4	640	25	1044	0	2506
Massive, soft, somewhat fractured and slightly weathered shale sequence susceptible to movement due to jointing. San Fernando Formation. E2E3sf	10	0.65	13	8.19	4	650	25	1077	0	2585
Massive, soft, somewhat fractured and slightly weathered shale sequence susceptible to movement due to jointing. San Fernando Formation. E2E3sf	40	0.65	25	8.19	4	650	25	1077	0	2585
Intercalations of fine to very fine grained, quartzose sandstones. Towards the base weathered shales	20	5	16	90	13	450	25	516	0	1238
Fissile Fractured Shales	0	0.65	10	8.19	4	640	25	1044	0	2506

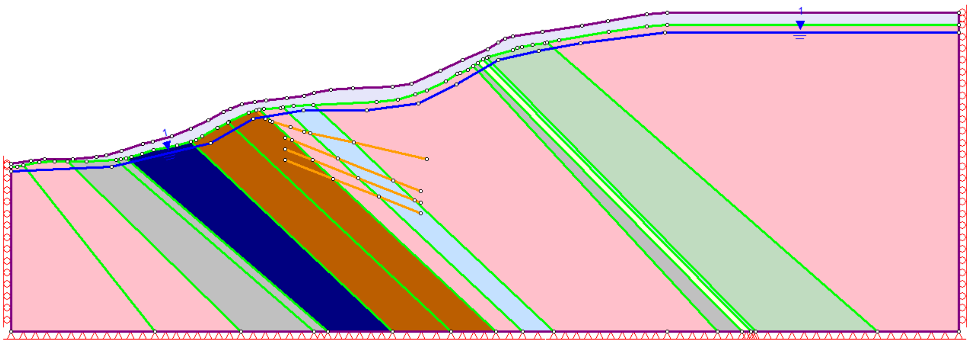


Figure 11. Parameters for the model and adopted stratification.

6.2. Stability model results

Based on the geotechnical parameters and the lithology previously mentioned, a stability analysis is performed using the SRM (Stregth reduction method) methodology, which allows the calculation of safety factors by reducing resistance parameters. The model obtained a maximum probable failure surface with a depth of 45 meters for drilling, which indicates that any HDD performed below this probable failure depth would not be affected by a global failure of the slope, which provides a starting point in depth to determine the design depth of the HDD.

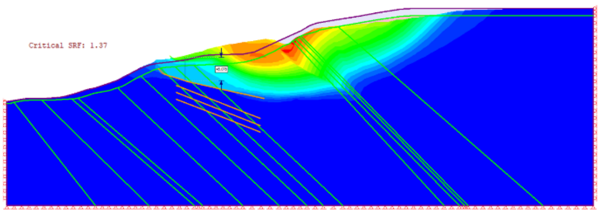


Figure 12. Result finite element stability model.

6.2.1. Conclusions stability model

- The global slope failure corresponds to a depth of 45 m, i.e., no HDD placed below this depth would be affected by a global slope failure.
- Although the F.S is greater than 1.0, i.e. the current slope condition is stable, this failure surface could be developed over time by softening of the rock with progressive failure over time, which will be dominated by residual rock conditions, however, if the HDD is placed deeper than this failure surface, the shear surface would not generate any effect on the HDD.
- It is worth noting a very important aspect, if only the colluvial landslide mechanisms were analyzed, there would be superficial faults with current F.S less than 1, so recurrent landslides are expected in this area, this aspect validates the need

to perform a deep HDD to avoid having to stabilize the colluvial zone.

6.3. 2D stress-strain convergence model results

A section was carried out to determine possible failures in the excavation of the HDD pilot test. Different models were made to verify the stability and displacements in the excavation at different points of the alignment.

Through the HDD modeling it is obtained that, if an 18-inch excavation is performed for the shale sector, there would probably be a convergence of 1.2% of the excavation, that is, a ratio between the radial displacement versus the radius of the excavation (Ur/R), which is a high value that would induce ground failure and block detachment.

