CONFIDENTIAL

Structural Assessment of the Amtrak Under River Tunnels in NYC Inundated by Super Storm Sandy

HNTB | September 2014

AMTRAK

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Executive Summary

Superstorm Sandy (Sandy) created a storm surge that resulted in sea water inundating two of Amtrak's New York City tunnels. The inundated tunnels were Amtrak's North (Hudson) River tunnel and East River tunnel. Sea water entered into ventilation shafts at First and Eleventh Avenues in Manhattan, at the portal from Lines 1 and 2 in Long Island City, Queens, and at the portal for the North River tubes in Manhattan. The sea water, which contains highly reactive salts, caused significant damage to Amtrak's signal and power systems, as well as to electrical and mechanical systems housed in the ventilation structures and these are the subject of an assessment being performed by others. This report addresses the damage that was caused to the structural components of the tunnels and presents recommendations to remedy this damage to meet the current state of practice for rail tunnels.

The limit of inundation was different for each of the tunnels. The East River Tunnel experienced more sea water exposure, with water levels reaching the crowns at mid-river. In contrast, the North River Tunnel experienced less sea water exposure, with water levels reaching above the bench walls at mid-river. Based on observations and discussions with Amtrak's personnel the majority of the sea water entered the East River Tunnel from the Queens portal and entered North River Tunnel from the Manhattan portal. The water was subsequently pumped out of the tunnels in a process commonly referred to as dewatering. The dewatering process, however, did not remove the salts, principally chlorides and sulfates that infiltrated the tunnels and coated various components.

Tunnel inspections were performed throughout the limits of the inundation in the tunnels. These inspections commenced with high resolution laser scanning, along with digital and thermal imaging. These were followed by visual inspection, investigation of notable deficiencies, and material sampling and testing. The inspections revealed a number of features in the tunnels have been and are being damaged by chlorides and sulfates. These include exposed steel members, delaminated and cracked concrete, embedded reinforcing steel, running and third rail systems, track ballast and the numerous electrical and mechanical systems. There were elements in the tunnels that were not accessible for inspection. These may, during the course of the work, exhibit damage and require remedial action.

In addition to the tunnel inspections, structural analyses were performed to determine whether the inundation caused either adverse stressing in the tunnel lining due to a change in the internal pressure or excessive stress in the linings and bolts due to their significant change in buoyancy. These analyses showed that in both instances additional stresses were induced in the tunnel lining. Although in one instance the induced stresses were significantly higher than the in-situ stress, these stresses were below the yield stress for the materials.

The most serious damage in the tunnels was found in the concrete bench walls. These bench walls, which run portal to portal, are an essential component of the tunnels. The structures provide emergency egress from trains when necessary as well as access to trains and track for emergency and other personnel. The interiors house ducts that contain electrical wiring, equipment, cables, and other essential equipment.

These bench walls were found to have a significant number of longitudinal cracks, severe spalls with exposed steel, and corrosion of embedded steel elements. Due to the porous nature of concrete, the continuous duct work, the cracks and various other factors, there were a multitude of paths into the structure of the bench walls for chlorides and sulfates. To a substantial degree, these substances could not be removed by the dewatering process and, when they were exposed to oxygen and moisture in the air after the dewatering was completed, they became damage-causing agents on their own. Due to their thorough infiltration of the bench wall surfaces and the ducts, these substances cannot be reliably removed.

One example of the damage being caused by the chlorides and sulfates was evident in an August 19th dislodgement in one of the North River tubes. A piece of the bench wall fell onto the tracks, which led to emergency repairs and train delays. Unless the damaged bench walls are replaced, such incidences will continue and worsen due to the processes known generally as chloride attack and sulfate attack. It is accordingly recommended that the bench walls be replaced with new bench walls, constructed at the proper height to meet current fire-life safety standards (National Fire Protection Association (NFPA) 130). As it is neither practical nor advisable from safety or other perspectives to construct the middle portion of a bench wall at different height than the two ends, it is recommended that the replacement be portal to portal.

With regards to the track system, chlorides became damage-causing agents when they thoroughly infiltrated the ballast, and then were exposed to oxygen and moisture in the air. The chlorides began to attack the rail system in the tunnels at that point, and this damage is continuing. As with the bench walls, there is no reliable method of correcting this damage other than through the complete replacement of the track structure, including the ballast. Without replacement, chloride attack is compromising and will continue to compromise the integrity and strength of the track and rails. Accordingly, it is recommended that the existing ballasted track system be replaced with a direct fixation track system, which is the current state of practice for rail tunnels. This work should be accomplished in coordination with the bench wall replacement to minimize service disruptions.

With regards to the tunnel linings, the chloride and sulfate removal can be achieved in part by pressure washing the impacted portions. In the ventilation structures, which house delicate mechanical and electrical equipment, an alternative means of removing the chloride and sulfate, such as chemical cleaning, should be used.

The inspections revealed, however, that there are areas where the concrete linings are delaminated. In these areas pressure washing alone cannot effectively remove the chlorides and sulfates. For these situations, it is recommended that the delaminations be removed, the exposed area pressure washed, and the concrete replaced. In addition, where concrete spalls occur these should be pressure washed and the concrete restored. For cracks equal to or greater than 1/8", these should be pressure washed and epoxy grouted.

Apart from the deficiencies noted in this report, we did not observe any indications that the tunnel linings themselves were unsound.

Cost estimates have been developed for the recommended work. The table below presents a summary of the costs. These costs include anticipated Amtrak force protection work. The basis of and the assumptions behind these estimates are provided in this report.

2014 $'s				
Tube	**Pressure Washing**	**Cracks and Delaminations**	**Bench Wall Replacement**	**Direct Fixation Track**
ERT Line 1	$2,700,000	$3,200,000	$119,000,000	$47,800,000
ERT Line 2	$2,700,000	$3,200,000	$111,000,000	$44,500,000
NRT- North	$1,900,000	$1,500,000	$124,700,000	$50,000,000
NRT- South	$1,700,000	$ 400,000	$124,700,000	$50,000,000
Subtotals	$ 9 million	$ 8.3 million	$479,400,000	$192,300,000
Grand Total	**$ 689 million**			

Notes: 1- Assumptions are presented in the section entitled "Cost Estimate".
2- Estimates for electrical and mechanical component restoration have been developed by others and are not presented in this report.

In addition to these near term costs, Amtrak should consider a contingency amount to cover costs associated with conditions that are not presently apparent, but may become evident as the other repair work is performed.

Introduction

During Sandy, two of Amtrak's New York City Tunnels were inundated with sea water. Sandy inundated Amtrak's North (Hudson) River Tunnel, which consists of two tubes and attached structures, and it's East River Tunnel, which consists of four tubes and attached structures. Sea water contains a number of highly reactive chemicals, most notably chlorides and sulfates. As a result of the exposure to these chemicals there has been significant damage to the tunnel structures and rail systems.

The New York City tunnels range from 12,000 to 13,500 feet in length, portal to portal. The portions of the tunnels that were inundated ranged from 2,300 to 4,200 feet. For the East River Tunnel, the inundation was complete in the mid-river areas with sea water reaching the crowns at mid-river, while in the North River Tunnel the inundation was less, with sea water reaching above the height of the bench walls at mid–river. The sea water was removed by a process known as dewatering. This process removed the water, but left chlorides, sulfates, and other chemicals coating the tunnels' components.

Through research of reference documents we have determined that the tunnels were constructed as part of the Pennsylvania Railroad system in the early 1900s. The means by which the tunnels were constructed were determined primarily by the geological conditions encountered during excavation. In bedrock, the tunnels were excavated using drill and blast methods; subsequently, a final lining of cast-in-place concrete was constructed within the profile of the excavated rock. In soil or mixed face conditions, the tunnels were excavated by driving shields under compressed air into place to provide temporary support for the erection of a cast iron initial lining. Subsequently, a final lining of cast-in-place concrete was constructed within the cast iron lining. The tunnels were fitted out with invert slabs to support the track structure and bench walls and to accommodate the electrical systems.

Purpose and Scope

The purpose of this assessment is to determine whether there has been damage to the tunnel structures and to make recommendations as to the type of repairs to be made to the tunnels. The scope of this assessment entailed inspections and structural analyses of the tunnels. These were conducted to determine the present condition of the tunnels and to provide information to aid in the assessment of damage.

Chloride and sulfate infiltration has caused and continues to cause damage to the tunnel structures. In addition to damage from chlorides and sulfates, the filling of the tunnels with sea water resulted in an unprecedented combination of loads and stresses on the tunnel structure. Structural analyses were performed to quantify the increase in weight and internal pressure from the inundation and to assess the effects of the elevated stress levels on the tunnel lining and components, and in particular the tunnel bolts.

The assessment provides a summary of various field investigations and analytical findings, as well as recommendations to remedy the damage. Cost estimates are provided for the required restoration.

History and Existing Conditions

General

Although built at the same time, the North and East River Tunnels were constructed by two different contracting teams. Although the tunnel lining designs are similar, there are distinct differences in some of the details. The following sections describe the general features and details of the tunnels and discuss similarities and differences in the design that impact this assessment.

East River Tunnel

The East River Tunnel consists of four single-track tubes that extend east of Pennsylvania Station from the vicinity of 6th Avenue, pass under the East River and emerge in Long Island City, Queens just west of Sunnyside Yard. The construction of the Tunnel was started in 1904 and the Tunnel opened in 1910. Rail service to Penn Station began on September 8, 1910. Note that only two of the four East River tubes (Lines 1 and 2) were inundated during Sandy.

Figure 1 – Alignment - East River Tunnel

Figure 1 illustrates the alignment of the East River tubes, while Figure 2 shows the typical profile of the tubes under the East River. In addition to the tubes, the system also has ventilation structures. Shafts at 1st Avenue in Manhattan and in Long Island City provide both ventilation and egress capabilities.

