

Sand-based mechanical leveling system to mitigate the effects of subsidence on structures in Mexico City

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ABSTRACT: Mexico City's infrastructure faces significant challenges due to regional subsidence, which leads to progressive differential settlements and compromises both the safety and serviceability of structures. This issue is further intensified by the city's dependence on underground aquifers for water supply, a practice that accelerates subsidence. Effectively addressing these conditions requires the development of innovative, cost-effective, and low-maintenance solutions to ensure infrastructure remains safe and functional over time. This paper introduces a mechanical leveling system specifically designed to mitigate differential settlements by utilizing the dual fluid-solid behavior of sand. The design prioritizes simplicity, cost-effectiveness, and minimal maintenance, making it a practical and adaptable solution for urban infrastructure affected by subsidence. Its first full-scale implementation was planned for an elementary school auditorium in the Iztapalapa borough, one of the most severely affected areas in Mexico City by this phenomenon, a project that remains under development. This work emphasizes the importance of innovative geotechnical solutions to address subsidence-related challenges and highlights the essential role of interdisciplinary collaboration in developing practical systems that enhance urban infrastructure resilience, with a focus on safety, functionality, and long-term sustainability.

KEYWORDS: sand, subsidence, differential settlement, tilt.

1 INTRODUCTION

Regional subsidence is an increasingly common phenomenon in densely populated urban areas, primarily associated with intensive groundwater extraction. In Mexico, cities such as Guadalajara, Tepic, Irapuato, León, Silao, Zamora, the State of Mexico, and Mexico City have experienced progressively higher subsidence rates. Similar conditions have been reported in countries such as Indonesia, China, Japan, Iran, and the United States, where subsidence is mainly attributed to groundwater overexploitation and, in some regions, to oil and gas extraction (Chaussard, et al., 2013; Hu, et al., 2004).

In all these cases, differential settlements cause structural damage, disrupt public services, and significantly increase maintenance costs. These effects accumulate over time and are especially pronounced in vulnerable areas with limited technical and economic capacity to respond, creating persistent conditions of urban fragility (Brugada, et al., 2022).

Mexico City exemplifies the challenges posed by subsidence. The city is located in a valley formed by volcanic events and lacustrine deposits, bounded by surrounding mountain ranges. The lacustrine zone corresponds to flat areas where the subsoil consists of thick layers of very soft, highly compressible clays, interbedded with dense sands, volcanic ash, and stiff layers formed by solar drying (Auvinet, et al., 2020). Decades of groundwater extraction driven by population growth have accelerated the consolidation of these soft soils, producing subsidence rates exceeding 30 cm per year in some areas. The combination of thick compressible deposits and irregular bedrock topography generates significant differential deformations that compromise the integrity of housing, schools, and essential infrastructure, particularly in zones with abrupt stratigraphic transitions.

Given this scenario, there is an urgent need for innovative, low-cost, and low-maintenance geotechnical solutions that help restore or preserve structural performance in vulnerable contexts. Most current approaches remain reactive, implemented only after significant deformation has occurred, and often involve complex or expensive interventions such as foundation reinforcement, sub-excavation, soil improvement, or mechanical and hydraulic leveling systems. Examples of mechanical leveling systems include the "pilotes de control", used in more than 700 buildings in Mexico City, and the Jack-Up System applied at the Passenger Terminal of Kansai

International Airport in Japan (Lopez, et al., 2021). While technically effective, these systems typically require frequent specialized maintenance and substantial investment.

In contrast, this paper presents a sand-based mechanical leveling system designed from a preventive and adaptive perspective. Although concepts involving sand flow have been previously applied in structures such as the Hotel Bamer in downtown Mexico City and certain API tanks, these were implemented as corrective measures long after construction. The system proposed here enables early, progressive adjustments in response to ground movements, reducing the likelihood of severe deformation before structural integrity is compromised.

The system was initially developed for a school auditorium located in the Iztapalapa borough of Mexico City, one of the areas most susceptible to subsidence-related damage due to the presence of buried geological mounds. The system has been validated through physical modeling and remains ready for application in similar conditions. The proposed approach aims to offer a simple, low-cost, and scalable alternative to mitigate the effects of subsidence in socially and economically constrained environments.

Finally, the system aligns with broader sustainability and resilience objectives. It supports the United Nations Sustainable Development Goals (SDGs) by promoting resilient and adaptable infrastructure in vulnerable zones (SDG 9), extending the lifespan of critical facilities and housing in subsidence-affected areas (SDG 11), and reducing environmental impacts through lower material consumption and fewer large-scale interventions (SDG 13).

