

## On the long-term behavior of piled foundations in a regional subsidence environment

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**ABSTRACT** Various cities and ample valleys and coastal plains in the world suffer regional subsidence, mainly due to groundwater extraction by pumping; examples of these are Mexico City, Jakarta, Shanghai, and Antwerp, among many others. Population growth, the scarcity of surface sources of supply, climate change, and even drought in several countries are exacerbating this situation. Subsidence manifests itself with substantial settlement of the land, cracking, and even flooding in coastal areas, for example. This regional subsidence has multiple effects that are both disadvantageous and silent for urban centers, such as damage to road infrastructure, historical monuments, drinking water, sewage systems, and, of course, to building foundations with piles or cast-in-situ shafts. Particular attention is paid in this paper to the last point, first describing the mechanism that gives rise to subsidence; then, we look at the development of compressions that occur in the strata located at different depths. The knowledge of these compressions is crucial for defining the long-term behavior that a foundation and building will experience, since in the first years the settlement of the foundation itself will prevail, but then by dominating the subsidence in the surroundings of that building, an apparent emersion of the edification will occur. The future implications of the differential vertical displacements between piled foundations and the subsoil under strong regional subsidence are exemplified in this paper with real cases of Mexico City (CDMX), warning that the infrastructure works and buildings that initially settle end up with an apparent emersion, over the years.

**KEYWORDS:** Regional subsidence, piled foundations, settlements, emersions, soft soils.

### 1 INTRODUCTION

Subsidence occurs in many locations around the world, often encompassing large regions, valleys, or coastal plains. This phenomenon occurs for reasons such as the exploitation or collapse of underground mining activities, the exploitation or release of hydrocarbons, and collapses of karstic structures, but mainly due to the piezometric drawdown caused by excessive pumping of deep aquifers. This situation has worsened in recent times due to population growth, the resulting need to expand agricultural land, and the development of industrial plants, compounded by the scarcity of surface water sources and frequent drought due to climate change. The central need, then, is to have a sufficient supply of fresh water.

Regional subsidence manifests itself in substantial ground settlements, ground cracking, and flooding. This subsidence has multiple adverse and hidden effects on urban centers, such as damage to road infrastructure, historical monuments, drinking water and sewage systems, and of course, on building foundations.

A large number of papers describe the evolution of regional subsidence of the ground surface in multiple regions of the world. Various interferometry techniques for analyzing satellite images are adopted. However, very little literature analyzes the specific effect of regional subsidence on piled foundations.

This article describes the mechanism by which regional subsidence impacts the foundations of buildings and urban infrastructure, particularly those built with piles or cast-in-situ shafts. Before presenting this point, emblematic cases of regional subsidence that occur around the world are discussed. Subsequently, we address the case of Mexico City (CDMX), where the substantial depletion of pore pressure due to the intense pumping of the local aquifer is combined with the very high compressibility of the thick clayey strata of its subsoil in the area of lacustrine origin.

### 2 REGIONAL SUBSIDENCE AT THE GLOBAL LEVEL

Regional subsidence is exacerbated in coastal areas due to the slow but inexorable rise in sea level caused by climate change. This situation occurs in 15 European coastal cities, as reported by

Boni et al. (2023); among them is Antwerp (Declercq et al., 2023), the second largest port in Europe, where the Scheldt River plain experiences an average settlement of 5.8 mm/year. Other cities such as London, Amsterdam, Valencia, and Marseille show average speeds of around 2 to 5 mm/year. The combination of effects creates a high risk of potential flooding that may occur and that will worsen in the future as these phenomena become more pronounced. The population and infrastructure of a city or even a country will be affected, ultimately representing very high costs.

In the case of Hamburg and Northern Germany (Kersten et al., 2017), the existing rock type, with the formation of sinkholes, has affected the stability of the ground. Boni's study (2023) also indicates that in Naples, volcanic activity is the main cause of subsidence in this city. On the other hand, mining in Greece has caused subsidence in the city of Athens, combined with seismic activity (Parcharidis et al., 2006). The exploitation of gas fields is another cause of subsidence, as is the case in Groningen, The Netherlands, which generates induced seismic activity and ground subsidence. It is worth mentioning that a large part of this city is located below sea level (De Jager and Visser, 2017), which exacerbates the situation. In The Netherlands, economic estimates have been made of the damage caused by regional subsidence, projected to 2050, which amounts to approximately 22 billion euros, confirming the importance of attacking the phenomenon.

