# Pore Pressure Measurements to Investigate the Main Source of Surface Subsidence in Mexico City

## Etude de la pression interstitielle dans le but de connaître la cause principale du tassement superficiel particulier à la ville de Mexico

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Summary

The intensive pumping from deep water bearing deposits under Mexico City has created a state of continuous surface subsidence and has introduced foundation engineering problems for many structures erected within the area where the wells for water supply are concentrated.

This paper shows the value of pore pressure measurements and settlement observations, on piezometers and benchmarks established at various depths in the subsoil beneath Mexico City, in order to study the seat and rate of the surface subsidence against the drop in the piezometric water levels.

The knowledge of the geological conditions, the stratigraphy of the sedimentary deposits and the index and mechanical properties of the subsoil materials, permitted the installation of piezometers and underground reference points at correct elevations where the seat of surface subsidence could be detected and the compression of the soft clay deposits measured.

The observations yielded numerical values that permitted the drawing of definite conclusions on the compression of the deposits, thus contributing to a better understanding of the phenomenon, and elucidating some of the problems of foundation engineering closely related with the surface subsidence taking place in Mexico City.

Sommaire

Le pompage intensif à grande profondeur pratiqué au-dessous de la ville de Mexico dans des dépôts aquifères crée un affaisssement continu de la surface; cet état de choses pose des problèmes de fondations dans le cas de plusieurs édifices érigés dans la zone où les puits artésiens sont concentrés.

Cet article souligne l'importance du rôle joué par les mesures des pressions interstitielles, les tassements des points de repère, les niveaux piézométriques établis à différentes profondeurs dans le sous-sol de la cité dans l'étude du siège et de la vitesse des tassements superficiels par rapport à la chute des niveaux d'eau piezométriques.

La connaissance des conditions géologiques locales, la stratigraphie des dépôts sédimentaires, ainsi que l'indice et les propriétés mécaniques des matériaux du sous-sol favorisent l'installation des piezomètres et des points de référence souterrains à des niveaux déterminés ce qui permet l'étude du tassement superficiel et la mesure de la compression des couches d'argile de faible consistance.

Les résultats numériques de ces observations ont permis à l'auteur de tirer des conclusions précises sur la compression des diverses couches; de cette façon le phénomène est mieux compris et plusieurs problèmes techniques de fondation étroitement liés au tassement superficiel particulier à la ville de Mexico ont pu être résolus.

## Introduction

The water extraction from the subsoil of Mexico City, to aid the water supply, takes place from a large number of wells drilled to a depth of between 50 and 500 m. In the city area the large pumping of water has created a strong drop of the piezometric water levels in the pervious strata, mainly from depths greater than 28 m. However, the surface water table has remained unaltered; first, because of the imperviousness of the thick clay deposit overlain by the water bearing top deposits; and second, because the water table in this area is perfectly supplied by many pervious fields interbedded in the upper crust of the subsoil under the city; as the old canals of pre-spanish and spanish times which were filled up by coarse materials. Most of these buried conduits had communication with Texcoco Lake.

The hydraulic gradient originated mostly in the vertical direction, due to the difference of piezometric pressures between the surface of the ground and the water bearing layers at greater depth, has produced a descending water flow across the high compressible clay deposits. The seepage stresses create a new state of stress producing consolidation of the clay deposits, thus originating the surface subsidence.

In order to find out the effective pressures in the subsoil and the velocity of subsidence of the surface of the ground the author has installed piezometers and benchmarks at different depths for each of his jobs in connection with the design of a large foundation. One of the most complete observations were those obtained for the solution of a foundation problem for a 43 stories building property of the Life Insurance Company "La Latino Americana" in which the author has had the privilege to act as a consulting engineer. In addition to the investigations made at the site to solve this problem, a set of piezometers and benchmarks were installed at a distance of about 260 m from this site in the City Park, Alameda Central. The object was exclusively the measure in this unloaded area of the city of the effects of the seepage stresses in the compressible clay deposits.

