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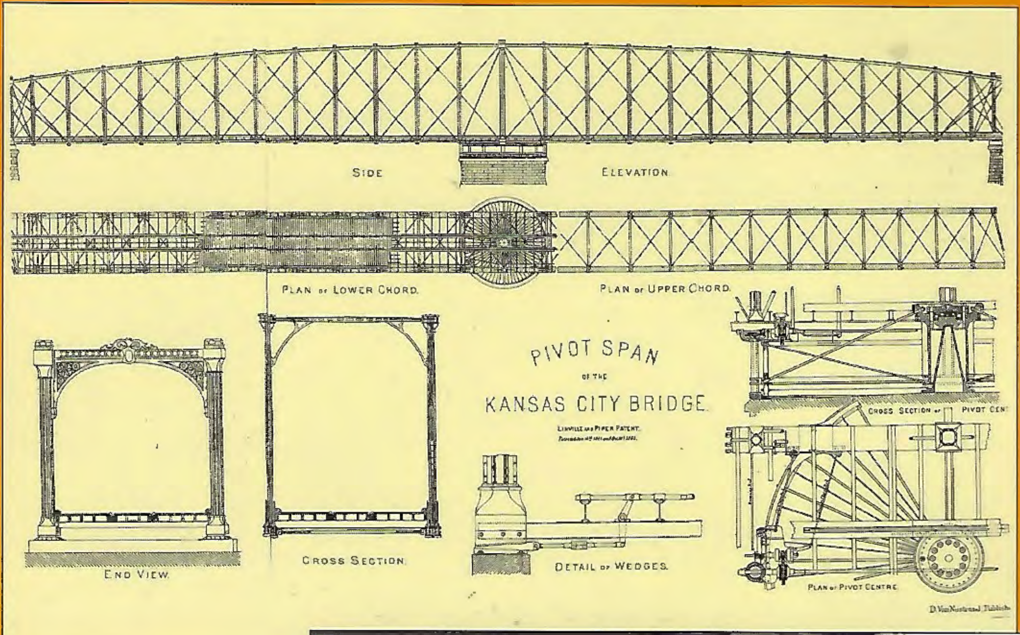
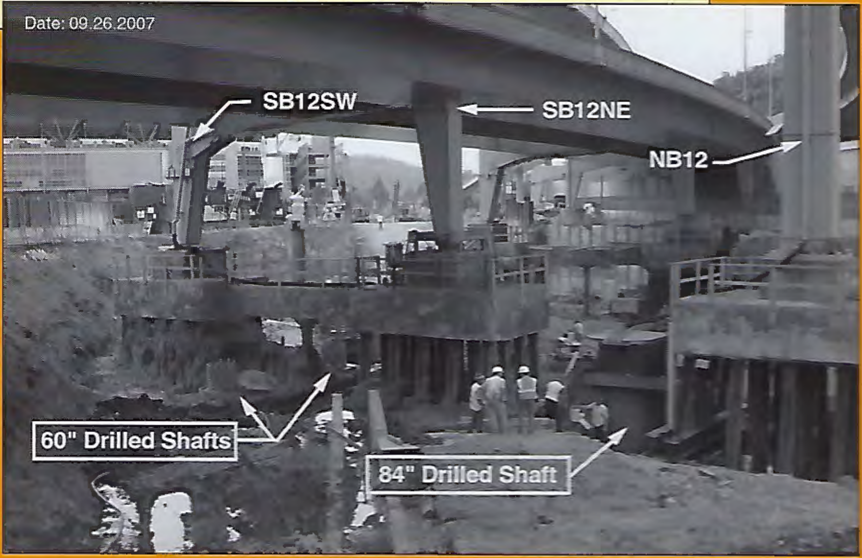
George S. Morison, Engineer



Underpinning Bridge Foundations



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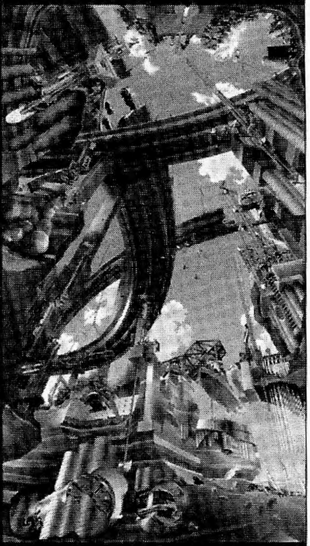

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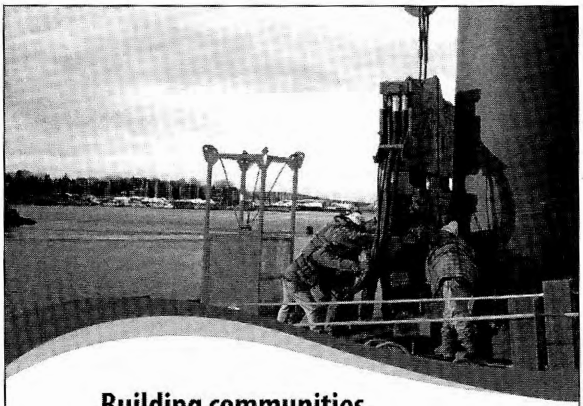

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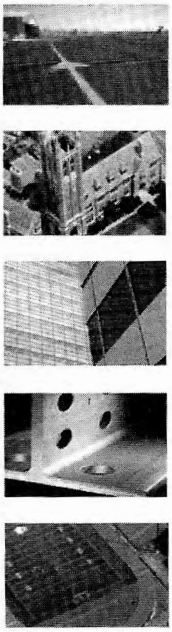

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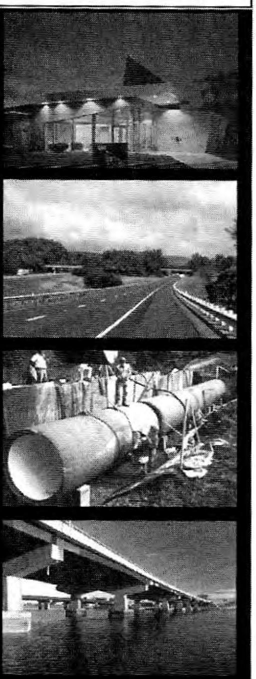

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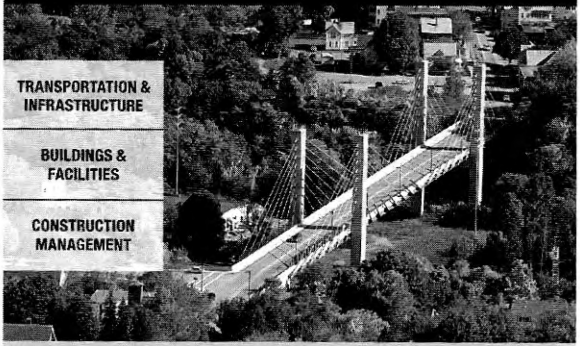

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Great Civil Engineering Practice, Past & Present

A few months ago, Bob Stevens, the President of our Section of ASCE, the BSCES, asked in the monthly newsletter, "Where has great civil engineering gone?" With this edition of *Civil Engineering Practice*, the Editorial Board brings you two articles that highlight the career of a great bridge engineer of the latter nineteenth century and provide an example of great civil engineering on a recently completed project in Pittsburgh. Maybe today our work seems a little mundane, particularly in reminiscing back one, two and three decades ago when Boston was a focal point of many great civil engineering achievements on a number of world-class projects. Perhaps we in the Boston area became a little spoiled with all those super-sized civil engineering challenges. Although the planning for new "great" projects in our area may have gotten a little slowed by the recession economy, public agencies and developers continue to plan and dream of the next great projects. The current issue of *Civil Engineering Practice* illustrates how a superb example of great civil engineering can be "lost" within the magnitude of the much larger project, the light rail transit (LRT) extension in Pittsburgh, as documented in the article by Panah, Pierce and Chong. Frank Griggs chronicles the engineering life of George S. Morison, who was one of the greatest bridge builders and design consultants of the late 1800s.

The underpinning of continuous-span welded steel box girders of a bridge that are rigidly framed into steel bents with welded connections to eliminate the existing pile foundation substructure to permit LRT construction is a feat of great engineering. Not that such work has not been done in somewhat similar situations for other tunnel construction projects, such as in Boston for the Big Dig or earlier for Back Bay Station construction, but any time a project requires very tight tolerances on structure movement it makes for a very substantial project. In Pittsburgh, Panah, Pierce and Chong describe details of the underpinning operation that had limits of 0.25 inch during construction and then 0.125 inch after the completion of construction.

Then, the engineering life of one of the great bridge engineers of the latter nineteenth century is woven into a series of ever more complex and challenging projects in Griggs's article about George S. Morison. This story is truly inspirational in regards to the drive and dedication of the Chief Engineer Morison, who achieved many "firsts" in bridge engineering and construction. In an era when it seems as though every bridge was pushed to be longer or carry heavier loads, the demand for such great engineering feats in the rapidly expanding United States continued to offer Morison a never-ending menu of opportunities to build longer and more substantial bridges. This article by Griggs, along with the books by David G. McCullough — *The Great Bridge: The Epic Story of the Building of the Brooklyn Bridge* and *Path Between the Seas: The Creation of the Panama Canal, 1870-1914* — should be required reading for all freshmen entering college to study civil engineering.

So don't think we don't have great civil engineering these days. While one person's personal engineering achievements may not be as wildly spectacular as those of George S. Morison, we are nonetheless stewards of the built environment and the masters of the infrastructure of modern society. Maintaining, repairing and rebuilding that infrastructure is probably as important as building the next new longest, highest, widest, deepest new project. While this edition of your BSCES journal, *Civil Engineering Practice,* brings you just two articles, we decided to forgo breadth for depth in this issue. We are constantly looking for timely, practice-oriented papers that might just highlight great civil engineering or a substantial issue of civil engineering practice. Perhaps you have worked on such a project, and would want to write a short technical piece, or maybe you can point us in the direction of another member who might be more appropriate to write about it. Please contact me or any member of the Editorial Board with ideas, suggestions or draft papers on an aspect of civil engineering practice that you would like to see in your BSCES journal.

Sincerely yours,

Jim Lambrechts

Professor Jim Lambrechts, P.E.
Wentworth Institute of Technology
(lambrechtsj@wit.edu)

Geo. S. Morison, Ch. Eng'r

With an unwavering quest for truth and accuracy, Morison parlayed a prolific bridge-building spree into an esteemed consulting career that ultimately changed global economics and politics.

FRANCIS E. GRIGGS, JR.

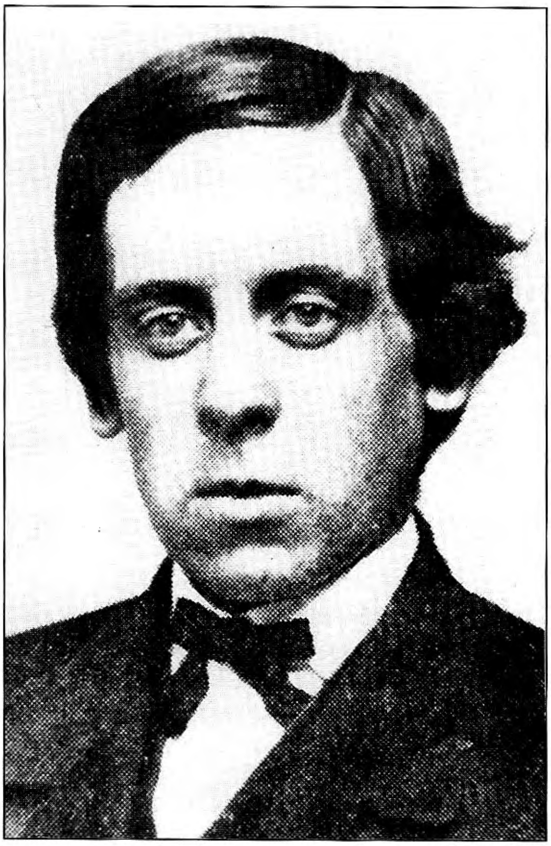
George Shattuck Morison was one of the greatest bridge builders of the late nineteenth century. He built many major bridges over the Missouri, Ohio and Mississippi rivers in the Midwest as well as many in the far West. He earned the title of Pontifex Maximus for his work, which he described in many monographs (that he also wrote himself). He was the first assistant of Octave Chanute who went on to an exceptional career. He was a member of many special commissions of engineers who passed judgment on a wide range of engineering projects, including the Panama Canal.

Early Life

Morison was born in New Bedford, Massachusetts, on December 19, 1842, the son of a Unitarian minister. He moved to Milton, Massachusetts, in 1846; however, he spent a great deal of time at his grandparents' home in Peterborough, New Hampshire. Family tradition had it that as a child he was a loner and did not seem to need friends his own age, being content to associate with adults. Family stories indicated that he frequently spent time in designing and building various mechanical toys, etc., and was independent and introspective.

At age 14 he went to Phillips Exeter Academy in New Hampshire, a school that his father and uncles had attended earlier. Even though the curriculum at Exeter emphasized the Classics, it did offer a significant amount of mathematics — a subject in which Morison excelled. After two years, he was accepted at Harvard University and began his studies, again in Classics, in 1859. His father graduated from Harvard, and it was thought that the young George might end up in the ministry like him. While at Harvard, he does not appear to have continued his study in mathematics and instead took the standard liberal arts curriculum, which included some science. He graduated ninth out of 121 students. As a student, however, his classmates would later write:

"that although the capacity of his mind and strength of his character were recognized



The Young George Morison.

they did not appreciate the fact that he was likely to become perhaps the most distinguished graduate of the class of 1863."[1]

The Civil War was in progress when he graduated and his father paid for a substitute so Morison would not be drafted and exposed to fighting. Instead, Morison went to St. Helena Island off the coast of South Carolina after it came under control of the Union forces in 1862. When Union troops took over the island, they found that most of the white plantation owners had already fled, leaving over 12,000 slaves who were now freemen. Many northern abolitionists came to educate the former slaves and help them run the plantations on their own. Morison spent a year on the island, and it is thought that he was involved in running one or more of the plantations. Part of the time it is believed he worked for the United States Sanitary Commission in northern Virginia.

He returned to Harvard in 1864 to study law. For the next two years, he was a successful student and won the prestigious Bowdoin Prize for best dissertation in his class.

Professional Life

He received a Bachelor of Laws degree in 1866 and went to work for the New York City law firm named Evarts, Southmayd and Choate, which was located at 52 Wall Street. He was admitted to the bar in New York State shortly thereafter. Evarts and Choate were Harvard Law School graduates and the firm was one of the most prestigious in the city, with a practice that spread across the country. Morison found that the practice of law was not to his liking and he noted that the law was "a heterogeneous mass of precedents through which cases were more often determined upon former decisions than upon the abstract merits."[2] He reflected on his situation, according to his nephew George A. Morison (whose memoir of his famous uncle furnishes most of the early history of the elder Morison). At the time, Morison came up with three alternatives for his future and entered them into his journal. These alternatives were:

- To continue the practice of law, and perhaps become a successful lawyer, which did not attract him at all;
- To study the theories behind the practice of law, and render signal service to his profession by formulating these theories either as a professor in a law school or elsewhere; or,
- To "relinquish the profession and enter without previous training the comparatively new profession of civil engineering, which with the development of our Western country, offered a unique opportunity to an original and ambitious mind."[3]

In order to reflect on his options further, he decided that, even though he was leaning to leaving the profession of law, he would wait until May 1, 1867, to make his final decision. On August 1, he resigned his position at Evarts, Southmayd and Choate and never returned to the practice of law. In the three months between his decision and resignation,

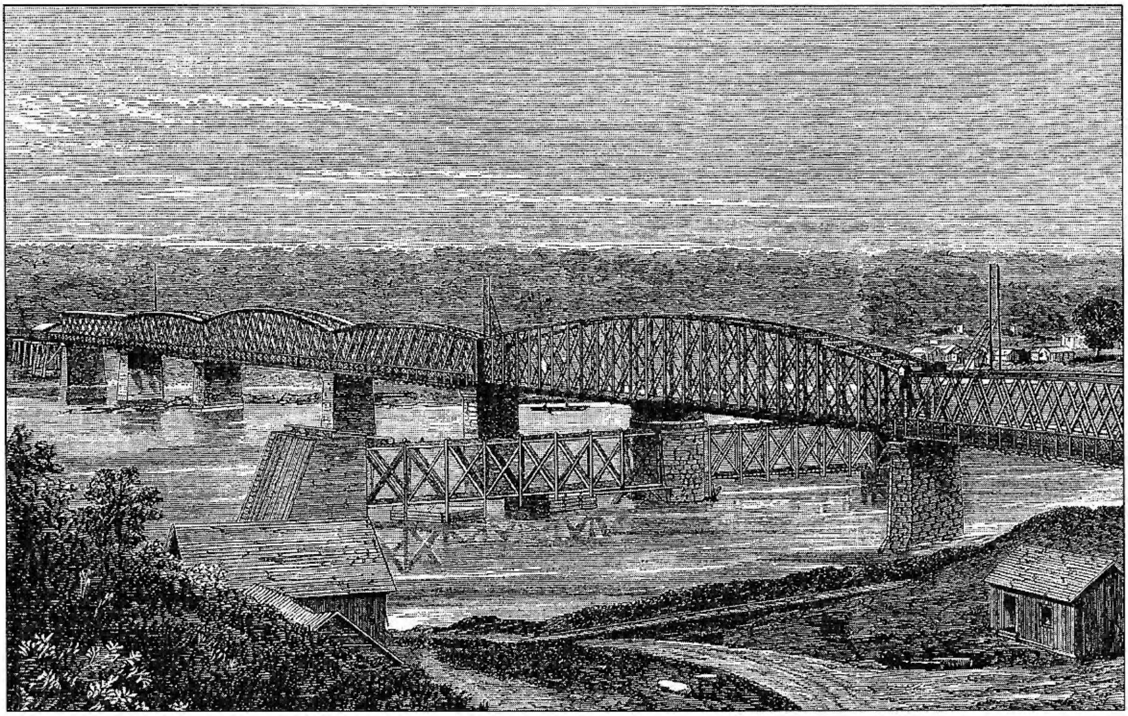


FIGURE 1. Kansas City Bridge 1869–1917.

he looked into potential openings in the field and identified people who could help him obtain his first job. There is little doubt that his colleagues in the law firm knew everybody who was anybody in the railroad business. His father also had contacts in Boston, and it was probably through them that he linked up with the so-called "Boston party." Members of the Boston party were financing projects of the Detroit railroad man James F. Joy, who was building extensions to the Michigan Central and the Chicago, Burlington and Quincy railroads in Illinois and Michigan. Octave Chanute was appointed Chief Engineer in January 1867 on the construction of a bridge across the Missouri River at Kansas City for the Hannibal and St. Joseph Railroad, one of Joy's subsidiaries. Joy wrote a letter recommending Morison to Chanute.

By an Act of Congress in July 1866, the bridge company was required to meet the same clearances as set forth for the Mississippi River bridges approved at the same time. If the bridge was to be a continuous span (no swing spans), it was required to be 50 feet above extreme high water, with all spans 250 feet long or greater, and piers parallel with the current. If the bridge had a swing span, it should be 160 feet clear on each side of the swing span pier, with adjoining spans not less than 250 feet in length. The spans had to be 30 feet above low water and not less than 10 feet above high water. These requirements were against Chanute's better judgment and he was forced to build the bridge with a swing span at 363 feet. He got some relief, however, from the War Department on the length of the adjacent spans and was allowed to build them at 134 feet and 200 feet instead of 250 feet (see Figures 1 through 4).

Prior to this project, the Missouri River had not been bridged, and the placement of foundations for piers in the turbulent river created many problems. Starting work on the foundations in the fall of 1867, Chanute developed techniques to design and place each pier foundation based on the different current and soil conditions found at each particular location. Between the fall of 1867 and May 5, 1869, work continued on the foundations when the masonry on Pier #2, the last of the five piers and two abutments, was completed. Chanute

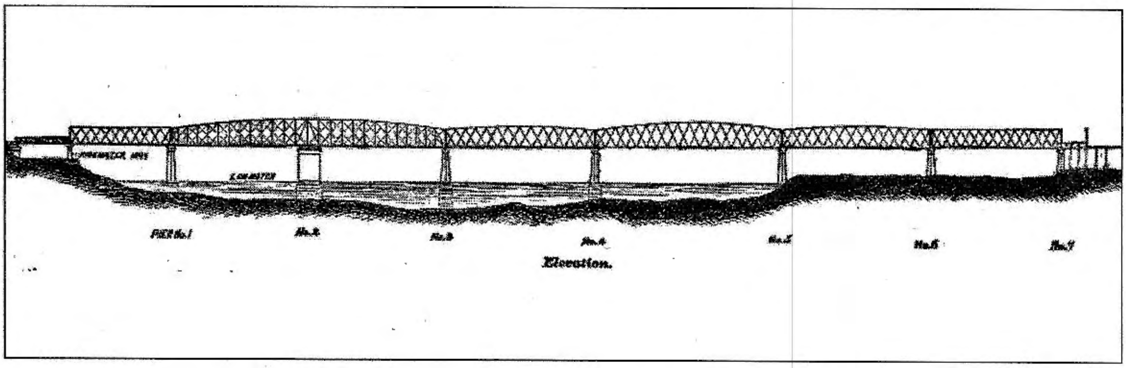


FIGURE 2. A profile of the Kansas City Bridge.

and another assistant engineer, T. Tomlinson, had completed designs for the fixed spans and thereupon in early August 1867 requested construction bids for the fixed spans based on either their design or designs proposed by the contractor. The contract to build the superstructure was awarded to Jacob Hays Linville and the Keystone Bridge Company on October 30, 1867.

Morison arrived at the project on October 16, 1867. He wrote in his journal:

> "took train to Kansas City; put up at Pacific House, a wretched place. Went to Kansas City Bridge office and presented my letters to Mr. Chanute, the Chief Engineer; he said he thought this a very poor place to learn, but in the afternoon he told me I might stay here and receive $60 a month and in the meanwhile consider whether it would be best to continue."[4]

Chanute may have remembered the day eighteen years previously when he approached the Chief Engineer of the Hudson River Railroad at Sing Sing, New York, with no letters of recommendation and no engineering education, saying that he wanted to be a civil engineer. When told there were no positions open, Chanute offered to work for nothing in order to learn the role of surveyor. The Chief Engineer later added him to the payroll and that marked the beginning of an illustrious career.

Chanute started Morison off measuring, for payment purposes, the volume of stone used in the masonry piers. Two days later, Morison was writing in his journal about this work, which he felt was "a simple and stupid task at which I suppose I must be kept for the present, it certainly does not furnish very good opportunities to learn engineering."[4]

However, even though the record is not clear just what Morison did to gain the confidence of Chanute, he advanced to the position of Assistant Engineer during the construction of the Missouri River bridge. There is little doubt that under the mentorship of Chanute and with a fair amount of self-study, Morison became a key member of the team. A month and a half after he began his civil engineering career, Morison began a program of study that would lead him to success. The program was:

> "To the end that my time may be spent with advantage, my mind improved, my professional standing bettered, and my life made a useful one, the following resolves are this day made:
>
> "*1st.* That my working hours (as far as they lie in my own choice) shall be from 8 A.M. to 6 P.M. while here in Kansas City, and that during these hours I will devote myself to the utmost to learn the practical work of an engineer.
>
> "*2nd.* That my evenings from 6:30 to 9:30 be devoted to study, not more than one evening in the week being ever excepted; my study to be systematic and thorough, and at least two-thirds of it to related to my profession.
>
> "*3rd.* That my Sunday be spent as a season of rest, my usual vocations, so far as by avoidance and anything but opposition it is

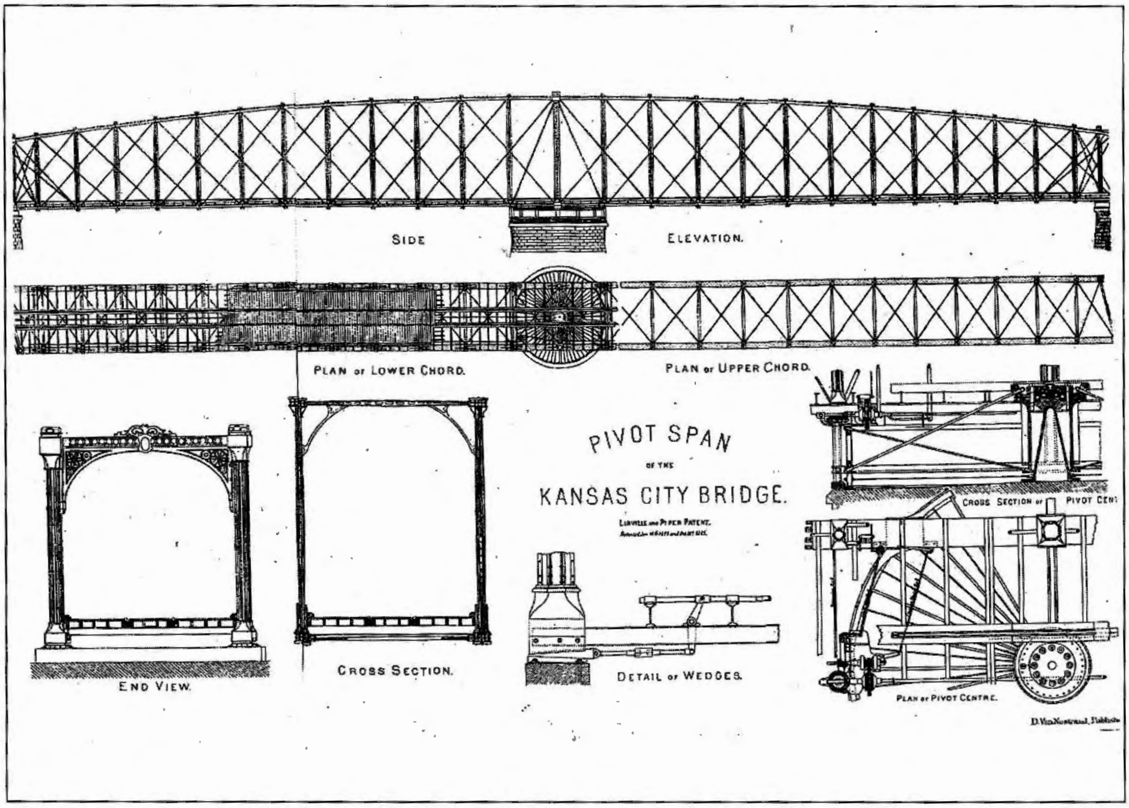


FIGURE 3. The swing span for the Kansas City Bridge.