2 CONCEPTUAL AND TECHNICAL BACKGROUND OF THE SAND-BASED LEVELING SYSTEM

2.1 Justification

Subsidence must now be considered as a fundamental hazard in structural design throughout Mexico City lacustrine zone; it is a regional long-term phenomenon, so communities must adapt to coexist with it, while engineers are responsible for ensuring safety and functionality over the service life span of the structures, considering stratigraphic variability and its evolution over time. This challenge intensifies in areas where morphological formations introduce abrupt changes in

subsurface stratigraphy. In the Iztapalapa borough, prominent geological formations such as “Peñón del Marqués”, “Cerro de la Estrella” and “Sierra Santa Catarina” cause dramatic variations in the thickness of compressible soils over relatively short distances, creating zones highly susceptible to cracking, (Figure 1).

In this context, differential settlements in urban areas generate consequences that extend beyond structural deformation, particularly in zones with high social vulnerability.

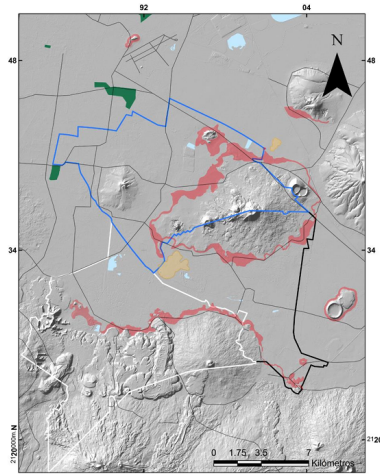


Figure 1. Areas classified as susceptible to soil fracturing (highlighted in red), with the Iztapalapa region outlined in blue. (Auvinet, et al., 2020)

In many neighborhoods of Iztapalapa, informal growth and self-built housing predominate, with most structures made of unreinforced masonry and frequently constructed without technical supervision, proper foundation design, or seismic detailing. As a result, even moderate settlements can cause severe cracking, tilting, and service disruptions that compromise both safety and functionality, (Figure 2).



Figure 2. Damage and magnitude of a step crack in Iztapalapa. (Auvinet, et al., 2020)

The damage is not limited to private dwellings. Schools, health clinics, and community centers also suffer from floor and wall drifts, misaligned doors and windows, ruptured plumbing, and in general loss of functionality due to differential settlement. This is evident in neighborhoods like “Santa María Aztahuacán”, where active cracking zones affect homes, streets, pipelines and public infrastructure, (Figure 3).

According to the “*Visor de Análisis de peligros, vulnerabilidad y exposición*” (Secretaría de Gestion Integral de riesgos y Protección Civil, 2017), the area remains highly vulnerable, in response, local authorities have oriented substantial economic resources to infrastructure rehabilitation, including repairs of pipelines, public buildings, and roadways, (Brugada, et al., 2022).

One of the most visible and damaging effects of the regional subsidence is the formation of cracks. In Iztapalapa, solutions like sand boxes have been implemented to mitigate step cracking in streets and parks (Auvinet, et al., 2020), yet the magnitude and persistence of the phenomenon exceed available

resources, reinforcing the need for preventive and low-complexity alternatives in housing.



Figure 3. Map of cracks in “Santa Cruz Meyehualco” and “Santa María Aztahuacán”. (Auvinet, et al., 2020)

Furthermore, although authorities have implemented response measures, the limited institutional capacity and economic resources often lead to a gradual deterioration that becomes normalized by the affected population. Families adapt to sloping floors, recurrent leaks, and fractured walls, frequently unaware of the increasing structural risk. In this context, the inability to address differential settlements becomes both a technical and social problem.

Addressing this challenge requires flexible structures capable of supporting differential settlements an equipped with systems that allow for frequent, simple interventions to control tilt or level deviations. To be viable in these communities, such systems must minimize dependence on complex maintenance, external machinery or specialized expertise, making them both technically effective and accessible in financial and operational terms.

2.2 Description of the Leveling System

The proposed leveling system operates similarly to seismic isolation systems, establishing a deliberate decoupling between the foundation and the superstructure. It consists of a container filled with clean, homogeneous silica sand, on which the structural supports rest, as illustrated in Figure 4.