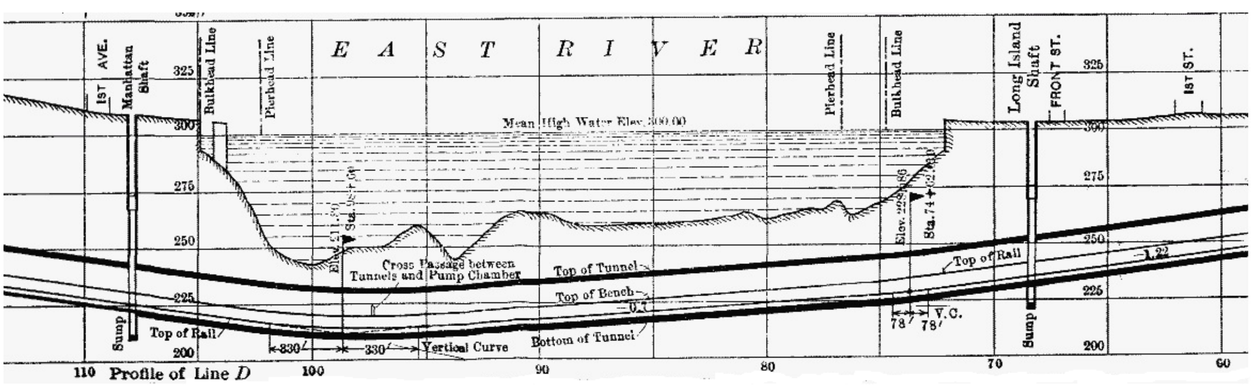


Figure 2 – Profile - East River Tunnel (Line 1)

The design and detailing of tunnel linings vary along the tunnel alignment. As a testament to the insight of the designers, portions of the tunnel linings were designed to be more robust based on perceived adverse loading and geotechnical conditions. Where structural analyses have been performed, the properties of the most critical lining section have been used, or in instances where a particular geologic feature has been investigated, the properties of the lining design installed in that area have been used.

The most common lining design used under the East River is presented in Figures 3a and 3b. It consists of an outer ring lining of cast iron and an inner cast-in-place concrete lining. The cast iron lining web plate is nominally 1-1/2 inches thick and thickens to 2-3/8 inches at the flanges. The concrete lining is unreinforced and nominally 2 feet thick. The bench walls are predominately unreinforced cast-in-place concrete; however, at the numerous electrical splicing vaults situated in the bench walls there is embedded steel reinforcement (Figures 4a and 4b).

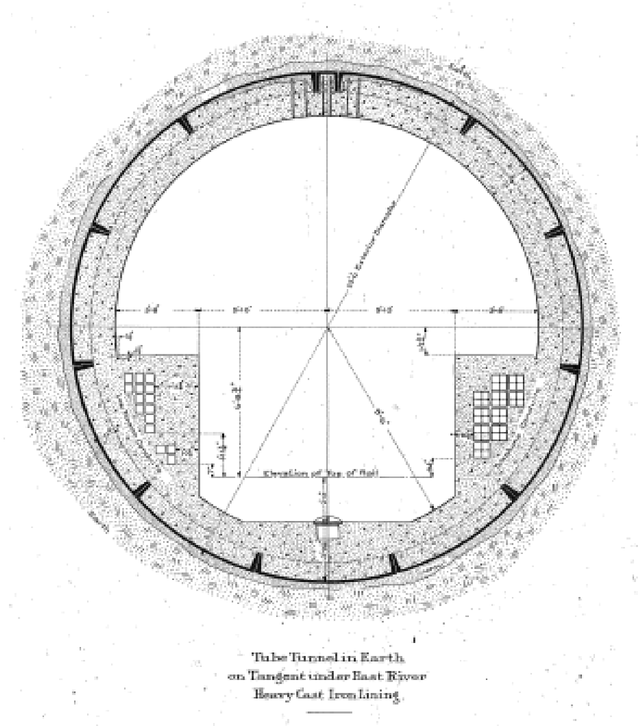


Figure 3a – East River Tunnel Lining

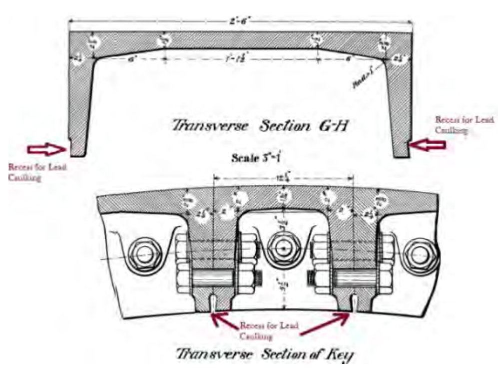
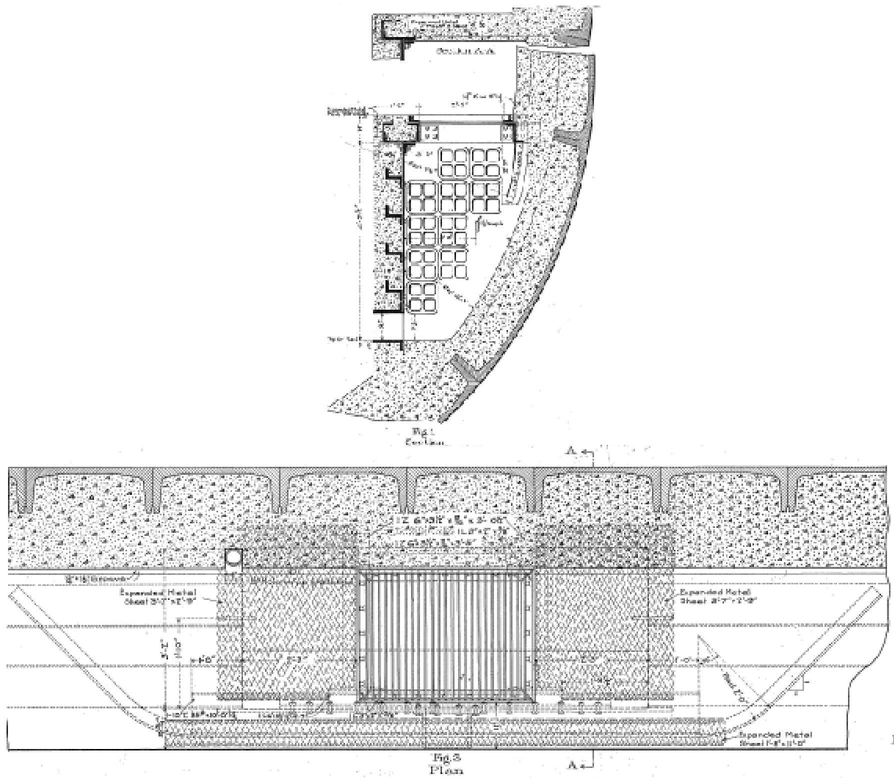


Figure 3b – Cast Iron Segment Details

The combination of the cast iron lining, concrete lining and the concrete bench walls provide sufficient weight to the tubes such that they are slightly negatively buoyant. Thus the tubes do not rely on the soil overburden to resist uplift. This is a beneficial feature with respect to potential river bed scour.

The bench walls in the tubes house the electrical systems supporting the railroad operations, as well as public telephone lines. The bench walls are predominantly unreinforced concrete. The concrete surrounds baked clay conduits. Adjoining conduit sections, nominally 2 feet long, were fitted with steel clips to maintain conduit alignment and continuity during concrete placement. At each splicing vault, there are embedded steel members. The splicing vaults are typically spaced at 400 foot intervals (Figures 4a and 4b).



Figures 4a and 4b – Splicing Vault Transverse Section

The East River Tunnel traverses a complex geologic profile. It begins and ends in bedrock, but also extends through mixed-face (rock and soil) and full face soil conditions. Figures 5a and 5b present the tunnel alignment super imposed on the geologic profile. These figures also indicate the extent of sea water inundation, although not to an exact scale.