possible, be suspended, and the day devoted to mental and religious study, to writing to friends, and to solitary walks with such other occupations as seem fitting to the day."[3]

There is reason to believe; given his ambition that he did follow these resolves. On the last day of the year he wrote in his journal:

> "And now with the close of this year this volume is concluded. It bears witness to wider changes than were ever anticipated when it was begun, and in whatever form my diary may be continued this will remain the record of the four years of doubt, vacillation and search which have formed the introduction to my life. How I am to succeed remains to be seen, but I sincerely hope and pray that the blunder which has wasted so much of these four years is to be expiated and that I may yet lead a good and useful life."[3]

For the next year and a half he worked on the construction of the bridge, which was opened for traffic and was dedicated on July 3, 1869. On that day *Engineering* quoted a Kansas City newspaper as follows:

> "Science and skill has woven from iron and stone a highway for the fleet feet of steam steeds. Massive in its great repose ere yet it has been starred thick with flags and electrified under the tread of the swart horse, steam-driven, it seems a monstrous genie upheaved from the restless river, and poised aloft in [seven] granite hands to be launched into the zenith of a nations' wonder, and fixed there a giant of skill, a mastodon of mechanism. It is a bridge of destiny. That network of iron bars was woven and interlaced by the cunning and skillful hand of Chanute, who embroidered upon the tawny tapestry of a grand old river, the grandest architectural picture of the century, and that bridge is standing

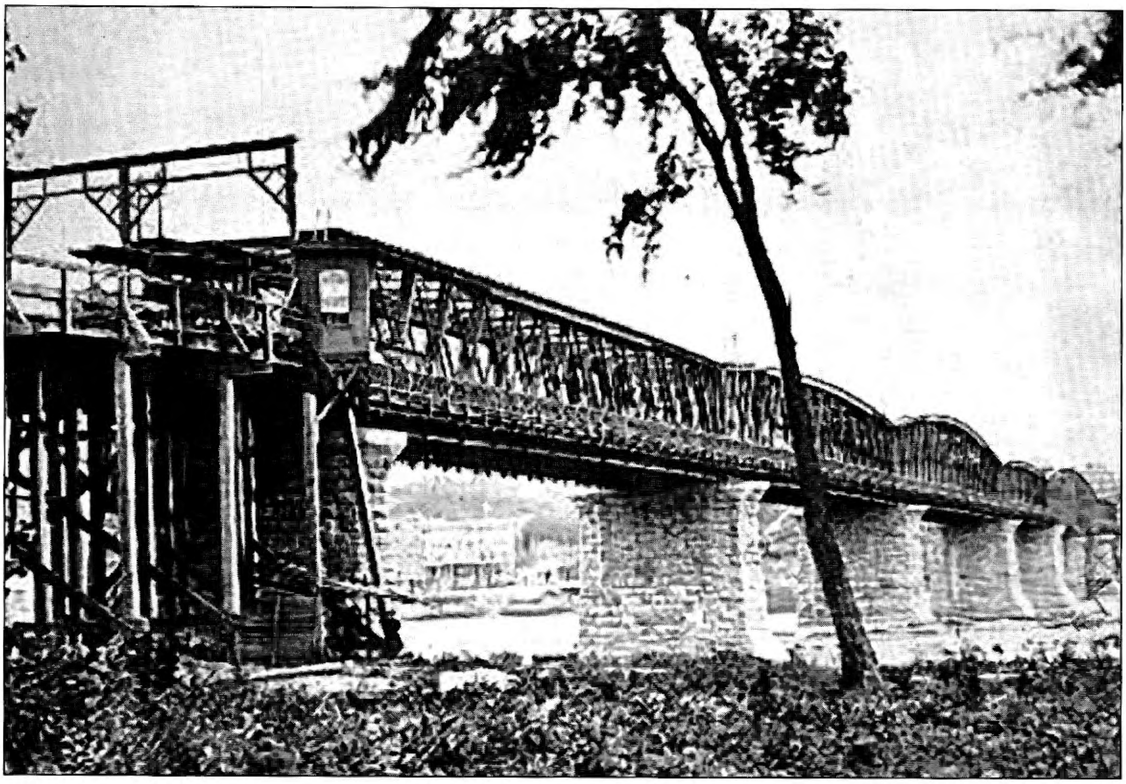


FIGURE 4. Looking towards Kansas City at the wood/iron trusses and the trestle.

there, the iron crown of Kansas supremacy."[5]

Chanute and Morison wrote of the bridge:

> "All the delays, difficulties and failures which took place were directly owing to the violence of the current, and its capacity for rapid scour. The precautions and watchfulness which these required, both by night and by day, were endless, and not always successful. The moods of the river were constantly changing, and its bottom and banks of most unstable regimen, thus causing no little anxiety and expense, while the absence of precedent in this kind of work, in this country, left the engineers to depend mostly upon their own resources."[6]

The bridge was set 47 feet above low water and 11 feet above high water. It was "constructed with a view to the allowing of buggies and wagons to pass over it when not in use by the railroads. There is a footpath along the side for its entire length... the roadway is 18 feet wide, and the footpath 4 feet."[7] The results of the test loading:

> "were entirely satisfactory, reflecting great credit on all concerned in its construction, especially upon the Chief Engineer, Mr. O. Chanute, who has shown the greatest scientific skill and administrative ability in its design and superintendence, and in successfully accomplishing the building of this, the first bridge across the Missouri River."[7]

Figure 5 shows Chanute and Morison and other engineers on the fixed span.

Descriptions of the bridge were carried in most of the engineering journals of the time with the most complete description being Van Nostrand's *Eclectic Engineering* magazine of September 1870 and *Engineering* (London) magazine on December 3, 1869.[5] In addition, Chanute and Morison prepared an illustrated report entitled, *The Kansas City Bridge*, which was published by Van Nostrand's in 1870.

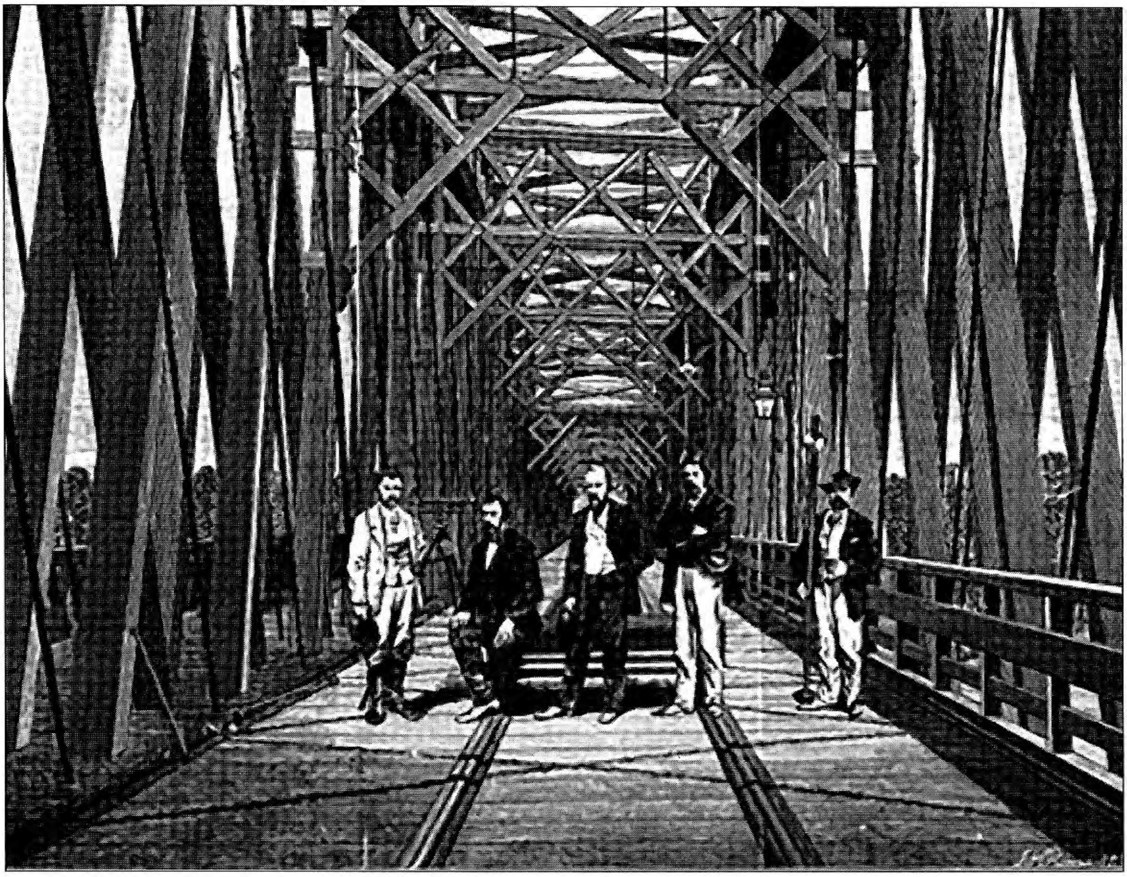


FIGURE 5. Chanute (center) and Morison (seated) on the fixed span of the Kansas City Bridge.

This report included an account of the regimen of the Missouri River, and the description of methods used for founding in that river.

Morison could not have found a better project, or a better mentor, to begin his career in civil engineering. A Kansas City newspaper reporting on the opening of the bridge noted that:

> "[t]he method employed in building this pier #4, which is a great triumph of engineering, was suggested by the Chief Engineer, Mr. Chanute, but the details were all worked out by a young Massachusetts man, Mr. G. S. Morison, who bids fair to take a high rank among civil engineers."[8]

Chanute was then named Chief Engineer for several railroads, called the "Joy roads" after that Detroit financer who promoted them. Morison accompanied Chanute as his assistant on the Leavenworth, Lawrence and Galveston Railroad where he remained until June 1871, leaving just before the line reached Coffeyville, Kansas. During his time on the Leavenworth line, he continued to learn from Chanute about railroad layout and construction. He continued his strict program of self-study and he took every opportunity to observe the work of, and study the plans of, other engineers who were working in the area. In July 1871, the Detroit, Eel River and Illinois Railroad gave Morison his first appointment as Chief Engineer. The line was initially designed to run from Ypsilanti, Michigan, to Logansport, Indiana, but it was built only through Indiana from Butler to Logansport. The line was completed in 1874, after Morison left in the spring of 1873. Apparently, even though it was an important

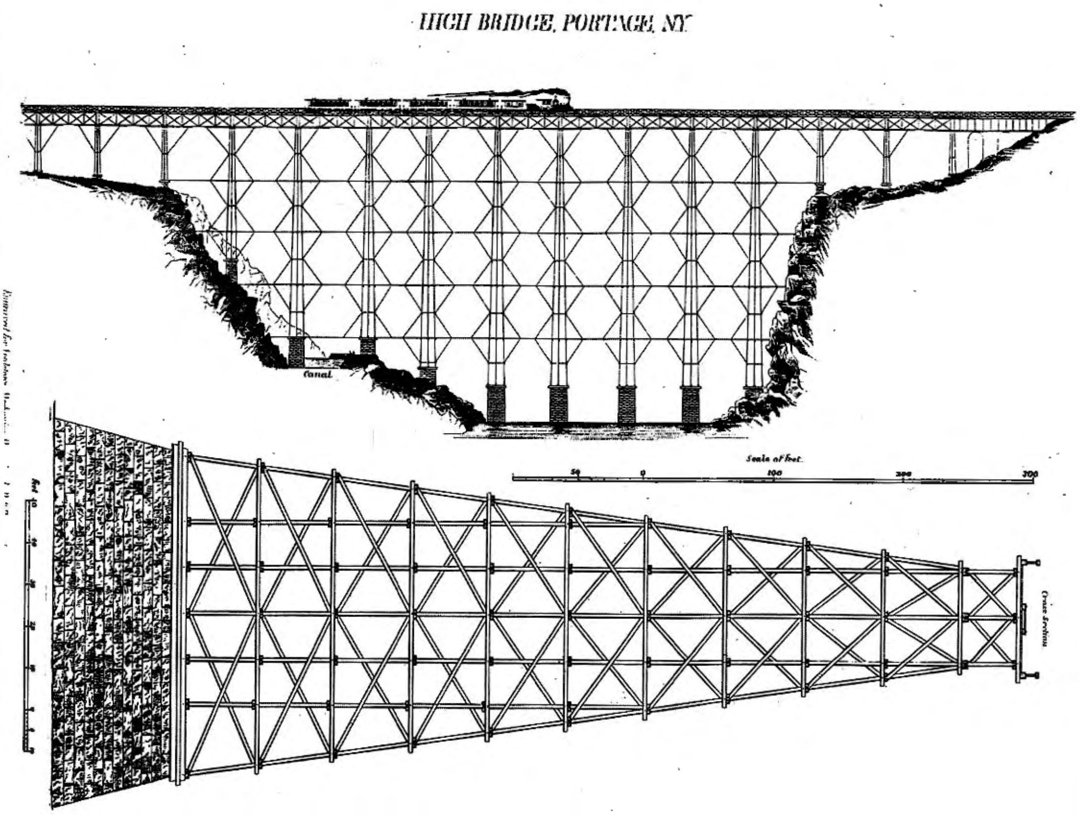


FIGURE 6. Seymour's portage viaduct across the Genesee Gorge.

position, Morison saw that the railroad was poorly managed and looked for another opportunity.

That opportunity came later in 1873 when Octave Chanute was named Chief Engineer for the Erie Railroad and asked Morison to be his chief assistant. At the time, when the Erie recruited Chanute, they planned a $50 million upgrade, with extensions to Chicago and Boston, including a major bridge over the Hudson River at Poughkeepsie, as well as double tracking and a change of gauge from 6 feet to the standard gauge of 4 feet 8.5 inches on the entire line. Shortly after Chanute and Morison arrived, however, the financial panic of 1873 made this plan impossible since an anticipated investment by English financiers disappeared. With only about $5 million in hand, they succeeded in changing the gauge, improving grades, double tracking and upgrading locomotives on the line, making it possible to increase the number of cars per train from 18 to 35. One of the first things Chanute did, with the assistance of Morison, was prepare a set of bridge specifications that bridge fabricators had to follow in proposing bridges for the Erie Railroad. They were not the first set of bridge specifications proposed, but they were one of the first.

A major challenge came on March 17, 1875, when a major ice jam took out the five-span double track bridge over the Delaware River near Port Jervis, New York. After building a temporary wooden bridge,

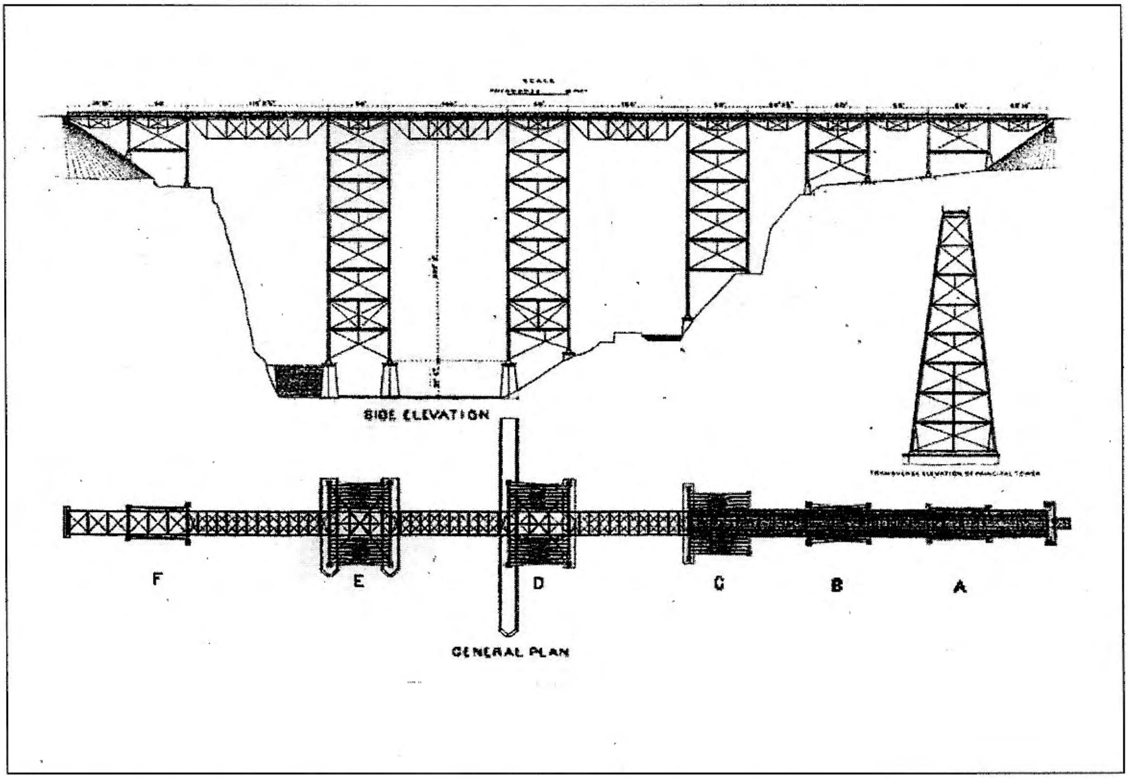


FIGURE 7. Morison's portage bridge replacement plan for the Genesee Gorge.

Morison, along with the Watson Manufacturing Company of Paterson, New Jersey, replaced the structure within forty days after its collapse. The next, and very similar, crisis was the replacement of the Portage Bridge, near Hornell, New York, over the Genesee River. The Genesee Gorge at the site was nearly 850 feet across and 234 feet deep. The massive wooden bridge that had been built across the gorge in 1851–52 by Silas Seymour burned on May 6, 1875 (see Figure 6). It appears from the record that Morison took the lead in designing and supervising the construction of an iron replacement span. Given the importance of the line, it was necessary to have a new bridge in place in the shortest possible time.

Morison described the process he used in designing the replacement bridge in his first published article, which appeared in the *Transactions of the ASCE* on November 27, 1875.[9] The Erie Railroad, probably at the suggestion of Chanute, made a decision to rebuild the bridge in iron, build new abutments and repair the piers. Morison cut the damaged piers back to sound masonry and encased some of them in concrete up to a new grade. At the same time, he designed new iron truss deck spans and new iron towers (see Figures 7 and 8).

The trusses were standard Pratt deck trusses and his iron towers were similar to other bridges that had been built around that time. What was significant about the bridge was the speed with which it was designed, fabricated, shipped and erected. A contract for the iron — once again with the Watson Manufacturing Company — was signed on May 10th. The first iron arrived at the site on June 30th and the entire structure was completed on July 29th, the track laid across on the next day and was tested under load on July 31st. The total elapsed time from the fire until the new bridge was open for traffic was eighty-six days. Of the design Morison wrote:

> "The plans of this viaduct were prepared in the hurry of a pressing necessity, and

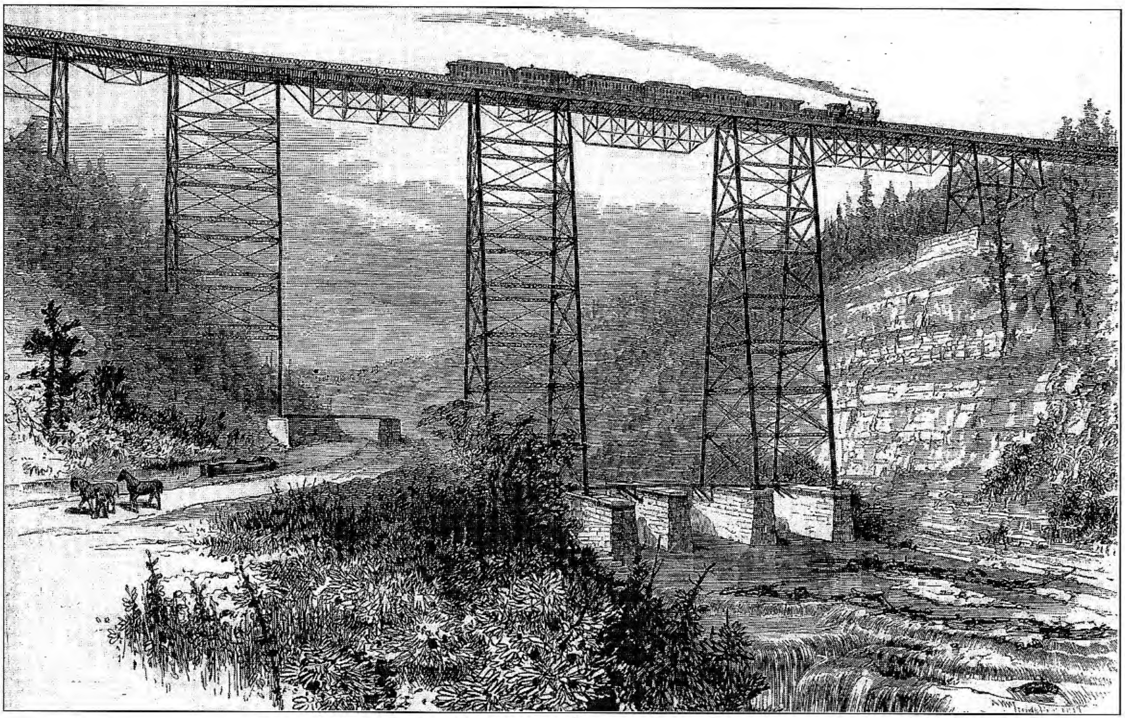


FIGURE 8. An engraving of Morison's replacement bridge for the Genesee Gorge.

were obliged to conform in a measure to the plan of the original timber structure. Had there been no masonry already standing it would have been preferred to place the two bents of each tower only 25 to 30 feet apart, [they were 50 feet apart] and so avoid the unusual length of the longitudinal struts. The main principle of the plan may be said to be that which characterized all American bridge building, and is the leading difference between the works of American and European engineering in the department; the concentration of the material into the least possible number of parts, a principle whose advantages are believed to be greater in large and lofty viaducts of the class of the portage bridge than in the construction of trusses of long span, to which it has been so generally and successfully applied."[10]

On His Own

Shortly after finishing the Genesee bridge, Morison left the Erie Railroad and formed a construction company with George S. Field named Morison, Field Company. Not much is known of the work completed by this firm, which was based in Buffalo, New York. Morison, apparently, gave little attention to the company, since he was now acting as a representative for the Baring Brothers & Co., a London financial institution. As was common at the time, British investors were stockholders in many American railroads. To protect their interests, they appointed men to serve on boards of the lines in which they invested. Morison was selected by Barings to sit on the board of the Eastern Railroad of Massachusetts between 1876 and 1888, the board of the St. Louis, Iron Mountain and Southern Railroad between 1876 and 1880, the Board of the Maine Central between 1877 and 1885, and finally on the board of the Ohio & Mississippi Railroad between 1884 and 1892. His work with Field and Barings over the next five years had him traveling over much of the country in order to observe work on the lines and to note the methods used in building and maintaining their bridges.

In 1880, Morison and Field terminated their relationship, with Field becoming a partner in the Central Bridge Company in Buffalo along with Charles Kellogg and Charles Maurice. In 1884, Maurice and Field formed the Union Bridge Company with Charles MacDonald and Edmund Hayes and located their manufacturing plant in Athens, Pennsylvania. Field and the Union Bridge Company became the fabricator of choice for many future Morison bridges.

Starting in 1880, Morison — now primarily a consulting engineer — received major contracts to build bridges over the Missouri, Ohio, Columbia, Snake, Des Moines, St. Johns and Mississippi rivers. Over the previous thirteen years, he had visited many of the major bridges built over the Missouri and Mississippi rivers. He saw T. C. Clarke's Quincy Bridge and Linville's Dubuque and Keokuk bridges over the Mississippi, as well as C. Shaler Smith's St. Charles Bridge over the Missouri. Following the Kansas City Bridge, the Missouri was crossed upstream at Leavenworth in 1871, St. Joseph in 1873 and Atchison in 1875. Over that same time period, Jacob Hays Linville led the move to change from combination cast and wrought iron bridges to all wrought iron, using his Keystone column sections for all compression members of the truss. Most bridges built were to Whipple's double intersection truss pattern, with the exception of the Omaha Bridge over the Missouri built by the American Bridge Company to the S. S. Post patent. It is not known if Morison visited Linville's bridges over the Ohio River at Steubenville, Parkersburg, Benwood or Cincinnati (where Linville used wrought iron almost exclusively for both his tension and compression members). Most importantly, for future projects, Morison had seen the Glasgow Bridge built in 1879 by General Sooy Smith over the Missouri in which he, for the first time, used steel as his bridge material. At the time, the use of steel was considered to be a major experiment. Morison learned from Chanute to make sure that he knew what other men had done previously and to only change methods or materials if the site and economics indicated that the owner would receive additional value in his structure from those changes. A listing of Morison's major bridges over the next fifteen years is shown in Table 1.

Morison's first contract for a major bridge of his own design and construction came when the Chicago, Burlington & Quincy Railroad (CB&Q) determined it needed a bridge across the Missouri River at Plattsmouth, Nebraska (about 80 miles north of the Kansas state line and just south of the junction of the Platte River with the Missouri). Charles Perkins of the CB&Q contacted him in February 1879 (when he was still associated with George Field) to visit Plattsmouth and determine the best location for a bridge. Earlier, two other engineers had prepared designs for a low-level bridge with a swing span and each picked a different site. Morison recommended a third site and a preliminary design and estimate for a high-level bridge to the company. Later in May, he was authorized to prepare construction drawings based on his preliminary design. For this bridge, he appointed C. C. Schneider as one of his assistant engineers. Schneider became the first of many Morison assistants to go on to very successful careers in bridge building on their own.

Morison's design was for two 400-foot through spans with three 204-foot deck spans (see Figure 9). The high spans had a clearance of 50 feet above high water. Pneumatic caissons by General Sooy Smith were used to place foundations for Piers II and III. (Sooy Smith had just finished the Glasgow Bridge and used the same equipment he used on that bridge for the Plattsmouth Bridge.) The other piers were either on piles or concrete footings. On the two channel spans, Morison used steel for his top chords, inclined end posts, lower chord links, counter ties and lateral rods. He used wrought iron for the rest of his members and for the 200-foot deck spans. The Keystone Bridge Company fabricated the iron and steel for the long spans and Kellogg and Maurice supplied the iron for the 200-foot spans and viaduct.

