GEOTECHNICAL ENGINEERING IN HISTORY

Advances in foundation engineering in Mexico (1957-2017)

Gabriel Auvinet, PhD
Instituto de Ingeniería, UNAM, Mexico

This paper is an updated version of one of three essays in which the author evaluated advances in the knowledge of soils and in the art of building geotechnical projects that have been achieved in the last 60 years in Mexico (Auvinet, 2018a, 2018b, 2019). This progress should be attributed to the research works and to the creativity evidenced by Mexican engineers during the execution of large and small projects. In this paper a review is made of progress attained in foundation engineering

The major advances in the foundation techniques achieved in the last few decades have been mostly witnessed in Mexico City, where particularly difficult subsoil conditions are encountered (Marsal and Mazari, 1959; Auvinet *et al*., 2017). In the capital of the Mexican Republic, the soil of the former lacustrine zone (Fig. 1, Zone III) shows very high compressibility and low shear strength. Foundation design in this area should also consider the regional subsidence induced by the extraction of potable water from deep aquifers, as well as pronounced site effects during seismic events. These issues have been dealt with in countless symposia during the period being reviewed (SMMS/SMIG, 1976, 1978, 1990, 1992, 2002, 2005, 2006, 2017).

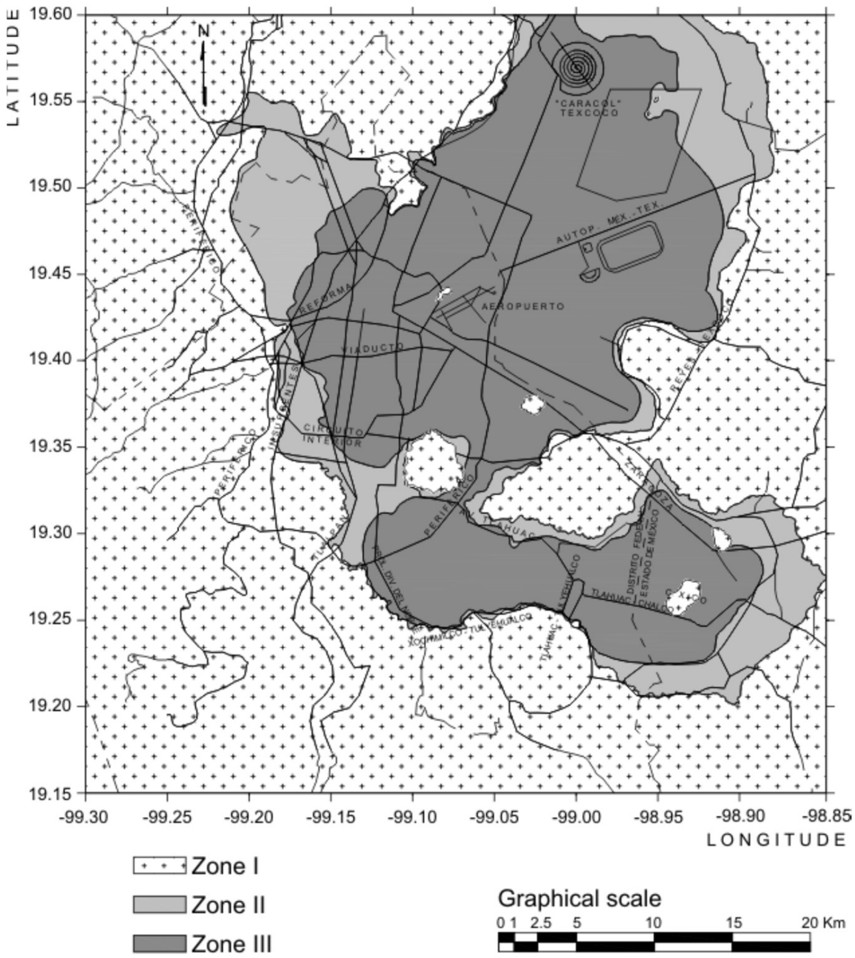

Figure 1. Geotechnical zoning of Mexico City urban area

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx

CONVENTIONAL FOUNDATIONS

Traditionally adopted solutions (figure 2) to solve the foundation of buildings in Mexico City range from shallow foundations for homes and buildings with a few floors, to concrete piles and drilled shaft foundations driven or cast *in situ* until reaching the first Hard Layer or the Deep Deposits found in the subsoil, in the case of heavy constructions.

Comprehensive reviews of these different types of foundations and their applicability in the different geotechnical zones of Mexico City, illustrated through several case histories, were presented by Reséndiz *et al.* (1970) and by Marsal (1986). Most of the concepts included in these references are still fully valid nowadays. Among the most recent reviews, mention should be made of those presented by Auvinet (1990, 1995), Auvinet and Reséndiz (1991), Holguín *et al.* (1992), Santoyo *et al.* (1999), Mendoza (2007), and Auvinet *et al.* (2017). The problem of foundations in former underground quarries dotted with galleries and voids in the subsoil has deserved special attention because it affects a large part of the Hill Zone (Zone I) to the west of Mexico City (SMMS/SMIG, 1976).

