Battery-Joralemon Street Tunnel

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Abstract: The construction of the Battery-Joralemon Street Tunnel is described. Built between 1903 and 1907, it was the first subway tunnel placed in service under the East River between Manhattan and Brooklyn. Both heading-and-bench rock tunneling and pressurized shield soft-soil tunneling techniques were used. Loss of control of the tunneling shield in partially saturated sands caused variations in alignment that made portions of the tunnel nonfunctional. Approximately 3,000 ft of the tunnel had to be reconstructed to enable subway cars to use the tunnel safely. Additionally, due to concerns regarding the stability of the tunnel in the soft soils, piles were installed under the tunnel to bedrock. The project was a crucible for subway contractors and engineers of the Rapid Transit Commission, especially Clifford M. Holland. His experience on the Joralemon Street Tunnel enabled him to efficiently and safely complete four other East River subway tunnels after the Dual System Agreement of March 1913.

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Introduction

Soft-soil subaqueous tunnels were literally and figuratively "cutting edge" early twentieth century engineering technology. At the time of their construction, these tunnels were viewed as marvels of human achievement, centerpieces of a time period defined by great strides in infrastructure development. Today, their continued functionality and usefulness attest to the sound engineering and construction practices behind them. Writers such as Gilbert et al. (1912); Vogel (1964); and West (1988) have documented the technological facets of soft-soil subaqueous tunneling, while writers such as Peters (1996); Bobrick (1981); and Hood (1993) have discussed the effects these tunnels have had on society. In the U.S., the pioneering North (Hudson) River Tunnels, the St. Clair River Tunnel, and the Pennsylvania Railroad (PRR) East River Tunnels are justly celebrated.

This paper discusses the lesser-known Battery-Joralemon Street Tunnel, the first subway tunnel placed in service under the East River, built between 1903 and 1907. It is currently used by No. 4 and No. 5 Lexington Avenue subway express trains carrying nearly 25,000 inbound passengers every weekday morning rush hour from Brooklyn to Manhattan, and 175,000 passengers in both directions in a 24 h day (R. A. Olmsted, personal communication, 2004). With the Harlem River Tunnel, it was one of the two subaqueous tunnels in William Barclay Parsons' original subway plans. The project was beset by heartbreaking construction difficulties that required unprecedented technological solutions. Perhaps the most appropriate description of the tunnel comes from J. C. Meem, one of the tunnel engineers, who stated:

"I think I may say here what is very firmly rooted in my mind as a safe statement of fact, that there has never been anywhere in the world a piece of work more difficult, or work which has eventually been carried out more successfully, than this East River Tunnel ... I do not believe that history has recorded or will ever again record the successful completion of any other piece of work more difficult than this Battery Tunnel taken in its entirety." [Discussion to Noble (1908)].

Meem's judgment was undoubtedly based on the demoralizing variety of soil and rock conditions through which the Battery-Joralemon tunnel had to be driven. By far the greatest difficulty was posed by the transition from unsaturated to saturated, boulder-strewn sands in the Brooklyn headings. Control and operation of the tunneling shields in this transition proved to be practically impossible. Despite superhuman effort, the tunnel deviated significantly from grade and required extensive reconstruction before it could be used.

After completion of the tunnel in late 1907, no additional subaqueous subway tunnels were begun in New York until after the March 1913 "Dual System Agreement" (Black 1937). This hiatus enabled Clifford Milburn Holland, a newly graduated engineer who breathed his "first air" in the Battery-Joralemon Street Tunnel in July 1906, to study and publish on the principal difficulties and construction-operations issues faced on the Battery-Joralemon Street Tunnel (Holland Collection, Kelvin Smith Library, Case Western Reserve University). With the benefit of this experience, Holland later successfully and safely completed other East River subway tunnels and his masterpiece, the eponymous Holland Tunnel (National Historic 1984).
Precursors and Contemporaries: Subaqueous Tunneling Technology in 1903

The Battery-Joralemon Tunnel was designed and built at a time when soft-soil, subaqueous tunneling technology had been in use and development for over 50 years. Typical tunneling operations and the dangers involved were known, although not fully understood. The development of the tunnel shield was key to subaqueous tunneling. The first use of the tunnel shield was in the River Thames Tunnel, built between 1824 and 1843 and designed by Marc Isambard Brunel and his son, Isambard Kingdom Brunel (Peters 1996). Brunel’s shield was a rectangular box, 22 ft, 3 in. tall and 37 ft, 6 in. wide, weighing 120 t and consisting of several independent sections (Vogel 1964). Brunel described it as an “ambulating coffer dam,” and it was the largest single piece of machinery used for building in its time (Peters 1996). Each independent frame of the shield was forced through the Thames sediments and clay by mechanical screwjacks that reacted against the green masonry tunnel lining.

Although Brunel’s shield concept was seminal, the innovations of Peter William Barlow, a resident engineer on the Lambeth Suspension Bridge in London, defined subsequent tunneling technology. Barlow observed circular caissons being sunk for the bridge’s foundations and realized that similar technology could be used to form a tunnel (Bobrick 1981; West 1988). In 1864 and 1868, Barlow patented a circular tunnel shield based on this idea (Vogel 1964). Instead of an ungainly box split up into several subcomponents, Barlow reduced his shield to a single unit that weighed only 2 1/2 t (Bobrick 1981). By making his shield circular, Barlow avoided potential construction difficulties from rotation of the shield about its axis. Barlow’s other important innovation was the use of a cast iron tunnel lining, formed by bolting together circular flanged segments as shown in Fig. 1.

Unlike previous masonry linings, the cast iron was immediately able to handle the reactive forces from the jacks pushing the shield forward. Barlow’s shield and cast iron lining were used for the Tower Subway, a pedestrian tunnel built by James Henry Greathead under the Thames from 1868 to 1869. Shields were later extended so that the most recently placed lining ring was still inside the tail end of the shield. This meant that the actual tunnel was slightly smaller in diameter than the shield. The gap between the soil and the shield was usually filled in with grout.

As tunnels increased in diameter, mechanical means for placing the increasingly heavy iron segments were developed. The St. Clair River Tunnel, connecting Sarnia, Ontario, and Port Huron, Mich., and built between 1889 and 1890, used two exceptionally large shields that were 21 ft, 7 in. in diameter and 16 ft long. Joseph Hobson, the chief engineer, designed counterweighted radial mechanical arms to erect the tunnel lining (The St. Clair Tunnel 1890; Opening 1891; Hyde 1995).

