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120 YEARS OF CAISSON FOUNDATIONS IN CHICAGO

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ABSTRACT

Chicago can be called the birthplace of the Skyscraper, and also the Drilled Shaft Foundation, both of which came into being late in the 19th century. The story of the Chicago Caisson begins with the presence of a thick deposit of soft clay beneath the City, and continues with the succession of building booms that have characterized the growth of the City over the last 140 years, beginning just after the Great Fire of 1871. During that first boom, new tall structures were built so rapidly, and amid such profound geotechnical uncertainty, that the process of designing a successful foundation became one of trial and error, with very little time between projects to observe behavior and make corrections. Eventually attempts to "float" tall buildings on shallow foundations above the soft clay were abandoned in favor of the first deep foundations, which bypassed the problem layer and found solid support on "hardpan" till or rock below.

This paper will briefly describe the origin of the modern Drilled Shaft Foundation, which has its evolutionary roots in the Chicago Hand-Dug Caisson. It will then trace the development of the Chicago Caisson into a mechanized process, with each advance assisted again by observed behavior, emerging load test methods, and constant improvement and innovation in equipment and methods to meet the needs of the next generation of taller buildings.

INTRODUCTION

Less than 20,000 years ago the last of the glaciers retreated from the Chicago region. They left behind sheets of glacial clay till, underlain by dense, over consolidated till ("hardpan") below which is the limestone bedrock, found about 100 ft. below street level. The most unusual feature in this profile is the unusually soft clay till that has historically been called "Chicago Blue Clay".

EARLY HISTORY

The founding fathers of Chicago really didn't care about what was under the ground. They recognized the importance of the city's location as a potential trade and transportation hub. With access to the east through the Great Lakes and access to the west through the Mississippi River system, the viability of the city was evident. Chicago's population grew rapidly. The City continued to grow through the Civil War years, but was dealt a devastating blow in 1871 by The Great Chicago Fire, leaving the city in ruins.

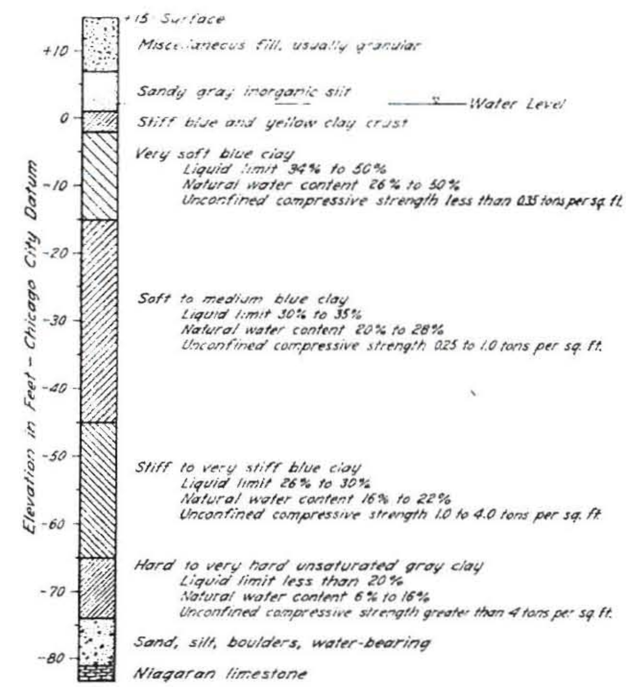

FIG. 2. TYPICAL SOIL CONDITIONS IN LOOP AREA

Fig. 1. Typical Chicago Soil Profile by Peck.

AFTER THE FIRE, THE BIRTH OF THE SKYSCRAPER

After the clean-up of the Great Fire came the first real building boom in Chicago's history. During this era, buildings were generally founded on shallow footings bearing on sand or clay. The sand or desiccated clays overly the soft compressible clay which, coincidentally, are thickest in what is now the heart of downtown Chicago. Many multi-story buildings were constructed between 1880 and 1890 on spread footings. The first multi story buildings were constructed with concentrated load bearing masonry walls. These early tall buildings suffered significant settlement as the soft clay underwent consolidation.

