RevMexAA (Serie de Conferencias), **19**, 109–117 (2003)

GEOTECHNICAL STUDY OF THE OAN/SPM

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RESUMEN

El estudio de caracterización geotécnica de San Pedro Mártir (SPM), Baja California, fué realizado en 2000 por la Gerencia de Estudios de Ingeniería Civil de la Comisión Federal de Electricidad (GEIC/CFE). El propósito principal de los estudios geológicos y geotécnicos es la caracterización del terreno en uno de los posibles sitios de construcción de un nuevo telescopio, lo cual además dará idea de las características de otros puntos en la zona del Observatorio Astronómico Nacional en San Pedro Mártir (OAN/SPM). El reporte completo del estudio geotécnico de SPM de la GEIC/CFE incluye resultados de los estudios topográficos, geológicos y geofísicos llevados a cabo en el sitio y en laboratorio. Aquí se presenta una revisión del estudio geotécnico y de los principales resultados. Se muestra que el subsuelo puede ser clasificado en tres horizontes o capas principales (A, B y C). El horizonte-A está constituido por roca descomprimida hasta profundidades de 1.3 a 3.0 m, la cual sería necesario remover para la cimentación. La capa B consiste de roca fracturada con un RQD ("rock quality designation") entre 65% y 80%, con un espesor de 10 a 12 m, y una alta capacidad de carga. Esto implica que la profundidad requerida de excavación para las zapatas de la cimentación es de 2 a 3 m, donde se alcanza un módulo de elasticidad adecuado. El horizonte C de 13 a 22 m consiste de roca (equisto gris) de caracter masivo con intrusivos graníticos, considerablemente menos fracturada, con un RQD superior a 90%. Para las tierras eleéctricas la capa B es adecuada por su baja resistividad.

ABSTRACT

The geotechnical characterization of the San Pedro Mártir (SPM), Baja California site was carried out in 2000 by the Gerencia de Estudios de Ingeniería Civil of the Comisión Federal de Electricidad (GEIC/CFE). The principal aim of the series of geological and geotechnical studies was to characterize the subsoil performance at one of the possible construction sites of a new telescope, which may also provide an idea of the characteristics of other locations at the Observatorio Astronómico Nacional in San Pedro Mártir (OAN/SPM) Sierra summit. The full report of the GEIC/CFE geotechnical study of the SPM site includes results from the topographic, geological and geophysical surveys carried out. In the present paper a review of the geotechnical study is presented and some of the important results are summarized. The study shows that the subsoil can be classified in three principal horizons or layers (A, B and C). The A-horizon consists of decompressed rock of depth 1.3 to 3.0 m, which has to be removed for the foundations. Layer B consists of fractured rock with an RQD (rock quality designation) between 65%-80%, a thickness of 10-12 m, and a high load bearing capacity. This implies that the required depth excavations for the foundation footings ranges from 2 to 3 m, where an adequate dynamic modulus of elasticity can be reached. Horizon C from 13 to 22 m, the maximum depth explored, consists of rock (gray schist) of massive nature with some granite intrusions that appears slightly fractured, with an RQD above 90%. For the electric grounding instalation the best place is layer B due to its lower resistivity.

Key Words: **GEOTECHNICAL — SITE TESTING**

1. INTRODUCTION

The Instituto de Astronomía of the Universidad Nacional Autónoma de México (IA-UNAM) is considering the construction of a new telescope, which is planned to be installed at the Observatorio Astronómico Nacional facilities located at San Pedro Mártir (OAN-SPM), in Baja California. With this purpose in mind, the Gerencia de Estudios de Ingeniería Civil of the Comisión Federal de Electricidad (GEIC/CFE) was asked to carry out a series of geological and geotechnical studies with the principal aim of characterizing the subsoil performance at the possible construction site. A full report of the GEIC/CFE geotechnical study of the SPM site carried out in 2000 was presented by Grijalva et al. (2001), including results of the topographic, geological and geophysical surveys.