Climate change is increasing the likelihood of extreme precipitation in many regions of the world. Recall, for example, the rainfall in the Valencia region in October 2024, where in some places the amount of rain for a year fell in one day. This led to extreme flash flooding in low-lying areas, precisely where regional subsidence is most pronounced.

Of course, the problem is global, with notable cases also found in the Americas, Asia, and Africa. Serious flooding problems are known in Jakarta, Indonesia, given its location on a relatively flat, low-lying floodplain subject to subsidence (Abidin et al., 2011). Similar risk exists in areas of Shanghai (Yue et al., 2015). In estuaries and floodplains such as the Mississippi River Delta in the USA and the Fraser River Delta in British Columbia, Canada, settlement records are on the order of 2 mm/year. However, higher velocities are generated by the anthropogenic action of pumping, as in the Po River Delta in Italy or the Nile

River (Saleh et al., 2019) in Egypt, with up to 15 mm/year. Chiba Prefecture in Japan is severely affected by subsidence problems from a gas field, tectonic movements, and groundwater extraction for agricultural and industrial use (Muramoto et al., 2023).

Africa is the continent with the most significant water scarcity. Therefore, the exploitation of the liquid is a priority in countries like Nigeria, where the extraction of water has caused considerable subsidence in four of its coastal cities, in addition to the rise in sea level due to climate change and exploitation of oil and gas deposits (Ikuemonisan et al, 2023).

In all the measurements or estimates of ground subsidence described here, various variants of satellite monitoring techniques have been used to quantify the evolution of vertical ground surface movements, analyzing images covering observation periods of up to 20 years. The exception to this is the practice in Taiwan, where not only a conspicuous case of subsidence is distinguished, but also its emphasis on measuring (Hung et al., 2023) not only ground surface movements, but also on recording the contribution to these movements of the different strata within the soil mass, down to depths of 300 m. Measurements in the alluvial fan of the Choushui River, the longest in the country, establish that between 2014 and 2018, subsidence accumulated 18 cm, causing problems for train operations, for example.

To understand the behavior of deep foundations in environments with regional subsidence, it is essential to understand the compression experienced by each stratum. The sum of the compression of each stratum determines the final settlement observed on the ground surface. Therefore, measurements of strata's compression at depth, such as those conducted in Taiwan, provides valuable information. These measurements allow researchers to understand the evolution of surface and underground subsidence from space using an automatic monitoring system with measurement points both on the ground surface and in wells. Monitoring not only displacements but also piezometric levels at depth allows researchers to understand the subsidence mechanism. It enables more rational use of pumping strategies and the management of the entire sensor system. The Internet of Things (IoT) technology they have developed has proven very useful.

### 3 REGIONAL SUBSIDENCE IN CDMX

To complete the drinking water supply to the population of Mexico City, down to more than 200 m-depth wells have been required for water extraction, resulting in significant piezometric drawdown due to the intense pumping that occurs at depth. Despite the depletion of pore water pressures occurring to a much greater depth than the highly compressible, soft clayey strata, the induced stress increments have a substantial impact on them. A clear and possibly extreme example of regional subsidence in the world has been occurring for decades, not on the coast of Mexico, but in the country's capital, at 2,240 meters above sea level, a metropolis that is home to one of the largest human conglomerations in the world. Here, at least, we do not have the sea level problems that coastal cities face. The issues arising from subsidence are enormous in Mexico City, since while in coastal European cities it occurs at a rate of several millimeters per year, in some regions of Mexico City it reaches speeds of several decimeters per year (Auvinet et al., 2023). There are places where subsidence occurs at speeds of little more than a millimeter per day.

Monitoring this subsidence has allowed to define (Figure 1) values as high as 40 cm/year. Since this movement is widespread,

the subsidence is not perceptible to the population, except when the apparent emersions exhibited by certain buildings and infrastructure projects are measured and analyzed, or when the effects of differential movements between adjacent buildings with different type of foundation are evident, or when differential settlements happen in short distances causing ground cracking.