The Home Insurance Building, built in 1885 was 12 stories tall, and is generally acknowledged to be the first "Skyscraper" in the U.S. It was the first building constructed with an iron skeleton frame instead of load bearing masonry walls. Spread footings were used under the interior columns in an effort to better distribute the loads, but the building still experienced large settlements.

Fig. 2. Home Insurance Building

Construction began for the Monadnock Building in 1891. The 16 story building was built using load bearing walls supported by rail-grillage footing foundations. When completed in 1893, the Monadnock Building boasted the title "World's Largest Office Building". The total building settlement over the past 125 years has been measured at over 20 inches. The engineering community in the late 19th century observed, but did not yet understand the process of consolidation of the soft clay beneath the City. It was a number of years before the science and art of foundation design could catch up to the demands of the new taller buildings and their higher gravity loads. During this time many of the new buildings required structural repairs during and after construction; the problem was especially acute in buildings where high-rise towers joined lower podium structures.

Fig. 3. Monadnock Building

WOOD PILES-CHICAGO'S FIRST DEEP FOUNDATION

As early as 1870, engineers were using driven timber piles to support grain silos along the Chicago River. Frustrated with the settlements they were experiencing in the new taller buildings, engineers elected to try using timber piles for building construction. The Grand Central Station project constructed in 1890 and the Garrick Theater project in 1892 were the first projects to implement this design. The first deep pile foundation systems utilized 50 ft. long piles driven through the soft clay into the stiffer clay till found below. Both projects proved to be structurally successful in limiting building settlement; however the neighbor of the Garrick Theater sued over damages their building experienced from the pile driving.

Fig. 4. Grand Central Station

Fig. 5. Garrick Theater

In 1894 construction began for the Stock Exchange Building, also with a foundation of driven wood piles. During construction, the owners for the neighboring Herald Building obtained a court order preventing pile driving alongside their building.

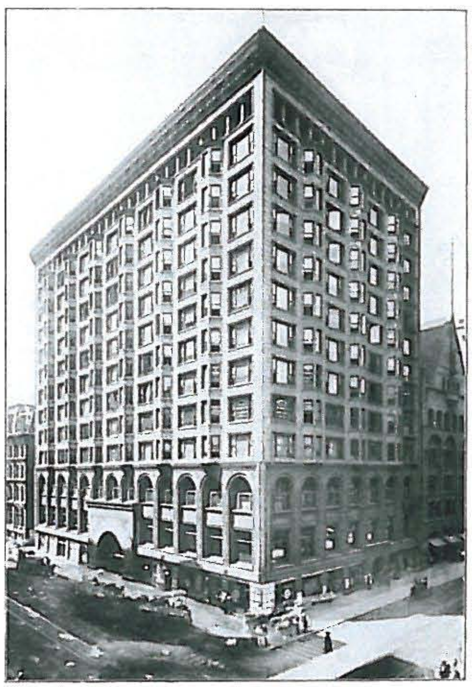

Fig. 6. Stock Exchange Building

THE CHICAGO CAISSON

An early consultant and now legendary Chicago foundation engineer General Sooy Smith was retained to devise a solution, which would eventually become standard practice for the next 60 or so years.

General Smith's design required eight hand dug "wells" to replace the line of piles at the property line. The shaft diameters ranged from 5'-0" to 6'-4" and the shaft bases were enlarged to 6'-6" and 8'-6" diameters, foreshadowing the future belled hardpan caisson.

After the use of hand dug "wells" for the Stock Exchange Building in 1894, the engineering and construction community slowly adapted to the new deep foundation element. The Chicago Hand-Dug Caisson gained acceptance and a new era of building construction began. The continued development of taller buildings as well as the construction of the Chicago Freight Tunnel System ended the practice of spread footings in downtown construction after about 1905.