The observations have been made for 3.5 years on benchmarks and piezometers at depths of 3, 34 and 49 m from the surface of the ground. They have yielded very significant information for the design of this particular building, and for the understanding of the seat of settlement of the ground surface.

The hydrostatic conditions encountered in the subsoil differ somehow for different places within the city. The compressibility of the clay varies also, therefore, the surface subsidence in the city has a different value according to the specific hydrostatic and mechanical properties of the clay at the particular area under investigation. The surface subsidence has originated many problems in engineering works, but mainly in the sewage system and the conduction of the polluted and pluvial waters out of the Valley of Mexico.

## Outline on Subsoil Conditions

The understanding of the problem discussed in this paper requires a brief discussion of the environment on which the subsoil in the lacustrine area of the basin of the Valley of Mexico was formed. The Valley of Mexico, Fig. 1, is situated at the south end of the highest part of the Mexican Plateau; it has the form of a closed basin extending in a north-south direction, it is bounded in the east by Sierra Nevada with snow peaks Ixtaccihuatl and Popocatepetl, about 5300 m above sea level. On the west and north-west the valley is bounded by the Sierra Madre Occidental. On the north it is limited by the Pachuca Range, and on the south, by the Ajusco Range with

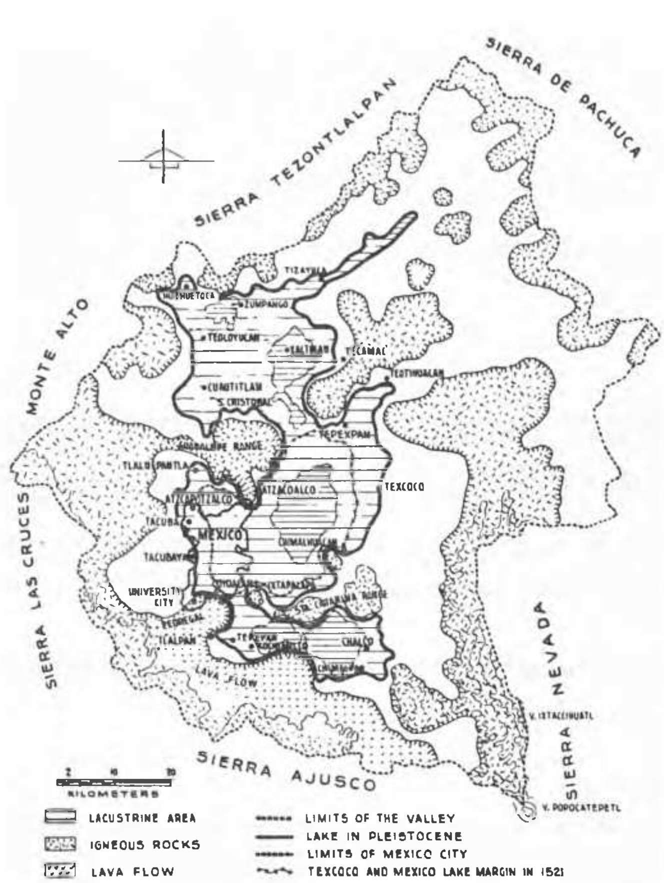


Fig. 1 Basin of the Valley of Mexico Showing the Lacustrine Area, the City Area, the Lake Margin in 1951 and also the Lakes Zumpago, Xaltocan, San Cristobal, Texcoco, Xochimilco and Chalco
Bassin de la Vallée de Mexico, montrant la zone lacustre, l'emplacement de la cité, le contour du lac en 1951 ainsi que les lacs Zumpago, Xaltocan, San Cristobal, Texcoco, Xochimilco et Chalco

4,000 m altitude. The Range of Guadalupe, Fig. 1, extending eastward towards the center of the basin forms the north protection of Mexico City. The lowest part of the basin has an altitude of 2,236 m above sea level.

