International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

International Journal of High-Rise Buildings
June 2025, Vol 14, No 2, 109-131
https://doi.org/10.21022/IJHRB.2025.14.2.109

The Foundation Systems of Tall Buildings: A Historical Review

Mir M. Ali[1] and Kheir Al-Kodmany[2†]

[1]*University of Illinois, Urbana-Champaign*
[2]*University of Illinois, Chicago, USA*

Abstract This paper presents a comprehensive historical and technical review of foundation systems in tall buildings, tracing their evolution from ancient construction methods to the sophisticated deep foundations used in today's supertall and megatall structures. It begins with early examples such as the Hagia Sophia and the Taj Mahal, highlighting how builders addressed geotechnical challenges long before the introduction of soil mechanics. The study then examines the development of shallow foundation systems—including spread footings, grillage foundations, and rafts—during the late 19th-century skyscraper boom in cities like Chicago and New York. It further explores the advancement of deep foundations, such as piles and caissons, which enabled taller and heavier buildings to rise on weak or soils of varied characteristics and terrains. Case studies of iconic towers demonstrate how foundation design adapts to local soil conditions, seismic risks, and structural demands. The paper also addresses contemporary innovations, such as sensor-based monitoring, AI-driven geotechnical modeling, and the use of high-performance materials. By linking historical progress with modern engineering practices, this study emphasizes the critical role of substructure innovation in the ongoing evolution of vertical architecture.

Keywords Shallow foundations, Deep foundations, Piles and caissons, Soil mechanics, Geotechnical engineering, Seismic design, High-performance materials, AI-driven geotechnical modeling

[†]Corresponding author:
Kheir Al-Kodmany
E-mail: kheir@uic.edu

1. Introduction

Foundations constitute the substructure of a building and are indispensable for the reliable support of the structure. Thus, it is considered part of the structure although it stands independently. It is a starting point of construction, although it is the last item for structural design, as it cannot be done until the superstructure is designed to evaluate the loads precisely. Foundations are buried and out of sight, and don't get public attention. Design or construction errors in the foundation are extremely costly, and in many cases, structural damages in the foundation are irreparable, and the entire building is condemned. Foundation failure in some instances may even result in the building's partial or complete collapse. All these problems burden architects, structural engineers, and owners with costly repairs and lawsuits. Structural engineers must consider this during the design process.

1.1. Research Significance

The foundation is the unsung hero of skyscraper engineering, inconspicuously bearing immense loads from the building above and ensuring the stability of the tall buildings of soaring heights. It is difficult to find detailed and consolidated information about the history and critical role of the foundations of tall buildings in the literature. As architectural ambitions have climbed, so have the demands placed on foundation systems. This paper traces the evolution of foundation systems for tall buildings, beginning with the simple shallow foundations of early buildings and progressing to the sophisticated systems used in today's supertall and megatall structures. By studying the chronological development of tall buildings from the earliest times, we can better understand today's foundation systems.

The main challenge in the foundation design of buildings is to prevent settlement, especially differential settlement that causes structural damage. Since antiquity, foundations have been designed to circumvent this problem by uniformly distributing structural loads or modifying foundations to adapt to load variations. With the height of buildings increasing with the advancement of technology, the foundation system evolved to carry increasing amounts of imposed loads, hand in hand with the evolution of skyscraper technology. It is essential to document this evolution in a single comprehensive paper.

1.2. Objectives and Scope

The primary objective of this paper is to explore the development and innovation of foundation systems in tall buildings from ancient times to the present, highlighting the critical role these systems play in enabling vertical growth in the built environment. By tracing the chronological development of foundation technologies—particularly the transition from shallow to deep systems such as piles and caissons—the paper seeks to illuminate how engineering advances have responded to increasing architectural ambition, site constraints, and environmental challenges.

The scope encompasses historical and contemporary foundation systems, particularly emphasizing how geotechnical conditions, urban density, and seismic risk have shaped design choices. The actual engineering design of the different types of foundations is not within the scope of this paper. The paper provides in-depth analyses of key foundation types, including spread footings, grillage systems, mat foundations, pile foundations, and caissons, contextualizing them within the urban histories of major cities such as Chicago and New York and other major cities of the world. It also examines modern innovations in foundation engineering through case studies of supertall and megatall buildings, including Burj Khalifa, Taipei 101, and Shanghai Tower. Since foundation systems were primarily born in Chicago and New York, more attention is being paid to these two cities. Since Chicago is the birthplace of skyscrapers, many innovations in the design and construction of tall buildings and their foundations took place during the Second Industrial Revolution.

By joining engineering history with contemporary practices, the paper contributes to a broader understanding of foundation systems as integral components of tall buildings' performance, stability, and sustainability.

1.3. Methodology

This paper adopts a multidisciplinary, historical-technical methodology grounded in architectural history, structural engineering, and geotechnical analysis. The approach combines:

- *Historical research*, utilizing primary and secondary sources on early construction methods, including archival materials, engineering records, and scattered scholarly publications.
- *Comparative analysis*, contrasting foundation solutions across periods and geographical contexts to illustrate how soil conditions, structural loads, and environmental risks influenced engineering choices.
- *Case study assessment*, where select buildings—such as the Empire State Building, Taipei 101, Shanghai Tower, Lakhta Center, and Burj Khalifa—are examined in detail to demonstrate how modern foundation systems are tailored to local geotechnical conditions and performance requirements.
- *Integration of contemporary literature*, including technical reports, journal articles, and conference proceedings from engineering and tall building organizations (e.g., CTBUH), to incorporate up-to-date insights on seismic design, deep foundation technologies, and construction methods and techniques.

This mixed-method approach allows the paper to move beyond a purely chronological account and engage critically with technological milestones, construction innovations, and contextual design imperatives shaping foundation systems for tall buildings.

1.4 Organization of the Paper

This paper is organized in several sections as follows (Table 1):

2. Ancient and Early Foundations

The ancient buildings were mainly built on stone, primitive concrete, bricks, and even wood bases spread under the building footprint and beyond. These foundations were developed based on intuition, primitive engineering notions, and environmental concerns and were the precursors of modern foundation systems. The Egyptians built the pyramids employing limestone blocks as their foundations. In Mesopotamia and Egypt, builders used raised mudbricks or clay platforms to create stable bases for their structures. Large, thick slabs called rafts or mats were used in the Indus Valley Civilization to distribute weights uniformly across soft or loose soil. Ancient Romans used primitive concrete with stone and brick or stone to build raised podiums to support buildings. The Roman aqueducts and Gothic cathedrals were built on deep underground piers (Vonstein, 2020). Mesopotamians and Venetians drove short timber piles into the ground to create a stable structural base in waterlogged areas.

Ancient builders understood how to use early forms of deep foundations, such as piles. The earliest known use dates back to around 4000 BCE, when wooden piles supported structures in Mesopotamia and Egypt. In the 3rd century BCE, China, builders during the Qin Dynasty used bamboo piles to stabilize buildings in areas with poor soil conditions. In Europe, pile foundations supported various structures throughout the Middle Ages and the Renaissance. Notably, during the construction of Venice in the 9th century, builders used piles extensively to support the entire city, which was founded on waterlogged soil. Several shafts were discovered in Mesopotamia, dating back to the period from 3000 BCE to 2000 BCE, and they form part of some of the excavations supporting structures for ziggurats (Gamallo, 2003). In Egypt, using a limestone caisson for the foundation of tomb structures around 2000 BCE is the most exceptional precursor of shaft or today's caisson (or drilled pier) foundations.

Foundation settlement was a common challenge in the construction of early tall buildings. For a detailed chronological overview of foundation techniques developed

Table 1. Paper Organization

Section	Description
1. Introduction	Offers an overview of the paper's themes, significance, and scope, emphasizing the critical role of foundation systems in tall buildings.
2. Ancient and Early Foundations	Reviews the evolution of early foundations, including notable cases like the Hagia Sophia and the Taj Mahal, and discusses primitive forms of piles and caissons.
3. Bridging Gaps in Knowledge	Explores the theoretical and technical limitations in foundation design before the formal development of soil mechanics.
4. Shallow Foundations	Details the development and application of spread footings, isolated piers, grillage, and raft foundations in early tall buildings, especially in Chicago and New York.
5. The Search for Appropriate Foundation Systems	Discusses the challenges engineers faced in developing foundation systems for early skyscrapers and the shift toward deeper systems.
6. Evolution of Deep Foundations	Describes the transition from shallow to deep foundations, emphasizing the urban geotechnical contexts of New York and Chicago.
7. Pile Foundations Reaching Greater Depth	Traces the historical development and material evolution, with 20th and 21st-century advancements.
8. Latter-Day Skyscrapers Using Pile Foundations	It presents global examples of tall modern buildings that utilize pile foundations, such as Petronas Towers, Taipei 101, and Burj Khalifa.
9. Caissons and Innovation in Deep Foundation	Explores the development and application of pneumatic and drilled caissons, with detailed case studies including the Woolworth Building and Willis Tower.
10. Seismic Considerations in Tall Building Foundations	Discusses foundation strategies for earthquake resilience, including mat-pile systems, soil-structure interaction, and emerging technologies.
11. Summary of Foundation Types for Tall Buildings	Provides a comparative summary table of foundation types, highlighting pros, cons, and typical applications.
12. Case Studies	Presents detailed case studies of tall buildings—Burj Khalifa, Shanghai Tower, Taipei 101, Empire State Building, and Lakhta Center—to illustrate foundation adaptation to site-specific challenges.
13. Foundations for the Future	Highlights emerging trends in foundation engineering, such as top-down construction, CFRC, intelligent systems, AI modeling, and ground improvement techniques.
14. Conclusions	Synthesizes foundation systems' historical and technical evolution and reflects on future directions for supporting the next generation of tall buildings.

before the First Industrial Revolution, see Gamallo (2003). It is discernible from this study that there are antecedents of all the different types of foundations that we know today, albeit in a primitive form. These foundations are shallow foundations, including spread and strip footings, raft foundations, and grillage foundations. Around 800 BCE, the Greeks were already aware that horizontal direction was the most critical element in earthquake events, and they struggled with finding a workable solution to mitigate the seismic effects on buildings caused by earthquakes. During the Hellenistic period, tied footings appeared in earthquake-prone regions.

2.1. Hagia Sophia

Completed in 537 CE in Istanbul, Türkiye, the Hagia Sophia is a monumental early structure in a highly seismic zone. Its foundation system combines shallow footings with deep substructures to manage the building's considerable mass. Constructed atop a mix of soft clay and harder rock strata, the foundation relies on expansive beds of stone and mortar to evenly distribute structural loads. Beneath portions of the building, underground vaults and cisterns help mitigate differential settlement by stabilizing the soil. Over the centuries, engineers added structural elements such as buttresses, arches, and piers to counteract both settlement and the impact of seismic forces.