Tunneling under compressed air was first used in the U.S. for the Hudson River Tunnels. These tunnels have a long and varied history, their construction spanning 30 years under prominent engineers such as J. H. Greathead, Charles Jacobs, and J. Vipond Davies. Dewitt C. Haskin, the tunnel’s first engineer, proposed the construction of a tunnel beneath the Hudson River to link New Jersey and New York City. In 1874, Haskin took out a patent for working under compressed air and implemented it in the tunnel in 1879. Haskin planned to use only compressed air and no shield or timbering at all (Moran 1924; West 1988). However, he could not accurately predict or account for the pressure distribution in the soft soil of the Hudson River. In July 1880 a massive and much publicized “blowout”—a burst of pressurized air that forces its way out of the tunnel and through the sediments causing a drop in air pressure in the tunnel which in turn allows cave-ins and flooding—caused the death of 20 workers (West 1988). This incident showed that compressed air alone was not a reliable support and did not provide for adequate safety for the workers. When construction of the tunnel was restarted in 1891, a shield was used in conjunction with pressurized air.

Not only were shield, lining, erection arm, and compressed air technologies largely developed at the time of the Battery-Joralemon Tunnel, but basic construction operations had been worked out as well. A key aspect of soft-soil tunneling was the operating air pressure, especially when traversing porous materials. The unit weight, porosity, shear modulus, and permeability of subaqueous soils can vary in an indeterminate manner. These parameters affect the pressure gradient along the height of the shield. Conversely, the air pressure inside the tunnel is necessarily uniform over the tunnel’s face and usually was set equal to the hydrostatic head at the midheight of the shield. Therefore there was a pressure imbalance at the plane of the shield’s face; the pressure in the soil and the pressure in the tunnel were not equal over the entire height of the face. This imbalance could and often did lead to problems such as flooding of materials at the bottom of the face or blowouts. Another important facet of tunneling operations was the steering of the shield to maintain line and grade. Engineers and contractors learned that to maintain line and grade the shield had to be pushed with “leading edges.” This procedure is illustrated in Fig. 2. In effect, the plane of the circular cutting edge was not maintained perpendicular to the theoretical tunnel centerline but was angled slightly to prescrib. These leads were changed on the basis of almost continuous checking of the line and grade of the completed tunnel (Fargie 1907; Holland 1916). The mechanical properties of the soft soil encountered determined whether the shield could be pushed through the soil.

Fig. 1. Manual placement of cast iron lining segments on the Tower Subway (Vogel 1964)
casualties. This tunnel was constructed between 1892 and 1893 under the direction of Charles Jacobs. It followed precedent by being shield-driven with the use of compressed air. However, the air pressure was so high in the tunnel, reaching 52 psi above atmospheric, that uncounted numbers of workers suffered and many died from the bends. Walton I. Aims, who would subsequently be a contractor on the Battery-Joralemon Tunnel, served as an engineer on the Ravenswood Tunnel and described its construction in detail (Aims 1896).

Use of a shield and pressurized air was not the only tunneling method being developed at the turn of the century. An alternate method, which is clearly less hazardous to tunnellers but requires more surface disturbance and construction, involves sinking completed sections of tunnels under the riverbed in dredged trenches. Black (1937) notes that in 1893 to 1894, H. A. Carson built a 9 ft diameter water line under Boston harbor by prefabricating 52 ft sections and sinking them into dredged trenches. The prefabricated-tube-in-trench method was also used for the River Seine Tunnel, the major subaqueous tunnel of the early Parisian subway system. This tunnel, completed in 1906, was a contemporary of the Battery-Joralemon Tunnel (The remarkable 1906). The tube-in-trench method was also used for the Detroit River Tunnel, built between 1907 and 1910 for the Michigan Central Railroad (Sinking the Detroit 1907). A modified trench method was used for the first Harlem River subway tunnel (Section nine 1903; The Harlem 1904). But the variety of soil and rock conditions and the heavy East River traffic precluded the use of the tube-in-trench technology for the Battery-Joralemon Tunnel.

Two East River tunneling projects were contemporary with the Battery-Joralemon Street Tunnel: the Steinway (also known as Belmont) Tunnel of the New York and Long Island Railroad and the Pennsylvania Railroad Tunnels. Access shafts for the Steinway Tunnel were begun in 1904 (The New York 1906), and by March 1907, the east and west headings were about 400 ft apart (The Belmont 1907). On September 24, 1907 a subway car made a demonstration run through the tunnel. However, because a completion deadline was not met, or more likely because the Steinway Tunnel posed a private competitive threat, the city voided the franchise to operate the tunnel. A franchise was not granted until after the city gained ownership of the tunnel. The Steinway Tunnel was not placed in service until June 25, 1915 (Miller 1915). The great Pennsylvania Railroad Tunnels were built under the direction of Charles Jacobs from 1904 to 1909 (Gilbert et al. 1912). Volumes 68 and 69 of the ASCE transactions are completely devoted to the PRR tunnels and the railroad's Long Island facilities. While the Pennsylvania Railroad Tunnels spread over many different geological conditions in and around New York City, the most expensive and difficult portions of the project were the East River tunnels, connecting Manhattan Island to Long Island (Gilbert et al. 1912). Gilbert describes the changing geology in the headings east from Manhattan, stating:

"The rock was Hudson schist and Fortham gneiss. The latter was slightly the harder and both were badly seamed and fissured. When the rock surface was encountered it was covered with a deposit of boulders, gravel and sand varying in thickness from 4 to 10 feet ... The rock surface was very irregular and it was covered with boulders and detached masses of rock hedged in coarse sand and gravel ... When the shields had entirely cleared the rock the material in the face had changed to a fine sand, stratified every few inches by very thin chocolate-colored clayey material ... The surface of the sand and gravel was
irregular but rising gradually ... East of [Blackwell’s Island] reef a large quantity of coarse open sand was present in the gravel formation before the clay appeared below the top of the cutting edge.” (Gilbert et al. 1912)

The mixed face of the East River made the choice of operating air pressure much more difficult. The air, which reached as high as 42 psi above atmospheric, had to be kept at relatively high pressures due to the overlying porous materials. As usual, the air pressure was kept at approximately the same pressure as the hydrostatic head at the midheight of the shield. This led to a pressure imbalance, allowing the top and the middle portions of the face to remain firm while the lower portion was not supported (Gilbert et al. 1912). Compressed air then escaped through the mixed face, increasing the rate of internal flooding and the hazard of a blowout. Jacobs and his engineers adopted the technique of preventive clay blankets, placing clay over those portions of the natural riverbed where the tunnel excavation passed close to the bottom of the water (The meeting 1908). This technique had previously been used for the Blackwall Tunnel, built between 1892 and 1896 under the Thames (Prelimi 1907). It was a simple yet effective means of decreasing the chance of blowouts that would also later be used for the Battery-Joralemon Street Tunnel.

No explicit evidence has been found on information or technology transfer between engineers on the PRR tunnels and engineers on the Battery-Joralemon tunnel, yet it is reasonable to assume that the techniques engineers on the PRR tunnels developed in response to the difficult conditions of the East River were known and considered by engineers of the Battery-Joralemon tunnel.