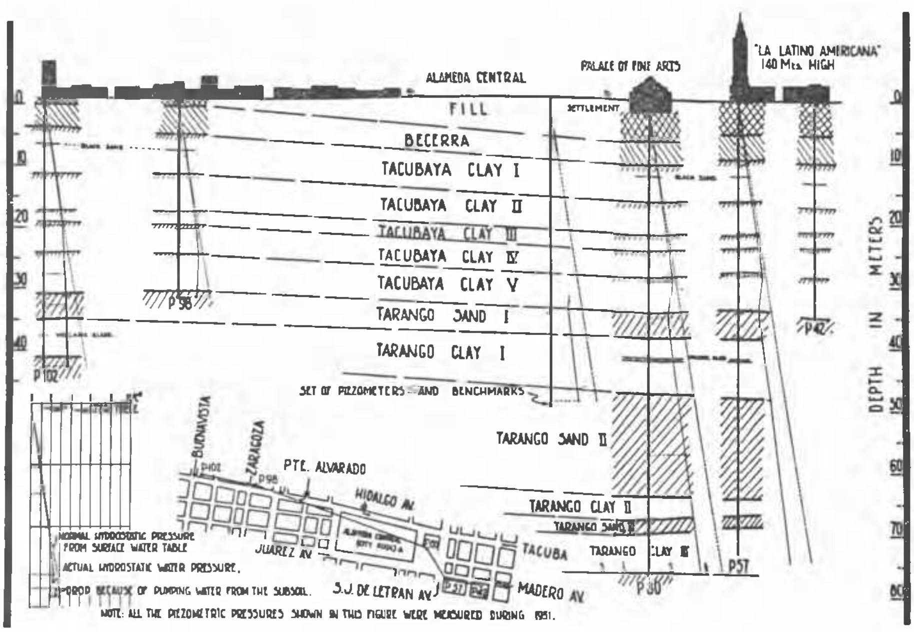


Fig. 2 Subsoil Profile Beneath Mexico City
Profil du sous-sol de la ville de Mexico