2.2. The Taj Mahal

Around 1632, when construction of the Taj Mahal began in Agra, India, engineers employed a combination of stone, mortar, masonry, timber, and deep well foundations to establish a stable base. This foundation system was carefully designed to support the monument's immense weight while minimizing the risk of differential settlement. Large cylindrical wells were dug into the ground at close intervals, filled with rubble, iron, and mortar, and then cased in timber to create a stable base (Figure 1). These wells act as piles that stabilize the riverbank sands by preventing settlement and shifting. Massive wooden planks form the core foundation and remain structurally adequate because of a constant supply of moisture from the Yamuna River to support the structure. The water in the river keeps the planks moist and prevents them from

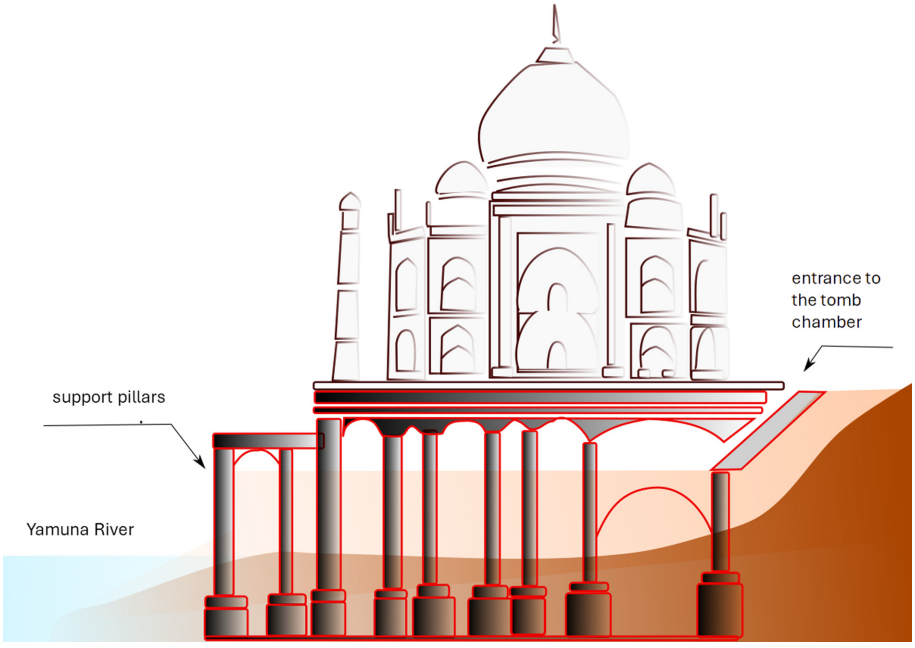


Figure 1. Foundation of the Taj Mahal showing large cylindrical wells. (Source: Wikimedia Commons)

shrinking. If the river dries up or changes course, the wood could lose strength and weaken its structure. A massive stone and mortar raft were placed over the well foundations to provide a stable platform for the structure.

Aside from the aesthetics of the Taj Mahal, its structure and especially its foundation system demonstrate advanced Mughal engineering in conjunction with geotechnics, hydrology, and material science, which have ensured its stability and durability for a few centuries. It remains both an architectural showpiece and an engineering marvel.

3. Bridging the Gaps in Knowledge

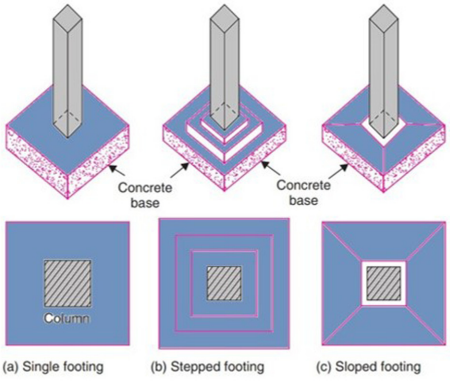
Between the past epochs and the First Industrial Revolution, beginning in circa 1750, foundation construction innovations proceeded slowly for several reasons. Adequate site investigation was not possible in the absence of soil exploration tools and techniques. There was no scientific method of evaluating settlement and the soil's bearing capacity, i.e., soil behavior under stress caused by imposed loads of buildings and other structures, as the discipline of soil mechanics was not yet born. Key advancements were made by Charles-Augustine de Coulomb and William Rankine in the 18th and 19th centuries, respectively, and later solidified by Karl Terzaghi, often considered the "Father of Soil Mechanics," in the early 20th century. His most influential contribution was his consolidation theory of 1925, which helped engineers predict settlement in soft clays, which is a critical consideration for the stability of buildings. Terzaghi significantly advanced the field and established soil mechanics as an independent engineering discipline through his research and development of fundamental concepts regarding effective stress and consolidation of soil.

The knowledge of evaluating live, wind, and seismic loads on structures was insufficient, as these loads are part of the total load imposed on the foundation. Also, the practical application of theoretical knowledge to deep foundations like piles and caissons was inadequate. The effect of water on the soil's bearing capacity and building settlement was another critical aspect that needed investigative research. Furthermore, significant gap existed in the understanding of the mechanical interaction between soil and structure during seismic events. Over time, intensive research and development gradually addressed these deficiencies, leading to more accurate models and improved seismic design practices.

4. Shallow Foundations

In cities like Chicago, where much of the early development occurred, simple foundations were often built on soft, compressible soils, leading to frequent settlement issues. Although spread footings helped mitigate this risk by distributing the building's weight and variable live loads over a broad area, they were not always sufficient to eliminate settlement entirely.

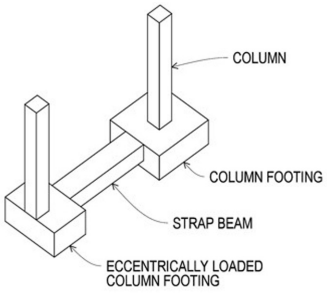
In response, engineers began experimenting with other methods to mitigate settlement problems. One early solution was to use wooden piles under pile caps comprised of spread footings. Wooden piles, driven into the ground, acted as supports to carry some of the building's load to deeper, more stable soil layers. This approach helped to reduce settlement in some cases, though it was still an



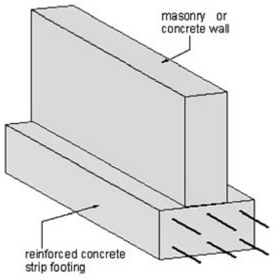
(a) Isolated Spread footings. (Source: civinnovate.com)



(b) Combined footing. (Source: www.ultratechcement.com)



(c) Strap footing combined footing but with a strap beam. (Source: Wikipedia.org)



(d) Strip footing under the wall. (Source: Tek1.com)

Figure 2. Types of Foundation Footings.

imperfect solution and was limited by the technology and materials available at the time.

4.1. Spread Footings

Spread footing is a basic shallow foundation designed and built to support superstructure elements like columns, walls, etc. It is the most widespread construction used to keep a structure from settling into the soil. Spread footings under columns usually consist of isolated, combined, and strap footings (Figure 2). It has a lower construction cost and an easier quality control process than other foundation types. Spread footings were and still are widely used for low-rise buildings due to their simplicity of design and construction. However, they are unsuitable for soft soil and in areas of variance in soil condition or heavy loads. In these cases, large footings tend to merge and interfere with the stress distribution in the soil under adjacent footings; thus, the use of isolated spread footings carrying heavy loads becomes impractical. Differential settlement is a critical issue for spread footings unless properly addressed. Therefore, these footings are usually inadequate for tall buildings because of their limitations. When continuous footings are used under walls they are called strip footings (Figure 2).

One of the earliest examples of a tall building that employed a simple foundation system is the 7-story Equitable Life Building in New York City, completed in 1870. At the time, the Equitable Life Building was considered a groundbreaking achievement in architectural design. Though modest by today's standards, the building was one of the tallest in New York at the time. It was built in an era when foundation engineering was evolving rapidly. Detailed construction records are not as comprehensive as those for modern tall buildings. Built on the soft, variable soils distinctive of lower Manhattan, the building utilized widespread footings constructed of masonry or concrete to support its steel frame. These footings distributed the substantial weight of the structure over a greater area, reducing the pressure exerted on the ground and mitigating the risk of uneven settlement. These footings were designed to distribute the building's load across a wider area of soil to prevent excessive settlement or failure of the foundation. The foundation worked well for the time because the building's height and weight did not exceed the load-bearing capacity of the materials and soil. Without the benefit of modern engineering techniques, the design depended on massive load-bearing walls and continuous footings to distribute the loads from the structure across a wide-ranging area. However, the Equitable Life Building's design hinted at the limits of such foundations as engineers began to recognize that taller buildings would require more sophisticated solutions.

4.2. Isolated Pier Foundation

By the late 1850s, the multistory commercial buildings in Chicago employed pier foundations in a system known as isolated piers. Frederich Baumann published the principles of these piers in his "Method of Isolated Piers" in a publication (Baumann, 1873). It was the first known statement of footings in the US (Peck, 1948). This foundation system was carefully selected as it accommodates the differences between the exterior and interior

building loads, for which traditional spread and raft foundations were inadequate under larger structures, transferring heavy building loads to the substructure.

As the structural framing developments in metal framing took place, foundation design was also being developed to accommodate these structural developments and heavier loads for tall buildings. Before 1883, most downtown Chicago structures were three to six stories and were supported on square or rectangular spread footings. Structures consisted of exterior.

Load-bearing walls with interior columns to carry gravity loads. Soil mechanics as a distinct civil engineering discipline was still unknown. Footing sizes were calculated by determining the soil's presumptive bearing capacity using primitive techniques based on experience and erring on the safe side. Little account was taken of precise soil conditions. Because of this, overdesign was often the result.

When the foundation system of the world's first skyscraper, the 10-story Home Insurance Building of 1885 in Chicago, was considered by its designer, William Le Baron Jenney, he was concerned about the differential settlement and the unevenness of loads. Spread footings were inadequate to carry the heavy loads from a 10-story building. He was conscious that there was a limitation on using isolated piers as buildings grew taller and heavier and thus became susceptible to settling, leaning, and building failure. He wanted to find a better method of uniformly distributing the heavy loads under the entire building (Jenney, 1885). He, however, employed the isolated pier system at the end, and it worked well. Clearly, a new type of foundation was needed for buildings with heavy structural loads in Chicago's soft soil.

4.3. Grillage Foundation

Another notable shallow foundation system from this era was the grillage foundation—a combination of iron and concrete designed to distribute structural loads evenly across the soil. This method proved especially applicable when a building's loads exceeded the soil's natural bearing capacity. John Wellborn Root was a key figure in the development of foundation systems during Chicago's high-rise surge of the late 19th century. His innovative work, particularly in adapting foundation systems to Chicago's swampy soft soils, has left a lasting legacy in the development of grillage foundations. He undoubtedly was an architect with prodigious engineering skills who helped advance this innovation, applying it to improve structural stability and long-term foundation performance on Chicago's poor soil.

