Construction of the Victoria Tubular Bridge

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Introduction

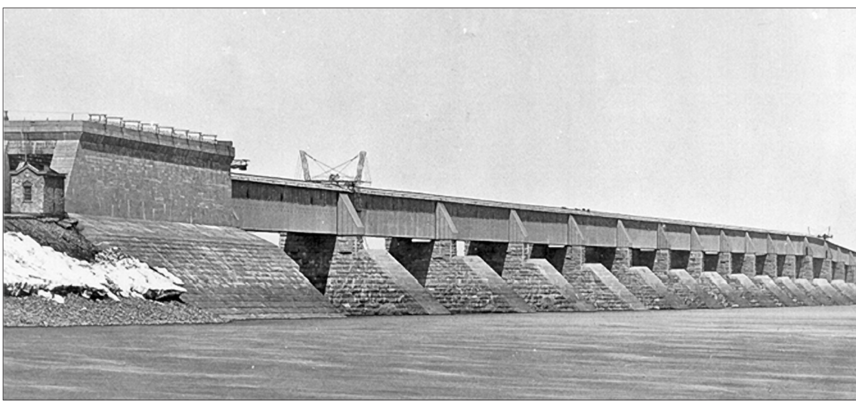
The Victoria tubular bridge was constructed in 1854–60 across the St. Lawrence River at Montreal by the Grand Trunk Railway of Canada. On its completion, the Victoria Bridge was widely regarded among the professional engineering community, both in Canada and abroad, as a monumental engineering achievement—"the Eighth Wonder of the World"—for its unsurpassed magnitude and boldness of conception, and for the feat of its construction under extremely difficult conditions.

The mammoth bridge consisted of a wrought-iron tube superstructure, 6,592 feet long, resting on twenty-four stone masonry piers of an innovative design, and was by far the largest bridge construction project undertaken anywhere in the world to that date. Indeed, at the inception of the project, many engineers doubted whether a bridge of such a magnitude could be constructed in Canada given the short six-months' working season, and the seemingly overwhelming demands of the St. Lawrence River bridge site.

This paper will assess the engineering achievement realized in the construction of the Victoria Bridge, the role played by Canadian contractors, and the impact of the bridge both on the City of Montreal and the country at large.

Background

The Victoria Bridge was constructed as an integral component of the Grand Trunk Railway (GTR), which was building its main line westward from the ocean port of Montreal through Toronto to Sarnia on the upper Great Lakes. In crossing the St. Lawrence River at Montreal, the bridge was intended to link the new GTR with the St. Lawrence and Atlantic Railway, and thereby provide Canada with uninterrupted rail access to an ice-free port, Portland, Maine, which was open year-round on the Atlantic sea lanes. As such, the construction of the Victoria Bridge marked the culmination of a national transportation strategy developed by the Montreal mercantile community to capture the trade of Canada West, and to compete with New York for a major share of the burgeoning trade of the American Midwest. Prior to the opening of the Erie Canal in 1825, Montreal had dominated the trade of the Great Lakes interior, but thereafter lost the American trade to the Erie Canal system focused on New York. The trade of the Canadian interior, however, continued to flow down the St. Lawrence River to Montreal owing to the system of colonial preferences for Canadian grain in the British market, and American tariffs on freight passing into or through the United States. Subsequently, the enlargement of the Lachine Canal (1842–1848) on Montreal Island, the construction of the St. Lawrence River ship canals system (1834–1848) and the enlargement of the Welland Canal (1842–1850), were undertaken as public works to reduce Canadian shipping costs, and to enable Montreal to compete once again with New York for the trade of the American Midwest.[1]



Victoria Bridge of the Grand Trunk Railway, 1873.
(Notman Photographic Archives, McCord Museum, Montreal)

While construction proceeded on the St. Lawrence River ship canals system, the Montreal mercantile community turned to address another critical concern. Montreal was excluded from the transatlantic trade for six months each winter during the freeze-up of the St. Lawrence River, whereas the port of New York was open year-round. Thus, when the Americans passed Drawback Acts (1845, 1846) enabling Canadian trade to pass through the United States in bond, exempt from American tariffs, Montreal interests undertook to construct a railway from Longeuil, on the south shore of the St. Lawrence River opposite Montreal, to an ice-free harbour at Portland, Maine.

The initial plan was to establish a ferry service across the river between Montreal harbour and Longueuil in summer, and an ice road across the river in winter, but John Young, the president of the newly chartered St. Lawrence and Atlantic Railway, soon realized that a bridge was essential. Only a bridge would provide the projected railway with an efficient and uninterrupted year-round access to the ice-free port. Hence several crossing sites were surveyed, and an American civil engineer, Edward F. Gay of Philadelphia, prepared a general plan for a combined road and rail bridge, over 11,000 feet long, consisting of 56 wood Burr-arch truss spans of 200- foot length, on masonry piers and abutments carried up 25 feet above the low water level, and resting on timber crib pier foundations below the low water level. The estimated cost of construction was $525,693. However, many engineers were openly sceptical as to whether it was feasible to construct a bridge across a two-mile-wide river, and whether such a low-level bridge, if once constructed, could withstand the ice shove each spring without being swept away.[2] This was a critical question, but in the economic climate of Montreal in the late 1840s, another question predominated: how could sufficient capital be raised to construct such a stupendous structure?

During the 1840s Montreal had begun to industrialize as new industries were established to take advantage of hydraulic power sites furnished by the enlarged Lachine Canal, which bypassed the Lachine Rapids in the St. Lawrence River just upstream of Montreal. The waterpower sites attracted iron foundries making castings and forgings, boiler and steam engine works, as well as a machine-tools industry, nail and spike manufacturers, shoe and clothing factories, metal-working plants, and flour mills, which augmented a marine engineering and shipbuilding (steamboats) industry established somewhat earlier. The economy of Montreal, however, continued to be driven by its role as an entrepôt for Canada in the exporting of grain, flour, potash, and timber, the forwarding of domestic and imported manufactured goods inland to Canada West, and the provision of banking and commercial services.[3] However, while industry prospered, by the late 1840s the Montreal mercantile community faced a disastrous economic situation.

With the ending of colonial preferences in the British market (1846–1849) and the concurrent passage of the American Drawback Acts, the farmers and merchants of Canada West no longer had any financial incentives to ship through the port of Montreal in preference to New York. Hence much of the trade of Canada West began to turn southward across the lakes into the American Erie Canal system to take advantage of lower ocean freight rates obtainable at New York. In 1848–49, with falling grain prices in Britain, grain exports through Montreal declined by 60%, giving rise to despair among the mercantile community and demands for annexation to the United States.[4] Moreover, a new threat emerged to Montreal's economy. American railroads building westward from New York and Boston were approaching Lake Ontario ports and the Niagara frontier. Fears arose that the rapidly growing trade of Canada West might become locked permanently into the New York commercial canal and railroad systems.[5]

To meet the American railroad threat, the Montreal mercantile community turned to the idea of constructing a trunk railway along the north shore of the St. Lawrence River–lower Great Lakes basin to connect the major towns of Canada West to Montreal. The trunk railway, together with the St. Lawrence ship canals and the projected St. Lawrence River bridge connecting with a railway to the ice-free port at Portland, would enable Montreal to dominate the trade of Canada West, and hopefully enable the city to once again compete successfully with New York for a major share of the American Midwest trade.

By the early 1850s, with grain prices rising in the British market and London money markets looking for investment opportunities elsewhere following the ending of the British railway-building boom, the prospect of building a Canadian trunk railway became a reality. Indeed, Canada was swept by a veritable railway-building mania as Canadians sought, through railway construction, to attain the economic prosperity that railway building had engendered in Britain and the United States during the previous decade.[6]

The Montreal promoters of the St. Lawrence and Atlantic Railway obtained a charter for the construction of a Montreal and Kingston Railway to connect Montreal with Kingston on Lake Ontario. Toronto interests chartered three railways which would interconnect: the Toronto and Kingston Railway; the Great Western Railway to run from Windsor, Niagara Falls, and Hamilton, to Toronto; and the Ontario, Simcoe and Lake Huron Railway to connect Toronto with Collingwood on Georgian Bay in the upper Great Lakes. Quebec interests chartered the Quebec and Richmond Railway, to connect Lévis on the south bank of the St. Lawrence River, opposite Quebec City, with Richmond on the St. Lawrence and Atlantic Railway. Once linked together the projected railways would provide Montreal with a railway system connecting the major towns of Canada West to Montreal, and the system would be open year round in having access to Portland at the terminus of the St. Lawrence and Atlantic Railway. The crucial link was the projected St. Lawrence River bridge at Montreal.[7] However, a number of questions remained unanswered: was such a bridge practicable? could it be designed to withstand the ice shove each spring? and what was the potential cost of constructing a two-mile-long bridge structure?

Almost immediately the Montreal and Kingston Railway engaged a Canadian engineer, Thomas C. Keefer, to prepare a plan and estimate for the construction of a St. Lawrence River railway bridge. By the spring of 1852 Keefer recommended a crossing site, and produced a plan that introduced two new innovations into North American bridges: viz., long approach embankments, which were to be used to reduce the length of the bridge structure, and a novel wrought-iron tubular span of 400-foot length, which was to cross the deep centre section of the river and provide a wide channel for timber rafts and steamboats to pass.

The embankments were to extend into five-foot-deep water a distance of 1,350 and 1,710 feet from either river bank, and the superstructure was to consist of 23 timber Burr-arch truss spans, each of 250 feet in length, in addition to the 400-foot tubular centre span crossing a 360-foot deep-water section of the river. Trains were to pass through the wrought-iron tube, which was to rest on piers 100 feet above low water; whereas the timber truss spans, constructed as trussed wooden tubes, would be on 70-foot-high piers adjacent to the tubes with the trains passing on top. Cribwork cofferdams were to be sunk in the river for the construction of the piers. Keefer estimated that his high-level railway bridge, with a single wrought-iron tubular span, would cost $1,600,000 and have a life span of 50 years. The piers and abutments were to be constructed of stone masonry, and Keefer suggested that eventually the timber spans might be replaced by wrought-iron tubes to form a permanent tubular bridge throughout.

The long embankments were intended to reduce the ice problem by maintaining much of the melting river ice in place out of the river current, but to protect the bridge further from ice action, Keefer proposed to retain in place the cribwork cofferdams. He planned to construct the cofferdams with a wedge-shaped upstream extension having a sloped solid face, which would deflect ice floes past the pier, and let the driven pack ice slide up the sloped face and ultimately fall back on itself. These so-called "shoes" or "Keefer shoes", in surrounding each bridge pier and extending upstream, would deflect and dissipate the energy of the ice striking against them, and in being detached from the pier masonry would possess a degree of elasticity to absorb the impact, pressure, and grinding of the ice. Moreover, they could be easily repaired from materials readily at hand. The cribwork "shoes" would be wider than the masonry piers, but would leave a 240-foot clear width for the passage of sheets of ice between them.[8]

The Burr-arch truss bridge proposed by Keefer was quite conventional in North America, with the exception of the innovative "Keefer shoes" and the proposed tubular span, which was quite novel and would have been a noteworthy span in its own right. In North America, and northern Europe, rough timber deflecting piers were occasionally built against the upstream base of masonry bridge piers, or as islands a short distance upstream of the piers, to deflect ice floes, but none on the principle proposed by Keefer.[9] On the other hand, the timber Burr-arch truss was a common type of railway bridge in contemporary North America, which was not the case with iron bridges.[10] Few iron railway bridges had been built in Canada, or the United States, prior to the mid-nineteenth century. With good timber being plentiful, a wood-truss bridge cost less than half that of an iron bridge of equal span.[11] Moreover, iron railway bridges rarely exceeded 100 feet in length,[12] whereas timber-truss railway bridges of a 250-foot span were not uncommon, although none exceeded 275 feet in length.[13] Thus the 400-foot tubular centre span of Keefer's proposed St. Lawrence River bridge was on a stupendous scale for a railway bridge in North America. Indeed, it was based on a new structural concept only recently developed in Britain.

The Tubular Bridge

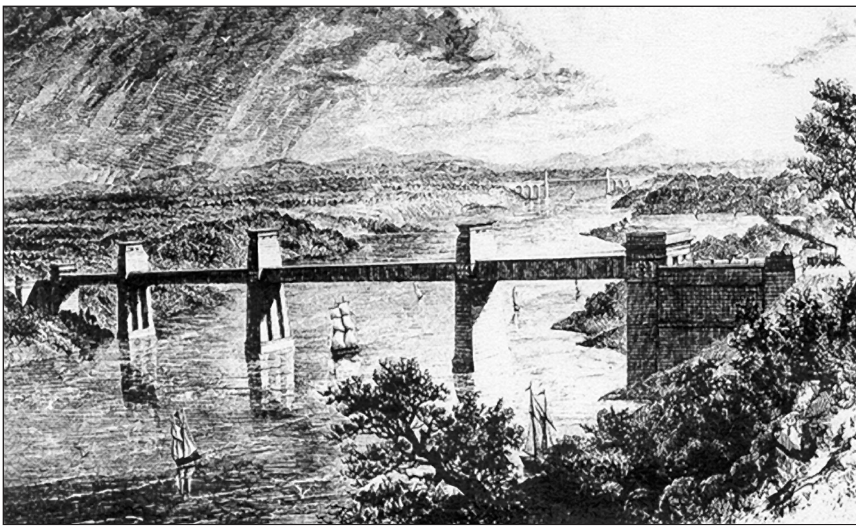
In Britain during the early 1840s cast-iron beams were widely used for constructing railway bridges of up to 40-foot span, and cast-iron beams trussed with wrought iron were used for spans extending upwards of 100 feet in length, but longer-span iron bridges were rarely attempted. Little was known about the strength of wrought iron, and many bridge engineers found the behaviour of cast iron too unpredictable in tension and under impact loads.[14] Long-span iron railway bridges were not a possibility until 1845 when Robert Stephenson, the chief engineer on the Chester and Holyhead Railway, instituted experiments with wrought iron in seeking to design a long-span railway bridge for erection over the Menai Straits in Wales.

At an early stage in the design process Stephenson studied suspension bridges, a type of structure then commonly employed for long-span road bridges. In 1830 a railway suspension bridge had been erected in England on the Stockton and Darlington Railway, but the passage of a moving train caused a severe undulation in the deck which ultimately destroyed the structure. Thus Stephenson began investigating ways to render the deck of a suspension bridge more rigid to accommodate the passage of trains. In observing the strength of the tubular form found in nature, such as in river reeds, wheatstocks, and bamboo, Stephenson hit upon the idea of constructing the bridge deck of a suspension bridge as a straight wrought-iron tube. As little was known about the strength of wrought iron in tension or compression, or the strength of the tubular form, in 1845 Stephenson engaged William Fairbairn of Manchester, England, to construct experiments to determine the strength of wrought iron. Fairbairn had a wide experience in constructing wrought-iron ships with hulls upwards of 250 feet in length, and was convinced that a wrought-iron tube employing a similar form of riveted construction would suffice for even longer-span bridges. Over a two-year period, a number of experiments were carried out with the aid of a mathematician, Eaton Hodgkinson, and formulae were developed for the strength of wrought-iron beams in tension and compression, and the relative strengths of circular, elliptical, and rectangular wrought-iron tubes were ascertained using scale models loaded to destruction.