The regional subsidence levels experienced by Mexico City are world records; considering just over 160 years during which direct records of topographic leveling are already available, subsidence of just over fourteen meters has been measured in certain areas (Marsal and Mazari, 1969; Tamez, 1992).

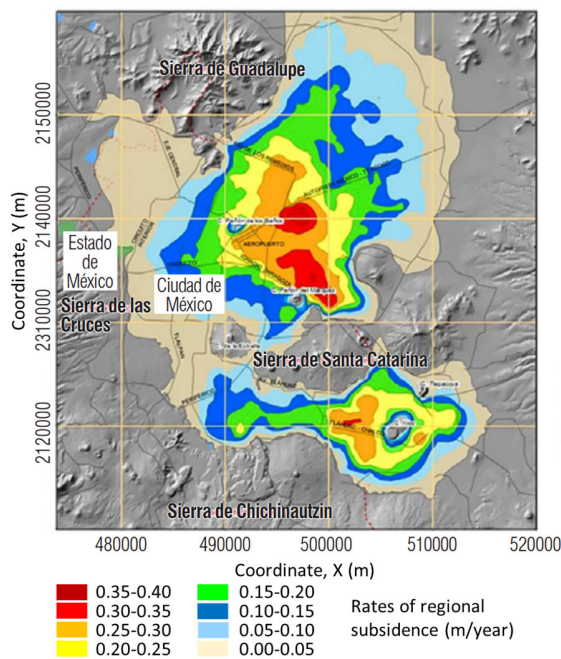


Figure 1. Rates of regional subsidence in Mexico City (NTC-Cimentaciones, 2023).

The mapping typically used in our area of regional settlement distribution corresponds to what occurs on the ground surface. However, the emersions exhibited by certain buildings or steel casings that served as pumping wells at great depths reveal that they move at different vertical velocities than those experienced by the natural terrain. For this reason, there is interest in understanding how much compression each of the large strata that constitute the subsoil contributes to this surface subsidence. Understanding the magnitude of the compression experienced by the different strata is of significant value for predicting the future building behavior, and then to impact the design of building foundations and infrastructure projects in Mexico City.

### 4 BRIEF STRATIGRAPHIC DESCRIPTION OF CDMX

The city has three distinct geotechnical zones. Zone I, or the Hills, consists of basaltic outflows to the South and soft rock deposits of volcanic origin to the West. Zone III, or the Lake Zone, which is the focus of this article, is composed of very soft, saturated clays of lacustrine origin (Marsal and Mazari, 1969). Among them, the Transition or Zone II is distinguished, with soils intermediate in nature between those mentioned above. Figure 2 shows a typical stratigraphic profile of Zone III, in which, beneath a layer or crust of anthropogenic deposits and soils affected by solar drying, there

are clayey deposits of very high compressibility and low shear strength, in the so-called Upper Clay Formation (UCF), which reaches depths of up to 20 and 35 m. This profile includes the tip strength from a CPT test and the number of SPT test blows. The average natural water content of this deposit is 300%, with prevalent extreme values of 400%, or more. Clay compressibility exhibits significant variability depending on the loading history, which determines areas with almost NC clays with light preconsolidation. Example of this condition is the downtown area whose average undrained strength at the UCF is 30 kPa. However, it is not unusual to find values as low as 10 kPa. Ample data on compressibility for Mexico City clay can be found elsewhere (Marsal and Mazari, 1969; Zeevaert, 1973; Santoyo et al., 2005).