The first, though inadequate, attempt at a grillage foundation using railroad rails embedded in concrete appeared beneath several footings of Burnham & Root's 10-story Montauk Building of 1882 in Chicago. The 12-story Rookery Building, completed in 1888, also by Burnham and Root in Chicago's financial district, featured the first fully developed grillage foundation. This system used a crisscross network of iron rails and structural beams encased in concrete to create a solid base, distributing the building's enormous weight over a large area. This effectively allowed the building to "float" on the soil, averting excessive settlement and creating a firm platform for the structure. Similarly, the Rand McNally Building of 1889 in Chicago, designed also by Burnham and Root, used steel rails for its grillage foundation (Figure 3).

The technique was further adopted and improved, notably with the use of I-beam grillages by Holabird and Roche in the Tacoma Building of 1889 in Chicago. Root's design became the dominant form of shallow foundation in Chicago until the early 20th century. Holabird and Roche incorporated an improved version—using I-beam grillages—into the 13-story Tacoma Building in Chicago, the same year, i.e., 1889 (Figure 4). The I-beam grillage proved more efficient and quickly became the dominant form of shallow footing until reinforced concrete spread footings emerged in the early 1900s. Meanwhile, military engineer General William Sooysmith promoted the use of piles, although the development of caisson foundations soon reduced their widespread adoption.

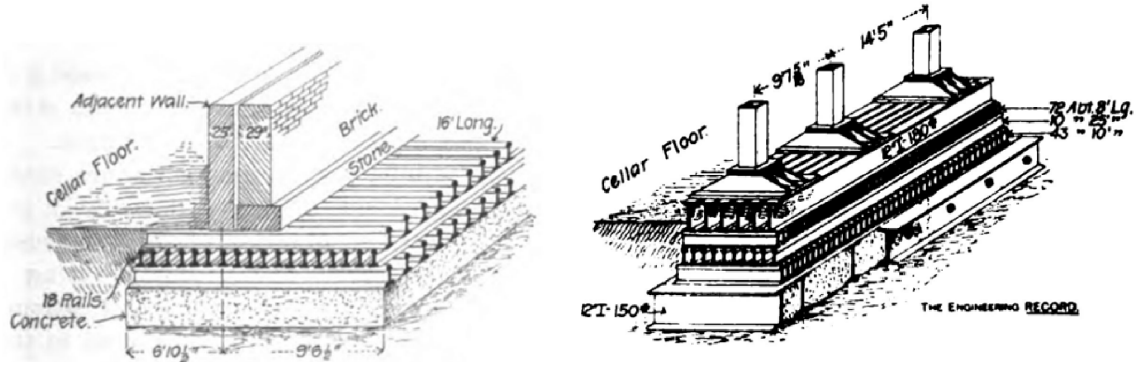


Figure 3. Figure 3. Left : Grillage Foundation Using Steel Rails. Right: The Case of Rand and McNally Building. (Source: Engineering Record, v.38, 1898)

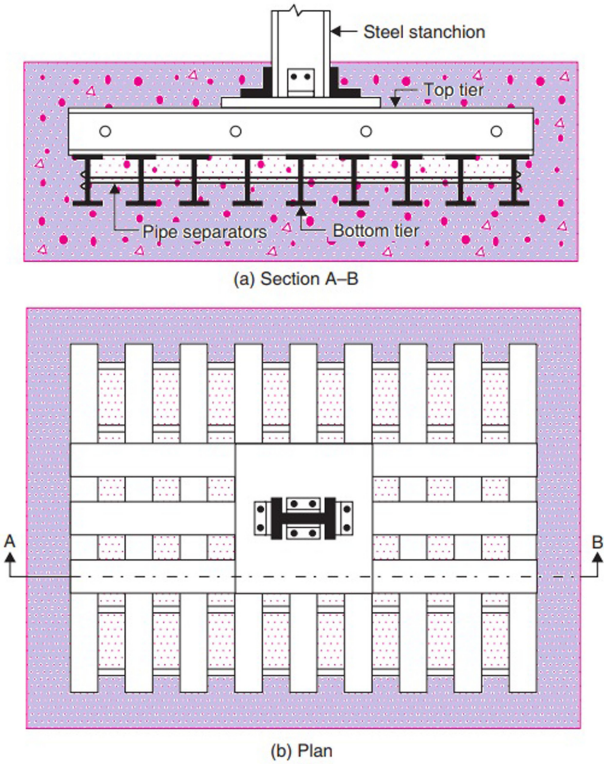


Figure 4. Grillage Foundation with embedded steel I-beam. (Source: civinnovate.com)

4.4. Raft Foundations

Another type of shallow foundation is called a raft foundation, also known as a mat foundation in current vocabulary. The Egyptians, Greeks, and Romans employed early forms of raft foundations in simple earthen slabs in ancient times, like rafts spreading loads from structures over large areas through continuous slabs or large combined footings. These foundations were then made from a thick slab of cement and stone that spans a vast area of soil and supports many columns and load-bearing walls, often under the entire building's footprint, and is a popular foundation system in cases where the soil's bearing capacity is very low that will require large spread footings. Hence, individual spread footings almost merge with each other, i.e., tend to overlap, or where there is a differential settlement problem. Contrasting traditional foundation types like shallow and deep foundations, a raft or mat foundation extends over the entire structure's footprint. This expansive coverage serves as a unified base that ensures uniform distribution of loads, minimizes differential settlement, and safeguards structural integrity (Figure 5).

In the early 19th century, concrete raft foundations were already in use, notably in the construction of Millbank Prison in London by architect Robert Smirke around 1815. A solid 457-millimeter (18-inch) thick concrete raft was laid beneath the entire structure to support it on soft, waterlogged soil. Later, in 1888, John Wellborn Root advanced this concept with the Rookery

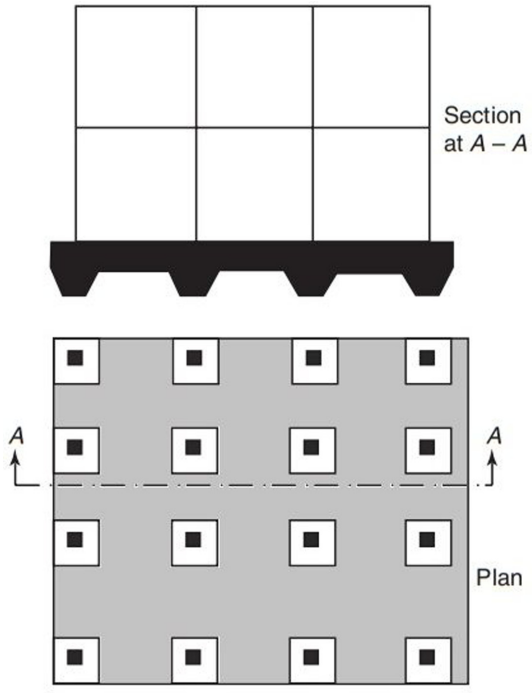


Figure 5. Mat Foundation with Thickened Slab Acting as Footings under Columns. (Source: civinnovate.com)

Building in Chicago by developing a "floating raft" system—an integrated foundation of thick concrete slabs interwoven with steel beams—to address similarly challenging soil conditions. This grillage foundation can be viewed as an evolutionary step toward the floating raft. By using crisscrossed iron or steel members encased in concrete to unify the base under a structure, Root's grillage system set the stage for the later, more extensive use of continuous mat foundations. With the introduction of reinforced concrete, mat foundations became a popular system in the 20th century either as an independent foundation or part of a combined system of mat atop deep foundation comprising either piles or caissons.

5. The Search for Appropriate Foundation Systems

The evolution of foundation systems in Chicago is particularly significant, as many modern practices trace their origins to innovations made by Chicago engineers between 1871 and 1915. During this formative period, engineers engaged in intense experimentation, seeking foundation solutions suited to varying structural loads and challenging soil conditions. As the design of tall buildings advanced, so did the necessity to develop foundations capable of supporting increasingly massive structures on soft, unstable ground. Chicago emerged as a global leader not only in tall building construction but also in foundation engineering (Randall, 1999). While steel-frame construction revolutionized superstructure design, engineers in Chicago simultaneously pioneered new foundation techniques to

support the resulting heavier loads and architectural ambitions for building taller.

During this period, engineers and architects also explored wooden friction piles, which proved significantly more potent than earlier foundation methods and served as precursors to modern deep foundation systems. These piles offered a promising solution to the persistent problem of differential settlement. However, pile foundations came with their own set of challenges. The pile driving process involved repeatedly dropping heavy hammers, which could damage nearby structures. Additionally, wooden piles were vulnerable to rot when exposed to fluctuating water tables caused by seasonal drying and wetting. To prevent decay, it was essential to keep the piles fully submerged. Due to these persistent issues, engineers cautiously approached the design of tall building foundations, especially as building heights reached 15 to 20 stories by the early 1890s. Nevertheless, the following two historic tall buildings demonstrate that engineers had not yet entirely abandoned spreading footings, particularly when stronger soils with high bearing capacity were available.

5.1. Monadnock Building

A notable example of that era is the 16-story historic Monadnock Building of 1891 in Chicago. It was one of the tallest and heaviest masonry buildings ever constructed. It was built at a time when the customary practice for high-rise construction involved shallow foundations in Chicago. The engineer, however, didn't find the isolated pier system suitable for this heavy masonry building. The building was constructed by employing shallow and massive modified masonry spread footings. The footings were designed to distribute the considerable loads from the building's thick load-bearing walls across a broad area. These footings were established on a naturally secure glacial deposit of the site, which was helpful. In the late 19th century, engineers optimized their foundation design for the materials, underlying soil conditions, and techniques available.

5.2. Ingalls Building

In the 16-story historic Ingalls Building of 1903 in Cincinnati, Ohio, the first reinforced concrete tall building employing a framed structural system was laid on reinforced concrete spread footings (Ali, 2001). The favorable soil condition at the site allowed for a shallow foundation system. In a reinforced concrete framed high-rise building highly vulnerable to settlement, concrete cracking, and significant damage, this was a gamble and an act of courage for the first such structure using a not-yet-perfected material that lacked sophisticated concrete technology. Also, soil mechanics as a scientific discipline had not yet been born. The successful performance of this foundation system was critical in validating that a tall building could be safely built using reinforced concrete, a material susceptible to cracking.