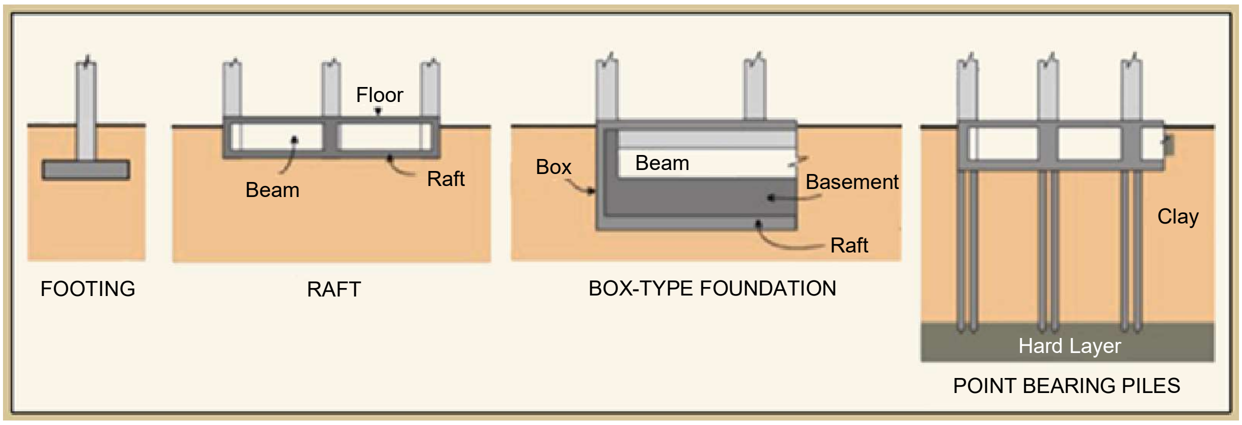

Figure 2. Traditional foundation systems used in Mexico City.

Shallow foundations

Shallow foundations are constituted by isolated or spread footings, or by continuous slabs. Their use at the Lake Zone is only acceptable for light-weight constructions covering rather small areas. Mention should be made that a load as small as 2 t/m^2 (20 kPa) applied on a wide area of the Lake Zone can induce total settlements of about 1 m, and differential settlements of approximately 50 cm. At the lacustrine zone, the design of shallow foundations is generally governed by the serviceability limit states since the contact pressures leading to exceeding the allowable settlements are generally much lower than those susceptible of inducing a shear failure. It is important to consider the load history at the site and possible overconsolidation of the soil before calculating the total and differential settlements. In the case of isolated footings, it is always recommended to contemplate the construction of cross beams to absorb seismic forces and to counteract the effect of cracking of the ground. Improvement of the soil by means of preloading with or without artificial drains prior to the construction of shallow foundations has not received proper attention as of to date in Mexico, despite its evident advantages (Auvinet, 1979).

Compensated foundations

Compensated foundations are defined as those where it is intended to reduce the net load increase applied to the soil by the foundation, with a previous excavation of the ground and the subsequent construction of a box-type foundation supported at a certain depth (Cuevas, 1936). Depending on whether the net load increase becomes positive, null, or negative, the foundation is classified as “partially compensated”, “compensated”, or “overcompensated”, respectively. The use of this type of foundations is limited due to the difficulties encountered when executing the relatively deep excavations, including the problems of slope or

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx

casing stability, water seepage control, and soil expansion due to unloading. For better results, it is also necessary for the box-type foundation to be fully waterproof or otherwise to install an automatic system for permanent pumping. Slender buildings resting upon a partially compensated foundation may become unstable upon occurrence of an earthquake. In the case of overcompensated foundations, the interaction with the regional consolidation may induce an apparent emersion of the box-type foundation with respect to the surrounding ground preventing its stabilization in the course of time.

Point-bearing piles and drilled shaft foundations

Piles or drilled shaft foundations supported by the first hard layer have been commonly used for tall buildings. Among them, special mention can be made of the Latin-American Tower that was, until recently, the tallest building with 43 stories of office space, an observation deck and a television antenna adding up to 196 m. Its foundation includes point-bearing piles supported by the first Hard Layer at a depth of 34 m (Zeevaert, 1973). This building, inaugurated in 1956, withstood without major damages the earthquakes of 1957, 1985 and 2017.

