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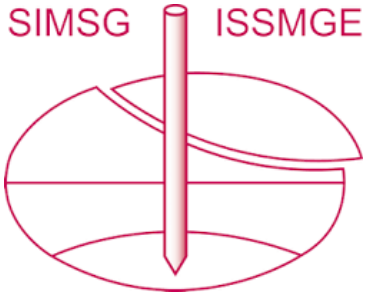


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# Geotechnical characteristics of glacial soil deposits at Punta Arenas in Chilean Patagonia

## Caractéristiques géotechniques des dépôts glaciaires du sol à Punta Arenas en Patagonie chilienne.

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ABSTRACT: In the city of Punta Arenas, Chilean Patagonia, soils of glacial origin were deposited during the Last Glacial Maximum (LGM), with soft, organic and alluvial materials dominating during interglacials and the post-glacial period. The superposition of sedimentary environments together with glacial loading and unloading events, resulted in a heterogeneous stratigraphic succession with a variety of mechanical properties. This study proposes a geotechnical classification for the different deposits, which include tills, glacio-lacustrine and overbank materials observed in the urban and sub-urban areas of the city. Undisturbed samples obtained from excavations and open pits were tested for their index properties, shear resistance and compressibility. Additional tests included X-ray diffraction. For the geotechnical classification a composite mapping technique was used which included information of a great number of existing borings. It was established that low quality soils are located in depressions molded by glacial action as well as in overbank areas, which were filled by layers of normally consolidated clays and organic materials interbedded with coarser-grained deposits.

RÉSUMÉ: Dans la ville de Punta Arenas, Patagonie chilienne, les sols d'origine glaciaire ont été déposés au cours du dernier maximum glaciaire (DMG), dont des matières meubles, organiques et d'alluvions dominent pendant les périodes interglaciaires et la période post-glaciaire. La superposition des environnements sédimentaires avec des événements de chargement et de déchargement glaciaires, ont-ils abouti à une succession stratigraphique hétérogène avec une variété de propriétés mécaniques. Cette étude propose une classification géotechnique pour les différents dépôts, qui comprennent l'amas de débris mineral de la moraine et les dépôts glacio-lacustres. Des échantillons intacts provenant de fouilles ont été testés pour leurs propriétés d'index, de la résistance au cisaillement et la compressibilité. Des tests supplémentaires ont été inclus comment ceux de diffraction des rayons X. Pour la classification géotechnique nous avons utilisé une technique de cartographie composite. Il a été établi que les sols de mauvaise qualité sont situés dans des dépressions résultant du travail du glacier ainsi que dans les zones de débordement, qui ont été remplis par des couches d'argiles normalement consolidées et des matières organiques interstratifiés avec des dépôts de grain plus grossier.

KEYWORDS: Magellan Lobe, Patagonia, glacial clay, till, consolidation, composite maps

## 1 INTRODUCTION.

The city of Punta Arenas is situated on the western shore of the Magellan Strait, (see figure 5). The pressure of rapid urban development has led to building construction on soils that are almost always saturated, and due to their low bearing resistance, high compressibility and excessive variation, present unfavorable conditions for foundation design. The origin of the soils is mainly glacial, being due to the cyclic advance and retreat of a glacial lobe during the LGM, which caused stratigraphic successions that are highly variable both laterally and vertically. Temperate conditions during interglacial events and the post-glacial period, allowed the deposition of soft clays and the proliferation of peat bogs. Sand and gravel were also deposited within the channels of a drainage system.

The local physiography is one of the most important factors in the classification or zonation of the soils. In the context of surface hydraulics, Punta Arenas is crossed in an east-west direction by six natural channels: the Los Ciervos, La Mano, and Las Minas Rivers, and the D'Agostini or Pitet, Llau-Llau, and Bitsch Creeks (see figure 5). The drainage patterns are variable; the southern area is dominated by the relict glacial morphology, with the La Mano River mostly confined to a glacial valley. In the central area, the Las Minas River is dynamic and frequently overflows its banks, with occasional mud flows being considered a risk factor. Finally, in the north, the hydraulic pattern is more disperse with little incision. This is problematic with regard to the impermeable basal sediments that increase the risk of inundation. Fine overbank sediments and peat bogs are thus situated in areas with low gradients, mostly in the northern part of the city, whereas coarser sediments are deposited by the Las Minas River in the central area.

