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Thirty years of experience in the characterization, spatial modeling and valorization of soft soils and glacial sediments: Contemporary Insights from Chilean Patagonia

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ABSTRACT: Underlain by extensive glacial sediments, Chilean Patagonia is currently facing significant geotechnical challenges related to the development of infrastructure required for large-scale green hydrogen projects. Accurate geotechnical characterization of these heterogeneous and often saturated soils is essential to ensure structural stability and support the sustainable development of future infrastructure. This study presents a comprehensive overview of the geomechanical characteristics of glacial sediments in Chilean Patagonia, with a focus on the Magallanes Region, where extensive geotechnical investigations have been conducted over the past three decades. Modern testing techniques—including geophysical methods and instrumented dynamic penetrometer have enabled accurate and efficient assessment of these soils in situ. Using the collected data, geostatistical models have been developed to analyze the spatial variability of mechanical properties, especially in the city of Punta Arenas. These models support localized seismic risk assessment and inform recommendations for the engineering valorisation of glacial soils, particularly for use as construction materials or sustainable foundation supports. The methodology developed in Patagonia offers a transferable framework for the sustainable characterization and reuse of glacial soils in similar geological contexts worldwide.

KEYWORDS: Glacial sediments; Geotechnical Characterization, Spatial Variability, Seismic Risk Assessment, Chilean Patagonia

1 INTRODUCTION

The Strait of Magellan region, in southern Chile, has been subjected to major geological events that have shaped the landscape and generated a wide range of heterogeneous sedimentary deposits. Cyclical advances-retreats of a glacial lobe resulted in the formation of both basal and flow tills, while the development and impoundment of a large proglacial lake led to the accumulation of glaciolacustrine sediments and relict shoreline features. Post-glacial and interglacial periods favoured the development of outwash plains, including swamps, peat bogs, and organic clays. Successive marine transgressions and regressions, combined with the fluvial activity of a complex drainage network, contributed to the deposition of alluvial and glaciofluvial materials.

In Punta Arenas, Chilean Patagonia, unlike other areas of the region, the glacial soils deposited during the Last Glacial Maximum (LGM) were covered by organic and soft alluvial sediments, forming a complex interaction of glacial and post-glacial units. This resulted in a heterogeneous stratigraphic sequence with highly variable mechanical properties. These heterogeneous deposits now form the foundation soils beneath the urban and suburban areas of Punta Arenas. Rapid urban expansion has led to construction on soils that are almost permanently saturated. Characterized by their low bearing capacity, high plasticity, significant compressibility, and marked spatial variability, these soils pose significant challenges for foundation design. Their geotechnical behavior is influenced by factors such as moisture content, texture, structure, mineralogy, and stress history. Furthermore, the wide variability in grain size and mechanical properties makes in-situ characterization difficult.

The present study addresses the pressing need for comprehensive geotechnical data in areas surrounding the Strait of Magellan, a region undergoing increasing industrial development. Activities such as hydrocarbon extraction and the deployment of large-scale Green Hydrogen projects—requiring extensive wind farms and associated infrastructure—demand robust geotechnical characterization. Such information is crucial for evaluating the suitability of local soils for use as structural fill, as well as for assessing the potential of aggregate and rock resources necessary for constructing road networks and turbine foundations.

1.1 *Geotechnical Exploration in remote areas*

Due to the foregoing, geotechnical studies were initially developed primarily in or near urban areas. Carrasco (1997) presented the first geotechnical zoning study of the subsoils in the city of Punta Arenas and completed recently by (Villarroel et al. 2024). Over time, it began to conduct studies for the development of various industrial areas. As a result, for the past 15 years, studies have been carried out for the petroleum industry, mainly in the Tierra del Fuego and San Gregorio sectors, and for more than 5 years for the development of large Green Hydrogen projects. These projects collectively cover over 350,000 hectares, which has involved exploring previously unexamined terrains from a geotechnical standpoint. To carry out these campaigns, complex logistical developments have been required. These efforts have yielded robust geotechnical information from various areas adjacent to the Strait of Magellan. Figure 1 shows the points for which some degree of geotechnical information is available, such as: stratigraphy, laboratory tests, dynamic cone penetration tests, geotechnical boreholes or a combination of these.