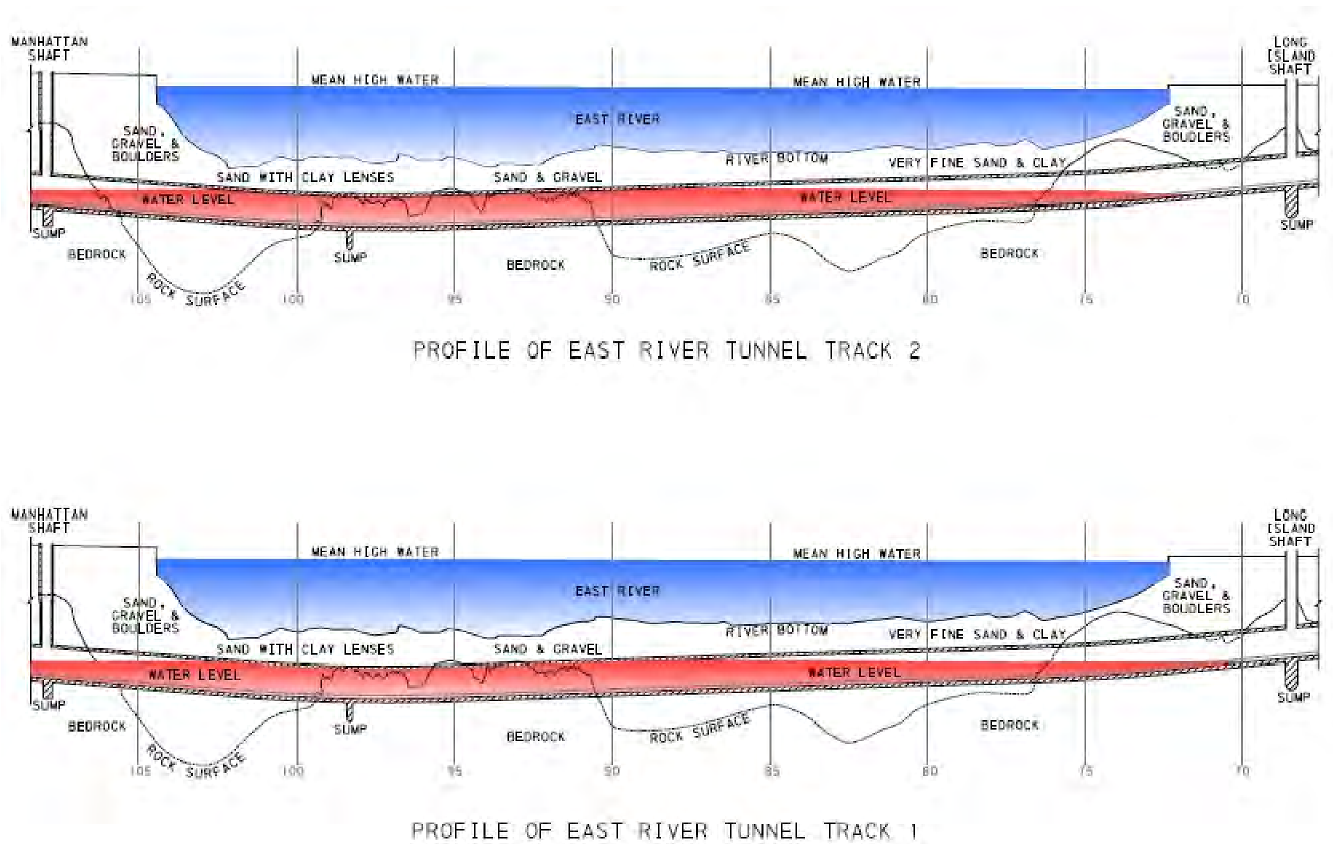


Figure 5a and 5b – Geologic and Inundation Profiles
(Note: Section used is from Penn Central Drwg Nos.265-266 and its vertical scale is exaggerated)

North River Tunnel

The North River Tunnel consists of two single-track tubes that extend from North Bergen, N.J. to 10th Avenue in New York City. As with the East River Tunnel, construction began in 1904 and the Tunnel opened in 1910. Train service from New Jersey to Manhattan began on November 27, 1910.

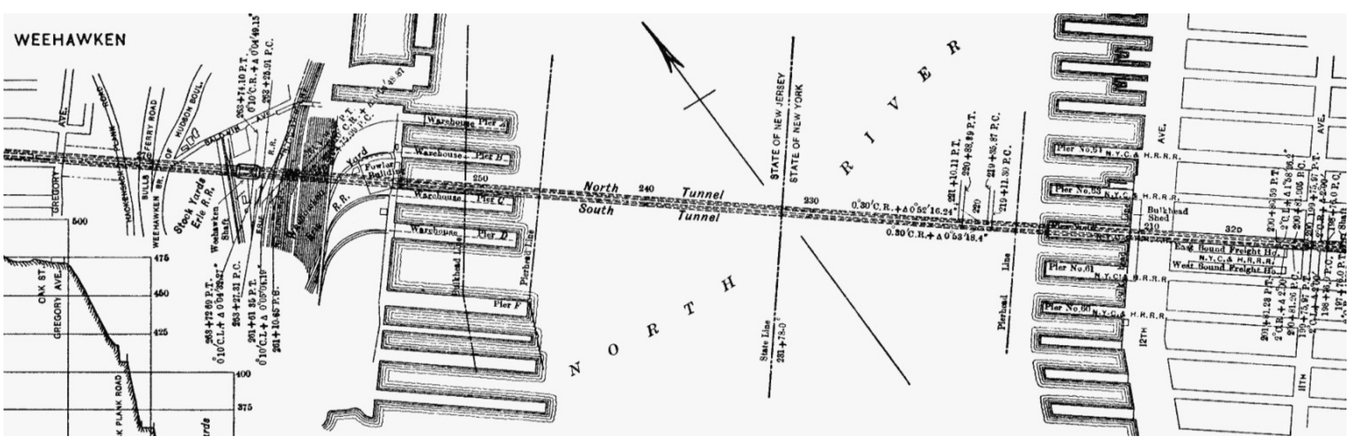


Figure 6 – Alignment - North (Hudson) River Tunnel

Figure 6 shows the alignment of the North River Tunnel, while Figure 7 presents a longitudinal section through one of the tubes. In addition to the tubes, the system also has ventilation structures. Shafts in Weehawken, NJ and at 11th Avenue in Manhattan provide both ventilation and egress capabilities.

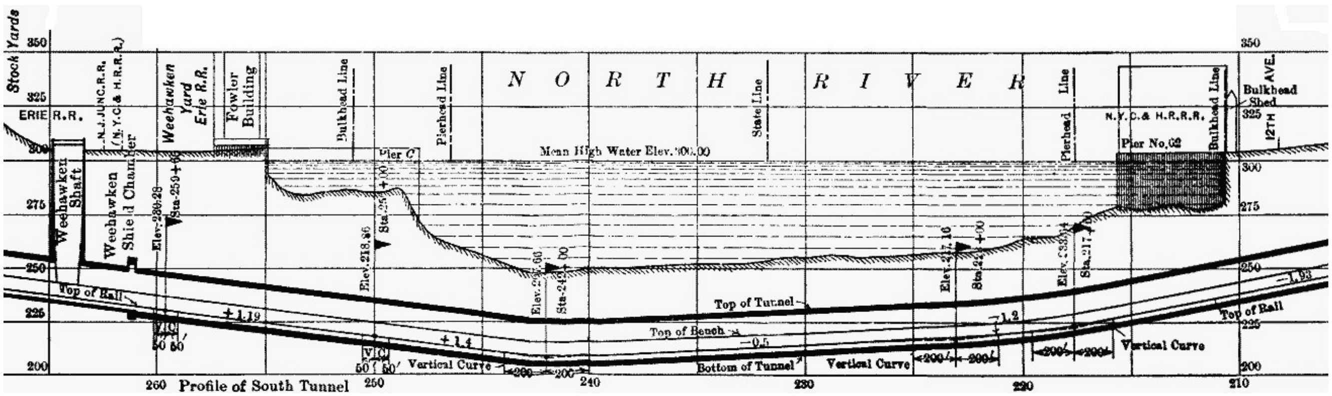
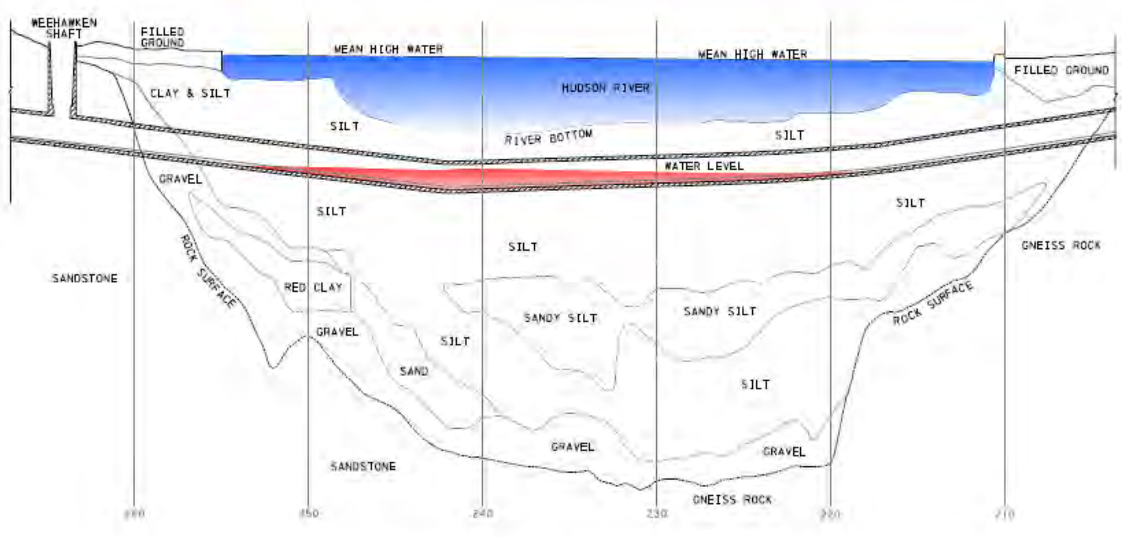


Figure 7 – Profile - North River Tunnel

The North River Tunnel traverses a geologic profile consisting of bedrock on the east and west shores of the River and predominately very soft clays beneath the river. Figures 8a and 8b present the tube alignment superimposed on the geologic profile. These figures also indicate the extent of sea water inundation, although not to an exact scale.



PROFILE OF NORTH RIVER TUNNEL NORTH TUBE

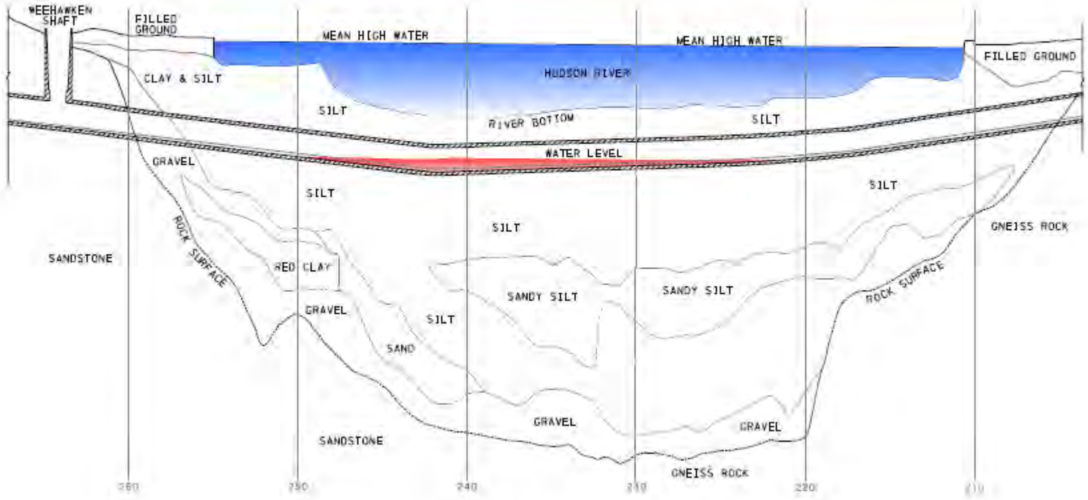


Figure 8a and 8b - Geologic and Inundation Profile, North River Tunnel, North and South Tubes
(Note: Section used is from Penn Central Drwg No.K-1303 and its vertical scale is exaggerated))

As with the East River Tunnel, the North River Tunnel design varies along the alignment and reflects the designer's interpretation of the loading and geologic conditions. Where structural analyses have been performed, the properties of the most critical lining section have been used, or in instances where a particular geologic feature has been investigated, the properties of the lining design installed in that area have been used.