Understanding the complexity of the geological processes that operated in the area, allows the soils to be classified according to their origin and loading history, which is a key factor in their geotechnical characterization. We propose a paleogeographic interpretation method that includes SPT (Standard Penetrometer Test) values, and differentiates and demarcates soils of low bearing capacity.

## 2 THE LGM ADVANCE AND RETREAT

In the study area at least five glacial advances (A - E) of the Magellan Lobe are recorded, which were dated using $^{14}C$ and cosmogenic isotopes (Bentley 2005, Clapperton, 1995, McCulloch, 2005a). The LGM is represented by glacial advance B and is characterized by the evolution of the Juan Mazía Peninsula (figure 5), which happened after 31,250 calibrated years before present (Cal yr BP) and culminated between 25,200 – 23,100 Cal yr BP, followed by advance C of lesser extent, dated between 22,400 and 20,300 Cal yr BP. Glacial advance D, also of smaller extent, culminated between 17,700 and 17,600 Cal yr BP, succeeded by a glacial retreat. Glacial advance E caused the damming up of a lake between 15,500 and 11,770 Cal yr BP. The retreat of this glacier coincides with the maximum cooling period referred to as the Younger Dryas in

the Northern Hemisphere, which was the last record of Pleistocene glacial advance (Bentley 2005, McCulloch, 2005a). The glacial processes deposited different sediments in the form of terminal, basal and lateral moraines, whereas glacial meltwater during the interglacial periods generated outwash plains. During warmer intervals peat bogs proliferated.

There is evidence that a large pro-glacial lake formed in the present Magellan Strait. Dating of a volcanic ash layer from the Reclus Volcano indicates that this happened before 12,640 ± 60 $^{14}$C yr BP (McCulloch *et al*. 2005b). The low level of the Atlantic Ocean and the glacial barriers between the fjords, which did not allow the influx of waters from the Pacific Ocean, favored the deposition of varved clay and glacio-lacustrine clays in a freshwater environment, thus preventing the development of quick clays.

## 3 SOIL CHARACTERISTICS

### *3.1 General*

The term "mazacote" is locally used to refer to a group of soft, bluish grey soils, considered in engineering as having poor geotechnical properties. Nevertheless, recognizing the complexity of depositional environments, events and structures that were superimposed during different geological periods, it is of prime importance to differentiate between push, basal and flood tills, outwash plains, lacustrine varved clays, organic clays, peat, and fine as well as coarse fluvial sediments with different compaction properties.

Till or moraine, a product of glacial erosion and plucking, is one of the most heterogeneous sediments because of its poor sorting. Its composition and structure depend on the manner in which it has been transported and the diagenetic history, so that it may vary from a dense till with a non-plastic matrix to a clay-rich till with a low consistency. Its sedimentary provenance is difficult to determine due to the fact that the material was transported from different, proximal or distal source areas, and subsequently suffered reworking. Geotechnically, it is important to differentiate between strongly pre-consolidated basal tills and melt-out till that is generally similar to normally consolidated clays.

The large pro-glacial lake and the presence of co-existing smaller lakes along the shores of the Magellan Strait provided the conditions for the deposition of lacustrine sediments, among which one of the most important types is varved clays.

The fine sediments associated with fluvial overbank areas with lower flow-regime currents, were deposited during modern inundation events, and geotechnically behave like normally consolidated clays (Vásquez 2012). These materials may show specific properties such as interbedded clay and silt, sedimentary structures including troughs and ripples (see figure 1), a high organic content (transported by water or formed *in situ* by local vegetation), laminas of coarse or fine sand with gravel lenses, the presence of sporadic gravel clasts with a maximum size of 1 cm, mica, carbon spheres, and strong oxidation.

Figure 1. Overbank fluvial sediments.

The glacial landscape, formed by rolling hills with abundant depressions, intermoraine channels and kettles, together with the Quaternary climatic changes, provided the necessary conditions for the evolution of peat bogs. Due to the fact that the area around the Strait was subjected to various glacial retreats, it is common to find significantly thick, vertically repeated peat bog deposits (see figure 4).

