Developments in Foundation Renovation: Les Promenades de la Cathédrale Project

Reinforcing and replacing an unstable foundation system without disrupting the structure's function poses a problem that requires an inventive solution.

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Situated in the heart of Montréal's shopping district, the Christ Church Cathedral, a replica of the fourteenth century cathedrals of England, has been given a new life with the help of a significant construction project named "Les Promenades de la Cathédrale." This $35 million project included constructing a new shopping complex and garage directly beneath the cathedral.

Background

The inception of the present cathedral took place in early 1857 by a committee that was formed after the first cathedral was destroyed by fire in December 1856. This committee chose the site on which the present cathedral rests after many meetings that brought out much diversity of opinion as to its location.

The chosen site was in the rural area of the expanding city. Surrounded by fields and orchards, it was situated on what was then marsh land. Little did this committee realize that this chosen site would be the source of complications that would require almost constant alterations to the cathedral over the next 130 years.

Frank Wills, of Salisbury, England, a specialist in the Gothic architecture of the fourteenth century, designed the cathedral that stands today. Unfortunately, he died in 1857 before the foundation walls were above ground. After his death, the work was completed under the direction of Thomas S. Scott, of Montréal, on the understanding that the intent of Wills's original plans and designs were to be maintained.

The overall dimensions of the cathedral are 203 feet in length by 109 feet at its greatest width. The principal feature of the structure is its spire. As initially designed, the spire rose 127 feet above the cathedral's tower (which itself was 102 feet above the ground) for a total height of 229 feet. This spire was one of the very few that was ever erected in stone in Canada.

Foundation Conditions

Historical records indicate that:

> "The building committee of the time showed undue caution in economizing in many important details and the present generation has paid dearly for the mistakes then made, of these, the most noticeable was the insufficient foundations."

The foundations rest on soil that consists of a mixture of sand, gravel and hard clay. This mixture is underlain by a 15-foot layer of very soft blue clay. These strata, in turn, overlie a layer of hard glacial till of varying thickness, under which bedrock is found.

The spire and tower rest on four footings composed of limestone rubble masonry set in lime mortar. They are connected by inverted arches that are designed to distribute the tower load over a large area. The pressure distribution proved to be inadequate, and it is the opinion of many experts that the foundations had not been properly designed to carry the structure loads.

The footing bearing level is within five to six feet of the very soft blue clay layer. According to the reports of experts who have examined the condition and configuration of the foundations, it was determined that each spire footing was carrying a load of 1,042 tons and applying approximately 12.8 tons per square foot at bearing load to the soil.

Allowing for a certain attenuation of the bearing stress at depth as a result of the inverted arches, the pressure at the top of the very soft blue clay was 8.5 tons per square foot. According to accepted practice, this stress level is far in excess of what a soft clay can support without resulting in significant post-construction settlement.

Early Settlement Problems

Before the construction of the cathedral was completed, it was noticed that as much as five inches of differential settlement had occurred in the spire foundations. A post-construction measurement taken in 1927 revealed that there was an additional settlement of 1.5 inches. It should be pointed out that this differential settlement at the foundation level caused the top of the spire to lean two feet from the perpendicular.

In order to avoid further settlement and possible endangerment to the structural integrity of the cathedral itself, the stone spire was taken down in 1927. The stone spire was replaced in the late 1930s and early 1940s with a light frame replica that was faced with aluminum.

In addition to the replica, nine support piles were added per existing footing in order to reduce the foundation load and to increase foundation strength. These support piles were 12 inches in diameter and were installed in three-foot sections using a hydraulic jack. Each pile was jacked to a resistance of 100 tons, penetrating a few feet into the glacial till and not even reaching bedrock. The top of each pile, along with each spire footing, was buried in gunite in order to ensure proper anchoring between the existing footing and the new piles. This technique proved to be successful in stabilizing the new spire.

Redevelopment: An Economic Necessity

The cathedral was faced with having to continue to pay huge yearly maintenance costs with resources from a declining membership. Since the cathedral was located on land of great commercial value, thirty years ago the cathedral formed a ruling committee that engaged in discussions with various developers regarding the fate of the site over the intervening years. This committee needed a new source of income, not only to stabilize the cathedral's foundations permanently, but also to ensure a future life for the cathedral itself and the services that it offers to the population.

An agreement was finalized between the developers and the cathedral authorities that met the needs of the church and local commercial interests. Under this agreement, the developers proposed to construct a new 34-

