Predictions of Settlements of Pond Berms Over Mexico City Clays

Francisco A. Flores[1(✉)], Iván Zárate[1], Jenny Ramírez[2], and Néstor O. Gordillo[3]

[1] IGM Ingenieros Geotecnistas Mexicanos S.C, Mexico City, Mexico
alonso.fafl@igmmexico.com
[2] Geosyntec Consultants, Toronto, ON, Canada
[3] Independent Consultant, Mexico City, Mexico

Abstract. This paper presents the long-term settlement predictions of up to 3.5-m tall, 33-km long berms around the perimeter of five water regulation ponds at the perimeter of Lake Nabor Carrillo. Settlements due to the construction of the perimeter berms were performed using Settle3. Three-dimensional numerical simulations of the regional subsidence were performed using the Modified Cam-Clay constitutive model in FLAC3D. Because of the very soft ground conditions, the field investigation includes cone penetration tests, standard penetration tests with a sampling of undisturbed samples, and the installation of vibrating-wire piezometers. The predicted settlements were sensitive to the compressibility properties of soil and consistent with historical settlement monitoring results.

Keywords: Settlement · subsidence · compressibility · Settle3 · FLAC3D

1 Introduction

Mexico City was built on former interconnected ancient lakes and a lacustrine system, where soil stratigraphy is highly soft and compressible (Zeevart 1957, Marsal and Mazari 1969, Mesri et al. 1975, Diaz Rodríguez and Santamarina 1999). The uniqueness of Mexico City lacustrine sediments requires a vast understanding of the fundamental aspects of local soil behavior, such as regional subsidence, Mexico City geotechnical properties, and highly variable piezometric water levels.

Lake Nabor Carrillo is an existing 100-Ha water body located about 24 km eastern outskirts of Mexico City that has been investigated over decades as part of the city's planned expansion. From 1972 through 1984, Murillo and Garcia (1978) regularly monitored the construction and performance of Lake Nabor Carrillo and reported average settlements of 15.4 cm/year with maximum settlements of 24.6 cm/year. Similarly, Rovirosa (1976) reported up to 80 cm embankment settlements over four years. A few years later, Rodriguez Torres (1982) monitored the perimetral embankments of Lake Nabor Carrillo and observed settlements from 44 cm up to 136 cm after two and a half years of monitoring.

R. E. Hammah et al. (Eds.): RIC 2023, AHE 19, pp. 432–438, 2023.
https://doi.org/10.2991/978-94-6463-258-3_43

This paper summarizes the long-term settlements predictions due to the construction of five water regulation ponds at the perimeter of Lake Nabor Carrillo within an area of 1,190 Ha. The design of these ponds considers the construction of approximately 33.5 km long perimeter berms with variable heights from 0.4 up to 3.5 m. This study presents the results of settlements calculations using two commercial software: (i) Settle3D for settlements due to the construction of the perimeters berms and (ii) FLAC3D for settlements due to regional subsidence.

2 Geotechnical Site Characterization

A total of 59 cone penetration tests with pore pressure measurements (CPTU) and 58 standard penetration tests (SPT) with thin-walled tube sampling were performed at the site. The CPTU tests were pushed through the entire layer of the most compressible soils, reaching up to 55 m below ground surface. An extensive laboratory testing program included one-dimensional consolidation tests, unconsolidated-undrained triaxial compression tests, and consolidated undrained triaxial compression tests. Vibrating wire piezometers were also installed to monitor the groundwater pressure variation. The location of the field investigation and piezometers, including the footprint of the pond, is shown in Fig. 1.

Overall, the soil stratigraphy of the site includes, from top to bottom, a 2-m thin crust layer, an upper very highly compressible clayey layer, a 3-m medium dense sandy layer, a lower clayey layer, and a more competent sandy layer. For this project, settlements are controlled by the upper clayey layer. Based on the field investigation, the authors identified two geotechnical zones. Zone 1 includes Pond 1, Pond 2, and Pond 3, characterized by a 28 to 38 m thick upper clayey layer and water content ranging from 300% to 400%. Zone 2 includes Pond 4 and Pond 5, where the upper clayey layer thickness varies from 40 to 53 m, with water content ranging from 200% to 350%.