6. Evolution of Deep Foundations

As the demand for taller buildings grew in the late 19th and early 20th centuries, engineers recognized that simple shallow foundations and spread footing systems were no longer sufficient for skyscrapers. The real solution to overcoming large settlements was to carry the loads to hardpan or bedrock, using deep foundations like piles and caissons. The increasing height of buildings made it possible due to the innovation of metal skeletal frame in 1885 for the Home Insurance Building in Chicago resulted in excessive loads imposed by taller buildings on the foundations, and traditional materials such as brick, stone, and wood used in conventional shallow foundations could no longer support these loads without excessive settlement or bearing failure of the soil. The use of reinforced concrete, combining concrete and reinforcing steel for shallow foundations in the early 1900s, partially alleviated the problem, but was inadequate for much taller buildings.

6.1. The Roles of New York and Chicago

Urban environments presented unique challenges for foundation design. Cities like New York and Chicago, where many early skyscrapers were constructed, often had poor surface soils unsuitable for traditional shallow foundations. In some cases, buildings were built near water, on soil with a high-water table, or landfills, further complicating the foundation design. As engineers and architects pushed the boundaries of building height and scale, new foundation technologies and materials became necessary to meet the challenges posed by these enormous structures. They realized that the real solution to large and differential settlements was to carry the loads down to hardpan or bedrock using piles or caissons. The transition to deep foundations represented a significant leap forward in the evolution of tall buildings. It allowed architects and engineers to construct increasingly taller and more ambitious structures than were ever envisioned. Pile and caisson foundations are the two types of deep foundations that allow modern-day tall, supertall, and megatall skyscrapers to be built in major cities worldwide. Although elevators and skeletal frames were essential for the birth of skyscrapers, tall and supertall buildings would be impossible without the construction of deep foundations in most of these buildings.

7. Pile Foundations Reaching Greater Depth

During the rule of the European provinces of the Roman Empire, piles were driven into the ground for soil improvement through compaction, not as foundations (Gamallo, 2003). Builders could not evaluate loads other than dead loads and quantify the soil's accurate stress and deformation under loads (Kerisel, 1985). The first automatic mechanisms for releasing the drop hammer appeared in the 18th century (Gamallo, 2003). Until the

early 18th century, this practice usually continued, assuming driving piles compacted the subsoil, increasing the soil's strength and reducing building settlement.

The need for carrying heavy loads imposed on the foundation in tall buildings gave rise to pile foundations, which involve driving long, slender column-like elements deep into the ground to reach a more stable and load-bearing subsurface strata like bedrock or compacted soil layers. With the availability of some theoretical field data, piles gradually gained acceptance as a building foundation system by the turn of the century. However, concerns remained about piles' strength, spacing, length, and diameter and the sequence of pile driving. This delayed the practical application of pile foundation for some time.

7.1. Industrial Revolution and Pile Foundations

The technological surge created by the steam power taking off during the First Industrial Revolution, generally dated between 1760 and 1840, and the development of iron and modern steel, as well as the electrical power revolution, revolutionized the construction industry during the Second Industrial Revolution, usually dated between 1870 and 1914. The pile foundation began to gain attention in the construction industry. In the early 1890s, engineers developed a cost-effective way to combat caving soil. The increasing cost of foundations and increasing downtown land costs provided a strong economic incentive to have maximum bearing pressure on hardpan without drilling to bedrock.

A pressure meter, developed by Louis Menard in France, allowed engineers to guess the hardpan's bearing capacity and deformation characteristics. By 1890, engineers recognized the possibility of using long piles (Beedle et al., 2007). They began using cast iron and later steel piles, which offered superior strength and durability compared to wooden piles. These could be used as friction piles, depending upon the skin friction between the soil and pile surfaces, or as bearing piles, depending upon the bearing of the pile tip on the hardpan or rock. Piles resist structural loads through skin friction along their surface or by bearing directly on hardpan or bedrock at their tip. General William Sooy Smith strongly advocated pile foundations and played a key role in promoting their use. However, the growing adoption of caisson technology at the time somewhat curtailed their widespread application. Despite this, piles persisted and eventually expanded as technological advancements improved efficiency and reliability.

7.2. Early Use of Piles in New York and Chicago

The 20-story Fisher Building, completed in 1896 in Chicago and designed by Charles Atwood, was constructed on friction piles without a continuous reinforced concrete pile cap. This omission contributed to differential settlement over time. Although reinforced concrete was already known in Europe and the United States by the early 19th century, its application in building foundations—particularly for mat or raft systems—was still in its early stages during the 1890s. By 1905, the Fisher Building had begun to lean, prompting plans for a 21-story addition that would help stabilize the original structure. During this intervention, most of the original piles were removed and replaced with caissons installed beneath the entire building (Chicago Tribune, 1905).

In 1899, the 30-story Park Row Building in New York City surpassed the Manhattan Life Building as the world's tallest building. It was built on about 3,900 spruce wood friction piles, each 305 millimeter (12 inch) diameter driven 7.6 meter (20 feet) deep into soils of clay and dense sand favorable for developing skin friction. However, such soil conditions were scarce in New York City, as in much of lower Manhattan, where the soil was too wet to create the required friction, or the sites were too small to permit many piles to be driven to carry the massive building.

Despite the deficiencies in their early stages, pile foundations revolutionized tall building construction by providing a reliable solution to the problems of weak or unstable surface soils. By transferring the load of the building to deeper, more stable layers of earth, engineers could use piles to support much heavier and taller structures. The introduction of pile foundations, having roots in ancient times, evolved from wooden and stone piles to modern steel and more popular concrete piles. The invention of modern-day reinforced concrete around this time marked a turning point in skyscraper design and enabled the rapid growth of urban skylines worldwide since the early 20th century.

7.3. Advances in the 20th Century and Beyond

The 20th century brought innovations in pile foundation technology. Modern piles are made from various materials, including wood, concrete, and steel, each chosen based on the specific requirements of the project and ground conditions. Concrete piles gained popularity due to their strength and adaptability. In modern times, pile foundations have become integral to construction, underpinning everything from skyscrapers to other structures. Reinforced concrete piles can be precast or bored (poured-in-place). When an existing adjacent structure is near the site, a bored pile is the option to avoid ground vibration that may damage the structure. Engineers have developed other techniques, such as pre-stressed and post-tensioned piles, helical piles, and steel pipe piles, for different applications deemed suitable for structural requirements and specific subsoil conditions. Improved machinery and techniques, such as hydraulic pile drivers and vibratory hammers, have increased the efficiency and precision of pile installation. Geotechnical engineering has also evolved, with sophisticated soil testing and computer modelling allowing for optimized pile design and placement.

The evolution of pile foundations is a testimony to

human inventiveness and adaptability. From the humble origins in ancient civilizations using wooden stakes to modern steel, piling technology has continually evolved to meet the demands of increasingly impressive construction projects. This enduring legacy underscores the critical role of pile foundations in the ever-advancing field of construction engineering. As cities grow, pile foundations will undoubtedly play a critical role in their construction.

8. Latter-Day Skyscrapers Using Pile Foundation

Many high-rises around the world have used pile foundations. Deep foundation techniques are used to support the building load and transfer it to the underlying bedrock. Early 20th-century tall buildings were built in coastal or waterfront cities where soft clay or soil fill could not support their loads. Pile foundations were used to transfer loads to deeper, more stable strata or bedrock. Advancements and experience in using deep foundation technology allowed tall buildings to rise safely.

One of the earliest notable buildings that used a pile foundation was the Royal Liver Building of 1911 in Liverpool, UK. Given the building's waterfront location and the soil conditions near the Mersey River, a pile foundation was used. The details about its foundation system, i.e., whether the building employed a pile foundation, a reinforced concrete mat, or a combination of the two, are unknown. Without explicit historical records, the exact nature of the foundation is not knowable. In the US and other countries, tall buildings used piles during the 20th century, where bedrock was far down in the ground, and caissons were cost-intensive. Examples of pile foundations are Torre Velasca of 1958 in Milan, Italy using concrete bored piles; Marina City completed between 1963 and 1967 in Chicago using driven steel H-piles; Torre Ejecutive Pemex of 1984 in Mexico City, Mexico, using deep friction piles; HSBC Building of 1985 in Hong Kong using driven steel H-piles; and Menara Telekom of 1999 in Kuala Lumpur, Malaysia, to name a few.

Caissons, however, became a popular building type in Chicago and New York because of the presence of bedrock within a reasonable depth of soil. Aside from that, in the early late 20th and 21st centuries, pile foundations experienced a resurgence due to advances in pile design and technology, and became popular for tall, supertall, and megatall buildings mostly outside the US. The following examples describe pile foundations for some supertall and megatall buildings.

8.1. Petronas Towers

Located in Kuala Lumpur, Malaysia, the 88-story supertall Petronas Towers of 1998 held the title of the tallest building in the world at the time until 2004. These twin towers were the tallest buildings in the world at the time of their completion, representing a symbol of Malaysia's modernity, prosperity, and engineering prowess. The Petronas Towers were constructed on a site with highly variable soil conditions, including soft clay areas, which posed significant challenges for foundation design. Extensive geological studies were done for the site (Baker et al., 1998). For the soft soil, 104 bored concrete barrette (i.e., very large) piles were employed in Tower 1 and 54 in Tower 2, extending to 40 to 105 meters (131 to 344 feet) at different locations in soil and weathered rock. A reinforced concrete 4.5-meter (14.5-foot) thick mat designed for wind and seismic forces was used on top of the piles as a pile cap.

8.2. Taipei 101

The 101-story Taipei 101 of 2004 in Taipei, Taiwan, also a supertall building, held the title of the tallest building in the world until 2010. It is an engineering and architectural feat. The site consists of soft clay and rock strata. Three hundred eighty bored concrete piles constitute the foundation. An additional 167 piles support the huge podium. The piles extend 80 meters (263 feet) into the ground, with 15 to 33 meters (49 to 108 feet) socketed into bedrock. A 3- to 4.7-meter (10- to 15-foot) thick reinforced concrete mat was constructed atop the piles in the central tower. Taipei is in northern Taiwan, which is prone to typhoons. The foundation was designed for high wind and earthquake activity, as the building is also in a seismically active zone. The water table was near the ground surface 2 meters (6.7 feet) below the ground surface. The use of a slurry wall and the pile foundation addressed the problem.

8.3. Shanghai Tower

This 128-story tower of 2016 in Shanghai is a megatall skyscraper and has been the second tallest in the world after Burj Khalifa (the tallest in the world) until 2023, and the tallest building in China. Its tiered design for high energy efficiency provides nine separate zones divided between office, retail, and leisure use. The foundation consists of 955 bored concrete piles extending to 56 meters (184 feet) and 52 meters (171 feet) in another area, passing through varied soil types. A 6-meter (20-foot) thick mat over the piles was constructed, which was analyzed by El Gendy & El Gendy (2018).