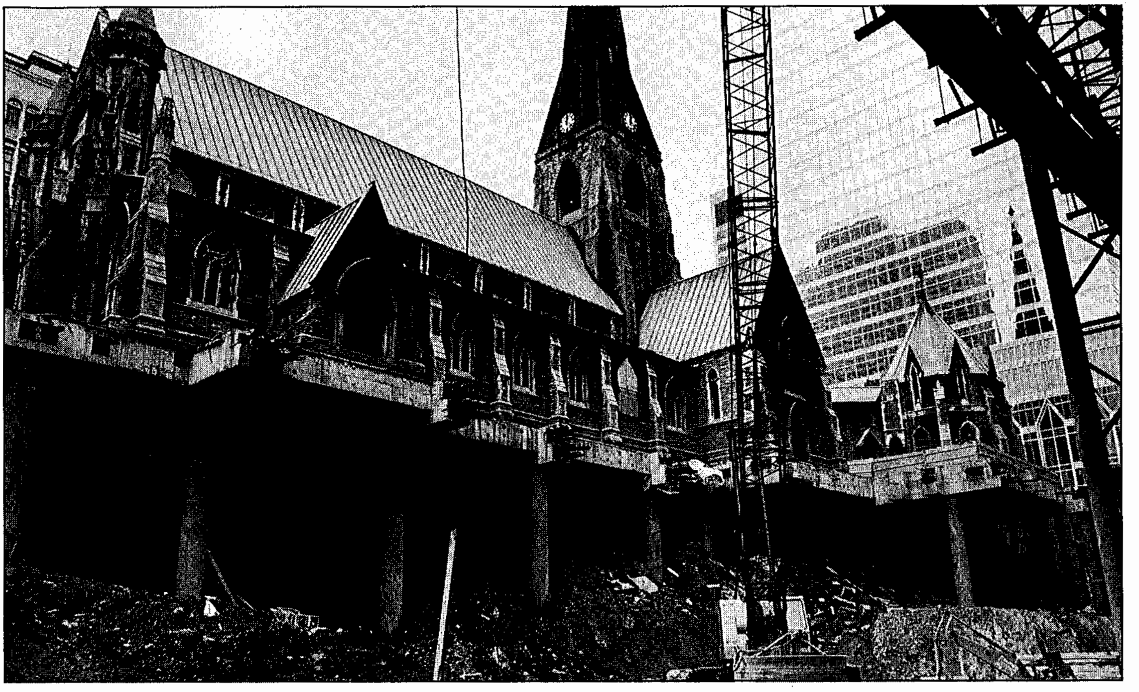

FIGURE 1. View of the cathedral from the bottom of the excavation.

story office tower on the cathedral's back lawn as well as a three-level underground complex that consisted of two levels of a retail shopping mall and a third level for parking. The below-grade space was to extend beneath the cathedral itself. Construction was to be accomplished without disturbing or altering the cathedral's structure or interrupting the services that are provided daily to the public.

Cathedral Preservation

The main technical and construction challenge was to support the cathedral while constructing the below-grade space beneath. This challenge was met by designing and building new foundations around the perimeter of the existing cathedral.

Within that constraint, the structural and foundation engineers were confronted with a major challenge to underpin the 18,000-ton cathedral and its spire, with little tolerance permitted for structural movement. At the same time, they had to provide maximum open space between the new columns for the new shopping center and garage underneath.

The underpinning design scheme developed by the structural engineers met the challenge in a creative fashion. The cathedral would rest on a concrete shelf that was to be composed of secondary reinforcing beams constructed on both sides of the existing masonry foundation walls and secured through post-tensioning (see Figure 1). The masonry walls were sandwiched between the new beams and the building load would be supported through friction. These secondary beams framed into the six-foot deep, T-shaped primary post-tensioned girders which, in turn, rested on the perimeter caissons at both ends. The beams connected the piles from one side to the other, and the perimeter caissons would transfer the loads down to the bedrock fifty feet below. This concrete shelf was to be constructed within the cathedral's basement where the headroom was limited to a maximum of seven feet.

The cathedral's now famous 3,000-ton spire would be supported by two post-tensioned beams sitting on four caissons each. These four caissons, in turn, would be placed directly under the existing footings. Executing this part of the design within the project itself constituted the most complicated and risky phase