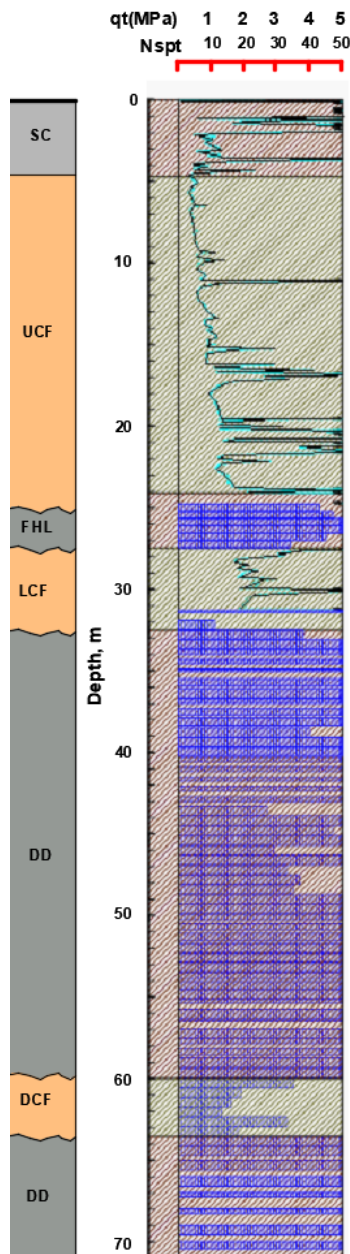


Figure 2. Typical stratigraphic profile in Zone III of Mexico City (Ibarra et al., 2018).

The First Hard Layer (FHL) underlies the UCF. It consists of compact sandy-silty soils with thicknesses of 2 to 5 m. Beneath this stratum is the Lower Clay Formation (LCF), which has more consistent clay-silty soils than those of the UCF, and with more sandy thin strata. After this layer are the so-called Deep Deposits (DD), consisting of compact granular soils mostly of alluvial origin, interbedded deep consistent clayey strata (DCF).

## 5 ABOUT SUBSOIL COMPRESSION IN CDMX, DUE TO SUBSIDENCE

It is often mistakenly assumed that the FHL or even the DD are immovable strata that do not settle. Measurements at the Metropolitan Cathedral (Downtown) reported by Santoyo et al. (2005) have shown that up to two-thirds of the regional settlement experienced by the land surface of Mexico City corresponds to the compression of the strata located below the FHL.

Measurements similar to those taken at the Metropolitan Cathedral were carried out during the development of the New Mexico City International Airport (NAIM) project in Northeast Mexico City, the construction of which was finally canceled. For this exploration, we placed deep-level topographic references at depths of 200, 100, 60, and 40 m, as well as one more on the ground surface. Topographic levelling carried out over a year on a bench located on a rocky hill considered fixed, allowed us to know the evolution of the settlements of each of these references at depth, as shown in Figure 3. It was possible to define that the surface of the land where the new airport was to be built settled at a speed of 14.2 cm/year; incidentally, 10 cm/year less than the rate at which the current Mexico City International Airport (AICM, Benito Juárez) is sinking.

The interpretation of Figure 3 allows us to establish the contribution of each thickness of sediments, considering the evolution of the depth of the deep reference levels. Of the annual settlement of 14.2 cm that occurs on the ground surface, the most significant contribution to this subsidence is given by the first 40 m with 5.8 cm of compression; from 40 to 60 m, 0.4 cm; from 60 to 100 m, 4 cm; and from 100 to 200 m, 4 cm.

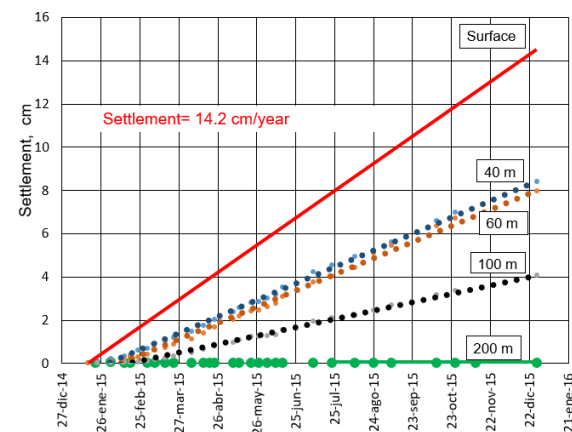


Figure 3. Record of regional subsidence at different depths in the NAIM during 2015.

Figure 4 shows the results from the deep-level benches of the Cathedral and the NAIM. The percentage contribution to regional subsidence recorded by each thickness between benches is shown. In Mexico City, measurements are only available down to 200 m depth, but underlying strata likely also contribute some

compression. Indeed, in the case of the alluvial fan in Taiwan (Hung et al., 2023), measurements show that the strata between 200 and 300 m produces 17% of the subsidence that occurs on the ground surface.