8.4. Burj Khalifa

The 163-story Burj Khalifa in Dubai, a megatall building completed in 2010 and currently the tallest building in the world, relies on a complex foundation system designed to support the tower of extraordinary height of 828 meters (2,717 feet). The foundation consists of 192 reinforced concrete bored piles, each extending about 50 meters (164 feet) into the ground, which consists of weak, sandy soil of Dubai and is anchored into a strong layer of rock. A 3.7-meter (12-foot) thick reinforced concrete mat was

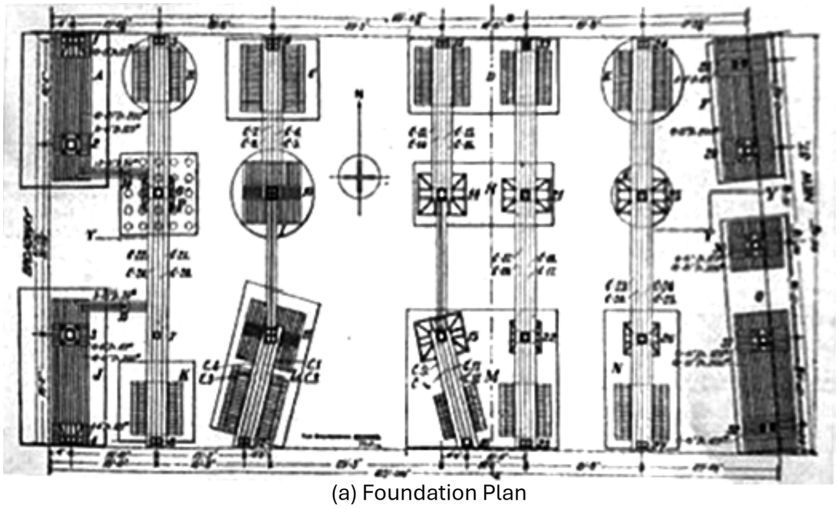
designed to cover the piles for high durability and strength. The concrete in the mat was poured in several phases to control the heat of hydration and ensure integrity. Engineers accounted for settlement, groundwater, seismic activity, and high wind in the design. Engineers conducted sophisticated soil testing and modeling to ensure the foundation would perform reliably under challenging conditions. They used high-performance concrete (HPC), specially formulated for durability and chemical resistance to combat the corrosive effects of Dubai's saline groundwater.

8.5. Merdeka Tower

The 118-story Merdeka 118 Tower of 2024 is a megatall skyscraper in Kuala Lumpur, Malaysia. It is now the second-tallest building in the world, surpassing Shanghai Tower. The tower's foundation was a serious aspect of its construction. Because of the enormous height of the tower, the immense weight and significant wind forces were paramount to the design of the foundation. Over 200 bored concrete piles extending to 60 meters (197 feet) were installed to transfer the building load to stable soil substrata. Because of soft clay layers, the piles were anchored into bedrock. A 4-meter (13-foot) thick mat slab using high-strength concrete was constructed over the piles. A self-supporting circular cofferdam was employed to facilitate excavation and minimize ground movement. The foundation utilized ultra-high-strength concrete with a high modulus of elasticity.

9. Caissons and Innovation in Deep Foundation

While pile foundations were a significant advancement, they were not the only deep foundation system developed during the skyscraper era. Another important innovation was the caisson foundation. The engineering work of General William Sooy Smith, a respected military engineer, in connection with the Waugoshanee lighthouse at the western entrance to the Straits of Mackinaw led him to design the first pneumatic caisson to be sunk in America in 1867, for which he received an award from the Centennial Exposition of 1876. Caisson construction methods were used in Chicago and New York, which set the trend for using caissons in other cities in the US and Canada. Since most cities were established near rivers, with the commercial districts in the lowest areas where the soil had a lower bearing strength under larger buildings, with easy accessibility to bedrock, caisson foundations became the popular choice for engineers (Vonstein, 2020).



(a) Foundation Plan

(b) Caisson Elevation

Figure 6. Manhattan Life Insurance Building, NYC. (Source: Engineering Record, 1894)

9.1. Manhattan Life Insurance Building

Caisson engineering has been used since at least the 19th century, with two prominent examples being the Eads Bridge of 1874 in St. Louis and the Brooklyn Bridge of 1883 in New York. In 1892, it was announced that architects Francis Kimball and George Thomson would initiate the tallest office building in the world for the Manhattan Life Insurance Company in New York City. Borings around the site revealed an assortment of saturated soil, glacial till, and quicksand. Piles were initially considered, but the idea was dropped as the New York City building code requirement would not be met (Engineering News, 1893). It is worth noting that pile foundations were estimated at 4 to 7 percent of construction cost for this building. Comparatively, the caissons represented about 10 percent of construction cost (Vonstein, 2020). However, for the average skyscraper employing caisson in Manhattan generally compelled building owners to add three to four stories, not only to offset the cost of the caissons, but also to offset the construction costs of added height and loss of floor space to accommodate additional elevators (Hill, 1904).

Because of the quicksand at the site of the building, standard caissons had to be ruled out. The solution was to use pneumatic caissons, since the quicksand could be contained through the use of pressurized chambers. Engineer Charles Sooysmith (son of engineer General William Sooy Smith) designed 15 circular and rectilinear caissons (Figure 6). The quicksand covered approximately two-thirds of the site, and one of the foundation piers near the center of the building was designed as wooden piers driven to bedrock (Engineering Record, 1894). After working for his father in Chicago for a few years, Charles moved to New York and changed the spelling of his last name to "Sooysmith" when he established his firm.

9.2. Chicago Stock Exchange Building

The foundation of the Chicago Stock Exchange Building was originally designed with a grillage foundation supported on wooden piles, but due to damage to adjacent buildings caused by vibrations from pile driving, construction was stopped (Chicago Daily News, 1893). Cassion was introduced to Chicago for this building for the first time in 1893 by General William Sooy Smith, a well-respected engineer, who was contacted to fix the foundation problem. He employed eight caissons along the rear of the building (Figure 7).

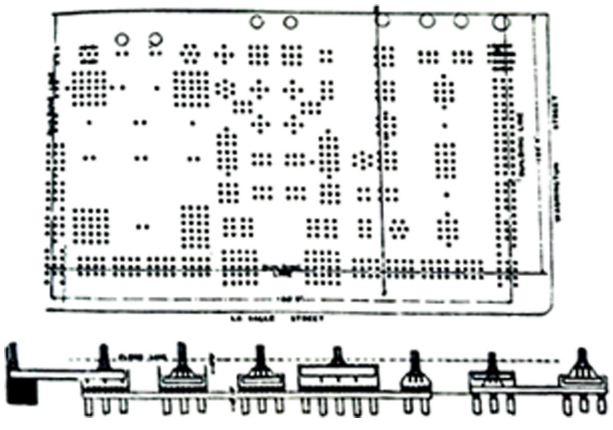


Figure 7. Foundation Plan for Chicago Stock Exchange. (Source: Railroad Gazette, 1894)

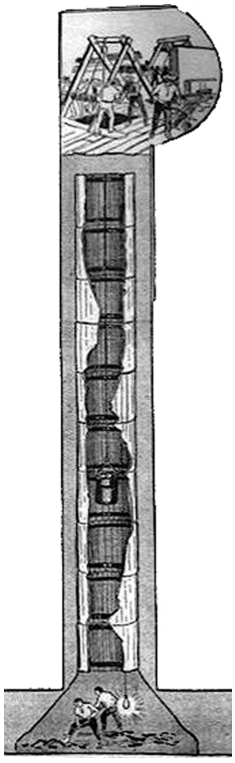


Figure 8. Illustration of the excavation for caissons showing sheet piling. (Source: Vonstein, 2020)

Unlike the pneumatic caissons used for the Manhattan Life Insurance building and he employed a technique called sheet piling used previously for the City Hall of Kansas City in 1891 and the Fifth Avenue Theater in New York (Vonstein, 2020) (Figure 8), in view of the poor soil condition of Chicago (Figure 9).

The use of this method, employing manual excavation, became popular in the Chicago Loop and became widespread there. As the ground was excavated, wood lagging in sections of 607 to 914 millimeters (2 to 3 feet) deep was added until hardpan was reached. The bottom was excavated at a 45-degree angle to create a wider base. Though this method was first used in Kansas City, because of its wider use in Chicago, it became known as the "Chicago Caisson" or "Chicago Method" (Jacoby & Davis, 1914) (Figure 10).

9.3. Old Colony Building

In 1896, Chicago employed the caissons for the Old Colony Building, which was completed in 1893, but its south wall settled faster than other walls within three

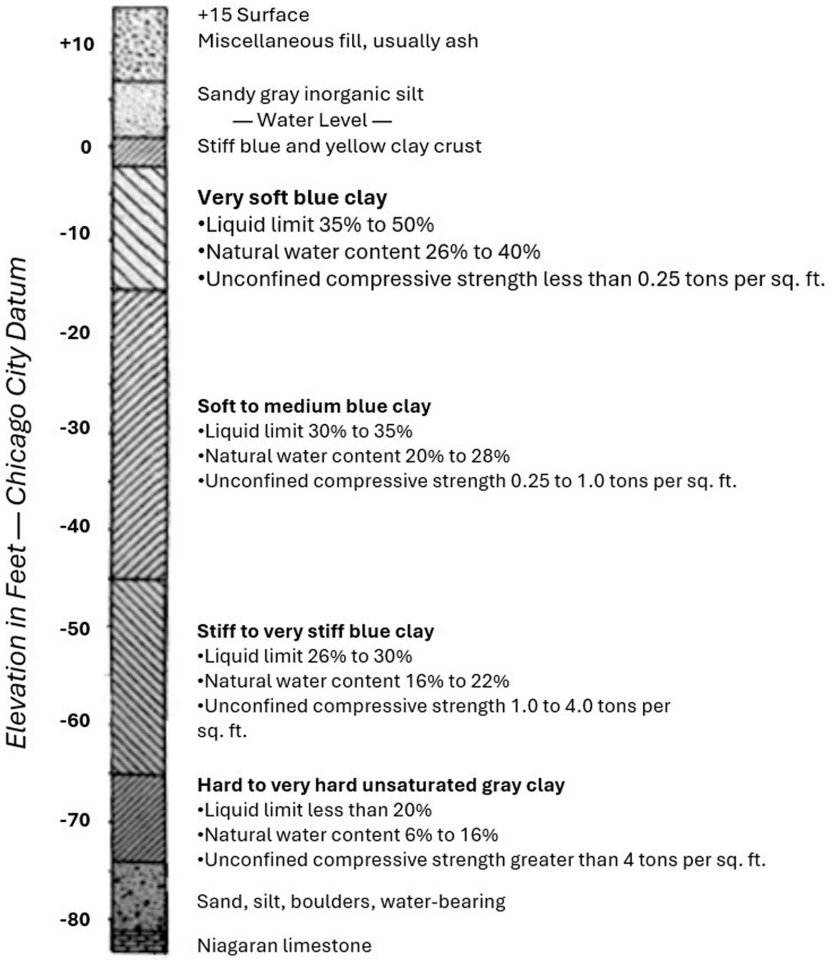


Figure 9. Average soil conditions in the Chicago "loop." (Source: Peck, 1948)

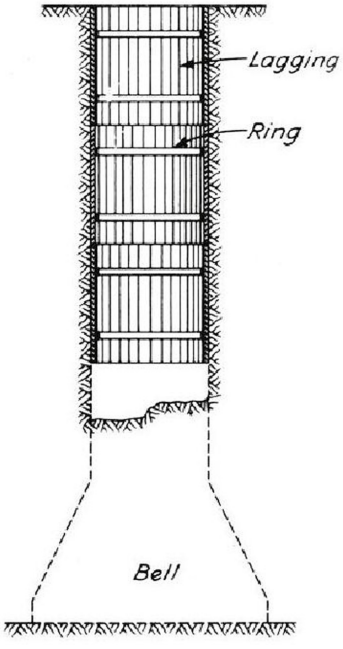


Figure 10. The "Chicago Method" of Caisson Construction. (Source: www.researchgate.net)

years. In 1896, Gen. Sooy Smith installed four sheet-pile caissons, removing the original footing under the south wall (Peck, 1948). The caisson technology transformed the construction of tall buildings and contributed to how New York and Chicago developed underground despite their poor soil conditions, which varied greatly. Caissons could be used where piles were unsuitable for buildings of greater height in certain soil conditions.