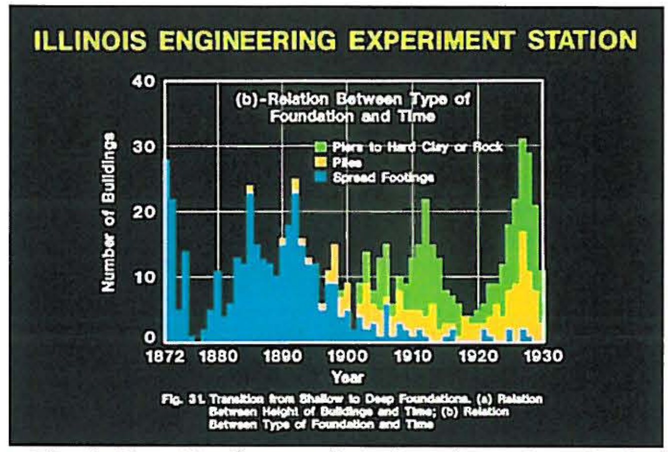

Fig. 7. Transition between Deep Foundation Type, Peck.

In 1899 the Methodist Book Building at 12 West Washington Street was the first to have an all-caisson foundation. In 1912 the first caisson load test was performed at Cook County Hospital, and ten years later another caisson load test was performed at Union Station; these early tests established an allowable bearing pressure of 12,000 psf on the hardpan.

Fig. 8. Load Testing Caisson at Union Station.

The method of installing Hand Dug Caissons was one of back breaking labor, common sense, and pure ingenuity. The work was performed under the risk of soil collapse, and the potential inflow of water and methane gas. The common procedure involved tongue and groove wood lagging installed and braced by iron rings to line the shaft and support unstable soils. Shovels and air spades were used to dig the clay, and small "derricks" were set up over each caisson, with a tripod and air-driven winch to hoist up the well buckets of spoil and lift the workmen in and out of the shafts. Typical practice was to dig the clay in increments of 5'-4", then the section would be lined with the lagging boards like the staves of a barrel. Each 5'-4" segment of the shaft was called a "set".

Fig. 9. Tripod Set-up with air tugger over hand-dug caisson.

Fig. 10. Dumping well bucket of excavated material. Note air tugger (winch) and Tripod.

Usually a crew of 3 men would work as a team to excavate the typical hand dug caisson, which was a minimum of 48" in diameter, allowing at least one man to work efficiently within the shaft. The team consisted of a headman, the dumper and a hand miner. The team was expected to dig 16 feet, or three "sets" of lagging, per 8 hour shift. Additional hand miners would be added if the shaft was large enough for more than 1 miner. This process was repeated until the required bearing depth on the hardpan was reached.

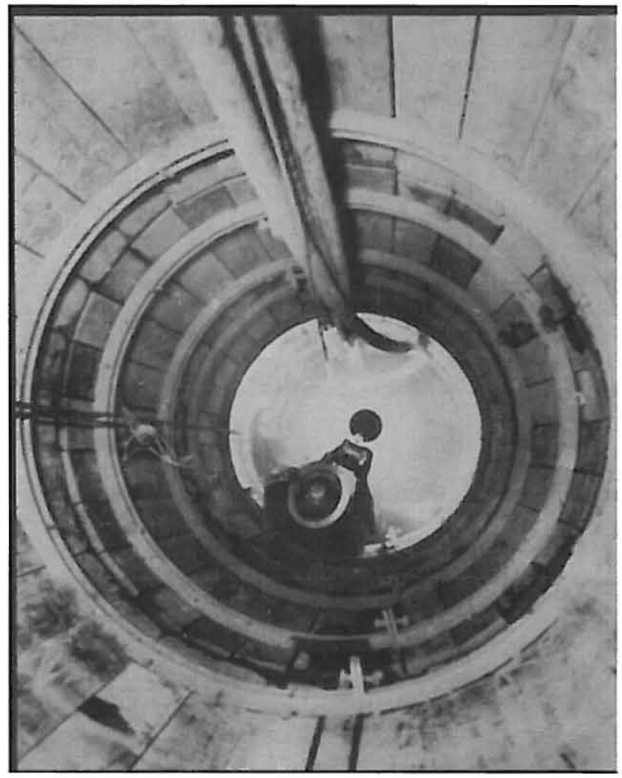

Fig. 11. Hand dug caisson to rock showing tongue and groove lagging with rings used to support the excavation.