Upon completion, as he and Chanute did with the Kansas City bridge, Morison wrote a complete book on the design and construction of the bridge, which was tested and opened on August 30, 1880. A team of engineers —

TABLE 1.
Morison's Major Bridges

Year	Location	River	Main Spans (# @ feet)	Truss Type	Material*
1880	Plattsmouth, Missouri	Missouri	2@400	Whipple	WI & Steel
1882	Bismarck, North Dakota	Missouri	3@400	Whipple	60% WI
1883	Blair Crossing, Nebraska	Missouri	3@220	Whipple	
1884	Ainsworth, Washington	Snake	4@248, swing 346	Pratt	
1884	Belknap, Montana	Columbia		Whipple	
1884	Marent Gulch, Montana	Marent	3@140, 2@128.33	Pratt	WI
1887	Omaha, Nebraska	Missouri	4@246	Whipple	
With Corthell					
1888	Sioux City, South Dakota	Missouri	4@400	Whipple	
1888	Nebraska City, Nebraska	Missouri	2@400	Whipple	
1889	Rulo, Nebraska	Missouri	3@375	Whipple	90% Steel
1889	Willamette, Oregon	Willamette	1@325, swing 340	Whipple	Steel
1889	Cairo, Illinois	Ohio	2@518, 7@400	Whipple	Steel
1889	Riparia, Washington	Snake	3@325, swing 324	Whipple	Steel
1890	St. Louis (Merchants)	Mississippi	3@520	Pennsylvania	Steel
Without Corthell					
1890	Jacksonville, Florida	St. Johns	4 fixed, 1 swing		
1891	Winona, Montana	Mississippi	1@360, swing 440	Parker	WI
1893	Bellfontaine, Missouri	Missouri	4@440	Baltimore	
1893	Leavenworth, Kansas	Missouri	2@320, swing 450	Parker	
1893	Burlington, Iowa	Mississippi	6@248, swing 356	Whipple	
1893	Memphis, Tennessee	Mississippi	1@621, 1@790	Cantilever	Steel
1894	Alton, Illinois	Mississippi	1@360, swing 450	Pratt	Steel
1898	Atchison, Missouri	Missouri	3 fixed, 1 swing	Pratt	Steel
1901	Boone, Iowa	Des Moines	1@300, 39 girders		Steel

Note: *WI = Wrought Iron

including Charles MacDonald of the Union Bridge Company — witnessed the test loading and inspected the bridge. MacDonald noted that:

> "I was impressed with the accuracy of the workmanship, and the symmetry and beauty of the structure as whole. I take pleasure in offering my congratulations upon the successful completion of this fine work."[2]

With the success of the Plattsmouth bridge, Morison established himself as one of the leading bridge engineers in the United States. His reputation led to contracts to design the Bismarck Bridge in North Dakota, the Blair Crossing Bridge in Nebraska (both bridges

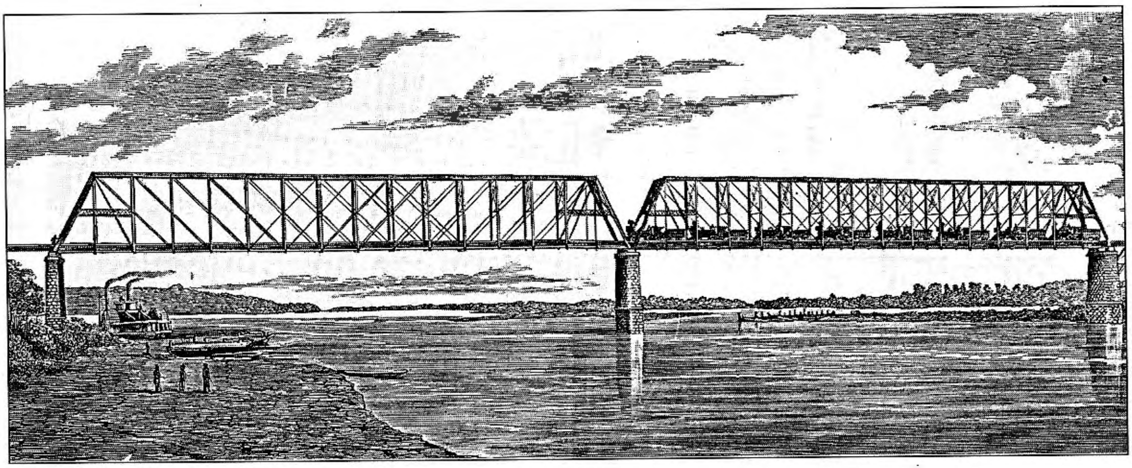


FIGURE 9. Morison's Plattsmouth bridge.

crossed the Missouri River). He also built his second viaduct, the Marent Gulch Viaduct in Montana, as well as bridges across the Snake and Columbia rivers before being given the job of rebuilding the Omaha Bridge.

In February 1887, he was asked by the Illinois Central Railroad to review the design for a bridge across the Ohio River at Cairo, Illinois, just above its intersection with the Mississippi River. On this project, he worked with a classmate from Philips Exeter, Elmer Corthell. Corthell went to Brown University to study for the ministry but like Morison changed his career to that of civil engineering. Cothrell worked with Captain James Eads on the jetties at the mouth of the Mississippi River and on plans for Eads's great ship railway across the Isthmus of Tehauntepec. Cothrell later worked on the bridge across the Mississippi River at Louisiana, Missouri. Both Cothrell and Morison, along with George Field, inspected the site and submitted a final report on March 23. What they recommended turned out to be the longest bridge in the world at that time, with fifty-two spans of Whipple trusses for a total length of 10,560 feet, and with a height above high water of 53 feet. Two spans were 518 feet long, making them the longest spans in the United States and only 18 inches longer than Jacob Hays Linville's span at Cincinnati across the Ohio River. Morison was designated Chief Engineer shortly after submitting this report. The spans for this bridge were the longest Whipple spans ever built and at that length showed a noticeable loss in rigidity.

Working With Cothrell

In April 1887, Morison and Corthell established a partnership that lasted for two years — until May 1, 1889. Morison moved from New York City to Chicago and set up a new office with Corthell. After preparing the plans for the bridge, he left Corthell in charge and took a six-month tour around the world with his sister, returning in February 1889. Before leaving he also prepared designs for bridges at Sioux City, South Dakota; Nebraska City, Nebraska; Rulo, Nebraska; and a bridge over the Willamette River near Portland, Oregon. Corthell, with the aid of his assistants, worked on all of these bridges.

When the Cairo Bridge was being constructed, the efficiency of design and erection by Morison and his team was evidenced when they built one of the 518-foot spans in just over four days. The journals of the time published photographs of the construction with the time of day the photos were taken. When completed on October 20, 1889, it was the largest and one of the most expensive bridge projects of the period — costing over \$2.6 million. The *Memphis Appeal* noted the bridge "spans the Ohio River at its broadest point. It is indeed one of the wonders of the world, a work that fills the beholder with amazement, so extraordinary is the demonstration of man's ability to overcome natural obstacles."[2]

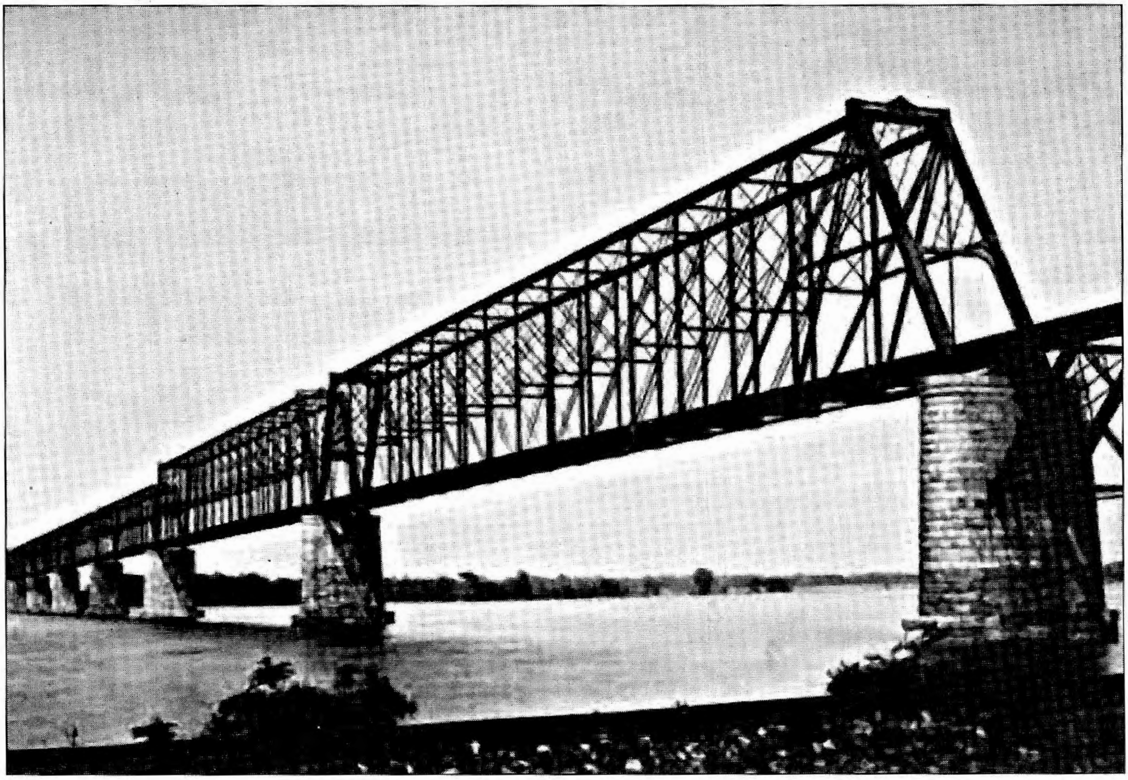


FIGURE 10. The Cairo Bridge.

The last project Corthell and Morison worked on together was the Merchants Bridge across the Mississippi at St. Louis just downstream from the Eads Bridge. Its three main channel spans carried twin tracks and were approximately 521 feet long, compared to the 502-, 520- and 502-foot spans of the Eads Bridge. For the first time, Morison and Corthell adopted the use of broken chord Pennsylvania trusses. The Union Bridge Company built the main spans and the approach spans were built by the Phoenix Bridge Company. The bridge opened in May 1890 after the partnership of Morison and Corthell was mutually dissolved.

On His Own Again

While Morison built many other major bridges (as shown in Table 1) perhaps his greatest bridge was the huge cantilever bridge over the Mississippi River at Memphis, Tennessee. It was clear to many in the 1880s that the Memphis area needed a railroad bridge across the river if it were to continue as a hub for goods moving from Kansas City to the Atlantic coast and back. There were already ten railroad lines entering the city from the west and east.

In late 1884, two corporations submitted a request to the U.S. Congress for authorization to build a railroad bridge at Memphis. The act called the "Casey Young Bridge Bill" was passed and granted the two companies — the Tennessee and Arkansas Bridge Company and the Tennessee Construction and Contracting Company, organized separately as private corporations in Arkansas and Tennessee — the right to build a bridge. The authorization was approved on February 26, 1885, with the following conditions:

- "The bridge is to be built with unbroken and continuous spans (in other words no swing spans).
- "The length of the channel spans (two in number) were not to be less than 550 feet.
- "No span shall be less than 300 feet.

- "The lowest part of the superstructure shall be no less than 65 feet above extreme high water."[11]

The two companies approached Morison about their bridges in 1886 before he started construction on the Cairo Bridge. Morison, based on preliminary information, "contemplated crossing the river with two long spans having a double pier on a single foundation in the middle of the river."[11] Throughout 1886, Morison took borings and worked on the design of foundations for the bridge and its superstructure. In February 1887, he submitted a report to the bridge company for a bridge with three 660-foot-long simple spans and a preliminary plan for a 1,300-foot cantilever span. This design would make the cantilever span the longest in North America and second only to the Firth of Forth Bridge, which was then under construction. The three-span proposal would cost $1,546,800 and his cantilever would cost $1,599,600. The three spans would be regular parallel chord trusses. Of these trusses Morison said:

> "While these dimensions are greater than those of any trusses yet built, they are entirely within practicable limits and not so great an undertaking now as 400 feet spans were twenty years ago."[11]

For the cantilever for the Cairo Bridge, he envisioned a Firth of Forth type cantilever, but built with American methods. He wrote:

> "I have estimated on making the cantilever 150 feet deep at the ends and building them with curved upper and lower chords, the masonry to finish ten feet above high water. This arrangement is not strictly in accordance with the requirements of the charter hitherto granted; it gives the required height [65 feet] for a distance of about 400 feet at the center, but this height is reduced at either side…
>
> "To secure lateral stability I have proposed to put the cantilever trusses 75 feet apart at the base and to build them in inclined planes, these planes to be put 15 feet apart at the highest point."[11]

He proposed making his anchor spans 375 feet long. His final conclusion was:

> "comparing the two structures when once completed, I think the three span bridge would be the better one for the railroads. It would be a perfectly simple structure, the expense for maintaining which would be a minimum. It would involve no complicated details, and as it consists of simply straight trusses resting on masonry piers, [it] would be subject to a minimum degree of disturbance should any slight settlement occur in the foundation. In brief, it would fulfill the universal requirement that the simplest structure is the best."[11]

Troubles with the original charter required that a new company, the Kansas City and Memphis Railway and Bridge Company, be formed. This company then went back to Congress in the winter of 1886-87 with a request for authorization to build the bridge. Congress denied the company's request. The company refiled the following year, and even though the charter was revised, it was revised in the wrong direction. The charter, approved on April 24, 1888, required that:

- "The bridge shall be made with unbroken and continuous spans.
- "The main channel span shall in no event be less than seven hundred feet.
- "The lowest part of the superstructure of said bridge shall be at least 75 feet above extreme high-water mark."[11]

The charter change thus increased the minimum span length and raised the clearance height by ten feet.

The authorization act appointed "three engineer officers from the Engineers Bureau to be detailed to the duty of examining, by actual inspection, the locality where said bridge is to be built and to report what shall be the length of the main channel span and of the other spans."[11] The board of engineers consisted of Col. W. E. Merrill, Major O. H. Ernst and Captain D. C. Kingman. They visited the site with Morison and after due deliberation could not agree on a span length. The two junior officers recommended a span of 1,000 feet and Merrill, the more experienced of the three and author of a book entitled *Iron Truss Bridges for Railroads* (published in 1878), recommended 700 feet. The Secretary of War, William Endicott, made his own decision, which was for "a clear width of 730 feet, at all stages of water."[11] He also wanted the bridge to handle "wagons and vehicles of all kinds [and] for the transit of animals."[11] Morison took Endicott's suggestion and made his channel span 790 feet with two side spans of 621.5 feet and added provisions for wagons and animals. His 790-foot span would be built as a cantilever, with all other spans being built on falsework. Morison wrote that the cantilever span "could have been built on falsework, but it could not have been raised until the fall of 1892, and this delay would practically have made nearly a year's difference in the earning capacity of the bridge."[11]

Morison knew this plan was not ideal and wrote that:

> "the arrangement that would have been most satisfactory to the engineer would have been three equal spans of about 675 feet each. If however, one span of extra length was required it would have been preferable to place it at the center, making this central span a cantilever structure, the cantilevers projecting from the ends of two heavy side spans. The arrangement required by the War Department, however, placed the long span next to the east shore, so that if this plan was built as a cantilever span it was necessary to provide an independent anchorage on the Memphis Bluff."[12]

His next decision was to determine the width of the span. He knew the bridge was had to be designed to handle one line of track and wagons; therefore, he knew his minimum width but what width was necessary to give the span the lateral stiffness to resist wind loading? He wrote:

> "The principal limit in determining this was the length of the central span. In the matter of transverse stiffness the position of this span corresponded with the separate spans of a common bridge; whereas, the longer span by its cantilever construction was held rigidly at the ends. The central span being 620 feet long, it did not seem wise to make the width between the trusses less that 30 feet. This corresponded with widths which have been adopted with good results in shorter spans. The channel spans of the Cairo Bridge are 518.5 feet openings and the trusses placed 25 feet between centers, the ratio between length and width being almost exactly the same as between 621 feet and 30 feet. A width of 30 feet was adopted."[12]

It appears, therefore, that the width was determined mostly by past practice and an intuitive feel for what was an appropriate value. The final information needed to complete the design was the truss pattern to be used, the loadings and the grade of steel to be used for each part. Morison chose a double-intersection Warren pattern since he thought it had "advantages in the manner in which it sustained the upper chords from which the work would be done."[12] This bridge would represent the first time he did not use the Whipple double-intersection truss pattern in any of his long-span bridges. He chose steel but of three different grades. He required "highest grade steel" with a minimum elastic limit of 40,000 psi for all the principal truss members, "medium steel" with a minimum elastic limit of 37,000 psi for the rest of his deck and members, and "soft steel with a minimum elastic limit of 30,000 psi for rivets and in locations where wrought iron was specified."[11]

With these design assumptions, he had to make the truss determinate so that he could find the reactions necessary to begin his truss design. The bridge was to be continuous over five supports so he needed to insert two pins in the structure. One was at the end of the easterly cantilever arm and one was at the end of the westerly cantilever arm. The truss between these pins was continuous. The continuous truss would be fixed at Piers I, III and IV and rest on expansion rollers on Pier II, and links at the end of the easterly anchor span (see Figure 11).

After completing the design, Morison sent out a very detailed specification for various

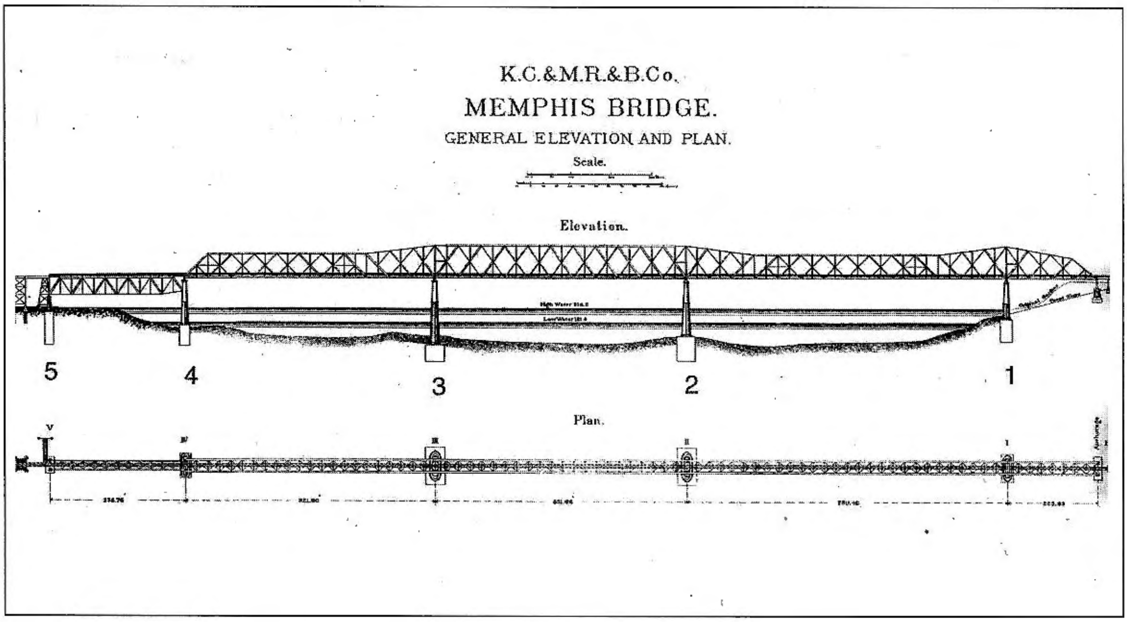


FIGURE 11. Plan for the Memphis Bridge.

bridge companies to bid on. The specification required that the contractor:

> "will be expected to verify the correctness of the plans, and will be required to make any changes in the work which are necessitated by errors in these plans, without extra charge, where such errors could be discovered by an inspection of the plans."[12]

Work did not start until late in 1888 when the company authorized Morison to build one pier because "the information to be obtained by sinking this pier might be of assistance in preparing the plans for the other piers."[11] Morison appointed Alfred Noble, who was then in the process of finishing the Cairo Bridge, as his resident engineer. Full-scale work was authorized to begin on January 1, 1889. While foundation work continued, the company went back to Congress to request that the 75 feet clearance be reduced to 65 feet. Morison prepared a report supporting the adequacy of 65 feet. He looked at the previously specified clearance on the Ohio River (which was 53 feet), the clearance on Eads's Bridge just upstream (which was 50 feet) and the height of pilothouse and stack on all steamboats then using the Mississippi River. He further argued the additional 10 feet of clearance would increase the heights of fill on the Memphis side, lengthen the approach on the Arkansas side and require locomotives to work harder getting up the slope, particularly from the west. All of these arguments were for naught and the 75-foot clearance remained part of the charter. The bridge profile required a 2,290.6-foot-long iron viaduct and a 3,097.5-foot-long wooden viaduct to get from the bridge deck elevation to existing grade on the Arkansas side of the river (see Figure 11).

The foundations were a major part of the project but with his pneumatic equipment, which was tried and tested successfully on the Missouri River and Ohio River bridges, along with an experienced work-force, Morison was able to sink the deepest pneumatic caissons in the country (with the exception of James Eads's caisson on the east end of the St. Louis Bridge). His maximum caisson tip depth was 130.5 feet below high water, or 5 feet less than Eads and about 50 feet deeper than Roebling at Brooklyn (the Manhattan caisson). For the first time, Morison, in order to prevent scour around his caissons wove together large mats (240 by 400 feet) of willow branches that had been wired together and sank them to the bottom with rocks. The mats were positioned so that the caissons would be installed in the center of the mats. The caisson easily penetrated the mats. When the caissons were completed, stone rip rap was placed on the mats to prevent future scour.

The superstructure contract was awarded to the Union Bridge Company, which, along with the Baird brothers, once again did the erection. The last phase of the project, namely the connection and "swinging free" of the suspended span of the main cantilever truss, took over two weeks and was a cause of some concern for Morison and his erectors. In Morison's own words:

> "the removal of all appliances from the west half span not only caused the free end to rise above the elevation intended, but, by reducing the strains in all members, caused the free end of the upper chord to be about 1 inch west of the place expected. On the other hand, the time required for erecting the span was greater than expected, so that the connection at the center was made much later in the season and at a higher temperature than had been assumed. These two changes in condition almost balanced each other... When the half spans met at the center they were so nearly the same elevation that little difficulty was met in driving the center pins of the upper chords, which closed the span and completed the connection between the upper chords and the web systems."[12]

However, this phase was the easy part. Taking the erection pins out at the ends of the lower chords of the suspended span proved to be much more difficult. These pins had to be removed to "swing" the suspended span. Morison admitted that he made a mistake when he calculated "the final position of the half span... [with] the erecting outfit of traveler, engines, lines and scaffolds... [remaining] on it until the span was swung."[12]

It is hard for us to imagine the problems they had in causing a little more than 4 inches of movement in a structure of over 700 feet in length and weighing over 7.5 million pounds. They had to rely mostly on temperature, but in the end it was the effective force that they put on a specially built toggle that resulted in the motion that loosened the erection pins at the east and west end of the suspended span.

The bridge officially opened on May 12, 1892, when the testing of the bridge was completed. The tests were made with eighteen locomotives placed on the deck at various locations. The tests were successful, with minimal deflections under the worst loading conditions.

Morison, evidently anticipating some criticism of his bridge by his colleagues, wrote:

> "In many respects the design of the superstructure may be criticized as not strictly economical. This is admitted, but such criticisms are ill-considered unless they include, not merely the metal in the superstructure, but all the material in the piers and masonry. The substructure of the bridge, which under the present design cost more than the superstructure, would have been rendered much more expensive by those changes which mere economy of superstructure design called for.
>
> "In the design attention was everywhere given to stiffness as well as to strain. This is a matter to which too little attention has been given, and which has often been overlooked in competitive designs. It is perfectly possible to design a structure in which no metal under any ordinary supposition will be over-strained, and yet without such overstrain vibration can exist which would be utterly inadmissible. This may occur in trusses of extreme depth, and also in structures with cantilever details in which loose fitting is permitted at expansion joints."[12]

The structure they erected was a 2,256.37-foot-long bridge, plus a 338.75 deck span on the westerly side of the river and long approach spans on each side of the river. The construction time from the beginning of the placing of the first caisson on December 21, 1889, to the end of steel erection was two years and four months. The total cost of the bridge (including approaches) was $2,542,365.45. Morison designed and built the longest cantilever span

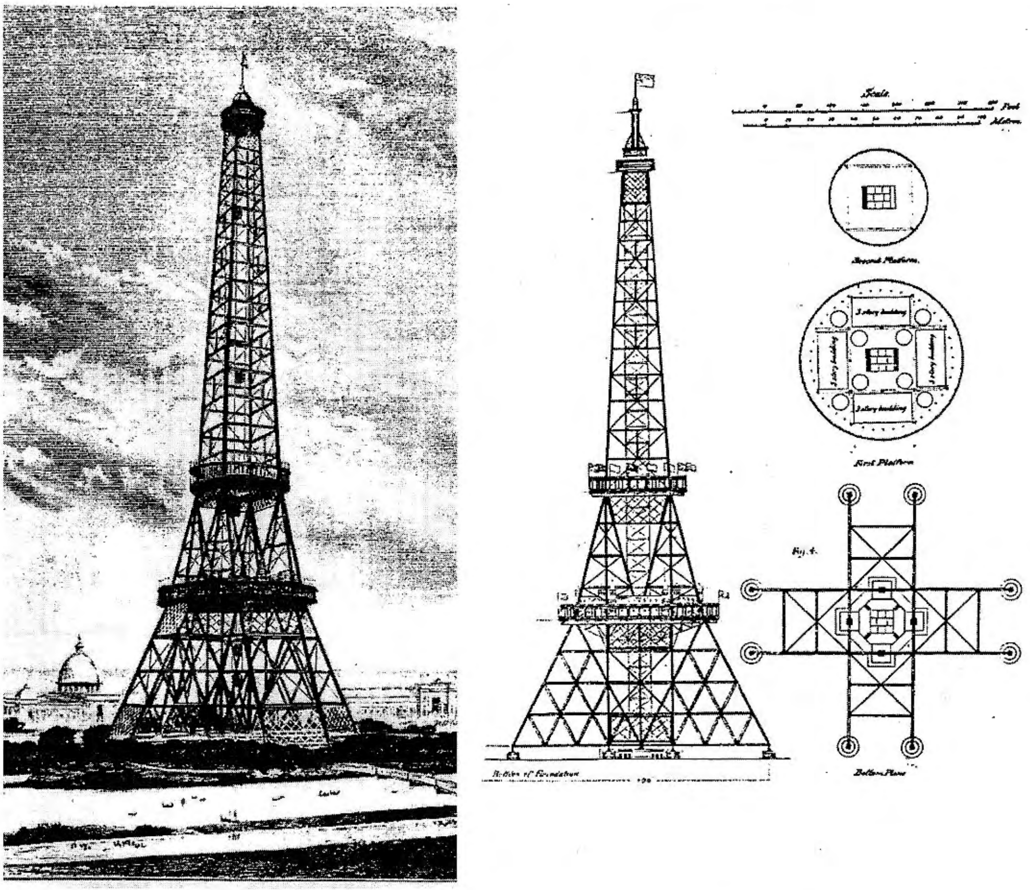


FIGURE 12. The Columbian Exposition tower.

in the United States and would hold this distinction for twelve years until the Monongahela River Bridge, with its 812-foot cantilever span, opened on 1904, despite a serious collapse during its construction. Morison held the record for a single span truss bridge as well as the longest cantilever. The *Railroad Gazette* called it:

> "one of the greatest bridges of the world, one that is remarkable not only for the length of the span, but for the depth of the foundations, the originality of the methods used in erecting them, and for the simplicity and skill in its design. No bridge anywhere nearly as remarkable has ever been so quietly built."[13]

Columbian Exposition Tower

Noting the success of Gustav Eiffel's 324-meter-high tower at the 1889 Paris World's Fair, the organizers of the Columbian Exposition, scheduled for Chicago between May and October 1893, solicited proposals for a tower of equal or greater height. Many proposals were submitted, but the organizers required that the proposers prove that they had the financial means to build, run and remove their tower. After it was clear that no one had submitted an acceptable proposal, Morison organized a group of men — including Andrew Carnegie, the Keystone Bridge Company and others, called the American Tower Company — to submit a proposal in October 1891 for a 1,120-foot tower that they indicated could be built for $1.5 million and in time for the exposition (see Figure 12).