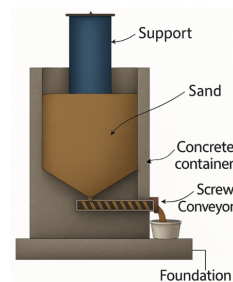


Figure 4. Schematic diagram of the system

The core function of the system is to allow controlled vertical adjustments. By extracting sand from the bottom of the container, the support elements gradually descend, maintaining a level superstructure even in the presence of differential settlement beneath the structure.

This system, known as the Stabilization and Leveling System through Sand Flow (SENA, for its acronym in Spanish), leverages the dual behavior of sand, a granular material capable of exhibiting both solid-like and fluid-like characteristics depending on the conditions (Flores, 2003). Under normal loading, the dense sand reliably transmits vertical stresses (Yang, 2016), while under dynamic forces it acts as a frictional interface resisting lateral loads at the contact with the supports. It is important to note that the superstructure is assumed to transmit negligible moments or tensional forces to

the base, meaning that the load transfer mechanism is predominantly axial. Under these conditions, seismic base shear is resisted by friction at the support–sand interface, ensuring adequate lateral stability. This assumption allows the leveling device to operate essentially under vertical compression, simplifying both the mechanical behavior of the sand and the calibration of the system.

Adjustments are performed via a helical mechanism located at the base of the container, which mobilizes the sand and induces localized flow (Jaeger, 1996). As sand is discharged, the supports settle in a controlled manner, with displacement directly proportional to the volume of sand extracted.

Unlike fluids, which follow Torricelli’s law, where discharge velocity depends on pressure head, dry sand exhibits a constant flow rate that is independent of the overlying pressure (Jaeger, 1996). This unique property enables precise adjustments without the need for complex auxiliary equipment or pressurized systems, ensuring predictable and reliable performance regardless of the structural load.

This particularity allows the control of the sand flow and enables the system to work independent of the magnitude of the loads transmitted by the superstructure.

The flow rate is established as a function of the sand exit area that will be used in the leveling system. The flow (mass per unit of time) of a granular material with density ρ through an opening of area A under the action of the gravity g , is:

$$\frac{dm}{dt} = k\rho\sqrt{g} A^{5/4} \quad (1)$$

Where, k is a characteristic constant of the granular material.

The dependence of the flow $Q = dm/dt$ with the area of the exit hole can be established with Eq. 2.

$$Q = c \cdot A^{5/4} \quad (2)$$

Where c is constant material-dependent.

$$c = k\rho\sqrt{g} \quad (3)$$

To obtain the constant c of the silica sand used on the system, the concept of the Atwood machine is used. This involves measuring the mass of sand that passes through a hole of diameter D , defined previously, per second (Flores, 2003).

The graph shown in Figure 5 presents the flow rate obtained for different exit areas. The flow rate is constant over time, and only the gradient of the line varies. In Figure 6 the same information but on a logarithmic scale is presented. In all cases, it is observed that the lines are parallel to each other, and the displacement in the x-axis depend on the different exit areas.

This particular behavior reveals that the flow rate depends only on the exit area and is independent from the pressure above.

Considering the flow rate defined previously for each exit hole, Figure 7 presents the characteristic curve of the silica sand used on the system; where the x-axis corresponds to the exit area, and the y-axis, the flow rate. The curve is given by the Eq. 4.

$$Q = 0.0357 \cdot A^{5/4} \quad (4)$$

Either with the graph included in Figure 7 or the use of Eq. 4, it is possible to determine the area of the bottom opening hole that feeds the helical element, controlling the sand flow rate depending on the descent velocity needed for the superstructure. Additionally, it is crucial that the descent is infallible and easily controlled.

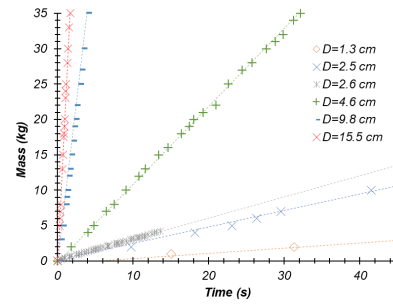


Figure 5. Time vs mass.

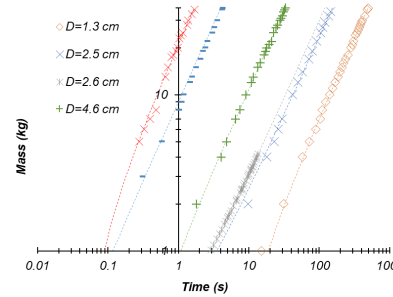


Figure 6. Log Time vs log mass.