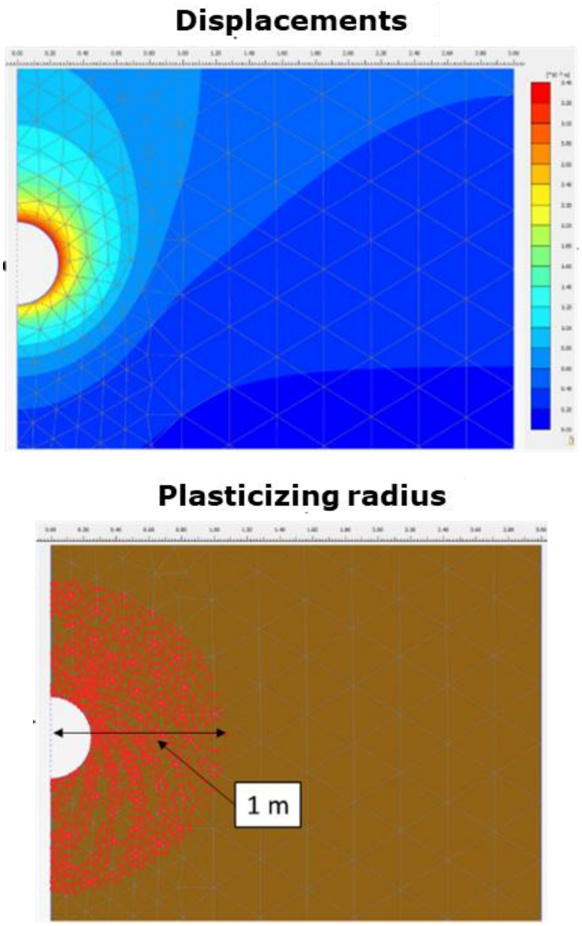


Figure 13. 2D stress-strain convergence model results.

6.3.1. Conclusions stress-strain model

It can be concluded from this section that the HDD section built in these shales will have problems of landslides due to the effects of plasticization of the rock mass, also, after the pilot excavation, this excavation will probably go from 18 in to 15 in.

The behavior of the HDD can be similar to a tunnel where there will be a convergence depending on the radius and a plastic radius will be generated; however, the problem is that this type of excavation has no support elements, therefore, the rock is left to plasticize in its entirety.

The results shown imply that borehole support is required or recommended to prevent the borehole from closing, which will have to be taken into account in the final designs and by the builder.

6.4. 3D stress-strain convergence model results

For this model, a cut was determined in which the transition between the weathered shale and the sandstones of the profile is made in order to evaluate what happens in the change of section.

As can be seen in the displacement mapping shown in Figure 14, there is significant convergence in the area where the shale is located, this proves what was presented in the 2D model that this area would be susceptible to present either convergence of the excavation (flow of material into the interior) or fall of blocks due to weathering of the rock, thus validating the reduction of the excavation diameter. It is also important to note that as we drill in the shale stratum there will be a transition zone (approximate length of 60 m) where the rock will converge less due to the effects of the change of material from sandstone to shale, additionally it is important to note that the sandstones due to their high permeability will have water infiltration in the excavation.

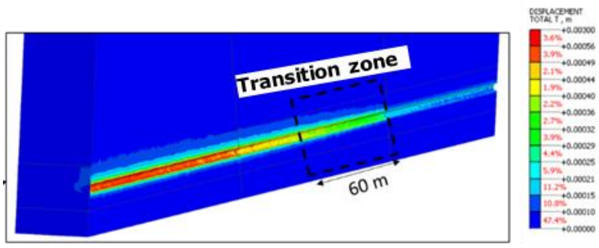


Figure 14. 3D stress-strain convergence model results.

7. Discussion HDD feasibility

7.1. Geology

The fault mirrors shown in Figure 5 do not pose a risk to the HDD, as several major structures in the world have been built under these conditions and have performed well for decades. The confinement to the depth of the HDD exerts a geologic control.