Transportation in New York: William Barclay Parsons and the IRT

Contemporary observers describe nineteenth century surface transportation in New York City as a “mob in locomotion” (Greene 1837) with streetcars “full of vermin” (McCabe 1883). In the context of the Brooklyn Bridge, McCullough (1972) notes that ferry crossings of the East River were also dangerous, overflowing with passengers who experienced winter rides “as treacherous as an Atlantic voyage.” Bobrick (1981) and Hood (1993) recount the political and social history of the New York subway system in detail. The first serious idea arose in 1866, a plan for an underground railway system called the Arcade Railway. William Barclay Parsons, perhaps one of the most well-respected engineers in the history of civil engineering, joined the Arcade Railway Company in 1885. Parsons had been attracted by the challenge of developing a subway system to compete with the “eis,” omnibuses, and trolleys on the overcrowded streets of New York. However, Parsons, a man who had already written several definitive texts on engineering practices in railway systems and waterworks, quickly found that the Arcade’s plans were nothing more than “highly colored pictures or prints” (Bobrick 1981). Disappointed with the lack of organization and technical capabilities of the company, Parsons and other employees of the Arcade split off to form a rival company, the New York District Railway. Parsons’ company and the Arcade Railway Company went through several lawsuits, arguing for their respective legacies in designing the subway system for the city. Both companies went bankrupt and dissolved (Hood 1993).

Instead of being disillusioned by this experience, Parsons became more intent on the construction of a working and practical subway system. Parsons lobbied for another chance at building the subway and studied the geology and topology of Manhattan and the surrounding areas. Parsons claimed that he had “familiarized himself with every foot of land on Manhattan Island” (Bobrick 1981). His efforts paid off when the Rapid Transit Act was passed in 1894, and a Rapid Transit Commission devoted to the creation of a subway was formed. Parsons was appointed chief engineer in charge of design of the entire project (Hood 1993). In 1895, an engineering plan based mostly on Parsons’ ideas was sketched out and submitted for approval (Bobrick 1981); but approval for use of public funds met several political and economic roadblocks. Parsons began to despair that the New York subway would never be built. In 1898, he traveled to China on a surveying commission; however, in March of 1899, Parsons was informed that the subway plans were about to be approved (Bobrick 1981). Parsons immediately left China and returned to his original passion, that of constructing the New York subway. The economic, social, and political processes that preceded the awards of the subway contracts are described by Katz (1979). A unique aspect of the Rapid Transit Act was that it mandated one contract for both construction and operation. That is, the successful bidder had to demonstrate the ability not only to build the subway but also to operate it under a 50 year lease with the City. Financier August Belmont II conceived and carried out the successful strategy. For construction expertise, Belmont formed a construction entity, the Rapid Transit Subway Construction Company, in “partnership” with contractor John R. McDonald. On January 16, 1900, McDonald was awarded “Contract No. 1” for the construction of the subway north from City Hall and across the Harlem River to the Bronx. In May 1902, Belmont formed the private operating entity, the Interborough Rapid Transit Company (IRT). Construction of the Contract No. 1 phase of the subway began in March of 1900 under the direct supervision of Parsons, who resumed his role as chief engineer of the Rapid Transit Commission.

Two subaqueous tunnels made the original subway line truly “interborough;” the Harlem River crossing to the Bronx and the crossing of the East River from Battery Park in Manhattan to Brooklyn. The first of these tunnels, the Harlem River Tunnel, consists of two single-track cast-iron tunnel tubes 16 ft in diameter (Gilbert et al. 1912). It had been determined early in the exploration that “the mud was ... so thin that tunneling by the shield method was practically out of the question” (The Harlem 1904; Compressed air 1904). Therefore the Harlem River Tunnel tubes were constructed with a version of the tube-in-trench method of tunneling. Trenches were dredged in the Harlem River, and tunnel sections were sunk as caissons. The land work was just as difficult as the subaqueous work. Since the land portions of the tunnels were under commercial streets, temporary wooden bridges were built over the trenches to support passing trolleys, carriages, and wagons (Hood 1993). The tunnelers also needed to maneuver around existing storage vaults, sewer systems, and utilities, either avoiding or supporting and shoring up the extant infrastructure. At certain locations of the tunnel’s path, blasting of the Manhattan schist was necessary. Parsons was chief engineer during the exploration, design, and initial phases of the construction of the Battery-Joralemon Tunnel; however, he did not see the project through its dangerous and difficult construction. Parsons gave very brief remarks at the official opening of the IRT subway on October 27, 1904. Shortly afterwards, Parsons resigned his position with the commission.
Battery-Joralemon Street Tunnel

The description of the Battery-Joralemon Tunnel that follows is based largely on contemporary papers in trade journals and on documents in the Clifford M. Holland Collection at Case Western Reserve University. The collection was donated by Mrs. Benita H. Low, Holland's daughter, to the Case Institute of Technology Archive of Contemporary Science and Technology in September 1965. The collection comprises eight boxes of materials. It includes drafts of some of Holland's manuscripts, notes for speeches, some of his homework assignments, and materials on all the East River subway tunnels. The collection has a copy of the Record Drawings for the Battery-Joralemon Tunnel, dated June 7, 1924 and signed by Robert Ridgway. These drawings are extraordinary, a tour-de-force of graphical display of information. Fig. 3 shows a portion of drawing C.2-S.2A No. Tube, Sheet No. 21, from stations 85+60 to 88+10 (Record drawings 1924). The drawing shows, in part:

- Excavation timeline;
- Concreting timeline;
- Air pressure timeline;
- Elevations;
- Soil types;
- Approximate location and sizes of boulders;
- River bulkhead and old piles;
- Warehouse building settlements;
- Type of cast iron lining;
- Clay blanket on riverbed;
- Information on blowouts;
- Locations of reconstruction;
- Average rate of shield progress, "including Sundays, Holidays and all delays;"
- An elevation of the theoretical and actual locations of "bottom of top flange and top of bottom flange of cast iron lining;"
- A plan of the theoretical and actual locations of "north and south flanges of cast iron lining;" and
- Data on concrete lining and grouting.

These Record Drawings are invaluable documents for civil engineering history and heritage. Among the most poignant items in the collection is a copy of "extracts from weekly reports" on the excavation covering the period from November 28, 1903 to
November 12, 1904, written by an anonymous site engineer. These notes give a glimpse into the actual working conditions in the tubes. They provide a stark contrast with the sanitized, matter-of-fact descriptions found in the trade journals.