For geotechnical and ground characterization purposes the GEIC/CFE team covered the following aspects:

- Topographic survey at scale 1:500 covering an area of 250 m $\times$ 200 m, and the location of three reference points with a GPS.
- Detailed geological survey covering an area of 5 hectares, to show lithological units, structures and geological discontinuities.
- Geotechnical exploration of the foundation area at three selected locations, by means of borings with no recovery of rock cores, reaching a maximum depth of 22 m. A video recording of the boreholes was done with the purpose of observing the condition of the rock mass with depth.
- Cross hole and down hole geophysical studies inside the boreholes, seismic refraction surveys, and vertical borings to determine the ground resistivity.
- Sampling of rock blocks representative of the *in-situ* material, to perform index and mechanical tests in the laboratory.
- Geotechnical characterization of the site and foundation recommendations.

2. DESCRIPTION OF THE SITE

2.1. *Location*

The OAN site is located in the San Pedro Mártir National Park, which belongs to the municipality of Ensenada close to the boundary with the municipality of Mexicali, in Baja California. The site coordinates are latitude N $31^\circ\,02'\,43''$and longitude W $115^\circ\,27'\,55''$. The elevation is 2800 m above mean sea level. The site is located approximately at the central portion of the State of Baja California between the towns of Colonet and San Felipe by the Pacific Ocean and the Gulf of California, respectively. The physical features found reveal an extraordinary natural site.

2.2. *Topographic Characteristics*

The topographic characteristics are presented in Fig. 1. The highest isoline in the map of the region constitutes the peninsular divide that separates the peninsula into two slopes facing East and West, respectively (Gulf of California and Pacific Ocean), and classified by the National Water Commission as hydrological regions RH4 and RH1.

Three types of relief features can be observed: a smooth relief is found toward the Southwest (Vallecitos zone), to the center and along a NW-SE direction there exists an area with moderate to sharp relief that constitutes the largest proportion of the area and where the site under study is located; and to the NE of the area there is a zone with very sharp and abrupt relief that is practically inaccessible and contrasts with the rest of the area (see Fig. 1).

The fact of being located at the divide zone where the climate is influenced by the Pacific and the Gulf of California and the Altar Desert (shared by México and Arizona, USA), favours a special climate in this zone. It is classified as type C(E)s temperate and sub-humid with rains during winter. The average annual temperature and rainfall are 6°C and 500 mm, respectively.

The site selected for the geotechnical study is located no more than 300 m apart from the divide, where the drainage features are oriented toward the East and West.

The moderate relief at the site discloses elevations and gorges caused by the differential erosion suffered by the ground, which is favoured by fracturing induced by the effective action of the major erosive agents such as water, ice, thermal variations and wind. This relief is moderate since any of its points is accessible.

The UTM coordinates of the site under study are X=646150 and Y=3435450. It is located near the Differential Image Monitor tower and located West of the current telescopes in operation. Maps of the exact location are presented in Grijalva et al. (2001).

3. GEOLOGY

The area under study falls within the physiographic province known as Península de Baja California, subprovince of Sierras de Baja California Norte, that constitutes approximately 80% of the State surface.

3.1. *The field work*

The field work included the following activities:

- Geology: Even though the work required implied detailed geology of the selected site (5 ha)