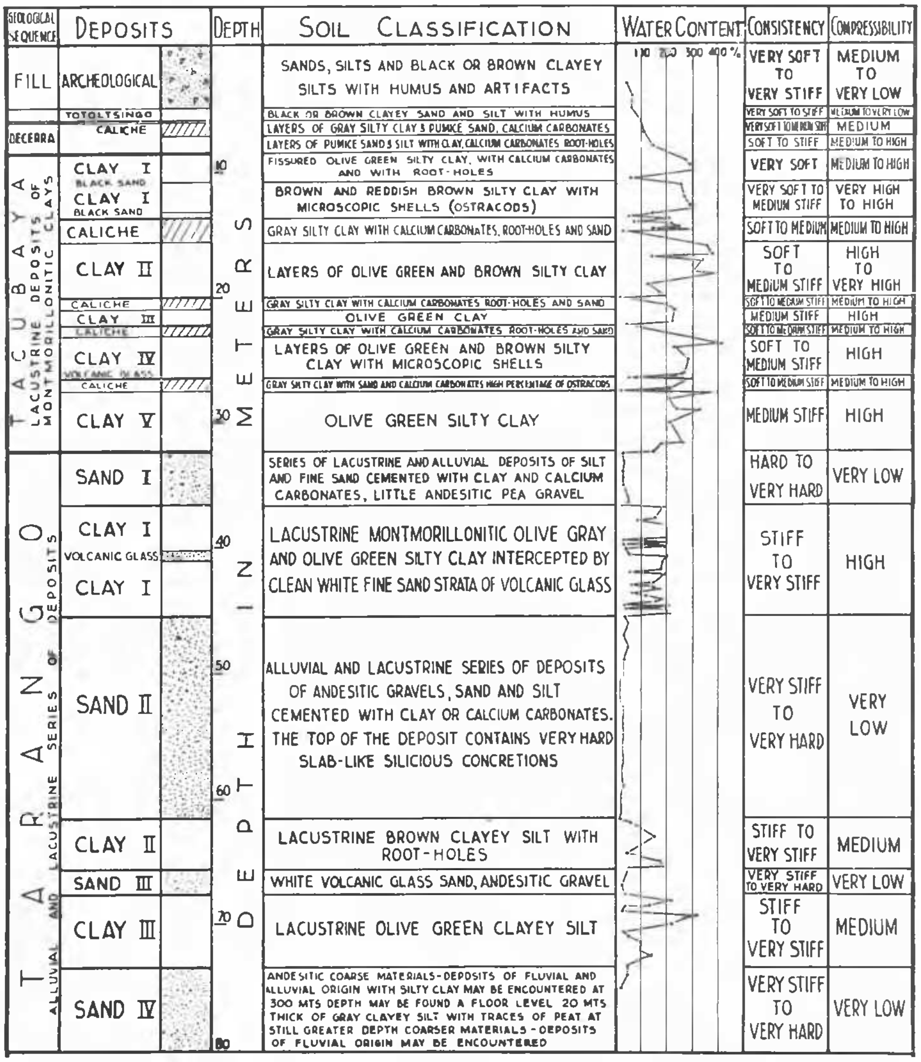


Fig. 3 Hydrostatic Water Pressures
Pression hydrostatique

Many small rivers flow into the valley. They bring rain water to the lowest part of the closed basin forming a series of shallow lakes. From north to south these lakes are: Zumpango, Xaltocan, San Cristobal, Texcoco, Xochimilco and Chalco; Texcoco being the lowest. In the present only a reduced area of Zumpango and Xochimilco have water during the dry season.

At the close of the Pliocene, when the great volcanic activity was about to end, the high peaks attained their maximum elevation and formed the large closed basin of the Valley of Mexico. At the north a low pass remained in water laid volcanic materials underlain by Cretaceous limestones. The large accumulation of fossils and water-laid sediments found during excavations made in the XVIIth century to open a drainage outlet for the basin of the Valley of Mexico suggests that this pass may have served as an outlet in the early Pleistocene into another valley to the north. Thereafter, the natural outlet was blocked and eventually a large lake occupied practically all the basin, Fig. 1.

The water level in the lake must have attained high levels elevations at the end of the Pleistocene. Late findings show that this water level was as high as 26 m above the present level of Texcoco Lake.

During the Pleistocene the deepest part of the great closed basin was filled by water-transported materials. The decomposed rocks of the surrounding hills were easily eroded and transported, as were the residual clays and pyroclastic materials, and the gravels and sands representing the disintegration products of andesitic rocks. All these materials accumulated in the basin and formed a series of deposits of gravel, sand, and silty clays believed to be several 100 m thick. In the city the upper surface of these deposits is encountered at depths greater than about 35 m.

The soft fine-grained lake deposits shown in Fig. 3 and in a geologic profile in Fig. 2 date from the late Pleistocene. These deposits appear to be the products of volcanic effusions of basaltic lava and very fine water-transported materials. The effusions were accompanied by explosions of great quantities of steam which formed dense clouds containing very fine volcanic ash and other pyroclastic materials. The materials carried by the clouds were deposited as a rain on the waters of the lake that occupied the basin. The very fine volcanic ash decomposed into bentonitic clay that has been classified as having about 20% of the mineral montmorillonite, and a large percentage of diatoms and ostracods. The clay fraction amounts to about 40%. The glass particles of sand size spread over the lake after steam explosions, forming thin clean lenses and layers that were immediately covered by the ultra fine and fine materials already in the process of sedimentation. The winds that entered the basin from the north-east dropped fine materials which helped to form the deep central lake deposits. The currents of water flowing toward the centre of the lake aided the transportation of the fine material, and copious rainfall may have washed the fine dust and ashes from the air.