9.4. Woolworth Building

Caissons were employed to construct other famous skyscrapers, such as the Woolworth Building of 2013 in New York City, the tallest building in the world at the time. The pneumatic caissons were used for the building because of the depth to bedrock and the waterlogged soil condition at the site. The underlying soil at the site is a mix of sandy soil and layers that include waterlogged strata, making open excavation or standard caissons unsafe and impractical. 69 pneumatic caissons were installed. Once each caisson had reached bedrock at a depth of about 30 to 37 meters (100 to 120 feet) below grade, they were filled with concrete. After the concrete hardened, a grillage of closely spaced steel beams was installed on

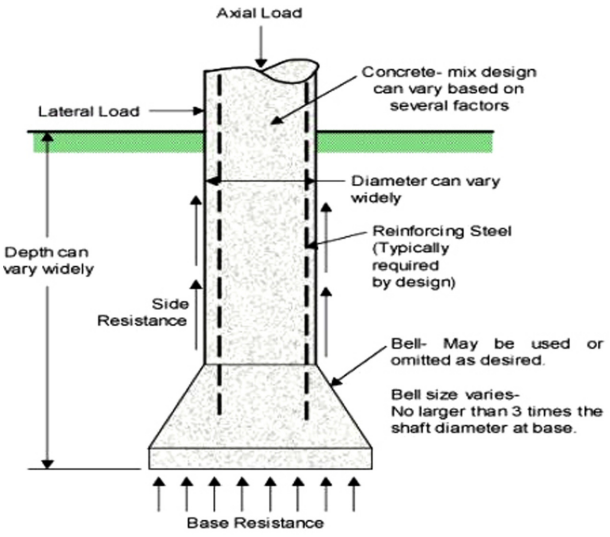


Figure 11. Belled Caisson. (Source: constructions-bd.blogspot.com)

top of each concrete pier to transfer the load from each steel column to bedrock.

9.5. Empire State Building

This 102-story building in New York, an architectural and engineering marvel built in 1931, reigned as the tallest in the world for about 40 years. There is some controversy about the actual foundation details of this building. The best information based on the authors' investigation shows that the foundation primarily consists of 55 pneumatic caissons for the Empire State Building, which was the prevalent practice for the foundation system for large buildings at that time. Careful consideration must be given, particularly for skyscrapers of this size, to factors such as soil composition, water table levels, and the weight of the building to ensure a solid and stable foundation.

The caissons were sunk into the ground until they reached solid bedrock. The depth of these caissons varies depending on the site conditions, ranging from 15 to 24 meters (50 feet to 80 feet). A 2.4-meter (8-foot) thick reinforced concrete mat sits atop the caissons, acting as a load-distributing platform for the steel columns, integrating the superstructure with the foundation. The thickness was designed to resist the tremendous axial loads from columns and localize the mat's shear stresses.

9.6. Drilled Caissons

Machine drilled caissons were invented to avoid intense labor and save time. Machine drilling is a highly effective means of supporting large structures like skyscrapers, with reduced risk of shifting, settling, sinking, or other potential issues accompanying traditional foundations. Thus, the weight is more evenly distributed on a grid of caissons, and drilling down to bedrock or a hard stratum ensures the most outstanding stability for



Figure 12. Drilling Equipment. (Source: OpenAI (https://openAI.com), July 2025)

large structures. The combination of pile and caisson foundations allowed architects and engineers to construct skyscrapers on previously unsuitable land, further fueling the growth of tall buildings in urban areas. These foundation systems provided the necessary stability and opened up new possibilities for building taller, more structurally ambitious skyscrapers. The caisson foundation system was convenient in cities like Chicago, where bedrock was deep beneath the surface. Engineers could create a solid foundation capable of supporting much taller buildings by sinking caissons through soft, unstable soil layers until they reached bedrock (Schock & Risberg, 2013). It was widely used in Chicago in the late 19th and early 20th centuries. As mechanical drilling was expensive, the hand-excavated Chicago Method continued for a long time along with machine drilling. In subsequent years, belled machine-drilled caissons became increasingly common (Figure 11). After World War II, the machine drilling method became more popular, especially with the availability of sophisticated drilling equipment (Figure 12).

9.7. The John Hancock Center

Support on bedrock at the bottom of the foundation system prevents differential settlement. The caisson

foundations technology continues to be applied in modern tall buildings, particularly in constructing supertall buildings. Chicago, the birthplace of the skyscraper, continued to push the boundaries of tall building construction throughout the 20th century, and caisson foundations remained a vital component of these innovations. One of the most notable examples is the 100-story John Hancock Center (renamed 875 North Michigan Avenue) of 1970, a Chicago icon. Standing at 344 meters (1,127 feet) tall, the John Hancock Center was one of the tallest buildings and the tallest multi-use building in the world at the time, symbolizing Chicago's engineering prowess.

The foundation system of the John Hancock Center consisted of 239 large, drilled reinforced concrete caissons, 57 of which were extended down to 58 to 64 meters (190 to 210 feet) to Chicago's bedrock, and 182 were anchored into hardpan at varying depths. Many were belled at the base to increase bearing capacity and stability. Given the city's challenging soil conditions, the caisson foundation system was critical to ensuring the stability of the building. This deep foundation system allowed the building to withstand gravity and wind forces. A 3-meter (10-foot) thick reinforced concrete mat at the top of all caissons evenly distributes the loads from the steel columns in the superstructure to the caissons and prevents differential settlement. This foundation system was a pioneering solution for its time, considering the building's enormous height and weight while overcoming the challenges of the geotechnical complexities of the site's condition. The tower remains a benchmark in foundation design (Figure 13).

9.8. The Willis Tower

The 110-story Willis Tower (formerly Sears Tower) of 1973 in Chicago was the tallest building in the world for nearly 25 years and is the tallest building in Chicago.

The foundation of the Willis Tower consists of 114 large, reinforced concrete drilled caissons, each reaching a depth of about 34 meters (110 feet) into bedrock. These caissons support the building, anchoring it deep into the soil and bedrock to ensure stability and structural integrity. It is supported by caissons that extend about 30 meters (100 feet) to the bedrock. These caissons transfer the building's loads to solid bedrock. A 3-meter (10-foot thick) reinforced concrete mat atop all the caissons helps

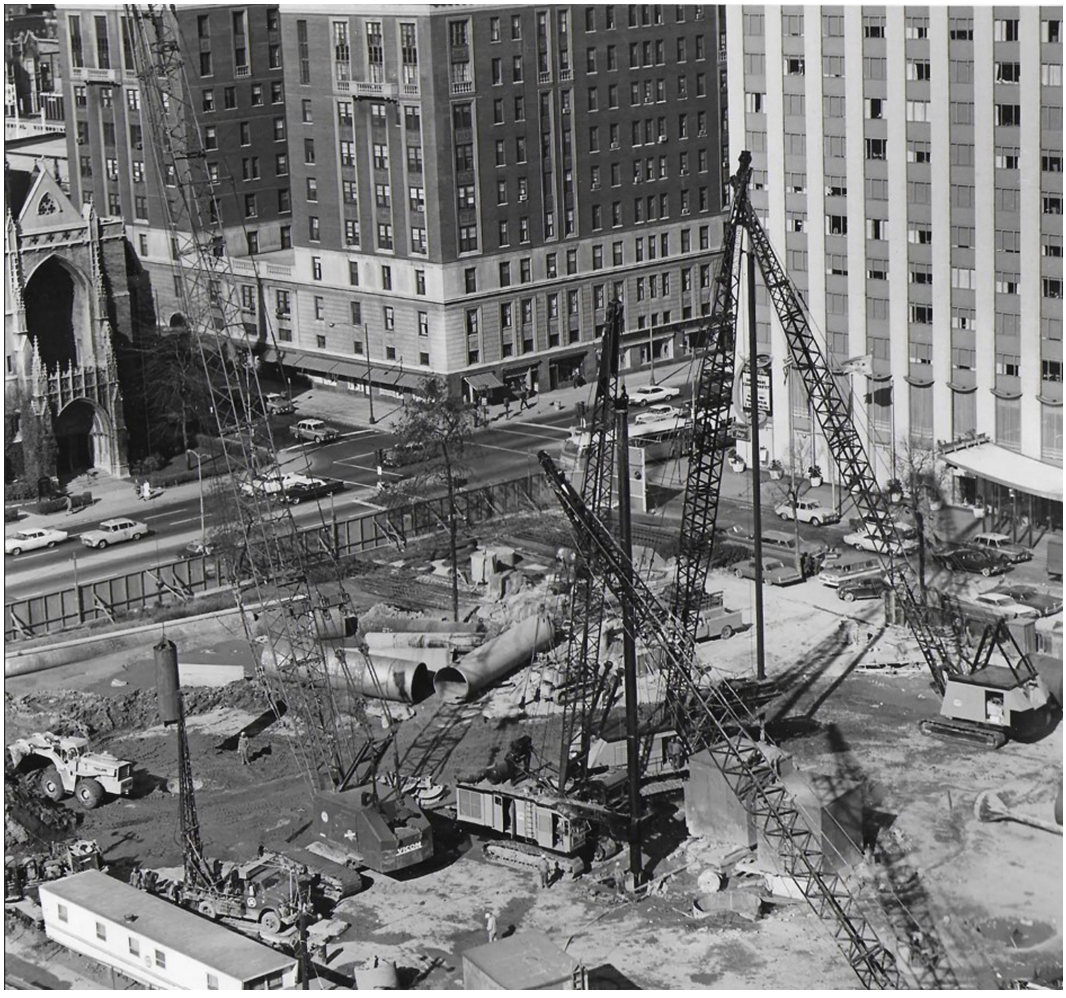


Figure 13. Laying foundation for John Hancock Center, Chicago. (Source: www.reddit.com)



Figure 14. Foundation Construction of Willis Tower, Chicago. (Source: Chicago History Museum)

distribute the structural loads from the tower evenly across the foundation and resist differential settlement. With the thick mat at the top, it efficiently resists wind loads, thereby maintaining structural stability and integrity of the massive building (Figure 14).