Fig. 4 shows plan and elevation views of the Battery-Joralemon Tunnel. The tunnel consists of two single-track tubes, about 28 ft apart, each with a clear diameter of 15 ft, 6 in. The tunnels have slopes of 3.1% with low points about 94 ft below mean high water. In a talk delivered before the Brooklyn Engineers’ Club on February 13, 1908, shortly after completion of the tunnel, Noble (1908) notes that the Board of Rapid Transit Railroad Commissioners (Board) adopted a resolution in favor of the Joralemon Street route on January 24, 1901. Both Noble (1908) and Prelini (1907) observe that the actual centerline of the tubes was moved slightly south after the start of construction so that it would fall between Brooklyn Piers 17 and 18 and thus avoid most of the pilings of Pier 17. Prelini (1907) also mentions that, after some litigation, the slip between Piers 17 and 18 was filled in. Prelini (1907) provides some details on the triangulation performed to establish the position of the tunnel. Two “fully braced” surveying quadrilaterals were closed to determine the distance between a station on Manhattan Pier 4 and another station on Brooklyn Pier 17. One of the triangulation quadrilaterals used the towers of the Brooklyn Bridge as observation stations, and “the distance between the bridge towers was measured by means of the 1,600 ft continuous tape, suspended from the lateral bracing at distances of 15 ft due north of the top chord of the stiffening truss on the north side of the footway” (Prelini 1907).

The subsurface exploration for the tunnel is described in Test borings (1902), by Prelini (1907), and by Noble (1908). Both wash borings and diamond drill borings (7/8 in. cores) were done. The work was performed in very difficult conditions caused by the congested East River traffic and tidal currents of up to 6 mph. Wash borings were done approximately every 80 ft along the tunnel centerline. Noble (1908) states that seven diamond drill borings were done; Prelini (1907) states that 12 were done. Noble describes some of the results of the explorations:

“The borings showed that the tunnel would pass generally through rock on the Manhattan side to a point near the middle of the river, and again through an up-crop of rock before reaching the Brooklyn side...the rock was generally found to be a good character mica schist or gneiss...under Joralemon Street and part way out in the slip between Piers 17 and 18 the sand was of ordinary coarseness and contained considerable gravel, cobbles and boulders of all sizes. Between the two rock formations and east of the Brooklyn reef, the sand was found to be extremely fine and often contained a certain admixture of clay. This material is of the same nature as the quicksand encountered in foundations in the lower part of Manhattan Island, and shows a similar marked tendency to run whenever disturbed.” (Noble 1908)

The exploration certainly identified the rock reef (sometimes called “Man-o-War” reef) in the middle of the river and hence the number of transitions in tunneling methods that were required (see Fig. 4). The coarse sand with boulders on the Brooklyn side and the transition from unsaturated to saturated conditions were also identified. It seems then that the contractors knew the variety of soils/rock that was going to be encountered. However, contemporary papers do not express concerns about properties and behavior of the various soils in subaqueous conditions nor about the number of different modes of excavation and shield operation that the subsurface conditions demanded. Having few precedents, engineers and contractors may have underestimated or not understood the difficulties posed by the varied soil conditions.

Board engineers designed the tunnel and prepared bid documents. In addition to the chief engineer, W. B. Parsons,
Fig. 5. Longitudinal and transverse sections of the shield and cast-iron shell (The New York and Brooklyn 1904b)

contemporary journals name three other Board engineers: George Staples Rice, deputy chief engineer; Robert Ridgway, division engineer; and J. C. Meem, assistant engineer (later on, G. S. Rice became chief engineer, Alfred Craven became deputy chief engineer, Fredrick Noble became division engineer, and J. C. Meem worked as an engineer for two of the contractors). The writers have not found documents relative to the detailed design of the cast iron lining, the reinforced concrete lining, the ventilation system, or other features of the tunnel. The Board authorized advertising for bids on June 12, 1902. The IRT Co., through its construction arm, the Rapid Transit Subway Construction Company, bid only $3 million to construct this portion of the subway, a project estimated to cost at least $8 million. With the extremely low bid, the IRT Co. assured itself of winning the contract and therefore that it would be the sole operator/lessee of the entire subway line. To appease critics of the single-operator condition, the lease was reduced to 35 years (Katz 1979). The contract was predictably awarded to the IRT/Rapid Transit Subway Construction Co. on July 24, 1902 and was executed as “Contract No. 2” on September 11, 1902 (Noble 1908). The Rapid Transit Subway Construction Co. in turn subcontracted all the work to three contractors: The Degnon Contracting Company for the Manhattan land portion, the New York Tunnel Company for the subaqueous tubes and part of the Brooklyn land portion, and Cranford and McNamee for the remainder of the Brooklyn land portion (Prelini 1907).

The tunneling shields, shown in Figs. 5–7, were designed for the New York Tunnel Company by Walton I. Aims, the engineer

Fig. 6. Erector arm and rolling platform on a Battery-Joralemon shield (The New York and Brooklyn 1904b)
who designed the shields for the Ravenswood Gas Tunnel. The shields were 16 ft, 11 1/4 in. in diameter and 9 1/2 ft long. They were double walled with an outer plate 5/8 in. thick and an inner plate 1/2 in. thick. Each shield had 14 hydraulic jacks with 8 in. diameter pistons with a 30 in. stroke. The shield was followed by a 14 1/2 ft by 10 1/2 ft traveling platform with a counterweighted erecter arm (The New York and Brooklyn 1904a,b). The platform traveled on rollers supported by movable brackets attached to the tunnel lining (see Figs. 6 and 7).

A total of five access shafts were excavated, three in 1903 and two in 1904 to 1905. One shaft in Manhattan provided access for both the south and north tubes. It measured 14 ft by 52 ft in plan and was begun on March 4, 1903 ("The Brooklyn Tunnel" 1903). Noble (1908) provides a chronology of the Brooklyn shafts and the excavation of the eastward headings:

"The first Brooklyn shafts, one for each tube, were located in Joralemon about 1300 ft. inland from the river, just west of Henry Street, and about 700 ft., from the end of the tunnel section. Excavation of the south shaft began April 16, 1903 and for the north shaft June 10, 1903. They were each 20 ft. by 24 ft. in plan, sheeted with 4 in. tongued and grooved sheathing, and extended 65 ft. below the surface to the bottom of the tunnel. The first portion of the tunnel to be built in Brooklyn was the length of about 700 ft. in each tube east from the shafts to the end of the section. The shield for the south tube was started east July 10, 1903 and reached the end of the section January 11, 1904. The shield for the north tube was started east September 15, 1903 and reached the end of the section January 16, 1904." (Noble 1908)

The first Brooklyn shafts were located so that their bottom elevations were approximately equal to the mean high water elevation. Therefore the eastern, landward headings proceeded in dry conditions and in "normal" air. The south and north westward shields began their slow descents into the saturated sand on November 12, 1903 and February 2, 1904, respectively. What followed was a prolonged nightmare of construction problems, inhuman working conditions, and constant fear of tunnel collapse.