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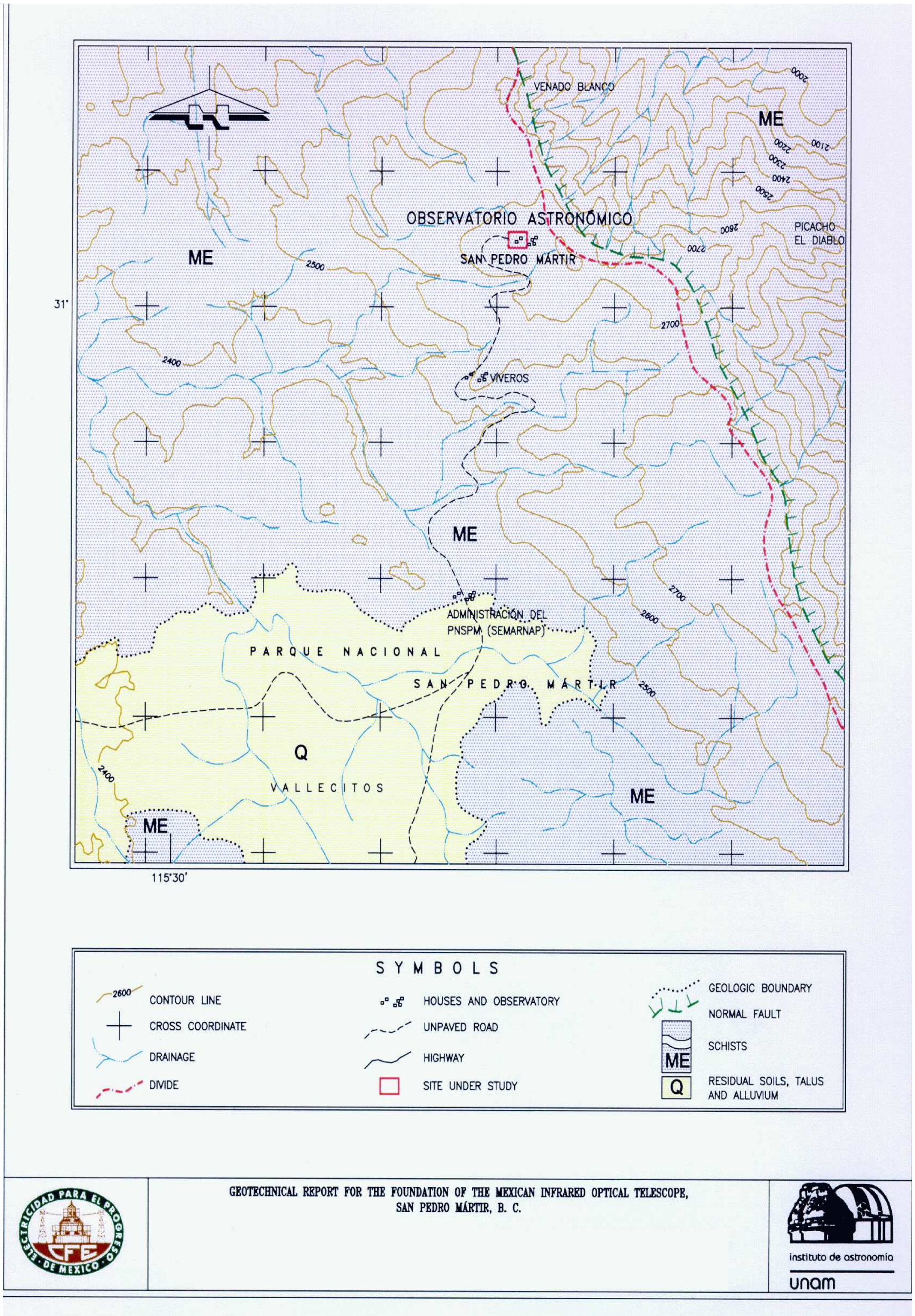

Fig. 1. Topographic and geological environment of the area, and location of the area and site under study.

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only, a survey was also made at an adjacent area with the purpose of becoming familiar with the geologic surroundings and to try to detect a structural tectonic feature with implications for the project site, as well as to determine the pattern of faults or discontinuities in the strata at the surrounding area and test site.

- A survey of 104 fractures was made, as well as 13 geologic descriptions of outcrops and/or structures. Four samples of rocks were collected for petrographic analysis.

- Drilling: Three borings with an average depth of 22 m were drilled with pneumatic equipment, that represent a cumulative depth of drilling of 66.30 m.

- Well conditioning: The three wells were conditioned with PVC pipe and closed, after the corresponding videos were shot and the geophysical records were taken, with the purpose of performing inside them the Cross-Hole and Down-Hole tests described in §4.

3.2. *Surface Geology*

The site of the detailed geological study (see Fig. 1) covers an area of 5 ha (200 m × 250 m). It shows a promontory toward its central part constituted of metamorphic rocks (schist) oriented mostly along the E-W direction, with elevations varying from 2790 to 2802 m.

Only two different types of rock outcrop at the area, with ages corresponding to the undifferentiated Mesozoic. According to their decreasing abundance the rocks can be classified as: schist of biotite, muscovite and quartz; and porphyritic granite of muscovite, biotite, and quartz. The schist is found at the base of the lithologic column found at the site; it was encroached by a dike stratum and its branches, which constitute the muscovite-type porphyritic granite. However, pegmatites of quartz and feldspar can be observed at an area adjacent to the test site and they are likely to correspond to the same intrusion.