The stress tensor obtained for the area confirms the compressional regime that generates the folds and reverse faults, and even the sinistral strike-slip component of the Loma de San José fault. This stress field has been previously identified in the surrounding area from focal earthquake mechanisms and with field data on striated fault planes. The tensor is considered a vector with direction and magnitude, which can be decomposed into structural planes of interest with a normal and a tangential or shear stress vector. It should be clarified that the stress field acts permanently causing energy to accumulate in some structures as it is oriented perpendicular to the tensor and along others it is released in movements if it is arranged at an angle of 30° with respect to the tensor (shear according to Anderson's Law), as confirmed by the minor faults found in the area with orientations subparallel to the families of conjugate or shear faults. Under this tensor, NE-striking structures move as dextral faults, while NW-striking structures move sinistrally. It is assumed that the structure is safer as it moves away from the critical angle with respect to the tensor. In the case of the HDD, the orientation with respect to the tensor varies between 50º and 60º, which makes it a low risk condition according to Anderson's Law.

7.2. Finite element models

Evidencing the results of the analyzed models, where some possible adverse effects are observed that must be mitigated and taken into account in the final designs, as well as in the choice of the type of drilling process and equipment.

In addition, there are two criteria that were essential when selecting the length and depth of the projected route for the HDD.

7.3. Drilling and hoisting areas

In the search to cross the landslide problem zone, it is necessary to cross the creek by means of the HDD, which implies a length of approximately 2000 meters of subway drilling.

This length contemplates two safe and wide enough zones to be used as working areas for the operation of the horizontal directional drilling both at the exit and at the arrival, for drilling and lingering.

7.4. Variable topography

The second criterion that makes the layout of the HDD feasible under the conditions of length and depth in which it is proposed is that, being located in an area of undulating topography but with a great variability of slopes and heights, the crossing with the La China stream is a low point, which is why the profile of the borehole is deepened to approximately 40 meters below the bed of the stream, thus avoiding finding alluvial strata in the middle of the borehole and sufficiently preventing possible effects due to scour.

8. Conclusions

The integration of the "big data" composed of all the studies carried out by different firms between 2021 and 2023 was achieved with a focus on the precision of geotechnical geological profiles and the definition of parameters for the finite element models.

An exploration campaign consisting only of spot drilling falls short for an adequate characterization of soils and rock strata for an area and depth as significant as required for the design and construction of a HDD in these complex conditions. Geophysical testing was essential to understand and validate the continuity or variability in strata conditions, verify moisture conditions, and correlate the consistency of the materials where no number of SPT hits were obtained. It should be noted that these geophysical tests require drilling with sample recovery to understand and calibrate the findings.

In the case study presented in this document, all the exploration, tests and geophysics show a total correlation with the detailed structural geology presented, which validates the profile to be used in the numerical analysis of deformation and stability in each of the properties of the lithologies.

Regarding the depth of the proposed HDD, in addition to the mass removal projection that determines a minimum acceptable depth of 45 m, the geophysical studies, drilling samples and rock mass classification were also taken into account, providing information that derives that the most acceptable depth should be greater than 60 m. However, the final determinant was the topography, since, with respect to the highest elevation of the pipe alignment (more than 100m at the highest point above the landslide), it would leave between 30 and 40 meters to the bed (talweg or watercourse) of the creek, which fully justifies such depth foreseen.

Regarding the length of the HDD and the location on the hillside, the limitations of the indigenous reservation and the limited area available for the construction maneuver were considered, which would require large volumes of excavation to be done elsewhere, which are unfavorable to the stability of the slopes where other infrastructure is located (oil pipeline, electrical towers and national road). The site currently defined is ideal and sufficient to cross the landslide and the body of water.

Modeling of the borehole stability under the rock quality conditions identified was carried out, which showed that, although there is an arc effect, it is to be expected that, in some of the most fractured rock layers, rock fragments will fall off, since the size of the HDD borehole is larger than the size of these rock fractions. This must be taken into account in the final designs and by the constructor in order to execute the drilling satisfactorily.

It is important to consider that in this case the RQD found are low, and taking into account the classification of the massif by RMR it is considered a poor quality rock, which implies that the builder must take this into account in the planning of the drilling work, using the proper technique, as well as the appropriate equipment to ensure the stability of the drilling and the continuity of the work.

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