It became common practice to enlarge the base of the caisson on the hardpan by the same hand digging methods to form a "bell" and increase the capacity of the caisson.

Hand dug caissons to rock became the preferred approach for some architects and owners, who sought the most secure foundations for their ever taller buildings. Digging below the hardpan brought new problems and challenges. In most areas of downtown Chicago, the till turns granular above the rock surface, usually accompanied by water under pressure. To get through this stratum and reach the rock, hand miners invented the "driving set", where the lagging boards were cut to an edge and driven into the soil ahead of the digging. In order to prepare for the driving of the sets through the water-bearing sand and gravel, the shafts had to first be enlarged to make clearance. Several sets above the presumed problem layer, the shaft diameter would be increased in equal stages. For each driving set that would be needed to reach the rock, an equivalent number of "widening out" sets were dug and lagged so that the original diameter of the caisson could be maintained when the bottom of the shaft reached the rock.

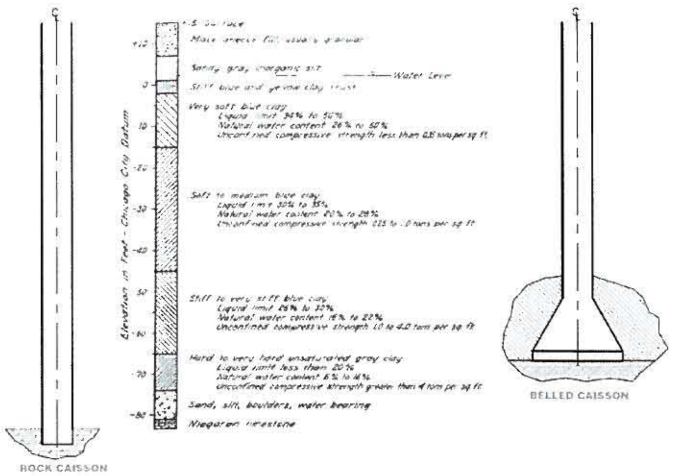

Fig. 12. Where caisson types are used in the typical Chicago soil profile.

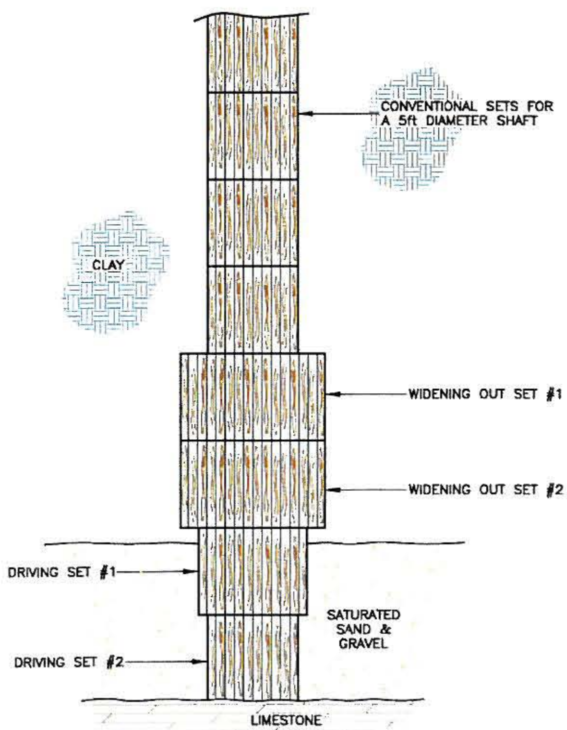

Fig. 13. Schematic of Hand Dug Rock Caisson with "Widening Out" sets and Driving Sets.

CHICAGO MACHINE DRILLED CAISSONS

The hand-dug caisson era extended well into the 1950's and 1960's, particularly with rock caissons, until mechanical drill rigs could be developed with enough power to penetrate through the hardpan and dense till overlying the rock. The Prudential Building, (41 stories) Chicago's first modern skyscraper and first major post-war building was undertaken in the early 50's on large hand dug rock caissons, which are visible today, after a basement expansion in the 1990's added 2 parking levels below the building. In the 1960's hand-dug caissons were installed from existing basements during demolition of the structure above to make way for the First National Bank Building (60 stories) in the heart of the Loop.