In this area, as well as at the site under study, two different types of rocks were observed, together with a thick dike of quartz and feldspar pegmatite, that because of its extension (± 25 m) could not be chartered at the scale used in Fig. 1. The dike outcrops at an area adjacent to the 1.5 m telescope and crosses toward the north side of the access road to the 2.12-m telescope, beside the so called "blue cottage".

Rocks outcropping at the site correspond to biotite, muscovite and quartz schist, which were encroached by a dike stratum of porphyritic granite. Residual slopes and soils can be observed as partial coverage of these rocks.

The biotite and muscovite schist is the most abundant and covers more than 90% of the surface; it can be generally found as a weathered and decompressed formation down to an average depth of 3 m. A fact that has favoured the development of an abundant vegetation of the conifer and xerophilous underbrush types. This vegetation is also found in areas where residual soils and/or slopes concentrate.

3.3. *Drilling*

Three exploratory borings of 6 inch diameter and depth of 22 m were drilled. They are labeled from south to north as X1, X2 and X3, at established locations. Upon completion of borings X1 and X3 they were flushed with air and a video camera was inserted in order to record the characteristics of the rock mass throughout their length. The recording was repeated in some intervals where the lens became blurred, as a consequence of internal and external temperature differences and also due to the moisture produced by water seepage of thawing at the surface that flowed inside the well. During the filming of well X3, approximately 2 m of water accumulated in the bottom. The detailed description of wells X1 and X3 is provided in the GEIC/CFE report by Grijalva et al. (2001).

Subsequently, the scheduled geophysical surveys were executed inside the three borings. After their completion the threaded 4-inch diameter PVC pipe casing was inserted with a plug at the bottom. After the casing was installed the annular space between the walls of the boring and the casing was grouted according to the specifications and the approved procedure.

3.4. *Structural analysis*

From the analysis of 104 fractures surveyed in the field, three families were found: F1 = N27°W/79°SW (frequency of 58/104), F2 = N87°E/86°NW (frequency of 39/104), and F3 = N6°W/19°NE. These fractures are found generally open at the decompressed zone due to the differential erosion that originally denuded their filling; in addition, most of the blocks have already been displaced. The fractures that could be followed and/or observed under the decompressed zone evidence smooth edges generally with openings smaller than 0.5 cm and lengths that do not exceed 2 m. Only a few of them are wider than 1.5 cm and very seldom the fractures have openings wider than 5 cm, since only five of them were observed having undulated edges completely sealed with small veins of silica and porphyritic granite; these fractures did not exceed 12 cm in width and the longest fracture measure was of about 3 m. The combination of these three families of discontinuities results in the formation of tetrahedral blocks peculiar to this zone, where the planes of the fractures of family F3 mark the limits of the floor and roof of the resulting blocks.

4. GEOPHYSICS

The geophysical studies for this project had the following objectives:

1. To determine the longitudinal (p) and transversal (s) wave velocities of the subsoil materials, and to calculate their dynamic (elastic) properties, from ground surface to a maximum depth of 22 m, at intervals of 1 m each, through the use of techniques of seismic velocity between wells (cross-hole setup) and of seismic velocity in a single well (down-hole setup). The dynamic parameters to be calculated are: Poisson's ratio, shear modulus, and Young's modulus.

2. To determine the electric resistivity of the ground down to a depth of 30 m, for the design of a grounding system for the protection of the building and of the related facilities.

3. To determine the model of seismic velocities at the area of interest, to support the development of the corresponding geologic-geotechnical model to a maximum depth of 20 meters.

4.1. *Geophysical methods used*

4.1.1. *Seismic velocity between wells (cross-hole)*

This technique uses a cross-hole setup to measure travel times of longitudinal (P) and transversal (S) seismic waves, that follow practically straight paths (through the layer itself) between two adjacent wells. The elastic energy is generated by a seismic power source (the transmitter) placed inside one of the wells, that sends a signal to a three-directional geophone (the receiver) placed inside the other well. In the cross-hole setup the travel time and distance between wells, makes it possible to determine the seismic velocity of the P and S waves along a direction practically parallel to the geologic layers at the site. From this information it is then possible to calculate the dynamic (elastic) *in situ* properties of the subsoil materials.