Ultimately it was established that wrought-iron tubes of dimensions sufficient for a train to pass through could be used for constructing railway bridges of up to 460 feet or more in clear span—a remarkable length, far exceeding any previous railway bridge of any type, wood or iron. Moreover, it was found that the wrought-iron tubes, constructed of boiler plates riveted together with angles and tees at the joints, would be sufficiently strong to stand alone as a railway bridge structure without the need for additional support from suspension chains. In the experiments, the circular and ellipitical tube forms proved somewhat stronger than the rectangular, but the latter was far easier to construct. Hence preference was given to the rectangular form, and Fairbairn found that if the top of a rectangular tube was constructed in a cellular fashion, it was by far the strongest.[15]

Subsequently Robert Stephenson used the results of the experiments to design and construct two long-span, wrought-iron tubular bridges of world renown on the Chester and Holyhead Railway in Wales:

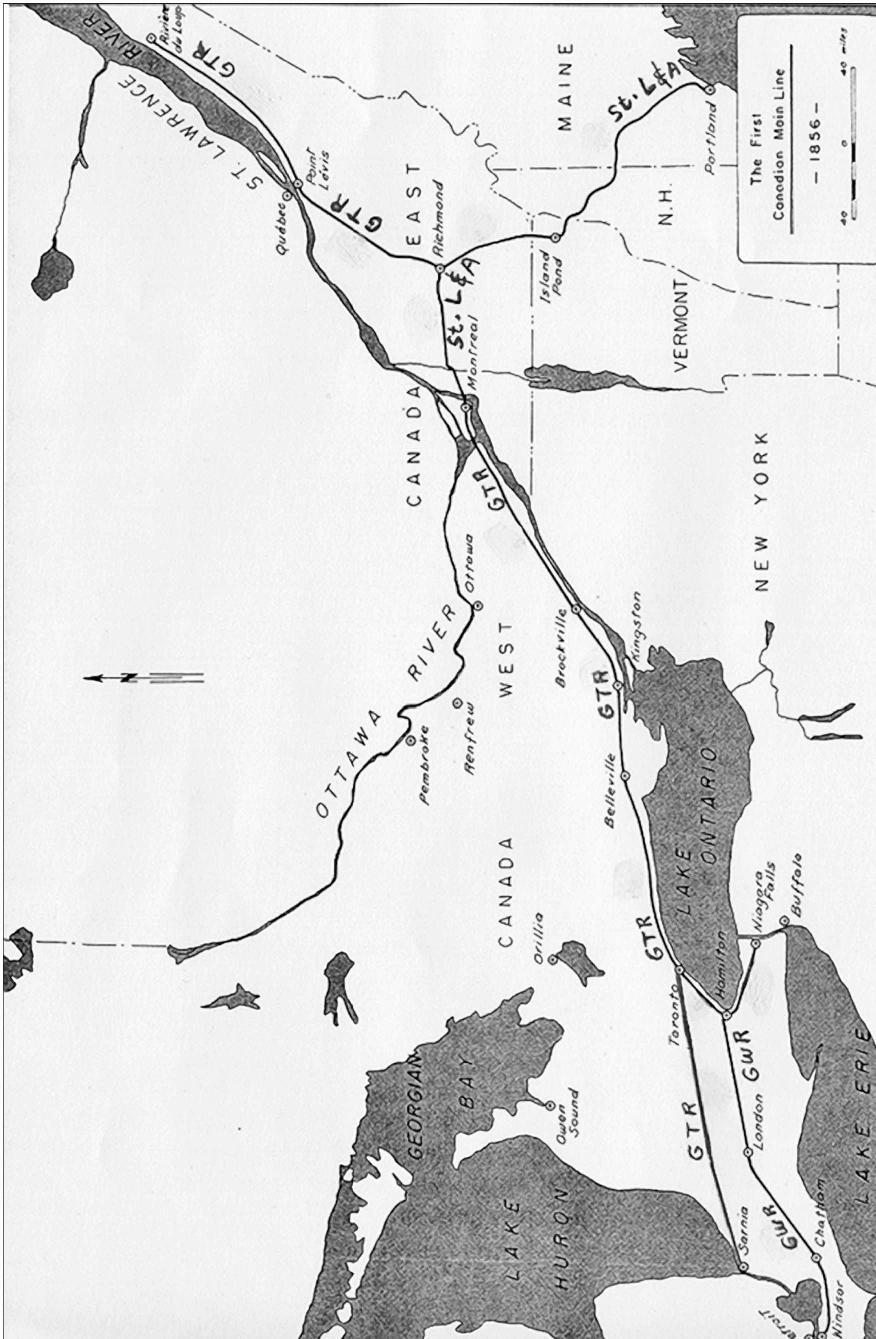
– the Conway Bridge (1848), a single-span, dual tube structure of 400-foot length, crossing the Conway River estuary at a height of 18 feet above the high-water level; and
– the Britannia Bridge (1850) a four-span, dual tube bridge (2 spans of 460 feet and two of 230 feet) with each tube forming a continuous structure 1,513 feet long, crossing the Menai Straits on high masonry towers 102 feet above the high-water level.[16]



Britannia Bridge, 1877. (Rosenberg and Vincenti, *The Britannia Bridge*, Plate 2)

At Montreal, Thomas Keefer seized on the new bridge-building technology to overcome a critical design problem—the need for an exceptionally long span to cross the deep mid-section of the river, and to accommodate the passage of squared-timber rafts and steamboats. The construction of the St. Lawrence River bridge, however, was soon taken out of the hands of the Montreal and Kingston Railway Company.

In spring of 1852 one of the Britain's largest railway-building firms, Peto, Brassey and Betts, had approached the Canadian government about building railways in Canada; and subsequently, the Grand Trunk Railway of Canada (GTR) was chartered to build a trunk railway from Montreal to Toronto with Peto, Brassey and Betts as the contractors and chief promoters of the railway. However, within a year the scope of the project escalated immensely as the GTR undertook to extend the projected Montreal-Toronto trunk railway farther westward to Sarnia, just across the St. Clair River from the American Midwest railroad system, and agreed to lease the St. Lawrence and Atlantic Railway as well as upgrade the existing trackage and complete the last sixty miles of that railway connection to Portland. Moreover, the GTR made a further commitment to build the projected



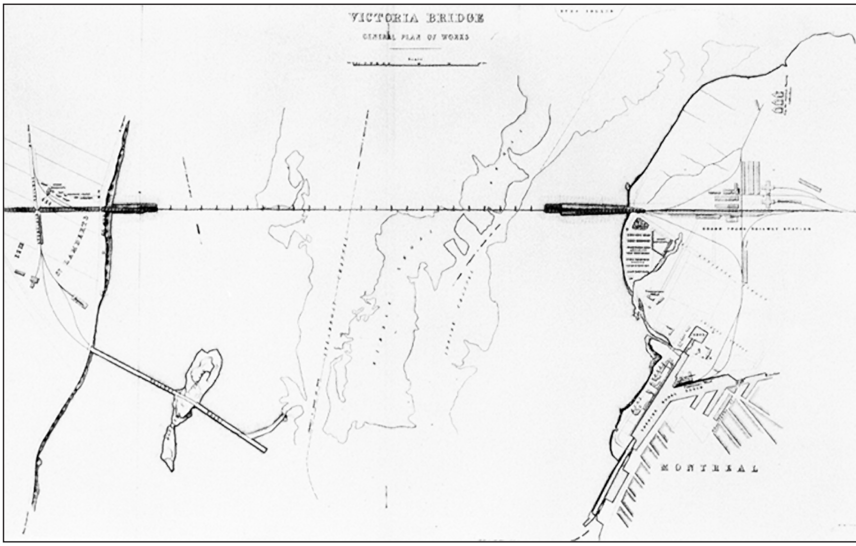
Map of the planned mainline of the Grand Trunk Railway (GTR), its St. Lawrence and Atlantic Railway subsidiary, and the contemporary Great Western Railway. (Stevens, *Canadian National Railways*, revised)

Quebec and Richmond Railway; and to undertake the immediate construction of a bridge, the "Victoria Bridge", to span the St. Lawrence River at Montreal. In effect, through negotiations to secure the surrender of the several existing railway charters, and a growing ambition to dominate the trade of the continental interior, the new Grand Trunk Railway grew from a railway initially chartered to build a 330-mile trunk railway from Montreal to Toronto into a project to build a 1,100-mile-long railway, by far the world's longest railway, and one which would include the world's greatest bridge.[17]

As it came to be envisioned by its British promoters, the GTR would not only dominate the trade of Canada West, even to the point of expecting to drive the lake steamboats out of business, but would also capture a large share of the American Midwest transit trade, once ice-breaker ferries were established on the St. Clair River to connect year-round with the existing American Midwest railroad system extending westward to Chicago. The Canadian trunk railway line would be shorter than any rail line that the Americans could construct south of the Great Lakes, and Portland was much closer than New York to Europe on the Atlantic sea lanes. However, the vital link in the transit system was the Victoria Bridge, which would connect Canada and the American Midwest by rail not only with Portland, but with American railroads serving the major cities and ports of the American eastern seaboard.[18]

Design of the Victoria Bridge

During the summer of 1852 a British railway engineer, Alexander M. Ross, was employed by the GTR to reconnoitre the line of the projected trunk railway, and to examine the bridge site and bridge plan proposed by Thomas Keefer for a St. Lawrence River bridge. Ross had served as resident engineer on the Chester and Holyhead Railway project during the construction of the Conway and Britannia bridges, and was subsequently appointed engineer-in-chief of the GTR with responsibility for designing the Victoria Bridge and the bridges on the Montreal-Toronto section of the trunk railway. In Canada, Ross conferred with Thomas Keefer, and recommended three major changes in Keefer's plan of construction for the St. Lawrence River bridge: viz., that the bridge site be moved half a mile upstream from Montreal; that the centre tubular span be reduced to a length of 330 feet with a 60-foot vertical clearance over the river; and that the timber flanking spans be replaced by tubular spans to render the bridge a permanent structure. A hydrographic survey of the river, undertaken in February 1852 by the Department of Public Works, had determined that the deep centre section of the river was only about 300 feet wide at a new site a half mile upriver, between Pointe St. Charles and the south shore at Saint Lambert. Hence the new bridge would be constructed about a half mile to the west of Montreal harbour where the St. Lawrence River was 8,660 feet wide.



Site of the Victoria Bridge, showing the wide deep channel in the centre of the St. Lawrence River, and shoals on either side of the deep channel. *(Le Pont Victoria)*

To reduce the bridge length, Ross adopted Keefer's concept of long built-up approach embankments, and planned to build an embankment 1,200 feet long on the north end of the bridge crossing, and one 800 feet long on the south approach. On the basis of calculations as to the cost of building various lengths of wrought-iron tube versus the cost of masonry in erecting piers, Ross determined that the most economical configuration was to flank the 330-foot centre span, at a height of 60 feet above water level, with twenty-four 242-foot-long tubular spans, twelve on each side of the centre span. An easy grade of 1 in 130 sloped each way from the centre span was adopted to provide a minimum vertical clearance of 36 feet under the outer spans for the passage of the flood waters and ice floes in the spring, while the centre span would provide an adequate height for the passage of steamboats.

During the winter of 1852–1853 Ross returned to England to prepare a plan and estimate for the Victoria Bridge, which was to be contracted out to Peto, Brassey and Betts. However, in England concerns were expressed by engineers as to whether such a large bridge could be constructed in Canada with its limited six-months' working season (mid-May to mid-November), and the directors of the GTR, in an effort to reassure potential investors, turned to Robert Stephenson. Initially Stephenson was engaged as a consulting engineer to review and approve Ross's plan of construction, but subsequently (at Stephenson's insistence) he was appointed joint chief engineer, with Ross, on the Victoria Bridge project. After visiting Canada in the summer of 1853 to examine the bridge site, Stephenson returned to England to report that the proposed bridge was not only feasible, but an economical and efficient design. Thereafter Stephenson's firm worked on the design details of the tubes, and the components were fabricated at the newly established Canada Works of Peto, Brassey and Betts at Birkenhead, England.[19]

A highly innovative contribution to bridge engineering was made by Alexander Ross, who designed the stone masonry substructure. After reviewing Keefer's concept of an ice-deflecting and impact-absorbing timber crib "shoe", and the extent of the potential ice problem, Ross discarded the Keefer shoe, and evolved the concept of an ice breaker pier. In effect, Ross designed the masonry bridge piers to act as ice breakers with an extended and inclined upstream face on a 1 to 1 slope, having a raised centre ridge. Thus, ice sheets propelled by the current would ride up on the sharp-edged ridge of the sloping pier face, thereby dissipating their energy, and the ice sheets would break apart under their own weight, resulting in the broken sections being carried harmlessly away between the piers. Moreover, the weight of the tubular bridge superstructure would increase the strength of the piers to resist the impact of the ice floes driven up on their sloped upstream face.[20]

On its construction, the Britannia Bridge was hailed as a stupendous engineering achievement, and as a construction project of "vast magnitude";[21] yet now the GTR planned to construct not only the first long-span wrought-iron bridge structure in North America, but the largest tubular bridge in the world.[22] It would require the erection of 25 tubular spans, with the 330-foot centre span alone being by far the longest iron bridge span in North America, and the building of two major masonry abutments, and 24 masonry piers ranging from 40 to 85 feet in height above the river bed, as well as two approach embankments, one of 1200-foot length on the north shore (Pointe St. Charles) and one of 800-foot length on the south shore (Saint Lambert).

The scale and mass of the components to be constructed in raising the proposed Victoria Bridge were truly amazing. The two approach embankments would be 40 feet high at the abutments, and 28 feet wide on top with sloping sides to combat ice pressures. The masonry abutments measured 242 by 34 feet at the base, rising to a height of 40 feet; and the piers were of solid masonry, 92 by 16 feet at the base, and narrowing with the slope of the ice breaker section, to 33 by 16 feet at the top. Moreover, the masonry was to be constructed of blocks of hard limestone weighing from 6 to 17 tons each, and laid in courses from 28 to 46 inches deep. The tubes of the superstructure were to be constructed of wrought-iron boiler plate, one-quarter to three-quarters of an inch thick, riveted together, and strengthened with tee and angle irons at the joints; and all of the 4,926 pieces comprising each of the twenty-four 242-foot span tubes, and the

10,309 pieces of the 330-foot centre tube, would have to be shipped from England, sorted, assembled, and riveted together to construct the tubes in place on the masonry piers high above the St. Lawrence River. Overall the bridge would require 8,250 tons of wrought iron, and over 3,000,000 cubic feet of masonry, exclusive of the several million cubic feet of timber required for the cofferdams and for the staging required to support the tubes during their assembly.

The Victoria Bridge tubes would be four times the length of the Britannia Bridge, or more than twice the combined length of its dual tubes, and the Victoria Bridge would be constructed under much more difficult and demanding conditions. Indeed, it would be the largest and most ambitious bridge construction project undertaken anywhere in the world to that date. It was expected that the new bridge would take eight years to construct at an estimated cost of $7,000,000, with the substructure—the masonry piers, abutments, and the two embankments — accounting for over 70% of the estimate.[23]

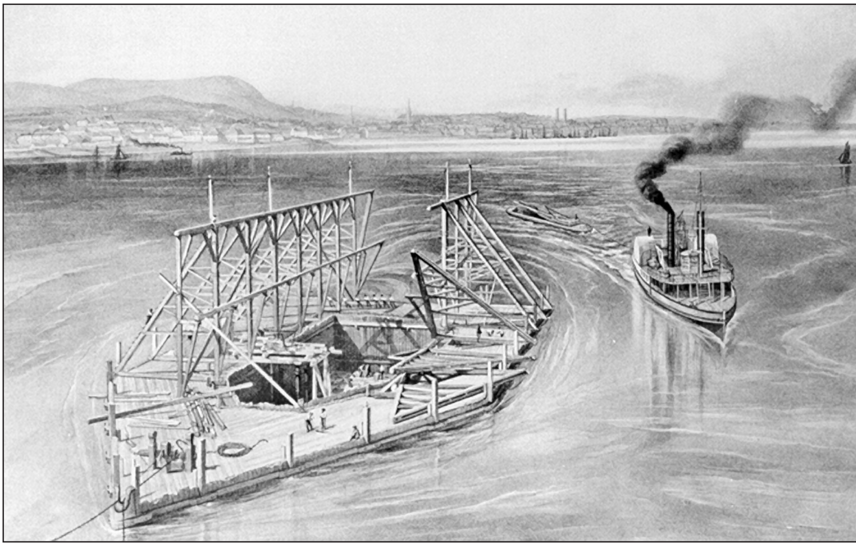
Construction of the Victoria Bridge

Work commenced on the Victoria Bridge project in the spring of 1854 at the selected bridge site where the river was comparatively shallow—no more than 22 feet deep where piers would have to be constructed. The most critical problem facing the engineering staff initially was how to ensure that each of the masonry piers, as constructed, could be raised above the summer water level in a single working season. It was critical to do so to enable the cofferdams to be removed before the freeze-up to provide a relatively free passage for the ice floes the following spring. Each winter, ice over 3 feet thick would form on the two-mile-wide river, and on the wider expanse of Laprairie Basin just upstream of the bridge site. In the spring, flood waters often rose 20 feet, and huge sheets of ice would break free from the river banks and shores of the lakes farther upstream. The ice sheets would float downstream on a strong seven-miles-per-hour current, driven forward by the force of a river that drained half a continent and had an average flow of 50 million cubic feet per minute. Moreover, the St. Lawrence River narrowed at the bridge site, and it was known that the ice floes in striking any major obstacle, or a sharp bend, in the river would pile up into ice jambs. On occasion an ice jamb would dam up the river, and rise up 20 or 30 feet in height before letting go with a terrible cracking noise. In the resultant ice shove, thousands of tons of tightly packed ice would be pushed forward under the pressure of the backed-up head of water, grinding down and crushing anything in its path. Hence the fear that the cofferdams, if left in place during the spring floods, would greatly obstruct the passage of the river ice, causing an ice jamb and a resultant ice shove with sufficient force to carry away the cofferdams and piers under construction.[24]

To obviate this construction problem, James Hodges, the superintendent of construction for the Victoria Bridge and Western (Montreal-Toronto) Division of the GTR and a long-time chief engineer of Peto, Brassey and Betts, suggested that large floating caissons be employed to form the cofferdams. The caissons could be constructed prior to the summer work season, and then floated out to the pier site and sunk to form the sides of a large wedge-shaped cofferdam with an open interior well. Once in place the cofferdam could be sealed with sheet piling and a clay puddle wall, and pumped out to provide a dry area in which the pier masonry could be constructed. The time saved in constructing a cofferdam would enable the masonry work to be raised in a single work season so that each fall the caissons could be pumped out, refloated, and removed before the onset of freezing temperatures. Thus each spring the river would be free of major obstructions that could cause an ice jamb, and each summer the work would be accelerated through re-using the floating caissons—or so went the plan.[25]

In the spring of 1854 stone quarries were opened on the north shore at Pointe St. Charles near the bridge site, and far to the south at Isle La Motte in Lake Champlain, and work commenced to construct the cofferdams for piers 1 and 2, as well as the north approach embankment and masonry abutment. However, little progress was made during the first two work seasons as the project was plagued by construction problems, financial difficulties, and labour strife that threatened the viability of the whole bridge project.[26]

At the commencement of construction, the floating caissons proved unwieldy and difficult to position in the strong current and amidst huge boulders, weighing upwards of 3 to 4 tons, which were found scattered on the flat limestone riverbed. In such conditions, it took so long to position, sink, seal, and pump out the caisson-cofferdams, that despite every exertion possible, the stone masonry of piers no. 1 and no. 2 were raised only 4 feet above water level, and the north abutment masonry raised only 6 feet above water level at the very end of the 1854 work season—too late to refloat the caissons forming the cofferdams of the two piers. Moreover, it was discovered that the main bed of the river, rather than being ledges of smooth rock, was covered with a 12- to 14-foot-thick layer of hard pan composed of huge boulders, gravel, and clay packed into a concreted mass almost as hard as the limestone rock itself, and intermixed with pockets of quicksand and mud. Hence the cofferdam for pier no. 3 was postponed, and it was subsequently established that to excavate pier no. 5 would require the removal of 3,000 tons of such material, including an 11-ton boulder. In such conditions, it was clear that the masonry piers could not be constructed in a single season using caisson cofferdams, and leaving the caisson cofferdams in place over the winter was not an option, as the caissons were not designed to withstand the pressure of an ice shove. However, there was a promising alternative.