10. Seismic Considerations in Tall Building Foundations

The history of seismic design of buildings dates to ancient times. The effect of earthquakes was intuitively understood by builders long ago. For example, the principle of preventing seismic waves in the ground from entering the structure by constructing on a layer of materials like sand that allow for movement, now known as the base isolation technique, was applied to ancient structures (Bayraktar et al., 2012). Tying isolated footings with ties to prevent movement and separation of the individual footings was also understood and applied during the Greek Hellenistic period. Not much research was carried out on the seismic effect on foundations in the first half of the 20th century because of an inadequate understanding of the complexity of soil-structure interaction and the impact of earthquakes on foundations. As a result, building codes did not address this issue because of a shortage of research data (Ali, 1995). Later, based on a comparative study of US Building Codes sponsored by the Portland Cement Association (PCA) in Skokie, Illinois, Ali published a paper on the topic (Ali, 1997).

As skyscrapers are increasingly built in seismically active zones, foundation systems must bear static vertical loads and respond dynamically to ground motion. Earthquakes introduce complex lateral and vertical forces that challenge a building's stability, especially in soft soil or sloped terrain. To mitigate these risks, engineers employ appropriate foundation systems that enhance strength and deformability. Another major concern for the engineers is the soil liquefaction phenomenon during earthquakes, in which granular saturated soil loses its strength and stiffness, behaving like a liquid gulping the foundation and part of the building into it (Castro, 1987; Huang & Yu, 2013). Such sites must be avoided for any building in seismic zones.

One common approach is using reinforced concrete mat (raft) foundations, which act as a rigid platform to distribute uniform seismic forces and minimize differential settlement. In Taipei 101, for example, a 4.7-meter (15-foot) thick concrete mat sits atop 380 deep piles, many

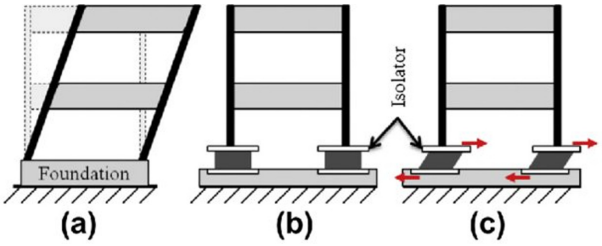


Figure 15. Seismic Base Isolation. (Source: www.researchgate.net)

socketed into bedrock. This foundation anchors the building against overturning and accommodates wind and seismic loading.

Bored piles and drilled shafts provide another key strategy, especially when socketed into rock. For instance, Burj Khalifa uses 192 piles extending 50 meters (164 feet) into the ground to transfer loads to a stable substratum, improving seismic resilience even in a desert environment.

Seismic foundation design also accounts for soil-structure interaction. Engineers may employ soil improvement techniques in areas with liquefiable or loose soils, such as grouting, stone columns, or vibro-compaction. Additionally, modern base isolation systems, although more common in low- to mid-rise buildings, are being adapted in modified forms for high-rises to decouple seismic energy from the structure (Figure 15).

Emerging technologies include embedded sensors to monitor seismic stresses in real-time and AI-based simulation tools that predict performance across various earthquake scenarios. As climate change and urban density introduce new risk factors, integrating seismic resilience into foundation design is prudent and essential.

11. Summary of Foundation Types for Tall Buildings

The following section outlines the major types of foundations used in tall building construction. Each foundation type is described along with its key advantages, disadvantages, and typical applications in various geotechnical and structural contexts. Table 2 provides a structured comparison of five primary foundation systems—spread footings, mat foundations, grillage, piles, and caissons—highlighting their operational principles, advantages, limitations, and typical applications in tall building projects.

12. Case Studies of Foundation Systems for Tall Buildings

This section highlights five iconic tall buildings and the foundation systems that enable their vertical ambition. Each case includes a brief building overview and a structured table summarizing its foundation design and geotechnical strategies. (Note: 1 meter = 3.28 feet)

12.1. Burj Khalifa – Dubai, UAE

12.1.1. Overview

The Burj Khalifa, the tallest building in the world at 828 meters, posed significant foundation design challenges. Constructed in a desert environment with weak, sandy soils and high salinity, the structure required a robust deep foundation system capable of handling extreme vertical loads, seismic events, and aggressive soil conditions. Engineers employed high-performance materials and sophisticated soil modeling to ensure long-term structural integrity (Table 3).

Table 2. Comparative Summary of Major Foundation Types in Tall Building Construction

Foundation Type	Description	Pros	Cons	Typical Applications
Spread Footing	Concrete pads that spread the load at column bases	Simple design, cost-effective, easy to build	Not suitable for soft soil or heavy loads; prone to differential settlement on soft soil	Low-rise buildings, good soil conditions
Raft (Mat) Foundation	Thick concrete slab spanning a wide area or totally under a building	Uniform load distribution, appropriate for soft soil, and seismic resistance	Heavy self-weight: A massive amount of concrete is required; needs to control heat of hydration	Mid- to high-rise buildings on soft soils and in seismic zones
Grillage Foundation	Steel beams (I-beams) encased in concrete for load spread	Good load distribution; faster construction	Labor-intensive; outdated by reinforced, latter-day concrete footings	Historic high-rises (e.g., Rookery Building, Chicago)
Pile Foundation	Long slender members (wood, steel, concrete) driven or drilled into deep strata	Reaches stable layers; can exploit skin friction; resists uplift & lateral loads; amenable to wet soil	Requires specialized equipment; possible noise/vibration for driven piles	Tall, supertall, and mega-tall buildings in coastal, soft, or seismic regions
Caisson Foundation	Deep watertight shafts (drilled or pneumatic) filled with concrete	Ideal for wet or unstable soil; precise installation	Costly; time-intensive; risk of labor hazards (esp. pneumatic caissons)	Dense urban settings, historic towers, and access to deep bedrock

Table 3. Foundation Summary for Burj Khalifa, Dubai

Parameter	Details
Foundation Type of Burj Khalifa	Deep Bored Reinforced Concrete Piles + Mat Foundation
Number of Piles	192
Pile Diameter	1.5 meters
Pile Depth	~50 meters
Mat Thickness	3.7 meters
Geotechnical Context	Loose sandy soils with high salinity
Key Challenges	Settlement control, corrosion due to salinity, no nearby bedrock
Special Features	High-Performance Sulfate-Resistant Concrete; continuous instrumentation

12.2. Shanghai Tower – Shanghai, China

12.2.1. Overview

At 632 meters, Shanghai Tower is China's tallest building and stands in a region with soft, alluvial soils and a high water table. Located in a seismic zone subject to typhoons and flooding, the project required a highly resilient foundation system with deep load transfer and seismic energy dissipation capabilities. Advanced performance-based seismic design and soil-structure interaction modeling were integral to the engineering strategy (Table 4).

12.3. Taipei 101 – Taipei, Taiwan

12.3.1. Overview

Taipei 101, once the world's tallest skyscraper, rises 508 meters in a high-risk seismic zone with soft soil conditions and frequent typhoons. The project faced extreme lateral load demands and required piles to be socketed into rock for added anchorage. Engineers



Figure 16. Burj Khalifa, UAE. The world's tallest building utilizes deep bored reinforced concrete piles and a thick mat foundation to overcome weak, sandy soil conditions and high salinity. (Source: authors)



Figure 17. Shanghai Tower, China. A megatall skyscraper supported by nearly 1,000 deep bored concrete piles and a massive reinforced concrete mat to address seismic risk and soft alluvial soils. (Source: authors)

Table 4. Foundation Summary of Shanghai Tower

Parameter	Details
Foundation Type	Bored Concrete Piles + Reinforced Concrete Mat
Number of Piles	955
Pile Diameter	1.0–1.2 meters
Pile Depth	52–56 meters
Mat Thickness	6 meters
Geotechnical Context	Soft clay, alluvium, high groundwater level
Key Challenges	Seismic resistance, typhoon winds, and lateral displacement control
Special Features	Seismic base design, FEM modeling, advanced soil-structure interaction

Table 5. Foundation Summary of Taipei 101

Parameter	Details
Foundation Type	Deep Bored Concrete Piles + Mat Foundation
Number of Piles	380 for the tower + 167 for the podium
Pile Diameter	1.5 meters (approx.)
Pile Depth	Up to 80 meters (15-33 meters socketed into bedrock)
Mat Thickness	3.0-4.7 meters
Geotechnical Context	Soft clay, near-fault seismic zone
Key Challenges	Earthquake resilience, wind uplift, and settlement control
Special Features	Seismic base isolation in adjacent systems, deep anchoring, and slurry walls



Figure 18. Taipei 101, Taipei, Taiwan. The supertall structure employs deep bored piles socketed into bedrock and a thick mat, enabling resilience against typhoons and seismic activity in a challenging geotechnical setting. (Source: Wikipedia, CC BY-SA 4.0)

developed a foundation solution that combined depth, rigidity, and damping capacity (Table 5).

12.4 Empire State Building – New York, USA

12.4.1. Overview

Completed in 1931, the Empire State Building was a marvel of its time. Rising to 381 meters required a reliable foundation in Manhattan's dense fill and shallow bedrock. Pneumatic caissons were used innovatively to sink to competent rock while working in waterlogged soils, enabling rapid construction on a tight schedule (Table 6).

12.5. Lakhta Center – St. Petersburg, Russia

12.5.1. Overview

The Lakhta Center is the tallest building in Europe, at 462 meters. Located on the northern outskirts of St. Petersburg near the Gulf of Finland, it faces extreme climatic conditions, including freezing temperatures and a high water table. The foundation had to be engineered to prevent frost heave, manage hydrostatic pressure, and stabilize the structure on weak clayey soils. The site also presented challenges due to proximity to water and the necessity of large-scale excavation below the groundwater level (Table 7).