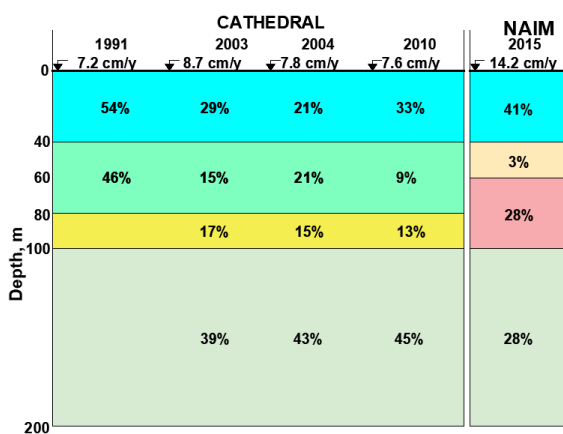


Figure 4. Compression of the different strata and their contribution to ground subsidence in Mexico City.

It can be observed in the evolution of the subsidence phenomenon (Cathedral) that the contribution of the shallower strata seems to decrease, proving that the most significant contributions to the regional surface subsidence that occurs in the heart of the capital are from the deep strata. This fact is due to a pumping process at greater depths, more intensely, and for more extended periods. In areas with a lower stress history and therefore with clays practically in a normally consolidated condition, these strata would have greater interaction with piled foundations, due to the mechanisms discussed below.

## 6 ABOUT THE EFFECT OF SUBSIDENCE ON DEEP FOUNDATIONS IN CDMX

The Mexico City Lake Zone features a considerable number of buildings, bridges, and viaducts that exhibit apparent emersion, either as a result of their pile tips resting on the FHL or as a result of cast-in-situ shafts resting on the DD. In both cases, the common characteristic is that their tip rests on a resistant and low-compressibility soil stratum. The mechanism that explains the emersion is as follows.

A certain amount of generalized settlement occurs in the FHL as a result of the compression of the subsoil below that level, due to the piezometric lowering induced by the pumping of water at depth. Added to this deformation of several centimeters or decimeters per year is the generally minimal compression of the stratum where the tips of the piles or piers rest, which occurs gradually as construction progresses. In the long term, and once the building no longer experiences significant load changes, the compression of piles or shafts themselves, as a structural element, can be considered relatively negligible. Therefore, while the vertical movement of the ground floor of a piled structure is practically the same as that experienced by the FHL, the subsoil of the UCF and surrounding SC continues to settle due to regional subsidence.

Thus, strictly speaking, a building sinks over the long term due to regional subsidence, if we compare its level to a fixed point, such as the one mentioned on a rocky promontory (Atzacolco bank). The subsidence of its ground floor will be essentially the

same as that of the base or tip of its shafts or piles. However, despite this subsidence, the building will exhibit emersion regarding the surrounding natural ground level. The magnitude of this emersion will be equal to the compression suffered by the thickness of the subsoil located between the ground surface and the foundation level of the pile's or shaft's tip. There are conspicuous examples in Mexico City downtown of rises reaching 1.7 m in the first buildings with point-bearing piles on the FHL.

The above-mentioned for piles or shafts resting on the FHL is strictly applicable to the case where the pile tips are carried to any level of the DD. Since the length of the piles covers a greater thickness of subsoil, the compression of the subsoil will be greater than if it were in the FHL, and consequently the apparent emersion will be greater.

Due to the large emersion exhibited by foundations with point-bearing piles, solutions were generated aimed at eliminating or at least reducing them (Zeevaert, 1973). Foundations with a concrete box placed at a certain depth were adopted, the objective of which was to replace the stress relieved by the excavation with the weight of that box and superstructure. As the buildings grew, friction piles were added to this solution, whose load-bearing capacity came from the adhesion-friction between the pile shaft and the soils of the UCF. In this case, designers took care to ensure that their tip did not touch the soils of the FHL, providing a "cushion" of approximately 3 m. Multiple buildings and viaducts with an initial design based on friction piles, currently (long-term) behave as "point-bearing piles" (Mendoza and Garcia, 2021) exhibiting apparent emersion. Considering the magnitude of the settlement of these foundations alone does not explain why the "cushion" has been exhausted, so in the vast majority of cases the simplistic explanation that the pile tips have reached the FHL is ruled out.