A floating caisson cofferdam, with the framework for the travelling gantry crane under construction. (Hodges, *Construction*)

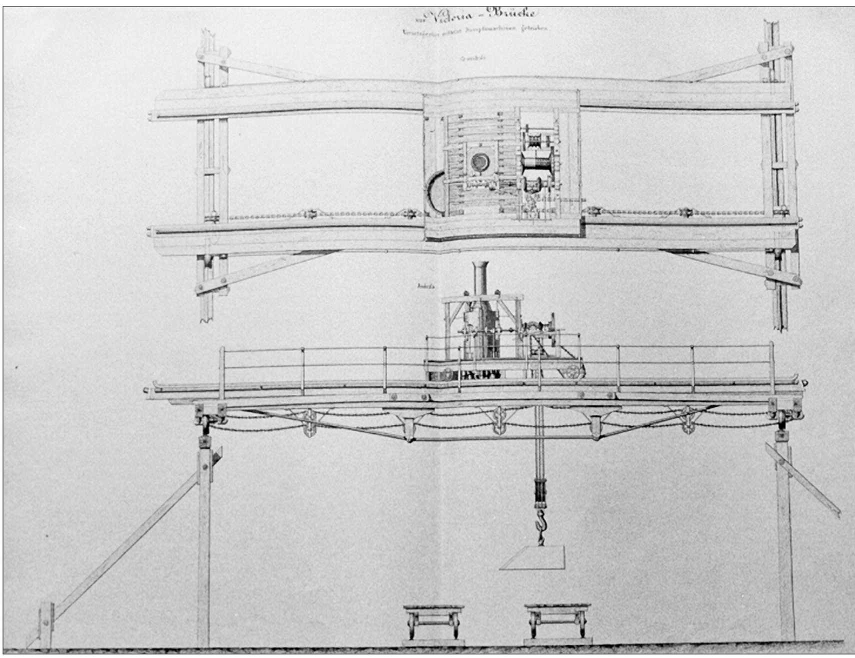
Faced with an obvious problem, late in the 1854 work season it was decided to try constructing timber cribwork cofferdams—a North American building technology widely used for bridge piers. After two failed attempts to tow a large timber crib out to a pier site and sink it into position in the face of the strong river current, the contractors decided to construct the timber cribwork cofferdams directly on site. A heavy timber frame was moored in the river current, and gradually sunk beneath the water surface as its weight increased with the adding of courses of timber and filling stone in constructing the cribwork. In this manner, timber cribwork cofferdams were properly positioned and constructed for piers no. 5 and no. 6 by Montreal contractors Brown & Watson, but too late in the season to commence the masonry work. The timber cribwork cofferdams were built in the form of a "Keefer shoe" with an upstream wedge-shaped extension having an inclined top sheathed with heavy timbers. However, the well of the cofferdam was also covered over, and the whole structure raised only a few feet above the summer water level. As such, the cofferdams were designed to withstand the impact of the spring floodwaters, and to facilitate the passage of the spring flood waters in carrying ice floes over and past the submerged structures.[27]

During the winter of 1854–55 flood waters reached an extraordinary height, and 20 square miles of the river in Laprairie Basin were covered with 124,000,000 tons of packed ice. When the ice moved forward the two caisson cofferdams were totally crushed, and all of the north embankment, some 9,000 cubic yards of fill material, was carried off. Only the two stone masonry piers, the masonry of the north abutment, and the two timber crib "Keefer shoe" cofferdams survived intact from an initial work season that James Hodges subsequently described as "a period of disaster, difficulty and trouble" during which he personally doubted that the bridge would ever be completed.[28]

From the very commencement of construction a severe labour shortage and numerous strikes and work stoppages had plagued the worksite. The GTR had imported masons, quarrymen, riveting crews, mechanics, crane operators, fitters, carpenters, and joiners, from Britain under contract to work on the Victoria Bridge, but when the men realized that wages in Canada during the railway building boom were up to 50% higher than the British wage levels specified in their contracts, they deserted the worksite in droves. As the cost estimate for the Victoria Bridge had been based on British labour costs, the necessity of paying higher wages introduced a potential major cost overrun, and labour costs continued to soar. The British tradesmen who remained on the job, and the skilled and unskilled labour force hired locally, were paid higher wages, but staged a series of strikes and work stoppages, demanding even further increases in wages as the cost of living soared with the railway building boom. Moreover, there was a chronic shortage of skilled labourers as agents from other railway-construction projects, in both Canada and the United States, continually lured men away with offers of even higher wages. The labour shortage was compounded in early July 1854 when cholera broke out at the worksite causing the death of upwards of 60 men and the flight of entire gangs of workers, and no sooner did the cholera outbreak end than the fall harvest in September drew away many of the local men. Only in October and November did work proceed at a satisfactory rate, but then the project had to be suspended with the onset of freezing temperatures in early December.

Financial difficulties added further to the dismal outlook. With the outbreak of the Crimean War in March 1854 interest rates had increased and GTR stock proved difficult to sell in British money markets, and by the spring of 1855 construction costs on the Montreal-Toronto trunk line were running twice as high as the estimate. Strapped for money, the GTR decided to focus on laying track on the Montreal-Kingston section of the mainline, which included another major tubular bridge, the St. Anne Bridge, crossing the Ottawa River at the head of Montreal Island. As a result, work languished on the Victoria Bridge project where the construction difficulties posed by the St. Lawrence River, the slow progress of the work, soaring labour costs, and a persistent shortage of labourers moved James Hodges to strongly advocate that the Victoria Bridge project be abandoned. The board of directors, however, decided to continue the work rather than abandon the infrastructure already in place;[29] and soon thereafter the project was turned around owing to the efforts of the Canadian contractors.

Once the contractors mastered the difficulties of constructing timber crib cofferdams in a strong 7 mph current, Hodges was astonished to see how quickly and cheaply these cofferdams could be constructed by the Canadians.[30] Moreover, huge savings in time and labour costs were subsequently achieved through a number of innovations introduced by Benjamin Chaffey, a Canadian contractor who had contracted for the construction of the south abutment and the adjacent piers, no. 24 and no. 23.[31]



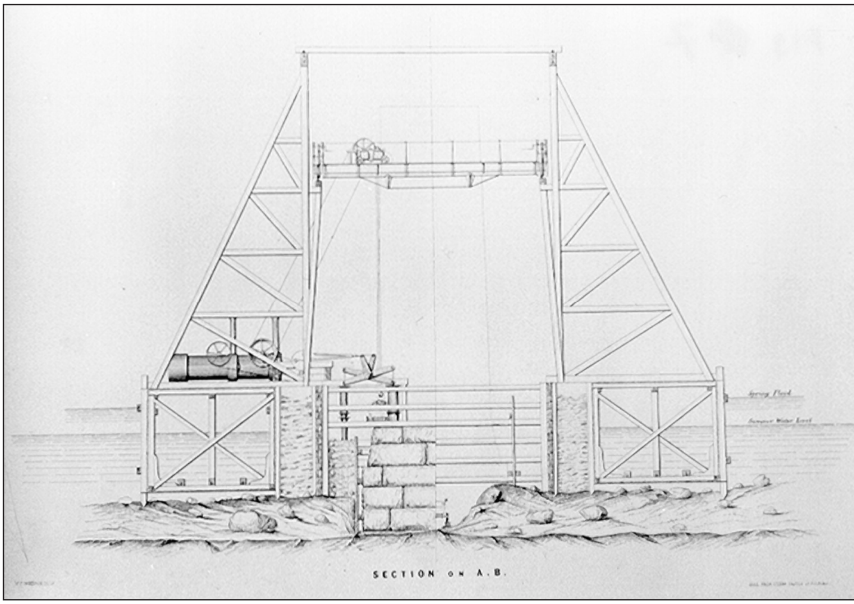
Elevation and plan view of the Chaffey steam-powered travelling gantry crane. (*Victoria Brücke bei Montreal*, Berlin, n.d.)

Prior to arriving in Canada, James Hodges had had a travelling gantry crane designed and built in England for use in unloading, sorting, stacking, and re-loading quarried blocks of stone in the stone yard of the projected Victoria Bridge project. Four men were needed to work the hand cranks to lift, traverse, and carry a load longitudinally along the gantry tracks; however, the prototype when built in the north-shore stone yard proved slow and difficult to operate and could barely move its own weight. Benjamin Chaffey, during the winter of 1854-55, totally re-designed Hodges' manually powered gantry crane and erected in the south-shore stone yard at St. Lambert a steam-powered gantry crane with a 60-foot horizontal boom travelling on a 1300-foot-long track supported on 20-foot-high gantries. A small steam engine and boiler were mounted directly on an extension of the travelling boom. Operated solely by a boy riding on the boom, the crane excelled in lifting, traversing, and travelling with blocks as heavy as 20 tons. Indeed, all three motions could be performed simultaneously, as the boom moved along the gantries at speeds of up to 4 mph. Over the course of the project, the Chaffey steam-powered travelling gantry crane proved a great labour-saving device in transporting over 70,000 tons of stone with ease and without mishap.[32]

Owing to the lack of capital, little new work was undertaken during the 1855 work season, and construction proceeded slowly. The masonry of piers no. 1 and no. 2 was completed, and pier no. 5 raised several feet above the summer water level, and the north abutment masonry raised from 6 to 20 feet above water level. The north embankment was also restarted and raised to a height of 20 feet above the river, and cofferdams were built for piers no. 3 and no. 4. Difficulties in excavating the cofferdams and in sealing pier no. 3 against leakage resulted in their being covered over for the winter without any masonry work being undertaken. On the south side, Benjamin Chaffey put in a timber crib cofferdam for the south abutment and adjacent pier no. 24, and struggled to excavate an 8-foot depth of hardpan and to raise the south abutment masonry to a height of 3 feet above the water level by the end of the work season. The timber cribwork cofferdam of pier no. 24 was simply roofed over for the winter.

To this point, the stone masonry was laid by means of a manually operated travelling gantry crane built over each cofferdam. The crane straddled a pier and extended out over the barge docking area; each gantry crane had two travellers of 36-foot span, which were used to lift and set the blocks of stone. Eight men were needed to work the manual cranks on the two-traveller booms of each crane, where a series of separate operations were required to lift the stone with the hoist jenny, traverse the jenny on the boom, move the boom along on the gantry track, and lower the stone onto its mortar bed. A number of manually operated travelling gantry cranes were likewise used, operating in parallel, in laying the stone masonry of the massive north and south abutments.[33] During the following year, however, a number of ingenious innovations revolutionized the laying of the stone masonry.

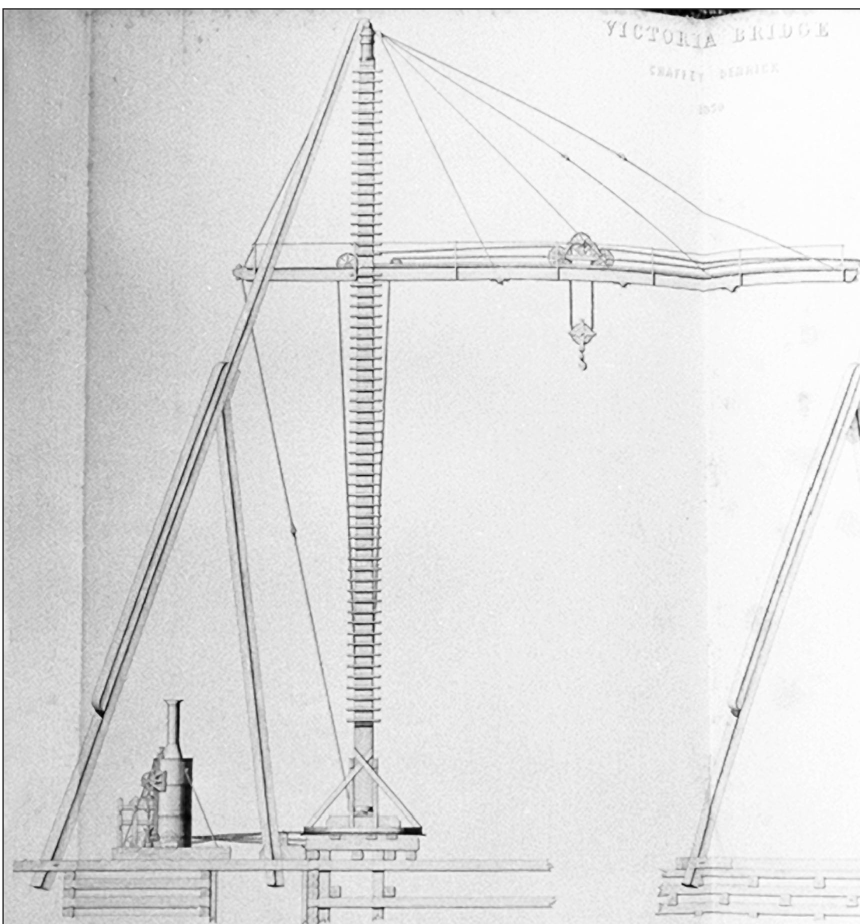
In early 1856 Benjamin Chaffey introduced steam power for laying stone masonry for the first time on the Victoria Bridge project and, insofar as the bridge engineers were aware, for the first time anywhere. Chaffey devised a drive system to enable steam power to run the hoisting drum of the jenny on the boom of the several travelling gantry cranes employed on the south abutment; this innovation was adopted subsequently by all the contractors to operate the hoist jenny on the travelling gantry cranes on the piers under construction. Power was supplied by the small steam engine used to work the pumps in dewatering the cofferdams, and power was transmitted by line shafting to which the spindles of the hoisting jenny could easily be connected and disconnected with the travelling boom in any position desired. Initially only the hoist jenny was steam powered; however, hoisting the stone blocks was by far the slowest part of the masonry work. The steam-hoist jenny reduced the lifting time required to one-tenth of what it had been, and greatly reduced both the construction time and cost of the masonry work.[34]



Cross-section of floating caisson cofferdam with steam-powered hoist on travelling gantry crane, and bell-crank pump. (Hodges, *Construction*)

During the summer of 1856 Benjamin Chaffey achieved a further breakthrough when he designed and constructed a steam-powered boom derrick for laying the stone masonry—a derrick that was fully powered in all its movements. It is not clear from contemporary accounts whether Chaffey invented what became the classic form for a boom derrick, or whether his ingenuity rested strictly in being the first to introduce steam power into its operation. What is clear is that Chaffey, early in the 1856 work season, used two horse-powered boom derricks to lay the masonry of pier no. 24 and, later in the same work season, built a fully steam-powered boom derrick which was used in laying the masonry of piers no. 5, no. 6, no. 7, and no. 23.[35]

The boom derrick had an 80-foot mast resting on an iron pivot-socket, and two long inclined wood support guys, connected to a pivot on top of the mast, to support the mast and let it rotate. Guy wires were also used to further anchor the mast. The boom consisted of heavy timber pieces bolted to each side of the mast a short distance from the top to form a long arm extending outwards and a short arm projecting to the rear. Heavy tie rods connected the end of the boom to the top of the mast and anchored the short arm to the top and bottom of the mast, forming two strong trusses capable of resisting the force of the weight of a 10- to 12-ton block of stone at the outer end of the boom. A hoist, mounted on a traveller, could be moved in and out along the boom, and activated to lift or lower a block of stone. The boom of the Chaffey boom derrick could rotate through 270E in sweeping over the whole working area of the pier. To rotate the mast/boom, a circular segment some 6 feet in diameter was bolted to the base of the mast, around which a chain passed and was connected to a drum.