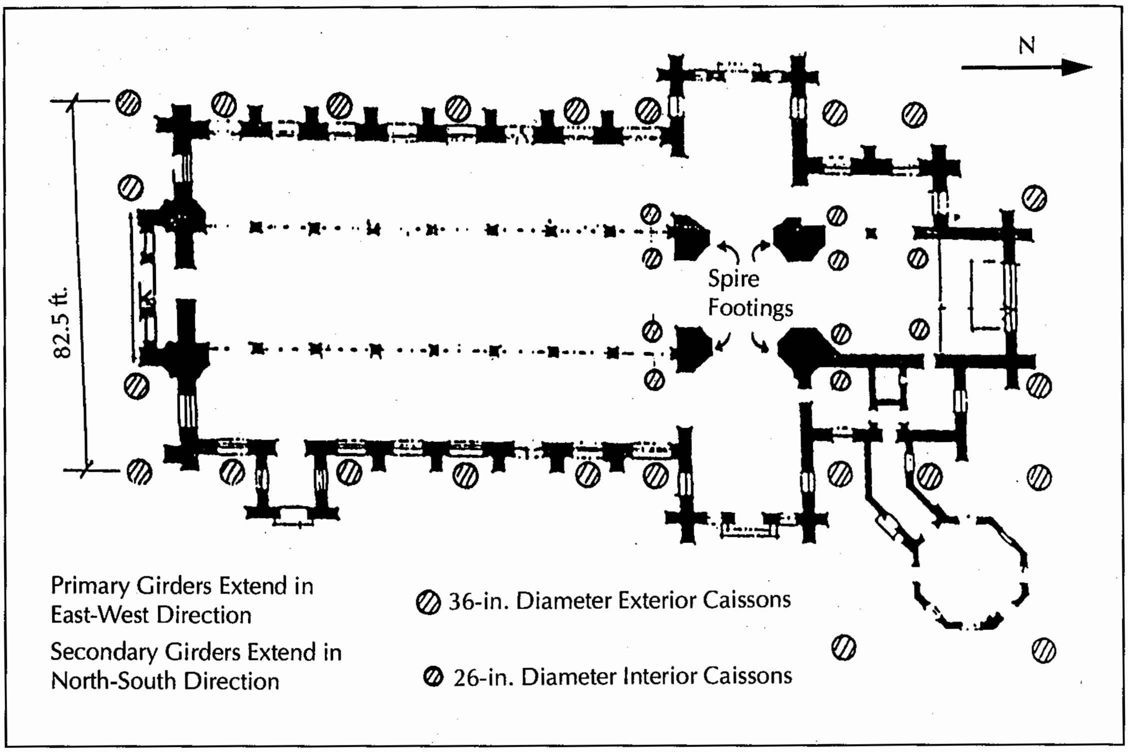

FIGURE 2. Plan view of the existing cathedral foundations and location of new support caissons.

of the construction.

Once the design was completed, the developers negotiated with several competent and experienced general contractors and awarded the contract to do the actual work involved in underpinning the cathedral in 1986.

Construction Scheme

After the contractor was awarded the contract, its top management immediately began to devise a construction scheme and method in order to successfully complete this "once in a lifetime" project. Similar to the structural design, the underpinning of the cathedral would be accomplished in two phases:

- Underpin the 18,000-ton cathedral
- Underpin the cathedral's 3,000-ton spire

The bottom elevation of the new concrete shelf was approximately two feet higher than the cathedral's existing masonry footings. The first operation in the construction scheme was to level the ground surrounding the cathedral, thereby permitting the piling operation to begin.

A total of 33 caissons were socketed into bedrock to transfer the cathedral's weight. Twenty-three of these caissons were 36 inches in diameter and the remaining ten were 26 inches in diameter. Figure 2 shows the location of these caissons. The 36-inch diameter caissons that surrounded the exterior of the cathedral were driven just one foot away from the existing walls, thus clearing the edge of the existing masonry continuous walls. All caissons were driven and drilled by use of conventional methods of hammering and drilling.

The 36-inch diameter caissons carry loads ranging from 750 to 2,600 kips and are socketed into undisturbed bedrock to a depth of anywhere from five to twelve feet. Permanent casings for these caissons were driven in one full length section in order to avoid splicing and to ensure a plumb final product that had no

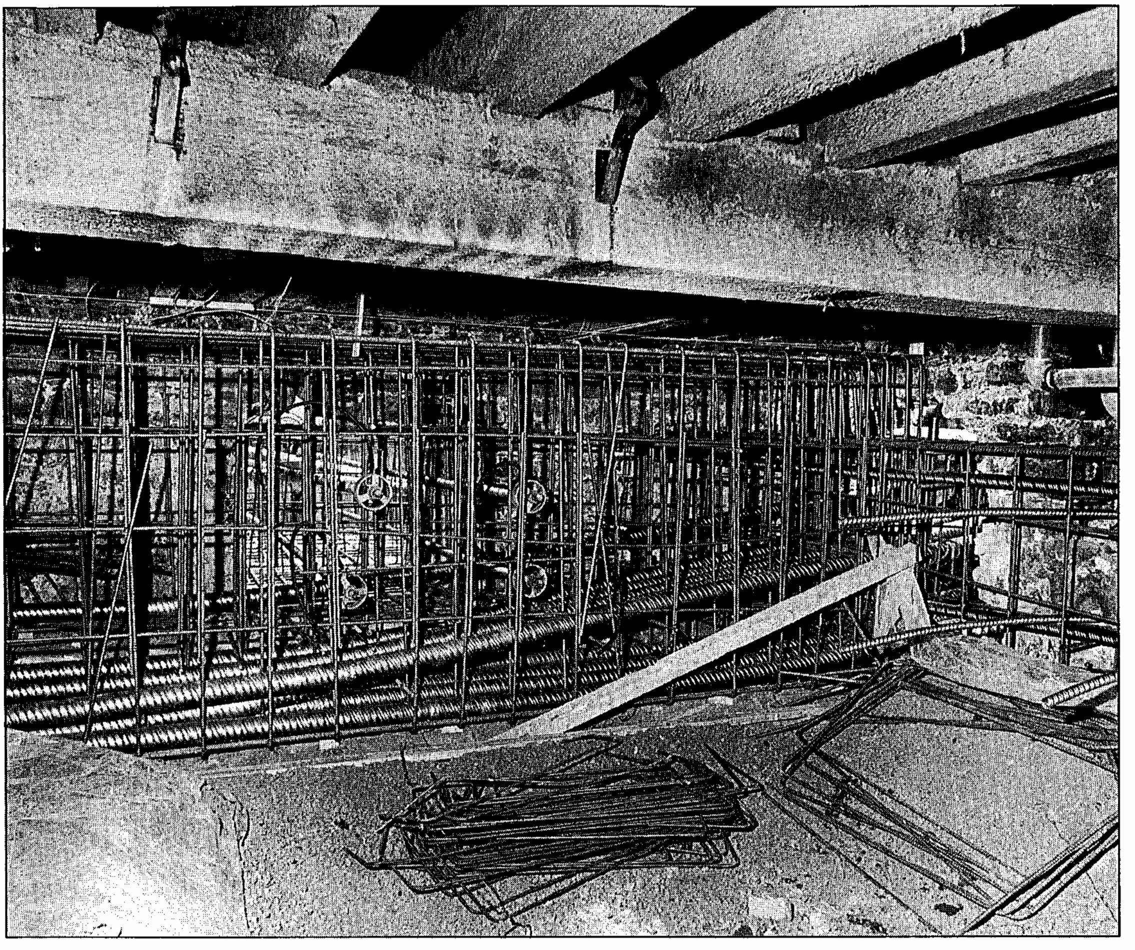

FIGURE 3. A primary beam within the cathedral's basement. Note the limited headroom.

weak links. Vibrations caused by the driving of these caissons were monitored carefully and regularly in order to ensure that they were below the maximum allowable limit and thus avoiding any possible damage to the unreinforced masonry of the fragile cathedral.