### *3.2 Structures*

The soils derived from glacial environments show structures such as cracks, fractures, and complex deformation that depend on the material, the flow regime, the types of forces to which they had been subjected, as well as the water content. Sandy sediments deposited by slow currents may show undulating, continuous laminas, whereas soft sediments such as silty clay, if they have a high humidity content, develop structures like load casts, soft-sediment and recumbent folds, chaotic bedding, fluid escape structures, and polygonal mud cracks, *inter alia*. During field work it was common to observe slickensides, smooth oxidized surfaces caused by foliation slip in the tills, which indicate the intermittent laminar flow of fluids along discontinuities. At a macro-scale, the collapse of sub-vertical blocks in excavations could also be observed (see figure 2A). This can be explained by the vertical loading caused by the overlying glaciers and the subsequent lateral pressure-release within the excavations.

Another specific characteristic of the study area is the significant sub-glacial deformation of the sediments due to the shear force exerted by the overriding glaciers (see figure 2B). In road cuts, moraines show complex folds, faults and foliations with orientations indicating the direction of glacial advance.

Figure 2. Structures in glacial sediments, Punta Arenas. A) Collapse of sub-vertical blocks in excavations. B) Foliations in sub-glacial till.

### *3.3 Geotechnical characterization*

Undisturbed soil samples were collected within the urban and sub-urban perimeter of the city, which were tested in the Laboratory of Solids and Particulate Matter of the Faculty of Physical and Mathematical Sciences of the University of Chile. Descriptions of the samples indicate specific components and structures such as the presence of carbon particles, plant roots, sedimentary structures such as ripples, micro-lamination, varved clay, laminas of coarse and fine sand with gravel lenses, the presence of gravel (which complicated the cutting of test cores), mica, and rapid oxidation in contact with the atmosphere.

The variety shown by the soils in terms of plasticity, (see figure 3) is surprising, which demonstrates that the glaciation left its mark in the extreme differentiation of the deposits. This

ample spectrum reflects the percent of clay size materials, as well as the number and types of clay minerals, which vary according to the depositional environment, humidity, depth and amount of weathering.

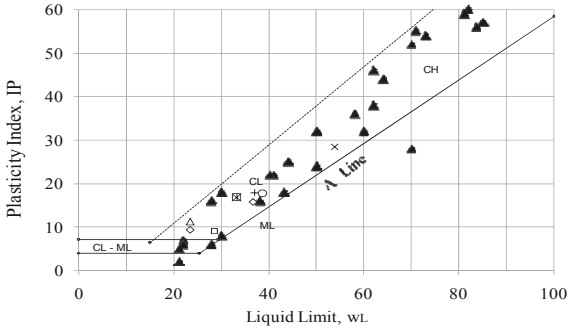


Figure 3. Casagrande Chart. Wide range shown by the types of soils, above line A.

Considering the above, granolumetric tests were carried out with laser beam technology in the Sedimentology Laboratory of the University of Chile with a Mastersizer 2000, determining that the clay fraction, with a size less than 0.002 mm, does not exceed 15%. Because it is the clay fraction that largely controls the soil behavior, X-ray diffraction analysis was also carried out with a crystal powder diffractometer SIEMENS D5000, in the Crystallography Laboratory of the Department of Physics of the University of Chile. Of two samples analyzed, two types of clay minerals were identified: vermiculite and montmorillonite. Vermiculite is an alteration product of biotite (mica), whereas montmorillonite belongs to the smectite group, typically formed by the alteration of volcanic ash. Both minerals have a large cation exchange capacity and are expanding clays. The soils showed clay activities between medium and high (Vásquez 2012).

Using edometric tests and classifying the samples with reference to their sedimentary environment, one can determine that the soils that had not suffered geological loading, have larger initial void ratios ($e_0$) and compression indexes ($Cc$), whereas soils with a marked glacial deformation and a history of loading have lower $e_0$ and $Cc$ values (see table 1), which directly influence their compressibility.

Table 1. Results of edometric tests, with soil samples classified by their origin (Vásquez 2012).

| ID sample | Sedimentary environment | *Cc* | *Cr* | $e_0$ |
|---|---|---|---|---|
| $M5LS_{40}$ | Lacustrine | 0.30 | 0.05 | 0.77 |
| $M5LS_{20}$ | Sub-aqueous, high energy | 0.42 | 0.065 | 1.35 |
| Planta Lana | Fluvial inundation | 0.31 | 0.03 | 1.06 |
| Chiloé-Briceño | Basal till | 0.13 | 0.019 | 0.56 |
| Cereco | Push till | 0.12 | 0.04 | 0.63 |