More recent buildings with point-bearing piles resting upon the first Hard Layer or on the Deep Deposits, are also worth mentioning. Among them, “Torre Mayor” stands out with 55 floors above street level and four basement levels bounded by a box-type foundation covering a plan area of 80 × 80 m to a depth of 16 m. It is supported by 251 drilled shaft foundations with diameter ranging from 1 to 1.5 m excavated to depth from 46 to 52 m. This tower is fitted with energy dissipators to reduce seismic forces.

The solution of point-bearing piles or drilled shaft foundations in the lacustrine zone may however represent serious shortcomings. Due to the regional consolidation, the piles driven to the Hard Layer undergo large stresses induced by negative skin friction. Furthermore, such buildings evidence in the long term an apparent emersion with respect to the surrounding ground that is likely to affect the contiguous constructions. The foundation slab ceases to be in contact with the soil and the structure is bound to sustain damages if the building has not been designed for this condition. In addition, the piles loose lateral confinement on their upper part and become vulnerable to overturning moments and shear forces of seismic origin. The column of the Monument to the Independence located at Paseo de la Reforma of Mexico City is an outstanding example of foundation protruding with respect the surrounding ground, attracting the attention of visitors to the capital city (Ruiz-García, 1958, and Ruiz-García and Springall, 1978).

SPECIAL FOUNDATIONS

In few fields Mexican engineers have demonstrated such imagination, creativity, and boldness as in the design and construction of special foundations (see figure 3) for infrastructure works and buildings in the lacustrine zone of Mexico City.

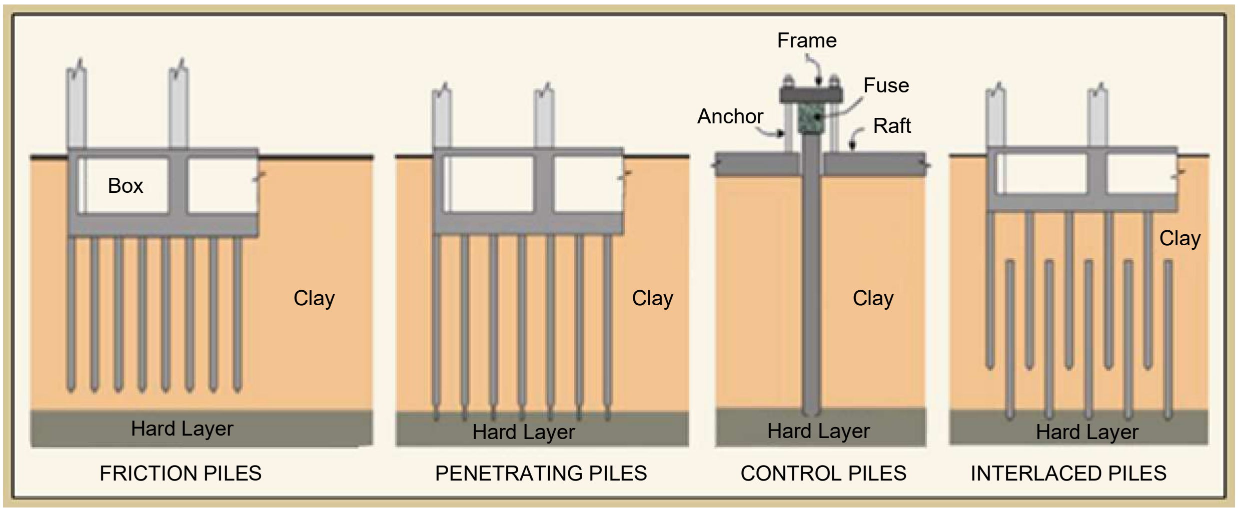

Figure 3. Special foundation systems in Mexico City

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx

Foundations on friction piles

In the decades of 1960 and 1970, for buildings of medium height and in order to prevent the protruding problems associated to point-bearing piles, it was suggested to use driven friction piles whose tip remains, several meters above the first Hard Layer. These "floating" piles allow the building to settle together with the surrounding ground upon occurrence of the regional subsidence. Frequently, the piles are combined with a box-type foundation. A design "rule of thumb" was "to consider part of the building load by compensation, and the rest with friction piles with a safety factor of 2".

However, it was quickly realized that the design of these foundations should explicitly consider the complex interaction among soil, piles, and the box foundation. To perform this type of analysis several approaches were proposed (Zeevaert, 1973; Reséndiz and Auvinet, 1973). Incorporation was made of the concept of neutral point corresponding to the elevation in which the soil and the pile evidence no relative movement. This axis divides the lower part of the pile where positive skin friction is developed, from the top part, where negative skin friction is present. To apply the method proposed by Reséndiz and Auvinet (1973), algorithms and software were developed to calculate the stresses and deformations in the soil; they have been recently updated (Rodríguez and Auvinet, 2018). Field investigations made on instrumented piles (Auvinet and Hanell, 1981; Mendoza, 2004 and 2007) have contributed considerably to a better understanding of the static and seismic behavior of this type of foundations and have played an important role in the development of the Technical Standards for Design and Construction of Foundations, of the New Building Code for Mexico City (GCDMX, 2017).