On November 18, 1903, at the south tunnel heading, while still in normal air, cracking was observed in some of the tunnel segments. With the bottom of the shield in approximately 2 ft of water, pumping became necessary to place the lower segments of the tunnel lining. On December 10, with approximately 4 ft of water at the base of the shield, tunneling was stopped to build a brick bulkhead so that the tunnel could be pressurized. Despite the bulkhead, when the pressurized air was released into the heading, air leakage through the sand face prevented any significant pressurization of the tunnel. From January to May 1904, the air pressure in the south tunnel never exceeded 2.5 psi (Record drawings 1924). From November 1903 to May 1904, the south tube heading advanced approximately 415 ft, or only about 2.3 ft per day. This very slow advance was possibly only because of constant, heavy pumping by multiple pumps. It is now understood that the pumping increased the effective stresses in the sand, which in turn led to settlements and increased pressures on the tunnel lining. Many buildings along Joralemon Street settled 3 to 4 in. as the shield progressed underground. The soil pressures caused cracking in the cast iron lining and distortion of the circular cross section of the tunnel. In addition, the pumping undermined the shield, and control of the grade and line became practically impossible. On February 18, as the shield was being pushed, its "cone plate" was bent by a boulder. The boulder had to be fractured by a dynamite charge, and repairs took approximately 2 months to complete. Pushing was resumed on April 5, but on April 30, a site engineer wrote:

"Progress of the shield was very slow, averaging one ring per day for seven days. Delays are becoming almost continuous, owing to (1) soft ground in bottom due to pervision (sic) of water in bottom, (2) settlement of shield and tube, which leads to cracking of plates, and (3) boiling up of sand and water under the advance ring in the tail of the shield, which leads to settlement of the tube. Work was shut down to pack the jacks on Monday, Tuesday and Saturday, twelve hours each time. If a sufficient air pressure could be maintained most of the trouble could be avoided I believe. With about 6000 cu. ft. of air pumped into this tube per minute the maximum pressure maintained was only about 2-1/2 lbs., the air escaping freely through the sand... The shield has lost grade in a serious way this week in spite of constant efforts made to hold it up. In consequence the top of the tube at the end of the week was about 1.5 ft. low. The tube in settling has also flattened, so that the vertical diameter measures about 5° less and the horizontal one 5° more than 15.5 ft. Most of the settling seems to occur during the erection of the bottom plates of the lining, when constant pumping is necessary to lower the water sufficiently for the purpose." (Holland Collection—"Extracts")

On May 3, 1904, tunneling at the south tube was stopped with the top of the tube "about two feet below grade" (Holland Collection—"Extracts"). The pumping was continued but the excavation was not resumed until November 4, 1904.

Pushing the north tube shield of the westward Brooklyn heading began on February 2, 1904, despite the difficulties in the south tube. Excavation proceeded without compressed air until March 19, when it was halted to construct a bulkhead. When that work was completed, pressurized air was "turned on" on May 4, a day after the south tube heading was shut down. As before, the north heading could not be pressurized. No air pressures greater than
3 psi were achieved until July 19, 1904. The tunnelers again resorted to pumping in order to be able to place the lower segments of the tunnel lining. Additionally, 6 in. diameter holes were drilled in the bottom plates of the rings, and well heads were installed. By June 4, pumping was in progress at five well heads (Holland Collection: "Extracts"). The effects of the pumping were the same as those at the south tube; cracked lining segments (even though sections that were 14% heavier had been adopted), distortion of the cross section, building settlements, and extreme difficulties in maintaining line and grade. By May 21, the tube had "assumed a grade of about 5% instead of 3.1%" (Holland Collection: "Extracts"). By May 28, the top of the tube "was about 2.4 ft. too low" (Holland Collection: "Extracts"). By June 18, to reduce the distortion of the cross section, the contractor was "placing chains every fourth or fifth ring across at the horizontal diameter to act as tie rods, being kept taut by means of turn-buckles" (Holland Collection: "Extracts"). By July 23:

"The heat in the heading has been greater on account of the warm weather, and its effect is noticed in the falling off of the efficiency of labor. The contractor has boxed in the receivers and air pipe with a view to cooling the air, but the cool surface is too little to show any appreciable effect on the temperature of the air, which discharges into the heading at a temperature of about 110°F." (Holland Collection: "Extracts")

On August 5, 1904 W. Barclay Parsons and G. S. Rice visited the tunnel. They found a partially flooded south tube, halted since May 3; the north tube heading fighting water with no effective air pressurization; no routine shield operation; cracked plates; leaks; intolerable working conditions; and, above all, completed sections with grade variations that clearly made them nonfunctional. In a later report, Rice took the predictable position of a design engineer:

"The cause of the trouble was the failure of the subcontractor to maintain a sufficient air pressure at the shield to keep out the water, and so keep the ground in a proper condition to maintain the weight of the shield. Instead of keeping the pressure high for this purpose, which might have been done by increasing the supply of air, or by the use of special devices or methods to diminish its loss, the excess of water was diminished by pumping. The effect of this pumping was to draw the sand from underneath the shield, the heavy weight of which caused it to settle gradually...." (Report on the defects 1906)

Rice did not estimate the supply of air that would have been sufficient nor did he specify the "special devices or methods." The Engineering Record issues of March 5 and March 12, 1904 contain two extensive articles on the Battery-Joralemon Street Tunnel, with exceptional graphical details of the tunnel alignment and of the shields (reproduced in Figs. 5-7) but with no mention of the desperate struggles at the Brooklyn headings.

Tunneling conditions finally began to improve at the end of August 1904, when the top to the tube was approximately 9 ft below mean high water and the face material was a finer, denser sand. This more impervious soil and the installation of a new bulkhead, closer to the heading, enabled an air pressure of 8 psi to be maintained, enough to control the ingress of water at the base of the shield. Use of the "tie rods" was discontinued. By September 13, 1904, the shield was now "steered with ease" and "no pumps are now being used" (Holland Collection: "Extracts"). By October the tunneling rate was 8.3 ft per day. On November 7, 1904, with the north heading approximately 100 ft east of the river bulkhead, excavation was shut down in order to drive an access shaft just west of Furman Street and to restart the south heading. The closer-in access shaft meant that spoil did not have to be transported east of Furman Street, where the tunnel leaked, had cracked plates, and needed grade corrections.

Excavation at the south tube of the Brooklyn west headings restarted on November 8, 1904. A timber bulkhead was built practically at the end of the shield, and, as a result, enough air pressure could be maintained to control the water. By December 4, the excavation rate was 8 ft per day. As tunneling progressed, it became practice to build bulkheads at close spacing to limit the length of tube through which air leakage could occur and thus enable sufficient air pressure to be maintained. Excavation proceeded well but was halted on February 16, 1905 with the heading 80 ft east of the river bulkhead, approximately the same location as the north tube. This enabled the new access shaft for the south tube to be built and excavation at the north tube to be resumed.