4.1.2. *Seismic velocity at a single well (down-hole)*

This method makes use of the down-hole setup, according to which the seismic source (transmitter) is located at the surface, very close to the well opening, whereas the detector is displaced inside the well at selected depth intervals.

Observed travel times are corrected in order to refer them to vertical distances and to plot a time vs. distance graph (dromochrone), where the distances correspond to the detector depths. It is therefore possible for the waves to cross all of the existing layers between the source and the seismic detector, as well as, if applicable, to define reversals of velocity along the well.

4.1.3. *Seismic refraction survey*

This method is based on the paths of minimal propagation time of elastic waves generated by a disturbing source placed at a superficial or very shallow place known as triggering point (transmitter), until reaching one or more boundaries and returning to the geophones (receivers), placed at ground surface. This technique implies that the underlying strata have increasingly higher seismic velocities. The aligned setup of shots is known as seismic refraction survey (TRS). The minimum times of the longitudinal wave (P) are plotted in terms of the position of the geophones in the line survey, for the purpose of constructing the time distance diagrams (domochrones), and to determine the two-dimensional (2D) model from their analysis and reversal. The seismic cross-section, defined by the propagation velocities of the layers and by the depths of the contacts between them, is interpreted in terms of the general conditions (lithology, relative density, fracturing and/or alteration) of the materials found at the site.

4.1.4. *Vertical Electric Borings*

This activity is based on the study of the electric potential induced artificially in the ground by means of a pair of power electrodes (A and B) mounted at the ground surface. The potential difference produced is registered between electrodes M and N. For this type of setup, electrodes A-B and M-N are aligned; electrodes A y B are exchanged symmetrically with a logarithmic sequence of distances, but M and N remain with a constant spacing until the reading of the potential difference becomes very small, at which point the spacing between M and N is increased to enhance the resolution, maintaining only the condition AB $>$ 5 MN inherent to this device.

4.2. *Geophysical Interpretation*

The reported values evidence that the superficial layer of weathered material is found to a depth of 1 m for the area where the cross-hole setup was located. The material quality improves as the depth increases. Zones with low velocity correspond to highly fractured rocks, while for high velocity the rock shows little fracturing.

Differences can be found between the results of the X1 and X3 cross-hole study and the down-hole results. The differences are due to the anisotropy of the rock mass (vertical velocity is generally smaller than the horizontal one if the materials appear like rather horizontal layers or deposits). However, in general there is a good correlation in the depth and thickness of the most important changes of velocity recorded.

From the cross sections of seismic refraction it is seen that the topmost layer, with a longitudinal velocity ranging from 600 to 950 m s^{-1}, has a thickness varying between 3.0 and 5.0 m. These values are significantly higher than those found from the seismic studies on the borings. The differences are due mostly to an overestimate of 1 to 2 m in the thickness of the top layer along the sections of seismic refraction due to an effect of the setup used in this technique: in the TRS the distances between the sources and the geophones closest to them were not sufficiently small to achieve a good "sampling" of the superficial seismic unit. The other factor is of local nature, and it can be due to the removal of approximately 1 m of weathered material or soil that was found prior to the execution of the borings.

From the results of the interpretation of the vertical electric borings it can be inferred that the subsoil underlying the area is constituted mostly by three geoelectric units, known as U1, U2 and U3. A brief description is given below.

Unit U1 is constituted by cover material, mostly of soils or weathered and fractured rock that can be found at all stations. It has resistivity values ranging from 2000 to 3600 ohm-m and thickness that varies from 5 to 15 m.

Unit U2 underlies unit U1 and has a resistivity ranging from 280 to 420 ohm-m, and a thickness from 12 to 20 m. It has been considered that this unit represents the zone with the least resistivity within the area under study. The lowest value has been reported closest to the surface but it can also be found at a depth of 5.0 m. It is therefore considered that this is the best zone for the installation of the electrical grounding systems.

Unit U3 underlies U2 and represents the geoelectric substratum for the study reported herein.