This apparent emersion has a partial explanation (Mendoza et al., 2022) by the change over time in the resistance and compressibility properties of the soils close to the FHL, in terms of the consolidation process. Concerning this effect, Ovando and co-authors (2007) have shown the gain recorded in cone tip resistance in CPT tests carried out at the same site in Mexico City but on different dates; the first in 1986, and then in 2000. In the same testing programs, a light increment in the preconsolidation pressure samples was also recorded for the most recent tests.

Conventional friction pile design in Mexico City adopts a total stress approach with undrained shear strength. However, as the undrained conditions gradually disappear over time, the stress increases caused by foundation loading become effective, resulting in greater strength and lower compressibility of the soils around the piles. Combining the compression experienced by the UCF due to subsidence and the gain in soil stiffness near the piles as they consolidate under the applied loads, explains partially the transformation in the behavior of foundations initially designed as friction piles.

Given the unique challenges posed by Mexico City's exceptionally high subsidence rate, a building with a piled foundation will primarily experience settlement due to the foundation-structure system in the initial years. Still, the tendency is to reduce its settlement rate. However, as the regional subsidence in the building's surroundings continues at a relatively constant rate, it begins to dominate the performance of the system.

The emersion described above causes serious problems for the operation and aesthetics of buildings and infrastructure. An example of this is shown in Figure 5, which shows that the long-term emersion of the initially designed friction-piled box

foundation from the supports of the viaduct (Metro) provokes a deficient and dangerous operation of the lower road.

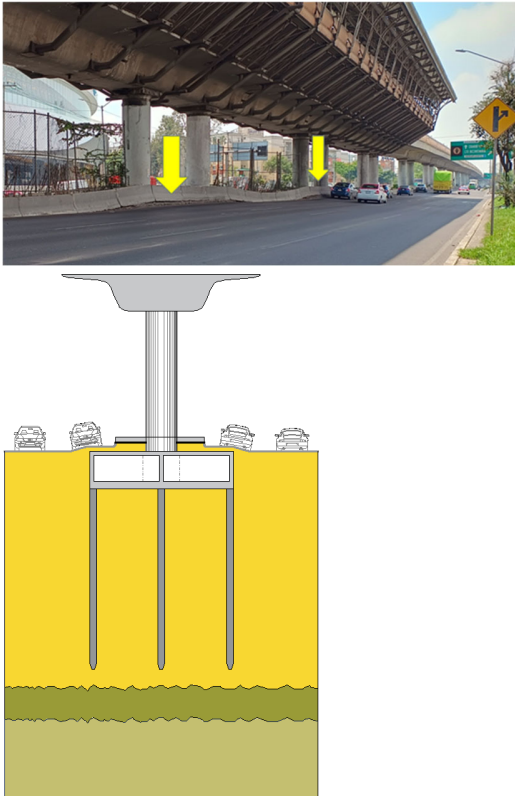


Figure 5. Emersion of a piled box foundation for the Metro viaduct, affecting the lower road.

The case history of a mixed foundation composed of a box and friction piles for a bridge in Mexico City (Mendoza et al., 2000, 2004) is presented below, which exemplifies the above.

The movements of support 6 of an urban bridge were recorded from the beginning of its construction and for approximately 9 years of operation, a period during which it suffered settlements of five decimeters, as shown in Figure 6. These settlements were already evident after four years of operation, with a clear depression of 40 cm (Figure 7a), even generating local flooding when heavy rains occurred. Its piles were working by positive friction practically along their entire length. However, as shown

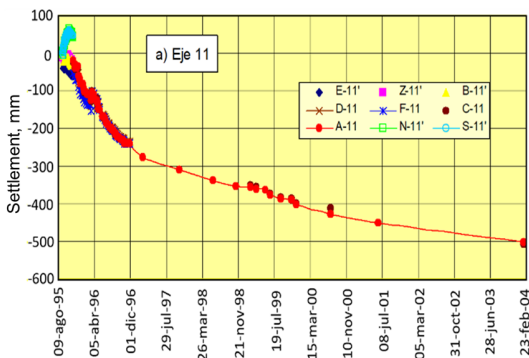


Figure 6. Evolution of the settlement of support 6 of the Impulsora Bridge in Mexico City (Mendoza et al., 2000).

in Figure 7b, taken after 25 years of operation, it had a noticeable promontory as a result of the foundation's emersion, in the same area where a depression had existed years before.