From the end of the volcanic effusions to the present time a fill has been forming in the lake region. It consists largely of pycroclastic material transported from the high plains, of decomposed rocks and of residual clays, eroded from the hills and mountains surrounding the basin. Minor volcanic activity during this time is recorded by lenses of clean volcanic sand interbedded in the top waterlaid deposits.

The geological sequence and stratigraphy of the materials in the subsoil beneath Mexico City is shown in Fig. 3; it shows also the water content profile and the average consistency and compressibility that may be encountered in these materials.

From the surface of the ground to a depth of about 6 m archeological deposits may be encountered, underlain by alluvial sediments corresponding to the closure of the Pleistocene. From about 9 m to 33 m we found a silty clay deposit, with very high water content, of soft to semi-rigid consistency interbedded with numerous sand layers formed by rains of pyroclastic materials. Other particularly important layers correlate with semi-dry periods during the formation of this deposit which may be divided, as shown in Fig. 3, in five typical clay layers representing respectively different periods of sedimentation. To a depth of between 33 and 38 m we may find a stratum of series of deposits of fine sand and silt with a variable cementation produced by calcium carbonates and clay. Piles for building foundations are resting on this stratum within the central part of the city. From a depth of about 38 to 48 m an olive green silty clay deposit with high water content may be found, usually intercepted at the middle by two white volcanic glass sand strata. From a depth of about 48 m follows a continuous series of deposits of gravel, sand and silt. To a greater depth, as shown in Fig. 3, cycles of alluvial and lacustrine sediments may be found, which become coarser with depth.

The thickness of the deposits called Becerra, Tacubaya and Tarango in Fig. 3, are so far tentative to identify the different layers and correlate them with the geology under study in the upper ridges of the lacustrine area. For building foundations in Mexico City area the hydrostatic and mechanical properties of these deposits is very important. However, about 15 to 20%