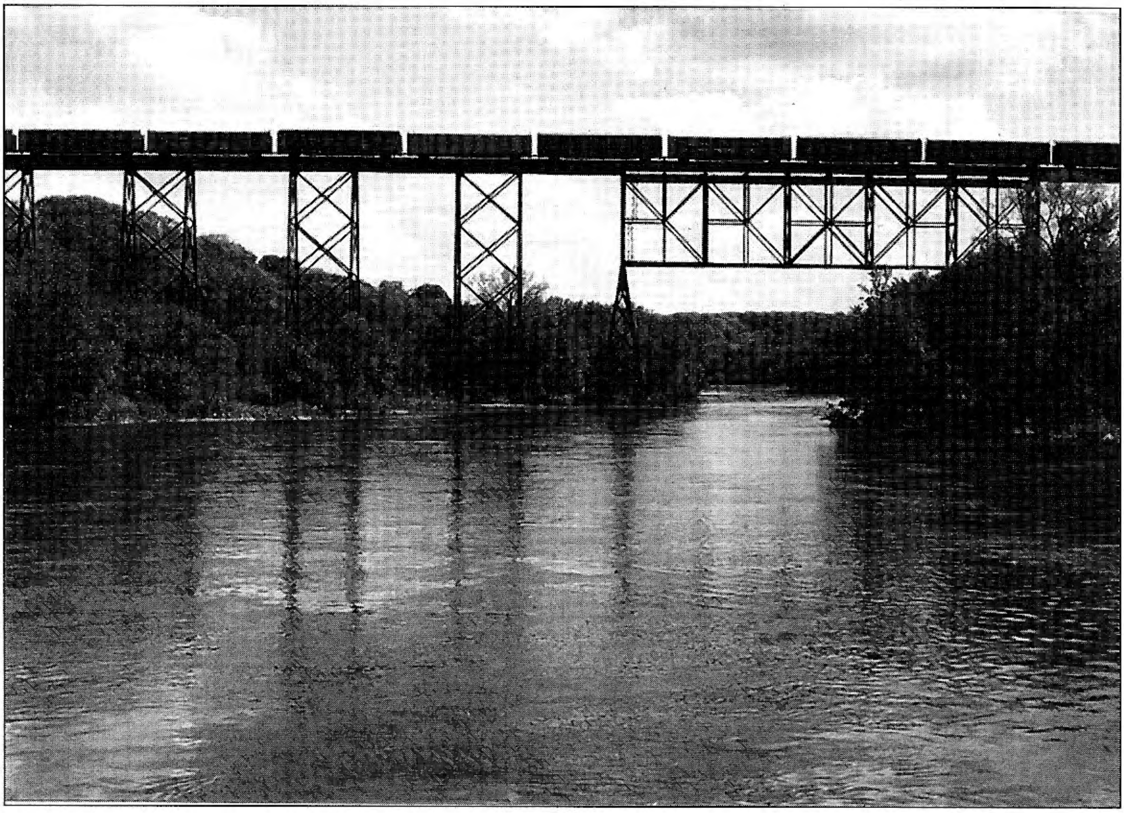


FIGURE 13. The Kate Shelley Bridge over the Des Moines River.

The tower consisted of a central concrete core that housed eight elevators and that was flanked by a steel framework starting with a Greek cross 400 feet wide at the base and tapering to 40 feet square at the lantern. The main circular concession platform was at 200 feet above grade; the second platform was 400 feet above grade. Morison estimated that 75,000 people a day would go up the tower and yield a total of $4 million in income in admission fees over the duration of the exposition. After an early show of interest by financiers, it was clear that Morison and his group could not get the project bankrolled. Instead, the iconic structure of the exposition would be George Washington Ferris's giant wheel.[14] Even though he did not build his tower, Morison was one of the leaders of the American Society of Civil Engineers (ASCE) who planned the International Engineering Congress at the exposition and to which he presented a paper on his Memphis Bridge superstructure.

As a resident of Chicago and one of the leading advocates of steel in structures, it was not a large leap for Morison to propose a design for the highest structure in the world at that time. As in many endeavors, however, mega-structures need a large influx of money to build and that influx just was not available.

Later Works

The financial panic of 1893 slowed down bridge and railroad construction around the country. Morison only built the Alton Bridge in 1894 over the Mississippi River and his Atchison Bridge, to replace a pontoon bridge, over the Missouri River in 1898. Three years later, he built his greatest viaduct over the Des Moines River — now called the Kate Shelley Bridge (see Figure 13). The bridge is 186 feet high and consists of thirty-nine deck plate girders (for a total of 2,386 feet in length) and the main span (a deck pin truss) is 300 feet in length. With the completion of this bridge in 1901, Morison finished his river bridge building career in the Western United States. However, starting in 1894 he spent most of his time serving on Boards of Engineers in New York and Washington, D.C.

Hudson River Bridge

After several proposals and several proposed locations, an act was finally passed by Congress in 1894 authorizing the New York and New Jersey Bridge Company to build a bridge between 59th and 60th streets across the Hudson River. The act included a stipulation that the War Department had to approve the structure. Gustav Lindenthal's North River Bridge Company had also been approved by Congress to build a bridge across the river here but lacked the financial backing to proceed. The act requested President Grover Cleveland to appoint a board of "five competent, disinterested expert bridge engineers, to recommend to the Secretary of War 'what length of span, not less than 2,000 feet, would be safe and practicable for a railway bridge across the Hudson River between 59th and 69th Street.'"[15] The five men selected were: William Burr, Morison, Theodore Cooper, L. G. F. Bouscaren and Major Charles W. Raymond. Raymond represented the United States Army Corps of Engineers and was required to sit on the board; he was also appointed chairman. The civilian members of the board were all acknowledged leaders of the profession and Raymond compiled a fine record with the Corps of Engineers. Prior to the appointment of this board in early January 1894, the Secretary of War also appointed a Board of Army Engineers:

> "to investigate and report their conclusions as to the maximum length of span practicable for suspension bridges and consistent with an amount of traffic probably sufficient to warrant the expense of construction."[15]

The latter committee, with Raymond also as its chairman, consisted of Capt. Edward Burr and Capt. William Bixby. This committee received an unusual charge from the Secretary of War since he required that the committee delve into financial matters. The purview of the War Department was usually to ensure that navigation was not impeded by any bridge over navigable waters and, thus, not interfere with the nation's defenses. This committee concluded:

> "that $23 million is a reasonable estimate for a six-track railroad suspension bridge 3,200 feet long, and they consider the amount of traffic which such a bridge would accommodate sufficient to warrant the expense of construction."[16]

Their comprehensive report in the words of *Engineering News* was "one of the most valuable and instructive engineering investigations of the day."[17]

The Morison board concluded that, as reported in the *Engineering Record*:

> "a single span from pier-head to pier-head, built on either the cantilever or suspension principle, would be safe. The estimated cost of the 3,100 foot clear-span cantilever being about twice that of the shorter span, your Board considers themselves justified in pronouncing it impracticable on financial grounds... While from such a professional view they must pronounce the suspension bridge practicable, they do not in this conclusion give an opinion on the financial practicability and merit of either plan."[15]

In their studies, the board had also looked at a 2,000-foot cantilever with a river pier. Based upon these studies, the Secretary of War disapproved of the proposed cantilever of the New York and New Jersey Bridge Company.

For comparison purposes, the Morison board also had Theodore Cooper, probably with the advice and approval of the board, design a suspension bridge. His 3,100-foot span bridge, with two huge stiffening side trusses pinned at mid-span, was frequently called the plan recommended by the Secretary of War (see Figure 14). Cooper was then retained by the New York and New Jersey Bridge Company to advise them on how they could design such a bridge that met the requirements of the War Department.

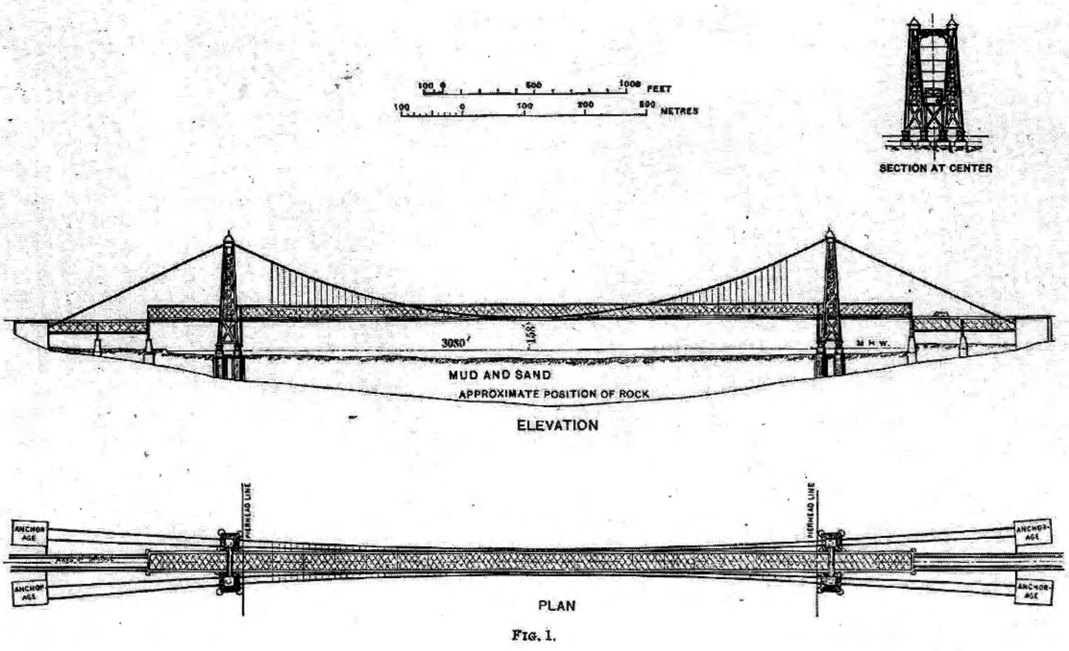


FIGURE 15. Morison's plans for a North River Bridge.

> designs, by competition, for a bridge or viaduct across Rock Creek on the line of the extension of Connecticut Avenue, and the sum of two thousand dollars is appropriated therefore."[19]

The engineers who were invited to submit plans were L. L. Buck, Morison and William H. Breithaupt.

The prizes would be $600, $500 and $400 for the first-, second- and third-place designs. The letter inviting the engineers to submit their designs stated:

> "it has seemed best to us to restrict the number of participants in such a degree as will enable a suitable prize to be awarded to each one, while at the same time preserving the competitive nature of the designs and securing for the District of Columbia a proper equivalent for its out-lay. . . It is believed that the procedure will commend itself as sound from every point of view, and that it will conform to the spirit as well as the letter of the act."[19]

The deck of the structure was to be at elevation 150 feet, with a roadway width of 50 feet and 10-foot sidewalks on each side. Provision had to be made for two lines of electric railways across the viaduct, as well as for water mains, gas mains and electric conduit. All metal work was required to correspond to Cooper's specifications for steel highway bridges. The act specified that:

> "the structure will be topographically located in a conspicuous site, and its proportions, type and style should comport with this fact and with the dignity of the thoroughfare of which it is a part."[19]

In addition to fixing some design specifications set by the act, the board instructed the designers to:

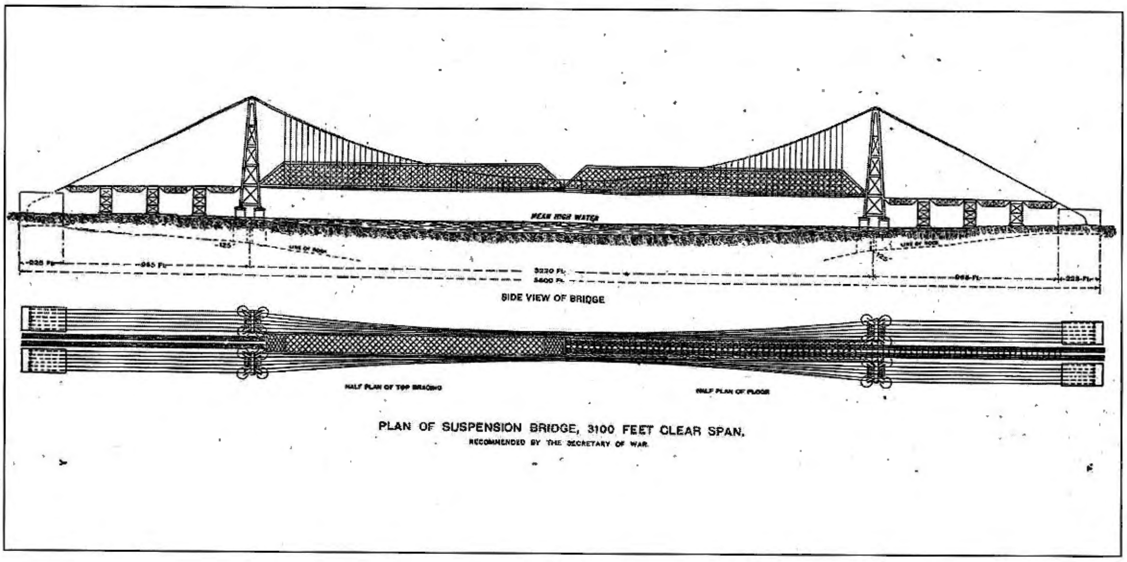


FIGURE 14. Cooper's suspension bridge design for the Hudson River.

Based on Morison's experience on this board, he wrote a lengthy paper (122 pages with discussions) entitled "Suspension Bridges – A Study" and presented it to ASCE on October 21, 1896.[18] In that paper, he proposed a design for a 3,000-foot span suspension bridge "corresponding to the dimensions proposed for the North River at New York" (see Figure 15).[18] The most unique feature of his design was his proposal to cantilever his deck truss out 150 feet from each tower, with a 500-foot anchor span, thus eliminating the need for suspenders for the ends of the main suspended span. His cable was also different than the cables that the Roeblings used in their bridges; instead of having continuous parallel wires from anchorage to anchorage, he had twisted ropes, fabricated off-site to the correct lengths, which were socketed at the tops of the towers and anchorages. Many men associated with suspension bridges contributed to the discussion about the differing designs. Some were supportive of Morison's approach and some were unsupportive. As might be expected, the longest discussion (fourteen pages) was by Gustav Lindenthal. He summarized his thoughts with:

> "it is gratifying to the writer, that the author has arrived at the same general view he held and promulgated long ago, namely, 'that a great suspension bridge which would be well adapted to railroad service, would involve no insurmountable difficulties of construction,' and at an estimated cost, the total of which does not greatly differ from that of the writer. That he does not agree, however, with all the views of the author, this discussion sufficiently indicates."[18]

Morison estimated that the bridge, using steel towers, could be built for $22.5 million and be finished within five years. However, a bridge would not be built across the Hudson for another thirty-five years.

In 1895, Morison was elected President of ASCE. Under his presidency, the *Proceedings and Transactions of the Society* were changed, and he was involved in the decision to build a larger office for the staff and library.

Connecticut Avenue Bridge (Taft Memorial Bridge)

In 1897, the federal government sponsored a design competition for a bridge to carry Connecticut Avenue over the Rock Creek Valley near its junction with the Potomac River in Washington, D.C. The act stated that:

> "The Commissioners of the District of Columbia are hereby authorized to secure

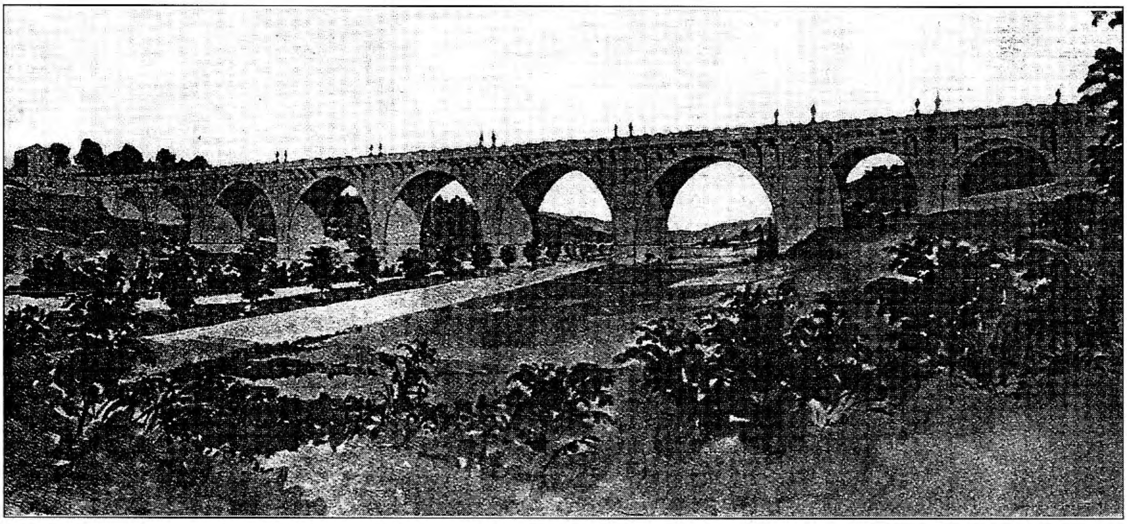


FIGURE 16. Morison's winning design for the Rock Creek Bridge.

> "submit whatever seems best to you in the direction of more fully setting forth your intention and informing this board for their judgment thereof. In determining the comparative merits and suitability of submitted designs the cost of execution will be given a proper weight by the board of awards."[19]

Up to two designs could be submitted by each engineer but no engineer could receive more than one prize. The designs were to be submitted on or before December 1, 1897. That deadline gave the participants only two months to prepare designs since the invitation letter was dated September 28, 1897. The main incentive to the three engineers was the statement:

> "the Commissioners further intend to recommend to Congress, in reporting the results of this competition, that the most meritorious design be used in the construction of the proposed viaduct; that a suitable appropriation for the work be made, and that in its execution the services of the author of the design so used be employed in the capacity of consulting engineer."[19]

The bridge would cross Rock Creek, which flowed through a 120-foot deep canyon at the site, which was just above the intersection of the creek with the Potomac River. It would cross the creek as well as Belmont Avenue, Waterside Drive and a proposed new street along the creek valley. The government was looking for a monumental structure, but many people would not see this bridge in profile since the structure was constrained to be a deck type. This design stipulation required that the parts of the bridge that could be seen by vehicles and pedestrians had also be of a monumental scale.

Buck and Breithaupt submitted two entries while Morison submitted a single entry. Morison's entry in the competition is shown in Figure 16.

The commissioners selected the design by Morison as the first place entry. They evidently were in favor of a concrete structure since it could be made "to simulate, if desired, the highest class of finished stonework, or it can be prepared as a monolithic type, which shall possess the simple dignity of massiveness."[19] The *Engineering News* concluded its review of the competition by noting that Morison "handles masonry with the same boldness and mastery of details as generalities which characterize his famous metallic structures."[20]

The bridge, started in 1898 but not completed until 1907, was based on the plans of Morison but with modifications. The major change was to drop the cast iron brackets, which Morison used to cantilever his sidewalks 10 feet off his main arch structure. The brackets were "molded to harmonize with the masonry, and their proposed use is a provision which reduces the cost of the structure in a marked degree."[20] The idea of a cantilever was retained but they were to be concrete moldings about 2 feet in width. In addition, Morison's spandrels were infilled with concrete between the minor arches above the main arch; in the final design this detail was omitted.

Morison died in 1903 and the bridge was finished under the guidance of W. J. Douglas, bridge engineer, with E. P. Casey serving as architect. Great care in the final design was taken to make the concrete look like masonry through the use of molded concrete blocks and jointing. The entire concrete surface was bush hammered to give a uniform surface texture. The bridge was renamed in 1931 in honor of President William Howard Taft.

Arlington Memorial Bridge

A bridge across the Potomac River connecting Arlington, Virginia, with the District of Columbia had been under study since the administration of President Ulysses S. Grant. Designs for a truss bridge and a series of steel arch bridges, all with movable spans, were prepared in 1888. Plans for a suspension bridge with a central span of 1,100 feet with two 652-foot side spans was proposed by Col. Peter Connover Hains in 1890.

In 1899, Congress put this bridge forward, creating an engineering board and appropriating $5,000:

> "to enable the Chief of Engineers of the Army to continue the examination of the subject and to make or secure designs, calculations and estimates for a memorial bridge from the most convenient point of the Naval Observatory grounds, or adjacent thereto, across the Potomac River to the most convenient point on the Arlington estate property."[21]

This bridge was to be very symbolic since it connected the Lincoln Memorial with the Arlington National Cemetery, as well as connecting the North with the South. The *Engineering Record* put its significance very nicely, writing:

> "the location between the capital city of the living and the city of the noble dead would be graced in a most beautiful and fitting manner by this memorial structure."[22]

The engineering review board eventually determined:

> "[t]hat the most expeditious and probably the most satisfactory method of carrying out the provisions of that act would be through a competition of a limited number of prominent and experienced bridge engineers and designers invited to present designs in accordance with general outline specifications to be drawn up under the supervision of the Engineer's Department."[21]

The list of engineers invited to submit designs consisted of Morison, L. L. Buck, William Burr and William R. Hutton. The government engineers, in drawing up the specifications, were looking for a bridge that was monumental in nature. In July 1899, the designers were told to submit two designs, one with:

> "a steel structure for the river spans with provision for the street cars on a deck below the roadway and the other for an all-masonry structure with no provision for the street car tracks. The original requirements also called for a 40-foot roadway and two 10-foot sidewalks; a draw span with a clear opening of 125 feet; a clear headway of 24 feet above low tide under the lowest part of the superstructure and at least 40 feet under the center of the channel spans, so that the draw need not be raised for the passage of small boats. The superstructure of the main bridge over the Potomac was to be of steel, while the open work of the approaches could be of steel or masonry."[21]

Later, the requirements were significantly changed to permit:

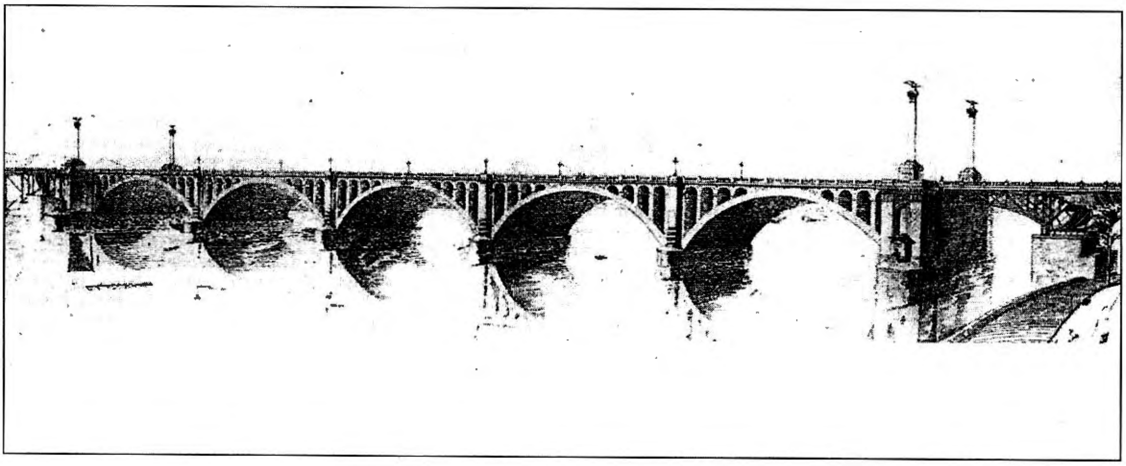


FIGURE 17. Morison's Arlington Bridge plan.

> "plans contemplating the use of such materials for piers and superstructure as might appear to them to be most appropriate, provided the masonry was durable and suitable to the character of the structure."[22]

With this rather significant change, the engineers would now be able to design structures using their own experience and creativity.

This competition, again in the words of the *Engineering Record*:

> "was the most important in the field of bridge design which, it is believed, has ever occurred, and the names of the competitors constitutes a guarantee that no better results could be expected than those which the competition would produce."[22]

The prizes would be $1,200, $1,100, $1,000 and $900 for first, second, third and fourth place.

Morison's design was for a 4,020-foot-long bridge, with the main feature being a series of five Melan arches similar in appearance to his Connecticut Avenue Bridge (see Figure 17). He flanked these approximately 180-foot spans with 64-foot bascule spans at each end. The rest of the structure was a conventional steel viaduct.