The most common lining design used for the North River tubes is presented in Figure 9. It consists of an outer ring lining of cast iron and an inner cast-in-place concrete lining. The cast iron lining web plate is nominally 1-1/2 inches thick and thickens to 2-3/8 inches at the flanges. Unlike the East River Tunnel, the North River Tunnel concrete lining is reinforced, with reinforcement limited to the roof and invert areas. The concrete is nominally 2 feet thick. This additional reinforcing was included in the design to provide the tunnel more bending capacity for situations where the tunnel support changed from hard rock to soft soil. Special lining segments were fabricated for the tunnel invert to allow for the possible installation of piling, should settlement become an issue. Although these provisions were provided, piling was never needed nor installed. As with the East River Tunnel, the bench walls are predominantly unreinforced cast-in-place concrete. In both tunnels, splicing vaults are situated in the bench wall at approximately 400 foot intervals (Figures 4a and 4b). These have embedded steel members.

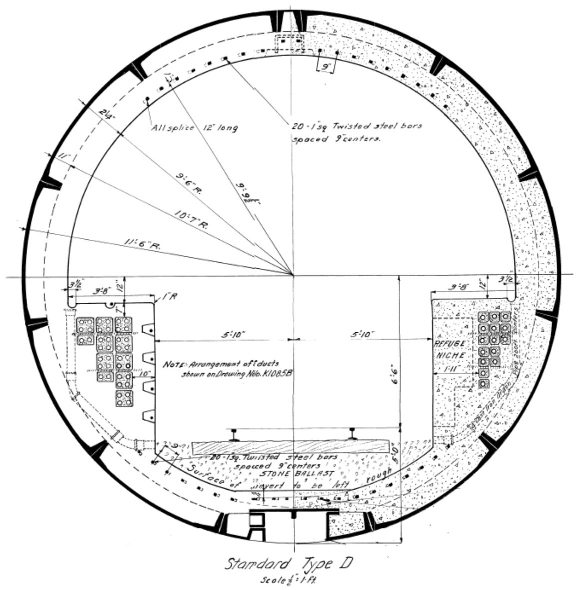


Figure 9 – North River Tunnel Lining Cross Section

As with the East River Tunnel, the North River Tunnel does not rely on the soil overburden to resist uplift. The combination of the cast iron lining, concrete lining, and the concrete bench walls provide sufficient weight to more than counteract buoyancy.

Effects of Chlorides and Sulfates

Following Sandy, the tunnels have been and are being damaged by the effects of the salts left behind after dewatering. The salts have infiltrated the bench walls, track structure, and portions of the concrete linings where they have had and continue to have detrimental effects. Salt is an acid that reacts with concrete paste and aggregate by lowering the pH of the concrete and increasing the porosity of the material. In addition, salts attract water, so the presence of salts in the concrete is drawing moisture into the material. Salt is also accelerating the carbonation process; carbonation slowly reduces the pH levels in concrete through contact with the carbon dioxide (in air), which causes physical damage to reinforcing steel (Cretedefender, 2012)[4].

Among the many salts present in sea water, chlorides and sulfates are the most prevalent and most detrimental to the structural elements of a tunnel. Chloride ions act as a catalyst to initiate the corrosion of otherwise protected cast iron and embedded reinforcing steel. The concrete itself is subject to chemical attack from the sulfates.

Reinforcing steel and cast iron embedded in concrete are inherently protected against corrosion by passivation of the surface due to the high alkalinity (pH of 12 to 13) of the concrete. At the high pH, a thin oxide layer forms on the metal that prevents the natural tendency of the atoms to dissolve through corrosive chemical reactions. Corrosion of embedded cast iron or steel commences when the passive layer is destroyed, or if the concrete's ability to provide passive protection is compromised (Portland Cement Association (PCA) 2014)[5]. The introduction of chlorides reduces the alkalinity of the concrete and allows embedded steel to corrode.

An intrusion of chloride ions into concrete causes corrosion of embedded steel or cast iron. When present above a certain threshold, water-soluble chloride ions penetrate and break down the protective oxide film, which results in corrosion. Where oxygen and moisture are also present, a corrosion cell develops leading to accelerated damage of the base metal, with the rate of corrosion controlled by availability of water and oxygen (PCA 2014).

Corrosion of reinforcing steel and other embedded metals leads to the damage of concrete. When steel and cast iron corrode, the resulting rust occupies a much larger volume than the steel alone, resulting in expansion of the metal. This expansion produces a buildup of internal pressure and ultimately localized fracture, in the form of cracking (or crack enlargement), delamination, and spalling (PCA 2014). These deficiencies lead to further damage to embedded metal by water-soluble chloride ions, moisture and oxygen. In addition, the breakdown of steel and fracturing of concrete reduces its overall strength.

Concrete also is damaged by sulfates. Sulfates, which are salts of sulfuric acid, react with the alkaline concrete paste to create highly expansive crystals, which, like corrosion of metal, increases internal pressure and leads to the cracking of concrete and spalls (Cretedefender, 2012).

Inspection Approach

The tunnel inspections were carried out in two phases. Phase 1 consisted of performing high resolution photogrammetric, laser, and infrared scans of the tunnels. This activity involved the use of sophisticated and powerful scanning equipment capable of quickly collecting and storing vast amounts of data for the purposes of creating an electronic picture of the features of the tunnel lining and bench walls. Using this picture, the major tunnel deficiencies were identified and mapped in order to target the considerably slower visual inspection and testing operations of Phase 2.

Phase 2 of the inspection consisted of visual inspection, in-depth inspection and non-destructive testing of major deficiencies identified in Phase 1, and concrete sampling and testing operations. These activities were performed by three to four teams over the course of eleven track outages during the month of May, 2014. This work consisted of the following:

1. Visual inspection and verification of the type, magnitude and extent of deficiencies identified by tunnel scanning
2. In-depth inspection and investigation of the integrity of the concrete lining and/or concrete bench walls using sounding and various non-destructive testing methods.
3. Core drilling to obtain concrete samples from the lining or benches for laboratory testing.

The combination of the information from these two inspection phases provided the basis for the assessments and recommendations presented in this report.

Phase 1 –Tunnel Scanning

A specialty sub-contractor, SPACETEC Datengewinnung GmbH (Spacetec) was contracted to perform photogrammetric, laser, and infrared scans of the tunnels as Phase 1 of the study. Spacetec provided the equipment (a TS3 scanner) and technicians to perform the surveys in each of the inundated tunnels. The TS3 scanner was mounted to the rear of a flatbed hi-rail vehicle provided by Amtrak and positioned to provide the transmitter/receiver an undisturbed and unobstructed 360 degree sweep of the tunnel. The scanner was moved through the tunnel at a relatively constant speed of approximately 1 mph during the scanning and data collections process. Scanning was performed during overnight track outages from March 13-26, 2014.

Spacetec’ s TS3 scanning system was capable of performing simultaneous photogrammetric, laser, and infrared scanning in a single pass through the tunnel, allowing for full scanning of each of the tunnels in a single outage. The TS3 scanner was equipped with a mirror that rotated at 300 Hertz (cycles per second), enabling rapid collection of large amounts of data. The scanner recorded at high resolution, typically at 10,000 pixels per 360 degree rotation; this resolution enabled the imaging of fine scale features, such as cracks as small as 1/16 inch in width.

Once collected, the scan data required processing to correct for the 360 degree nature of the tunnel and to show a true scale display. In addition to the geometric correction, the thermal data were corrected for any air temperature drift detected during the course of the scanning. Spacetec and partner firm AID Professional Engineers (AID) collected and processed all data from the tunnel scanning and interpreted the results in order to map all of the significant defects in the tunnel lining.

After processing, the scan data provides precise geometric information for all the exposed features of the tunnel. This includes the cross sectional dimensions, identification of all equipment and utilities in the tunnel, cracks, spalls, other structural damage, as well as water infiltration. The thermal data from the survey can also indicate hidden defects, such as water infiltration occurring behind the interior lining.

As mentioned above, SPACETEC’s scanner captures thermal imaging in addition to photography and a 3-D laser point cloud. Every thermographic surface point corresponds to a color coded temperature interval with a temperature resolution of 0.1°C and to one of the 16 colors from black to white as shown below in Figure 10.