Meanwhile, seismic design codes in Chile have evolved from relying on strength parameters to emphasizing stiffness indices derived from geophysical testing. The accumulation of geophysical data for Punta Arenas enables preliminary assessments of the city's specific seismic conditions and provides a valuable benchmark for future investigations.

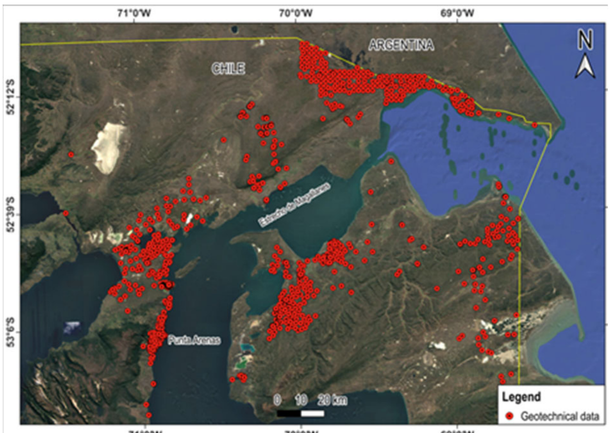

Figure 1*: Points with available geotechnical information near the Strait of Magellan. Self-sourced.*

1.2 *Soil exploration and improvement techniques evolution*

The initiation of soil treatments or improvements in Patagonia dates back to the time of indigenous peoples, such as the Kaweskar ethnic group. They constructed communication paths using the "embaralado" technique, which consisted of a horizontal palisade made of small, thin logs, allowing passage through very wet forested areas. Subsequently, with the founding of the first cities and the arrival of predominantly European immigrant populations in the late 19th century, soil improvements for the first brick masonry buildings essentially involved a significant soil densification through the incorporation of large boulders, decreasing in size towards the surface—a technique inherited from the ancient Romans. By the late 20th and early 21st centuries, soil improvement for large buildings involved driving water-resistant timber piles, which exhibit good resistance to degradation under saturated conditions. Furthermore, for the construction of major roads, particularly in peatland or "mallín" areas, "embaralado" was also used as reinforcement and support for fills in the formation of pavement layers.

Over time, increasing societal demands and new environmental regulations made the timber pile and boulder improvement techniques increasingly restrictive, necessitating the adoption of new soil improvement methodologies. Consequently, large projects currently executed on the soft or loose soils of Patagonia have progressed towards incorporating high-tech and high-strength geotextiles or geogrids for superficial improvements, or compacted gravel piles as deep foundations. These, of course, still require aggregate materials sourced from other soil units.

2 CHILEAN PATAGONIA & MAGALLANES REGION

2.1 *Geological and geomorphological context*

The formation of the Southern Patagonian Andes began in the Middle-Late Jurassic, creating an island arc and the "Rocas Verdes" Basin. The latter, initially extensional, was filled with volcaniclastic and turbiditic sediments. Subsequently, in the Late Cretaceous-Paleogene, the closure of the Rocas Verdes Basin led to the Magallanes Fold-and-Thrust Belt and the development of the Magallanes Basin to the east of the Andean orogen, with a sedimentary infill up to 7 km thick. Since the Neogene, the Magallanes-Fagnano Fault has been a key tectonic factor.

Glacial activity has significantly shaped the geomorphology of this Patagonian zone. During the Last Glacial Maximum (LGM), an extensive ice field covered the region, including Seno Skyring, Seno Otway, and the Strait of Magellan, as part of the larger Patagonian Ice Field. The ice retreat, between 18 and 15 thousand years before present, formed extensive proglacial lakes which, with the global rise in sea level, transformed into the fjord system of the Strait of Magellan. These glacially excavated fjords and bays became depositional areas for glacial, glaciomarine, and glaciolacustrine sediments (Breuer, S. et al., 2013)