Morison's design, however, did not win approval. The Board of Officers did not give a very detailed analysis of their reasons for their decision, simply stating that:

> "after full consideration of the various plans for the proposed bridge and approaches, including the architectural features, ornamentation, and cost, the Board places the comparative merits of the design as follows. . . the Board is of the opinion that the general design of Mr. Burr designated as the first in the order of merit, meets the conditions of the problem and should be adopted, subject to certain recommendations and modifications set forth in the report."[21]

Isthmian Canal Commission

In 1875, President Grant authorized the survey of seven routes that were proposed for a canal to cross between the Atlantic and Pacific oceans. As a result of that study, the Nicaragua route became the "American" route across the isthmus. A private French company obtained a concession from Columbia and started work on a sea-level canal in 1880 under Ferdinand de Lesseps, the builder of the Suez Canal. Due to disease, corruption and the Chagres River, the company went into receivership in late 1888. The New Panama Canal Company was formed to protect the work that had already been done and to perform enough work to maintain the concession from Columbia.

In March 1895, President Grover Cleveland appointed a Nicaragua Canal Board to:

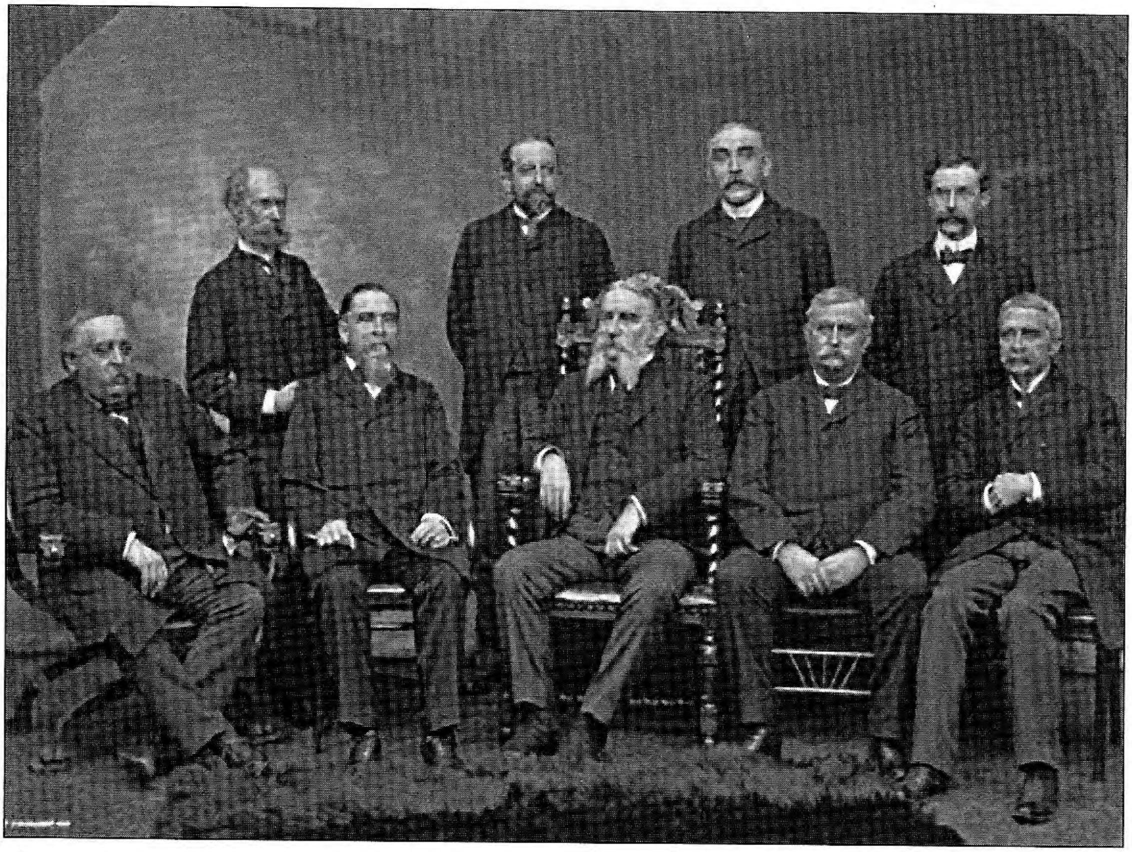


FIGURE 18. The Isthmian Canal Commission. Morison is in the front row on the far left. His protégé Alfred Noble is second from right in the first row. Civilian engineers on the commission were Lewis Haupt (far left back row) and William Burr (second from left, back row).

> "make the survey and examination necessary in order ascertain the feasibility, permanence and cost of the construction and completion of the Nicaragua ship Canal by a certain route mentioned in the act, and to consider the plans, specifications, and estimates therefore."[23]

This board of three engineers included Alfred Noble, Morison's long-time assistant, and recommended an extensive study to serve as the basis for a final plan.

In 1897, President William McKinley appointed a Nicaragua Canal Commission to study the route through Lake Managua. Headed by Admiral Walker, the commission, called the First Walker Commission, included Lewis Haupt and Col. Peter Connover Hains. The commissioners went to Nicaragua with a large staff of engineers in December 1897 and studied the Nicaragua route for a three-month period. In addition, they also visited Panama. The commission reported to the President in March 1898. They recommended some changes to the earlier report and estimated that the canal through Nicaragua could be built for just over $118 million, reaffirming what many had expected — that the Nicaragua route was the best choice. Several senators rejected the report and urged one more comprehensive study, including the Panama route. President McKinley appointed a new commission in March 1899, with Admiral Walker again as chair of what was renamed the Isthmian Canal Commission (see Figure 18).

The commission went to Paris to study all of the records of the New Panama Canal Company and talk with their engineers and administrators. After this visit, they journeyed to the isthmus, with Morison heading up a committee (consisting of himself, Prof. William Burr and Lt. Col. Oswald Ernst) to study the Panama route and other alternative routes. After working almost constantly for two years, the commission sent its report to the printers on November 30, 1899. The commission decided that Nicaragua was the best route, with the exception of George Morison. The main factors influencing the commission's decision were that Columbia could not give the right to build a canal in Panama without the approval of the new Panama Canal Company and the price the New Panama Canal Company wanted for its concession, equipment, etc., was excessive. Although no firm price had been given to the commission, the figure of $109 million had been discussed. They determined that Nicaragua was:

> "the most practicable and feasible after considering all the facts developed by the investigation and having in view the terms offered by the New Panama Canal Company, which were so unreasonable that its acceptance cannot be recommended by this commission."[23]

Morison in his minority report had argued that the commission was wrong in assuming the New Panama Canal Company would not sell its property and rights to the United States. He also placed a value of $40 million on the French property and concession.

In its final report dated November 16, 1901, the commission again recommended the Nicaragua route since the cost was estimated to be $45 million lower than the Panama route. What the report noted, however, was that there were many physical advantages to the Panama Route and the main reason they recommended Nicaragua was the price the New Panama Canal Company was asking for their works. They wrote that their recommendation was influenced by "having in view the terms offered by the new Panama Canal Company."[23] Morison signed this report apparently under the belief that the French would drop the asking price and if that occurred, then his case could be made for the Panama route. His minority report to the commission's first report, however, was picked up by the *New York Journal* and the *Chicago American* and used it to attack the findings of the final report. It is clear that Morison still thought the Panama route was the best since he gave several talks in support of that position subsequently over the next several months.

On December 10, 1901, he wrote directly to President Theodore Roosevelt stating his five reasons for opposing the recommendations of the commission. Evidently, Morison was unhappy with the way the press (the *Journal* and *American*) were handling his minority report and wanted to write directly to President Roosevelt since he had been "led to do so largely by the kind assurances which you have given me that you know my record and value my opinion."[23] He gave five reasons for his action and wrote:

> "I have not changed my views since I signed the minority report in August. I still feel that the Panama route is very much better than the Nicaragua route, and I sincerely hope that matters may yet take a shape which will permit our involvement to complete the unfinished work at Panama rather than to build the Nicaragua canal."[23]

The matters that were yet to take shape was the price demanded by the French

On January 4, 1902, the New Panama Company agreed to sell its rights and property to the United States for $40 million. The commission issued a supplemental report on January 18, 1902, at the urging of President Roosevelt, stating:

> "After considering the changed condition the Commission is of the opinion that the 'most practicable and feasible route' for an isthmian canal. . . is that known as the Panama route."[23]

Having convinced Theodore Roosevelt and Senator Mark Hanna that Panama was the right route, and after an extensive lobbying campaign by Philip Bunau-Varilla (an engineer for the Panama Canal Company) and Nelson Cromwell (an attorney and lobbyist), the Spooner Act, an amendment to the Hepburn

Act that called for a canal in Nicaragua was passed in the Senate on June 19 and signed into law by President Roosevelt on June 28. Morison's testimony at the Senate's hearing were in the words of author David McCullough "unassailable." Morison told the Senate committee that the Panama plan was sound, the dam at Bohio could be built and the Chagres River tamed and that "we can get rid of yellow fever by killing the mosquitos."[23] In describing the Culebra Cut, the cutting of the canal through the cordilleras, he noted that it was:

> "a piece of work that reminds me of what a teacher said to me when I was in Exeter over forty years ago, that if he had five minutes in which to solve a problem he would spend three deciding the best way to do it."[23]

The record is clear that without Morison the United States would probably never have built a canal at Panama. His persistence in the face of an almost universal belief that Nicaragua was the proper route was in keeping with his ideas on bridge building. He believed that once he studied an issue and came to a logical and correct solution, he had no reason to change his opinion and was obligated to convince others of their errors. Morison, therefore, deserves great credit for his work on the commission and President Roosevelt noted that he changed his mind about Panama based on the counsel of his engineers on the commission. His engineer in this case was George S. Morison.

Williamsburg Cable Commission

On November 10, 1902, a worker's shanty on top of the Manhattan tower of the Williamsburg Bridge caught fire. According to the newspapers at that time, it was a spectacular fire while it lasted. Within a week, Gustav Lindenthal, New York's Bridge Commissioner, appointed a commission consisting of L. L. Buck, the Chief Engineer of the Bridge, Morison and C. C. Schneider to report "as to the extent and manner in which repairs shall be made to the steel wire cables and to the other steelwork."[24] The commission's investigation indicated that 500 wires had:

> "been injured by heat in the two cables on the southern side of the bridge; 200 of the injured wires were in the outside cable and the injury was confined to the top of the cable over the saddle, and 300 were in the inside cable."[24]

After testing the wire, the commission found that the inside cable had its strength reduced by 6.5 percent while the outside cable (there were two cables on each side of the bridge) had its strength reduced by only 2.5 percent. However, since the wire as furnished was 12 percent stronger than specified, they determined that the cables were still stronger than needed. In order to make sure, they recommended that all the bad wires be cut out and replaced by new ones. With these repairs, the cables were only 0.5 and 2.0 percent weaker than prior to the fire. They were quick to point out, however, that they were from 8 to 10 percent stronger than specifications.

The fire also burned the wooden cable supported foot walks. The only way up the tower to inspect the damage was by ladder or to be hoisted up. Morison's nephew wrote that Morison "considered it his duty to inspect these cables personally and although in his sixtieth year, he was hoisted in a skip to the top of the tower 332 feet about the river. Few engineers of his age would have deemed such a personal investigation necessary. When one of his engineering friends asked him afterward why he had done such a perilous thing, at his age and weight, his simple answer was the one word, 'Duty.'"[3]

Manhattan Bridge

Bridge Commissioner Gustav Lindenthal incurred the wrath of L. L. Buck and his associates when he changed the design for the Manhattan Bridge, then under construction, from a wire cable to a chain bridge in 1903. He claimed it would be faster and cheaper to build a chain bridge than a wire cable bridge and that it would also be more aesthically pleasing. This change resulted in an extensive debate among engineers in the city's newspapers and journals. New York City Mayor Seth Low was pressured to create a panel of engineers to report on these changes. He chose

Theodore Cooper (succeeding Major Raymond), Morison, C. C. Schneider, Mansfield Merriman and Henry Hodge. Hodge was a classmate of Henry LaChiotte, who was one of Lindenthal's main assistants and was one of the consultants on Blackwell's Island Bridge. Schneider designed several cantilever bridges and railroad bridges in the United States and Canada and became a member of the Board of Engineers on the new Quebec Bridge, as well as having served as Morison's assistant on several bridges in the West. Merriman was a professor and author, and Cooper was a well-known engineer and was in charge of the Quebec Bridge's design. It was definitely a blue ribbon panel. Cooper, Morison and Raymond also had worked together on the Hudson River Bridge Commission.

Given the charged political atmosphere, Morison and his team were well aware that they stepped into a very difficult situation. To make their task as clear and well defined as possible, they, working with Mayor Low, set down a list of four questions to be answered. These questions were:

- "Are the plans in accordance with advanced knowledge of suspension bridge design, with a view to economy of construction, provision for temperature stresses, rigidity under concentrated loads, and resistance to wind pressure; also as regards quality of steel and its protection against corrosion?
- "Will the strength, stability and carrying capacity of the bridge be adequate for any congestion of traffic that may occur on the railroad tracks, roadways and promenades?
- "Will the structure, as designed, be fireproof?
- "Do the plans permit of speedy erection of the superstructure, after the completion of the anchorage and tower foundations?"[25]

The mayor did not ask the panel to compare the original bridge with the Lindenthal design and make a recommendation as to which bridge would be the best for the city of New York; instead, he charged the panel to answer the four questions listed above with respect to Lindenthal's chain bridge. The panel made its preliminary report on March 9, 1903, and its final report on June 29, 1903. They determined in the preliminary report that the:

> "design contains three features which, though not properly novel, are departures from the common practices with suspension bridges, they are the cables, the stiffening trusses and the metal towers, each of which may be considered by itself."[25]

The last three questions were answered as follows:

- "The strength, stability and carrying capacity of the bridge *will* be adequate for any congestion of traffic that may occur on the railroad tracks, roadways and promenades *if the provisions for loads laid down heretofore are followed.*
- "The structure, as designed, *will be incombustible.*
- "*The design favors* speedy erection of the superstructure, *after the masonry is complete.*"[25]

The response to the last question is interesting since the commission simply stated that the design would permit speedy construction. It did not say how speedy, or if it would be "speedier" than a wire cable bridge. It also turns out that both the original and Lindenthal bridge would be incombustible.

In summary, in the commission's response to the first question, it concluded that:

> "the plans are in accordance with advanced knowledge of suspension bridge designing. They are likely to be as economical in construction as other forms of suspension bridges. They provide fully for temperature stresses. They provide for a structure of unusual rigidity under concentrated load. Ample provision is made for wind pressures. They are consistent with the best protection from corrosion."[25]

In the preliminary report, it withheld judgment on whether nickel steel links of the size

George S. Morison's tombstone.

required could be manufactured with adequate quality control. In the final report issued on June 29, 1903, after determining that nickel steel links of the size needed would be available, it reported they "unanimously recommend the adoption and execution of the proposed design of the Manhattan Bridge."[26]

The commission, under the leadership of Morison, was completely behind Lindenthal and his chain bridge. Morison signed the final report only several days before his death in July 1903. It came under great criticism by many engineers in the newspapers and journals of the day. The bridge was later changed back to a wire cable bridge by the next Bridge Commissioner, George Best, in 1904. The debate on which bridge would have been less expensive, faster to build and more pleasing to the eye went on for many years, but Morison was not able to support his positions, even though Schneider did. The main question was not answered until 1927 when Othmar Ammann, on his George Washington Bridge project, gave contractors the option of bidding wire cables or chain cables. The wire cables came in costing 10 percent lower than the chain cables.

Morison's Legacy

After a visit to Puerto Rico, Morison became sick in May 1903 and never recovered, dying on July 1, 1903. His obituary was carried in most major newspapers, especially in cities where he had worked. The engineering journals of the day included long summaries of his career and profiles of his personality. The first journal to carry a notice of his death was the *Engineering Record*, which noted:

"By the death of George S. Morison on July 1 the engineering profession has lost one of it most able and successful members, Along with engineering attainments of the highest order, he possessed a knowledge of the law and grasp of financial subjects that rendered his advice of exceptional value. While not a popular man among engineers, owing to his aggressive personality, he had the respect of practically everybody on account of his independence and great ability; and his wonderfully active mind and conversational gifts won for him among prominent men of affairs a large circle of strong business friends.

"His was an intensely individual personality marked by great abilities and marred by a few eccentricities, which those who knew him best readily overlooked. Unfortunately the eccentricities are always more noticeable than the sterling qualities, and it is probably doubly true in Mr. Morison's case.

"A gentleman long associated with Mr. Morison affords a glimpse of his character... I think I am safe in saying that most of the people who were connected with him any length of time learned to respect and admire him for his knowledge, his accurate judgment on most matters, and his absolute integrity and fairness towards all with whom he had dealings. His actions were regulated not so much by conventional usage as by what after mature thought he considered right. He had a reason for every act and the courage to act according to his reason. The kinder side of his nature was probably not so well know to people who came in contact with him in a business way only. That he had a large measure of this I was in a peculiar position for many years to know, and take pleasure in saying that to me this side of his character far outweighed any peculiarities which he may have had, and I am sure that most former members of his staff entertain the same feelings."[26]

A collaborative memoir in the *Journal of the Western Society of Engineers*, an organization with which Morison and his mentor Octave Chanute were long involved, was published February 1904, with one of the contributors being Octave Chanute. They wrote about him as follows:

"It is not necessary to state that such work required a mastermind, and when it is considered that Mr. Morison had no special technical training in engineering, but entered the field when he was nearly twenty-five years of age, it is indeed marvelous. Nature endowed him with a strong intellect, and a strong will, and he made the most of them. The whole grand success may be summed up in the word work. He had no influential friends to help him, whom he did not make himself by his indomitable energy and proven ability. He studied his work carefully and thoroughly, and the minutest detail was not too small to be worked out with the greatest consideration before it was executed. One of his rules was that if he had five minutes in which to do a thing he would take three, if necessary to think it out, and do it in the other two.... While Mr. Morison always studied out and knew every detail of his work himself, he was careful to surround himself with competent, faithful and conscientious staff. An indefatigable seeker after truth and the best obtainable, himself, he expected his staff to be no less energetic, accurate and conscientious in the work than he, and indolent or slovenly workers did not remain long in his service."[27]

It was also customary for ASCE to publish memoirs of its members upon their deaths. These memoirs were written by the deceased's colleagues. The Morison memoir was published in June 1905 and written by his former assistants C. C. Schneider and E. Gerber. Their nine-page memoir traced Morison's career and works and described his character in these words:

"He had a powerful intelligence which would have distinguished him in any calling, and added to that he had in large measure those special gifts which make a man an engineer in spite of accident of education. He had contrivance, he had a quick and clear perception of cause and effect in material phenomena; he had a feeling for the laws and forces of nature... With a strong mind, Mr. Morison had also a strong will. He followed his purposes, great and small, with a persistence and determination which made him hard to work with, but which secured his ends... Beneath these attributes, which were evident, were others, which were not evident to those who knew him but superficially. With all his strength and self-reliance, he was a very modest man... he was also a diffident man, and had in great measure that reticence about his own affairs which is characteristic of his race and of the region where he was born and bred. These characteristics should be kept in mind by those of his contemporaries who did not know him closely and who try to sum him up as he appeared to them... Although Mr. Morison was in his sixty-first year when he died, he was still growing intellectually, and as he was a man of great physical strength and of frugal and abstemious life, and of undiminished energy and abundant means, we can but feel that had he been spared he would have accomplished some great work greater than any which he yet done."[28]

His nephew, George Abbot Morison, summarized his character as follows:

> "[H]e never hesitated to express positively his impressions of things or individuals, sometime to the embarrassment of the latter. Like other powerful personalities, he was a person of prejudices... Such are the achievements and character of George Shattuck Morison... One cannot epitomize such a life as his, but perhaps the most striking characteristics of his personality to one who casually meets him is power. But the one word which guided all his actions, and which was the foundation for all of his achievements, is that word which stands alone on the blue stone in the Pine Hill Cemetery in Peterborough, VERITAS."[3]

This passage provides no better way to summarize a life as full and rewarding as that of George S. Morison. There is no better title than Pontifex Maximus to befit a man whose tombstone notes that he was a Civil Engineer and whose religion and commitment to truth shaped his engineering career and, to an extent, helped shape the development of the United States between 1867 and 1903, as well as the role of the United States in the world through most of the twentieth century as guardian of the Panama Canal.

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REFERENCES

1. *Record of the Class 1913*, 50th Anniversary of class of 1863, Harvard College.

2. Fraser, C., *Nebraska City Bridge,* HAER No. MB-2, 1986.

3. Morison, G.A., *George Shattuck Morison 1842–1903: A Memoir,* presented to the Peterborough Historical Society September 12, 1932, published 1940.

4. Morison, G.S., *Journal of the Western Society of Engineers, Memoir, Vol. IX,* February 1876.

5. *Engineering,* London, 1869.

6. Chanute, O., & Morison, G., *The Kansas City Bridge, With an Account of the Regimen of the Missouri River, and the Description of Methods Used for Founding in That River,* Van Nostrand, 1870.

7. *Journal of the Franklin Institute,* September 1869.

8. Newspaper article dated July 3, 1869, from Morison scrapbook, Peterborough, New Hampshire.

9. *Transactions of the ASCE,* 1875.

10. Morison, G.S., "The New Portage Bridge," *Transactions ASCE, Volume V,* 1876.

11. Morison, G.S., *The Memphis Bridge, A Report to George Nettleton President of the Kansas City and*

Memphis Railway and Bridge Company, John Wiley & Sons, New York, 1891.

12. Morison, G.S., 1893.

13. *Railroad Gazette,* June 1890.

14. *Engineering News,* "The Proposed Tower for the World's Columbian Exposition," December 5, 1891.

15. *Engineering Record,* "The North River Bridge, Report of Board of Engineers," September 8, 1894. [Report dated August 23, 1894]

16. Ammann, O., "George Washington Bridge: General Conception and Development of Design," *Transactions ASCE,* Volume 97, 1933.

17. *Engineering News,* Nov. 22, 1894.

18. Morison, G., "Suspension Bridges – A Study," *Transactions ASCE,* Vol. XXXVI, December 1896.

19. *Senate Document No. 96,* 55th Congress, 2nd Session, "Viaduct Across Rock Creek, District of Columbia," 1897.

20. *Engineering News,* April 30, 1898.

21. *House of Representatives Document No. 578,* 56th Congress, 2nd Session, 1899.

22. *The Engineering Record,* April 21, 1900.

23. McCullough, D., *The Path Between the Seas, The Creation of the Panama Canal 1870-1914,* Simon and Schuster, New York, 1977.

24. *New York Times,* November 16, 1902.

25. *Engineering News,* March 12, 1903.

26. *Engineering Record,* July 11, 1903.

27. *Journal of the Western Society of Engineers,* 1904.

28. *Transactions of the ASCE,* "George Shattuck Morison, ASCE Memoir," Vol. 54, June 1905.

A Method for Underpinning Bridge Foundations & Its Application in the NSC Project in Pittsburgh

The method described herein provides a practical way to underpin bridges in congested urban areas where virtually zero displacement is needed during and after construction.

FIROOZ PANAH, MATT PIERCE & KEITH CHONG

The North Shore Connector Light Rail Transit Project, owned by the Port Authority of Allegheny County (PAAC), in Pennsylvania, is a 1.2-mile extension of the existing underground light rail transit (LRT) system from the current terminus in downtown Pittsburgh to the north shore of the Allegheny River. Figure 1 illustrates the extension of the Gateway Line north under the Allegheny River; it also details future expansion possibilities to the north and west. The existing LRT system already serves southern communities of Pittsburgh with a dense network of rail and stations. The current project will provide major transportation improvements to the north shore, which is home to significant new development — including new professional baseball and football venues as well as various commercial expansions (see Figure 2).

As part of the North Shore Connector (NSC) LRT Project, PAAC is constructing underground stations and tunneling using both cut-and-cover construction methods and tunnel boring technologies to extend the system below the Allegheny River to its new terminus just north of Heinz Field. On the north shore, the LRT tunnel alignment extends west across Tony Dorsett Boulevard where the alignment crosses directly below three separate foundations of State Route 65 (SR 0065, also known as Ohio River

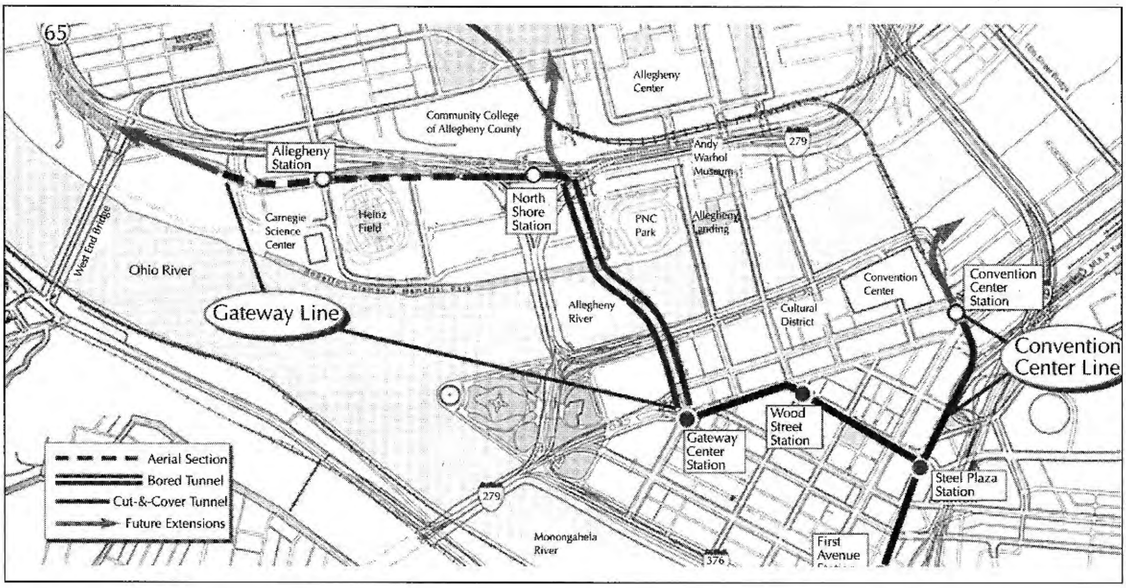

FIGURE 1. North Shore Connector LRT project plan overview.

Boulevard) northbound and southbound approaches to the Fort Duquesne Bridge, requiring the underpinning of the existing SR 0065 foundations.

Contruction on the project began in 2006. The tunnel boring machine started mining the first tunnel under the Allegheny River in January 2008. Work on the first tunnel was

FIGURE 2. Aerial schematic of the LRT north shore alignment.