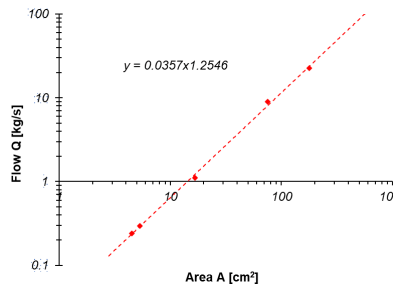


Figure 7. Exit area vs Flow rate.

Another important aspect to consider, is the way the sand descends through the container. To prevent P-Delta effects on the superstructure, adjustments must be slow, gradual, and fully controlled. Moreover, the system must ensure fail-safe operation to avoid unintended displacements during leveling procedures.

As in an hourglass, the flow of sand produces a cone-shaped surface. This shape can be controlled by modifying the design of the container’s bottom. The cone shape is a consequence of a phenomenon called funnel flow, in which only a central channel is mobilized, while the surrounding material remains stagnant. This causes phenomena such as rat-holing, uneven settlement, internal arching, or even jamming and structural failure (Jenkins, 1964).

This behavior was observed experimentally through a physical model in which sand layers were placed inside a flat-bottomed container, (Figure 8). Upon opening a hole at the base, a central flow channel formed while the surrounding material remained static, generating a cone-shaped surface depression, an unmistakable sign of funnel flow. To prevent such conditions, the bottom of the container is designed with inclined walls to promote mass flow, a discharge pattern in which the entire sand mass moves uniformly during extraction. This behavior is crucial to ensure that all particles contribute simultaneously to the descent of the support, maintaining vertical alignment and preventing localized instabilities.



Figure 8. Physical model and effect of funnel flow in the sand

2.3 Operation of the system

To implement the system in a structure, the ground floor slab must be designed as a transfer slab with only four supports, similar to a table. A SENFA device is placed beneath each support, and each unit must have its own independent foundation.

To represent the whole system and simulate the leveling process, we built and 3D-printed a scale model of the superstructure–SENFA–foundation–soil assembly, (Figure 9). The compressible soil was represented by hydrogel bubbles, which reduce their volume through water loss, while the basement layer was represented by gravel, generating an irregular surface. As shown in the model, the foundation consists of combined footings in one direction and strap beams in the other, primarily to prevent horizontal displacement caused by potential soil cracking.

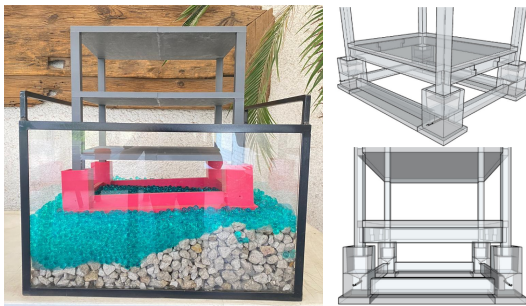


Figure 9. Scale model superstructure-SENFA-foundation-soil.

Once the structure exhibits a differential settlement detected by a simple level control (“bubble level”), the leveling process begins by identifying the highest point and then removing sand through the rotation of the screw conveyor. The structure’s response is almost instantaneous, and because the sand discharge is controlled, it can be stopped promptly when the bubble returns to its centered position. This procedure can be repeated over the years, and the differential settlement may go unnoticed by the users. Notably, the simplicity of the system allows safe manual operation by personnel without extensive specialized training.

Figure 10 illustrates the effects of regional subsidence and the leveling sequence. Note that in this representation, the leveling is illustrated as being performed after the maximum deformation has occurred.

To determine the dimension of the SENFA system we considered the cross section of the support from the super structure, the maximum estimated differential settlement, the rotation angle to determine the separation between the wall off the concrete container and the support, and the angle needed to bring on a mass Flow in the exit point. Also, to calculate the volume of sand needed to level the structure we considered three key points: first, the maximum estimated differential settlement, which includes settlement due to subsidence, short-term elastic settlement, and settlement from consolidation due to a net increase in stress. Although the settlement can be calculated analytically or through finite element analysis, due to the sensitivity of the parameters involved, it is prudent to

treat these as values within a range, establishing a margin of variation. Second, at the minimum operational level, we specified a thickness of sand to ensure that the supports never come into direct contact with the container walls. Third, we accounted for human factors. Since the leveling process is manual, we added an additional reserve thickness of sand to accommodate potential handling inaccuracies.