The geomorphology of the Magallanes Region is predominantly characterized by multiple glacial and marine landforms (Rodriguez et al., 2023). The former were generated by fluctuations in the advance and retreat of extensive ice lobes associated with the "Greatest Patagonian Glaciation" (GPG), which occurred 1.168 – 1.016 Ma (Mercer, 1983), and the "Last Glacial Maximum" (LGM), which occurred 44 – 11.3 ka (García, J.L. et al. 2018). During the GPG (Figure 2), glaciers formed large ice lobes that successively advanced and retreated along the main valleys and bays (Seno Skyring, Seno Otway, Strait of Magellan; Darvill et al., 2014). These glacial advance-retreat fluctuations are evidenced in a set of well-preserved relief forms, including morainic sequences, glacial lineations (drumlins), meltwater channels, and fluvioglacial plains. The morainic sequences correspond to lateral, ground, and marginal moraines of the Seno Otway and Strait of Magellan lobes. Consequently, these geoforms exhibit marine erosion, which is clearly evidenced in the marine terraces observed along the margins of the Strait of Magellan, Seno Otway, and Bahía Inútil.

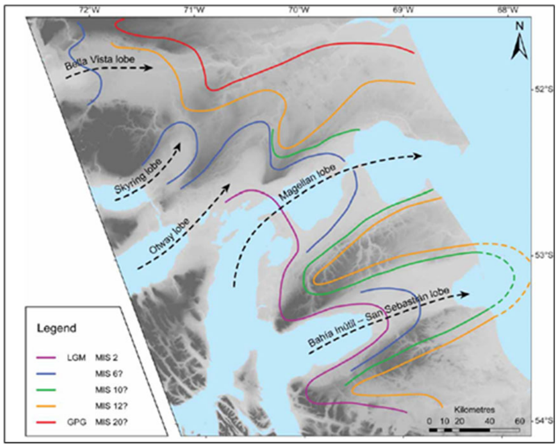

Figure 2*: Map showing the successive advance of the extensive ice sheet that covered the Magallanes Region. Greater Patagonian Glaciation: red lines. Last Glacial Maximum: purple line (extracted from Darvill, et al., 2014)*

2.2 *Seismic hazard*

Earthquakes in Magallanes are associated with relative movements, less than 20 mm/year, of three plates: South American, Antarctic, and Scotia. Therefore, seismicity is lower when compared to northern Chile (Cisternas and Vera, 2008), where the Nazca and South American plates are involved, converging at a rate of approximately 100 mm/year. However, two historical earthquakes occurred in 1879 and 1949 (M_W=7.5) associated with the Magallanes-Fagnano fault. Recent earthquakes have also been recorded in Magallanes up to July 2025, with the largest magnitude being M_W=7.5 (May 3, 2025), which occurred within the convergent/transcurrent margin between the Antarctic and Scotia plates, in the Shackleton Fracture Zone (Beniest, et al., 2023).

***Figure 3**: Geomorphological maps considered in this study. a) Glacial geomorphology of the Strait of Magellan ice lobe, southernmost Patagonia, South America (Soteres et al, 2020). b) Geomorphology of marine and glacio-lacustrine terraces and raised shorelines in the northern sector of Peninsula Brunswick, Patagonia, Straits of Magellan, Chile. (De Muro et al, 2018)*

3 MATERIALS AND METHODS

In a region such as Magallanes, characterized by superficial fractures, channels, rivers, coastal environments, islands, and extreme meteorological conditions, accessing sites using conventional equipment is often logistically complex, time-consuming, and costly. Under these constraints, portable methods capable of providing precise, reproducible, and high-resolution measurements, both in depth and laterally, are essential. While geophysical methods allow for the exploration of large soil volumes, they often lack the vertical resolution needed to capture fine stratigraphic details. In contrast, geotechnical soundings offer accurate point-specific data, though spatially limited. Given these logistical and operational challenges, the combined use of surface geophysical techniques (e.g., MASW, ReMi, HVSR) and portable instrumented dynamic penetrometers enables rapid, reliable, and cost-effective characterization of soft soil formations.