Additionally, consolidated isotropically undrained triaxial compression tests (*CIU)* were carried out on cylindrical test cores of 5 cm by 10 cm. These were subjected to strain-controlled deformation with a load velocity of 0.13 %/min. Friction angles of 22º, 26º, 30º and 35° were recorded, with cohesions varying between 0 and 0.26 kg/cm$^2$. For stratified soils and/or those with clear sedimentary structures (troughs, ripples), the volume of coarse fraction is that which most influences the high shear strength, whereas the fine fraction depends on the type and volume of clay present, reducing the undrained strength. It is evident that the percentage of sand and/or silt in the mixture (i.e., varved clay, overbank soils) has a strong influence on the shear strength, which is why it would be common to find different results in series of triaxial tests.

An important aspect to consider in the field is the horizontal and vertical heterogeneity of the sediments. Figure 4 shows the wide variation that occurs over a distance of less than 50 m in boreholes 1 and 2. As regards the occurrence of peat at a depth of about 12 m, it is linked to more temperate geological periods, in a sub-basin where fine, soft sediments were deposited together with intercalated horizons of coarse sediments (gravel, sand).

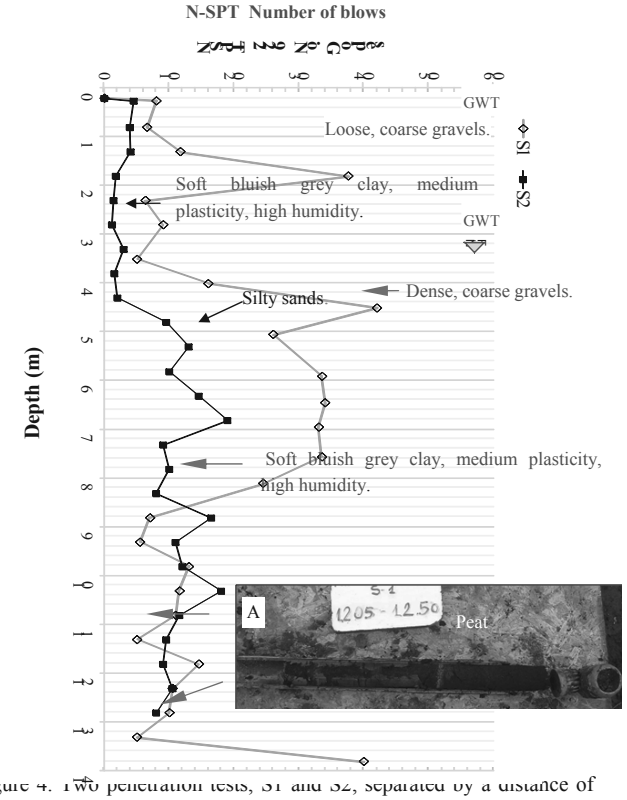


Figure 4. Two penetration tests, S1 and S2, separated by a distance of less than 50 m. A) Spilt-spoon sampler with peat, depth 12.0 m. (GWT) groundwater table.

## 4 TENTATIVE ZONIFICATION TROUGH COMPOSITE MAP

A composite map is the result of combining various maps of different types (e.g., topographic, sedimentological, paleontological) into a single map using a single set of contour lines. These maps accentuate parameters common in most or all of the contributing maps, and at the same time eliminate anomalies present in only one or a few of the latter. They can also show details which may not be visible in any of the contributing maps. The technique has been used in paleogeographic reconstructions and mineral exploration (Le Roux 1997). As applied here to a geotechnical problem, the soil strength characteristics were combined with SPT (Szigethi 1995-2010) and stratigraphic/sedimentological data, using 57 data stations distributed throughout the urban perimeter and the information of 110 geotechnical borehole data. The information was unified to a depth of 4 m.