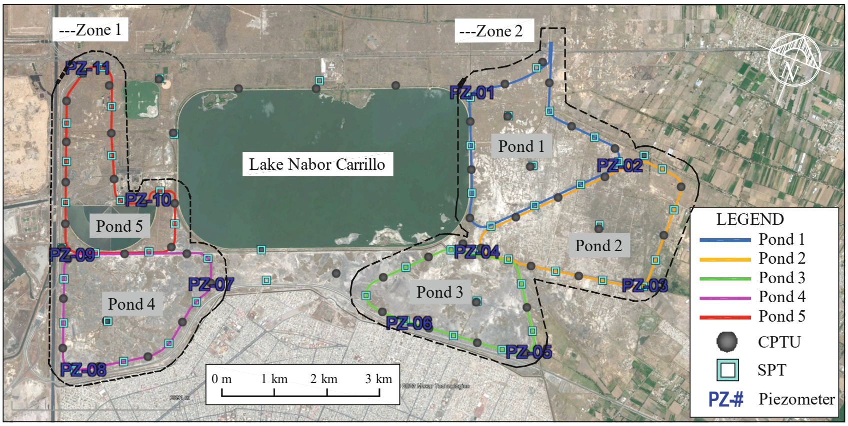

Fig. 1. Field exploration (Modified from Google Earth 2023)

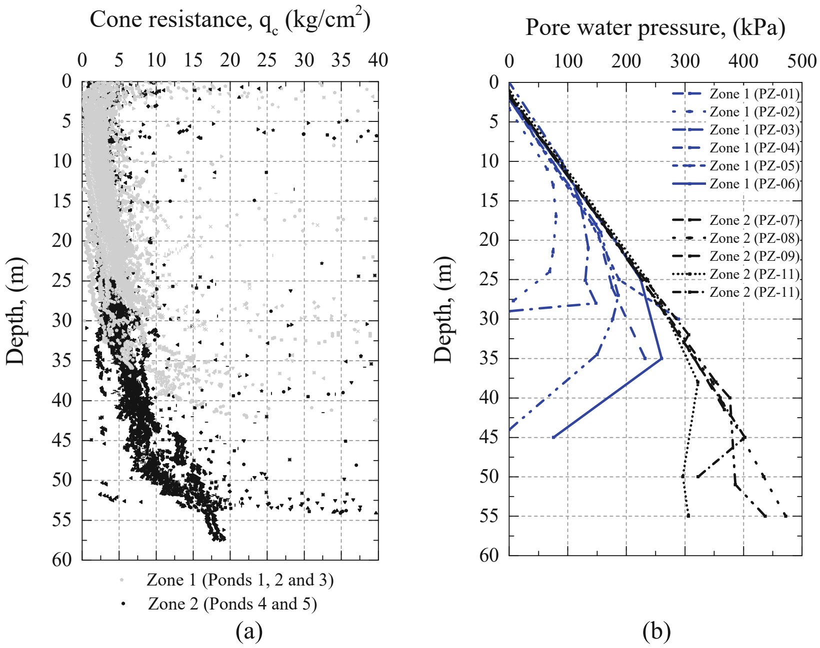

Fig. 2. Variation of a) cone resistance, qc; b) pore water pressure with depth

In both zones cone resistance increases with depth; however, the upper clay layer is ticker in Zone 2, as shown in Fig. 2a. The piezometers readings within the very highly compressible clayey layer per zone are shown in (Fig. 2b).

3 Settlements Due to Perimeter Berms Construction

Settlements due to the construction of the perimeter berms were computed in the former Settle3 software, Settle3D V.3.019 (Rocscience Inc. 2014). Each berm self-weight was represented by a distributed load applied at the ground surface, and the increase of stress with depth was computed using the Boussinesq theory. Load were grouped based on representative heights varying from 0.4 m to 3.5 m applied in a constant width of 4.0 m along the perimeter berms footprint. The calculations include three types of settlements: elastic, primary consolidation, and secondary consolidation.