3.1 *In-situ geotechnical and geophysical methods*

3.1.1 *Instrumented dynamic penetrometers*

In Patagonia, dynamic penetration testing has been practised since the late 19th century, beginning with early forms of dynamic cone devices such as Peck's apparatus. During this period, field assessments often relied on traditional construction tools to estimate the compactness or consistency of excavation surfaces (Carrasco, 1997). From 2007 onward, French instrumented lightweight dynamic cone penetrometers, known as Panda® test (Benz et al. 2024a) and hereafter iLDCP, were incorporated into geotechnical investigations and quality control programs, especially for assessing excavation seals and working platforms in oilfield operations. In 2012, instrumented heavy dynamic probing (iDPSH) (Benz et al. 2019; Benz et al., 2024b) was introduced as a complementary technique to borehole investigations, with over 1,050 tests performed to date. In early 2025, the first CPTu testing campaign was conducted in the region, offering the opportunity to compare cone resistance values with data from iDPSH profiles.

iLDCP and iDPSH devices are portable, easy to deploy, and generate extensive and reproducible datasets, making them particularly suitable for evaluating the spatial variability of soils. The resulting output, the penetrogram, also provides a nearly continuous measurement with depth, similar to that obtained from electric cone penetration tests (CPTu). This feature is particularly advantageous for the detailed characterization of various soil horizons, especially in heterogeneous sedimentary environments. A comprehensive description of the equipment, operating principles, and data interpretation methods can be found in the cited references.

3.1.2 *Geophysical methods*

Surface geophysical methods such as 2D MASW (Multichannel Analysis of Surface Waves), RéMi or MAM (Microtremor Array Method), and HVSR (Horizontal-to-Vertical Spectral Ratio) are lightweight, portable, and particularly well-suited for deployment in areas with limited access, such as glacial sedimentary environments composed of soft, saturated soils. These non-invasive techniques allow for the investigation of subsurface conditions across extensive areas while minimizing logistical constraints.

Following the Mw=8.8 earthquake in 2010, significant changes were introduced to Chile's main seismic design code, mandating geophysical tests for structures of certain importance. Consequently, starting in 2011, geophysical tests began to be performed to determine the shear wave velocity (V_{s30}). These tests have been predominantly conducted in urban areas, primarily using the ReMi and MASW methodologies. Similarly, from 2018 onwards, tests for determining the fundamental period of the soil (T_0) began to be carried out using the HVSR technique. Since 2023, this test has become necessary for the seismic classification of industrial structures. The execution of these tests in urban areas has allowed for the establishment of seismic zonations, which have been particularly useful for the city of Punta Arenas.

3.2 *Data Collection Strategy*

Considering that the objective of this work is to analyze the general geotechnical properties of various glacial soil units, a significant portion of historical laboratory test data has been considered. This data comes primarily from samples obtained from exploratory test pits up to 3.0 m deep, excavated for projects near the Strait of Magellan, in an area extending northeast from Punta Arenas. Most of the analyzed information corresponds to particle size distribution, plasticity, USCS classification, Modified Proctor, CBR, and shear strength tests. It is important to note that the city of Punta Arenas and its immediate surroundings have been excluded from this analysis because, as mentioned previously, the city's stratigraphic sequences consist mainly of post-glacial soils. To analyze the geotechnical variability specifically for the city, a separate analysis of DPSH test data and seismic classification parameters will be presented.

For the assignment of glacial soil units to points where geotechnical information is available, the geomorphological maps of the Strait of Magellan area and of glacial lake deposit units have been considered, as shown in Figure 3.

3.3 *Geostatistical Modeling Approach*

For the geostatistical modeling of iLDCP & iDPSH datas as well as for V_{s30} and T_0 geophysical tests, the open-source SGeMS software from Stanford University was used (Remy, 2005). Specifically, for the analysis of iLDCP & iDPSH data, a total of 108 tests were considered. These tests are located within an approximately 800 Ha quadrant of Punta Arenas, an area that exhibits the lowest V_{s30} values and the highest T_0 values. This is of significant interest as some sectors of the city could experience substantial adverse effects during major seismic events. This represents an increase of over 52% in data quantity compared to previous studies conducted on the same quadrant (Villarroel & Carrasco, 2021). For the geophysical tests, 206 tests for V_{s30} determination and 213 tests for fundamental period are available, with an average test densification close to 400x400 m. This meets the technical recommendations of the SESAME project for seismic microzonation, which suggests at least 500x500m. The complete results of this analysis are presented in previous investigations (Villarroel et al, 2024). The analyses involved determining experimental variograms, defining theoretical variograms, and applying the Ordinary Kriging estimation technique. Graphical interpretation and map generation were performed using QGIS software.