Fig. 14. Prudential Building (1951)

EQUIPMENT EVOLUTION

The first mechanical drill rigs to appear in Chicago during the 1950's were bucket rigs, which were so named because they had no turntable and could not swing; instead a side boom was used to pull the Kelly bar and digging bucket off to the side for dumping as it came up out of the hole. Bucket rigs were the Model T's of the drilled shaft industry, but in the hands of a skilled crew could rapidly drill and bell small shafts up to 60 ft. or so. The rotary drive mechanism was a 48" ring gear, through which Kelly bar and bucket had to pass, so bucket rigs worked best in all-clay strata (no casing) and could not drill larger than 42" diameter, unless reamers were used.

Fig. 15. 1950's era Bucket Rig.

The first truck augers came to Chicago in the late-fifties. Developed by Hughes Tool Company, these were modified from oil well drilling technology and were more powerful and versatile than the bucket rigs. The largest of these rigs, the LDH (Large Diameter Hole) and LLDH (Large Large Diameter Hole) models arrived in the 60's and were the final stage of truck-mounted rig development in Chicago. These machines were capable of excavating shafts up to 8 ft. diameter to a depth of 120 feet; like the bucket rigs, they were very dependent on the skill of the operator and "swamper", or ground man, for best performance and mechanical reliability.

Fig. 16. Early Hughes Truck Auger.

The first machine-drilled caissons in Chicago were a hybrid of methods; before belling tools were developed, the bucket rig or truck auger rig would drill the shaft, and the bells would be cut by hand. Steel casing instead of wood logging was used to get through any unstable layers. Although painfully slow and dangerous by today's standards, the machine-drilled shaft/ hand-dug bell was a dramatic improvement in efficiency. In the late 50's and early 1960's the Dodgen and Apex bell bucket designs were introduced, making the transition to a completely mechanical process. Installing a typical belled caisson on hardpan at 85 ft., a task that would have taken several days by hand crews working around the clock, could now be done in 3 or 4 hours.

The next step in the evolution of mechanized rigs was the advent of the crane-mounted drill attachment, which began to appear in the 1960's and culminated late in that decade with very large twin-engine platforms capable of delivering 400,000 ft.-lbs. of torque to 18" Kelly bars, mounted on 140-ton crawler cranes. Depending on crane size and Kelly length, these machines could be configured to drill shafts up to 20 ft. in diameter, and reaching to depths of 240 ft. Crane attachments are still in widespread use today; their best applications are in handling large belling tools, and long-reach drilling from barges for bridge foundations.

Fig. 17. Early Crane Attachment with First 7 ft. belling bucket capable of cutting a maximum 21'-0" diameter bell. (Circa 1963)

The equipment evolution of machine-drilled caissons in Chicago has been driven by the transition from the old hand-dug methods and the succession of building booms in Chicago over the last 50 years. The first of these waves, in the late 1960's and early 1970's, produced the tallest building in the world at the time, Sears Tower (110 stories). The last wave, ended by the 2008 recession, saw the foundations installed for the 150-story Chicago Spire.

DESIGN AND CONSTRUCTION ADVANCES - BELLED CAISSONS

Advancements in the art and science of geotechnical engineering were also moving rapidly in Chicago. The early City code limit of 12 ksf for belled hardpan caissons had been increased to a "standard" of 20 ksf by applied theories on the known properties of the hardpan shear strength and internal friction. The new tall concrete buildings in the "first wave" boom of the 60's and 70's had design loads that would require caissons to rock, unless unit loads on the hardpan, and belled caisson sizes, could be increased. Both were done; at Lake Point Tower (70 stories) in 1969 and at Water Tower Place (74 stories) in 1972 a design bearing pressure of 30 ksf was used, and the powerful new crane attachments with large belling buckets cut bells up to 27 ft. in diameter.