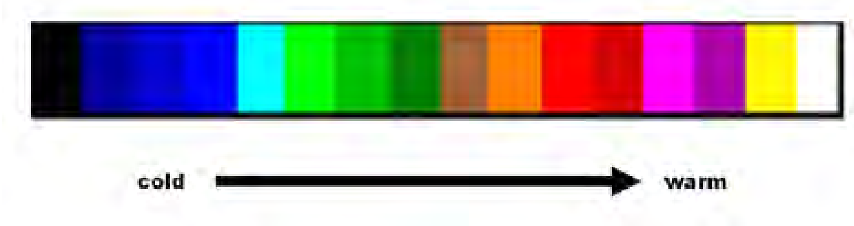


Figure 10 – Thermal Imaging Scale

The thermal recordings give an indication of defects in the tunnel structures that are not readily apparent to the naked eye. Warm areas typically indicate potential voids, while cool areas typically indicate areas of possible concrete delamination or water infiltration. Normal conditions are signified by colors ranging from green to orange. All three data recordings: thermal, photography, and 3-D are made at the same time and coincide with each other. These images allow for an objective assessment of potential structural integrity issues and water infiltration locations. Figure 11 presents an example of a typical scan output, the upper image shows the laser results and the lower image shows the thermal results. The scan results are presented in Appendix A.

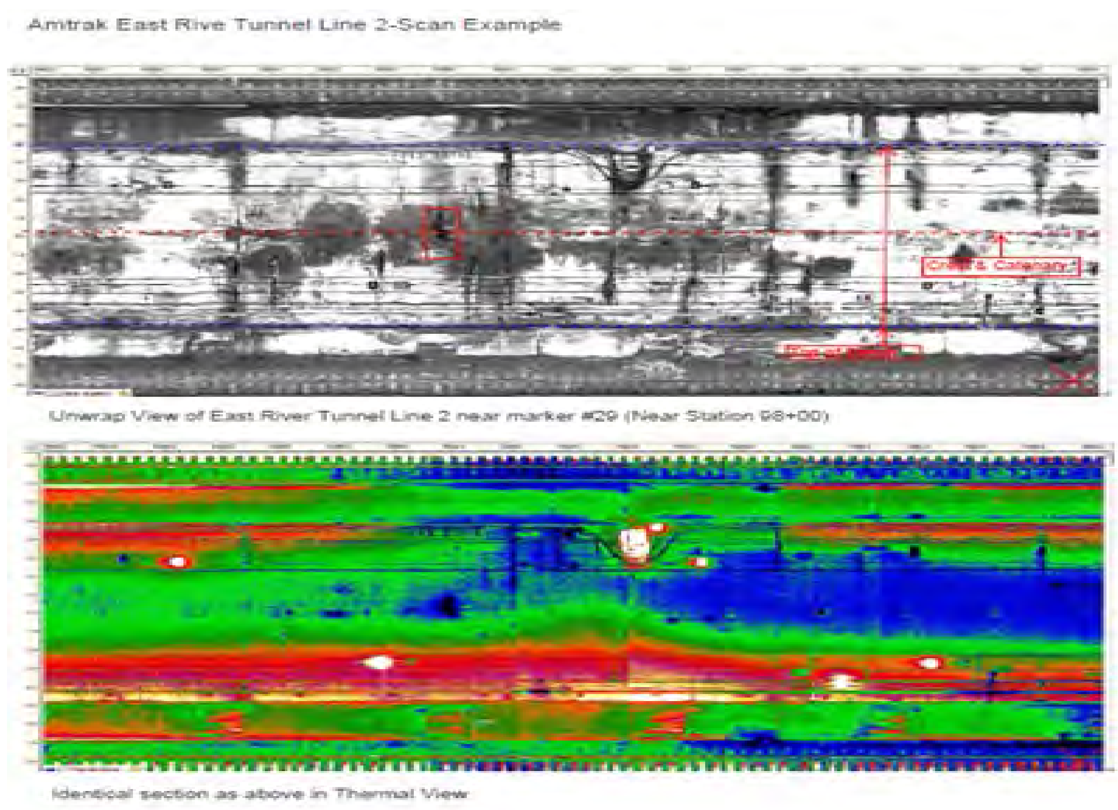


Figure 11 – Example of Scan Results

Phase 2 – Visual Inspection and Testing

The second phase of the tunnel inspection consisted of visual verification, in-depth inspection and non-destructive testing of the concrete at and adjacent to significant deficiencies identified by the tunnel scanning. This work was performed by three to four teams over the course of eleven track outages between May 6 and May 27, 2014.

Visual Inspection Limits and Approach

HNTB personnel conducted a visual inspection of structural components of East River Tunnel, Lines 1 and 2, and the North River Tunnel, North and South tubes. The limits of the visual inspection extend throughout the limits of the Sandy inundation as follows:

- East River Tunnel, Line 1: STA 70+00 to 110+50 (4,050 ft.)
- East River Tunnel, Line 2: STA 72+00 to 111+00 (3,900 ft.)
- North River Tunnel, North Tube: STA 216+00 to 259+00 (4,300 ft.)
- North River Tunnel, South Tube: STA 222+00 to 257+50 (3,550 ft.)

The primary purpose of this inspection was to assess the structural condition of visible and accessible portions of the concrete lining, as well as portions of the bench walls above the ballast on the track bed. Elements behind the bench walls and/or behind the concrete lining that were not readily accessible were not included within the scope of the inspection. In addition, inspection of the track bed itself, as well as non-structural systems such as signals, rail components, track supports, handrails, safety ladders, drainage and utilities, were not included within the scope of this work.

The results from the tunnel scanning were evaluated prior to performing the visual inspection and significant deficiencies within the limits of the inundation were identified and listed for follow-up inspection. HNTB inspectors performed a visual inspection to verify each condition and document the extent of the damage at each location. In addition, the HNTB team documented other noteworthy deficiencies not on the list but relevant to the overall condition of the tunnel within the limits of the inundation.

The concrete lining was hammer sounded in various locations to identify any delaminated (hollow) areas. Sounding was limited to suspect areas, including areas surrounding existing delaminations, areas exhibiting surface defects indicative of poor consolidation of concrete, some areas of more extensive cracking or areas with other visual anomalies. Ground penetrating radar (GPR) was used to supplement the sounding survey. The GPR results were used to investigate suspect delaminated concrete, as well as locate the cast iron flanges to aid in the positioning of the concrete coring.

The sounding performed was limited to those areas which could be reached from the track bed and from either bench area; this generally included all areas below the 10:00 and 2:00 locations of the circular section. Due to the limited extent of the sounding and the limitations in accessing the crown areas, additional areas of delamination or damaged concrete may exist beyond those identified in the visual inspection (see Figure 12). In particular, the condition of the concrete below the ballast and behind the bench walls is not known.

In addition, HNTB visited the ventilation shafts at 11th Avenue in Manhattan and Long Island City. The tours allowed for the general observation of these structures and did not involve scanning or detailed hands-on inspections. These observations indicate that these ventilation shafts did not sustain structural damage during the inundation.

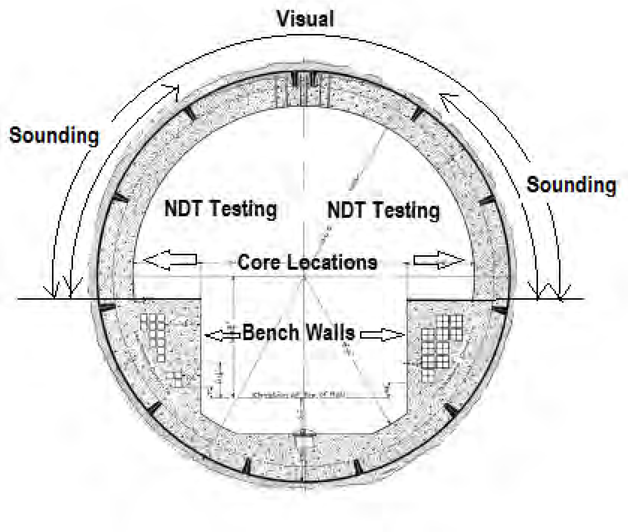


Figure 12 - Limits of Visual Inspection

Definitions Used for Visual Inspection

HNTB defined ten primary categories of concrete deficiencies and one category of metal deficiency for this assessment:

1. Cracks
2. Map cracks
3. Spalls
4. Efflorescence
5. Incrustation
6. Staining
7. Concrete delamination
8. Honeycombing
9. Voids/holes
10. Leakage
11. Metal corrosion with section loss

Many of the conditions identified during the inspection of the concrete lining exhibited characteristics of more than one type of the deficiency above. A brief definition of these defects is presented for clarification:

- A crack is defined as a linear separation, break, or fracture in the concrete, generally caused by tensile forces exceeding the tensile strength of the concrete (USDOT, 2005)[2]. During the Sandy inundation, any cracks present would have provided a path for sea water to penetrate the surface of the concrete lining, with wider cracks generally allowing deeper penetration. Cracks were further classified as either moderate or severe based on the maximum width of the separation. Cracks up to and including 1/8 inch in width were classified as moderate cracks, while cracks over 1/8 inch in width were classified as severe cracks. This criteria is consistent with the classification in the 2005 Federal Transit Administration Highway & Rail Transit Tunnel Inspection Manual (HRTTIM) (USDOT, 2005), with the exception that the HRTTIM categories of minor and moderate cracks were combined for this assessment.

- Map cracks are networks of interconnected cracks that vary in size and form patterns on tunnel slabs and walls. Areas of map cracking were identified during the inspection and classified by width similar to individual cracks.

- A spall is a type of damage to concrete that is typically defined by pitting, chipping, or flaking of the concrete and is evident as a depression in the concrete surface. Spalls were further classified as either moderate or severe based on the dimensions and depth of the depression. Moderate spalls were less than or equal to 1 inch deep and 6 inches diameter with no exposed reinforcement, while spalls over 1 inch deep, larger than 6 inches across, or with exposed reinforcing steel were categorized as severe spalls. This criteria is consistent with the classification in the 2005 HRTTIM (USDOT, 2005), with the exception that the categories of minor and moderate spalls were combined for this assessment.

- Efflorescence is a crystalline deposit of salts (carbonates, sulfates, chlorides) that forms on or near the surface of concrete, due to the recrystallization of these compounds upon evaporation of the water that brought them to the surface. Efflorescence is usually white, but can also be yellow/brown when accompanied by staining when iron oxides are present. Localized incrustations may occur at points where a source of outside water exits the concrete.