4 RESULTS

4.1 *Summary of Soil Properties*

For the current study, the geomorphological units with the most representative available information have been selected: Last Glacial Maximum Moraine Drift (I); Ribbed Moraine Terrain (II); Outwash Plains (III); and Drumlinized Terrain (IV). Additionally, the unit defined as First Order Terrace (V) has been considered. This unit, along with the "Glaciolacusters" unit, could present the main geotechnical challenges because these areas are predominantly characterized by a soil locally known as "mazacote," which corresponds to a very soft, bluish-grey soil, mainly clayed, having poor geotechnical properties.

In Table 1, geotechnical parameters of interest corresponding to each of the identified geomorphological units are presented. Figure 4a–b illustrates the characteristic grain size distribution curves, including their standard deviations, and the Casagrande plasticity chart, which highlights the wide range of soil types present in the region, most of which plot above the A-line, indicating silty to clayey fine-grained soils with low to intermediate plasticity.

In general, all the units analyzed exhibit contractive behavior. Unit V presents a saturated or near-saturated condition with average Su values of approximately 15 kPa.

4.2 *Performance of Testing Methods*

4.2.1 *Efficiency and reliability in remote areas*

Geotechnical reconnaissance in remote areas of Patagonia is extremely complex due to the conditions detailed previously. However, current tools allow for improved reduction of ground uncertainty. For example, the portable iLDCP penetrometer enables a quick and effective preliminary assessment of soil consistency/compactness and can even be integrated into compaction control mechanisms for work platforms.

In Figure 5, the results obtained with iLDCP penetrometer tests are shown. These tests were conducted on a "Ribbed Moraine Terrain" unit, first in its natural, undisturbed condition, and subsequently after the completion of the fills that form the work platform necessary for the access of heavy oil exploration equipment. Graphically, a considerable increase in cone resistance can be observed. It is also possible to estimate the soil thickness that forms the work platform, which in this example, would be approximately 0.50 m. This, in turn, allows for the validation of design assumptions. It is important to mention that, due to the suitability of their geotechnical properties, the fills used to form these work platforms generally come from the units denominated "Outwash Plains."

The use of the iLDCP portable penetrometer has also proven fundamental in optimizing soil improvement designs. In projects where environmental conditions prevented the use of suitable external materials, the execution of test sections and subsequent control with the iLDCP allowed for the identification of the optimal combination of reinforcements. This methodology ensured the operational safety and stability of the work platforms, as detailed in previous publications by the authors (Carrasco et al., 2024).

In recent years, extensive geotechnical exploration campaigns have been carried out for the engineering development of Green Hydrogen projects. Given the difficulties of expeditious access to the terrain with drilling equipment, the execution of iDPSH tests has been prioritized as a preliminary ground reconnaissance tool. Furthermore, to validate the obtained results and facilitate their interpretation, pairs of iDPSH and CPTu tests were conducted in geomorphological areas corresponding to Glaciolacustrine and Ribbed Moraine Terrain units. Figure 6 shows the comparison between both tests, revealing very similar resistance profiles, with a more significant difference in values near 1 MPa, which are associated with the presence of the "mazacote" type soil (a very soft bluish-gray clay).