The 26-inch diameter caissons were to be installed within the cathedral's basement where the headroom was confined to a maximum of seven feet (see Figure 3). For these caissons a special pile driving rig was fabricated that consisted of a platform on steel beams upon which a winch, motor and boom were placed (see Figure 4).

Underpinning the Cathedral

Openings were made through the three-foot thick cathedral foundation walls. These openings were reinforced to keep them stable, thereby allowing passage for the driving rigs. Also, all mechanical services and piping—including electrical — had to be re-routed and raised in order for the rig to manoeuvre to the desired locations within the cathedral's basement.

The permanent casings for the fifty-foot long, 26-inch diameter caissons were driven in sections that did not exceed five feet in length due to low headroom of the confined space. Each casing section was carefully and properly welded to the previous one. Eight of the 26-inch diameter caissons were used to support the cathedral's spire, while the remaining two were used as interior supports for one of the primary transfer girders.

Once the operation of driving and drilling of the caissons was completed, each was visually

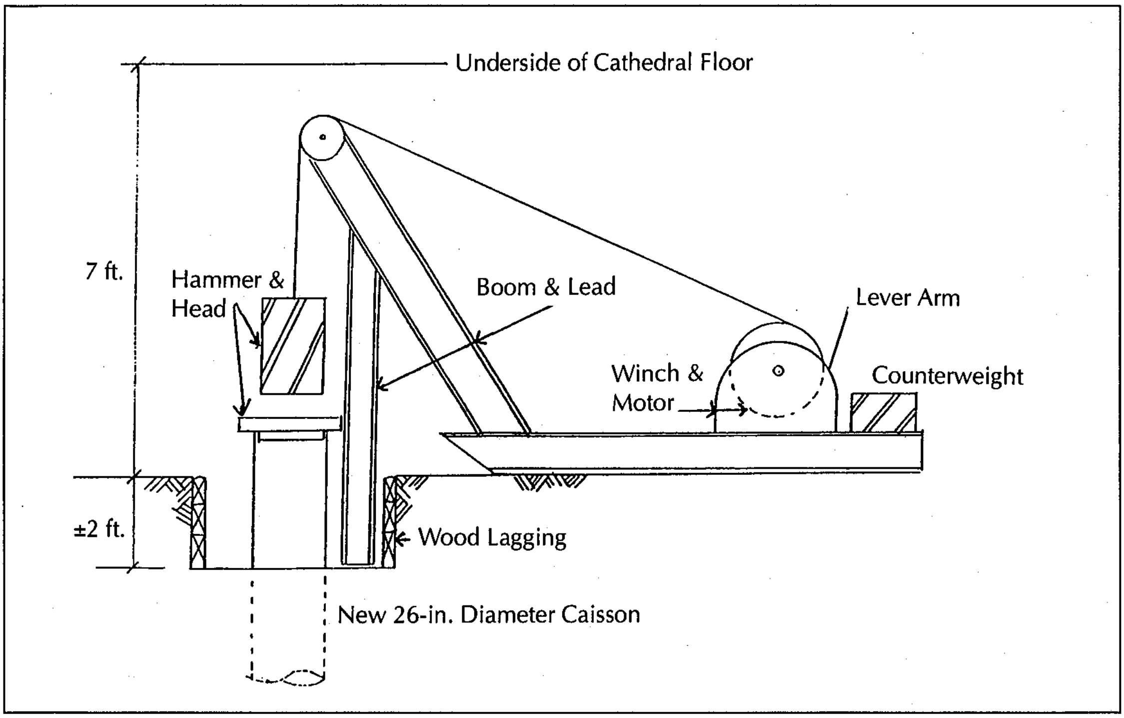

FIGURE 4. Special piling rig.

inspected by having a crane lower a person inside a basket within the caisson to ensure that its socket was anchored into sound and unfractured bedrock. Each caisson was reinforced and filled with 5,000 pounds per square inch (psi) concrete and was then ready to carry its superimposed load.

When the caissons were installed in position on either side of the cathedral's exterior walls, outlining the grid system for cast-in place primary transfer girders and secondary beams, preparatory work was started to clear the way for fabricating the concrete shelf (see Figure 5). The new girders and beams were cast in place within the cathedral's basement that was being used as a storage area. The basement floor, which was anywhere from one to three feet higher than the bottom elevation of the girders, was composed of a slab on grade over 50 percent of the area and just earth over the remaining area.

The openings made through the cathedral's foundation walls also served as access ports for the small excavation equipment that was used to rip out the existing slab on grade and lower the ground within the basement to the bottom elevation of the primary girders.