- Incrustation is a crust or hard coating formed on the surface of concrete or on aggregate particles (ACI, 2013)[3].

- Staining is a discoloration of the concrete surface caused by the passing of dissolved materials through the material that are deposited on the surface upon evaporation of the water. Staining can be of any color, although yellow/brown staining is indicative of potential corrosion of the underlying reinforcement (USDOT, 2005).

- Concrete delamination is when the concrete separates along planes parallel to the surface, typically in a layered fashion. Areas of delamination produce a hollow sound when struck by a hammer and are identified by sounding of concrete.

- Honeycombing refers to a concrete condition where small open spaces are present between coarse aggregates due to inadequate consolidation during construction (ACI, 2013). The shape of the aggregate is visible within these areas, giving the defect a honeycomb appearance (USDOT, 2005).

- Voids or holes are defined as spaces or irregular defects in the concrete lining that were not a result of a delamination or spall. Voids or holes were typically small but relatively deep spaces of missing concrete. Voids or holes would have provided a path for Sandy sea water to infiltrate the concrete and potentially affect the underlying reinforcing steel or cast iron lining of the tunnel.

- Leakage is characterized by water penetration through the lining and is further classified based on observed inflow. Active moisture is used to describe conditions where the lining was damp/wet or where inflow was less than 30 drips per minute. Leakage is used to describe conditions of inflow greater than 30 drips per minute.

- Metal Corrosion with section loss refers to steel members observed to have undergone sufficient metal loss to have a substantive effect of the member’s strength properties.

Visual Inspection Summary – East River Tunnel

During Sandy, the East River Tunnel experienced a significant inundation of sea water. Based on information provided by Amtrak, the majority of the sea water entered from the Line 1 and 2 portals in Queens. The sea water crested above top of rail for up to 4,206 feet of Line 1 and up to 4,061 feet of Line 2. Within this region, the concrete lining and bench walls were directly exposed to sea water, with full exposure of all tunnel elements for 1,430 feet between Stations 88+18 and 102+48. These components exhibit numerous deficiencies throughout the inundated regions.

Based on the visual inspection, the concrete linings of East River Tunnel Lines 1 and 2 appear to be in fair condition. The tunnel linings are sound. However, work is needed to address damage from chlorides and sulfates deposited on the various tunnel components. In addition, work is needed to arrest ongoing damage from this chloride and sulfate infiltration. The concrete bench walls of East River Tunnel Lines 1 and 2 appear to be in poor condition.

Moderate cracking of the concrete lining was typically observed throughout the inspection limits of Lines 1 and 2. The majority of these cracks were transverse cracks 1/16 inch wide or less, although one transverse crack up to 1/8 inch wide was found in Line 2 at Station (STA) 108+42 (Photos E1, E2). The concrete lining also exhibited a few isolated longitudinal and short diagonal cracks, which were generally 1/16 inch wide or less, and were widely scattered throughout the tunnels (Photos E3, E4, and E5). A 30-foot longitudinal crack was observed in Line 1 between STA 90+36 and 90+66, and a short longitudinal crack up to 3/32 inch wide was observed at Line 1 STA 81+00. Map cracking was observed in scattered locations of the concrete lining, with all pattern cracks in the moderate range and generally less than 1/32 inch in width (Photo E6). No severe cracks (over 1/8 inch wide) were observed in the exposed portions of the concrete linings of Lines 1 and 2.

Severe cracks were commonly observed in the bench walls. In general, these cracks were oriented longitudinally along the vertical surface of the benches, were up to 1/2 inch in width at some locations, and in several cases the cracks extended over 100 feet in length. One of these cracks was over 500 feet long, extending from Line 1 STA 100+00 to 105+20 (Photo E7). There was also a second longitudinal severe crack at Line 1 STA 105+20 up to 3/4 inch wide and 25 feet long (Photo E8).

Spalls were found in two isolated locations in the concrete lining of the tubes. The lining exhibited a severe spall 3 square feet by up to 5 inches deep at Line 1 STA 92+77 and two severe spalls totaling 2 square feet by up to 2 inches deep with exposed metal at Line 1 STA 104+38 (Photos E9, E10).

In the bench walls, numerous severe spalls were observed above and adjacent to the manhole refuge niches. Many of these spalls were locally very deep, with some exceeding 12 inches in depth, and the steel reinforcing members were exposed (Photos E11, E12, E13, E20). Since generally positioned above the refuge niches near the top of the walls, the missing concrete compromised the walking surface on the top of the benches; at many locations, steel plates had been installed on the top of bench to bridge the concrete missing from these spalls. Away from the manhole niches, the bench walls exhibited only a few isolated spalls, which generally occurred at locations of splicing vaults (Photos E14, E15). These spalls were generally large and deep with exposed steel members.

Numerous areas of efflorescence and incrustation were found on the inside face of the concrete lining throughout the limits of inspection in East River Tunnel, Lines 1 and 2.

Concrete delamination was noted at only one location in the concrete lining, at Line 1 STA 106+44, where a 5 square foot concrete patch in the north wall exhibited a hollow sound when tested with a hammer. The bench walls likely contain areas of hollow, delaminated concrete adjacent to many of the numerous spalls; one such hollow area was observed at Line 2 STA 90+38 (Photo E20). Comprehensive documentation of the extent of this widespread damage in the bench walls was not feasible due to project constraints.

Honeycombing was observed in only one location in the East River Tunnel, over a 20 square foot area at Line 2 STA 72+43 (Photo E21). No Voids/Holes were found in the concrete linings of the East River Tunnel.

Areas of moisture, with leakage less than or equal to 30 drops per minute (dpm), were observed at a number of locations within the limits of inspection in the East River Tunnel (Photos E3, E4, E6, E9, E10, E16, E17, E18, E19).

Metal corrosion and section loss was observed at the single location in each tube where the junction shield was visible and accessible.

Deficiencies in the tubes below the ballast and behind the bench walls could not be observed.

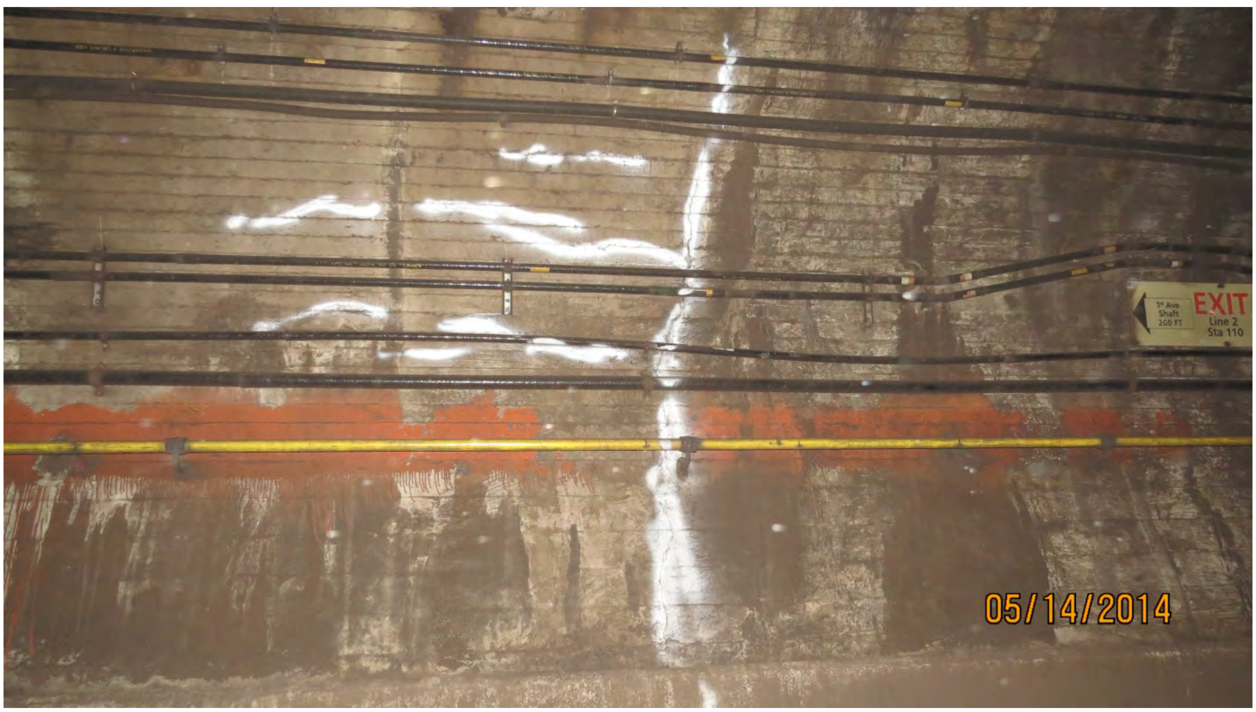


Photo E1: Typical Transverse Moderate Crack up to 1/16" wide, South Wall, Line 2 Station 109+90. Photo Ref. GK07-020, looking South.

**Photo E2: Transverse Moderate Crack up to 1/8" wide, North Wall, Line 2 Station 108+42.
Photo Ref. GK07-045, looking Begin, North.**

**Photo E3: Longitudinal Moderate Crack with Efflorescence near Crown. Isolated Damp Spots with Active Moisture on South Wall, Line 2 Station 109+90.
Photo Ref. GK07-023, looking End, Up.**

Photo E4: Longitudinal Moderate Crack up to 1/16" wide Staining, Efflorescence and Active Moisture, South Wall, Line 1 Station 88+26. Photo Ref. GK09-033, looking Begin, South.