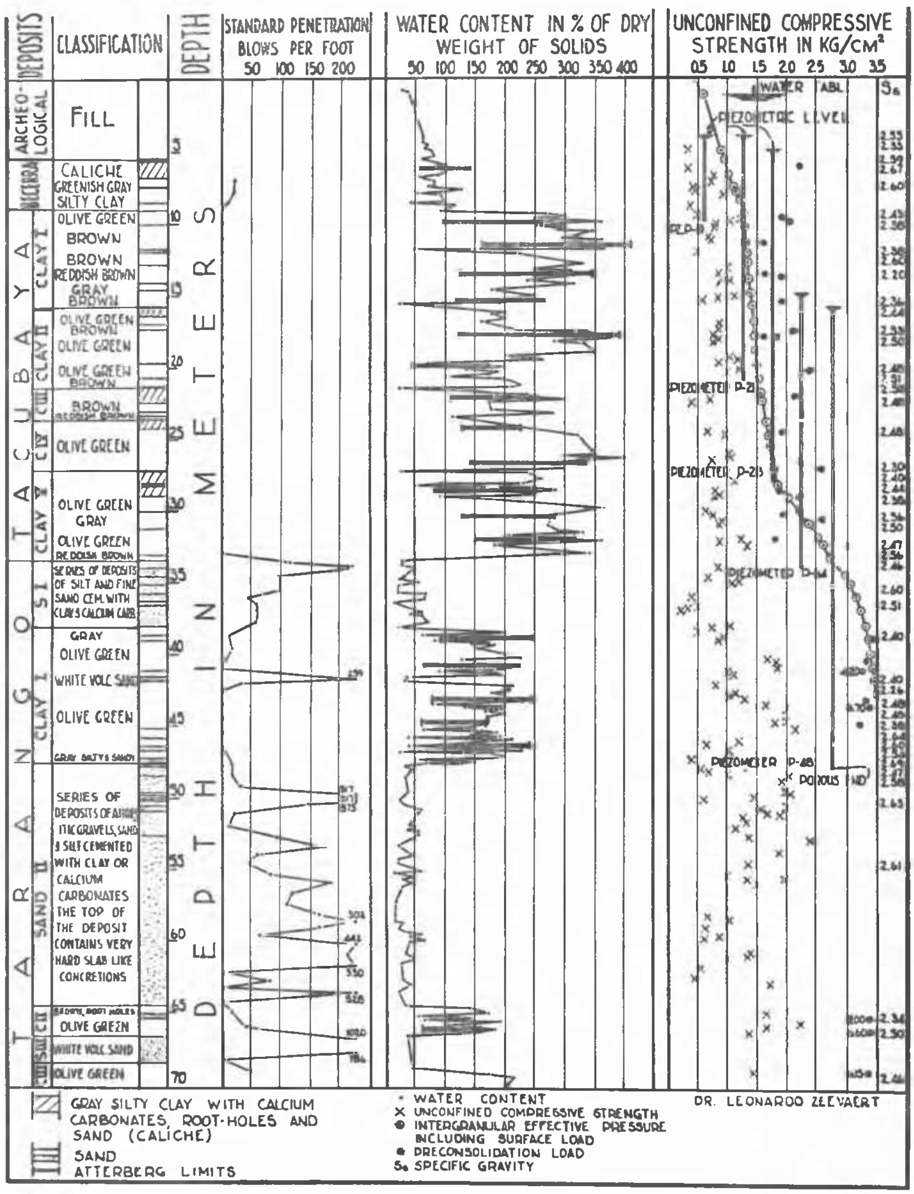


Fig. 4 Subsoil Characteristics Beneath Mexico City
Caractéristiques du sous-sol de la ville de Mexico