Fig. 3 shows part of the timeline of the excavation of the north tube after restart on February 18, 1905. The tube now had to cross the river bulkhead, then proceed between Brooklyn Piers 17 and 18 and finally under the East River channel. Within 20 ft of the bulkhead, the cast iron lining was changed to one that was 40% heavier than that used at the start of the westward headings. An air pressure of 16 psi was being maintained. Near the bulkhead, the tunnel intercepted old piles that had to be cut/removed, causing small blowouts on March 3 and 4. On March 7, after crossing additional piling, a major blowout occurred that flooded the tunnel. Excavation resumed on March 20, but on March 27, 1905, with the top of the tunnel under about 14 ft of sediments, and about 28 ft below mean high water, a major blowout occurred. One of the sandhogs, Michael Creedon, was caught by the outrush of air and blown through the river sediments, before surfacing on the East River (see annotations on Fig. 3). Clifford Holland later commented on the incident:

"In the construction of the present subway tunnel between Manhattan and Brooklyn several blow-outs occurred ... One of these blow-outs occurred on the Brooklyn side of the East River as the headings were passing out under the river at the bulkhead. The progress of the shield had been greatly delayed during the cutting-off of the piles which were encountered at the face, and during this time the continual escaping of the air in front of the shield had weakened the cover overhead so much that the air rushed out in great 'blows.' Several men working at the face, in attempting to stop the leakage, were caught in a sudden out-rush of the air and thrown upward toward the top of the shield. One man was buried in the mud at the top of and in advance of the shield but he was rescued after about fifteen minutes and still conscious and able to talk. The air escaping through the mud must have kept him alive. At the same time, another man was blown completely out of the tunnel and after passing up and through 30 ft. of river mud and water he reached the surface of the East River and was picked up by a passing boat. Although he had a most unusual experience, he was not seriously injured and is again at work on the tunnels now under construction." (Holland 1914).
E. L. Doctorow, in his novel, *Ragtime*, fictionalized the incident:

"An engineering miracle was taking place, the construction of a tunnel under the East River from Brooklyn to the Battery ... One day there was a blowout so explosive that it sucked four workmen out of the tunnel and blew them through twenty feet of river silt and shot them up through the river itself forty feet into the air on the crest of a geyser." (Doctorow 1975)

The incident halted tunneling. Sail-cloth was spread over the depression left by the blowout and a layer of clay was dumped on top. The clay blanket was eventually extended approximately 740 ft toward the middle of the river. From the resumption of tunneling on April 16 to the end of October 1905, the north tube advanced without incident, but the air pressure increased from 16 to 32 psi. On November 5, 1905, the tube had advanced to the submerged midriver rock reef. Mixed-face and rock tunneling methods now had to be used. Eleven months were spent tunneling approximately 400 ft through the reef. The tunnelers then had to transition again to soft soil tunneling until December 1906 when the east heading from Manhattan was met.

The south tube of the western Brooklyn headings was restarted on May 12, 1905. The south tube also had to traverse the river bulkhead and old pilings but now with the experience of the north tube to aid its progress. A clay blanket had already been placed in the slip between Piers 17 and 18 to within 1 ft of the surface of the water. No blowouts occurred, but the tunneling was shut down on June 15, when the heading temperature reached an unbearable 110°F. It was resumed again on September 15 and reached Man-o-War reef on March 21, 1906. Changing to mixed-face/rock tunneling methods, the tunnelers bored through approximately 370 ft of rock in 9 months. Soft-soil tunneling was then resumed until March 1907 when the Manhattan eastern heading was met.

The Manhattan east headings posed different problems and required different tunneling methods. Approximately 2,200 ft of rock tunneling was required before the tubes reached the East River sediments. However, the tops of the tubes were close to the top of the bedrock, leaving only a "thin roof" of possibly fractured rock along most of the length. Therefore the "heading and bench" tunneling technique was used. This method is described in *The New York and Brooklyn (1904a)* and is shown in Fig. 8.

A heading about 8 ft high was bored by drilling a pattern of 6 ft deep holes and blasting with dynamite, "carefully apportioned to avoid lifting the thin roof" (The New York and Brooklyn 1904a). The rock roof was supported by timber arches at 5 ft on center. Periodically, test holes were drilled into the roof to determine the thickness of the rock above the heading. A "bench" about 12 ft high was kept about 20–30 ft behind the heading and removed prior to the placement of the iron lining. No shield was used, but the air pressure was slowly increased from atmospheric to 32 psi by the time the tubes entered the river sediments. Approximately 3 years were needed to bore through 2,200 ft of rock. Unlike the Brooklyn west headings, water did not cause problems and there was little risk of blowouts. However, two major incidents occurred. On December 8, 1903, the timber framing in the north tube collapsed, flooding the tunnel. The collapse was sealed by draping sail-cloth on the river bottom and placing 2,500 bags of sand and clay. Excavation was resumed on January 2, 1904. In the south tube, on January 28, 1905, a fire started from a lit candle in the pressurized air and eventually burned approximately 100 ft of timbering and led to the collapse of the rock roof. Tunneling was halted until March 25, 1905 (Record drawings 1924).

When the tubes emerged from the rock and entered the sediments, excavation was halted to install shields. Soft soil tunneling techniques were then adopted until the Brooklyn headings were met, west of the submerged rock reef. The meeting of the shields in December 1906 and in March 1907 did not mean, however, that the tunnels were completed. Because reconstruction that had begun earlier was still in progress, the pressurized air was maintained until August 1907.

The Holland Collection at Case Western Reserve University and the referenced papers do not contain descriptions of operations or rules for work in pressurized air. But "caisson disease" or the "bends" was a serious problem at the Battery-Joralemon Street Tunnel. Fourteen sandbags died from the bends. "In five months in which record was kept" there were "674, some times 25 per day" cases of the bends (Holland Collection). An unsigned letter to the chief engineer, dated March 3, 1906, states:

"I regret to report 33 cases of bends and one death in the force of the New York Tunnel Co. employed in the Manhattan headings of the East River Tunnels during the current week. The recent increase of air pressure in the Manhattan headings from 19 lbs. on February 17 to about 33 lbs. at present, with the accompanying sudden increase in the number of cases of bends, has resulted in a falling off of more than 50% in the force working in these headings with a corresponding delay in the work." (Holland Collection)

A letter to the chief engineer dated May 9, 1907, states:

"Below is a list of those who have been treated for the bends at the Brooklyn Hospital from March 21 to May 4, inclusive. The list is probably very incomplete. None of the cases were fatal, as far as was known." (Holland Collection)

The list described 136 cases. A similar letter dated August 9, 1907 described 500 cases from May 14 to August 9, 1907. Clearly, safe rules for human operations in compressed air needed to be defined.
Repair/Reconstruction of the Battery-Joralemon Street Tunnel

As late as September 1905, Engineering Record gave no indication of the problems and the condition of the Brooklyn west headings (Progress 1905). The paper only noted that “considerable new plant has been added” to provide compressed air. However, the contractors, engineers, and the Board all knew that portions of the Brooklyn west headings did not provide adequate clearance for the passage of subway cars. Because movements of the tubes and distortions of the cross sections occurred during construction, the stability of the tubes after construction and during operations also became a concern. Moreover, if the tunnels moved in the soft sediments, there were fears that the tunnel lining might become overstressed at the transition from the rigid support of the rock reef to the soft sediments.