**Photo E5: Diagonal Moderate Crack 6' long x up to 1/32" wide near Crown, transitioning to Transverse Moderate Crack, South Wall, Line 1 Station 83+21.
Photo Ref. GK11-033, looking End, South.**

Photo E6: Map Cracking, with cracks up to 1/32", North Wall, Line 1 Station 97+78. Incrustation with Efflorescence and Active Moisture visible in background, at Line 1 Station 97+85. Photo Ref. GK11-083, looking End, North.

Photo E7: Longitudinal Severe Crack over 500' long x up to 1/2" wide near base of North Bench Wall, Line 1 Stations 100+00 to 105+20. Photo Ref. GK08-062, looking Begin, North.

Photo E8: Longitudinal Severe Crack 25' long x up to 3/4" wide, North Bench Wall, Line 1 Station 105+20. Photo Ref. GK08-058, looking Begin, North.

Photo E9: Severe Spall 2' long x 1.5' wide x up to 4" to 5" deep near Crown, South Wall, Line 1 Station 92+77. Incrustation, Stalactites, Efflorescence and Active Moisture with inflow of 15 drops per minute adjacent to Spall. Photo Ref. GK11-055, looking Begin, South.

Photo E10: Severe Spall 6' long x 12" wide x 1" deep at 10:15 position with exposed steel, North Wall, Line 1 Station 104+38. Stalactite and point of Active Moisture also visible. Photo Ref. GK08-067, looking Begin, North.

Photo E11: Typical Severe Spall with exposed steel adjacent to manhole refuge niche, South Bench Wall near Line 1 Station 100+77. A steel plate was installed to cover missing concrete along the top of bench walking surface. Photo Ref. GK08-081, looking End, South.

Photo E12: Typical Severe Spall with exposed steel adjacent to manhole refuge niche, North Bench Wall near Line 2 Station 86+14. A steel plate was installed to cover missing concrete along the top of bench walking surface. Photo Ref. GK12-039, looking North.

Photo E13: Full-Height Severe Spall with exposed steel extending between manhole refuge niches, North Bench Wall near Line 2 Station 82+14. No steel plates were installed to cover missing concrete along top of bench. Photo Ref. GK12-042, looking End, North.

Photo E14: Severe Spall with exposed steel at Splicing Vault, North Bench Wall near Line 1 Station 79+87. Photo Ref. GK11-023, looking End, North.

Photo E15: Severe Spall with exposed steel at Splicing Vault, South Bench Wall near Line 2 Station 103+99. Photo Ref. BBS1 IMG_0028, looking End, South.

Photo E16: Efflorescence, Damp Incrustation, and Active Moisture along transverse joint, North Wall, Line 2 Station 91+50. Moderate buildup of incrustation on wall and top of bench. Photo Ref. GK10-079, looking Begin, North.

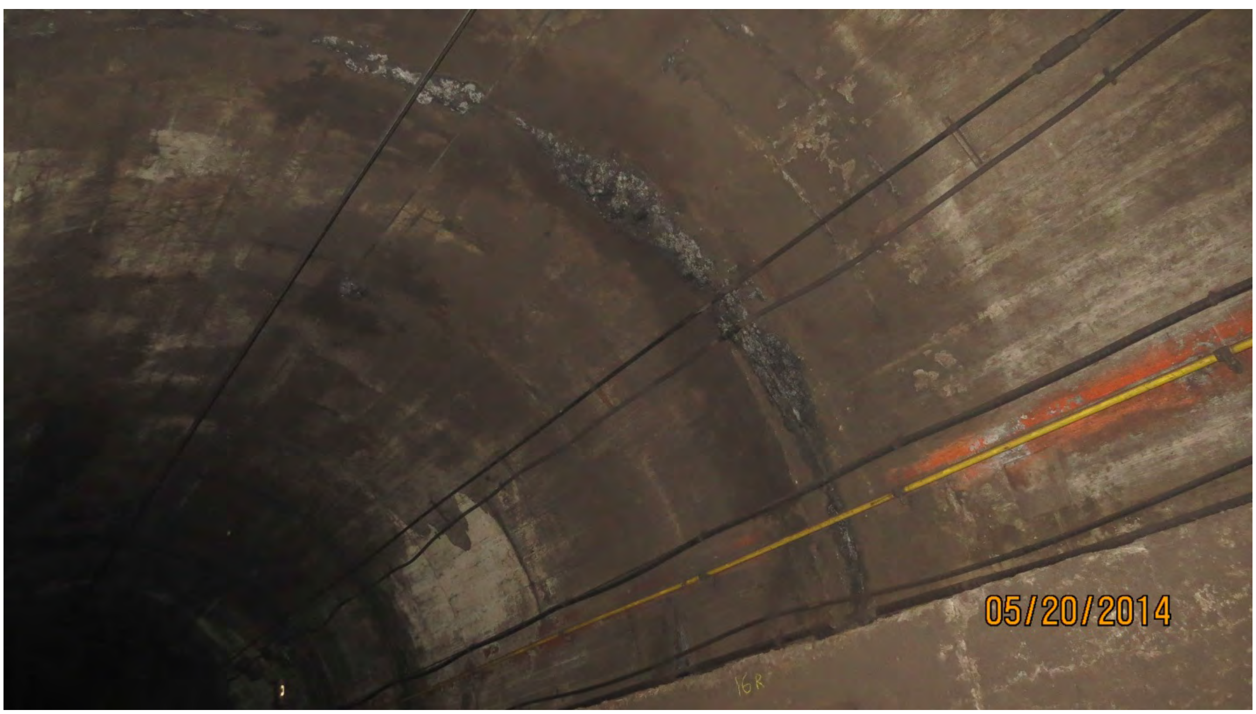


Photo E17: Efflorescence, Damp Incrustation, and Active Moisture along transverse joint, North Wall, Line 1 Station 95+29. Photo Ref. GK11-071, looking End, North.

Photo E18: Efflorescence, Damp Incrustation, and Active Moisture along longitudinal joint, South Wall, Line 1 Station 95+45. Photo Ref. GK11-078, looking Begin, South.

**Photo E19: Efflorescence, Damp Incrustation, and Active Moisture along longitudinal joints near Crown, South and North Walls, Line 2 Station 79+68.
Photo Ref. GK12-049, looking End, Up.**

Photo E20: Cracked, Delaminated Concrete adjacent to Severe Spall with exposed steel on North Bench Wall, Line 2 Station 90+38. Total deficient area was 18' long x full height x up to 16" deep locally, near manhole niche. Photo Ref. GK12-029, looking Begin, North.

Photo E21: Honeycombing over an area 4' long x 5' wide adjacent to top of bench, South Wall, Line 2 Station 72+43. Photo Ref. GK12-072, looking South.

Visual Inspection Summary – North River Tunnel

During Sandy the North River Tunnel experienced a significant inundation of sea water. Based on information provided by Amtrak, the sea water entered the tunnels from the Manhattan portals and crested above the top of rail for up to 3,212 feet of the North tube and up to 2,307 feet of the South tube. Unlike the East River Tunnel, the North River Tunnel was not inundated to the crown. The water level rose above the bench walls. The concrete linings, bench walls, and track structures in and around the submerged portions of the tubes were infiltrated with chlorides and sulfates. These components exhibited numerous deficiencies throughout the inundated regions.

Based on the visual inspection, the concrete linings of the North River Tunnel, the North and South tubes, appear to be in fair condition. The linings are sound. However, work is needed to arrest the ongoing damage to tunnel components from chloride and sulfate exposure. The concrete bench walls of the North River Tunnel, both North and South tubes, appear to be in poor condition.

In general, cracking was not widespread in the concrete linings of the North River tubes. Cracks of moderate size were observed at several scattered locations throughout the inspection limits of the North and South Tubes. These cracks were all transverse cracks 1/16 inch wide or less (Photos N1, N2). No severe cracks (over 1/8 inch wide) were observed in the exposed portions of the concrete linings. Map cracking was also not observed in the concrete linings of the North River Tunnel, within the inspection limits noted above.

Cracking of concrete was much more prevalent in the bench walls of the North River Tunnel. While some scattered longitudinal and transverse cracks of moderate size were observed (Photos N3, N4), the majority of the cracks in the bench walls were severe cracks over 1/8 inch in width. In general, severe cracks in the bench walls, oriented longitudinally along the vertical surface of the benches, were up to 7/16 inch in width at some locations, and in several cases the cracks extended over 100 feet in length (Photos N5, N6, and N7). Notable conditions include a longitudinal severe crack 5 feet long by up to 5/16 inch wide at North tube Station 233+36 that was positioned between the top of the bench and the manhole refuge niche (Photo N6). Near South tube Station 243+20, a longitudinal severe crack 110 feet long by up to 1/4 inch wide exhibited scattered moderate spalls along the crack opening and extended through an area of delaminated concrete (Photo N7). Between South tube Stations 222+54 and 222+88 there was a longitudinal severe crack, 34 feet long by up to 5/16 inch wide that terminated in an area of delaminated and spalled concrete.