The elastic settlements were estimated based on the Young Modulus, the corresponding change in vertical total stresses, and the thickness of the compressible stratum. The primary consolidation settlements were computed using a non-linear material with the compressibility index, recompression index, initial void ratio, and overconsolidation ratio, based on the Terzaghi theory. The secondary compressibility index was used for the calculation of secondary consolidation settlements calculation assuming that the vertical strain varies linearly with the logarithm of time. These settlements were computed up to 50 years at intervals of 10 years.

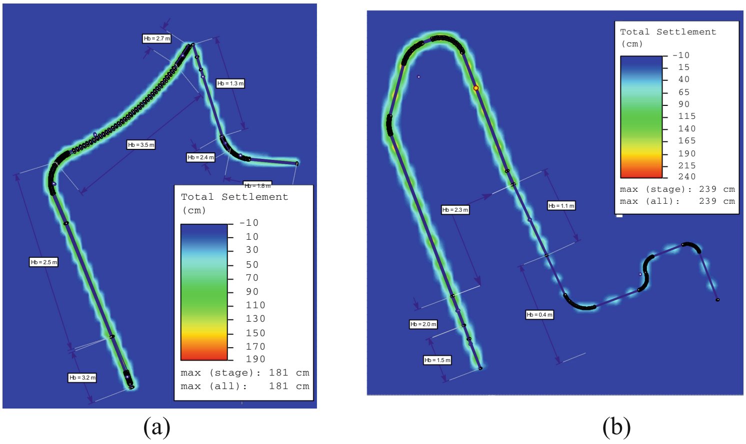

Fig. 3. Total settlement at (a) north of Pond 1 and (b) north of Pond 5

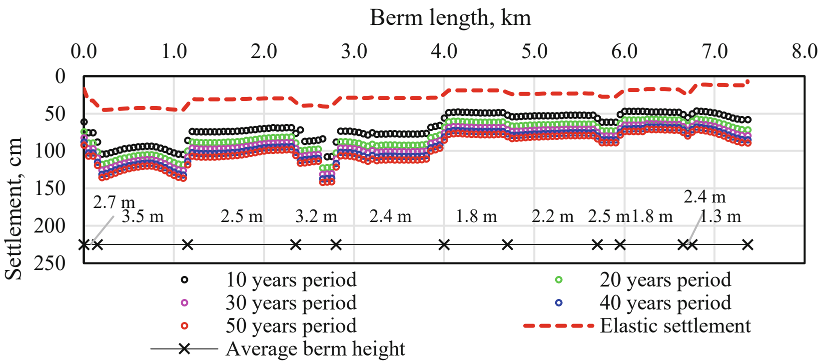

Fig. 4. Long-term settlement due to perimeter berm construction in Pond 1 (Zone 1)

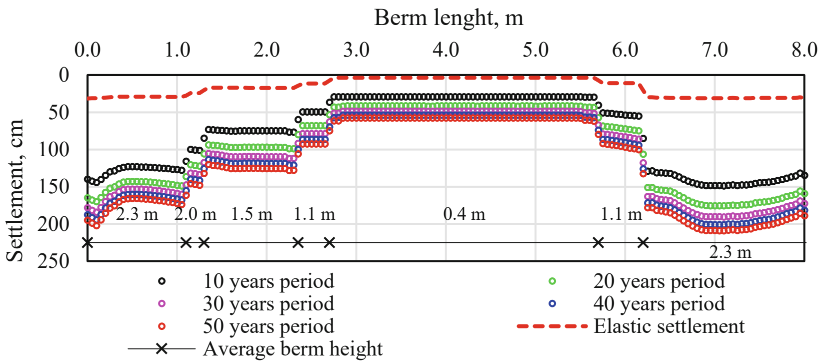

Fig. 5. Long-term settlement due to perimeter berm construction in Pond 5 (Zone 2)

Due to the large extension of each pond perimeter, models were fragmented to optimize the computational time for calculations. In this paper, the results of two representative ponds are presented (i) Pond 1 from Zone 1 and (ii) Pond 5 from Zone 2. Figure 3 shows the total settlement contours at year 50 obtained for the north of Pond 1 and north of Pond 5. A summary of elastic settlements and settlements due to consolidation for all periods is shown in Fig. 4 and for Fig. 5 Pond 1 and Pond 5, respectively.