In recent years, a new type of friction pile not connected to the substructure and known as *rigid inclusion* is being increasingly used for improvement of the soil, for foundation of low rise buildings (Auvinet and Rodríguez, 2006).

Foundations on point-penetrating piles

The point-penetrating piles (Reséndiz, 1964a and 1964b) were conceived to increase the load bearing capacity of friction piles with a contribution from the point but controlling the latter to prevent emersion. The tip has a diameter smaller than the rest of the pile for purposes of favoring its penetration into the supporting stratum through the combined effect of the load and of the negative skin friction. The tip may be of reinforced concrete (Reséndiz, 1964a y 1964b; Ellstein, 1980) or of steel (Reséndiz, 1968). In this latter case, it is possible to impose a more accurate restriction to the point bearing capacity by selecting a cross section with a predetermined yield value; however, it has been observed that the flexibility of the point hinders proper positioning of the pile. Among the projects where this solution was applied, special mention can be made of the Sports Palace, a 180-m diameter dome supported by 1500 piles, that was built for the 1968 Olympic Games (Reséndiz, 1968).

Foundations on control piles

The so-called "control piles" are point-bearing foundation elements fitted at their top with a device that controls the load transmitted to each pile with the possibility of unloading them completely for purposes of inducing corrective movements in the case of buildings evidencing some tilt (González-Flores, 1948). These piles have been frequently installed *a posteriori*, during the service life of the structure, for underpinning purposes (González-Flores, 1981; Auvinet and Gutiérrez, 1989).

The various control systems available have been reevaluated by several authors (Martínez-Mier, 1975; Correa, 1980; Aguilar and Rojas, 1990; Rico, 1991). Close to one thousand buildings have been equipped with this type of system in Mexico City. Recent studies related to the rheology of the control systems based on wooden cubes have thrown valuable information for the better use of these systems (López-Acosta and Martínez, 2017; Martínez, 2017).

Foundations on interlaced piles

Foundations based on interlaced piles (Girault, 1964, 1971, 1980) are constituted by a set of conventional friction piles connected to the substructure ("A" piles), and by another set of point bearing piles supported by the Hard Layer ("B" piles). "B" piles are detached from the foundation slab and are submitted to negative skin friction. With this layout it is possible to decrease the magnitude of the stresses induced in the soil by the weight of the structure. In addition, the cushion of soil between the point of "A" piles and the Hard Layer, and

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx

that existing between the head of "B" piles and the foundation slab absorbs the shrinkage of the Upper Clay Formation and therefore prevent the apparent emersion. This system has been used in various buildings and as foundation of hydrocarbon storage tanks (Menache, 2006).

UNDERPINNING WORKS

The unacceptable behavior of the foundations of some old or modern buildings have led to remarkable underpinning works during the last few decades.

Underpinning of *Capuchinas* Church

At the International Congress of Soil Mechanics and Foundation Engineering held at the city of Stockholm, Sweden in July 1981, González-Flores presented the underpinning works that had been executed at *Capuchinas* Church, built in 1787, adjacent to the Basilica of Guadalupe in Mexico City (González Flores, 1981). He described before the audience how this structure, that evidenced an important tilt attributed to the subsoil heterogeneity, had been lifted 3.5 m in 72 days after driving 159 control piles with 80-t capacity each and length varying from 15 to 30 m. Prior to the execution of this operation, care had been taken to encase the very cracked masonry foundation, measuring 4 m in width and 5.5 m in height, between two L-shaped cross beams, linked at their top and bottom by braces placed every 3 m. The lecture of González-Flores left astonished the best international experts and deserved an enthusiastic congratulation from the chairman of the session, Jean Kerisel, the then president of the International Society of Soil Mechanics and Foundation Engineering.

Geometric correction of the Metropolitan Cathedral

Differential settlements sustained by the Metropolitan Cathedral of Mexico City have induced tilting and cracking of the structure. A study performed in 1991 showed that the differential settlement between the apse and the west tower was equal to 2.42 meters.