Figure 7. Medium-term settlement and long-term emersion in a piled box foundation in Mexico City.

This situation necessitated constant releveling of the pavement, first by adding layers of asphalt, and more recently by removing them. This simple solution for the pavement is not so simple for the interaction between this bridge and the adjacent structure of a Metro station on a non-piled foundation, to which it serves as an access. The differential vertical displacements between the two structures are of utmost concern and require constant attention (Mendoza and García, 2023).

Another effect that we have observed in several emerged piled foundations in Mexico City is, under a long-term basis, the generation of voids between the lower bed of the bottom slab and the foundation soil, as shown schematically in Figure 8. This phenomenon leaves the connection of the pile or shaft head with the foundation beams exposed, leading to a short column condition and thus a possible structural failure of the piles, mainly in the event of seismic events. Faced with this situation, we distinguish two different approaches. One approach is to practically and structurally separate beams and piles, allowing them to work only under axial load. The other is to reinforce and detail the area near the pile heads to resist the bending moments that develop. Experiences in Mexico City and recent ones in Wajima Japan after the Mw 7.8 earthquake on the Noto Peninsula on January 1, 2024 (Mendoza et al, 2024) where a building collapsed completely, showed the need to link this connection to resist not only the stresses mentioned above but also to have the capacity to transmit tension loads for extraction work, to achieve the resistant torque of the foundation against the seismic overturning moment.

In addition to the emersion and possible voids generation below a piled foundation in a regional subsidence environment,

there is an additional factor that designers must consider in the structural design of piles and cast-in-situ shafts. This factor is the negative friction generated in the shaft of these foundation elements (NTC-2023) by the drag force generated by the surrounding soil, which moves downward at a speed greater than that of the piles or cast-in-situ shafts.

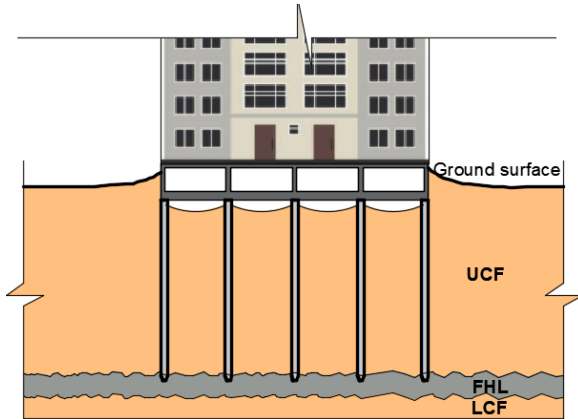


Figure 8. Voids forming beneath the foundation slab due to severe emersion in Mexico City.

## 7 CONCLUSIONS

This paper has exposed the diverse problems faced by alluvial fan regions, ports, and cities around the world, as a result of subsidence. This phenomenon occurs mainly due to the piezometric drawdown generated by intense and prolonged water pumping. The induced regional settlements in ports and coastal cities will be critical in the future due to the sea level rise caused by climate change.

The subsidence phenomenon finds a conspicuous example in the lacustrine region that occupies a large area of Mexico City, where regional subsidence in certain portions reaches rates of up to one millimeter per day. In an environment of intense regional subsidence, such as that experienced by Mexico City, problems in buildings, viaducts, and bridges with piled foundations have manifested in the form of apparent emersion, affecting roads, urban services, and historical monuments, and generating problems between adjacent structures due to differential movements.

This paper has documented that in an environment of intense regional subsidence, piled foundations will inevitably suffer apparent emersion over the long term. This emersion has, in several cases, led to the creation of voids between the foundation slab and the subgrade soil, thereby losing contact and, consequently, the contribution of the slab. Furthermore, it makes the piles more vulnerable, especially to seismic events, due to a short column condition.

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