In order to provide for a smooth surface finish, plywood sheets were laid out on compacted grade. These sheets formed the underside of the girders and beams that would be visible in the final product.

One side of the girder was then formed, after which all reinforcement and sleeving for the post-tensioning cables were simultaneously placed. The second side was formed and the beam construction was then inspected by the structural engineer. The beams were constructed using 5,000 psi concrete.

In the existing foundation walls and column bases, which were embedded in the new concrete, two-inch holes were drilled through and dywidag bars were placed into the holes and then post-tensioned as the concrete attained the required strength. These post-tensioned dywidag bars sandwiched the existing foundation walls between the new concrete beams and thus ensured proper friction hold and load transfer between the old and the new foundation systems (see Figure 6).

FIGURE 5. Beam surrounding the existing cathedral foundation prior to pouring concrete.

All primary transfer girders were monolithically poured, and construction joints were only tolerable in the mid-span of secondary beams. A super plasticizing agent was used in the pumped concrete in order to enable the proper flow between the reinforcing bars and to ensure the required cover.

The post-tensioning of the new concrete shelf began after the 28-day curing period after the last concrete pour was over in order to ensure maximum strength. The first step was to tension the dywidag bars, securing the compressive hold between the existing masonry foundation and the newly-poured secondary beams. The bars were tensioned with a force of 110 kips. Secondly, cables in the secondary beams were stressed with a force ranging from 400 to 1,200 kips, thus providing additional hold and transferring the loads to the primary girders. Lastly, the primary girders themselves were stressed with forces ranging from 2,500 to 9,000 kips.

Once post-tensioned, the new concrete shelf supported all of the cathedral's loads and, through the caissons, transferred them to the underlying bedrock, thus completing the work involved in first phase of construction. Prior to beginning the next construction phase, eight-inch thick filler slabs were poured between the beams and girders in order to provide a complete sound and fire protection system between the cathedral and the new shopping complex.

Underpinning the Spire

The next phase of construction was to underpin the 3,000-ton cathedral spire. In this case, the

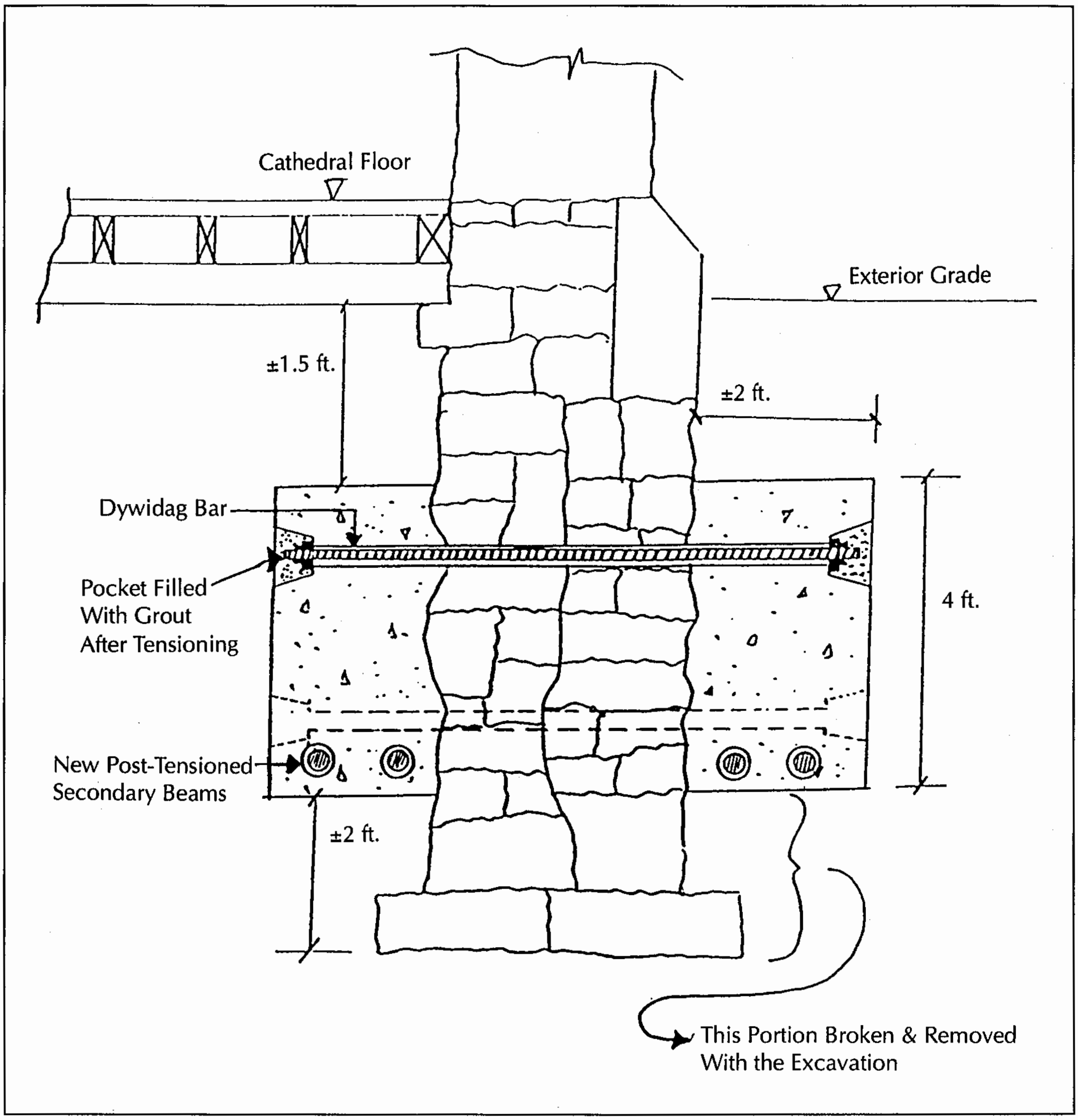

FIGURE 6. Typical section of the existing foundation walls and column bases showing the load transfer system.