Table 1*: Summary of geotechnical properties of the analyzed units. NP (%) values indicate the proportion of data within the unit that is classified as Non-Plastic. Under USCS Classification.*

Property	Geomorphological unit I	II	III	IV	V
NP (%)	59	8	89	35	0
LL (%)	17 ± 2	24 ± 5	21 ± 4	22 ± 4	34 ± 7
IP (%)	5 ± 1	9 ± 3	7 ± 4	7 ± 3	15 ± 6
Máx modified Proctor Density (kg/m^3)	2157 ± 95	1995 ± 112	2192 ± 62	2069 ± 85	1710 ± 126
Óptimum Moisture Content (%)	6.6 ± 0.9	10.4 ± 2.5	6.1 ± 0.9	8.0 ± 1.4	16.8 ± 3.9
CBR (%)	32 ± 15	9 ± 6	71 ± 17	16 ± 10	3 ± 1
φ (°)	35 ± 1	32 ± 2	35 ± 3	29 ± 3	28 ± 2
Cohesion (kPa)	5 ± 1	7 ± 3	8 ± 4	7 ± 1	7 ± 4
USCS Classification	SM SM-SC	CL SM-SC	GP GW-GM	SM SC	CL CL-CH
Number of Data	27	131	108	26	15

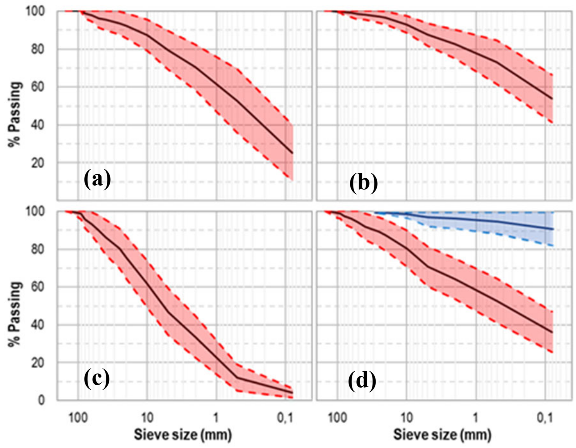

Figure 4a*: Grain size distribution curves. The black lines represents the average values. Red shading indicates plus/minus one standard deviation. a) LGM Moraine Drift. b) Ribbed Moraine Terrain. c) Outwash Plains. d) Drumlinized Terrain (Red) and First Order Terrace (Blue).*

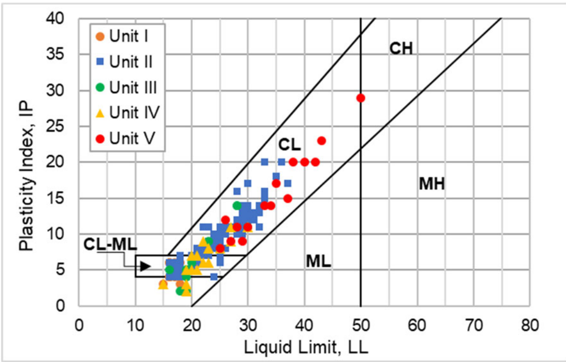

Figure 4b*: The soils exhibit a wide range of variability, predominantly plotting above the A-line, indicating silty and clayey fine-grained materials of low to medium plasticity.*

4.3 *Spatial Variability Maps of Punta Arenas*

While the estimation maps for V_{s30} and T_0 variables for Punta Arenas had been presented in previous works by the authors, Figure 7 shows a new graphical interpretation of the obtained results. It's evident that the supposedly most unfavourable zones in seismic terms correspond to the northeastern sector of the city. Here, V_{s30} velocity values are around 180 m/s, and fundamental period (T_0) values are greater than 1 second. These soil deposits are generally fine-grained, loosely compacted, and in a saturated state, and therefore could be susceptible to the phenomenon of liquefaction.

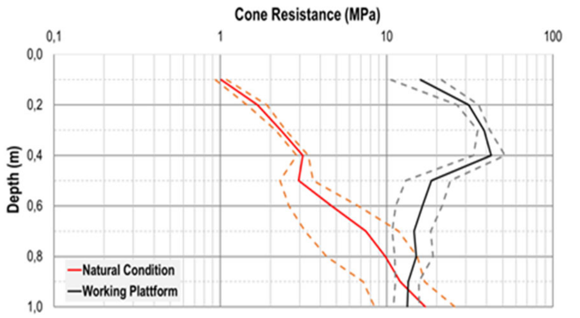

***Figure 5**: Results of iLDCP tests for the construction of oil exploration platforms in a Ribbed Moraine Terrain Unit, Tierra del Fuego, Magallanes.*