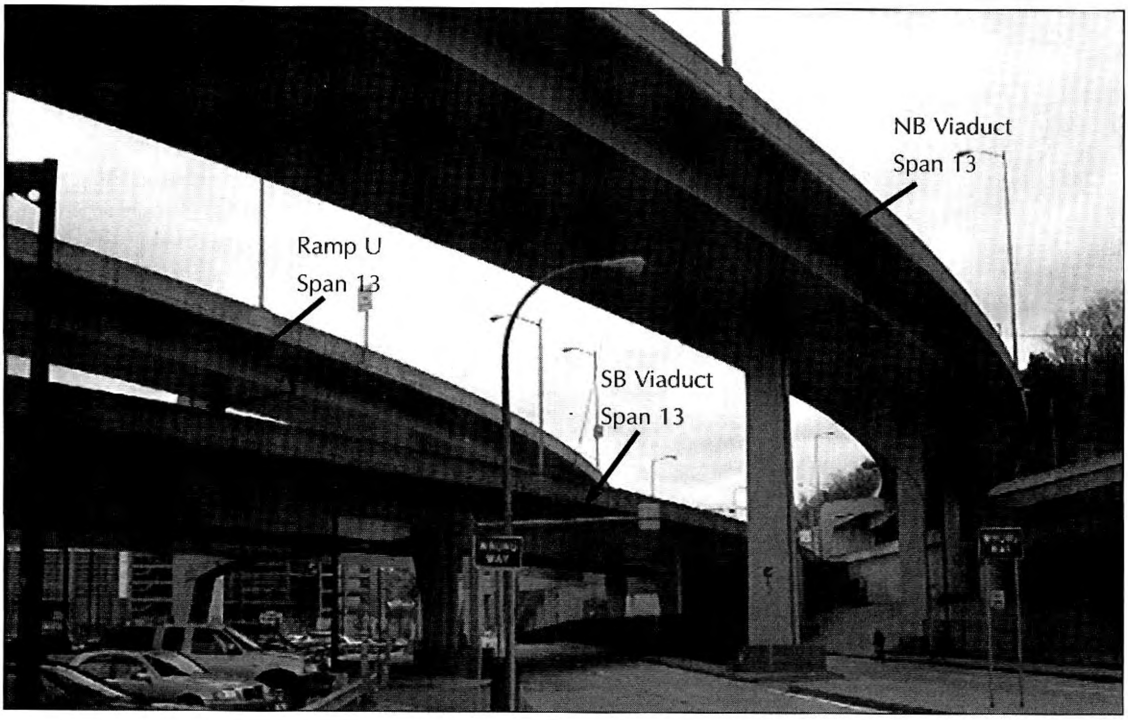

FIGURE 3. Adjacent SR 0065 NB and SB viaducts, with the Bent 13 expansion joint location shown.

finished in July 2008, and the second tunnel was done in early 2009. Current schedule calls for the NSC to be open in 2011.

Existing SR 0065 Viaducts

The SR 0065 viaducts, which are owned and operated by the Pennsylvania Department of Transportation (PennDOT), are a key link between northwest Pittsburgh communities, downtown Pittsburgh and various southern destinations. The viaducts were constructed in the late 1960s and typify the welded steel construction techniques of the era. These unique viaducts, which carry SR 0065 northbound and southbound across the north shore to the Fort Duquesne Bridge, extend a total length of 1,500 feet and reach a maximum height of 45 feet. The two adjacent structures (northbound and southbound) are a series of curved three-span continuous structures consisting of welded steel box girders rigidly framed into steel support bents with welded connections. The northbound (NB) viaduct features a single roadway level carried by a single three-webbed box girder and supported by fixed single-column steel bents. The adjacent southbound (SB) viaduct features two stacked roadway levels supported by pinned two-column steel bents. The lower SB level is carried by two box girders while the upper level (Ramp U) cantilevers over the lower and is carried by a single box girder. Figure 3 shows the relative location and size of the viaducts as well as the cantilevered Ramp U. Each steel bent is supported by concrete pedestals and pile caps founded on bedrock with end-bearing pile foundations.

Problem Definition

Various LRT alignments were investigated, including those that allowed for an unobstructed passage of the tunnel under the viaducts. Such an alignment required an S-curve to weave around the viaduct foundations, which conflicted with the alignment of an anticipated aerial structure just west of the viaducts and the location of an underground station just east of the viaducts (see Figure 1 for the aerial structure and North Shore Station). Subsequently, the current

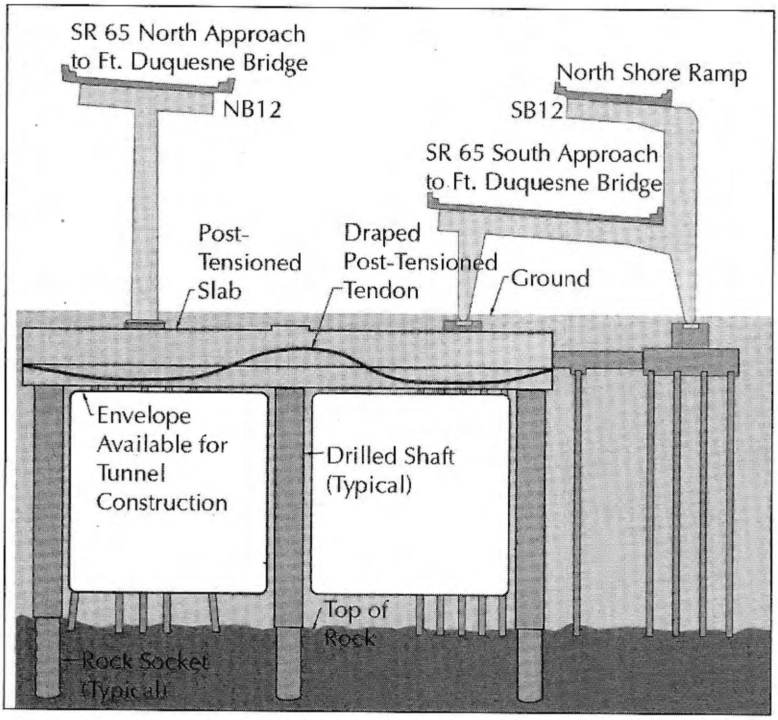

FIGURE 4. Underpinning of SR 0065 — schematic of the Bent 12 underpinning is shown.

LRT alignment crosses directly below one NB and two separate SB viaduct foundations (three total), requiring the removal of steel H-piles that extend about 40 feet to the bedrock below. Figure 4 illustrates the underpinning concept that allows for the tunnel construction.

The alignment skew relative to the viaducts dictated the need for the construction of two individual underpinning systems. The supports requiring underpinning were columns of Bents NB12 and SB12 (Bent 12 underpinning) and Bent SB13 (Bent 13 underpinning). Once completed, the Bent 12 underpinning will carry the pile caps of the bent NB12 and SB12 northeast (NE) column, and Bent 13 underpinning will support the pile cap of the SB13 southwest (SW) column. Figures 5 and 6 illustrate the relationship of the underpinned supports. Bents NB12 and SB12 are middle supports of the two adjacent structures between Bents 10 and 13S (carrying Spans 11 through 13), with a structure length between expansion joints of 318 feet (SR 0065 NB) and 303 feet (SR 0065 SB). Bent 13N is an expansion bent that is the end support of a second three-span continuous structure between Bent 13N and Bent 16 (carrying Spans 14

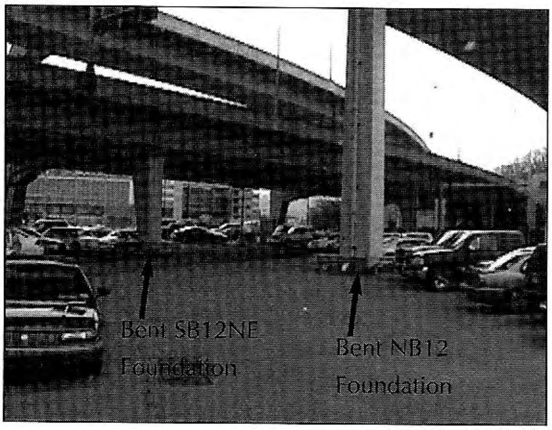

FIGURE 5. SR 0065 supports requiring underpinning — Bent 12 underpinning carries Bent SB12NE and NB12 foundations.

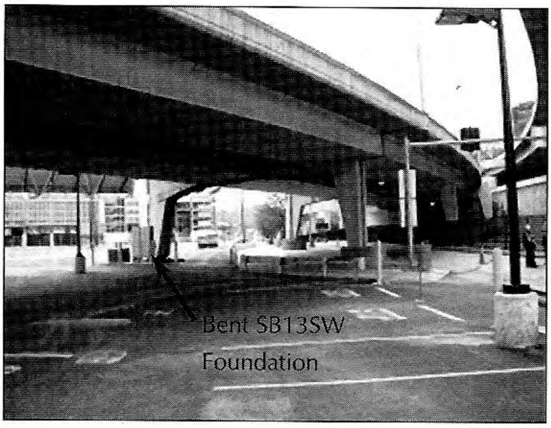

FIGURE 6. SR 0065 supports requiring underpinning – Bent 13 underpinning carries the Bent SB13SW foundation only.

through 16). Figure 3 shows Span 13 and the Bent 13 support location with Spans 14 through 16 in the background. The separate bents of the Bent 13 expansion joint location share a common footing and, therefore, the same pile foundations. Consequently, Bent 13 underpinning will carry the end supports of two successive three-span units of the SR 0065 viaducts.

Solution Evolution

Several alternative underpinning systems were investigated, including an above-grade steel transfer girder (see Figure 7), a sub-grade conventionally reinforced concrete transfer beam, a post-tensioned monolithic concrete slab (see Figure 8), a post-tensioned inverted concrete tub and a post-tensioned inverted concrete T-beam. Two primary project requirements drove the evolution of the solution:

- the underpinning systems must bridge the alignment completely and not bear any load on the tunnels below; and,
- the underpinning systems must control deflections of the SR 0065 viaduct foundations to less than 0.25 inch maximum vertical displacement during construction and 0.125 inch on completion of construction.

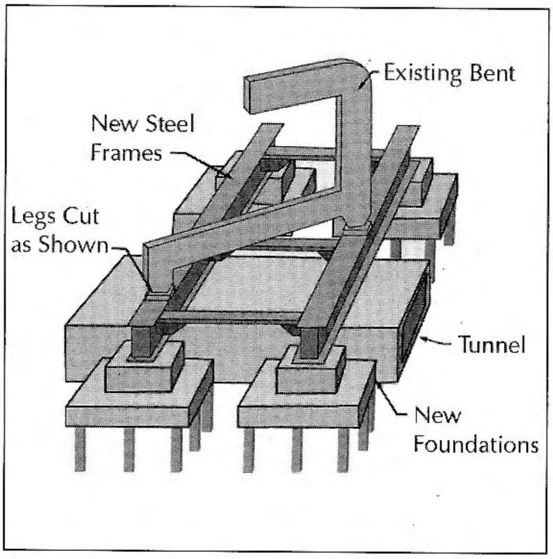

FIGURE 7. Steel transfer girder underpinning alternative.

The steel transfer girder and reinforced concrete transfer beam conceptually provided sufficient capacity to bridge the tunnel alignment while utilizing hydraulic jacks to unload

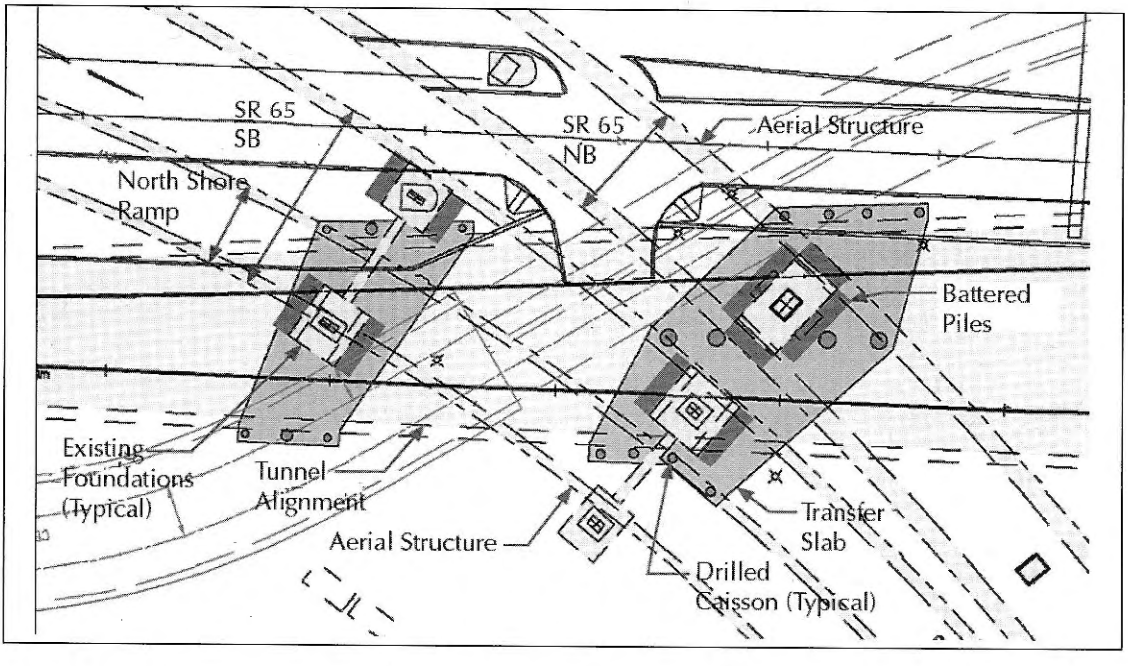

FIGURE 8. Monolithic concrete slab underpinning alternative.

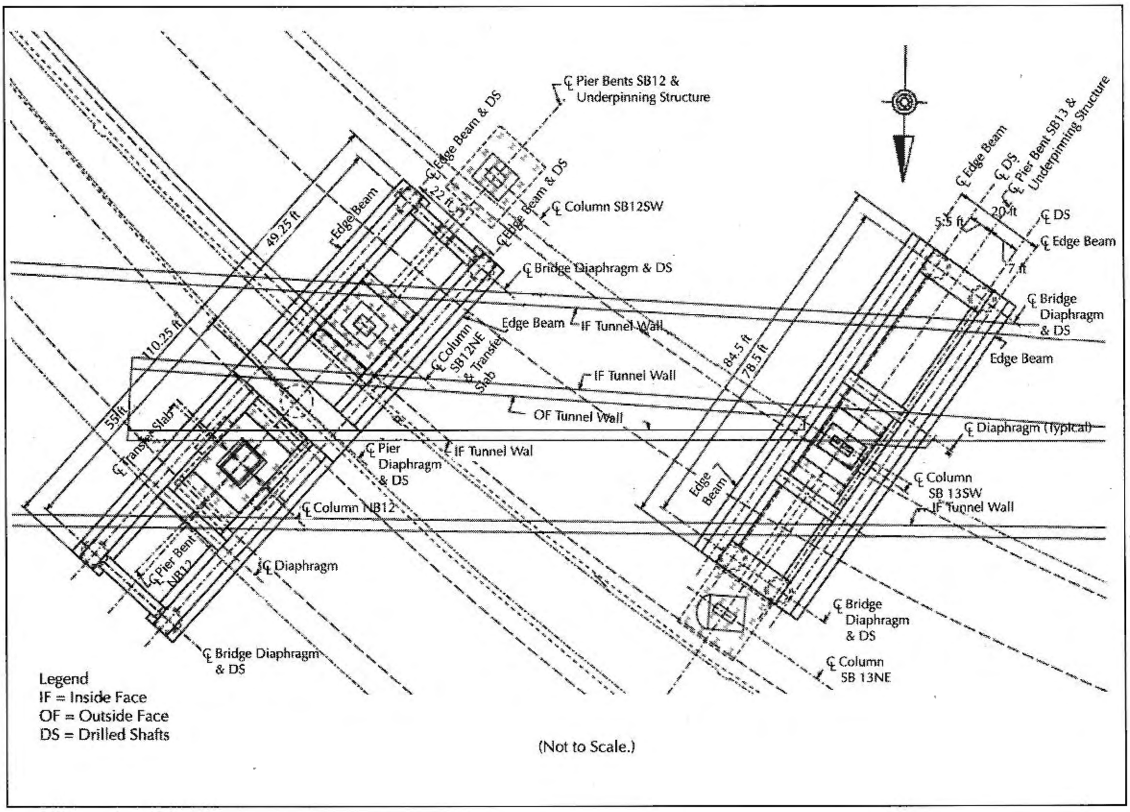

FIGURE 9. Plan view of the underpinning systems.

the foundation piles. These systems, however, were not conducive to providing cambers to counter successive deflections induced by staged load transfer (pile cutting). The steel girder alternative also presented potential corrosion and deterioration concerns. Post-tensioning was deemed a more reliable and compatible means of controlling load transfer and the associated deflections of the viaducts. The post-tensioned monolithic concrete slab consisted of two large post-tensioned slabs supported on a series of drilled shafts spanning the tunnels and supporting the viaduct foundations. The disadvantage of this system was the relative flexibility and complex geometry, which would make deflection control difficult.

The search for a durable alternative with large stiffness resulting in negligible deflections led to the development of a post-tensioned inverted concrete tub section. Conceptually, a 1-foot gap would be provided between the undersides of the viaduct pile caps and the tub section where hydraulic flat jacks would be placed. The envisioned purpose of the jacks was to maintain the pile caps stationary as the viaduct loads were being transferred from the piles to the tub section through the pile cutting process. This alternative provided a good means for controlling deflections and for the transfer of vertical loads; however, its weaknesses became apparent as the lateral loads exerted on the viaduct pile caps were considered. The flat jacks were unable to transfer these loads and temporary struts were needed to transfer footing lateral loads to the underpinning structure as vertical and battered piles were cut, which further complicated this alternative.

Subsequent modifications to the post-tensioned inverted concrete tub section led to the preferred solution. First, the 1-foot gap and the flat jacks were eliminated in favor of direct contact between the tub section and the pile caps in order to allow for the direct transfer of the vertical and lateral loads. Second, it was decided to offset the deflections at each stage

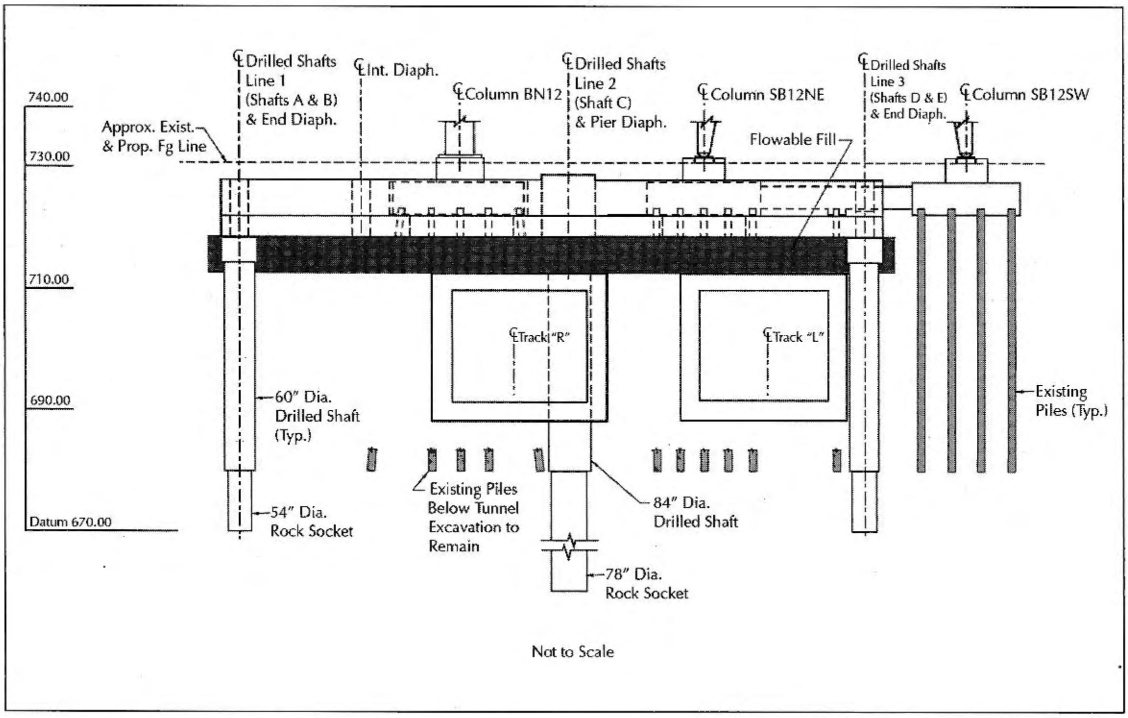

FIGURE 10. Bent 12 underpinning elevation.

of the load transfer using sequential post-tensioning. Third, areas of the tub section not in contact with the pile caps were eliminated in order to save on construction material and to reduce backfill surcharge loads. In effect, the tub section was transformed into two edge beams with slabs (transfer slabs) spanning between the edge beams to support the viaduct pile caps; the drilled shaft foundation concept remained unchanged. This alternative was found to satisfy project requirements of constructability, durability, redundancy and viaduct displacement limitations.

Underpinning System Overview

The proposed underpinning structures were similar and each was composed of concrete transfer slabs, inverted T-beams (edge beams), diaphragms and drilled shafts. Figure 9 shows the underpinning components and the relationship between the tunnel alignment and the viaduct foundations. The transfer slabs were located under the existing pile caps in order to carry the loads upon the removal of the piles. The loads were then transferred from the transfer slabs to the edge beams and from there to the drilled shafts. Diaphragms were provided to control axial rotation and lateral displacement of the edge beams and to distribute lateral loads between the edge beams. The end diaphragms of the Bent 13 underpinning also contributed to the transfer of loads to the drilled shafts while the middle pier diaphragm of the Bent 12 underpinning transferred the loads to the middle drilled shaft support.

Bent 12 underpinning (see Figure 10) was a two-span continuous structure where the edge beams spanned between three rows of drilled shafts. The end supports consisted of two 5-foot-diameter shafts, while the middle support was a 7-foot-diameter mono-shaft located between the left and right track single-cell tunnel box structure below. The Bent 12 underpinning had a total length of 104.25 feet, spanning 55 and 49.25 feet between supports. The underpinning connections were pinned at the two ends and were monolithic (moment connection) at the center support. Bent 13 underpinning (see Figure 11) was a 78.5-foot single-span structure supported on

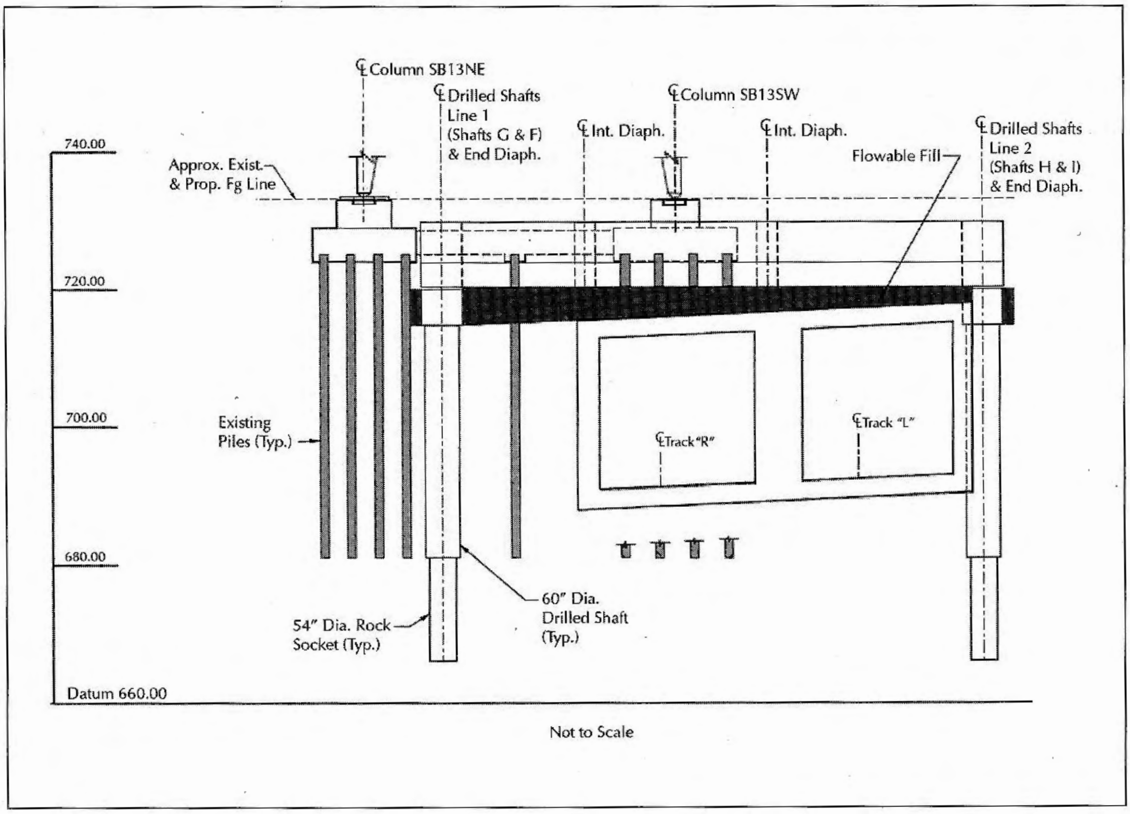

FIGURE 11. Bent 13 underpinning elevation.

two rows of two 5-foot-diameter shafts. The connections were pinned at the two ends. The two underpinning structures had a total of nine drilled shafts, all of which penetrated into bedrock. The 7-foot-diameter shaft was exposed during the excavation and construction of the tunnels and was therefore designed as an unbraced column. The 5-foot-diameter shafts were outside the support of excavation (SOE) and were placed and utilized with limited exposure. The drilled shaft design included the impact of the adjacent SOE lateral movements.

Viaduct Load Development

The viaduct load development commenced by establishing the viaduct structure geometry and the extent of the underpinning impacts on the viaduct structures. A software package was utilized to develop the complex curved geometry based on the available existing structure plans and field observations. The geometry information was then used to develop detailed three-dimensional models of the viaducts.

The viaduct loads and section properties were developed in accordance with the AASHTO *Standard Specifications* (16th edition) and supplemented by PennDOT's *Structures Design Manual (DM-4)*. Structural analysis and design software was employed to generate the foundation loads based on the applicable viaduct loading conditions, including:

- Dead loads;
- Live loads (HS25 and PennDOT's 204 kip permit load [P-82]);
- Thermal forces;
- Wind loads (including wind on live load);
- Braking forces; and,
- Centrifugal forces.