Figure 10. Scale model, differential settlement caused by regional subsidence and irregular basement, before and after leveling

3 APPLICATION, ADAPTATION, AND SCALABILITY

3.1 Prototype development for a specific case study

The construction of a school complex is planned in Iztapalapa, Mexico City. The project demands the construction of an auditorium, that is placed on a critical zone of the property land, where the layers of the soil have an abrupt variation due to the thickness strata produced by the presence of a buried mound of volcanic materials.

According to “Sistema de Evolución del Hundimiento y Espectros de Diseño Sísmico”, the regional subsidence velocity recorded in the area ranges between 14 and 22 cm of settlement per year. Therefore, an average subsidence rate of 18 cm/year was assumed.

The geological–geotechnical scenario for the study site was developed from the results of the geotechnical and geophysical exploration campaign, as well as laboratory and in situ tests. As shown in Figure 11, the thickness of the compressible clays varies drastically within the same property.

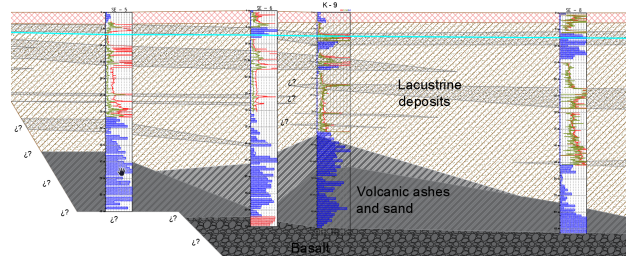


Figure 11. Representative stratigraphic section.

Figure 12 presents the total displacement in the specific zone where the auditorium will be located. As it is shown, the differential settlement is on the order of 30 cm over 3 m. This condition is independent of the load condition, so, when considering the loads of the superstructure, the inclination will be accentuated. Based on a finite element model analysis, the implementation of the SENFA system was considered a viable, low-maintenance, and cost-effective alternative to control the tilt of the superstructure in a public school.

3.2 Field Applications and Scalability of the SENFA System

The SENFA system was designed and evaluated for a public-school auditorium in Iztapalapa as a pilot application to control structural tilt caused by differential settlements in a challenging geotechnical context (Amezcuca, et al., 2024).

Although the full-scale installation has not yet been carried out, the complete development process yielded detailed structural, architectural, and construction plans that

demonstrated the system's feasibility, constructability, and compliance with load-transfer requirements and site constraints. This level of definition positioned the system as a fully engineered solution ready for implementation. The design was further supported by physical modeling and operational analyses, providing a solid technical basis for deployment. As an innovative geotechnical alternative, SENFA now stands at a technology-ready stage, with pilot-scale field applications being the logical next step to evaluate long-term performance under real subsidence conditions.

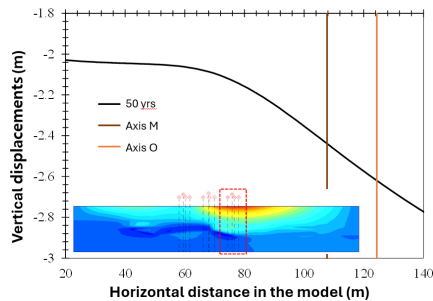


Figure 12. Graph of vertical displacements

Although the initial configuration was tailored to the auditorium's specific geometry, loads, and stratigraphy, the SENFA concept is inherently adaptable. Its modular nature, simple mechanical components, and minimal maintenance allow deployment across diverse structural typologies and site conditions. Designed exclusively for downward adjustments consistent with the unidirectional nature of regional subsidence, SENFA avoids one of the main limitations of existing leveling systems, the need for hydraulic lifting equipment, which is highly expensive, technically demanding, and generally feasible only for well-funded structures. In socially vulnerable buildings, these operations often require taking facilities out of service, placing them in more unfavorable conditions. In contrast, SENFA allows progressive adjustments without lifting the structure, offering a more accessible and operationally viable alternative.

3.3 Limitations of the system

The system requires access to the discharge mechanism through a small basement or service shaft. Although installation at ground level is possible, this configuration restricts adjustments to the upper floors only. In seismic regions such as Mexico City, the system is best suited for low-rise structures, up to three stories, where negligible bending moments are transmitted to the base. This practical constraint defines the range of structural configurations for which the system can operate effectively.

The system's performance also benefits from maintaining the sand in stable material conditions to ensure consistent flow during adjustments. Therefore, it is advisable to include adequate sealing or simple protective covers to control ambient humidity levels. Potential groundwater ingress can be prevented by considering the site's historical maximum groundwater level and integrating appropriate isolation or drainage measures into the design.