Fig. 18. Caisson Installation at Water Tower Place (1972)

Fig. 19. Water Tower Place - large crane attachment augering 10 ft. diameter shaft (1972)

Fig.20 Water Tower Place - large "Apex" belling bucket (1972)

Fig. 21. Water Tower Place - hand cleaning 27 ft. bell. (1972)

Fig. 22. Water Tower Place - hand trimming top of 27 ft. diameter bell. (1972)

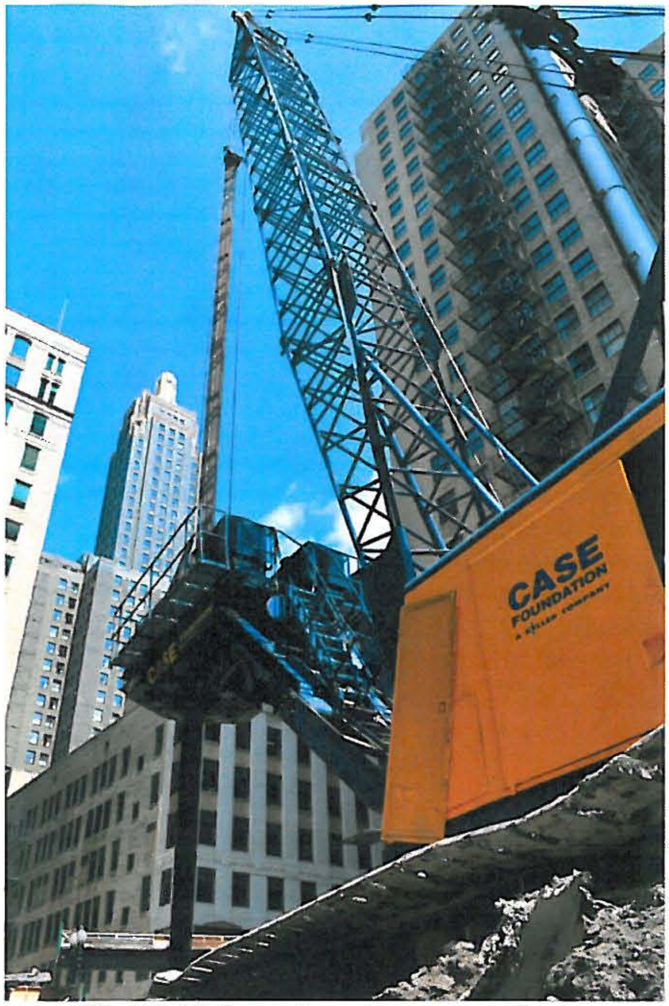

Fig. 23. Modern twin engine crane attachment

DESIGN AND CONSTRUCTION ADVANCES - ROCK CAISSONS

Rock caisson drilling methods evolved into a purely mechanical process in similar fashion. The early truck-mounted rigs lacked the power to efficiently drill through the dense bouldery till over the rock. The powerful crane attachments developed in the 1960's overcame those conditions. Instead of wood lagging, the shafts were lined with full-length steel casing; carbide teeth on the edge of the casing enabled the crane attachments to screw the casings into the rock to seal out water and running sand. Hand crews were also still very much a part of early machine-drilled rock caissons; before the development of efficient mechanical rock excavation tools, tripods would be set up over the open caisson once the casing had been installed, and hand miners would enter the shaft with air breakers to remove unsuitable rock and do a final cleanup. At the Hancock Building in 1966, the first of the Chicago "Supertalls", one caisson was hand mined to 192 ft. (47 ft. into rock) to get to the bottom of a vertical seam of soft claystone.

Chicago code changes after the Hancock influenced the caisson design for the next 2 "Supertalls" of the early 70's, the Sears Tower (110 stories) and Standard Oil Building (80 stories). Permanent casing was now a design requirement, but it allowed designers to use higher allowable stresses in the caisson concrete. Coupled with the code's allowable increase in bearing pressure with greater penetration into rock, reduced shaft sizes with higher capacity became economical. Rock caisson designers sought the most cost effective balance between steel casing diameter and wall thickness, concrete strength, and rock socket excavation. At this time, and for the next 20 or so years, a design bearing pressure of 140 tsf was selected as the most optimal combination of those factors. To achieve this, the caissons would be socketed 3 ft. below sound rock and could be designed with a conventional 5,000 psi concrete mix. Rock caisson construction during this period evolved into a completely mechanical operation; the rock sockets were excavated with carbide-tipped augers and large-diameter drag-tooth core buckets, and workmen entered the shafts only for final cleaning of the base and to drill a probe hole beneath the socket to check for open joints or seams in the rock.