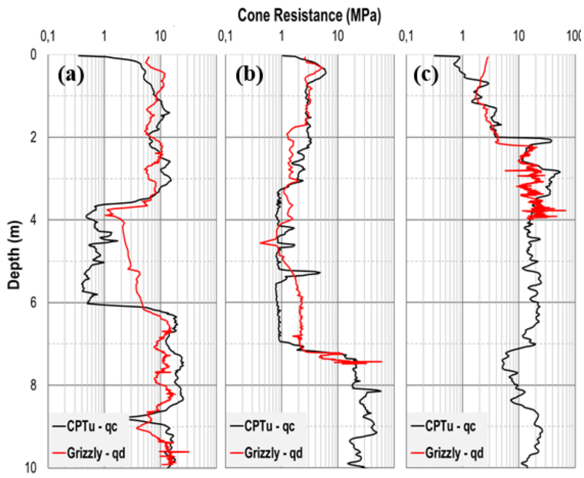

***Figure 6**: Comparison of CPTu and iDPSH results in Glaciolacustrine (a) and (b), and Ribbed Moraine Terrain (c) geomorphological units.*

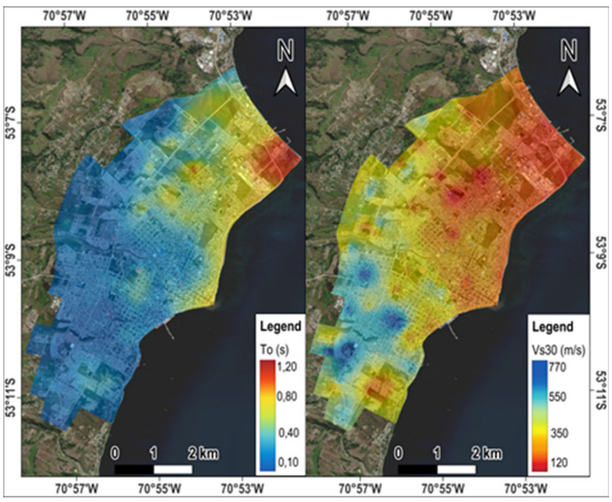

***Figure 7**: Estimated V_{s30} and T_0 Maps for the city of Punta Arenas.*

To analyze the variability of the northeastern sector of Punta Arenas, the geostatistical modeling of iLDCP & iDPSH test results was updated, increasing the test densification in the area by 52% compared to the previous study. Figure 8 shows the obtained results, indicating that a large part of the study area exhibits average cone resistance (q_d) values ranging from yellow to red tones. These zones would have a good correlation with Ishihara's liquefaction susceptibility index (LPI) (Villarroel et al, 2021). In particular, the western sector of the quadrant studied shows a wide area with extremely low cone resistance values, which are associated with the presence of thick organic deposits.

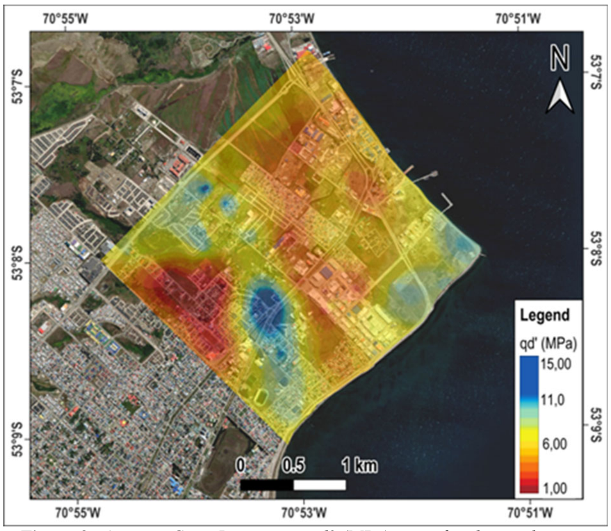

***Figure 8**: Average Cone Resistance, qd´ (MPa), map for the northeastern sector of Punta Arenas, Magallanes Region. Updated as of July 2025.*

5 DISCUSSION

- *Implications of Variability on Risk Seismic*. The joint analysis of the estimated V_{s30} and T_0 maps provides a preliminary seismic classification for specific areas of Punta Arenas. This information is a valuable tool during the initial phases of engineering development and for land-use planning. Given the presence of potentially liquefiable soils in the city's northeastern sector, it's imperative that geotechnical studies for future projects include the relevant standard tests to confirm or rule out this potential.