In February 1906, Charles M. Jacobs, Chief Engineer for the PRR East River Tunnels, was called in by the contractor to make recommendations (Grade corrections 1906). Jacobs proposed “to construct an outside shield enclosing the section to be repaired and within it to entirely remove the old tunnel and replace it by a new one.” Understandably, his expensive, complicated recommendation was not followed. J. C. Meem, then chief engineer for Cranford and McNamee, the contractor for the land portions of the tunnel east of Clinton Street, suggested a method for lowering the elevation of the invert. The procedure, shown in Fig. 9, required a series of steps to remove the lower cast iron segments and replace them with a reinforced concrete cradle. A successful trial of the method was carried out and it was adopted for the actual reconstruction, which began on April 1, 1906.

Lowering the invert could not solve all the clearance problems, however. In some locations, the “roof needed to be raised.” In this context, an extensive trial and evaluation of soil freezing was performed (The freezing process 1906). A refrigeration plant was constructed and installed in the tunnel. Studies were performed on the radial extent of freezing in time. However, ground freezing was not adopted; the actual technique used is depicted in Fig. 10 (Completion 1907; Grade correction in 1907). It required loosening the upper tunnel lining segments, drilling holes in their webs, and “bleeding” the material behind them until they could be jacked outward radially. New reinforced concrete and brick linings were then built, as shown in Fig. 10. The locations of the reconstruction are indicated by bold lines in Fig. 11. In all, 2,739 ft of invert and 210 ft of roof were reconstructed.

On July 2, 1906, Clifford M. Holland (see Fig. 12) breathed his “first air” in the Battery-Joralemon Street Tunnel (Holland Collection). He began tunnel work in summer temperatures, in air pressures of about 30 psi, at a time when the east headings were transitioning into soft soil, the west headings were in the rock reef, and the repairs had been ongoing for 3 months. Unfortunately, there are no documents in the Holland Collection at Case Western Reserve University that reveal the first impressions of the 23-year-old new Harvard graduate.

One of the controversial issues that remained involved the possibility that the tunnel might move in the soft soil during op-
Fig. 11. Profiles of the north and south tubes of the Battery-Joralemon Street Tunnel showing areas of reconstruction (Grade correction and pile 1907)

Corrections and possibly over-stress the lining at the transition from the rigid rock supports to the softer sediment support. But there was no clear reason to expect movement since: "The weight of the completed tube with concrete lining and track is about 11,000 lb. per linear foot, and that of the train 2,000 more, making the maximum total of 13,000 lb. per linear foot, as compared with 14,000 lb. for the volume of water displaced" (Driving concrete 1907). Therefore, in the judgment of Chief Engineer George S. Rice and the Board, the tunnel was stable and auxiliary supports were not necessary. However, the IRT Co., which had the contract to operate trains in the tunnel, needed complete public confidence in the safety of the tunnel. Therefore the Rapid Transit Subway Construction Co. decided to construct piles under the tunnel, without "authorization or approval of the Board of Rapid Transit Commissioners." The Board, however, made no objection "against the contractor's putting in these foundations" (Grade correction and pile foundations 1907). The idea of constructing piles under a submerged tunnel had been considered for the PRR East River Tunnels but was rejected after only one experimental pile was built. Therefore the design and installation of piles under the Battery-Joralemon Tunnel was unprecedented. Figs. 13 and 14 show the piles and describe the method of installation. Water jets and hydraulic jacks were used to drive the piles in 5-ft segments.

Four short piers and 58 pairs of piles were built for the south and north tubes. Spacings of approximately 30 and 50 ft were used west and east of the submerged reef, respectively. The deepest pile extended about 76 ft below the cast-iron lining. Fig. 11 shows that the piles were installed for the entire length of soft soil west of the reef and for a distance of approximately 700 ft east of the reef. The work was done concurrently at several locations and around-the-clock using three 8-h shifts, in 34 psi air. All the piles were installed between March 19, 1907 and July 23, 1907. This achievement had a significant human price: Over 500 cases of the bends were documented from May 14 to August 9, 1907 (Holland Collection). At the same time as the piles were being installed, the last major component of the tunnel, the ventilation system, was being built.

Ventilation of the Battery-Joralemon Street Tunnel

A ventilation system was installed in the tunnel primarily for emergency conditions in which trains were blocked or stalled in the tubes (Ventilation 1907). Fig. 15 shows sections of the Battery Park ventilation station. The system was designed to supply
50,000 ft³ of air per min from a pair of nozzles with a combined cross-sectional area of about 10 ft². Under most conditions, air was to be blown in the direction of travel of a train (typically west in the north tube and east in the south tube). However, for the condition where the shortest evacuation path was in the travel direction of the train, the system was designed to be able to reverse the direction of the blown air. This was accomplished by vanes positioned by electro pneumatic actuators. The actuators had an independent power supply and were remotely controlled by dispatchers who were in communication with the trains. The system became operational after the start of regular service through the tunnel on January 9, 1908.

**Clifford Milburn Holland and the “New” East River Subway Tunnels**

The Battery-Joralemon Street Tunnel was successfully completed largely because of great perseverance, ingenuity in the face of problems, luck, and personal sacrifice. Although Holland worked on the tunnel only from July 1906 to its completion at the end of 1907, he was able to observe rock tunneling, soft-soil shield tunneling, concrete lining work, grade corrections, installation of piles, construction of the ventilation system, and, above all, compressed air work conditions and their effects. A memoir on Holland’s life was published in the 1926 *ASCE Transactions* after his tragic early death on October 27, 1924. The memoir, written by two of Holland’s former bosses, Robert Ridgway and Frederick Noble, notes that, when the new East River tunnels were being planned, Holland:

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Fig. 12. Clifford Milburn Holland (Library of Congress)

Fig. 13. Elevation view and description of installation of concrete piles (*Record drawings* 1924)
and proved most useful, besides giving Mr. Holland a breadth of recorded information on the subject few could equal.” (Memoir 1926)

The Holland Collection at Case Western Reserve University includes drafts of his manuscripts on “Settlement and piles,” “The East River material,” “East River Tunnels,” and “Subaqueous tunneling in New York City with special reference to the design of the cast iron lining and the method of shield operation.” The collection also includes copies of some of the comparative tables he prepared on completed tunnels. Ridgway and Noble continue:

“When in 1914, contracts were let for the Old Slip-Clark Street and Whitehall-Street-Montague Street tunnels, Assistant Engineer Holland was entrusted with direct charge. His age was then thirty-one, but there was no question as to his fitness. His responsibilities were afterward increased when contracts were let for the Willoughby Street, Fourteenth Street, and Sixtieth Street Tunnels, making the contract value under his charge about $26,000,000. With five double-tube tunnels, of which four were subaqueous, in progress at once, involving a vast amount of engineering and official detail, with frequent emergencies requiring him to visit widely separated points and render quick, sure decisions at any time of the day or night, the situation would have dismayed any but a man of great courage, ambition and exceptional ability.”(Memoir 1926)