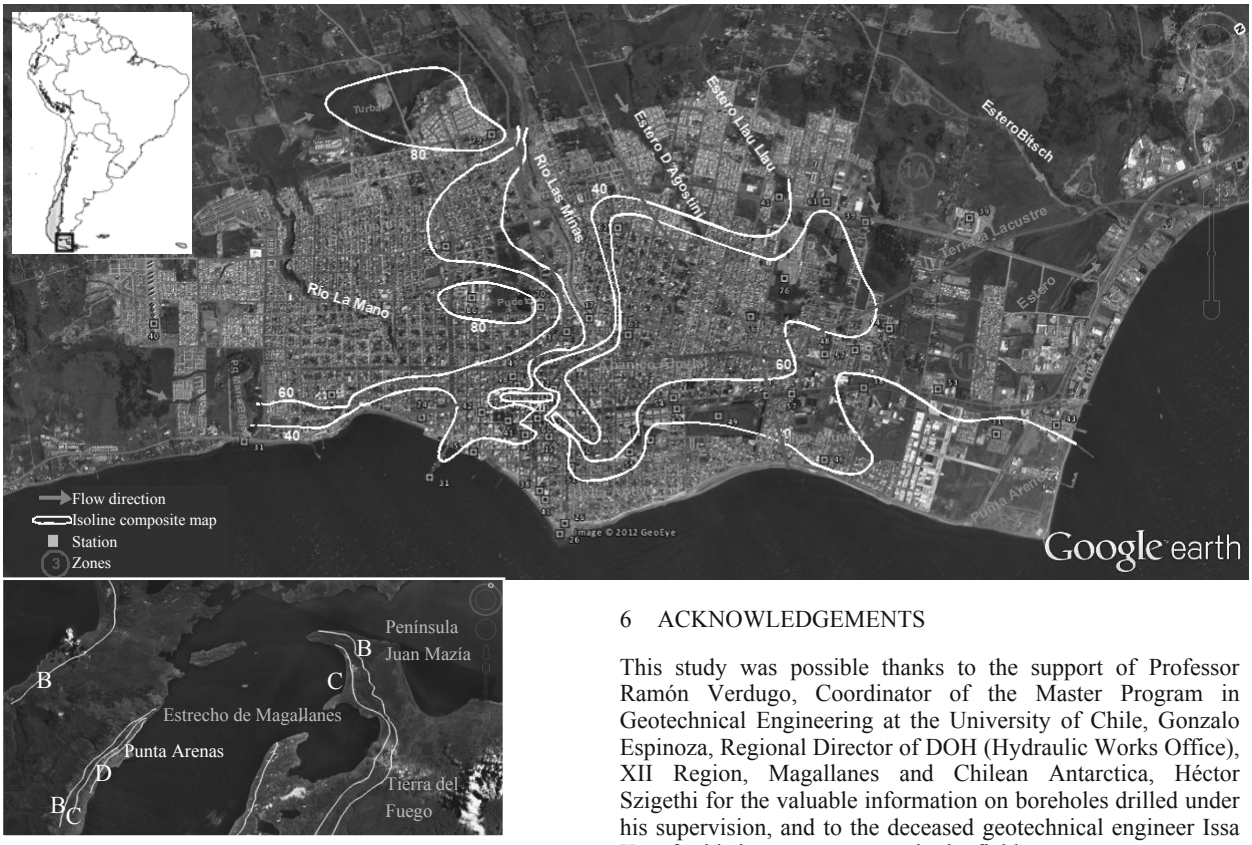


Figure 5. Location map of the study area. Composite map of Punta Arenas. Google Earth view of the city and Magellan Strait with stages of deglaciation labelled B-D, where B is the oldest and D the youngest moraine (after Bentley *et al*. 2005).

Using a spreadsheet and normalizing the data of topographic elevation, type of sediment (employing a scale of 1 to 7 for the coarsest to finest sediments, respectively) and the mean number of blows (N-SPT) for every station, the resultant composite value varies between 1 y 100 for the 57 stations. Finally, the composite values were contoured and interpreted (see figure 5).

The composite map technique highlights the sub-basins scoured by glacial action, in which soils of low bearing capacity (soft clays and peat) coincide with isolines having values higher than 60 and clearly demarcated by isolines having values above 80 (see figure 5). Additionally, the phreatic water levels in these areas are close to the surface, which is one of the most unfavorable conditions for foundation design.

## 4 CONCLUSIONS

Soils in the city of Punta Arenas show an extraordinary variation in their index and engineering properties, which makes them difficult to assess for sound geotechnical designs.

The combined, non-dimensional parameters of the composite map reveal the complex geological processes these areas have experienced. A study of the geological events during the Last Glacial Maximum allows the characteristics of the soils to be explained in terms of composition as well as in their effect on existing structures.

The composite map allows the definition of a tentative zonation which shows areas with more compressible soils and low shear strength associated with depressions containing lacustrine sediments such as clay and peat.

## 6 ACKNOWLEDGEMENTS

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