5. GEOTECHNICAL INSPECTION

The geotechnical field inspection consisted in a trip to visit the vicinity of the possible construction site of the new telescope building, with the purpose of observing the configuration of the existing rock formations and to gather information related to the structural characteristics of the rock mass that will govern the design of the foundation. In addition, a basic inspection was made of the buildings of the other telescopes in operation, to observe the existing condition and the types of foundation that were built to support them.

After the site was surveyed, five fragments of rock were collected, each with an approximate diameter of 30 cm, as representative samples of the in situ rock mass. The purpose of the laboratory tests which involved trimming specimens in order to determine the index and mechanical properties of the undisturbed rock. The rock samples selected were identified and protected for their shipping to the Laboratorio Central de Mecánica de Rocas of the GEIC/CFE in Mexico City.

6. SEISMICITY

According to the seismic zoning of the Mexican Republic, described at the Manual de Obras Civiles of CFE, the area under study belongs to seismic zone "C". This is characterized by type-I soils (firm ground, with wave propagation velocities in excess of 700 m s^{-1} or moduli of stiffness higher that 85000 t m^{-2}), a seismic coefficient (c), and a ground acceleration (ao) of 0.36 g, after assuming structures of the B-group (structures where an intermediate degree of safety is required). For the case of Type-A structures, as it could be the case of the main supporting body of the telescope, the coefficients referred to before would be 1.5 times higher.

It is important to point out that for the structural design of the telescope it would be possible to use the design aids included in the Manual de Obras Civiles of CFE, to apply the Building Code for the State of Baja California, or to resort to the guidelines established by the Building Code for the State of California, USA.

However, in order to better define the design spectrum at the site a seismic risk assessment could be carried out. Mention should be made that a report on the seismic activity at San Pedro Mártir is currently available; it was prepared by the CICESE in January 2000 and it could become part of such a study.

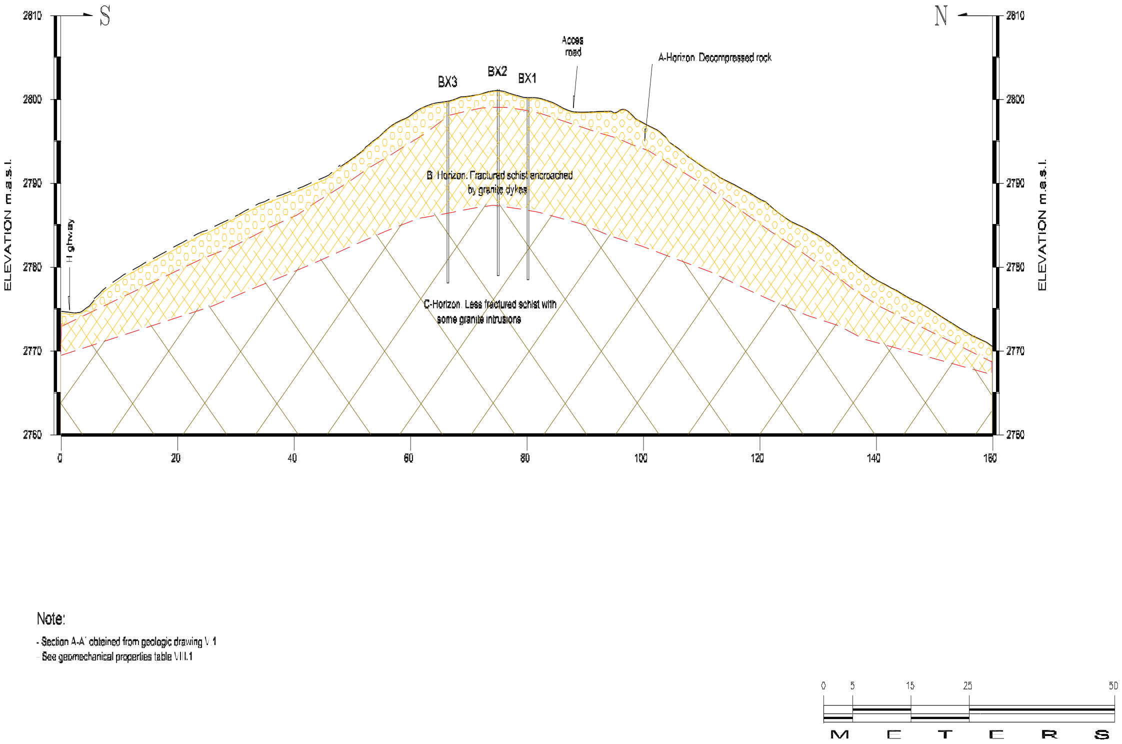

Fig. 2. Stratigraphic profile of the subsoil.