To prevent the differential settlements from increasing even more, it was decided to proceed with a "geometric correction" of the Cathedral and of the adjacent church, "El Sagrario". Implementation was made of the so-called sub-excavation system involving the extraction of soil from under the foundation at the zones with less settlement for purposes of inducing local settlements bound to eliminate or to reduce the differential settlement and the distortions occurring at the structure. This outstanding system had already been used in the past by González-Flores to recover the verticality of buildings with tilting problems such as the case of Serfin building, at the crossing of Bolívar and 16 de Septiembre streets, among others, but its application at the scale of a monument with the dimensions of the Cathedral required the development of novel techniques. To carry out this project (Tamez *et al.*, 1992), 30 shafts were excavated with external diameter of 3.4 m down to a depth of 20.0 m, corresponding to the first stratum of compressible material of the upper clay series. From inside these shafts, it was possible to extract horizontally with a controlled slow motion cylindrical samples from the soil with a 10-cm diameter and 1.0-m long tube, driven by steel rods capable of penetrating up to 6.0 m into the soil mass. The cavities left by the sub-excavation after extracting the tube sampler constitute small circular cross-section tunnels that tend to collapse inducing the expected settlements at the surface. The process demands a rigorous control of the volume of soil extracted and an intensive instrumentation. The results obtained by applying this clever and safe technique have been widely satisfactory. It was possible to decrease the unevenness between the apse and the west tower by approximately one meter. These works have been reported in multiple publications and presentations in Mexico and abroad.

Modern buildings

Many modern structures have also been underpinned by substituting the existing piles with control piles (Auvinet and Gutiérrez, 1989), or using sub-excavation (Santoyo and Segovia, 1995).

LESSONS LEARNED FROM EARTHQUAKES

On September 19, 1985, Mexico City was shocked by a major earthquake with magnitude 8.2 that left serious consequences, including many losses of human lives. From a geotechnical point of view, this dramatic event became quite illustrative. The different foundation systems were found subjected to extreme conditions that put in evidence their advantages and shortcomings. About 13% of the foundations on friction piles sustained

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx

permanent deformations (tilting, settlements) and, in one case, total failure due to overturning of the building. Lessons learned from the observations performed in this occasion were extremely valuable and they constitute the basis of the current methods of design of foundations in Mexico City. It was specifically concluded that:

- The designs oriented to the control of settlements/emersions of foundations should also consider the possibility of permanent subsoil deformations or of soil failure under seismic conditions.
- Friction piles are likely to lose an important part of their load bearing capacity when subjected to a seismic condition, due to soil remolding and to widening of the bore hole in which they are embedded.
- This last effect is particularly critical in the case of friction piles lacking the capacity of self-absorbing the weight of the structure (design in terms of deformations for control of settlements) and therefore operating under limiting conditions.
- The dimensions and the geometry of the box-type foundation are essential to guarantee the stability of the foundation of slender structures when the piles lose part of their bearing capacity.
- In soft soils undergoing a process of consolidation, it is recommended that the review of the limit states of failure includes the verification that at least one of the following load bearing capacities becomes sufficient to guarantee the stability of the building:
  a. Load bearing capacity of the soil-footings or soil-foundation slab system. The load bearing capacity of the piles are then disregarded.
  b. Load bearing capacity of the soil-piles or soil-drilled shaft foundations systems. The load bearing capacity of the soil-foundation slab system is then disregarded.

The philosophy of design of deep foundations inherent in the most recent updating of the Technical Standards for Design and Construction of Foundations in Mexico City after the earthquake of September 19, 2017 (GCDMX, 2017) is still based in the observations mentioned in previous paragraphs.

ADVANCES IN THE CALCULATION OF NEGATIVE SKIN FRICTION ON POINT-BEARING AND FRICTION PILES

For purposes of foundation analysis, it is possible to perform a detailed numerical modeling assisted by computer programs based on finite elements or finite differences currently available for foundation analysis in two and three dimensions (see figure 4; Rodríguez, 2011).

With these models it has been possible to reach the following conclusions about the negative skin friction likely to be developed in the pile shaft when subjected to regional consolidation (Auvinet and Rodríguez, 2017):

- To calculate the negative skin friction, it is necessary to resort to models in which the subsoil consolidation and the development of the positive and negative skin friction on piles are considered as coupled phenomena. In fact, the stress redistribution in the soil associated to the negative skin friction affects the process of consolidation, and reciprocally.
- The analyses performed with this approach show values of the negative skin friction that are, in general, frankly smaller than those estimated in the past, particularly in the case of piles forming part of a cluster. Recent 3-D models (Pineda, 2016; Rodríguez, 2017) have confirmed that the central piles sustain only the effect of seepage forces associated to piezometric drawdown and that only the peripheral piles, particularly those at the corners, are bound to withhold larger loads, corresponding to the mobilization of the shear strength of the soil along the pile shaft.
- The explicit soil-pile interaction analyses show on the other hand that, in the case of point-bearing piles supported by a hard layer and in the presence of negative skin friction, there is no possibility of a loss of strength due to unconfining of the supporting stratum, an issue that had received a lot of attention in the past (Zeevaert, 1959, 1963).

The results of these studies have been included as part of the Technical Standards for Design and Construction of Foundations of the New Building Code for Mexico City (GCDMX, 2017).