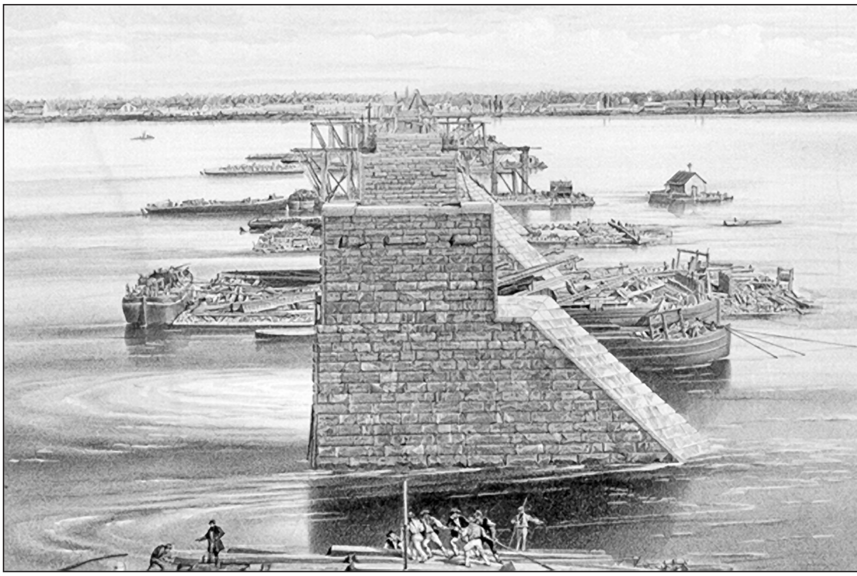


Elevation and plan view of the steam-powered Chaffey boom derrick.
(Hodges, *Construction*)

The boom derrick was driven by steam power applied through a system of friction pulleys and drums and connecting chains, which enabled a single operator to impart three motions simultaneously, lifting the stone, swinging the boom, and running the stone inwards toward the mast, by simply working clutch and brake levers. For piers no. 24 and no. 23, Chaffey constructed a tramway on temporary timber crib piers out to the work site so that stone could be loaded on the trucks by the steam-powered travelling gantry crane in the stone yard and taken off the trucks at the cofferdam sidings by the steam-powered boom derrick at pier no. 23 and by the horse-powered derrick at pier no. 24. Chaffey subsequently carried the temporary tramway out as far as the cofferdam of pier no. 19, beyond which the stone for the other piers, in deeper water, was transported on barges towed by steam tugs.[36]

Using Chaffey's steam-powered boom derrick, which James Hodges described as "a most perfect derrick", over 216,000 cubic feet of masonry was set in the month of September 1856 at a rate of 13 cubic feet per working minute, and the masonry of pier no. 23 was laid up in October-November in less than seven weeks. This represented a singular achievement as generally timber crib cofferdams could not be constructed, sealed, pumped out, and excavated to bedrock before mid-August, leaving only 16 weeks to raise the masonry of a pier several feet above the water level to enable the cofferdam to be removed before the onset of winter weather. Moreover, this period of time had proved barely adequate to raise the masonry piers above water level in the comparatively shallow water at either end of the crossing. It would not have been adequate for raising masonry piers above water in the deeper mid-river sections. However, with the steam-powered boom derrick, and the steam-powered hoist jenny of the gantry crane, the constricted masonry construction period was no longer a problem. A masonry pier could be easily constructed to its full height, and the cofferdam removed, in a single short working season, while effecting major savings both in time and labour costs.[37]

During the first two work seasons, 1854 and 1855, without steam-powered equipment, only two masonry piers were built to their full height, a third pier and the south abutment were carried up just above water level, and the north abutment and approach embankment were raised to a height of 20 feet above water level but were still incomplete. However, the steam-powered gantry cranes and boom derricks introduced by Benjamin Chaffey enabled seven piers to be fully completed during the 1856 work season, as well as the rapid completion of the two masonry abutments.[38] Employing the North American timber crib building technology and the steam-powered boom derrick and steam-powered hoist on the travelling gantry cranes, the construction of both cofferdams and piers proceeded equally rapidly during the 1857 working season. Eight cofferdams were constructed, and six of the masonry piers were built to their full height.[39] Moreover, the first wrought-iron tube of the Victoria Bridge, tube no. 1, was erected during the 1857 season by a British contractor, James Hodkinson, who had contracted for the erection of all of the tubes.



View of the stone masonry piers, showing the broad expanse of the St. Lawrence River. (Hodges, *Construction*)

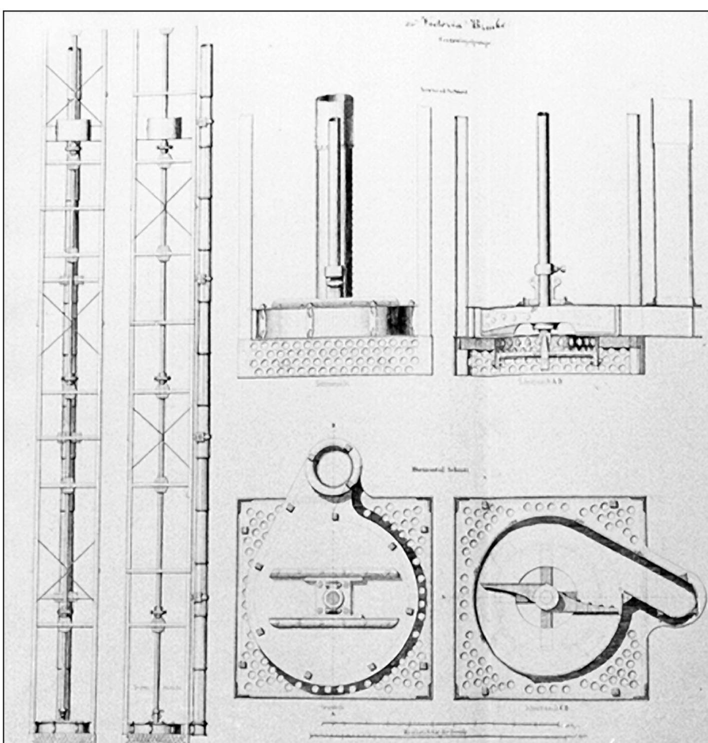
On the Victoria Bridge project the strong river current, numerous shoals, and the ever-present danger of squared-timber rafts running out of control and striking barges anchored in the river precluded floating the tubes out to the bridge site and hoisting them up onto the piers as had been done on the Britannia Bridge. Hence it was decided to assemble the tubes in place, but this required in turn the erection of high timber staging to provide a rigid and level platform on which to assemble them. Here the Canadian contractors turned to North American timber bridge-building technology. They erected timber trestle bridges as staging in shallow water and, in deeper water, erected staging consisting of a conventional North American wood Howe truss bridge supported on temporary timber crib-work piers placed between the masonry piers. The Howe truss, which consisted of heavy timber chords with diagonal braces in the truss panels, bolted together with vertical wrought-iron rod posts, could be rapidly erected and easily dismantled for re-use, thereby speeding the assembly of a succession of tubes. Moreover, the staging was constructed of materials readily at hand.[40]

Only one seemingly intractable problem was experienced during the 1857 work season as cofferdams 8 and 9 experienced continual flooding, defying all efforts to pump them out. Ultimately cofferdam 8 had to be abandoned for the season, whereas at cofferdam 9 the pumping-flooding problem was solved through the mechanical ingenuity of Benjamin Chaffey.

On the Victoria Bridge project, James Hodges had introduced heavy steam-powered reciprocating pumps, imported from Britain, to dewater the cofferdams. Each pump consisted of two 18-inch cast-iron cylinders in which a pump piston worked to force water into a vertical discharge or force pipe and to draw water into the pump chamber via a suction pipe, operating on the combined forcing-and-suction-pump principle. The two pump rods were attached to a bell-crank that worked them alternately through a geared connection with the piston of a steam engine. The reciprocating pump worked well, but caused severe vibrations and concussions that continually jarred the cofferdam and resulted in heavy leakage, and on occasion breakages in the sheet piling with the water rushing in, washing out the clay puddle wall seal, and flooding the cofferdam. Each time a cofferdam flooded, the heavy pump had to be moved, new sheet piling driven, and washed out sections of the puddle wall replaced before the pump could be repositioned and the pumping recommenced. On cofferdams 8 and 9, the pumping problem was particularly severe as both rested on an exceptionally poor foundation of hard pan riddled with piles of large boulders. On such a foundation the vibrations of the heavy bell-crank pump caused frequent breaches in the sheet piling seal, and flooding, which prevented the cofferdams being pumped out.

To overcome this vexing problem, Benjamin Chaffey designed a steam-powered centrifugal forcing pump. It was built in two sizes, according to the power required, and consisted of a circular cast-iron shell of 15 or 24 inches in diameter and 6 or 9 inches in width, in which an impeller was mounted that revolved at a high speed to force water up a 7-inch-diameter ascending or force pipe. The Chaffey centrifugal pump, which was submerged at the bottom of the still water in the cofferdam well, had a horizontal chamber, and the impeller, which consisted of two straight radial vanes forming a single arm, rotated on a long vertical shaft driven by a steam engine at the top of the cofferdam. The centrifugal pump, vertical drive shaft, and force pipe, were held in place by a light timber-framework tower built against a downstream corner of the cofferdam. The pump inlet was on the bottom of the chamber, and consisted of several apertures in the centre of the casing. Water was drawn into the central inlet by the partial vacuum created as the water was pulled away from the centre by the centrifugal force generated by the speed of the impeller rotation and by the pressure of the head of water above the submerged pump. The pump discharged the water outwards from the rotating impeller vanes, under pressure, through a tangential outlet on the outer circumference of the pump chamber. The outlet was connected to the force pipe, which discharged at its top into a trough that carried the water outside the cofferdam.

The larger of the Chaffey centrifugal pumps was capable of discharging 800 to 1,000 gallons a minute out of the force pipe, and lowered the water at a rate of 2 feet per hour, emptying a cofferdam in from 3 to 10 hours depending on the depth of the water. As such, the centrifugal pump matched the discharge capacity of the heavy reciprocating pumps that Hodges had imported from England. The Chaffey pump had to be driven at very high speed, but required far less power to operate than the reciprocating pumps. Moreover, the Chaffey centrifugal pump was far lighter, and easily portable. When a cofferdam was pumped out, a 4-foot-square sump well was excavated one foot into bedrock and the centrifugal pump installed therein with drains leading to the sump to keep the cofferdam well totally dry. Even on the deeper parts of the works, the centrifugal pump proved able to raise the water to a height of 20 feet or more in a highly efficient manner. Moreover, the Chaffey centrifugal pump solved the vibration and concussion problem, and consequently greatly reduced the leakage and breakage experienced in pumping out the coffer dams. It quickly lowered the water in cofferdam no. 9, and subsequently was used to pump out the south abutment and twelve more cofferdams on the Victoria Bridge project.[41]



Cross-section views of the Chaffey centrifugal pump, and framework support tower. (*Victoria Brücke bei Montreal*, Berlin, n.d.)

Benjamin Chaffey of Brockville, at mid-century. *(Le Pont Victoria)*

At a time when centrifugal pumps were just beginning to be introduced into production and commercial use in Britain and France and when manufacturers and theoreticians were involved in trying to understand the characteristics of whirling fluids and the optimum performance efficiency characteristics of the new centrifugal pump — the most proficient shape for the vanes, the relationship between the speed of rotation, volume of discharge, and height of lift obtainable, and the shape of chamber required to minimize shock and eddies — Benjamin Chaffey succeeded in producing a high-performance centrifugal pump well suited for de-watering construction sites.[42]

Indeed, steam-driven centrifugal pumps similar to Chaffey's centrifugal pump in their general configuration, vertical drive power system, and fully immersed pump-chamber working arrangement, subsequently came to be recognized as ideal for draining cofferdams and lock pits. Centrifugal pumps were rugged, light and durable with few mechanical parts and no valves to wear out, and could handle dirty water, sand and small stones without clogging.[43] When rotated at a high speed, centrifugal pumps ultimately proved substantially more efficient than reciprocating pumps in forcing water up to heights of 30 feet, although reciprocal pumps were much more efficient beyond that height.[44]

Once cofferdam 9 was successfully pumped out using the new Chaffey centrifugal pump, the pier masonry was rapidly laid up, reaching a height of 18 feet 4 inches above water level at the onset of the winter's frost on December 3rd. To enable the pier to be carried up to its full height after the frost set in, a novel stone-laying technique was introduced that had been developed earlier by the Canadian contractors constructing the St. Anne's Bridge on the GTR mainline crossing of the Ottawa River.

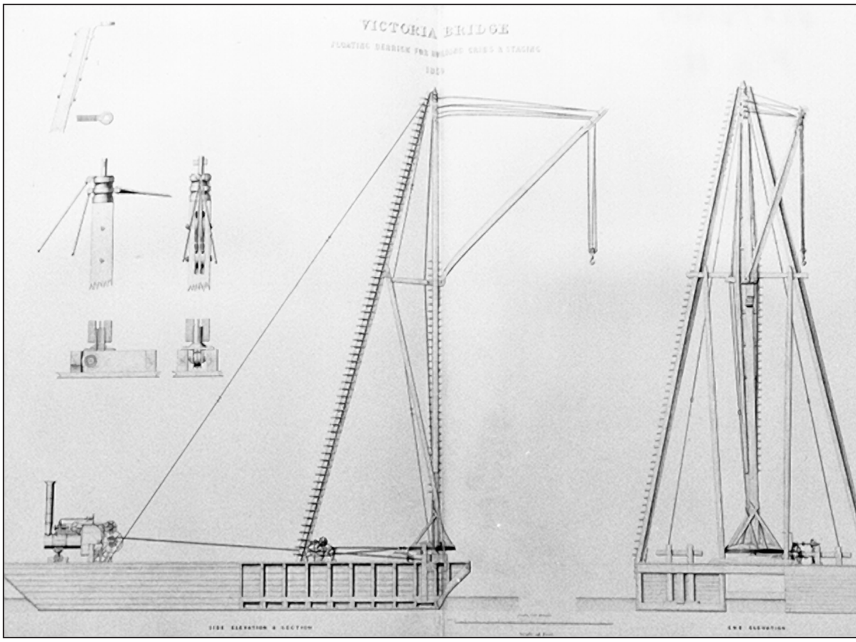
Following the onset of freezing weather, the stone courses on pier no. 9 were laid dry and tightly spaced, without mortar. To set each block of stone a 3-inch-wide strip of asphalt was placed along the outer edges, but set back on the front face to allow for a later pointing of the joints. Vertical shafts, or flues, about 1 foot square were left open throughout the full height of the masonry as the courses were laid up. The dry laying of the stone enabled masonry work to continue during freezing weather, thereby extending the working season. In the spring, once the frost was out of the masonry, the stonework was pointed on the face joints of the pier, and liquid grout mortar poured down the interior shafts. In this manner, the grout penetrated into all of the joints left in the masonry to form a solid unit of masonry.[45]

No sooner was the masonry completed on pier no. 9 than work proceeded during the winter of 1857–58 in constructing five cofferdams in the middle of the river. Concerned about the potential difficulties of trying to construct timber cribs in the strong current at mid-river, James Hodges decided that it would be easier to construct the cofferdams for piers no. 14, 15, 16, and piers 12 and 13 on either side of the center channel, through holes cut in the river ice. Previously, several timber cribwork cofferdams had been roofed over and left in place for the winter and they had survived the spring ice shove intact. However, the decision to speed construction through undertaking winter work, and risking the placing of timber cribwork cofferdams in the path of the ice shove, proved disastrous.

In the spring of 1858 water levels were exceptionally low and with the pressure of millions of tons of ice moving forward, the ice shove dislodged the new structures. Several cofferdams were driven 300 feet downstream, and others from 30 to 100 feet, which necessitated their being removed and rebuilt. Almost all of the winter's work was lost, and divers had to be employed for much of the summer in getting the stone out of the cofferdams so that they could be removed and new ones built.[46] This tedious work, however, was expedited by several new innovations, at least one of which was introduced by Benjamin Chaffey.