TABLE 1

GEOTECHNICAL CHARACTERIZATION OF THE SUBSOIL

Horizon	Depth (m)[a] From	Depth (m)[a] To	Thickness (m)	RQD[b] Inferred (%)	GSI[c]	E_m[d] (MPa)	Dynamic parameters (Average)[e] V_P[f] ($m\ s^{-1}$)	V_S[g] ($m\ s^{-1}$)	E_d[h] (MPa)	G_d[i] (MPa)	ν[j]
A[k]	0.00	1.30-3.00	1.30-3.00	<2.5	<40	2300	1398	594	2313	832	0.39
B[l]	1.30-3.00	13.00	10.00-11.70	65-80	83	7300	2567	1230	10945	4104	0.34
C[m]	13.00	22.00	>9.00	>90	92	22600	4045	2192	32620	12624	0.29

[a]The depth zero (0.00) is referred to the ground surface (∼2806 masl).
[b]Rock Quality Designation
[c]Geological Strength Index
[d]Modulus of deformability (static)
[e]The dynamic parameters are taken from the crosshole study results.
[f]Primary or compressional velocity
[g]Secondary or shear velocity
[h]Dynamic elasticity modulus
[i]Dynamic shear modulus
[j]Dynamic Poisson's ratio
[k]Decompressed rock
[l]Fractured schist encroached by granite dikes
[m]Less fractured schist with some granite dikes

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7. GEOTECHNICAL CHARACTERIZATION OF THE SUBSOIL

After integrating the field and laboratory results and the geotechnical analysis carried out, the subsoil can be classified in terms of its geomechanical properties in three principal horizons simplified as follows:

- A-horizon (decompressed rock)

  From the ground surface to depths ranging from 1.3 to 3 m, there exists a decompressed rock constituted by schist blocks with nominal diameters varying mostly between 0.3 and 1 m, and occasionally equal to 1.5 m. These materials constitute the cover layer of the site and the thickest layers can be found outside the area where the borings were drilled. The values of the dynamic modulus of elasticity and rigidity, obtained from the cross-hole study, are 2313 MPa for the former, and 832 MPa for the latter. The average value of Poisson's ratio is 0.39. The results of the down-hole survey indicate values from 1000 to 1081 MPa for the modulus of elasticity, and from 352 to 388 MPa for the modulus of rigidity. The static modulus of deformability, E_m, is 2300 MPa. This horizon has been classified as a poor rock stratum with value of the GSI < 40.

- B-horizon (fractured rock)

  Between 1.3-3 m and 13 m in depth. The subsoil is constituted by gray schist, encroached by granite dikes; it evidences a moderate fracturing which is found generally closed and sealed with silica. Values of RQD from 65 to 80% are assigned to this layer. The dynamic modulus of elasticity and rigidity, vary from 6283 and 19076 MPa for the former, and from 2324 to 7273 MPa for the latter. The static modulus of deformability (E_m) is 7300 MPa and Poisson's ratio is 0.34. According to the geomechanical classification, this horizon has been assigned a GSI value of 73, equivalent to rock masses of regular to good quality.

- C-horizon (slightly fractured rock)

  From 13 m to the maximum explored depth (22 m), the rocks continue to gray schist, of massive nature with some granite intrusions; however, it appears less fractured than the rock above. The fractures observed were also closed and sealed. Because of the physical characteristics observed in the video tape and of the field and laboratory velocity ratio of compressive waves, an RQD higher than 90% can be assigned. The values of the dynamic modulus of elasticity and rigidity, ranged from 17865 and 42748 MPa for the former, and from 7013 to 16664 MPa for the latter. Poisson's ratio for these materials is 0.29. The results of the down-hole survey reported also values varying between the ranges mentioned before. The static modulus of deformability of the rock mass is 22600 MPa, a value similar to the average of the stratum. A GSI>90 has been assigned to this layer, which is typical of rock masses with good to excellent quality.