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx

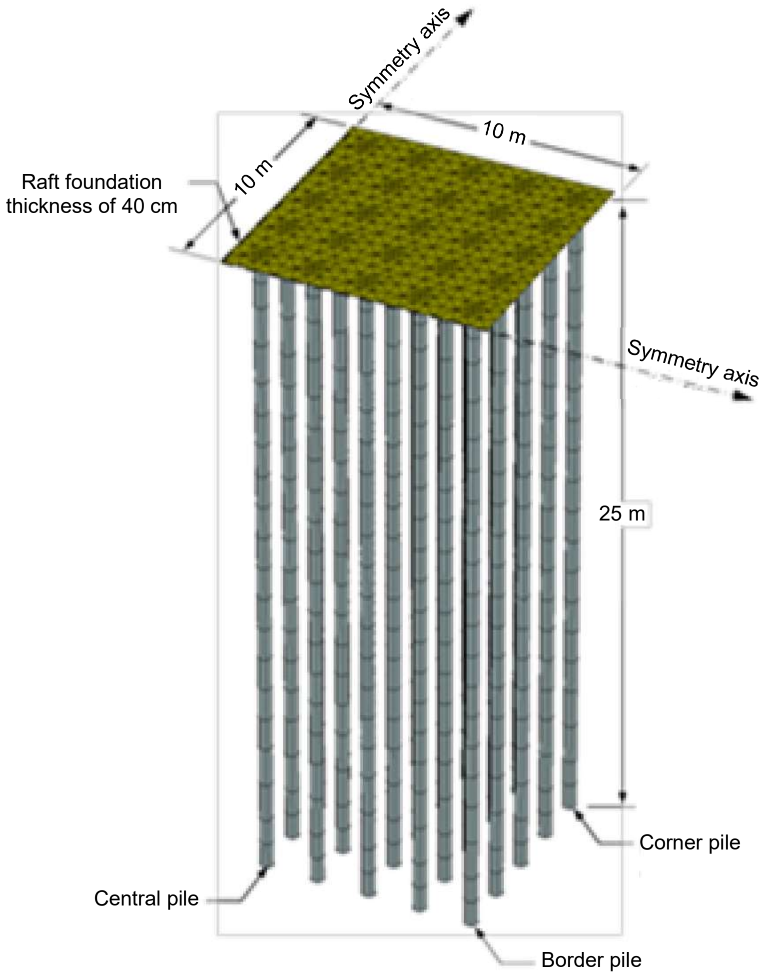

Figure 4. 3-D numerical model of a deep foundation

References

Aguilar, J. M., y E. Rojas (1990). Importantes mejoras en los dispositivos de control de pilotes. *Memoria de la XV Reunión Nacional de Mecánica de Suelos*. San Luis Potosí, México.

Auvinet, G. (1979). Precarga en arcillas del Valle de México. *Memoria del Simposio sobre mejoramiento masivo de suelos*. México: Sociedad Mexicana de Mecánica de Suelos (SMMS): 100-102.

Auvinet, G., y J. J. Hanel (1981). Negative skin friction on piles in Mexico City clay. *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering,* 2: 599-604. Estocolmo.

Auvinet, G., y E. Gutiérrez (1989). Instrumentación de un edificio en proceso de recimentación. *Memoria del simposio sobre recimentaciones*. México: SMMS: 137-148.

Auvinet, G. (1990). Análisis y diseño sísmico de cimentaciones en el Valle de México. *Memoria del simposio Ingeniería sísmica cinco años después del sismo de 1985*. México: SMMS.

Auvinet G., y D. Reséndiz (1991). Foundations on soft soils: design criteria. Special invited lecture. *Proceedings, 9th Pan-American Conference on Soil Mechanics and Foundation Engineering,* IV: 1629-1649. Viña del Mar.

Auvinet, G. (1995). Análisis y diseño sísmico de cimentaciones según el Reglamento de Construcciones para el Distrito Federal. *Memoria del simposio La ingeniería civil a 10 años del sismo de 1985,* 1: 80-90. México: Cenapred.

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx

Auvinet, G. and Rodríguez J.F., (2006), “Rigid inclusions in Mexico City soft soils: history and perspectives.”, Proceedings, International Symposium on Rigid Inclusions in Difficult Soft Soil Conditions, may 11-12, ISSMGE TC36, pp. 25-31, México D.F. ISBN 968-5350-17-5.

Auvinet, G., E. Méndez y M. Juárez (2017). *El subsuelo de la Ciudad de México*, Vol. III, Complemento a la tercera edición del libro de R. J. Marsal y M. Mazari relativo a los avances en el conocimiento del subsuelo en el periodo 1959-2016. México: Instituto de Ingeniería, UNAM.