In addition to constructing three additional cofferdams and masonry piers during the 1858 work season, Benjamin Chaffey also constructed a major portion of the south embankment and the staging for supporting five tubes. To lift the heavy staging timber into place, Chaffey designed and built a floating barge crane. It consisted of a large jib-crane mounted on two barges lashed together, and was worked by horse power. The floating barge crane was subsequently converted to steam power, and used by all contractors to speed the erection of the staging for the tubes. James Hodges immediately thereafter introduced several steam-powered floating barge jib-cranes of a slightly different design to speed up the work of dismantling the timber crib cofferdams. Once a quantity of the stone was removed from the cofferdam cribs by divers, the powerful barge cranes were able to rip up large sections of timber work, weighing upwards of 20 to 30 tons, in a single lift.[47]

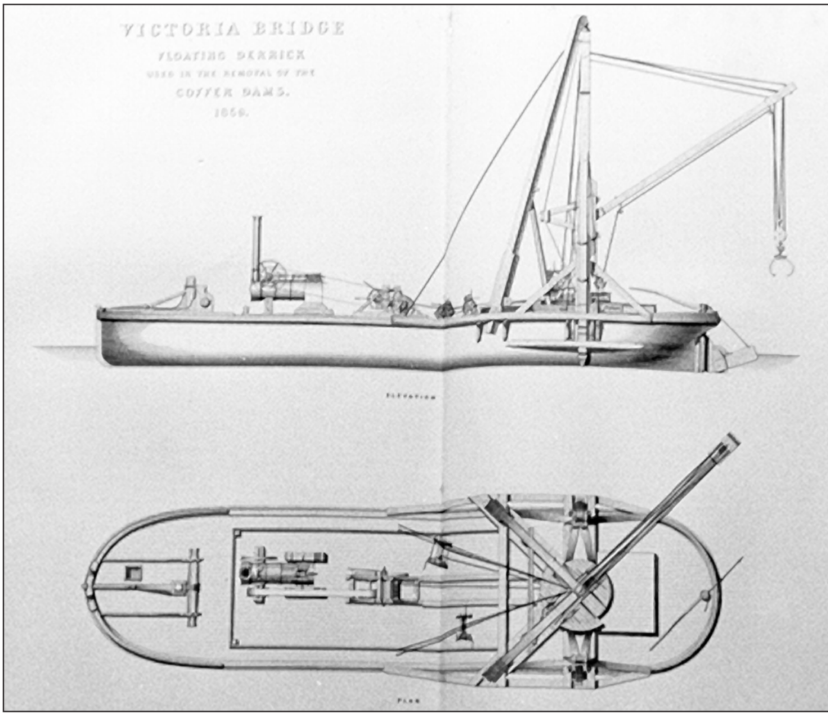
To expedite the excavation work in constructing cofferdams, yet another innovation was introduced during the 1858 work season. A steam-powered steam shovel dredge—a so-called "dipper dredge" or "dredger" was designed and built for use in excavating the well of the cofferdams down to bedrock, and for deepening the clay puddle chamber. To seal a cofferdam, a 6-foot-thick puddle wall of densely packed clay impermeable to water was



A Chaffey steam-powered barge jib-crane, with double hull, used for erecting staging. (Hodges, *Construction*)

compacted between two rows of sheet piling driven between two sections of the cribwork surrounding the well of the cofferdam. Prior to constructing the clay seal, the puddle wall chamber had to be excavated below the river bed beyond any danger of water seeping underneath. The dredger, which was mounted on tracks laid on top of the cofferdam, was operated by a steam-powered winch, and had a long bucket arm capable of reaching down to bedrock. In mechanizing yet another labour-intensive activity, it greatly speeded up the excavation of the cofferdam wells and puddle wall chambers and thereby helped further in addressing the persistent problems of the short working season, and the high cost and scarcity of labour on the Victoria Bridge project. The dredger proved unable to excavate the hard pan, which had to be broken up by hand, but it did quickly remove the loose material and boulders from the excavations.[48]

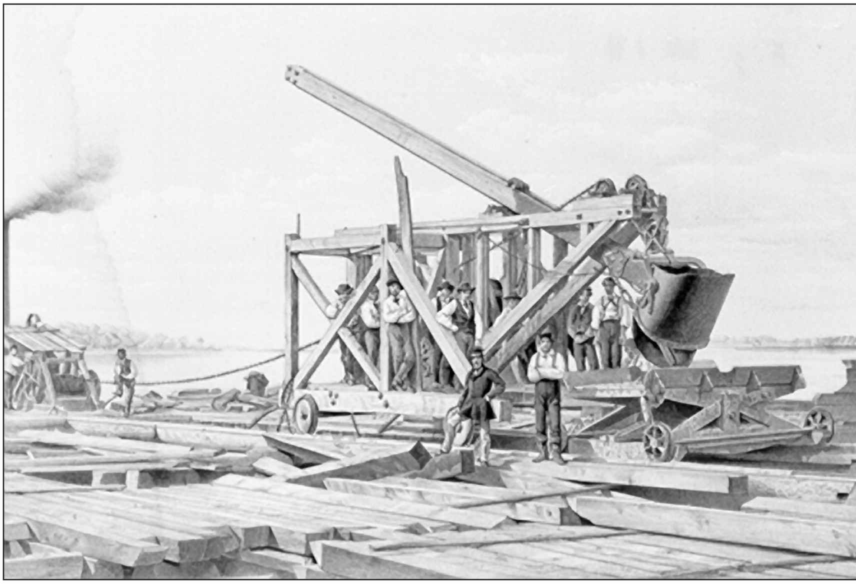
Despite the serious setback of the spring of 1858, and the delays occasioned by the need to dismantle the five displaced timber crib cofferdams, a great deal of work was accomplished during that summer work season through employing the innovative steam-powered construction equipment: the travelling gantry crane and boom derrick developed by Benjamin Chaffey, James Hodges' derivative steam-powered barge jib-crane, and the cofferdam dredger, as well as the horse-powered boom derrick and barge jib-crane introduced by Chaffey. A total of six new cofferdams were con-



James Hodges' steam-powered barge jib-crane, single-hulled, used for dismantling timber crib cofferdams. (Hodges, *Construction*)

structed, cofferdam 8 was rebuilt, and five masonry piers were raised to their full height, with two additional piers carried up a short distance above water level. Among the piers completed were piers 12 and 13, which were the two highest piers, rising 85 feet from bedrock on either side of the deep centre section of the river.[49]

The erection of the superstructure also proceeded rapidly during the 1858 work season. As early as January 13, 1858, work commenced on tube no. 25 at the south embankment, and a succession of tubes were assembled over the summer, working outwards from both ends of the bridge on temporary staging erected between the piers. Each of the 242-foot-span tubes consisted of some 4,926 pieces of wrought iron, which had been cut, punched and marked in England with the number of the tube, thickness of the plate, and its position keyed to a working drawing which was furnished to the work gangs assembling the tube. Each piece could thus be identified quickly in the sorting yard at Pointe St. Charles, and delivered to the worksite in the proper order, and at the time required, in the process of assembling a particular tube. This process constituted a marvellous organizational achievement in what today would be referred to as "just-in-time' assembly-line system. Indeed, there was only one reported occasion when

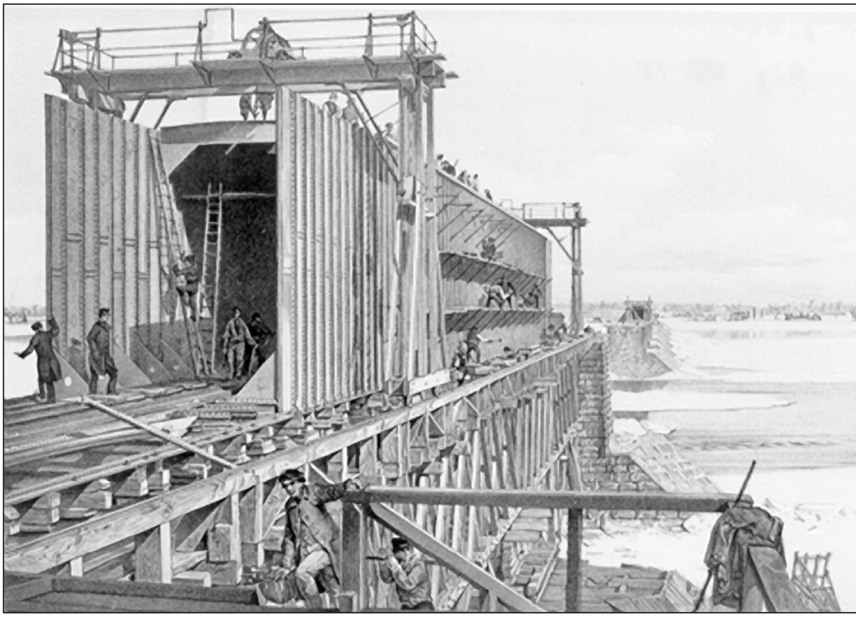


A steam-powered dipper dredge for excavating cofferdams. (Hodges, *Construction*)

the work in assembling a tube was delayed for a short period because of a failure to deliver tube components on time and in the order required.

The sorted components for each tube—plates, strips, keelsons, gussets, and tee and angle irons—were conveyed to the work sites by a small shunting locomotive running on a temporary tramway built outwards on the floor of each successive tube, and were lifted into position by a manually operated gantry crane with high legs—a Wellington crane—running on a track laid on the top chords of the Howe truss staging. Platters quickly assembled the sections of a tube using temporary bolts to align and hold the components in place for riveting. Work commenced with the laying of the floor, followed by the sides, and finally the roof of a tube. To speed the riveting, gangs of rimmers worked throughout the night, by the light of bonfires, to ensure that all rivet holes were properly lined up, and reamed out if need be, for a rapid insertion of the hot rivets the next day.

To further speed the pace of assembly, large sections of the side plates —six plates with four T-bar joints—were riveted together by steam-powered machines in a large workshop/foundry established at Pointe St. Charles, and were transported to the worksites on a shunting locomotive.[50] At the height of activity during the summer of 1858, some 3,040 men were employed on the Victoria Bridge project, together with 142 horses, 4 locomotives, 6 steamboats, and 72 barges. Work proceeded simultaneously in constructing cofferdams, building masonry piers, erecting staging, assembling the wrought-iron tubes, transporting tube components on the tramways, and barging blocks of dressed stone, staging and cribwork timbers,

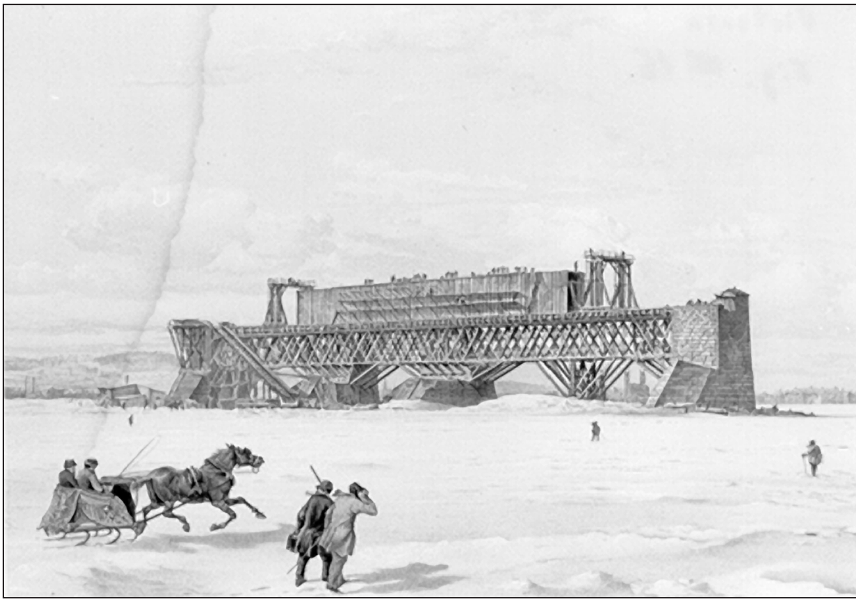


Assembling the Centre Tube with Wellington Cranes, winter 1858–59.
(Hodges, *Construction*)

and clay puddle, to the worksites at mid-river, as well as the wrought-iron tube components to the south shore for conveyance to the south spans.[51]

Faced with freight piling up in Montreal with the completion of the GTR mainline from Montreal to Toronto, and in viewing the rapid pace of construction during the 1858 work season, the Grand Trunk Railway directors offered the bridge contractors a bonus of $300,000 if the bridge could be opened to traffic by the end of the 1859 work season, two years ahead of schedule.[52] The contractors responded by introducing pay incentives for the work crews. Rather than being paid a daily wage, the riveting gangs were henceforth paid the equivalent of a day's wages for driving 180 rivets. As a result some gangs made as much as 4 days' wages by working a 16-hour day, and the riveting gangs generally averaged 1.5 days of work for each working day throughout the work season. To maintain high standards, an inspector examined each day's work. Any rivets that were not well formed had to be cut out and replaced by the riveting gang responsible for the original work.[53]

Through the introduction of innovative construction equipment, a superb organizational effort, and strenuous exertions on the part of the contractors, workmen, and superintending engineers, a total of eleven wrought-iron tubes were erected during the 1858 work season. However, at the close of the 1858 working season, 13 tubes remained to be constructed, including the large centre tube of 330-foot span, as well as two masonry piers and



Staging supporting the Centre Tube, winter 1858–59.
(Hodges, *Construction*)

their respective cofferdams. Two piers were above water level, but yet to be carried up to their full height.[54]

If the bridge project were to be completed in one year, it was essential that further progress be made during the winter months. Since it was critical to keep the middle channel open for the passage of steamboats and squared-timber rafts during the summer months, it was decided to construct the 330-foot-long centre tube during the winter of 1858–59. The staging was erected in December, and in January 1859 a road was formed on the ice for sleighs to transport the ironwork, some 10,309 pieces, to the worksite, where an inclined tramway was built rising over 60 feet from the ice surface up to the staging deck. Then a race began against time to assemble the tube before the spring ice shove. The work was pushed forward night and day, interrupted only on days when the temperatures dropped below minus 20E Fahrenheit, or when water vapour in the air coated the men and the works with ice, forcing them off the job. Despite numerous cases of severe frostbite, the work proceeded rapidly. By March 21, the centre tube was fully assembled and the riveting was approaching a conclusion. On March 25 the ice began to move in Laprairie basin, causing a momentary panic as the wedges were quickly driven to lower the centre span onto its piers. Three days later the ice shove struck. It drove the temporary timber crib piers of the staging 2 feet downstream, but did not dislodge the centre span.[55]

With the commencement of the summer work season the major remaining danger was that timber rafts might strike and dislodge the staging of one or more of the final 12 spans which were to be constructed in the middle of the river. The staging had to be sufficiently strong to resist the impact of heavy squared timbers lashed together in large rafts, 250 by 40 feet, and carried on a current running at up to 7 mph. On some days anywhere from 15 to 35 timber rafts might pass through the bridge site, carrying the previous winter's harvest of timber from the Canadian interior downriver to Quebec for export.

On May 3, 1859, work commenced to construct the last two cofferdams and erect the staging for 12 tubes. Construction proceeded rapidly. The masonry of the last pier was completed in September, through laying up 108,000 cubic feet of masonry in just over six weeks, and the staging for the last tube was erected in October. By mid-December 1859 the last of the twelve tubes was completed, marking a phenomenal achievement whereby James Hodkinson's men succeeded in erecting 3,474 lineal feet of wrought-iron tubing, including the centre span, in the course of less than a year. Moreover, the last two cofferdams, and almost all of the staging, were removed by the contractors before the close of the work season.

During the summer of 1859 a number of squared-timber rafts struck against masonry piers as they were trying to pass through the bridge substructure while the river was partially blocked by the staging for the mid-river spans, and by the centre span staging before its removal early in the summer. However, disaster threatened on only one occasion. In October, during a strong gale, four rafts piled up against the staging for tube 14, and a great pressure of water was brought to bear that threatened to carry away the staging and the tube under construction. However, the rafts broke up under the pressure of the backed-up water, and the pile of timbers was removed before any critical damage was done. The only loss was several days of work.[56]

On November 15, 1859, the first crossing of the St. Lawrence River was made when a small shunting locomotive passed through the Victoria Bridge from Montreal to St. Lambert on the construction tramway. A period of feverish activity followed in completing the riveting of the tubes and laying track, and on December 12, 1859, the first freight train rolled through the bridge headed for Portland. Five days later, on Saturday, December 17, an unofficial opening was held for citizens of Montreal of whom more than 1,000 passed over the Victoria Bridge in a train trip lasting but 7.5 minutes from abutment to abutment.[57]

Despite severe labour shortages, soaring wage rates, a short working season, and major underwater construction problems, the Victoria Bridge was completed 18 months ahead of schedule, and at cost almost 10% less than the $7,000,000 original estimate. Overall the bridge cost $6,346,133, of which $300,000 was a bonus paid to the contractors for pushing forward the work in 1858–59.[58]

The completed bridge consisted of 25 tubes with an aggregate length of 6,592 feet, carried a single track railway of 5 foot-6-inch gauge, and soared 60 feet above the St. Lawrence River on massive masonry piers and abutments. Excluding its extensive approach embankments, the Victoria Tubular Bridge was still four times longer than the renowned Britannia Bridge, but differed only slightly in the design details of the tubes. The Victoria Bridge was unique, however, not only in its magnitude, but in the design of its innovative ice-breaker piers, and in its long approach embankments, which brought the total length of the bridge crossing to an unprecedented 9,144 feet.[59]

Impact of the Victoria Bridge

Both during construction and on its completion the Victoria Bridge drew numerous spectators who were reportedly awed by the sight of the unprecedented magnitude, grandeur, and boldness of the immense structure.[60] It was variously described in engineering journals of the day as "an engineering monument in the New World"; as "one of the greatest engineering works of our time"; as "a remarkable structure, without rival upon the continent of America'; as "perhaps ... the most stupendous and imposing work of its class in the world"; and as "the Eighth Wonder of the World". Indeed, its construction was regarded as an epic event in the history of North America.[61]

One of the best general descriptions of the engineering achievement embodied in the Victoria Bridge was expressed in an American engineering journal decades later:

> The Victoria Bridge over the River St. Lawrence at Montreal was constructed nearly half a century ago, and … has enjoyed a world-wide reputation as an engineering achievement. It was the first great railway bridge built in America, was the longest and most costly on this side of the ocean, and possibly in the world, at that day.… The conditions under which it was built were exceptionally severe. For much of the work no precedent of equal magnitude existed. The substructure work was hazardous and expensive by nature and tedious in execution, but was carried out with notable success. The superstructure was of dimensions enormous at that time, of an elementary type, few examples of which were available in the development of long span bridges,… [62]

The broad extent of public recognition of the engineering achievement realized in constructing the Victoria Bridge was attested to by the events surrounding its official opening. In the summer of 1860, His Royal Highness Albert Edward, Prince of Wales (and future King Edward VII), made a special visit to Canada to open "the World's Greatest Bridge", and on August 25 laid the last stone of the north abutment and drove the last rivet in the centre span. In the evening, to celebrate the official opening of the bridge, the City Hall dome and the commercial establishments along St.