Table 1 gives a summary of the previous information, including the average values of the geotechnical parameters for each horizon, whereas Fig. 2 depicts a stratigraphical profile of the subsoil, where the position of the horizons and boreholes referred to above can be observed.

8. RECOMMENDATIONS FOR DESIGN AND CONSTRUCTION

The new telescope requires a stiff structure and adequate foundation to strongly restrain the differential settlements, particularly those induced by the accidental wind and seismic loads determined from the structural analysis.

Due to the characteristics of the subsoil, it has been considered convenient to support the main structure of the telescope by means of a shallow foundation with reinforced concrete strip footings, resting directly in the in-situ rock mass at a depth at which the ground provides the mechanical properties suitable for the appropriate structure-rock interaction. Along this line, the building adjacent to that of the telescope shall be founded upon concrete footings, but independent of the main supporting structure.

Based on these premises, it has been considered that the foundation depth of the footings shall underlie the superficial materials existing at the site, at a depth ranging from 2 to 3 m (B-horizon), and penetrate into the rock, after it has been cleared, to an approximate depth of 0.5 m, where the dynamic modulus of elasticity of the ground reaches no less than 10945 MPa and the load bearing capacity becomes equal to 12.4 MPa. At those parts where weathered and fractured material is observed, possibly corresponding to the presence of the granite dikes, the excavation should reach deeper until the appropriate rock is found.

For the purpose of analysis, the dynamic modulus of elasticity should be reduced to 66% of the original value, i.e. 7300 MPa, after assuming that the equivalent RQD at such depth is 65 to 80% lower, and that the average static modulus of elasticity of the intact rock is of about 23150 MPa. In this way, it would be considered that the static modulus would be of about 30% of the static modulus corresponding to the intact rock, as recommended in the technical literature.

Settlements expected at the ground will have an elastic nature, small in magnitude and occurring mostly during the construction and assembly stages of the structures. For the evaluation of these settlements a modulus of deformability of the of the rock mass (Em = 7300 MPa) should be considered, as well as a value of 0.3 for Poisson's ratio, and the application of the solutions given by the theory of elasticity for homogeneous media, since we are dealing with a subsoil constituted by massive rock.

Recommendations for the excavation and placement of the foundations:

- Remove the superficial layer of decompressed rock, with a thickness of about 1.5 m at the zone where the borings were drilled and of about 3 m outside of this zone, to cover an approximate area of 80 × 60 m. This shallow stratum that presents values of compression wave transmittal smaller than 1400 m s^{-1} can be excavated with a heavy D-9 tractor fitted with ripper, assisted by backhoes operating as usual or equipped with hydraulic hammers.

- Once the foundation depth is reached, all loose material should be removed, the exposed surface should be inspected, and its surface cleaned thoroughly, particularly at the contact areas of the footings. The removal of loose rock blocks could be done with pneumatic hammers or by increasing the number of passes of the ripper.

- If the surface following the previous activities still evidences protrusions and voids which are inconvenient for the footings, it should be smoothed with concrete having a minimum strength of 15 MPa (150 kg cm^{-2}), until a uniform surface is obtained.

- At the same sites where it is decided to place the footings, ditches with a minimum depth of 0.5 m should be excavated for the purpose of embedding to a certain depth the base of the footings into the rock. This excavation could be performed with pneumatic hammers.

- Due to the high load bearing capacity of the ground, as compared to the loads likely to be transmitted by the structure, it is recommended for design purposes to limit the minimum width of the footings to 1 m.

It is worth mentioning that the rocks at the site (particularly the schist) are not recommended to be used as aggregates for concrete mixing, because they could react with the alkalis of the cement, due to a high mica content, producing expansive effects.

B. Sánchez wishes to acknowledge financial support from Comisión Federal de Electricidad, Coordinación de la Investigación Científica and the TIM project (Fondo-TIM), which made these studies possible. The Instituto de Astronomía acknowledges the professional contribution of the Gerencia de Estudios de Ingeniería Civil of the Comisión Federal de Electricidad to the geotechnical characterization of OAN/SPM.

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