Holland’s extended paper, “Two of the dual system tunnels under the East River,” published in the Public Service Record of October 1914 at the start of the work on the Old Slip-Clark Street and Whitehall-Montague Street tunnels, is his manifesto on tunneling (Holland 1914). In the paper, Holland discusses all the main issues and the methods/procedures that would be followed for the new tunnels. He begins by stating his judgment that, in the East River, “the fine sand and clay cannot be pushed aside in driving the shield as is the case under the North River” and therefore “the tunnel shield may be described... not as an excavating machine but as a protection for the men carrying on the excavation.” Holland explicitly addresses human operations in compressed air:

“The air for the compressors is to be drawn from pure outside sources and cooled after compression so as to keep the temperature in the tunnels and caissons moderate at all times... To provide for the safety of the men while

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Fig. 14. Cross section showing concrete piles (Grade corrections and pile 1907)

Fig. 15. Ventilation station at Battery Park (Ventilation 1907)
tunneling under the river, flying gang-ways, safety screens and emergency locks are to be located high up in the tunnel for their escape... The emergency lock is to be located as high up in the bulkhead as practicable and large enough to hold an entire heading shift... The quantity of air supplied is to be sufficient to prevent accumulation of carbon dioxide gas to a greater amount than one part in a thousand by volume... Hospital air locks under the supervision of a medical officer are to be installed at each shaft for the treatment of the men, as well as rest-rooms, bathing facilities and hot coffee... No person is to be employed in the compressed air until after he has been examined by a medical officer and found to be fit to be engaged in such work... No candles or matches are to be allowed in the tunnel where roof timbering is exposed in compressed air... The lighting of the tunnels is to be by electricity... Telephone connection is to be maintained from each heading and lock to the power house and to the office of the engineering corps...” (Holland 1914)

In 1909, the New York State Legislature enacted a law containing provisions for decreasing work time in compressed air as a function of the air pressure. In his paper, Holland suggests the following schedule (Holland 1914):

<table>
<thead>
<tr>
<th>Pressure (lbs)</th>
<th>Total number of hours worked</th>
<th>Number of hours worked per shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-22</td>
<td>8</td>
<td>7 1/2 h (1/2 h out for lunch)</td>
</tr>
<tr>
<td>22-30</td>
<td>6</td>
<td>3 on, 2 off, 3 on</td>
</tr>
<tr>
<td>30-35</td>
<td>4</td>
<td>2 on, 4 off, 2 on</td>
</tr>
<tr>
<td>35-40</td>
<td>3</td>
<td>1 1/2 on, 4 1/2 off, 1 1/2 on</td>
</tr>
<tr>
<td>40-45</td>
<td>2</td>
<td>1 on, 5 off, 1 on</td>
</tr>
<tr>
<td>over 45</td>
<td>1 h 20 min</td>
<td>(as arranged)</td>
</tr>
</tbody>
</table>

Holland notes that: “Under the above schedule the number of men required to carry on the work in a heading under a pressure of 30 pounds will be twice the number required in normal air” (Holland 1914).

In addition to changes in compressed air operations, the new East River tunnels incorporated significant new design features and construction methods. From the start, the Brooklyn access shafts were located at Furman Street, near the river bulkhead, so that they intercepted the tubes at elevations well below mean high water. These shafts were sunk as caissons using compressed air and “were designed as permanent structures to provide for ventilating the tunnels after the trains are in operation” (Holland 1914). The headings from the caissons were begun in an ingenious way by injecting cement grout horizontally into the soil to form a solid mass (Railroad building 1915). This technique was developed by John O’Rourke, chief engineer of the Flinn-O’Rourke Co., the contractor for the Old Slip-Clark Street Tunnel.

O’Rourke also conceived and patented (U.S. Patent No. 1,235,233) a new grouting technique that dramatically improved shield operations. On the Battery-Joralemon Street Tunnel, Portland cement grout was injected radially at points very close to the end of the shield in order to fill the space between the cast iron lining and the surface of the bore. But the grout had a tendency to “run back into the tunnel,” and, if shield progress was delayed, it could bind the shield as it hardened. Moreover, when some of the cast iron segments were removed for grade corrections, it was observed that the grout did not provide a uniform coating of the cast iron but rather followed “paths of least resistance,” forming hardened lumps away from the tunnel lining. O’Rourke developed the equipment and the process for pneumatically filling the space between the shield and the surface of the bore with gravel or coarse sand. This compacted material immediately provided support for the tunnel and minimized movements of the soil and hence surface settlements. Cementitious grout was injected only later, when it could not bind the shield and flow back in to the tunnel (East River 1915).

To decrease the risk of blowouts, clay blankets above the riverbed also became part of normal operations. The clay blankets were contained between submerged rock berms and then covered with a layer of rock (Railroad building 1915).

The locations at which east and west headings met were controlled by stopping tunneling at one of the headings. For the new East River tunnels, the locations were controlled to occur in rock, where the “heading and bench” method facilitated connections and necessary adjustments in line and grade. Holland also wrote on surveying procedures to maintain line and grade and procedures for steering the shield (Holland 1916). His judgment was that “continuous repetition of survey work is the only guarantee of precision” and “errors of personal equation are worked out by having at least two parties working on each line independently, dependence being placed on a large number of observations by different instrumentmen.” He acknowledged that: “The placing of the cutting edge of the shield in a proper position after making allowances for settlement and other considerations is worked out by experience” (Holland 1916).

The above changes, as well as others, produced measurable improvements in the construction of the Old Slip-Clark Street and Whitehall-Montague Street tunnels. In a memorandum to then Chief Engineer Daniel L. Turner, Holland wrote that for both tunnels: “There have been 800,000 decompressions with air pressure up to 37 1/2 lbs, yet there has been but one death due to compressed air sickness on the entire work with less than 200 reported cases of the bends.” Holland understood that many more cases were unreported, but believed that “none have been serious” (Holland Collection). One major blowout that killed two men did occur on the Whitehall-Montague Street Tunnel, and in total, 10 men were killed in the construction of both tunnels. The maximum tunneling advance for six working days was 95 ft, approximately twice the maximum rate at the Battery-Joralemon Street Tunnel (Holland Collection). Regarding the positions of the new tunnels, “it has been unusual to have the line or grade of the completed structure vary more than 2 in. from the theoretical” (Holland 1916). Holland also proudly noted that “tunnel work has been carried out under the streets of Brooklyn with a minimum disturbance to overlying property” and “the maximum settlement of any building along Clark Street or Montague Street is 3/4 in.” (Holland Collection).

**Conclusions and Observations**

The Battery-Joralemon Street Tunnel realized the dream of a subway crossing of the East River. Its construction required great sacrifice and involved unprecedented grade corrections and pile installations. It was a crucible for contractors and engineers of the Public Service Commission, especially Clifford Holland. Under Holland’s leadership, subsequent East River subway tunnels incorporated significant design, operational, and construction innovations that successfully addressed problems of shield operation and steering, grouting, and above all, human operations in compressed air.
Acknowledgments

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