At the tallest berm, results show a maximum long-term settlement of about 140 cm over 50 years due to the construction of a 3.5-m tall berm in Pond 1. Similarly, for the tallest berm in Zone 2, long-term settlement estimations were computed as 210 cm over 50 years. Although Zone 2 tallest berm is only 2.3 m, settlements in this zone were higher because of the presence of a thicker upper clayey layer. During the first ten years, the average settlement due to berm construction in both zones is about 80 cm, consistent with previous in-situ monitoring results (Rovirosa 1976).

4 Settlements Due to Regional Subsidence

Three-dimensional simulations were performed using the finite-difference platform Fast Lagrangian Analysis of Continua (FLAC3D). Mesh was generated using MIDAS GTS, as presented by Flores and Ayes (2016). For these simulations, the Modified Cam-Clay constitutive model was used to represent the highly compressible soil layer. Modified Cam-Clay parameters were estimated from one-dimensional consolidation tests. The normal consolidation line, λ, and the slope of the elastic swelling line, κ, used for Zone 2 are presented in Fig. 6a. The material constant, M, associated with the critical state line was estimated from the consolidated undrained triaxial compression test performed as 0.97 to 1.58.

The decrease rate of the pore water pressure versus depth was estimated with the Carrahan et al. 1969 algorithm for a 50-year period in 10 years intervals (Fig. 6b). The initial hydrostatic pressure was consistent with the piezometric readings shown in Fig. 2. This estimated initial hydrostatic pressure resulted in consolidation coefficients ranging from 6.18E-08 to 7.90E-08 m^2/s. The predictions at different year periods resulted in a more realistic estimation of the reduction of effective stress and long-term settlements. The largest settlements due to regional subsidence were obtained at the divider berm between Pond 4 and Pond 5. Results along this divider are shown in Fig. 7. For the first ten years, the consolidation rate is about 8 cm/year, decreasing to less than 1 cm/year after 40 years.

5 Summary and Conclusions

This paper focuses on the predictions of long-term settlements of up 33 km long perimeter berm to be constructed over very high compressible soils at Lake Nabor Carrillo in Mexico City. Elastic and consolidation settlements were computed using the software Settle 3. The regional subsidence was computed using three-dimensional models developed in FLAC3D. In FLAC3D, the highly compressible clayey layer was modeled using the Modified Cam Clay constitutive model. Based on piezometric results, the hydrostatic pore pressure was estimated to better represent site conditions. Further, estimation of

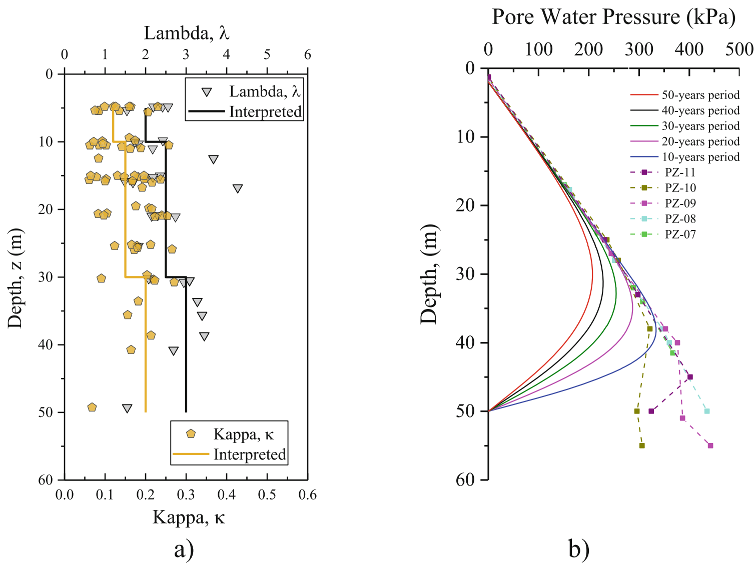

Fig. 6. a) lambda and kappa parameters for Zone 2; b) pore water pressure calculated with the Carrahan et al. (1969) algorithm for the regional subsidence calculations of Zone 2