new support concrete transfer beams had to be placed directly beneath the spire foundation that was composed of masonry piers interconnected by inverted masonry arches (see Figure 7). The inverted masonry arches were used to provide greater load distribution to the soil. Two independent 16-foot wide by 44-foot long by five-foot deep transfer beams, each supporting two of the masonry piers, had to be installed in order to transfer the loads down to the bedrock through the eight new 26-inch diameter caissons that were driven during the first phase of the construction.

In following the construction method established in the first phase, excavation of the earth beneath the cathedral began. In the region around the spire footings, a working earth shelf was left (see Figure 8). This shelf was accompanied by a one to one soil berm in order to maintain stability.

FIGURE 7. A view directly beneath the cathedral showing the new transfer beams now supporting the spire.

The excavation under the actual footings was accomplished using hand tools and small excavation machines. As the excavation progressed under the footings, jacked three-inch diameter high steel strength (HSS) sections were installed to serve as temporary supports along with the 12-inch diameter piles that were installed in the early 1940s. Portions of these older piles were now exposed by this construction. This foundation system ensured that there was no movement of the footings while the preparatory work was completed to put in place the new concrete transfer beams. In partially exposing the existing piles that were assumed to carry their loads through skin friction, there was a fear of possible additional settlement. To counter this possibility, some of the secondary post-tensioned beams (which had been completed in the first phase) had been socketed into the spire masonry piers to act as brackets and replace the potential skin friction loss that would occur by exposing the piles (see Figure 8).

While performing this part of the work, it was discovered that one of the four foundation piers was five feet deeper than the other piers. This condition posed a major architectural problem since clear headroom in the final product was already down to a minimum. Therefore, it was decided to remove the extra five feet of footing.

Once the hand excavation was completed for one transfer beam, the inverted arch linking the two masonry piers was also removed since

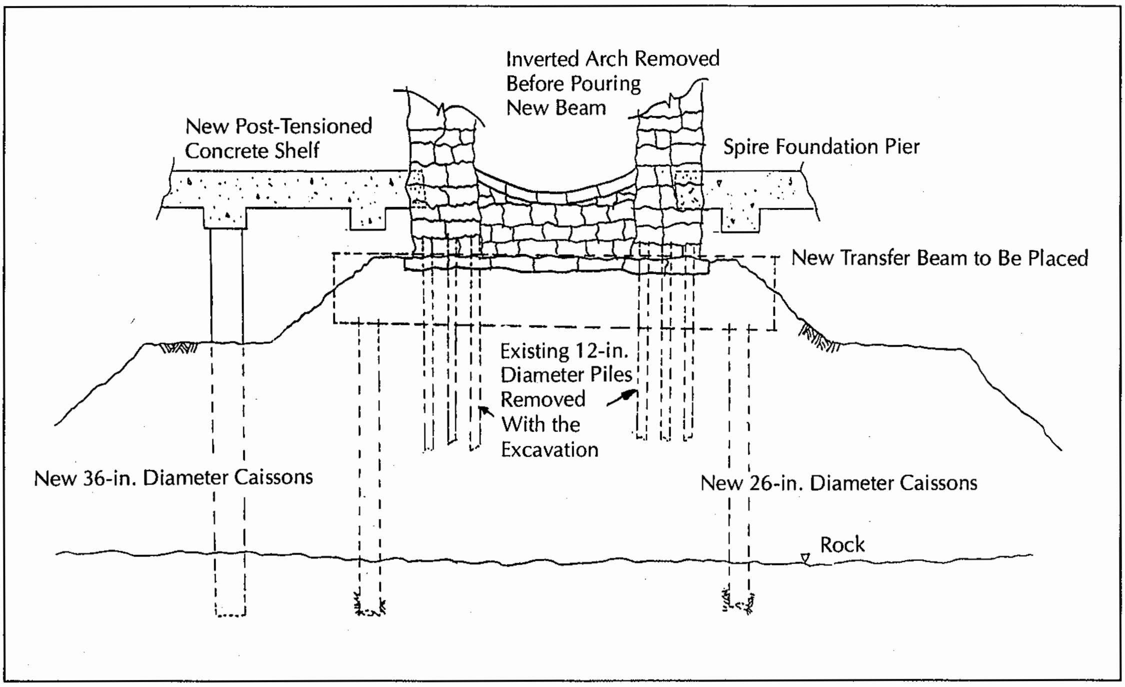

FIGURE 8. A section through the spire.

it would serve no purpose in the final product. Similar to the method employed in the first construction phase, the soffit for the new transfer beam was formed by placing plywood sheets onto a compacted grade. Once one side was formed, then the reinforcement and sleeving for the post-tensioning cables were installed. After that, the balance of the formwork was completed and finally it was concreted. The same procedure was used for placing the second transfer beam.