Fig. 24. Large-diameter limestone cores recovered during rock socket excavation.

MODERN HIGH CAPACITY CHICAGO ROCK CAISSONS

Development of high-strength concrete, new load testing methods, and advances in rock excavation tooling have combined to reshape rock caisson design and construction practice for the tallest new buildings in Chicago.

The current Chicago code provides for 100 tsf end bearing with 1 ft. of penetration into sound rock, and an additional 20 tsf for each additional foot of embedment into rock, to a maximum of 200 tsf. Since there is no question of bearing capacity failure in the limestone bedrock at 200 tsf and higher, designers have looked for more efficiency with higher loaded elements, with the limiting factor being the structural, rather than the geotechnical capacity of the caisson.

Exceeding the code requires load testing, and this has been done economically by unit-load testing with Osterberg cells placed at the bottom of the first production caisson as a confirmation test. Rock caissons for the Trump Tower (90 stories) in 2005 were designed and installed at 250 tsf; two years later the Aqua Building (80 stories) was built with the same design. Both of these structures have 10 ft. diameter rock caissons grouped beneath their cores; each of which has a capacity of 35,000K.

Foundations for the proposed 150-story Chicago Spire were installed in 2008 in a very efficient circular layout of 34 ten-ft. diameter rock caissons with a design bearing pressure of 300 tsf and a capacity of 42,500K; these are believed to be the highest capacity single deep foundation elements ever installed in the U.S.

MODERN ROCK EXCAVATION TOOLS

This latest generation of tall concrete buildings with high-capacity rock caissons has required the development of more efficient equipment for excavation of deep rock sockets. Rather than carbide tipped drag-tooth coring or augering tools, percussion tools operated by high pressure air have been developed, using a "cluster drill" arrangement of downhole hammers in a canister housing. For the largest 10 ft. diameter shafts, 3 passes are needed; a 60" diameter pilot bore, followed by 90" and 114" "openers" to reach the full diameter rock socket.

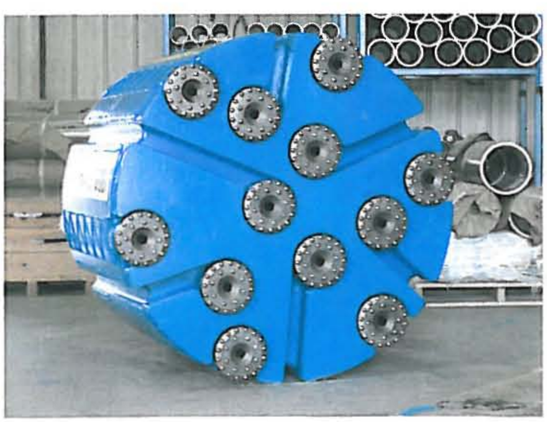

Fig. 25. 60" Cluster Drill

Fig. 26. Cluster Drill in use at Trump International Tower. (2005)

Fig. 27. Discharging cuttings from calyx basket above 60" cluster drill – Trump International Tower (2005)

Fig. 28. 60"to 90" Hole Opener - Trump Internatinal Tower (2005)

Fig. 29. 90" and 114" Hole Openers with calyx baskets in place above the canisters - Trump International Tower. (2005)

These tools need extremely large volumes of high-pressure compressed air to operate the hammers, but are very effective in reducing the limestone to sand and gravel-sized chips, which are evacuated from the drill face by the escaping air, which blows the cuttings up and over the canister into a calyx basket.

Fig. 30. Discharging cuttings from calyx basket above 114" Hole Opener – Trump International Tower (2005)

CUSTOM CHICAGO CAISSON FOUNDATIONS

The advances in geotechnical engineering and drilled shaft construction methods over the last 30 years have provided cost-effective foundation solutions on difficult sites in Chicago.