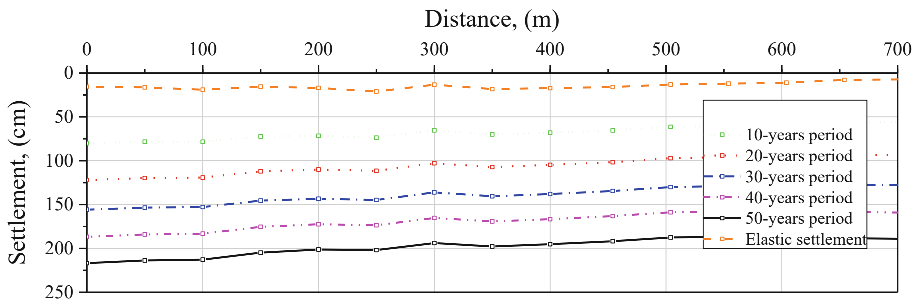

Fig. 7. Long-term settlement due to regional subsidence at the divider berm between Pond 4 and Pond 5, both in Zone 2

the decrease rate of pore pressure with depth were also computed for a more realistic estimation of the variation of effective stress over time.

Elastic and consolidation settlements were computed for different berm heights. Consolidation settlements were presented for a total period of 50 years at intervals of 10 years. For the tallest berms per zone, elastic and consolidation settlements were computed as about 1.4 m and 2.1 m for a period of 50 years for Zone 1 and Zone 2, respectively. About 70% of these settlements occur over the first 10 years, for where the regional subsidence was computed to be at a rate of 8 cm/year. The maximum regional subsidence was also observed in Zone 2, at the limits between Pond 4 and Pond 5, resulting in up to 2.2 m of settlements. The results of this study were further used for the project designers to evaluate ground improvement solutions that could reduce the expected settlements.

References

Carrahan B., Luther H.A. and Wilkes J.O. Applied Numerical Methods. John Wiley and Sons USA (1969).

Diaz-Rodriguez J.A. and SantaMarina C. Thixotropy: the case of Mexico City soils. XI Panamerican Conf. on Soil Mech. and Geotech. Eng. 441–448 (1999).

Flores F.A. and Ayes J.C.: Generación de mallas complejas mediante una interfaz Midas/GTS-FLAC3D", XXVIII Reunión Nacional de Ingeniería Geotécnica SMIG, Mérida, Yucatán (2016).

Marsal, R.J. and Mazari, M.: The Subsoil of Mexico City. Contribution to the First Panamerican Conference on Soil Mechanics and Foundation. Engineering, Ciudad de México, México (1969).

Mesri, G., Rokhsar, A., and Bohor, B.F. Composition and compressibility of typical simples of Mexico City clay. 25:3, 527–554 (1975).

Murillo, R. F. and Garcia, G. A. Ex-Lago de Texcoco, El Subsuelo y La Ingenieria de Cimentaciones 51–82, Simposio de la Sociedad Mexicana de Mecanica de Suelos, Mexico (1978).

Rocscience, Inc., (2014–2016), Settle3D v.3.019, Toronto, Ontario, Canada

Rodriguez Torres, J.L. Aspectos geotécnicos del bordo perimetral al lago Dr. Nabor Carrillo en el ex vaso de Texcoco. Tesis profesional. Mexico UNAM. (1982).

Rovirosa, C.A. Efecto de una Precarga en las Arcillas del Lago de Texcoco, Tesis Profesional (1976).

Zeevart, L. Foundation design and behaviour of Tower Latino Americana in Mexico City. 7:3, 115–133 (1957).