James Street from Victoria Square (the Haymarket) to the Place d'Armes were brightly illuminated with gas lights. British warships in the harbour fired off Congreve rockets, and fireworks were ignited on barges moored to the piers of the bridge. Five days of receptions and festivities followed in honour of the prince's visit. The streets of Montreal were illuminated each evening in the blaze of light from candles and gas lights, and crowded with distinguished visitors from Britain, the United States, and elsewhere in Canada.[63]

The opening of the Victoria Bridge marked the completion of the Grand Trunk Railway, and the end of Canada's first railway-building boom. The Montreal mercantile community now had a year-round rail-transportation system that linked most of the major towns of the provinces of Canada and the American Midwest (by a ferry system at Sarnia) to Montreal, and via the Victoria Bridge with Portland on the transatlantic sea lanes, and with the major American cities and markets of the Atlantic seaboard. In sum, during the Canadian railway-building boom between 1853 and 1859, fourteen railways were constructed in Canada contemporaneous with the building of the Victoria Bridge, and integrated into a railway system in which the largest of the new railways, the GTR, had over 972 miles of track.[64]

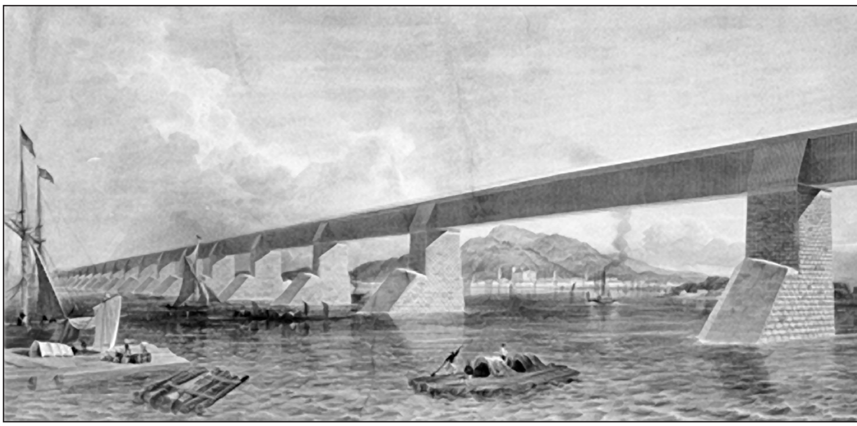
In subsequent years the GTR never managed to capture more than a fraction of the trade of the American Midwest despite the high hopes invested in the Victoria Bridge. A superior ship-canal system (the enlarged Welland Canal and the new St. Lawrence River ship canals system, versus the Erie barge canal) and an unparalleled trunk railway and ferry system linking the Midwest directly to Montreal and Portland proved insufficient to capture the trade of the American interior. The hegemony of New York continued unabated owing to far cheaper ocean freight rates at that major port, the predominance of Great Lakes steamboats and sailing vessels in transporting bulk cargoes at comparatively low cost from Chicago to lower lakes ports for transhipment into the Erie Canal and eastern American railroads, and the westward extension of eastern American railroads which by the late 1860s managed to link New York, Philadelphia, and Baltimore with Chicago by uninterrupted rail lines, thereby dramatically reducing American freight rates.[65]

In contrast, the impact of the Grand Trunk Railway on Canadian trade patterns and development was enormous. Within Canada, the GTR and its lynch-pin, the Victoria Bridge, played a critical role in recapturing the trade of Canada West for Montreal, and in enabling Montreal to henceforth dominate the trade of Canada East. Through greatly reducing transport costs, the new trunk railway system and the St. Lawrence River ship canals system enabled Canada to continue to compete in British markets with foreign wheat despite the loss of colonial preferences, and to export from Portland, via the Victoria Bridge link, during the winter months when prices were often higher. The Victoria Bridge also enabled agricultural products to be shipped directly to the United States year-round to take advantage of soaring American demand—and rising prices—as America underwent a rapid process of industrialization and urbanization both during and after the Civil War of 1861–1865. The Victoria Bridge link to an ice-free port on the transatlantic sea lanes, and to the markets of the American eastern seaboard, proved critical in re-establishing Montreal as the entrepôt for Canada's export/import trade, and thus in ensuring that Canada's political and economic development would take place along east-west lines for generations to come.

The railway building boom and construction of the Victoria Bridge brought prosperity to Canada through generating a strong demand for wage labour, manufactured goods, and agricultural products, and led to the establishment of heavy industries and the replacement of cottage industries by factories employing wage labourers. Canada underwent a process of industrialization and urbanization as the new railway centres such as Montreal, Toronto, Hamilton, Saint-Hyacinthe, and Sherbrooke, grew rapidly as industrial centres and in population during the 1860s and 1870s. Driven by new market demands, the development of steam and waterpower sites, a ready access to rail transport, British immigration, and a growing wage-labour force, the railway cities emerged as metropolitan centres in supplying industrial and manufactured goods to extensive rural hinterlands, in marketing dairy products to urban consumers, and in shipping agricultural produce to domestic and foreign markets, with the Victoria Bridge playing a crucial role in the viability of the new industrial economy.[66]

The construction of the Victoria Bridge transformed the city of Montreal and its suburbs. A major GTR workshop, including a foundry, rolling mill and machine shop with lathes and drilling machines was established at Pointe St. Charles, employing hundreds of workers in manufacturing tools and equipment for the bridge project, and in constructing rolling stock for the railway. Over 2,500,000 rivets were manufactured for assembling the tubes, as well as nuts and bolts, and steam rivetting machines were built to prefabricate large sections of the sides of the tubes. English-style row houses were erected for the higher-paid skilled workers in Montreal; the surrounding rural districts of Saint Gabriel, Ste. Anne, and St. Henri were settled by the workers and their families.

The economic prosperity generated by the bridge project, and GTR shops, benefited workers, mechanics, merchants, and manufacturers, and resulted in the construction of new warehouses, factories, and stores in Montreal, and a new wharf for ocean vessels, as well as the paving and macadamizing of city streets. New mansions were also built by a number of the leading merchants, who profited immediately from their investment in manufacturing and industrial enterprises and in providing provisions and services to meet the demands of the railway boom and the bridge-project contractors and workers. The population of Montreal and its suburbs almost doubled during the bridge-building years, and Montreal was transformed from a commercial entrepôt and nascent industrial centre into Canada's leading industrial and manufacturing sector and her major transportation hub.[67]



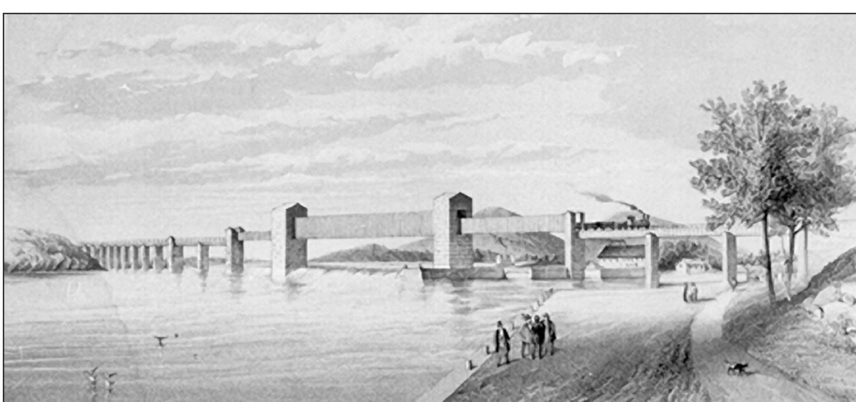
Artist's depiction of the Victoria tubular bridge, n.d. *(Le Pont Victoria)*

Both at the time of its opening, and in subsequent years, much was written in the popular press about the remarkable Victoria Bridge, and it was recorded in numerous paintings, drawings, and photographs.[68] Although the Victoria Bridge was widely seen as an engineering masterpiece, it never attained the status of a work of art. When viewed from a distance, its plain, utilitarian design, its long, narrow, linear profile extending far across the horizon, and its lack of a dramatic physical setting, all acted to detract from the visual impact of its mammoth proportions, and to lessen rather than enhance the appreciation of its aesthetic qualities.[69]

Nonetheless, to Victorians the construction of the gigantic Victoria Bridge represented a triumph of man, and his ingenuity, over the formidable forces of Nature in the surmounting of one of her mightiest rivers, and "her hithertofore irresistible winter forces". It spoke to the Victorian belief in material progress through human enterprise and industrial technology as the trade of Canada was freed from the constraints of Nature, and would no longer stagnate for six months of each year. For Canadians, who formed a new country on the confederation of the British North American colonies in 1867, the Victoria Bridge was a highly recognizable national landmark. It was viewed as a symbol of technological progress in the new young country, the Dominion of Canada; while for Montrealers, the Victoria Bridge stood as well as a symbol of the city's new-found industrial status.[70]

As a construction project, the Victoria Bridge was also distinguished in being the site where Canadian contractors introduced a new invention into bridge construction—the steam-powered Chaffey boom derrick—as well as a high-performance centrifugal pump developed by Benjamin Chaffey, and where an innovative use of steam power was made in powering travelling gantry cranes, barge jib-cranes, and cofferdam dredgers. Moreover, the Victoria Bridge marked the introduction of the novel wrought-iron tubular bridge to North America, by far the largest of its type ever built, and the development of an innovative ice-breaker pier which subsequently served as a prototype for bridge piers in northern waters. It was also the first long-span wrought-iron railway bridge built in North America, and heralded a new era of railway bridge building as wrought iron quickly superseded wood and cast iron as the material of choice for North American bridge engineers.

While the Victoria Bridge was under construction, the Grand Trunk Railway built a number of multi-span tubular bridges on its new mainline employing short 60- to 150-foot spans. Most consisted of wrought-iron tubes in a deck configuration with the railway running on top of the tubes, or were composed of tubular girders supporting a bridge deck. One other major multi-span through-tubular bridge was constructed on the GTR mainline: the St. Anne Tubular Bridge (1858) crossing the Ottawa River at the head of Montreal Island. It comprised three long tubular centre spans through which the trains passed, with tubular deck spans on either side carrying the tracks along their top.[71] However, few, if any, tubular bridges were constructed thereafter in North America, as the tubular bridge was soon superseded by a more cost-effective bridge-building technology for constructing long-span structures.[72]



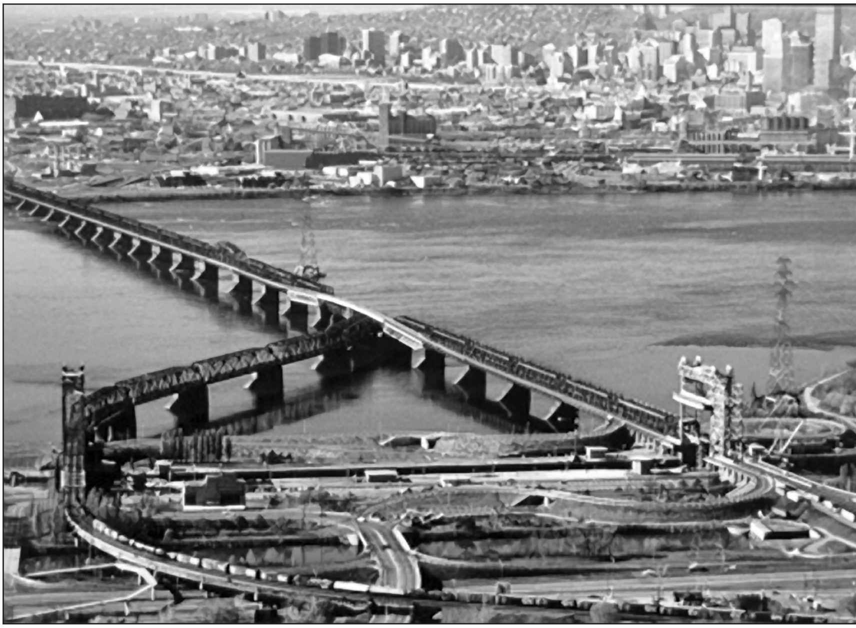
The St. Anne's tubular bridge at the western tip of Montreal Island. (Hodges, *Construction*)

Taking advantage of the technical information and formulae developed by Fairbairn and Hodgkinson on the strength and properties of wrought iron, engineers in the United States and Russia were able during the 1850s to design, on the basis of stress-analysis calculations, highly efficient long-span, wrought-iron truss bridges. By the 1860s, if not earlier, it was apparent to all bridge engineers that truss bridges were much more economical in materials, fabrication and erection costs than tubular bridges. Henceforth in Europe, wrought-iron, riveted truss bridges were erected where long spans were required; and in the United States, a wrought-iron, pin-connected truss bridge was soon developed that was far less costly even than the European riveted truss in materials and erection costs. In North America the era of long-span iron-truss bridges commenced in 1863 when American railroads began erecting wrought-iron pin-connected structures with spans of 320-foot length, and subsequently longer, over the Ohio River in extending their rail lines westward to Chicago.[73]

Despite its rapid obsolescence as a bridge prototype in terms of construction costs, the tubular-bridge concept was structurally sound. Once in use, there was only one problem experienced with the Victoria Bridge. On such a long enclosed structure, the holes cut at 60-foot intervals along the side panels to illuminate and ventilate the interior proved inadequate to carry away the smoke and fumes. Moreover, the problem worsened in the early 1870s, when the switch from wood-fired to coal-fired locomotives added corrosive gases to the mix. Hence, to ventilate the 6,592-foot-long tubular bridge a 20-inch-wide slot was opened along the longitudinal centre line of the roof, and covered with a monitor to keep out the rain and snow.[74]

The Victoria tubular bridge remained in service until 1897 when the Grand Trunk Railway, faced with heavy traffic demands, undertook to double-track its mainline and replace all single-track bridges. In that year, the piers of the Victoria bridge were widened somewhat at the top of the sloping ice-breaker section, and the masonry bridge portals were removed to accommodate a wider double-track bridge. A new steel, pin-connected, Pratt truss bridge, the Victoria Jubilee Bridge, was constructed around the tubular bridge on the existing piers and abutments using the tubes, through which the trains continued to run, as staging for the erection of the new structure. To accommodate horse-drawn vehicles the floor beams of the new bridge were cantilevered outwards beyond the trusses of the railway bridge to support a roadway on either side. Henceforth the new Victoria bridge served not only rail traffic, but was an important highway artery connecting the City of Montreal and the south shore. On completion of the new Victoria Jubilee Bridge, the old tubular bridge was dismantled.[75] The original abutments and piers continue to exist to this day, attesting to the efficacy of their design in resisting the annual ice shove, and their high standard of construction.

During the construction of the St. Lawrence Seaway (1954–59), a Victoria bridge construction project once again saw the introduction of an innovative design feature. To cross over the Seaway channel excavated along the south river bank, the Victoria Jubilee Bridge was extended in length,



The Victoria Jubilee Bridge of 1897, with the diversion branch added in the 1950s to accommodate the St. Lawrence Seaway. (Canadian National Railways, 1987)

and forked into two branches with a vertical lift bridge in each extension to carry traffic over the St. Lambert lock of the Seaway. Thus when one lift bridge was open to enable a ship to enter or leave the lock, traffic could be directed by a system of directional lights to pass over the closed bridge, thereby eliminating any interruption in traffic flow over the bridge on a ship passing through the Seaway lock.[76]

Conclusion

On its completion in 1859 the Victoria Bridge was widely regarded as one of the great engineering monuments of all time. It was indeed by far the largest bridge of its day, and did introduce a novel structural concept to North America on a hitherto unprecedented scale. However, its true significance as an engineering monument lay not so much in its massive physical properties and structural details as in the successful construction of a bridge of such magnitude under the most trying of circumstances.