Auvinet, G., and J. F. Rodríguez-Rebolledo (2017). Criteria for the design of friction piles subjected to negative skin friction and transient loads. *Ingeniería, Investigación y Tecnología,* (3) XVIII: 279-292.

Auvinet, G., (2018a), “*Avances en la caracterización estratigráfica del subsuelo y en el análisis de su comportamiento (1957-2017)*”, Revista Geotecnia, SMIG, No 248, pp. 11-15, Julio-agosto, CDMX. México.

Auvinet, G., (2018b), “*Avances en la ingeniería de cimentaciones (1957-2017)*”, Revista Geotecnia, SMIG, No 249, pp. 15-20, septiembre-noviembre, CDMX. México.

Auvinet, G., (2019), “*Avances en la ingeniería de obras geotécnicas, (1957-2017)*”, Revista Geotecnia, SMIG, No 250, pp. 11-16, febrero, CDMX. México.

Correa, J.J. (1980). Estado actual del conocimiento sobre pilotes de control. *Memoria de la Reunión Conjunta Consultores-Constructores, Cimentaciones Profundas*. México: SMMS.

Cuevas, J. A. (1936). The floating foundation for the new building for the National Lottery of Mexico. *Proceedings, First International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1: 293-301. Cambridge: Harvard University.

Ellstein, A. (1980). El pilote penetrante o P3. *Memoria de la Reunión Conjunta Consultores-Constructores Cimentaciones Profundas*. México: SMMS.

Girault, P. (1964a). A new type of pile foundation. *Proceedings of the Conference on Deep Foundations*, Vol. 1: 329-341. México: SMMS.

Girault, P. (1964b). Discussion. *Proceedings of the Conference on Deep Foundations*, Vol. 1. México: SMMS.

Girault, P. (1971). Fricción negativa y asentamientos de cimentaciones sobre pilotes. *Memorias de la Sesión Especial No. 8, Seventh International Conference on Soil Mechanics and Foundation Engineering*, México.

Girault, P. (1980). Pilotes entrelazados, teoría y funcionamiento. *Memoria de la Reunión Conjunta Consultores-Constructores Cimentaciones Profundas.* México: SMMS.

Gobierno de la CDMX, GCDMX (2017). Normas Complementarias para Diseño y Construcción de Cimentaciones. México.

González-Flores, M. (1948). Level control in buildings by means of adjustable piling. *Proceedings of the Second International Conference on Soil Mechanics and Foundation Engineering,* Vol. 1: 52. Rotterdam.

González-Flores, M. (1981). Raise of a side-settled XVIII century church in Mexico City. *Proceedings of the X International Conference on Soil Mechanics and Foundation Engineering*: 101-105. Estocolmo.

Holguín, E., C. Gutiérrez, A. Cuevas, y J. A. Segovia (1992). *Diseño geotécnico de cimentaciones*. México: TGC Geotecnia.

López Acosta, N. P., y E. Martínez Hernández (2017). Caracterización mecánica de materiales empleados como celdas de deformación en pilotes de control. *Geotecnia* 243: 15-26. México: Sociedad Mexicana de Ingeniería Geotécnica (SMIG).

Marsal, R. J., y M. Mazari (1959). *El subsuelo de la Ciudad de México*, Vols. I y II. 3ª Ed. publicada en 2017 con motivo del 60 aniversario de la fundación del Instituto de Ingeniería, UNAM. México.

Marsal, R. J. (1986). Notas sobre el diseño y construcción de cimentaciones en el Distrito Federal. México: SMMS.

Martínez Hernández, E. (2017). Estudio del comportamiento mecánico de materiales empleados como celdas de deformación en el sistema de pilotes de control. Tesis de maestría. Programa de Estudios de Maestría y Doctorado, UNAM. México.

Martínez Mier, J. (1975). *Influencia del hundimiento de la Ciudad de México en el comportamiento de cimentaciones piloteadas*. México: DEPFI, UNAM.

Menache, A. (2006). New investigations in design and applications of interlaced piles into high compressibility and low shear strength soil deposits. *Proceedings of the Symposium on Rigid Inclusions in Difficult Soft Soil Conditions*. México: TC36, ISSMGE.

Mendoza, M. J. (2004). Comportamiento de una cimentación con pilotes de fricción en la Ciudad de México bajo carga estática y sísmica. Tesis doctoral. Programa de Maestría y Doctorado en Ingeniería, UNAM. México.