The dead loads of the SR 0065 viaducts were calculated in the structural analysis and design program to the bottom of the columns and combined with the base plate, concrete

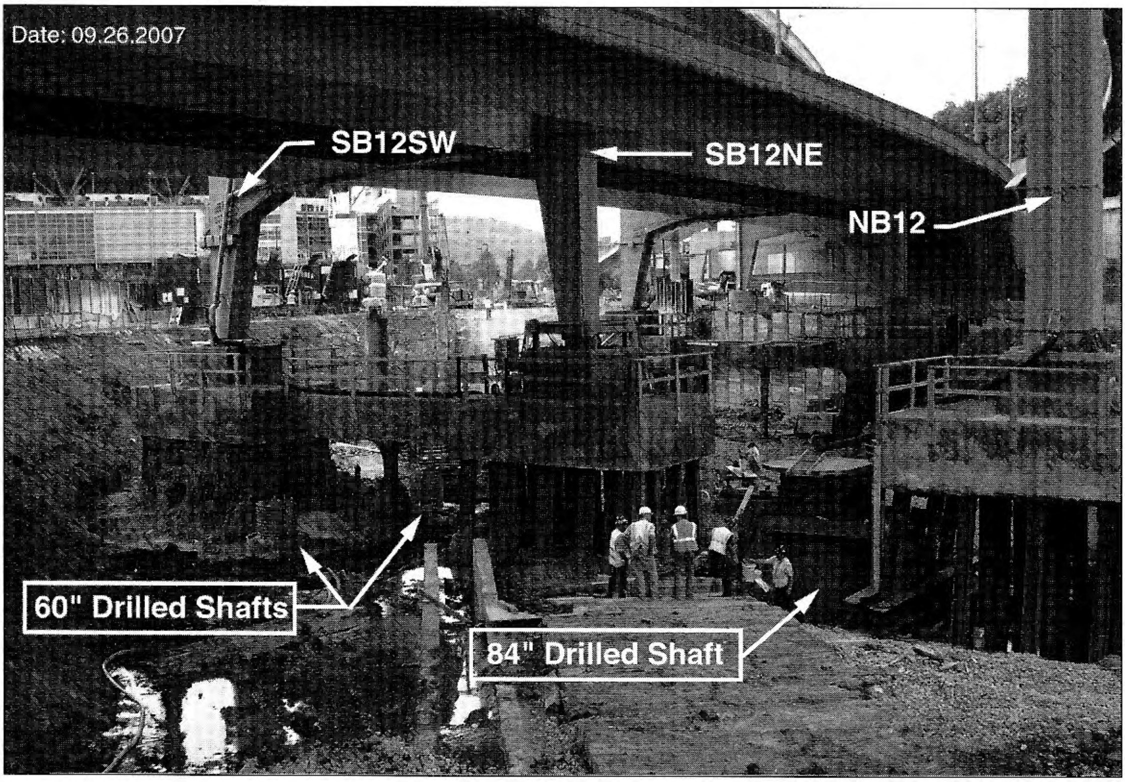

FIGURE 12. Bent 12 underpinning with foundation piles exposed.

pedestal and pile cap loads for application on the underpinning system. Live load influence lines were generated as well in the structural analysis and design program, from which the maximum and minimum live load reactions for each underpinned foundation were determined. Load force effects were determined in all three orthogonal directions and transformed to the plane of the underpinning structures for design application.

Underpinning System Design & Analysis Approach

Construction Sequence. The construction sequences of the two underpinning systems were an integral part of their design and were devised to ensure the safe transfer of the loads to the new foundations and to meet the displacements limits of 0.25 inch during construction and 0.125 inch in the final (permanent) configuration. The general construction sequence for both underpinning structures was similar. The sequence for Bent 12 underpinning, which was somewhat more complex than the Bent 13 underpinning due to the two-span configuration, started with local excavation, which was required to increase the headroom below the viaducts in order to build the drilled shafts and to verify the as-built bottom of pile cap elevations prior to the construction of the drilled shafts. The initial excavation depth was 4.5 feet below the bottom of the pile caps.

With the drilled shafts in place, the pier diaphragm was constructed at the top of the 7-foot-diameter mono-shaft followed by construction of the edge beams (see Figures 10 and 12). Placement of the intermediate and end diaphragms was the final step in the underpinning system assembly. At this stage, excavation proceeded under the edge beams. The intent was to ensure the edge beam's deflection due to self-weight that would occur prior to the load transfer (pile cutting) and prior to jacking the post-tensioning tendons. The excavation then proceeded deeper under the viaducts' pile caps, exposing the underside of the pile caps and the top 7.75 feet of the

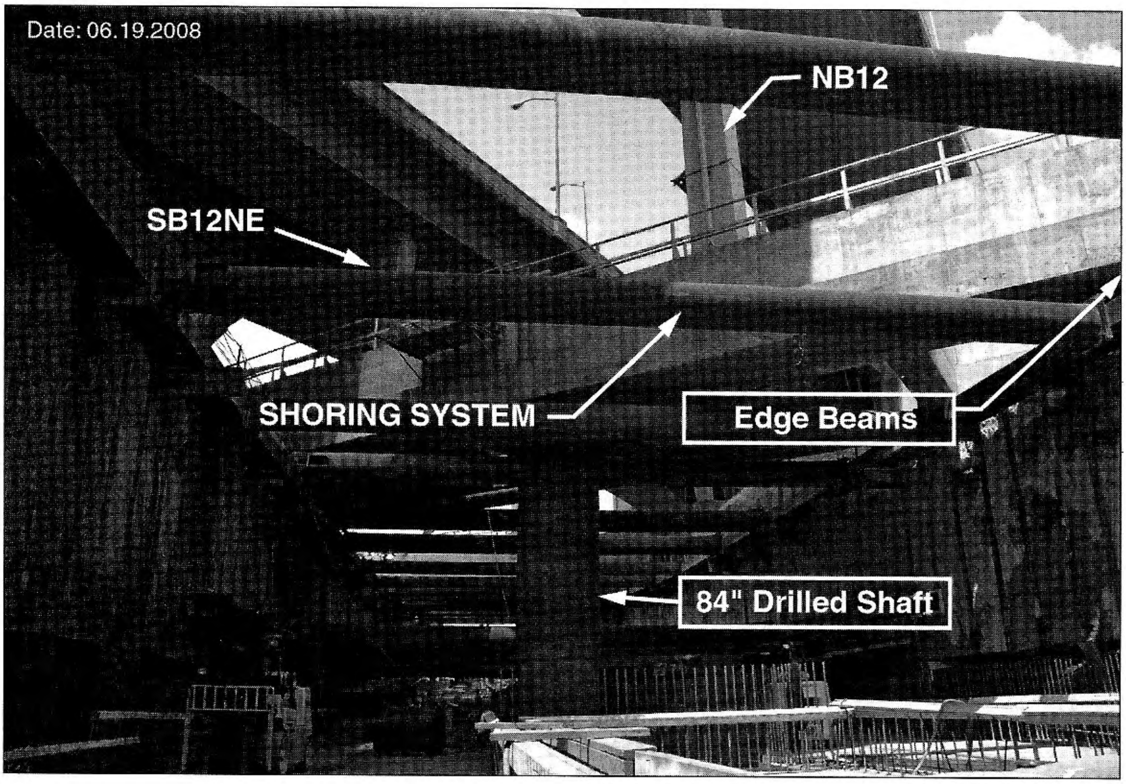

FIGURE 13. Bent 12 underpinning in place and foundation piles removed.

piles. The underside of the pile caps and the top 4 feet of the piles, which were to remain in place and encased in the transfer-slabs, were cleaned by sand blasting. Transfer slabs were constructed so that a 3-inch gap was provided between the top of the transfer slabs and the bottom of pile caps. This gap was subsequently filled with a non-shrink grout to provide full contact and support.

The post-tensioning and pile cutting procedures commenced only after the aforementioned 3-inch gap was grouted and cured so that the axial and lateral pile loads could be transferred to the transfer slabs. Two of the six tendons were jacked in the edge beams, relieving a portion of compression in the piles. Doing so allowed for cutting approximately a third of the piles. The post-tensioning and pile cutting process was repeated two more times until all tendons were jacked, all piles were cut and the loads were fully transferred to the underpinning structures. Throughout this process, displacements at the base plate of the viaduct columns were measured and monitored. The piles were removed in two stages. Segments of piles that were exposed directly below the transfer slab were removed (approximately 3.75 feet of pile) after the load transfer was complete. The remaining parts were removed during tunnel excavation, facilitating cut-and-cover construction and the advancement of the LRT tunnel. On completion of tunnel construction, a flowable backfill was placed under the edge beams extending from the top of tunnels to the bottom of edge beams. The flowable backfill was used as a backfill expedient and not as a structural element. Flowable backfill was also placed between the pile caps and the edge beams. The final stage of construction was the placement of structural backfill to the finished grade and the placement of pavement at the surface. Figure 13 shows the completed Bent 13 underpinning in service with piles removed and tunnel construction in progress.

Design & Analysis of Transfer Slabs & Edge Beams. The design approach for transfer slabs and edge beams was to develop suitably sized

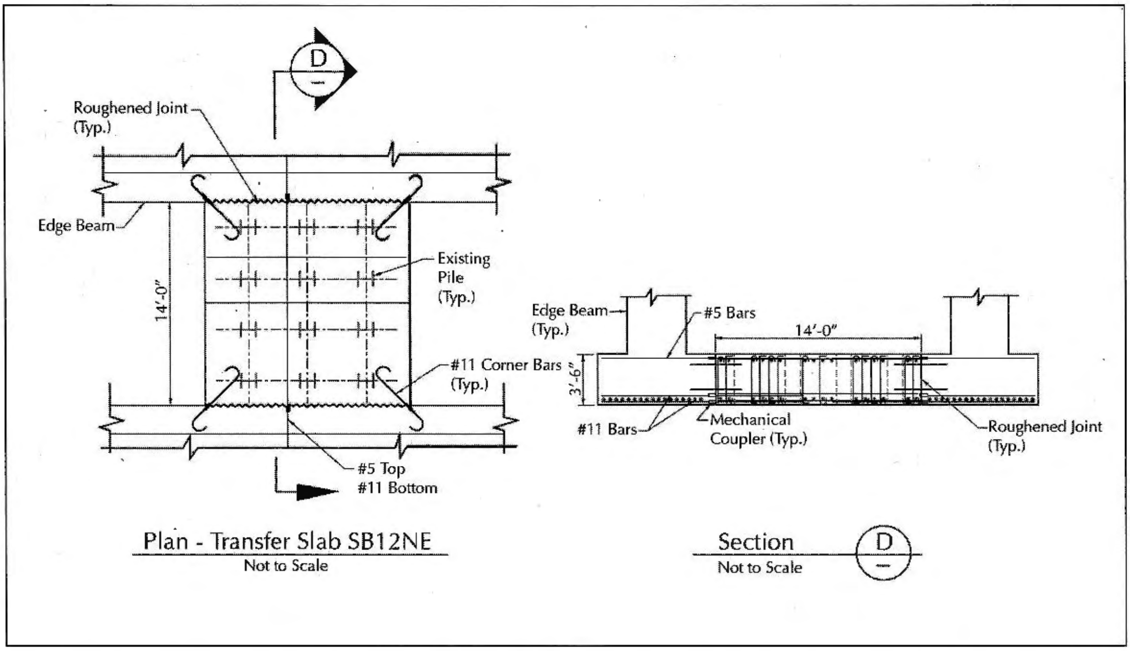

FIGURE 14. Typical underpinning transfer slab supporting the existing SR 0065 viaduct foundation.

and constructible components based on AASHTO and PennDOT loading and design criteria and to control displacements at all stages of construction. The load factor method was used for the design of the transfer slabs and the diaphragms. The post-tensioned components of the edge beams and the intermediate diaphragms were designed using service loads and checked against factored loads. The concrete strength (*f'c*) was 6,000 pounds per square inch for the edge beams and transfer slabs.

The 3.5-foot deep transfer slabs (see Figure 14) were slightly narrower than the pile cap they support and were reinforced concrete structures that transfer loads to the edge beams through shear friction. Sufficient reinforcement was provided to take flexure at the top and bottom of slabs and to transfer shear to the edge beams. A three-dimensional structural anaylsis and design model was used to analyze the transfer slabs by applying a finite element analysis method.

All the diaphragms, with the exception of the Bent 12 underpinning pier diaphragm, were reinforced concrete structures. The pier diaphragm at Bent 12 was post-tensioned.

The edge beams were post-tensioned using six tendons consisting of twelve 0.6-inch-diameter tendons with two contingency ducts provided. The contingency ducts were grouted at the end of construction regardless of use. Figure 15 illustrates the tendon profile across the asymmetric spans of the Bent 12 underpinning. The tendons were jacked in three stages. At each stage, prior to pile cutting operations, two tendons were jacked in the edge beams. The force and profile of the tendons were designed to not only provide the required camber for displacement control but also to ensure that the edge beams remained in compression during all stages of construction. No tension was permitted in the edge beams under either of the following two load combinations:

- prestressing force and permanent dead load; or,
- prestressing force, permanent loads, and live load.

The analysis and design of the edge beams was carried out using a program that was capable of performing a step-by-step time-

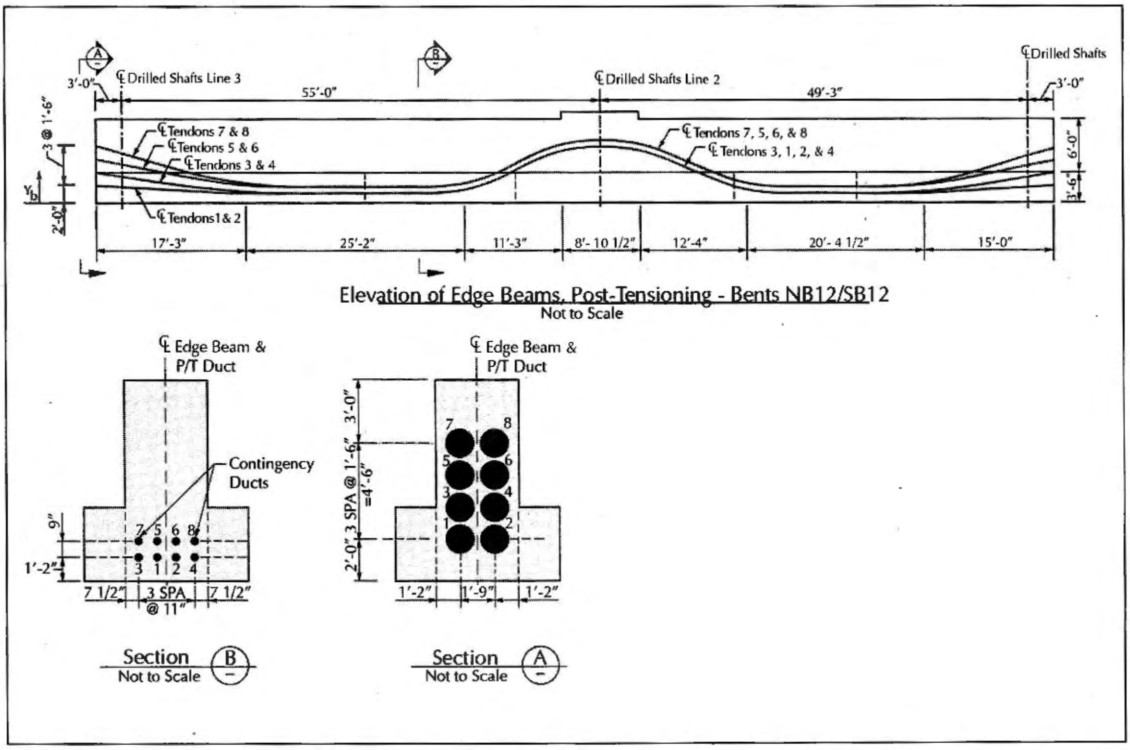

FIGURE 15. Edge-beam tendon profile.

dependent analysis. Time-dependent induced forces such as creep, shrinkage and post-tensioning losses were accounted for at each stage of construction. Creep and shrinkage-induced strains, variation of modulus of elasticity and concrete strength with time were modeled using 1991 CEB-FIP model code, which is widely used in the industry for the design of post-tensioned segmental concrete bridges. Forces, stresses and displacements were calculated at each stage of construction as well as at completion and thirty years after the completion of construction. In addition to time-dependent analysis, a corresponding structural analysis and design model was developed to analyze the transfer slabs, to obtain drilled shaft loads and to adjust the time-dependent model for the three-dimensional effect where required. The flexibility of the drilled shafts was considered and modeled in both the time-dependent and three-dimensional structural analysis and design models.

Prediction of Displacements. Since the SR 0065 viaducts consisted of steel box girders that were framed into steel bents with welded connections, these rigid connections were susceptible to foundation settlements that could induce significant stresses into the superstructure. Therefore, displacement control at each stage of construction and at the completion of construction was imperative. Displacements were monitored at the base plate of the three affected columns. During construction, the net vertical displacements were limited to no more than 0.25 inch and on completion of construction to no more than 0.125 inch.

The displacement calculations were carried out using structural analysis and design as well as time-dependent analyses for the transfer slabs and the edge beams, respectively, with hand calculations for the short- and long-term drilled shaft axial shortenings. The results had to be adjusted carefully for the construction staging effects. Displacements of the underpinning structures occurring prior to load transfer (prior to grouting of the 3-inch gap between the transfer slabs and the pile caps, and post-tensioning) were not relevant and were taken out from the net displacement. These displacements included instantaneous displacement due to the self weight of the edge beams and diaphragms, the associated elastic shortening of the drilled shafts and rock settlement. Relevant downward displacements were due to the self weight of the viaducts, viaduct live loads, the backfill and surcharge. The displacements components were:

- Edge beam instantaneous and long-term deformations due to creep and shrinkage;
- Transfer slab deformation;
- Drilled shaft axial shortening; and,
- Rock settlement.

All these components were considered in the calculations. The post-tensioning forces resulted in camber, offsetting the downward displacements. The post-tensioning was designed to ensure that the net displacements were kept within the allowable displacement limits at all times.

The calculations showed that the maximum live load deflection at the base plate of the viaducts under the governing live load (PennDOT P-82 permit loading) was 0.0625 inch. The viaducts were to be open to traffic during construction when this maximum displacement occurred. On completion of construction, no live load deflection was expected due to the placement of flowable backfill below the edge beams.

Drilled Shafts. A total of nine drilled shafts supported the two underpinning structures: five for Bent 12 underpinning and four for Bent 13 underpinning. These shafts wre designed to transfer loads to bedrock through side friction only. There were four 60-inch-diameter drilled shafts and one 84-inch-diameter drilled shaft supporting the two-span continuous Bent 12 underpinning. The 84-inch drilled shaft extended 36 feet into rock, with a 78-inch diameter rock socket. The single-span Bent 13 underpinning was supported by four 60-inch-diameter drilled shafts. The concrete strength (*f'c*) of the drilled shafts was 5,000 pounds per square inch.

Two primary types of forces were considered in calculating the displacement at the top of the drilled shafts and applied in design. Type 1 forces include thermal, post-tensioning, creep and shrinkage of the underpinning system. Type 2 forces are those external to the underpinning system including the viaduct loads. Where applicable, forces induced by movement of the adjacent SOE system were also estimated and included in the design of the drilled shafts. Design of the drilled shafts and calculation of lateral displacements required the use of a program for the analysis of the deflection and capacity of piles under lateral loads (COM624P) to verify the underpinning system stability, and to check displacements at the top of shafts using Type 2 service (un-factored) forces. The lateral forces at the top of the drilled shafts were combined using the square-root-of-the-sum-of-the-squares (SRSS) method.

COM624P analysis was used to perform a serviceability check in the drilled shafts by applying the combined Type 1 and Type 2 service forces. Concrete design software (pcaColumn) and the results from COM624P were used to design the drilled shafts and rock sockets. In using pcaColumn, moment magnification of the drilled shafts was considered by assuming the column length to be four times the diameter of the shaft. Using this parameter ensured a length higher than the point of fixity of the drilled shafts, which was in the range of 2.5 to three times the diameter. The boundary conditions used in the pcaColumn analyses were free at the top and fixed at the bottom for the 5-foot-diameter shafts, and restrained at top and fixed at bottom for the 7-foot-diameter shaft.

pcaColumn again was used to design the 7-foot-diameter shaft as an unbraced column, since the shaft was exposed during construction and would behave like a column until it was backfilled. Factored loads obtained from a three-dimensional structural analysis and design model were used for this analysis. The boundary condition used in the pcaColumn analysis was restrained at the top and fixed at the bottom with the true column length applied. The 7-foot-diameter drilled shaft was integrally connected to the pier diaphragm. The point of application of loads to this shaft was located at the centroid of the pier

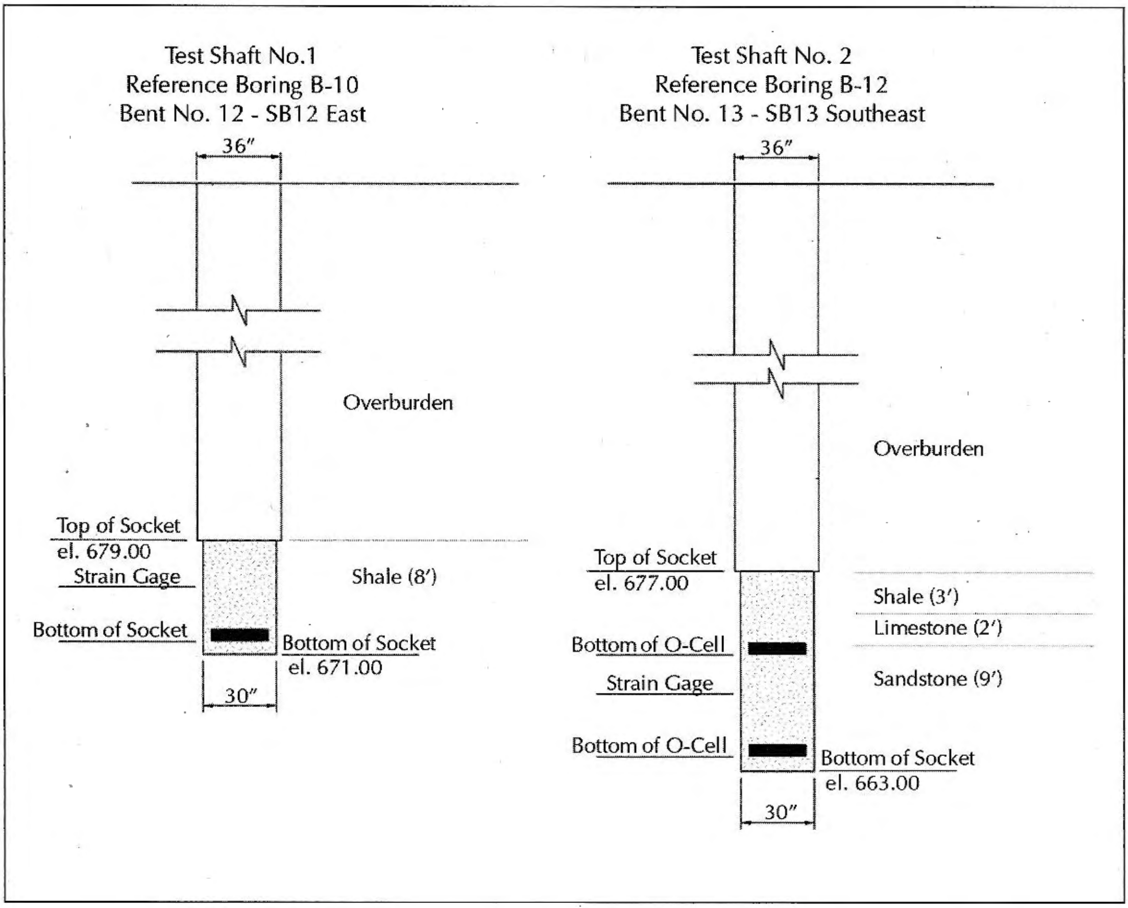

FIGURE 16. Drilled shaft load test schematic.

diaphragm (4 feet above the top of shaft); therefore, the height of the 7-foot-diameter shaft was modeled to this point. The 10- by 14- by 10-foot high pier diaphragm restraining the top of the drilled shaft was modeled in COM624P applying a 4-foot-deep, 10-foot-diameter shaft in determining displacements for the 7-foot-diameter shaft.

Drilled Shaft Load Test. The bedrock in the vicinity of the underpinning consists of layers of shale and sandstone. To verify the bedrock design parameters, two 3-foot-diameter drilled test shafts with 30-inch-diameter rock sockets were used in the proximity of the proposed production shafts and were subjected to the Osterberg Cell (O-Cell) load test. The O-Cell load test was done prior to the construction of the production drilled shafts. The primary goal of the load test was to verify drilled shaft settlement values, rock socket side friction values and end bearing response. The integrity of the production shaft concrete was tested using the cross sonic log (CSL) method. A total of eight CSL tubes were provided: four within the drilled shafts, with another four extending to the rock sockets.

The O-Cell is a sacrificial jack-like-device that can be installed within the drilled shaft, or in this case, within the rock socket as shown in Figure 16. Strain gages were proposed to help determine the contribution of load response from the overburden soils, sections of the rock socket and the end bearing component. The first test shaft was constructed with one O-Cell and one level of strain gage within 8 feet of rock socket. The second test shaft consisted of two O-Cells and one level of strain gages within 14 feet of rock socket. Each of these cells had a 1,250 ton capacity and a diameter of 21 inches. The O-Cell load test was to com-

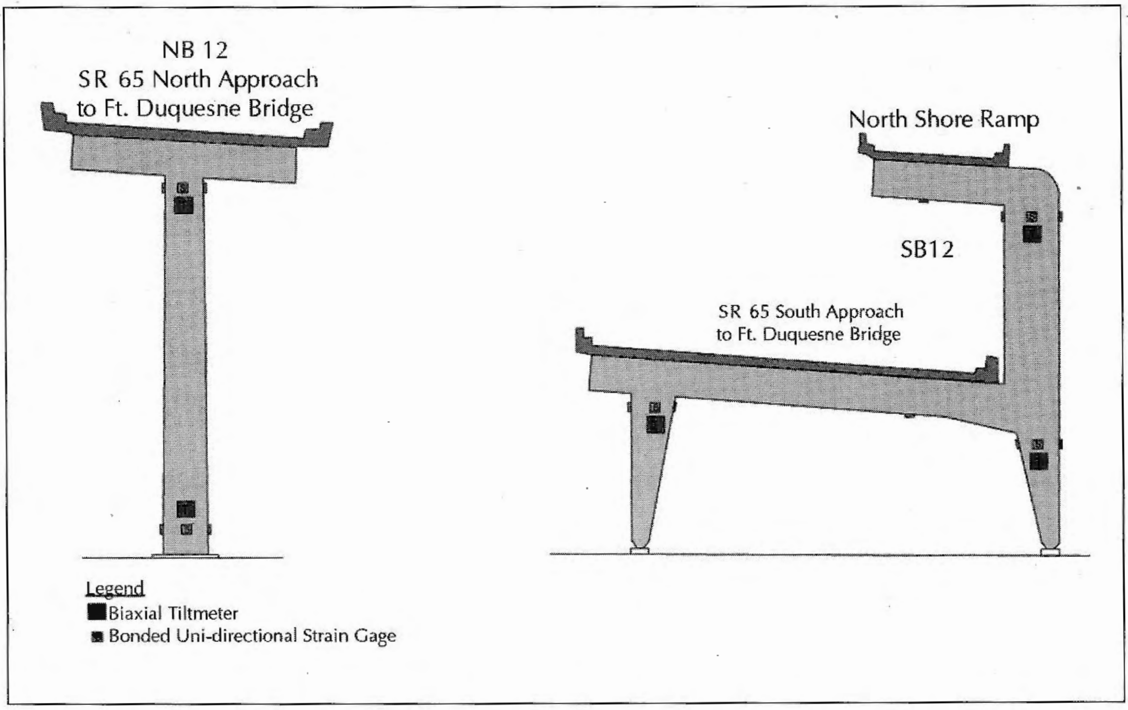

FIGURE 17. General strain gage and tiltmeter locations.

mence after concrete strength of 5,000 pounds per square inch was achieved.