12.6. Comparative Examination of Case Studies

To illustrate the evolution and diversity of tall building foundation systems, five globally significant skyscrapers were selected for detailed comparison. Each case study highlights a unique combination of geotechnical context, design challenges, and innovative foundation strategies

Table 6. Foundation Summary of Empire State Building

Parameter	Details
Foundation Type	Pneumatic Caissons + Reinforced Concrete Mat
Number of Caissons	55
Caisson Depth	15–24 meters (50–80 feet)
Mat Thickness	2.4 meters
Geotechnical Context	Urban fill over shallow bedrock
Key Challenges	Groundwater control, schedule constraints, heavy axial loads
Special Features	Use of compressed air to excavate, and early adoption of deep caissons



Figure 19. Empire State Building, NYC, USA. The iconic skyscraper rests on pneumatic caissons sunk to bedrock and a reinforced concrete mat, facilitating rapid construction on Manhattan's waterlogged soils. (Source: authors)

tailored to the structural demands and environmental constraints of the site.

The **Burj Khalifa** in Dubai, for example, rests on weak, sandy soil with high salinity, requiring the use of deep bored piles and a thick mat foundation. Advanced high-performance concrete and soil modeling techniques were used to address extreme axial and lateral loads.

Similarly, the **Shanghai Tower** was constructed on soft, layered soils with a high groundwater table. Engineers adopted a performance-based seismic design approach and implemented an extensive bored pile and mat foundation system to ensure flood and seismic resilience.

Taipei 101, located in a high-seismic zone with soft clay and shallow bedrock, faced the dual challenge of typhoon winds and earthquake forces. Its deep pile foundation extends into bedrock and is supported by a slurry wall system to enhance lateral stability.

The **Empire State Building**, constructed in the early 20th century, utilized pneumatic caissons to reach bedrock beneath dense urban fill. Despite limited geotechnical knowledge at the time, the use of caissons and a mat foundation distributed structural loads efficiently, reflecting early innovations in skyscraper foundation engineering.

Lastly, the **Lakhta Center** in St. Petersburg addressed the extreme conditions of soft soils, high groundwater, and a cold climate. Its foundation system incorporated large-diameter bored piles, hydro-insulation, and thermal adaptations to manage frost resistance and hydrostatic uplift.

These case studies collectively demonstrate how foundation systems are intricately adapted to their environments,

Table 7. Foundation Summary of Lakhta Center

Parameter	Details
Foundation Type	Bored Piles + Reinforced Concrete Mat
Number of Piles	264
Pile Diameter	2.0 meters
Pile Depth	65 meters
Mat Thickness	3.6 meters
Geotechnical Context	Soft clay, high groundwater level, cold climate
Key Challenges	Frost resistance, hydrostatic uplift, and long-term soil consolidation
Special Features	Hydro-insulation systems, high-strength concrete, thermal design for Arctic-like conditions



Figure 20. Lakhta Center – St. Petersburg, Russia. Europe's tallest building is supported by deep bored piles and a reinforced concrete mat, engineered to address soft clay, high groundwater, and Arctic climate conditions. (Source: Wikipedia, CC BY-SA 4.0)

balancing structural performance, safety, and site-specific constraints. A comparative summary is provided in Table 8.

13. Foundations for the Future

Future skyscrapers will encounter significant challenges in advancing foundation systems capable of supporting their enormous structural loads. As buildings grow taller, foundations must contend with increasingly complex issues, including diverse geological conditions, rising water tables due to climate change, limited construction space in dense urban areas, and the risk of damaging existing underground infrastructure. Meeting these challenges will require adopting innovative techniques such as vibration-free piling, advanced underpinning, and top-down construction. For supertall buildings, foundation failure is not tolerable, and absolute reliability is required. Achieving this level of reliability will depend on data-driven design and the integration of AI to analyze soil behavior and optimize foundation performance. As these structures are expected to last for decades, implementing embedded sensors to monitor foundation health continuously will become increasingly important.

The future of tall building foundation design and construction is tilting towards more effective and sustainable resolutions. Technological advances in materials science, computer-aided design, geotechnical engineering, and a better understanding of soil-structure interaction are compelling technical modernizations in deep foundations, including soil improvement techniques. As cities continue to build upward, the next generation of tall buildings will require foundation systems that are not only structurally robust but also intelligent, adaptive, and environmentally responsive. Emerging technologies are transforming the future of foundation engineering by enabling greater precision in design, enhanced resilience under complex loading conditions, and improved sustainability through innovative materials and real-time monitoring systems.

13.1. Top-Down Construction Techniques

Advancement of top-down construction techniques is increasingly prevalent in dense urban environments where minimizing disturbance and hastening project timelines are paramount. This construction method will influence digital twins to spur progress and manage activities with several trades. Moreover, self-healing concrete solutions are being deployed to address groundwater access (Xiao & Sun, 2016). Integrated with embedded sensors, these materials provide early warning of leaks or settlement, enabling proactive maintenance and augmenting the durability of substructures.

13.2. Carbon Fiber Reinforced Concrete

In response to growing environmental concerns, carbon-reinforced concrete (CFRC) is emerging as a promising alternative to traditional steel reinforcement. CFRC utilizes carbon fiber grids that are corrosion-resistant, lightweight, and offer increased strength and durability while reducing the volume and weight of structural elements. (Guo et al., 2021). Foundations constructed with CFRC require less upkeep, aligning with the sustainability objectives of future supertall and megatall skyscrapers.

13.3. Smart Foundations and Embedded Monitoring Systems

Innovative foundation systems now incorporate embedded sensors within piles and mats to monitor performance in real-time (Barkalov, et al., 2019; Marwedel, 2021). These instrumented piles are equipped with fiber-optic sensors, strain gauges, and accelerometers to track load distribution, settlement, vibration, and temperature changes during and after construction. This data facilitates predictive maintenance, early detection of anomalies, and long-term performance validation, transforming foundations into active, self-reporting infrastructure.

13.4. AI-Based Geotechnical Modeling

Advances in artificial intelligence and machine learning

Table 8. Cross-case analysis of five global high-rises, detailing foundation types, geotechnical challenges, and design strategies specific to each context.

Building	Foundation Type	Geotechnical Context	Design Challenge	Foundation Details
Burj Khalifa Dubai, UAE	Bored Piles + Mat Foundation	Weak, sandy soil with high salinity	Supporting the world's tallest building on non-bedrock terrain	192 bored reinforced concrete piles. **Diameter**: 1.5 m. **Depth**: ~50 m. **Mat Thickness**: 3.7 m. **Special Features**: Sulfate-resistant High-Performance Concrete (HPC); advanced soil modeling and monitoring to ensure performance under high axial and lateral loads.
Shanghai Tower Shanghai, China	Bored Piles + Mat Foundation	Soft, layered soil with a high groundwater table	Ensuring seismic and flood resilience for a megatall tower	955 bored concrete piles. **Depth**: 52-56 m. **Mat Thickness**: 6 m. **Special Features**: Designed for typhoon and seismic conditions using performance-based seismic engineering and finite element analysis.
Taipei 101 Taipei, Taiwan	Bored Concrete Piles + Mat Foundation	Soft clay, shallow bedrock, high seismic risk	Resisting lateral forces from typhoons and earthquakes	380 piles for main tower + 167 for podium. **Depth**: Up to 80 m (15-33 m socketed into bedrock). **Mat Thickness**: 3-4.7 m. **Special Features**: Deep anchoring; slurry wall; proximity (200 m) to an active fault line; designed for wind uplift and seismic resistance.
Empire State Building, New York, USA	Pneumatic Caissons + Mat Foundation	Dense urban fill with access to bedrock	Supporting record-breaking height with early geotechnical limitations	55 pneumatic caissons. **Depth**: 15-24 m (to bedrock). **Mat Thickness**: 2.4 m. **Special Features**: Early 20th-century innovation; distributed loads from steel columns; accommodated saturated soils using caissons.
Lakhta Center St. Petersburg, Russia	Bored Piles + Mat Foundation	Soft clay, high groundwater level, cold climate	Managing hydrostatic uplift and frost resistance in Arctic-like conditions	264 bored concrete piles. **Diameter**: 2.0 m. **Depth**: 65 m. **Mat Thickness**: 3.6 m. **Special Features**: High-strength concrete; hydro-insulation systems; thermal design adaptations for extreme weather.

are revolutionizing geotechnical site assessment and foundation design. AI algorithms can process vast datasets from soil boring logs, cone penetration tests, and sensor networks to develop predictive models of subsur-face behavior. These models enhance the accuracy of load-bearing predictions, optimize foundation dimensions, and simulate responses under seismic or flood conditions. AI also aids decision-making under uncertainty, a key factor when dealing with complex or variable subsurface environments (Wang et al., 2020).

13.5. Ground Improvement Techniques

Ground improvement and stabilization technologies are also evolving to accommodate foundations in previously unsuitable soils. Techniques such as jet grouting, deep cement mixing (DCM), soil nailing, and soil freezing can modify in-situ soil properties to increase strength, reduce compressibility, and improve seismic response (Puppala, et al., 2017). For example, in East Asia, DCM is widely used to construct stable foundations in soft marine clay. At the same time, jet grouting is effective for underpinning and retrofitting foundations in urban renewal projects.

Collectively, these advancements represent a shift in how foundations are conceived—not merely as underground static structural components, but as dynamic, responsive systems embedded with intelligence and aligned with broader goals of robustness, durability, and sustainability. As cities grow taller and more complex, the foundations of the future will need to support not just physical loads, but the evolving performance expectations of an urbanizing, data-driven world.

14. Conclusions

The growth of foundation systems for tall buildings highlights the remarkable progress made in engineering and construction techniques over the past centuries. From the early days of shallow foundations supporting buildings of modest heights to the sophisticated deep foundation systems used in today's tallest structures, each advancement has played a crucial role in enabling the rise of skyscrapers and ensuring their stability. Indeed, the foundations of tall buildings have come a long way.

The development of pile foundations and caissons marked a significant turning point, allowing engineers to build taller buildings by reaching deeper, more stable soil layers. This innovation set the stage for subsequent advancements, which offered even greater depth and stability, and

mat foundations, which distributed the load across a wide area to support the immense weight of supertall structures. Further refinement of the foundations is expected regarding their design and construction.

As cities grow and vertical expansion becomes essential, foundation systems will remain a cornerstone of successful skyscraper development. Future innovations—ranging from advanced materials to cutting-edge techniques for mitigating seismic forces and adapting to climate change—will play a pivotal role in shaping the next generation of high-rise construction.

The ongoing quest for taller, more resilient, and efficient buildings will drive further advancements in foundation systems, ensuring that the structural integrity of skyscrapers remains robust in the face of evolving architectural and environmental challenges. By building on past innovations and embracing new technologies, engineers will continue to push the boundaries of what is possible, creating skyscrapers that stand as enduring symbols of human ingenuity and architectural excellence. The future of tall building foundations will warrant a comprehensive approach, incorporating advanced technologies, sustainable practices, and a deeper understanding of the intricate soil-structure interaction.

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