The tubular bridge had been developed earlier in Britain, and proven as a structural concept on the Conway Bridge (1848) and Britannia Bridge (1850) prior to its introduction on the Victoria Bridge; and the strengths and properties of the new structural material, wrought iron, had been already ascertained through laboratory testing and captured in mathematical formulae. Only the ice-breaker piers of the Victoria Bridge were of a truly innovative design, and they did have a major impact in bridge construction in northern waters. Otherwise, the Victoria tubular bridge did not have any long-term impact on Canadian bridge building as a design prototype, as it was soon superseded by a much more efficient type of structure—the pin-connected, wrought-iron truss bridge—capable of spanning equally long spans at far less cost.[77]

The Victoria Bridge did have a major impact on the development of Canada's rail-transportation system and trade patterns. It contributed greatly to shaping the growth, infrastructure and industrial development that transformed Montreal into Canada's leading industrial centre, and for a time Canada's major metropolis; and it was likewise instrumental in ensuring that Canadian trade would flow on an east-west axis through Montreal for generations thereafter, rather than southward into American transportation systems to the benefit of American mercantile interests. Judged by its socio-economic impact, the Victoria tubular bridge was indeed a triumph of engineering, but the ultimate engineering achievement —the *sine qua non*—lay in its construction.

The construction of the Victoria Bridge was an outstanding engineering achievement not only of national, but also of international significance in its day; and it was Canadian contractors who made a critical contribution to that achievement. They invented new construction equipment and introduced innovative ways of adapting steam power to work construction machinery and material-handling equipment that had a dramatic impact on the evolution of the project. These innovations, many devised by Benjamin Chaffey, a Brockville contractor, enabled a severe labour shortage and soaring labour costs to be overcome through effecting great savings in labour demands, construction time and costs, and made it possible to surmount seemingly intractable construction problems. Within two years, difficulties that had threatened the very viability of the Victoria Bridge project were overcome, and a looming costly failure was turned into a triumph of construction engineering. Through the efforts of Canadian contractors a bridge construction project, unsurpassed anywhere in the world at that time in magnitude and complexity, was brought in under budget and ahead of schedule. Moreover, it was accomplished in a situation where adherence to traditional construction practices would have resulted in long delays and massive cost overruns, if not total failure and the ultimate abandonment of the bridge project.

Notes

1. William L. Marr & Donald G. Paterson, *Canada: An Economic History* (Toronto: Gage Publishing Co., 1980), 91–133; Robert W. Passfield, "Waterways" in *Building Canada: A History of Public Works* (University of Toronto Press, 1988), 117–120. Three major ship canals were built to by-pass rapids on the upper St. Lawrence River: the Cornwall Canal (1842–43); the Beauharnois Canal (1842–45), and the three short components of the Williamsburg Canals (1844–48) at Farran's Point, and at the Rapide Plat and Galops rapids. In conjunction with the enlarged Welland and Lachine canals, they provided an uninterrupted navigation for schooners to pass from the Great Lakes to the harbour of Montreal.
2. Charles Legge, *A Glance at the Victoria Bridge, and the Men Who Built It* (Montreal: John Lovell, 1860), 6–37; John Young, *The Origin of the Victoria Bridge* (Montreal: D. Bentley & Co. Printers, 1876), 6–10; G.R. Stevens, *Canadian National Railways*, vol. I (Toronto: Clarke, Irwin & Co. Ltd., 1960), 52–62. Other critics pointed out that a drawbridge would be needed to pass steamboats and that although Gay proposed that a 60' span drawbridge might be inserted into his structure, even he admitted that piers only 60' apart would pose a grave danger, risking the destruction of the bridge through obstructing the ice shove.
3. Gerald J.J. Tulchinsky, *The River Barons, Montreal Businessmen and the Growth of Industry and Transportation 1837–53* (Toronto: University of Toronto Press, 1977), 210–213; *Le Pont Victoria Un lien vital/Victoria Bridge The Vital Link*, McCord Museum of Canadian History (Exhibition Catalogue), May 1992, 23–25.
4. Marr & Paterson, *Canada: An Economic History*, 91–100, 137.
5. A.W. Currie, *The Grand Trunk Railway of Canada* (Toronto: University of Toronto Press, 1957), 3–5; Legge, *Glance at the Victoria Bridge*, 30–31.
6. Kenneth Norrie & Douglas Owram, *A History of the Canadian Economy* (Toronto: Harcourt Brace Jovanovich, 1991), 225–227. The railway-building boom was fostered by the Railway Loan Guarantee Act (1849) and the Municipal Loan Act (1852) by which the Canadian government backed bond issues by railway companies and municipalities under certain conditions (*ibid.*).
7. Marr & Paterson, *Canada: An Economic History*, 140–141; Norrie & Owram, *Canadian Economy*, 225–227; Stevens, *Canadian National Railways*, 97–108.
8. Legge, *Glance*, 43–49; Young, *Origin*, 17–19, 29; "Design for a Railway Bridge Over the St. Lawrence River at Montreal" by Thomas C. Keefer, 1852, reproduced in *Le Pont Victoria/Victoria Bridge*, 39.
9. "Report on Victoria Bridge (Dec 1855)", *The Canadian Journal of Industry, Science, and Art* (Toronto), No. IV, July 1856, 473.
10. J.G. James, "The Evolution of Wooden Bridge Trusses to 1850," *Covered Bridge Topics*, Winter 1998, 9–16 (reprinted from *Journal of the Institute of Wood Sciences*, 1982). Generally timber Howe-truss bridges predominated on North American railways at mid-century, with Burr-arch truss bridges being well represented among the longer spans.
11. Theodore Cooper, "American Railroad Bridges," *American Society for Civil Engineering Transactions*, vol. XXI, July 1889, 12–13; L.W. Edwards, "Early American Bridges," *The Surveyor* (London), vol. 83, 17 March 1933, 324–325. Long-span, wrought-iron railroad truss bridges — bridges of over 300' span — were not built in the United States until the early 1860s (Cooper, 17).
12. James, "Evolution of Wooden Truss Bridges," 15.

13. "Great Spans in Railway Bridges", *The Engineer* (London), 2 Dec 1859, 400. As of 1859, the longest timber-truss railway bridge span in the United States was a 275' span on the Cascade Bridge, New York and Erie Railroad (*ibid.*).
14. P.S.A. Berridge, *The Girder Bridge After Brunel and Others* (London: Robert Maxwell Publishers, 1969), esp. 7–9. The largest wrought-iron bridge in Britain as of the early 1840s was a tubular girder structure carrying a roadway over the Polloc and Govan Railway near Glasgow. Six tubular girders, each 18" deep, supported the transverse floor beams of the 31.5' span. A number of long-span, cast-iron-arch highway bridges were designed by English bridge engineers in the early 19th century, but none were built. The longest cast-iron bridge ever built was John Rennie's Southwark Bridge over the Thames River in London. This triple-arch structure had a centre span of 240', and two side spans of 210' each (H.G. Tyrrell, *History of Bridge Engineering*, Cleveland, Ohio: published by author, 1911, 150–151).
15. See Andrew Robertson, "A Chapter in Bridge Engineering a Century Ago", *Engineering* (London), Sept 1950, vol. 70, 205–207; Berridge, *The Girder Bridge*, 20–23, 59–62; and Nathan Rosenberg and Walter G. Vincenti, *The Britannia Bridge: The Generation and Diffusion of Technological Knowledge* (Cambridge, Mass.: MIT Press, 1978). Concurrently experiments were also conducted in Britain, by order of a parliamentary committee, to establish the strength of cast iron in compression and tension, and under impact loads, in response to the collapse of a 98' span of a trussed cast-iron railway bridge over the River Dee on May 24, 1847. Ironically, Robert Stephenson was the designer of that bridge (Robertson, "Bridge Engineering", 206–207; Berridge, *Girder Bridge*, 9–13).
16. G. Drysdale Dempsey, *Rudimentary Treatise, Tubular and other Iron Girder Bridges, Particularly Describing the Britannia and Conway Tubular Bridges; With a Sketch of Iron Bridges* (Bath: Kingsmead Reprints, first published London: Virtue Brothers & Co., 1864), 96–132. The Britannia Bridge was designed as a suspension bridge with masonry towers from which the chains were to be suspended to support the tubular deck; however, as testing proceeded during the building of the substructure, Fairbairn proved that the tube structure alone was sufficiently strong for a long-span railway bridge of up to 460' span, rendering the suspension chains redundant. Hence, they were never installed on the Britannia Bridge.
17. Currie, *Grand Trunk Railway*, 7–14; Sir Arthur Helps, *Life and Labours of Mr. Brassey, 1805–1870* (London: Bell & Daldy, 3rd. ed., 1872). 184–185.
18. James Hodges, *Construction of the Great Victoria Bridge* (London: John Weale, 1860), 2–3; "Grand Trunk Railway–Victoria Bridge", *Canadian Journal*, 1854, 242; and *Le pont Victoria/Victoria Bridge*, 29–30.
19. Hodges, *Construction,* 3–4; Legge, *Glance*, 56–57; Young, *Origin*, 18–22; "Stephenson Report on Victoria Bridge (Dec 1853)", *Canadian Journal*, July 1856, 472; "The Grand Trunk Railway–Victoria Bridge", *Canadian Journal*, 291; National Archives of Canada, RG 30, Vol. 12502, File 359-1, "Death of Alexander M. Ross, Esq., Engineer, Victoria Bridge", *The Leader* (Toronto), 27 Aug 1862; and *ibid.*, letter, George Tate to Hugh Ross, 30 Sept 1862. On Robert Stephenson's death in 1859, his nephew, Robert George Stephenson, initiated a controversy by asserting in print that Robert Stephenson alone had conceived and designed the Victoria Bridge — a totally false claim asserted in "The Victoria Bridge, Montreal", *The Civil Engineer and Architect's Journal*, Vol. 23, 1 June 1860, 157–158. On the controversy see Young, *Origin* 23–29.
20. Legge, *Glance*, 58–61. The timber-crib ice-deflector "Keefer shoes" would have occupied 25% of the surface area of the river, whereas the Ross masonry ice-breaker piers took up only 7% of the water surface. The masonry ice-breaker piers were 92' long by 22.5' wide at their base, with the upstream face carried up to

a height of 6' below the summer low-water level where it sloped upwards and inwards on a 1 to 1 slope to a height of 30' above the low-water level to form the ice breaker. The face was stepped in 10' at the top of the ice-breaker slope, and then carried almost straight up, with a 3" in 10' batter on all sides, to the top of the pier, which measured 33' in length by 16' in width (*ibid.*).

21. Rosenberg & Vincenti, *The Britannia Bridge*, 4–7.
22. David Plowden, *Bridges: The Spans of North America* (New York: Viking Press, 1974), 79.
23. Legge, *Glance*, 70, 88. The estimate was: Approaches and Masonry Abutments, $1,000,000; Masonry Piers, $4,000,000; Tubular Superstructure, $2,000,000. The Victoria Bridge abutments were of a hollow cellular construction with the masonry cells filled with compacted earth, stone and gravel to form a solid mass (*ibid.*). No difficult underwater conditions were experienced in constructing either the Conway or Britannia bridges (Berridge, *The Girder Bridge*, 48, 60). Each Victoria Bridge span was constructed with sides of light ¼" boiler-plate skin on the center 70' of the tube, with successively thicker plating in each 35' section of the tube sides progressing towards the ends (Legge, *Glance*, 68).
24. Hodges, *Construction,* 6–8; "The Grand Trunk Railway–Victoria Bridge", *Canadian Journal*, 1854, 291; "The Victoria Bridge, Montreal", *Civil Engineer and Architects Journal*, 1 June 1860, 157; Plowden, *Bridges*, 79. On the power of an ice shove to move masonry piers weighing 150 tons, see Hodges, 22. The wide river at the Victoria Bridge site, however, was less subject to ice shoves than the narrower channel just downstream at Île Sainte-Hélène where 30'-high ice jambs were a common annual experience.
25. Hodges, *Construction*, 86; Legge, *Glance*, 93–95.
26. Legge, *Glance*, 128–130; Hodges, *Construction*, 9–12, 23–34; Stevens, *Canadian National Railways*, 271–273. During the winter of 1853–54, an observatory with a large transit was built on Pointe St. Charles, and the location of the piers was marked by anchoring buoys to the riverbed through holes cut in the ice, and 2 steam tugs, 25 barges and 6 floating caissons were constructed at Montreal. Stone quarried in the Isle La Motte quarry was transported by barge on Lake Champlain, and then by rail to the bridge site on the Champlain and St. Lawrence Railway, Canada's first railway (1836). Originally constructed as a 12-mile-long portage railway connecting the Richelieu River at St. Jean to Laprairie on the St. Lawrence River, it was extended southward in the early 1850s to Rouses Point, New York, on Lake Champlain, and at its north end to Saint Lambert opposite Montreal, just upstream of Laprairie.
27. Hodges, *Construction*, 5, 11–12, 19–28; "Report on Victoria Bridge (December 1855)", *Canadian Journal*, July 1856, 471–472; Legge, *Glance*, 93–96, 128. Floating caisson cofferdams were used thereafter only for piers 7, 17 & 18, where the riverbed was bare rock, relatively flat, and free of large boulders, allowing the caissons to be well seated. The floating caissons were placed in a wedged-shaped configuration to form a cofferdam whereas the timber cribwork cofferdams, with the exception of the several 'Keefer shoe' cofferdams built to withstand the ice shove during the winter of 1854–55, were rectangular in shape, but with a sloping upstream face.
28. Stevens, *CNR*, 269; Hodges, *Construction*, 29; Legge, *Glance*, 130.
29. Stevens, *CNR*, 261–273; Hodges, *Construction*, 23–35; *Vital Link*, 45. By the summer of 1854, some 8,000 men were employed just in building the GTR mainline from Montreal to Toronto (Stevens, *CNR*, 265). In the Crimean War (1854–56),

Britain fought, along with her allies France and Sardinia, on the side of Turkey against Russia.

30. Hodges, *Construction*, 21.
31. Legge, *Glance*, 131. Little is known about Benjamin Chaffey (c. 1806–1867), beyond that he was a builder and canal and railway contractor from Brockville on the upper St. Lawrence River, and a member of an entrepreneurial family noted for its mechanical ingenuity. His father and two uncles, on emigrating to Canada from England following the Napoleonic Wars, established a major steamboat-building enterprise at Brockville and Kingston, as well as a distillery, grist mill, carding mill, and saw mill at a nearby waterfall, Chaffey's Mills on the Cataraqui River. The Chaffeys built marine engines, passenger-freight steamers, and tug boats, as well as operated steamboats engaged in the forwarding, iron ore, and lumber trades on the Great Lakes. Benjamin's nephew, George Chaffey, a self-taught engine mechanic/draughtsman/mechanical engineer, later invented a new form of propeller widely adopted for lake and ocean steamers, and designed light-draught steamboats that set speed records for passenger-freight steamers on the Great Lakes and Ohio River (1870s), and was the founder and pioneering genius of large-scale irrigation colonies at Riverside (1881) and Ontario (1882), California, and at Mildura (1887) and Renmark (1889), Australia, as well as in the Imperial Valley (1900), California, that revolutionized irrigation practices in both the United States and Australia.
32. Hodges, *Construction*, 32–33; Legge, *Glance,* 132–133; *Spons' Dictionary of Engineering*, Vol. III, 1874, 2244–2245. Powered by two 3-hp steam engines, the Chaffey travelling gantry crane could lift at a rate of 6' per minute, travel along the gantry track at 30' per minute, and traverse its load on the traveller beam at a rate of 20' per minute *(ibid*, 2245). J.W. Woodford, the mechanical engineer on the Victoria Bridge project, assisted Benjamin Chaffey with the travelling gantry crane (Legge, *Glance*, 133). Presumably Woodford prepared the working drawings. All contemporary commentators, including James Hodges, credit Benjamin Chaffey alone with being the "mechanical genius" responsible for the innovation.
33. Legge, *Glance*, 130–131, 102–104.
34. Ibid., 136, 104–105; Hodges, *Construction*, 38.
35. Hodges, *Construction*, 37; Legge, *Glance*, 135. Benjamin Chaffey may well have introduced his innovative horse-powered boom derrick as early as 1854 at the Isle La Motte quarry on Lake Champlain where the quarrymen had previously quarried common building stone in blocks no greater than one ton in weight. To handle heavier loads, Chaffey reportedly introduced "remarkable contrivances" whereby a horse, or two men, could lift and transport 20-ton blocks of stone with ease (Legge, 132).
36. Legge, *Glance*, 105–107, 136–137; Hodges, *Construction*, 37, 48. *Appleton's Dictionary of Machines, Mechanics, Engine-Work, and Engineering* (New York: Appleton & Co., 1851, Vol. I, Plate 1031) shows a boom derrick, "Savage's Derrick improved by W. J. McAlpine", but it is manually operated and has the boom near the bottom of the mast, like a yard arm on a ship mast. Moreover, it does not have the sophisticated trussing of the Chaffey boom derrick which is, in effect, a prototype of the modern boom derrick used in high-rise building construction.
37. Hodges, *Construction*, 38. In England, steam-powered cranes were just beginning to be introduced in the mid-1850s for unloading colliers and general cargo vessels, but these small jib cranes had a lift of only 20' and a half-ton hoisting capacity ("On Loading and Discharging Vessels", *The Engineer* (London), 20 Jan 1856, 24, and 7 March 1856, 120).