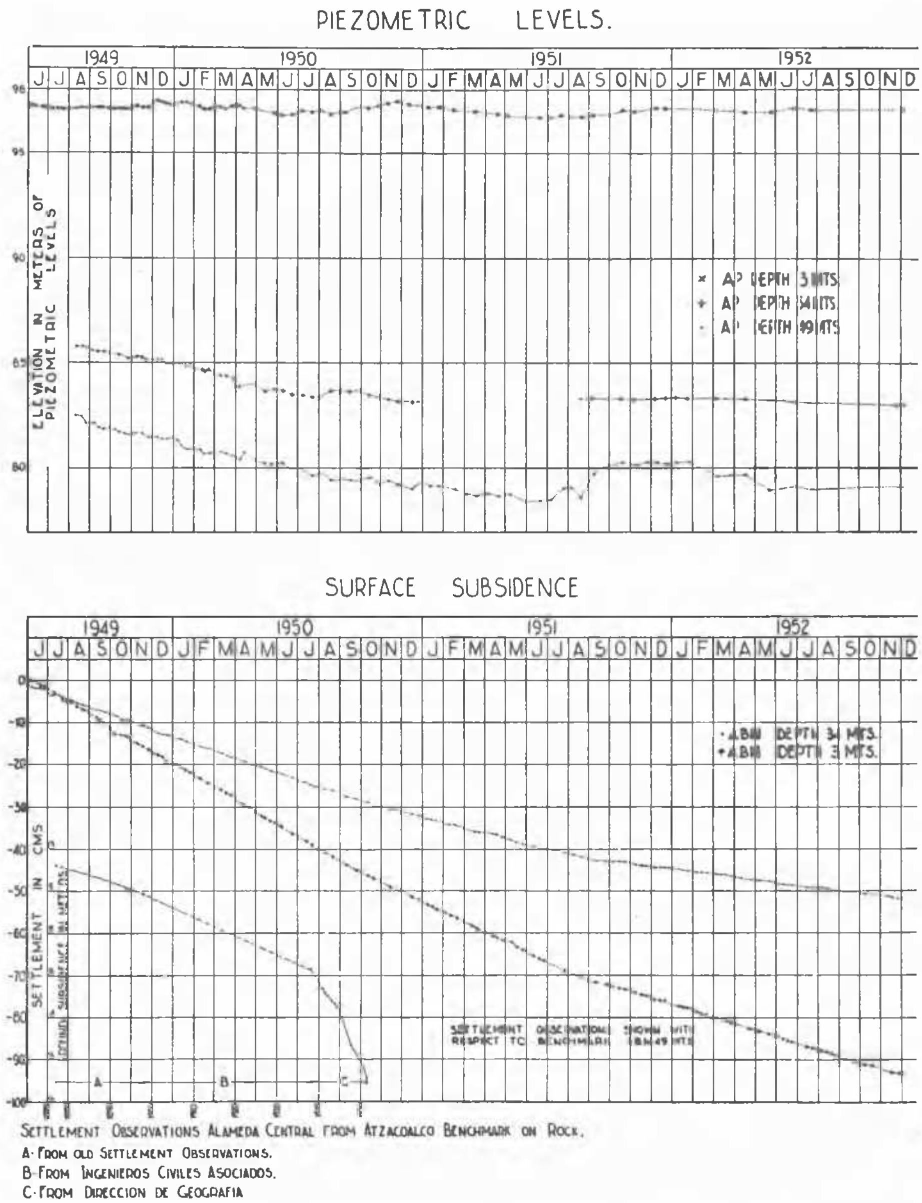


Fig. 5 Piezometric Levels and Surface Subsidence
Niveaux piézométriques et tassement de surface

of the total surface subsidence of Mexico City, with respect to the mountains, may be attributed to the compressibility of the unconsolidated deposits encountered at depths greater than 50 m.

The geologic section illustrated in Fig. 2 shows the actual piezometric pressure existing in the places marked. The piezometric levels were measured with series of piezometers installed at different elevations in the pervious materials as shown in Fig. 2, at depths of 8, 14, 28, 34, 48 and 75 m. These pervious strata contain volcanic ashes, pumice sand and ostracods shells in the Tacubaya deposits, and andesitic sands in the Tarango deposits. The layer found at 28 m in the Tacubaya deposits is particularly pervious and contains a high percentage of ostracods shells and concretions. From information shown in Fig. 2 it may be seen that the sand stratum at 28 m appears to be a good water bearing stratum, since piezometric levels in the upper layers have remained practically unaltered in spite of pumping from the deep water bearing deposits. However, at a depth of 33 m a considerable drop of the piezometric level has taken place. Equally important is the drop that may be observed in the more pervious deposits at depths of 48 and 75 m. A soil profile is condensed in Fig. 4, in order to acquaint the reader with the characteristics of the subsoil materials of Mexico City to a depth of 75 m.

## Piezometric Pressure and Surface Subsidence Measurements

The behaviour of the subsoil deposits because of pumping from deep water bearing strata is of vital importance in Mexico City. To reach a conclusion about this phenomenon, observations of piezometric pressures and settlements are necessary. Fig. 5 shows observations with time of piezometers and benchmarks installed at depths of 3, 33 and 49 m in the city park where no other important influence may be assumed to exert except that caused by pumping water from the ground. The piezometric measurements show that from June 1949 to November 1950 a practically constant drop in pressure was taking place at depths of 33 and 49 m, with an average of about 20 cm per month. However, the surface water table has remained practically unaltered during the whole period of observations (Fig. 5). In correlation with the drop of piezometric levels the surface subsidence shown in Fig. 5 took place at a practically uniform rate in the same period. The rate of settlement reduced toward July 1951 as the rate of drop in the piezometric levels decreased to about 10 cm per month.

At the completion of the new aqueduct bringing water to reinforce the general water supply of Mexico City a certain amount of wells was cancelled. The effect was practically instantaneously observed as the rate of drop of the piezometric levels decreased considerably. As a matter of fact from July 1951 to the present the piezometric levels have practically remained unchanged. This effect was immediately registered in the settlement measurements, shown in Fig. 5. Neverthelesss, the settlements of the ground surface and of benchmark ABN34 have continued at a practically uniform rate of 18.4 cm and 7.9 cm per year respectively.