Instrumentation & Monitoring. An instrumentation and monitoring program specific to underpinning operations was proposed to monitor displacements of the underpinning structures and SR 0065 viaducts as well as strain behavior of the viaducts.

The locations on the underpinning structures identified for monitoring included points on top of the edge beams located immediately above the center line of the drilled shaft. At these points, linear variable differential transformers (LVDTs) were installed to monitor and verify rock settlements and drilled shaft axial shortening at specific stages of construction as load on the drilled shafts was increased. This information was used to adjust the post-tensioning force, if needed, to offset the differences between the anticipated and actual rock settlement values. Additional critical locations included the base plates of underpinned columns NB12, SB12NE and SB13SW. Three LVDTs were called for at each location (two separate locations on NB12 and one location on each SB base plate) to monitor potential movements in the orthogonal directions, providing a total of twelve LVDTs for displacement monitoring. A total of eighty-four locations were identified on the bents and superstructure of the viaducts for strain gages in order to monitor potential impacts to the strain behavior of the steel structures. An additional fifty-four tiltmeters were provided throughout Spans 11 through 16 to monitor viaduct movements. The tiltmeters and strains gages were generally located at the top of columns for Bents 11, 12, 13, 14 and 15, with additional strain gages provided at several points on the superstructure and bent cross beams. Figure 17 illustrates general locations of the strain gages and tiltmeters at a typical bent location.

The contract provisions required that the contractor limit the stresses in the structures and the associated deflections during excavation, construction of the new underpinning systems and transfer of the load to the underpinning systems. The movement and stress limits are shown in Table 1.

The contractor was also required to employ independent firms to monitor the stresses in the superstructure during construction and to

TABLE 1.
Project Specification Threshold & Limiting Values

Instrument	Threshold Value*	Limiting Value*
Tiltmeter	0.15°	0.20°
Bonded Strain Gages	±50 microstrain	±100 microstrain
LVDTs	±0.25-inch (uniform vertical displacement)	±0.50-inch (uniform vertical displacement)
	0.25-inch (differential displacement between bent legs)	0.50-inch (differential displacement between bent legs)

Note: *Threshold values and limiting values represent response values for duration of construction.

inspect the viaducts both before and after construction. The special provisions further required that the instrumentation be installed and monitored for thirty days prior to any construction activities in order to establish a set of baseline readings for the viaducts. These data showed the actual stresses recognized by the structure and were used as a check on the stress limits contained in the contract special provisions. The stresses and displacements in the SR 0065 support bents were periodically monitored during construction and continuously monitored during the load transfer. Project specifications dictated the frequency that data must be reported and also specified "threshold" and "limiting values" beyond which action would be required by the contractor to ensure worker safety and to preserve the integrity of the viaducts.

Durability & Redundancy. Measures had been incorporated in the underpinning structures to ensure their durability. These measures included but were not limited to:

- use of epoxy coated reinforcing bars, incorporation of the latest research and technology in grouting post-tensioning tendons;
- provision of 3-inch minimum cover for concrete;
- provision of a water proof membrane at the construction joints, edge beams, and transfer slab; and,
- crack control by maintaining concrete in compression at all times.

The expected useful service life for the underpinning structures is one hundred years, which is based on the fact that by incorporating all the recommended industry measures for post-tensioned structures to accomplish durability, it should attain the targeted life expectancy for post-tensioned bridges. Therefore, it is expected that the underpinning structures will have a much longer useful life than the remaining life of the existing forty-year-old SR 0065 viaducts.

Redundancy was provided through primary load path (post-tensioning) and secondary load path (mild steel reinforcing).

Post tensioning provided the camber required for deflection control and carried the service and ultimate loads imposed on the underpinning by the SR 0065 viaduct structure. The industry standard of care for the post-tensioned structures was maintained by providing multi-tendons in lieu of fewer larger tendons, so that corrosion of one tendon would not be detrimental to the entire structure. The post-tensioning tendons were fully grouted.

Retrofit of SR 0065 Viaducts. As part of the current NSC project, and due to the anticipated permanent underpinning displacements, select box girders of the northbound and southbound viaducts were retrofitted by providing internal transverse bottom flange stiffeners. The channel stiffeners (shown in Figure 18) were installed throughout the negative moment regions about pier Bent SB11 and NB11 to brace the bottom flange in compres-

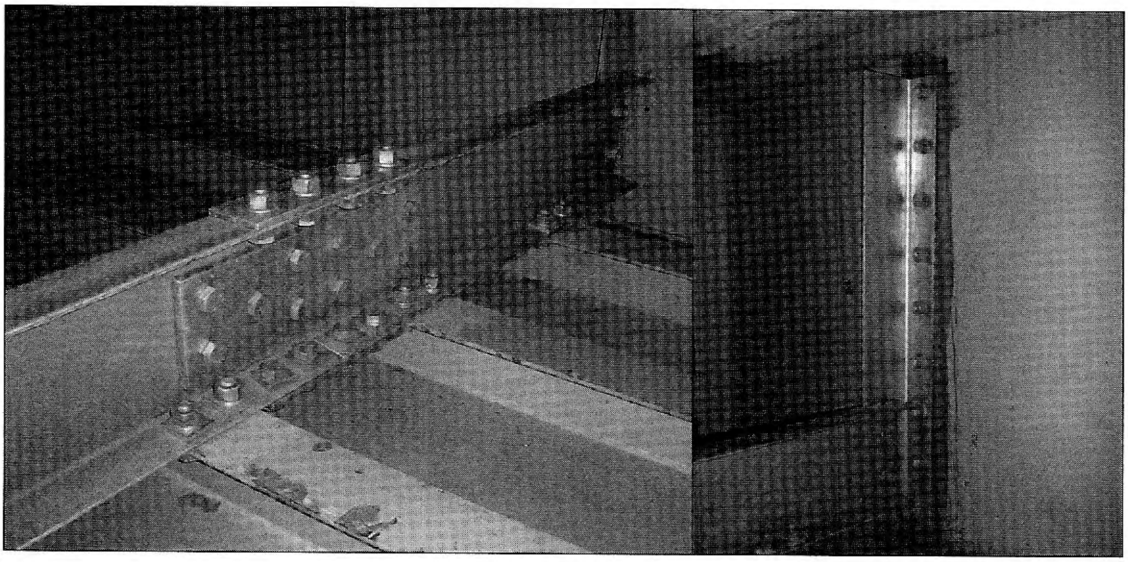

FIGURE 18. SR 0065 viaduct box girder retrofit.

sion and ultimately offset potential displacement effects on the overall live load capacity of the viaducts. The need for, and the extent of, the viaduct retrofits were determined as part of a live load capacity assessment, which demonstrated potential adverse impacts to the capacity of the adjacent negative moment regions about Bent 11 due to anticipated heave at the Bent 12 underpinning location.

The channel sections were field bolted to the existing web and bottom flange stiffeners of the box girders; and in the case of the northbound three-webbed box girder, a connection angle was also installed on the middle web to allow for the connection of the channel stiffener.

Conclusion

As the need for construction of tunnels and major utilities in congested urban areas increases, there will be more instances of conflict between these structures and existing bridge foundations. The underpinning of these foundations would be particularly challenging where bridge superstructure and piers are connected monolithically or where straddle bents are use. To protect these bridges against cracking, differential displacement or tilting, owners of these bridges would demand stringent deflection tolerances as well as durability provisions. The method developed for the NSC project provides a practical way for underpinning bridges particularly where virtually zero displacement is desired.

For this project, the two underpinning structures were constructed successfully and the actual measured displacements were well within the tight tolerances during and after completion of the construction. The durability measures implemented for this project will ensure that the underpinning structures outlast the bridges they support.

NOTES — *Cogo-PC Plus geometry software was utilized to develop the complex curved geometry based on the available existing structure plans and field observations. The geometry information was then used to develop detailed three-dimensional STAAD models of the viaducts. The analysis and design of the edge-beams was carried out using the program BDII by Interactive Design Systems.*

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Friended by a Bridge

In the best of all worlds, bridges could belly up to the bar with us and watch a baseball game (or two), as well as be there to drive us home.

BRIAN BRENNER

Ben Mezrich's book, *The Accidental Billionaires*, tells the story of the birth of Facebook. Mezrich describes the two Facebook creators as asocial Harvard nerds who came up with the idea in their dorm rooms. Their simple concept was for a website that could electronically duplicate social networking. The website would create a virtual world on which college students could interact. All of the intricate social behaviors of students could play out on the website, but freed of the physical and time limitations of actual meetings.

The developers first came up with their idea by thinking of finding a better way to meet girls. Apparently they were not so successful in the non-virtual world. The website, initially named "Thefacebook," was an instant success. Within days of its initial release at Harvard, the majority of the students had signed up and prepared their own pages. From that point on, the site experienced exponential, viral growth. The site was launched for access at one college after another, and at each one it was an instant hit.

In the early days of Facebook, membership was exclusive to college communities. You could join for free, but you had to have a college email address. The site was developed for students, but that didn't stop professors from joining as well. Since I had a Tufts email address, I signed up. My plan was to snoop on my students and prepare Powerpoint presentations for class using photos from their pages. Other than my name and a picture, I didn't post much information about myself. I didn't list my likes or dislikes, or whom I wanted to meet. At this point I wasn't networking using Facebook. Even if I wanted to, I didn't have any adult friends to connect with on the site.

Facetime in the Real World

Eventually, the two Facebook founders realized that their audience was growing up, graduating college and moving on (without their college email addresses). So, to keep their customer base, they decided that membership in the Facebook club would be broadened to include everyone. At that point, the site's exponential growth increased exponentially (not sure if that's mathematically possible, but it sounds good [and Brian's editor is letting him get away with this one]). Facebook was now out to conquer the on-line world. Soon, my adult friends were becoming members, and they started to "friend" me online. (BTW, "friend" as a verb is a Facebook innovation. It means to invite someone for online friendship. To "friend" in Facebook means that you are inviting someone to be recognized as part of your online list of friends. BTW, "BTW" is a widely texted abbreviation for the expression "by the way.") Of course, we were friends already in real life, but this friendship was a new type spawned on the website. We would be electronically linked, with special privileges like being able to see each other's wall, photo albums, videos and all sorts of other intimate electronic secrets contained on the Facebook pages.

After a while, the adults started to get into it. Just like with kids, there was a certain social competitiveness by seeing who could garner the greater number of friends on your page. College and grade school kids had hundreds and even thousands of Facebook friends, but for adults, topping a hundred meant that you were wildly popular. If I did keep track of how many friends my friends had, I would have noticed that I had more virtual friends than most of my friends. This statistic meant either that I was very popular and cool, or that I was a nerd limited to bragging about my virtual social success.

An Inanimate Friend

At about the time I made the transition to an actual, social Facebook user, I was friended by a bridge. I was invited for friendship by the Capilano Suspension Bridge in British Columbia. The Capilano Suspension Bridge is a Canadian tourist attraction near Vancouver. It is a daring pedestrian cable bridge suspended high over a deep gorge. For visitors to Vancouver, it is someplace to go. During our honeymoon, my wife Lauren and I spent a few days in Vancouver and since it was a prominent bridge, of course we visited.

Bridges are great, and I was pleased to become friends with the Capilano Suspension Bridge. However, I was a little bit confused by the request. Although bridges are excellent structures, they are definitely not alive, so it was not clear to me how the bridge could friend me, or why it would even want to. Yet, I could not resist and I accepted the invitation. The bridge entered my Facebook social network.

Building a Relationship

Over time, we got to know each other, at least virtually. The bridge has a fairly robust network of friends and activities, especially considering that it is inanimate (well, it does sway in the wind, but still it's not sentient — yet). In many ways, our new bond bridged our differences (being primarily one of living versus not being alive) and I started to see the bridge as more alive than he really was. I could see from our friendship that Capilano, or Cappy, as I like to call him, lives a charmed, exciting life, hanging as he does in that precarious position over the gorge. Cappy is also quite the party bridge. He's a swinger who's always on the lookout for fun and a good time.

With the world coming to Vancouver for the Winter Olympics in February 2010, Cappy apparently was attracting a lot of attention. After one's fill of skiing and curling (that's ice shuffleboard to the uninitiated), visiting a nice bridge turned out to be a good way to round out the trip. Cappy was greeted by hordes of new visitors, and not just on-line guests, but actual live human beings. It must have been exciting for him to meet all of those new people.

Just Like Us

So, in the end, I was pleased to learn that on Facebook bridges are like people. After being friended by the Capilano Suspension Bridge, I decided to take the bull by the horns and invite other bridges for friendship. To date, I have friended the Golden Gate Bridge, the Brooklyn Bridge and the Verrazano Bridge. The Sydney Harbor Bridge has not accepted my friendship yet — she is truly playing hard to get — but I hope that some day she will enter the orbit of my bridge friends as well. In addition to having great new bridge colleagues, my overall friend total has increased and I have become even more popular than before. Not that I'm keeping count.

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Geotechnical Instrumentation for Deep Excavations in Boston, Chris M. Erikson, Steven R. Kraemer & Edmund G. Johnson, Spring 1992, pp. 47-66

The Hazard From Earthquakes in the Boston Area, Patrick J. Barosh, Spring 1989, pp. 65-78 [Discussion by William Weiler, Fall 1989, pp. 82-84. Response by author, Fall 1989, pp. pp. 87-89.]

Heathrow Express Cofferdam: Innovation & Delivery Through the Single-Team Approach — Part 1: Design & Construction, Alan J. Powderham, Spring/Summer 2003, pp. 25-40

Immersed Tube Tunnels: Concept, Design & Construction, Thomas R. Kuesel, Spring 1986, pp. 57-78

Innovative Design for Tunnel Exchange & Excavation Support for the CA/T I-90/I-93 Interchange, James R. Lambrechts, Paul A. Roy & Stephen Taylor, Fall/Winter 1999, pp. 43-62

In-Situ Testing for Site Characterization & QA/QC for Deep Dynamic Compaction, Heather J. Miller, Edward L. Hajduk, Kevin P. Stetson, Jean Benoit & Peter J. Conners, Fall/Winter 2007, pp. 19-36

Measures to Minimize the Effects of a Deep Excavation on Two Adjacent Office Buildings: The Abutters' Perspective, Lewis Edgers, Richard Henige, Thomas L. Weinmann & Kenneth B. Wiesner, Spring/Summer 2001, pp. 53-66

Microtremor Measurements to Obtain Resonant Frequencies & Ground Shaking Amplification for Soil Sites in Boston, Kristin E. Hayles, John E. Ebel & Alfredo Urzua, Fall/Winter 2001, pp. 17-36

Modeling the Effects of Soil-Structure Interaction on a Tall Building Bearing on a Mat Foundation, Lewis Edgers, Masoud Sanayei & Joseph L. Alonge, Fall/Winter 2005, pp. 51-68

Observational Evidence for Amplification of Earthquake Ground Motions in Boston & Vicinity, John E. Ebel & Kathleen A. Hart, Fall/Winter 2001, pp. 5-16

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The Performance of a Remotely Controlled Fiber Glass Pipe Jacking System, Dipak D. Shah, Sajjan K. Jain & Robert W. Prybella, Jr., Spring 1992, pp. 7-28

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Pipe Jacking Forces in Soft Ground Construction During Utility Installation Related to Central Artery/Tunnel Project Construction, John M. Pecora, III, & Thomas C. Sheahan, Fall/Winter 2004, pp. 29-44

The Place of Stability Calculations in Evaluating the Safety of Existing Embankment Dams, Ralph B. Peck, Fall 1988, pp. 67-80

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Predictions & Observations of Groundwater Conditions During a Deep Well Excavation in Boston, Chris M. Erikson & David A. Schoenwolf, Fall/Winter 1993, pp. 37-52

Pumping Test Program for the Central Artery/Tunnel Project in Downtown Boston, Abdelmadjid M. Lahlaf, Francis D. Leathers & Iqbal Ahmed, Fall/Winter 2000, pp. 63-78

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Seismic Response Analysis of Cobble Mountain Reservoir Dam, Alfredo Urzua, John T. Christian, William H. Hover, Ivan A. Hee & Stanley Bemben, Fall/Winter 2002, pp. 7-24

A 70-Foot-Deep Mixed-Face Excavation, Richard M. Simon, Robert J. Palermo & Harry E. Risso, Spring 1991, pp. 57-68

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Slurry Wall Construction for a Cut-and-Cover Tunnel, Philip Bonanno, Donald T. Goldberg & Amol R. Mehta, Spring 1987, pp. 75-88

Trenchless Technology Considerations for Sewer Relocation & Construction, Arthur A. Spruch & John Struzziery, Spring/Summer 1996, pp. 95-102

Tunnel Boring Machine Excavation of the Beverly Sewer Tunnel, George W. Hartnell, III, & Andrew F. McKown, Fall 1991, pp. 93-110

Tunneling Projects in the Boston Area, David Woodhouse, Spring 1989, pp. 100-117

Tunneling Through Soft Ground Using Ground Freezing, Helmut Haas, Spring/Summer 2006, pp. 45-70

Underground Engineering for the Central Artery/Tunnel Project, Thom Neff, Spring/Summer 1996, pp. 7-10

An Underpinning Scheme for the Red Line Subway at South Station, Boston, Burton P. Kassap, Spring 1992, pp. 67-86

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HISTORY

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BSCES Honorary Members [John T. Christian, William J. LeMessurier, Maurice A. Reidy, Jr., & Kentaro Tsutsumi], Fall 1988, pp. 89-93

Cape Cod Canal, H. Hobart Holly, Spring 1987, pp. 109-113

The Charles River Basin, H. Hobart Holly, Fall/Winter 1993, No. 2, pp. 77-80

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The Engineering Center: One Walnut Street, Boston, H. Hobart Holly, Fall 1990, pp. 91-94

In the Footsteps of Giants: The History of the Founders of Earth Pressure Theory From the 17th Century to the Late 19th Century, Nabil M. Hourani, Fall/Winter 1996, pp. 79-92

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Lee Marc G. Wolman, Fall/Winter 2006, pp. 65–67

Lenticular Iron Truss Bridges in Massachusetts, Alan J. Lutenegger & Amy B. Cerato, Spring/Summer 2005, pp. 53–74

Lowell Waterpower System, H. Hobart Holly, Fall 1986, pp. 141-144

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The Middlesex Canal, H. Hobart Holly, Fall 1992, pp. 104-106

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Protecting Historic Buildings on the Central Artery/Tunnel Project: The Project Conservator Program, Beatrice Nessen, Spring/Summer 1996, pp. 21-30

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The Limited Benefits of Flood Control: An Interview With Lu Qinkan, Chen Kexiong, Spring/Summer 1997, No.1, pp. 99-103

Long-Range Surface Water Supply Planning, Richard A. Vogel & David I. Hellstrom, Spring 1988, pp. 7-26

Mamaroneck Effluent Pumping Station Wet Well Model Study: Necessity or Redundant Design Precaution?, Peter J. Barthuly & Mahadevan Padmanabhan, Spring 1990, pp. 69-84

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The Three Gorges Project & Sustainable Development in China, Dai Qing, Spring/Summer 1997, No.1, pp. 73-92

Urban Stream Restoration & Daylighting — Is Boston Ready for Another Emerald Necklace?, Vladimir Novotny, Spring/Summer 2009, pp. 43-64

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STRUCTURAL

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Applying Orthotropic Deck Design to a Vertical Lift Bridge, W.J. Gaddis & P.W. Clark, Fall 1989, pp. 65-68 [Discussion by Ali Touran, Fall 1990, pp. 95-97.]

Aqua Teen Hunger Force Attacks I-93!, Brian Brenner, Spring/Summer 2007, pp. 71-75

Bridge Rehabilitation, Frank Stahl, Fall 1990, pp. 7-40

Building Technology for Microelectronics Clean Room Design, William L. Maini, Michael K. Powers & Mario J. Loiacono, Fall 1986, pp. 7-26

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Design and Construction of the Circular Cofferdam for Ventilation Building No. 6 at the Ted Williams Tunnel, Minhaj Kirmani & Steven C. Highfill, Spring/Summer 1996, pp. 31-50

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Design of a Suspension Bridge Anchorage System, William R. Hughes, Spring/Summer 1993, No. 3, pp. 41-54

Design of the High Street Ramp, Boston, Abdol R. Haghayeghi & Peter J. Quigley, Spring/Summer 1993, pp. 29-40

Designing & Analyzing Prestressed Concrete Members Using a Capacity Diagram, Lucian Nedelcu, Fall 1989, pp. 75-81

Designing & Building the Sagadahoc Bridge Between Bath & Woolwich, Maine, George R. Poirier, Bruce VanNote, R. Kent Montgomery, William J. Rohleder, Jr., & C. Eric Burke, Spring/Summer 2005, pp. 37–52

Effects of Increased Wind Loads on Tall Buildings, Masoud Sanayei, Lewis Edgers, Joseph Alonge & Paul Kirshen, Fall/Winter 2003, pp. 5-16

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Evaluation of the Canoe Creek Bridge Abutments, Bohdan I. Czmola, Spring 1987, pp. 59-74

An Examination of Up/Down Construction: 125 Summer Street, Boston, Farzad Khabiri, Spring 1991, pp. 25-38

General Design Details for Integral Abutment Bridges, Amde M. Wolde-Tinsae & Lowell F. Greimann, Fall 1988, pp. 7-20

Go Jump Off a Bridge, Brian Brenner, Fall/Winter 2008, pp. 61-64

An Innovative Design for the Flood Protection System of a Riverside Development, Gunars Richters, Spring/Summer 1993, pp. 5-12

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Major Engineered Structures in Boston, Edmund G. Johnson, Spring 1989, pp. 89-99

Managing Human Error in Structural Engineering, David P. Brosnam, Spring/Summer 2008, pp. 33-46

Massachusetts Earthquake Design Codes, S.A. Alsup & K.E. Franz, Spring 1989, pp. 79-82 [Discussion by William Weiler, Fall 1989, pp. 85-86. Response by author, Fall 1989, pp. 90-91.]

A Method for Underpinning Bridge Foundations & Its Application in the NSC Project in Pittsburgh, Firooz Panah, Matt Pierce & Keith Chong, Fall/Winter 2009, pp. 41-58

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The Performance of Highway Bridges in the Northridge, California, Earthquake, National Center for Earthquake Engineering Research, Fall/Winter 1995, pp. 5-26

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Planning the First Central Artery in Boston, Cranston R. Rogers, Fall/Winter 1998, pp. 57-60

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A Model Coastal Zone Building Code for Massachusetts, Ad Hoc Committee on Coastal Zone Building Codes of the BSCES Waterway, Port, Coastal & Ocean Engineering Technical Group, Fall 1991, pp. 21-30

Modern Marina Layout & Design, Duncan C. Mellor, Spring 1992, pp. 87-102

The Rehabilitation & Modernization of Fitting Out Pier 2 at Portsmouth Naval Shipyard, Cheryl W. Coviello, Fall/Winter 2006, pp. 5–20

Replacement of the Sandy Hook Front Range Light, Noah J. Elwood & Chris Lund, Spring/Summer 2003, pp. 51-62

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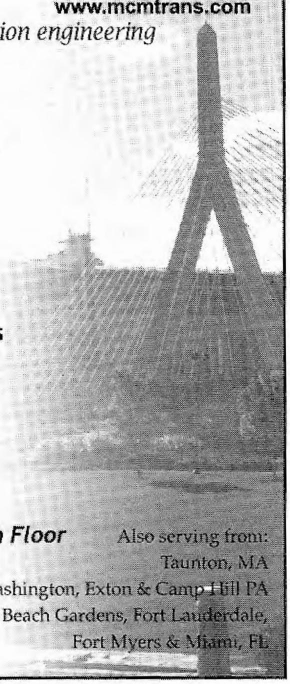

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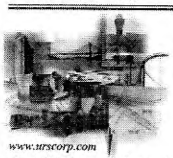

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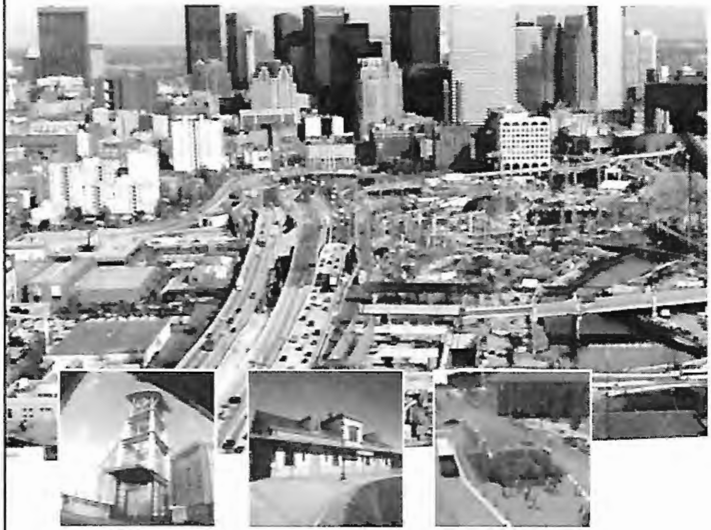

Tobin Bridge as seen from Boston Harbor.
Photo by Patrick Barber.