38. In 1856 pier 5 was completed and piers 6, 7 and 23 were built with the Chaffey steam-powered boom derrick, and pier 24 by the horse-powered derrick. Piers 3 and 4 were built with gantry cranes equipped with the steam-powered hoist jenny introduced by Chaffey. Benjamin Chaffey's abilities as a contractor were recognized in his being given contracts for constructing additional cofferdams and piers, as well as the staging for a number of the tubes. He ultimately constructed piers 24, 23, 22, 21, 20, 19, 16, 15 and 14, the south abutment and embankment; contractor John O. Hodge built piers 10, 11, 12 and 13, and the north abutment and embankment; Brown and Watson of Montreal built piers 5 and 6 (Hodges, *Construction*, 103). The remaining eight piers were presumably built by other masonry contractors.
39. Hodges, *Construction*, 42–53. Piers 18, 19, 20, 21, 22, and 9 were completed in 1857 (*ibid.*, 48).
40. Hodges, *Construction*, 42, 54–55; Legge, *Glance*, 139. The Howe trusses had a 20' depth, were heavily constructed with chords 14" by 24", composed of three 8" x 14" ribs with 8" x 8' panel braces and 8" x 10" counterbraces (*ibid.*, 114).
41. Legge, *Glance*, 98–101; Hodges, *Construction*, 48; "The Victoria Bridge, Montreal", *The Engineering Record*, Vol. XXXVIII, no. 21, 468. The cofferdam wells were 125' by 52' and, in the deepest part of the river, held stillwater up to a depth of 15' or more that had to be pumped out and carried up over the cofferdam, which was raised several feet above the surface water level.
42. The first practical centrifugal pump was invented by John George Appold of London, England, and exhibited at the Great Exhibition of 1851 in London. It had a vertical impeller, 12" in diameter and 3" thick, with six curvilinear vanes, driven by a low-pressure steam engine (28 psi), coupled by belting to the horizontal drive shaft. The pump casing had a central inlet, 6" in diameter, and discharged water on the periphery of the impeller, under pressure, into a vertical force pipe. The Appold pump was able to discharge 1600 to 1800 gallons per minute at a height of 10 feet with the impeller rotating at 800 rpm, obtaining a 50% work efficiency. Subsequent experiments established that the higher the speed of rotation of the impeller, the higher the water could be raised and the efficiency increased reputedly as high as 70% ("The Centrifugal Pump", *The Civil Engineer and Architect's Journal*, Vol. XIV, 14 June 1851, 326–327). James Stuart Gwynne also exhibited a practical centrifugal pump at the Great Exhibition. However, most of the centrifugal pumps manufactured for sale during the following two decades were based on the Appold pump model, and with a short suction pipe that descended into the water to be raised (E. & F.N. Spons, *Spons' Dictionary of Engineering*, Vol. III, London, 1874, "Centrifugal Pumps", p 1948). On subsequent improvements in the centrifugal pump, see Charles Singer, E.J. Holmyard, A.R. Hall, and T.I. Williams, *A History of Technology* (Oxford: Clarendon Press, 1978), "Hydraulic Machinery", Vol. V, 524–526.
43. *Appleton's Cyclopaedia of Applied Mechanics: A Dictionary of Mechanical Engineering and the Mechanical Arts* (New York: D. Appleton & Co., 1880), Vol. II, 606–612. At least one pump of later manufacture closely approximated the Chaffey centrifugal pump in its general configuration, vertical drive power system, and fully immersed pump chamber working arrangement — the "Heald & Sisco Centrifugal Pump" (*ibid.*, 609–610 and Fig. 3531). This later pump, however, incorporated the expanding Thomson whirlpool-chamber design improvement, and most probably a more sophisticated and efficient impeller than the Chaffey pump with its uniform circular chamber and two straight radial vanes forming a single-arm impeller. It is highly unlikely that the Chaffey centrifugal pump had any influence at all on the subsequent evolution of the centrifugal pump in its various manufactured models, given that there was ongoing contemporary research on more-sophisti-

cated models than the Chaffey pump. In principle, the centrifugal pump was but a reversed turbine. If water were run down the force pipe into the outlet of a centrifugal pump, it would have been driven in reverse, acting as an inflow turbine in turning the drive shaft.

44. Robert G. Blaine, *Hydraulic Machinery* (London: E. & F.N. Spon, 1897), 128.
45. Hodges, *Construction*, 48. See also "Victoria Bridge", *Engineering Record*, 29 Oct 1989, 466. Felt strips were used on the St. Anne's bridge piers, rather than strips of asphalt as on the Victoria Bridge.
46. Hodges, *Construction*, 45–47; Legge, *Glance*, 142–143.
47. Legge, *Glance*, 116, 140–143; Hodges, *Construction*, 70, and Plate 17. For the definition of a "jib crane" see T.C. Collocott and A.B. Dobson, eds., *Chambers Dictionary of Science and Technology* (Edinburgh: W. & R. Chambers, 1974), 644.
48. Hodges, *Construction*, 42–47; Legge, *Glance*, 96. Contemporary accounts do not mention whether Benjamin Chaffey designed and built the steam-powered dipper dredge; however, it was the contractors who were responsible for constructing the substructure and securing equipment for use thereon. The GTR engineers had heavy responsibilities elsewhere in laying out and constructing hundreds of miles of railway trackage, inclusive of bridges and viaducts, as well as in overseeing the manufacture of the rolling stock and in designing and erecting buildings and other railway infrastructure on the new Grand Trunk Railway. Regardless of who designed it, the dredger was an innovative piece of equipment developed on the Victoria Bridge project to address a particular construction problem.
49. Hodges, *Construction*, 45–54, 58; Legge, *Glance*, 142–143, 124. Piers 8, 10, 12, 13, and 17 were completed, and piers 14 and 15 raised a distance above the summer water level.
50. Legge, *Glance*, 118–120; Hodges, *Construction*, 42–55; "Victoria (St. Lawrence) Bridge", *The Engineer* (London), 9 Sept 1859, 183. A large machine shop/foundry was established by the GTR at Pointe St. Charles in 1854 (see Paul Craven and Tom Travers, "Canadian Railways as Manufacturers, 1850–1880", in Douglas McCalla, *Perspectives on Canadian Economic History* (Toronto: Copp Clark Pitman Ltd., 1987), 118–143.
51. Legge, *Glance*, 124. Of the labour force, 450 men worked in the two stone quarries at Pointe St. Charles and Isle La Motte, 500 worked on the barge fleet, and 2,090 worked on the bridge works. A total of 26 lives were lost during construction, mostly through men falling into the river and drowning before lifeboats could reach them (*Le pont Victoria/Victoria Bridge*, 49).
52. Hodges, *Construction*, 52; Stevens, *CNR*, 270.
53. Legge, *Glance*, 122.
54. Hodges, *Construction*, 54. Piers 11 and 16 remained to be constructed. Piers 14 and 15 were above water, but yet to be raised to their full height. The tubes were laid out with a 4½" camber to allow for the settling of the scaffolding, and compression of the packing and wedges during construction, and were designed to have a 2½" camber once the wedges were driven out (Legge, *Glance*, 119).
55. Hodges, *Construction*, 56–60. On the coldest days, January 10–12, the thermometer at the bridge recorded a temperature of 36E below zero Fahrenheit.
56. Hodges, *Construction*, 63–69, 111; Legge, *Glance*, 139, 147. The staging for the last tube could not be removed before the end of the work season. Hence, some of the stone was removed from the timber-crib pier foundations, and the staging was left in place to be carried away the following spring.

57. Legge, *Glance*, 148–152; "Opening of the Victoria Bridge for Traffic", *Montreal Gazette*, 19 Dec 1859. In the spring of 1860, the embankments were protected with rip rap; holes were cut every 60', along the neutral axis of the side of the tubes, to illuminate the interior; a wood gable roof, sheathed in tin, was erected along the top of the tubes to shed the snow and rain; and the bridge was painted using a traveller mounted on a roof track (Hodges, *Construction*, 72–73).
58. Legge, *Glance*, 70, 84; Plowden, *Bridges*, 79.
59. Hodges, *Construction*, 82. On the Victoria Bridge extra plates and longitudinal keelson stiffeners were used to strengthen the top and bottom of the tubes, rather than the cellular construction used previously on the Britannia Bridge. Moreover, the Victoria Bridge tubes were continuous only in two-span units to allow for expansion and contraction of the tubes in the extremes of temperature in the Canadian climate, with each double tube anchored to the masonry pier at its centre and resting on expansion rollers on its end. An 8" gap was left between adjacent double-span tubes at their bearings on the piers, and the centre tube was freestanding with expansion rollers at one end. The Victoria Bridge tubes were 16' wide throughout to accommodate a 5'6" gauge track, but varied in height to accommodate the slope of the railway tracks, with each double-span continuous tube component increasing by 6" in height from a tube height of 18'6" for the double-span tube at each abutment through to a height of 22' for the centre tube. In contrast, the Britannia Bridge was a continuous structure with tubes 14'8" x 22'9" for the 230' spans, and 14'8" x 30' deep for the 460' spans (Legge, *Glance*, 65–68).
60. "Report on Victoria Bridge (December 1855)", *Canadian Journal*, July 1856, 407; *Montreal Gazette*, 19 Dec 1859.
61. "The Victoria Bridge, Montreal", *Civil Engineer and Architect's Journal* (London), Vol. 23, 1860, 157–158; "The Grand Trunk Railway–Victoria Bridge", *Canadian Journal*, Vol. 2, 1854, 290; "Victoria (St. Lawrence) Bridge", *The Engineer* (London), 9 Sept 1859, 183; "The Victoria Bridge", *The Engineer* (London), 16 Dec 1859, 431; Berridge, *The Girder Bridge*, 45.
62. "The Victoria Bridge", *Engineering Record* (New York), Vol. 38, no. 21, 22 Oct 1898, 444. No difficult conditions were encountered in constructing the substructure of either the Britannia or Conway bridges. The Britannia Bridge cost £601,865 and the Conway Bridge £145,190 (Berridge, *Girder Bridge*, 48, 60). As of 1857, one pound sterling was pegged at $4.866 Canadian currency by the Canadian government.
63. *Le Pont Victoria/Victoria Bridge*, 85–93. The visit of the Prince of Wales was also marked by the construction of a Crystal Palace, a colonnaded pavilion, several triumphal arches, and a grand pavilion in which a gala ball was held on August 27 (*ibid.*, 77–87).
64. Canada, *General Report of the Commissioner of Public Works for the year ending June 30, 1867* (Ottawa: Hunter, Ross & Co., 1868), 606, Appendix 20, "Railways in the United Province"; Norrie & Owram, *Canadian Economy*, 225–227; Christopher Andreae, *Lines of Country: An Atlas of Railway and Waterways History in Canada* (Toronto: Boston Mills Press, 1998), 90–91. In 1850, all of the British North American colonies combined had but 66 miles of railway track whereas by 1860 the Province of Canada (present-day Ontario and Quebec) alone had 2,188 miles of track.
65. Currie, *Grand Trunk Railway*, 59, 222–226; Norrie & Owram, *Canadian Economy*, 230. By 1869, the New York Central, Pennsylvania, and Baltimore and Ohio railroads had reached Chicago with uninterrupted lines through bridging the Ohio River. To improve its competitive position, the GTR also subsequently established an uninterrupted rail communication with Chicago through constructing the St.

Clair Tunnel (1888–1891) under the St. Clair River to replace its car ferry between Sarnia, Ontario, and Port Huron, Michigan. Designed and built by a Canadian engineer, Joseph Hobson, it was the first major subaqueous tunnel in North America, and a world's first in combining the use of cutting shields, cast-iron tunnel lining, and a compressed air working environment (28 psi) to prevent water oozing into the excavation from a porous clay riverbed.

66. *Le pont Victoria/Victoria Bridge*, 105–123; Marr & Paterson, *Economic History*, 140–141; Norrie & Owram, *Canadian Economy*, 205, 227–232. The GTR alone spent $67 million on railway and bridge construction between 1853 and 1859, a sum far greater than all Canadian government expenditures on public works — canals, bridges, roads, public buildings, timber slides, and lighthouses — from 1841 through to the confederation of the British North American colonies in 1867 (Norrie & Owram, *Canadian Economy*, 227).
67. *Le pont Victoria/Victoria Bridge*, 105–117, 123; Jean-Claude Marsan, *Montreal in Evolution* (Montreal: McGill-Queens Press, 1990), 173, 179; Norrie & Owram, *Canadian Economy*, 227, 237; Legge, *Glance*, 118. A temporary machine shop was also established at Saint Lambert with a steam riveting machine to prefabricate side sections (*ibid*., 118).
68. *Le Pont Victoria/Victoria Bridge*, 17.
69. Marsan, *Montreal in Evolution*, 252–254.
70. Legge, *Glance*, 30; *Le pont Victoria/Victoria Bridge*, 17–19.
71. Hodges, *Construction*, Plate 1, "Railway Bridge over the Rapids at St. Anne's"; List of Grand Trunk Bridges renewed on the St. Lawrence and Atlantic Railway, 1857-1859; Dianne Newell and Ralph Greenhill, *Survivals, Aspects of Industrial Archaeology in Ontario* (Toronto: Boston Mills Press, 1989), "Early Grand Trunk Railway Bridges and Stations", 46–68.
72. Tyrrell, *History of Bridge Engineering*, 196–197; Zerah Colburn, "American Iron Bridges", *Minutes of the Institution of Civil Engineers, 1862–1863* (London), 1863, 542; Rosenberg & Vincenti, *The Britannia Bridge*, 46, 67. In Britain only one other large tubular bridge besides the Britannia and Conway was built: the Brotherton Bridge (1850), a dual-tube, 255' span structure carrying the York and North Midland Railway over the Aire River. One other major tubular bridge was apparently constructed over the Damietta Branch of the Nile River in Egypt. None, however, approached the scale of the Victoria Bridge (Tyrrell, *History of Bridge Engineering*, 197). The last through tubular bridge in North America, the St. Anne Bridge, was demolished in 1899 on the GTR double tracking its mainline. Today, only the Conway Bridge remains extant of the long-span tubular bridges constructed in the mid- nineteenth century.
73. B. Baker, *Long Span Railway Bridges* (London: E. & F.N. Spons, 1867), 4–14; Cooper, "American Railroad Bridges", *ASCE*, 15–17, 31; John A. Roebling, *Long and Short Span Railway Bridges* (New York: Van Nostrand, 1869), 39–40; Rosenburg & Vincenti, *The Britannia Bridge*, 46, 67. On the Ohio River, a succession of railroad bridges were built with record length spans for wrought-iron, pin-connected truss bridges: 320' in 1864; 390' in 1870; 420' in 1872; 519' in 1876; and 550' in 1889 (Cooper, "American Railroad Bridges", 17). The development of the cantilever bridge during the 1880s, and the introduction of steel, enabled even longer-span railway bridges to be constructed, culminating in the 1800' clear span of the Quebec cantilever bridge in 1917. For an overview of the development of the wrought-iron truss bridge in North America, see Robert W. Passfield, "The Turcot Riveted Arch-Truss Bridge: As rigid and unyielding as a stone arch", *IA: The Journal of the Society for Industrial Archeology*, Vol. 23, No. 2, 1997, 21–48.

74. *Le pont Victoria/Victoria Bridge*, 67. When tested on 15 Dec 1859 with a three-engine train 520' long, comprising flat cars loaded with large blocks of stone, the centre tube deflection was less than 2" under the test load, and the span resumed its original level on the load being removed (Legge, *Glance*, 149–150).
75. "The Victoria Bridge", *Engineering Record*, Vol. 38, No. 23, 488–491, No. 24, 510–512, No. 25, 534–536.
76. P.G.A. Brault, "Montreal Area Bridge Alterations for the St. Lawrence Seaway", *Engineering Journal* (Montreal), October 1957, 1451–1452.
77. Theoretically, as bridge engineers of the day recognized, the tube was a superior structure to the truss in economy of materials for a given loading and length of span. However, in practice there was a limit to the thinness of wrought-iron plate that could be manufactured and rivetted, which when added to the extra material needed to lap the plates for rivetting and the labour-intensive nature of the work required in constructing a rivetted tube, combined to make the wrought-iron tube structure more costly and time-consuming to construct than the truss bridge (Roebling, *Long and Short Span Bridges*, 39). Today, with extruded thin-walled steel tubing, welded joints, and advances in concrete construction technology, the superiority of the tubular form can be, and is, realized in many facets of modern bridge construction.