Prior to placing the concrete for the transfer beams, six-inch long Nelson studs were welded to the existing 12-inch diameter piles for additional load transfer. Hoses that could be used for future grout injection were also placed in order to fill any possible voids that may have been produced at the interface of the new concrete and existing masonry piers. Once the concrete reached the specified strength of 5,000 psi, the cables were then stressed to a force of 10,000 kips.

Throughout the cathedral underpinning operation, vertical movements were closely monitored by an independent inspection company. The results showed that movements were at a maximum 0.2 inch, falling well within the tolerable limits.

Once the new post-tensioned concrete shelf was completed and the cathedral solidly resting on it, and deflections were shown to be within tolerable limits, the balance of the excavation started. All masonry foundations hanging from the underside of the new concrete beams were broken and removed. The existing 12-inch diameter piles underneath the spire were cut to the underside of the transfer beams and also removed.

The new caissons were temporarily braced during the excavation, since they would otherwise remain free-standing over their entire height of 50 to 55 feet until the new retail floor slabs were poured. These floor slabs provide permanent bracing for the new caissons. The temporary braces were fabricated from 12-inch diameter HSS and then were cut and removed. Rock excavation was accomplished with the use of hoe-rams (hydraulic hammers mounted on backhoes) since dynamiting was strictly forbidden due to the potential structural damage to the cathedral from the intensity of the would-be blast vibrations.

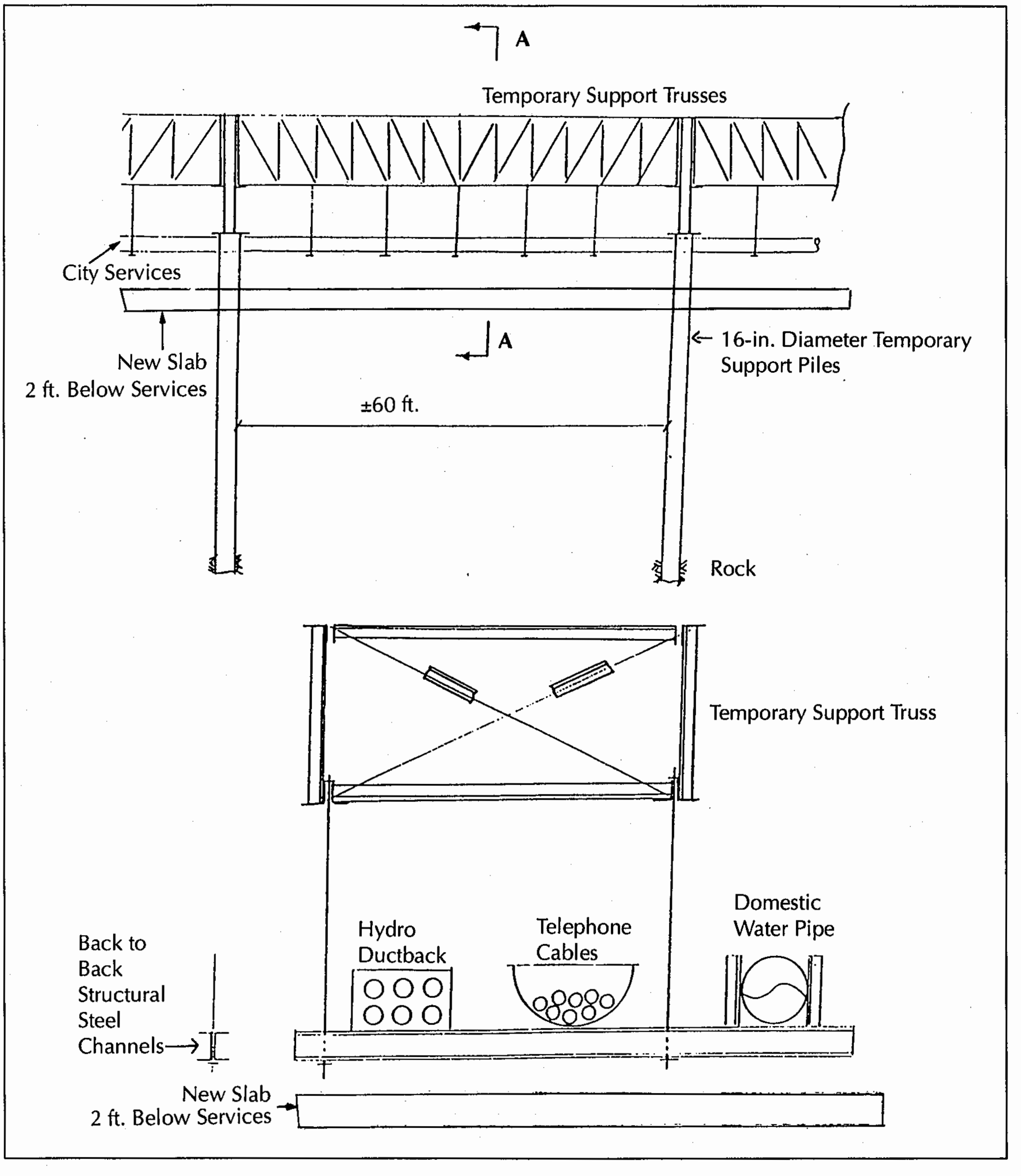

FIGURE 9. Details of the temporary support structure for city services.