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx

Mendoza, M. J. (2007). *Comportamiento y diseño de cimentaciones profundas en la Ciudad de México*. Academia de Ingeniería, México.
Pineda, V. (2016). Fricción negativa en grupos de pilotes en la zona lacustre de la Ciudad de México. Tesis de maestría. Programa de Maestría y Doctorado en Ingeniería, UNAM. México.
Reséndiz, D. (1964a). On a type of point-bearing pile through sinking subsoil. *Proceedings of the Conference on Deep Foundations*, Vol. 1: 385-403. Mexico.
Reséndiz, D. (1964b). Comportamiento de pilotes de sección variable apoyados en la punta en la Ciudad de México. *Ingeniería Civil* 125: 42-50. México.
Reséndiz, D. (1968). Características, instrumentación y comportamiento inicial de la cimentación del Palacio de los Deportes, las obras olímpicas. *Ingeniería*. Número especial. México.
Reséndiz, D., G. Springall, J. M. Rodríguez y R. Esquivel (1970). Información reciente sobre las características del subsuelo y la práctica de la ingeniería de cimentaciones en la Ciudad de México. *Memoria de la V Reunión Nacional de Mecánica de Suelos*, t. I. México: SMMS y Publicación 276 del Instituto de Ingeniería, UNAM.
Reséndiz, D., and G. Auvinet (1973). Analysis of pile foundations in consolidating soils. *Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2: 211-218. MoscowRico Álvarez, A. (1991). Sistemas mecanizados para pilotes. Tesis profesional. Facultad de Ingeniería, UNAM. México.
Rodríguez, J. F. (2011). Modelado del comportamiento de pilotes e inclusiones sometidos a consolidación regional en la zona lacustre de la Ciudad de México. Tesis doctoral. Programa de Maestría y Doctorado en Ingeniería, UNAM. México.
Rodríguez, C. (2017). Diseño geotécnico y estructural de pilotes de fricción y de punta sometidos a hundimiento regional en la zona lacustre de la Ciudad de México. Tesis de maestría. Programa de Maestría y Doctorado en Ingeniería, UNAM. México.
Rodríguez, J. F., and G. Auvinet (2018). Analytical model for friction piles in consolidating soft soils. *Ingeniare*. Santiago [en edición].
Ruiz García, S. (1958). Monografía de la Columna de la Independencia. México: Departamento del Distrito Federal. Noviembre.
Ruiz García, S., y G. Springall (1978). Recomendaciones para restituir las condiciones originales de la cimentación del Monumento a la Independencia. México: Archivo GEOTEC. Octubre.
Santoyo, E., y J. A. Segovia (1995). *Recimentación y renivelación de estructuras y monumentos*. México: TGC Geotecnia.
Santoyo, E., E. Ovando y J. A. Segovia (1999). Evolución de las cimentaciones en la Ciudad de México, partes 1 y 2. *Vector de la Ingeniería Civil* 21 y [illegible] México.
Sociedad Mexicana de Mecánica de Suelos [illegible]iedad Mexicana de Ingeniería Geotécnica, SMMS/SMIG (1976). Cimentaciones en zonas minadas de la Ciudad de México. Memoria del simposio celebrado el 10 de marzo. México.
SMMS/SMIG (1978). El subsuelo y la ingeniería de cimentaciones en el área urbana del Valle de México. Memoria del simposio celebrado el 10 de marzo. México.
SMMS/SMIG (1990). El subsuelo de la cuenca del Valle de México y su relación con la ingeniería de cimentaciones a cinco años del sismo. Memoria del simposio. México.
SMMS/SMIG (1992). Experiencias geotécnicas en la zona poniente del Valle de México. Memoria del simposio realizado el 19 de junio. México.
SMMS/SMIG, II UNAM, ISSMGE TC36 (2002). Foundations in difficult soft soil conditions. Memoria del simposio. México.
SMMS/SMIG (2005). La ingeniería geotécnica a 20 años del sismo. Memoria del coloquio conmemorativo realizado el 7 de septiembre. México.
SMMS/SMIG, II UNAM, ISSMGE TC36 (2006). Rigid inclusions in difficult soft soil conditions. Memoria del simposio realizado el 11 y 12 de mayo. México.
SMMS/SMIG (2017). *Ingeniería de cimentaciones profundas*. México.
Tamez, E., E. Santoyo y A. Cuevas (1992). La Catedral y el Sagrario de la Ciudad de México. Corrección del comportamiento de la cimentación. México: SMMS.
Zeevaert, L. (1959). Reduction of point bearing capacity of piles because of negative friction. *Proceedings of the First Pan-American Conference on Soil Mechanics and Foundation Engineering*, Vol. III: 1145. México.

Zeevaert, L. (1963). Foundation problems related to ground surface subsidence in Mexico City. ASTM (STP) 322: 57-66.
Zeevaert, L. (1973). *Foundation engineering for difficult subsoil conditions* [2ª Ed., 1983]. Nueva York: Van Nostrand, Reinhold.

Valle de Bravo 19, Col. Vergel de Coyoacán
Alcaldía. Tlalpan, C.P. 14340, Ciudad de México.
55 5677 3730 | 55 5679 3676
www.smig.org.mx