The hydrostatic pressure distribution with depth in piezometers installed for building foundations at two sites close to the City Park are shown in Fig. 2. The general situation of the piezometric levels at these sites shows that the upper part of the soft clay deposit, from about 28 m to the surface of the ground, has not suffered an appreciable reduction because of pumping in the deep water bearing strata. The drop has started in the first hard stratum at a depth of 33 m and in the following sand strata series at greater depths. These observations have an important significance in the conclusions that will be outlined in conjunction with the observations reported in the preceding paragraphs.

## Conclusions

The rate of settlement and rate of drop of the piezometric levels obtained from Fig. 5 and discussed in the last paragraph are summarized in Table 1.

From Figs. 2 and 3 we see that the seat of consolidation of the upper clay deposit of Tacubaya extending to a depth of 33 m has taken place in the lower part of this deposit, that is, to a depth of between 28 and 33 m, corresponding to the Tacubaya Clay V. This clay layer is limited in its upper part by a pervious layer of volcanic ashes, pumice and large amount of ostracods sand. It appears to be a fairly good water bearing stratum that supplies enough water as to maintain the normal hydrostatic pressure in the upper deposits, thus avoiding large seepage stresses in the upper-most part of the deposit.

The second clay deposit called Tarango Clay I is responsible for the largest share in the surface subsidence, its consolidation had reached as much as 20 cm per year in 1949, Fig. 5. The hard stratum of 33 m in depth settled 52 cm from June 1949 to December 1952. The upper clay deposit, Tacubaya, settled only 41 cm in the same period, giving an amount of 93 cm for the total surface subsidence in the last 3.5 years with respect to benchmark ABN49 installed at 49 m depth.

It appears from general observations carried out on a rock benchmark, by the Dirección de Geografia of Mexico, Fig. 5, that the rate of surface subsidence of the Alameda Central was about 42 cm in 1949. Therefore, the rate of subsidence of the deposits at greater depth than 49 m was only about 15% of the total subsidence observed.

From the practical point of view the conclusions mentioned above have a large bearing on deciding building foundations on piles because of the fact that piles resting on the 33 m hard stratum have to sustain a large negative friction due to the compression of the Tacubaya Clay V. The negative friction on the piles is to a large extent dependent on the drop in the hydrostatic pressure in the hard deposit at 33 m depth. The effective pressure because of the drop in the piezometric pressure, where a building rests on piles, is transferred to the piles, and therefore, the larger the drop, the larger will be the negative friction on the piles. The piles of certain buildings constructed in the past are overloaded and show difficult working conditions because of the large negative friction. Therefore a building on piles has to be designed so as to take a surface subsidence which is dependent on the exact hydrostatic conditions and mechanical properties of the clay at the site in consideration. Observations of specific sites show that the consolidation of the upper clay deposit ranges between 5 and 15 cm per year; therefore precautions have also to be taken regarding the public utilities to buildings on piles.

Table 1

| *Date* | *Rate of Settlement of Benchmarks with Reference to ABN49* | | *Rate of Drop of Piezometric Level* | |
|---|---|---|---|---|
| | *ABN3 3 m/depth cm/year* | *ABN34 34 m/depth cm/year* | *AP34 34 m/depth m/year* | *AP49 49 m/depth m/year* |
| June 1949 to Nov. 1950 | 35.0 | 20.0 | 2.20 | 2.75 |
| Nov. 1950 to July 1951 | 27.9 | 15.0 | 0.35 | 0.75 |
| July 1951 to Dec. 1952 | 18.4 | 7.9 | 0.35 | 0 |


## Acknowledgment

The author wishes to express his gratitude to the Life Insurance Company "La Latino Americana" for permitting him to use the data in Fig. 5 for publication and also congratulates the engineering staff of the same organization on their careful time observations of piezometric levels and settlements, which have undoubtedly contributed to the understanding of the seat of surface subsidence in Mexico City and have provided valuable information for future engineering foundation design.