- *Valorization of Glacial Soils*. One of the most suitable options for soil treatments or improvements involves using the existing on-site soil as fill material. However, there are certain soil units or types where this would not be technically advisable, primarily due to their low CBR (California Bearing Ratio) capacity. At a national level, the Road Manual of the Ministry of Public Works of Chile is one of the most widely used normative bodies for civil works design, and specifically in the field of embankments, it recommends that they should not be constructed with materials having a CBR less than 10% (MC-V5, 5.205.201). According to this, and considering the historical laboratory test data from samples extracted in Patagonia, the soils that could not be used as embankment material are those classified under the USCS system as: CH; ML-MH; MH; CL; and, CL-ML. These are primarily associated with the "Glaciolacustrine" and "Ribbed Moraine Terrain" geomorphological units.

Conversely, soils belonging to the "Outwash plains" geomorphological unit exhibit a grain size distribution that is well-suited for various specifications for Base and/or Subbase materials. For example, they comply with some of the grain size specifications established in the Road Manual of the Chilean Ministry of Public Works and in the ASTM D2940 standard. According to the geomorphology maps considered in this study, this unit spans an area greater than 3,000 km^2. Therefore, the potential volume of usable aggregate materials from areas near the Strait of Magellan could exceed 3,000 million m3, even if only 1 meter of available thickness is considered.

- *Sustainability Perspective*. Despite the high potential for aggregate resources, there are areas where the availability of such material may be scarce or non-existent. This necessitates adopting new methods to reduce the carbon footprint of projects. Thus, in recent years, particularly in the Ribbed Moraine Terrain and Glaciolacuster geomorphological units, soil improvement projects have been carried out incorporating high-performance geogrids. This has allowed for an average reduction of 30% in the required fill thickness compared to an unreinforced scenario. In 2022, the first helical pile foundation solution for a storage tank was executed, which minimized the excavation depth and the need for aggregate materials.

6 CONCLUSION

The evolution of geotechnical explorations in Patagonia has strengthened the geotechnical reconnaissance of previously unexplored terrains. This has yielded essential data for the engineering development of various industrial projects in the Region. Likewise, the application of dynamic penetration tests has been crucial for the geotechnical zonation of Punta Arenas, also serving as a fundamental tool for the design and control of work platforms for heavy equipment.

The integration of geotechnical data with geomorphological mapping revealed that each unit analyzed exhibits distinct geotechnical properties, allowing for the assignment of a characteristic soil type to each. This information is highly valuable in the early stages of large industrial project planning, as it enables a preliminary assessment of the site's geotechnical suitability, spatial variability, and the potential reuse of local soils for fill or improvement purposes.

Preliminary geotechnical investigations of large land areas can provide valuable information even during a project's environmental assessment phases. This data is crucial for evaluating the potential reuse of on-site soil, or the necessity for surface improvements or deep foundations. These are critical variables for estimating a project's emissions, carbon footprint, and the various human and technical requirements for its construction.

Moreover, it's crucial to emphasize that the information cross-referencing process presented in this work is dynamic. Variations or changes may occur as the amount of data is reinforced over time with new geotechnical explorations. This applies to both the tentative geographical delimitation of geomorphological units and their geotechnical properties. Therefore, it's highly recommended to continue developing geomorphological studies in areas further away from the Strait of Magellan,

Finally, this study confirms the high heterogeneity of geotechnical units in Patagonia, influenced by its complex glacial history. Among these, certain critical areas in the city of Punta Arenas stand out, requiring special attention. Likewise, geomorphological units with tremendous strategic potential as sources of aggregate materials are identified, which are essential for the region's industrial development. The feasibility of their extraction, however, will be subject to the coexistence of various national technical and environmental regulations.

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