Early Generation Foundation Obstructions

There are no "green" sites left in downtown Chicago, and developers frequently deal with 2 or even 3 generations of existing foundations remaining in the ground after demolition to make way for new buildings on prime downtown sites.

Existing caissons from the hand dug era, and the early machine dug era, are frequently encountered; they are normally not reusable, but must be accounted for when designing a new caisson system. Complete removal of old caissons is prohibitively expensive and is never attempted, but "near miss" caisson installation close to old caissons has become relatively common. New shafts can be placed adjacent to old, but new bells cannot be cut into the concrete of old bells. Instead, the new caisson is extended beneath the bottom of the existing caisson, to allow belling below and within the hardpan stratum. This involves the additional time and expense of coring through the existing bell, but there is a small offset of savings because designers can take advantage of higher bearing pressures available with deeper embedment into the hardpan; up to 60 ksf, rather than the standard 20-35 ksf at the surface of the hardpan. This has led to more economical foundation layouts even on unobstructed sites, allowing smaller, high-capacity bells to be grouped closer together directly under the load path.

On sites with existing belled caissons present and thin hardpan, the new caissons must be extended below the hardpan into the granular and water-bearing till. Filtered dewatering wells are used to temporarily lower the head pressure in the granular till, allowing the bells to be excavated and concreted in this dry. This has been far less costly than the option of extending new caissons to the rock.

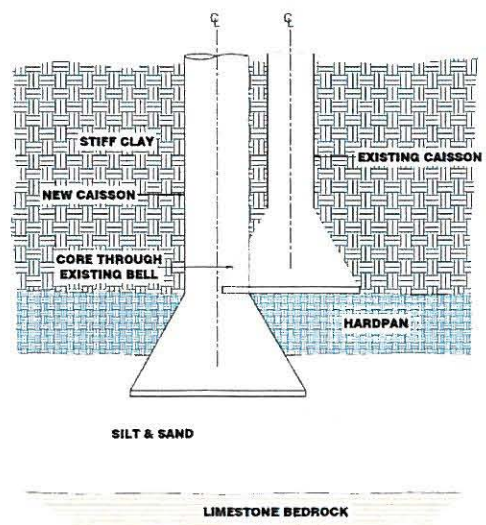

Fig. 31. Installation of new caissons below the hardpan and beneath existing abandoned caissons.

Slurry Displacement Rock Caissons

On sites where the hardpan stratum is missing, slurry caissons to the rock surface have become economical over the last 15 years. Again, load testing and equipment advances have played a role in developing this as a better option for some projects than piles to rock or high-capacity rock caissons. O-Cell testing on the first production caisson is used to confirm an end bearing pressure of up to 90 tsf at the rock surface. No permanent casing is used; instead, the easy to handle and environmentally benign polymer slurry is used to stabilize the shaft excavation through any cohesionless layers overlying the rock.

Fig. 32. Large Bauer hydraulic drill rig installing polymer slurry displacement caisson at Rooselvelt University.(2010)

The latest generation of drilling rigs, the all hydraulic European-style machines, are ideal for this application; they can apply heavy crowd forces to the Kelly and drilling tools to penetrate the dense till and remove any loose or weathered rock at the rock/soil interface. The polymer slurry column provides a very clean fluid environment for the tremie placement of concrete, after which the slurry is reclaimed and reused.

High Capacity CFA Foundations

The large new European hydraulic drill rigs have also made possible the installation of continuous flight auger (cfa) piles in larger diameters than the 14"-24" augercast piles that are more commonly used. The power of these machines, coupled with heavy duty continuous flight augers, allow penetration through very dense soil and into weathered rock. O-Cell load testing has confirmed a design load of 1,000 tons on 48" cfa foundations in St. Louis, and a future project has been permitted in Chicago using these large cfa elements. Cost comparisons have shown this prototypical "drilled shaft foundation" to be more economical than either steel piles or conventional drilled caissons to rock, but it remains to be seen where this new drilled foundation will have its place in future deep foundations in Chicago.

Fig. 33. Installing 48" Diameter CFA Piles to Rock. (2011)

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