Protecting Adjacent Utilities

The underpinning of the cathedral would seem to be the main focus for the successful execution of the project. However, the new shopping complex would span under the bordering streets and connect to the adjacent buildings, and would complicate the design and construction process. Such a scope for the project would require excavating the streets without disrupting such city services as sewers, water, electrical and telephone services and so forth, creating another problem in this already complex project. The solution to this problem was to

FIGURE 10. A view showing the temporary support system of city services along with the excavation in progress and the pouring of concrete in the background.

temporarily support these services during the construction of the project.

The general contractor conceived and had a supporting system designed that would solve this problem. This system consisted of placing support piles spaced at 60-foot intervals longitudinally on either side of the services. Trusses were then placed on the piles to support the loads of the services (see Figure 9). The 60-foot spacing, chosen to allow the excavation equipment to work efficiently and cost-effectively, worked out very well. In addition, the structural slab, spanning between the trusses, served as the new roadway (see Figure 10).

Once the top structural slab was completed, the trusses and piles on which the street was rebuilt were removed. The loads of the services were transferred by placing compacted gravel underneath the services up to the bottom of the structural slab and the temporary support elements were then discarded.

Summary

The underpinning of the cathedral began in February 1987 and was completed in September 1987. The excavation under the cathedral and the neighboring streets was completed in April 1988 and the shopping complex was opened to the public in September 1988 (see Figure 11). All of these dates were well within the construction schedule that was established before the commencement of work on the project. In addition, no appreciable settlement was found for the new foundation system

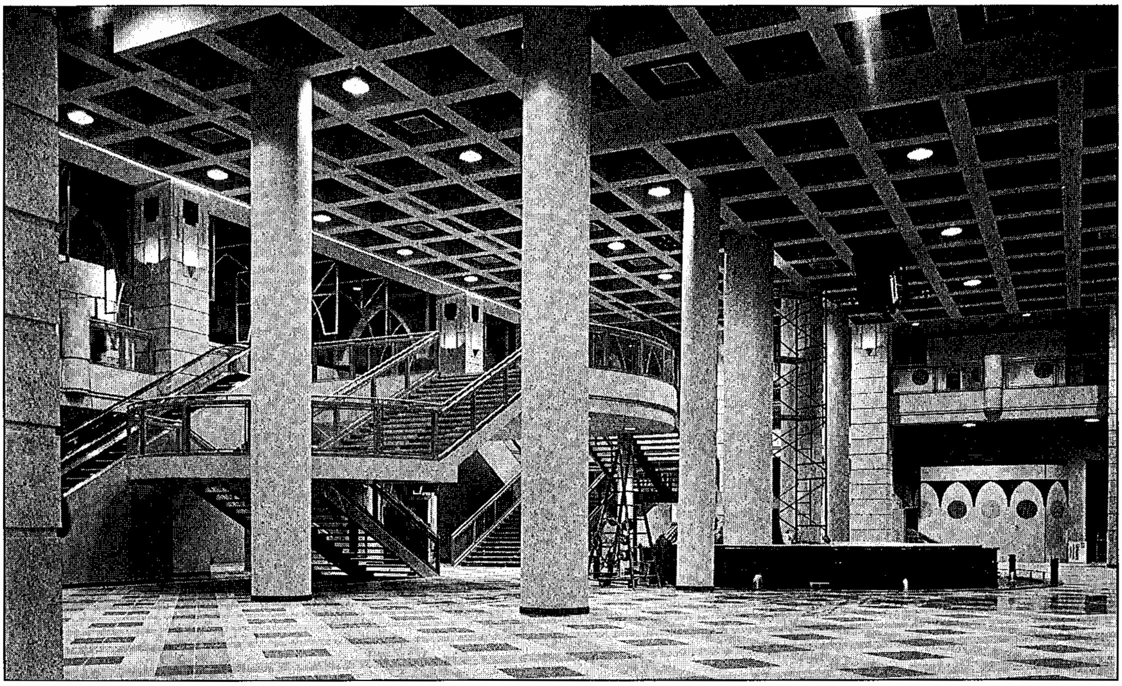

FIGURE 11. A view of the interior of the new shopping complex and the open grid ceiling below the new concrete shelf.

during or after construction.

The successful completion of this construction project not only stabilized the cathedral's foundations, but also permitted the preservation of a historical monument, evidence of Montréal's great heritage. It is also evidence that structural and foundations systems can be designed and construction methods can be employed that can meet challenges that are normally thought too difficult or impossible to meet.

ACKNOWLEDGEMENTS — *The team that was involved with Les Promenades de la Cathédrale project consisted of Westcliff Developments, Inc., First Québec Corp., Groupe Co-Operants and the Cathedral authorities — developers; Quinn, Dressel Associates of Montréal — structural and foundation engineers; Magil Construction Ltd. of Montréal — general contractor; and, Webb Zerafa Menkes Housden — architects.*

NOTE — *This article is a follow-up to a presentation based on the actual construction of the project made by Joseph Gutstadt, President of Magil Construction Ltd., to the Geotechnical Group of the Boston Society of Civil Engineers Section/ASCE on October 27, 1988 at the Massachusetts Institute of Technology.*

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