Notwithstanding these considerations, the system remains advantageous when compared with conventional solutions such as foundation reinforcement, sub-excavation, or hydraulic and mechanical jacking systems. Its low cost, minimal maintenance needs, and operational simplicity make it particularly suitable for urban areas with limited technical and economic resources. These characteristics position SENFA as a practical and scalable alternative for managing differential settlements in subsidence-affected environments

3.4 Integration into Various Structural Systems

One of the main advantages of the SENFA system is its ability to integrate with different structural configurations without requiring major architectural or structural changes. The principle, supporting the superstructure on independent, adjustable devices linked through a transfer slab, can be adapted to various construction materials and methods.

In masonry buildings, the transfer slab can be cast directly over load-bearing walls to distribute loads toward the devices. In steel structures, the system connects through base plates and anchor bolts, while in reinforced concrete frames it can be incorporated into the beam-and-slab system. Modular prefabricated housing can also be placed on the transfer slab (Figure 13).

The modularity of the SENFA devices facilitates their use in both new construction and retrofitting projects. In existing buildings, local excavation beneath supports and the installation of a partial transfer slab allow implementation without dismantling the structure. This versatility enables engineers to tailor the integration process to site constraints, available materials, and the intended service life.

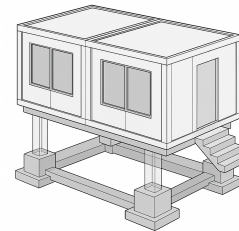


Figure 13. Example of SENFA system implementation in a modular prefabricated structure.

3.5 Operational Scalability

The SENFA system was conceived to operate with minimal technical requirements, reducing dependency on specialized machinery or highly trained personnel. This operational simplicity makes it feasible for communities with limited technical and economic resources to implement, monitor, and maintain the system over long periods. By enabling manual operation and localized adjustments, the SENFA system can extend the service life of buildings in subsidence-prone areas without costly or disruptive interventions.

Scalability is achieved through its modular design: the number of devices, their arrangement, and the type of transfer slab can be adapted to structural loads, soil conditions, and available materials. This flexibility allows for application in both small-scale community facilities and larger infrastructure projects, using the same fundamental principles.

This approach aligns with the United Nations Sustainable Development Goals (SDGs), particularly:

- SDG 9 –by promoting resilient and adaptable infrastructure in vulnerable zones.
- SDG 11 –by extending the lifespan of critical facilities and housing in areas affected by ground subsidence.
- SDG 13 –by reducing the environmental impact of construction through lower material consumption and fewer large-scale interventions over time.

By integrating low-maintenance mechanisms into building design, SENFA supports a more sustainable and equitable development model in which technical innovation directly addresses social vulnerability.

3.6 Potential for Widespread Implementation

Although developed for the lacustrine zone of Mexico City, SENFA's principles are applicable in many subsidence-affected regions, such as Jakarta (Abidin, et al., 2009), Bangkok, New Orleans, and the Mekong Delta. Its adaptability, low maintenance needs, and compatibility with local materials make it suitable for both resource-constrained settings and large-scale infrastructure.

Beyond its technical merits, SENFA supports SDG 17 – Partnerships for the Goals, fostering collaboration between governments, academia, and industry to promote resilient and sustainable construction practices. By shifting from reactive repair to proactive design, the system offers a scalable path for mitigating subsidence impacts globally.

4 CONCLUSIONS

Progressive subsidence in Mexico City and many other urban regions remains one of the most pressing geotechnical challenges, with direct consequences for structural safety, serviceability, and overall urban resilience. Traditional responses, often reactive and high-cost, are not always feasible in socially or economically vulnerable settings.

The SENFA system offers a preventive and adaptive alternative for managing differential settlements. By leveraging the dual behavior of sand, it enables precise, low-maintenance adjustments that reduce the need for large-scale corrective interventions. The detailed design and validation stages demonstrated its scalability, constructability, and suitability for diverse structural configurations in subsidence-affected environments.

This work presents an experimentally supported, low-cost approach that highlights the importance of modularity, operational simplicity, and interdisciplinary collaboration when developing context-appropriate geotechnical solutions. Continued pilot applications and long-term monitoring will further refine the system and expand its applicability under real ground-movement conditions.

Although the challenge is considerable, SENFA shows that proactive and accessible engineering can meaningfully improve the safety and functionality of urban infrastructure-transforming subsidence from an inevitable source of deterioration into a condition that can be anticipated, managed, and mitigated.

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