Severe spalls were found scattered throughout the concrete linings of the North River Tunnel and were generally large and roughly 4 to 5 inches deep with exposed rebar. A few groups of severe spalls in close proximity to each other were also observed. The depth of these spalls generally did not extend past the inside layer of reinforcement. Severe spalls in the concrete linings were observed at 5 locations in the North tube and at 13 locations in the South tube. Notable conditions include the following:

North Tube Station 251+75: Two severe spalls with exposed rebar, 7 feet long by 1 foot wide by 4 to 5 inches deep and 2 feet long by 1 foot wide by 4 inches deep, South Wall near Crown, with adjacent Honeycombing and Active Moisture. (Photo N8)

North Tube Station 252+82: Three 4 inch deep Severe Spalls with exposed rebar, 6 feet long by 2 feet wide, 4-1/2 feet long by 1 foot wide and 3 feet long by 2 feet wide, on South Wall. Area of Delaminated Concrete 18 feet long by 5 feet wide between spalls. (Photo N9)

North Tube Station 259+00: Severe Spall 6 feet long by 4 feet wide by 5 inches deep with exposed rebar on South Wall. Areas of Concrete Delamination 6 feet long by 4 feet wide and 4 feet long by 3 feet wide adjacent to spall. (Photo N10)

South Tube Station 227+78:	Two Severe Spalls with exposed rebar, 10 feet long by 4-1/2 feet wide by 4 to 5 inches deep and 6-1/2 feet long by 3 feet wide by 3 to 4 inches deep, on South Wall. (Photo N11)
South Tube Station 256+00:	Several Severe Spalls up to 4 inches deep with exposed rebar over a 37-foot length of the South Tube. Spalls occur between the 10:00 and 2:00 positions on the South and North Walls. (Photo N12)
South Tube Station 256+80:	Severe Spalls up to 4-inches deep with exposed rebar between 10:00 and 2:00 positions on South and North Walls over a 50-foot length of South Tube. A 1 foot by 1 foot area near South tube Station 256+80 was a locally deep Void/Hole. (Photos N13, N14)

The bench walls exhibited several scattered severe spalls. These spalls were generally large and deep with exposed steel members. Areas of cracked and/or delaminated concrete were frequently observed in close proximity to these spalls (Photos N15, N16, N17, N18 and N19). Notable conditions in the North tube include a severe spall in the South Bench Wall, 29 feet long by full height by 2-1/2 inches deep, with exposed steel at North tube Station 226+96, and a severe spall, 16 feet long by 4 feet high by 2-1/2 inches deep, in the North Bench Wall at North tube Station 227+23. Notable conditions in the South tube include a severe spall, 5 feet long by 3 feet high by up to 4-1/2 inches deep, with exposed steel and an adjacent area of concrete delamination, 21 feet long by 3 to 4-1/2 feet high, in the North Bench Wall at South tube Station 222+54 (Photo N16). At South tube Station 238+50, there were two severe spalls with exposed steel in the North Bench Wall, 10 feet long by 1 foot high by up to 5-1/2 inches deep and 6 feet long by 3 feet high by 4 inches deep, with an adjacent 20 square foot area of delaminated concrete (Photo N17).

The bench walls in the North River Tunnel did not generally exhibit spalling of the concrete adjacent to the manhole refuge niches, as was common in the East River Tunnel benches. This condition was only observed at one North River Tunnel location. At South tube Station 241+03, there were two severe spalls with exposed steel on the South Bench Wall, 4 feet long by 3 feet high by 2-1/2 inches deep and 2-1/2 feet long by 1 foot high by up to 6 inches deep, as well as 40 square feet of delaminated concrete adjacent to a manhole refuge niche (Photo N18). The 6 inch deep spall occurred along the top of the bench and compromised the top walking surface of the bench (Photo N19).

There were only a few isolated areas of efflorescence scattered throughout the North River Tunnel (Photos N4, N20).

Incrustation on the inside face of the concrete lining was observed at many locations throughout the limits of inspection in North River Tunnel. This deficiency was frequently associated with leakage through the concrete lining and commonly occurred along leaking transverse construction joints. In general, the observed incrustation was less than 6 inches thick, with greater deposits in isolated areas. Deposits generally accumulated along the walls and on the top of the bench walls beneath the points of leakage.

Staining was not common in the North River Tunnel and only occurred at points of severe leakage in a few isolated locations.

Concrete delamination was identified only at a few locations. At North tube Station 252+82, an area of approximately 90 square feet was delaminated (Photo N9), near North tube Station 259+00, two delaminated areas totaling 36 square feet were identified (Photo N10) and in the South tube, there was an area of concrete delamination approximately 4 square feet near South tube Station 233+94. The areas of delamination that were observed were generally located adjacent to spalls visible in the lining

Concrete delamination was identified in the bench walls at 5 locations in the North tube and at 7 locations in the South tube. Areas of delamination identified in the bench walls were typically located adjacent to severe cracks and spalls. At North tube Station 222+64, a 36 square foot area of delaminated concrete was identified in an area of the South Bench Wall that was severely cracked (Photo N15), and at South tube Station 243+10 a 32 square foot area of delaminated concrete was observed along a longitudinal severe crack (Photo N7). Areas of delamination of approximately 80, 20 and 40 square feet were identified adjacent to severe spalls in the bench walls near South tube Stations 222+54, 238+50 and 241+03, respectively (Photos N16, N17, N18).

Honeycombing was observed in a few scattered locations in the North River Tunnel. When observed in the concrete lining, areas of honeycombing varied from 3 to 36 square feet in size, and were generally less than 3/4 inch deep. Honeycombing of the concrete lining was observed at North tube Stations 230+24, 243+04 and 251+75 (Photos N8, N24) and at South tube Station 247+45. Honeycombing was more widespread in the bench walls of the North River Tunnel, and the condition was common along the lower 1 to 2 feet of the bench walls (Photos N4 N5). Some sections of the bench walls exhibited widespread honeycombing throughout the full height of the wall (Photo N25).

Voids/Holes were only found in one location in the North River Tunnel, in the south wall at South tube Station 256+80 (Photos N13, N14). At this location, a 1 foot long by 1 foot wide portion of a larger severe spall transitioned to a locally deep hole in the lining. The depth of the hole could not be determined due to the location of the deficiency near the crown.

Areas of active moisture, with leakage up to 30 drops per minute (dpm), were observed in the concrete lining within the limits of inspection in the North River Tunnel. Documentation was performed at specific sites, selected based on the data from tunnel scanning, as well as at sites observed during the inspection.

As with the East River Tunnel, deficiencies in the tubes below the ballast and behind the bench walls could not be observed.

Photo N1: General View of Transverse Moderate Crack up to 1/16" wide on North Wall, North Tube Station 232+51. Photo Ref. GK03-036, looking North.

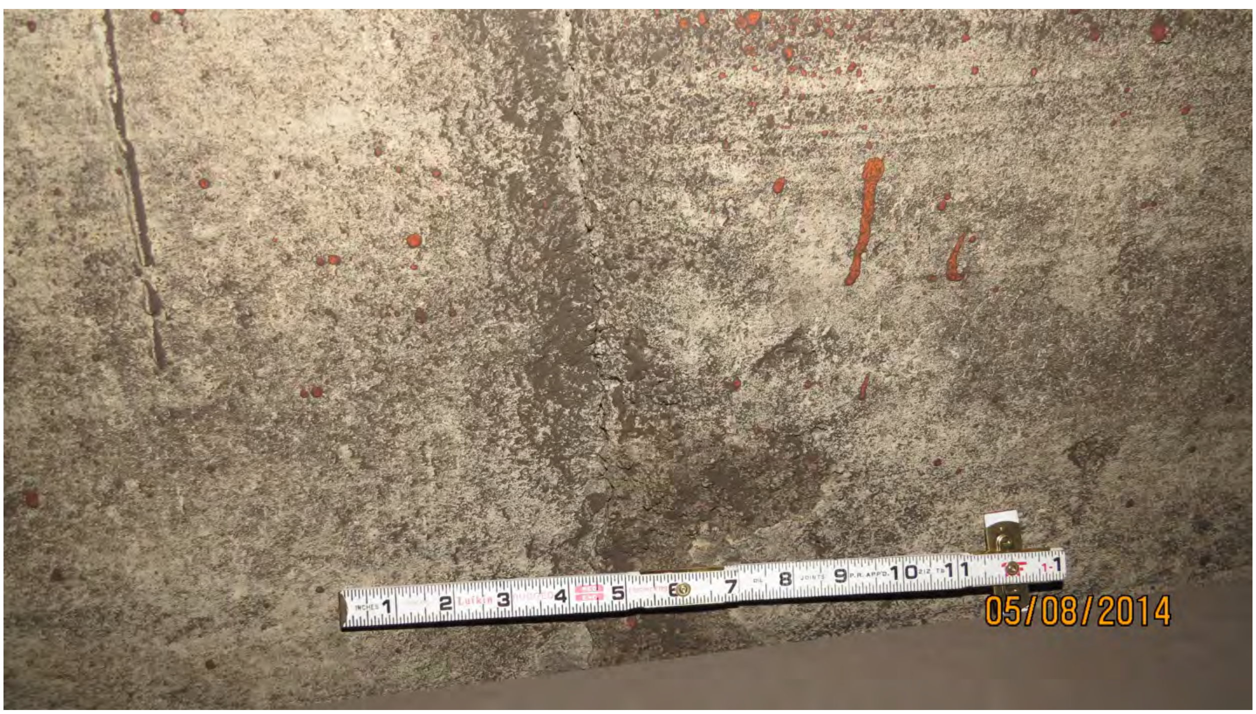


Photo N2: Close-Up of Transverse Moderate Crack up to 1/16" wide on North Wall, North Tube Station 232+51. Photo Ref. GK03-039, looking North.

Photo N3: Longitudinal Moderate Crack up to 1/8" wide and Transverse Moderate Crack up to 1/16" wide, South Bench Wall, North Tube Station 225+42. Note the high water line from the inundation near top of image. Photo Ref. GK02-031, looking End, South.

Photo N4: Short longitudinal Moderate Crack with efflorescence and Active Moisture with inflow of a few drops per minute. Crack is located near bottom of North Bench Wall, North Tube Station 224+66. Photo Ref. GK02-027, looking North.

Photo N5: Longitudinal crack up to 3/16” wide and scattered transverse cracks up to 1/16” wide, South Bench Wall, North Tube Station 246+81. Damp concrete on lower 2’ to 3’ of wall and honeycombing on lower 1’ to 2’ of wall. Photo Ref. GK06-034, looking End, South.

**Photo N6: Longitudinal Severe Crack 5’ long x up to 5/16”wide between manhole refuge niche and Top of Bench, North Bench Wall, North Tube Station 233+36.
Photo Ref. GK03-047, looking End, North.**

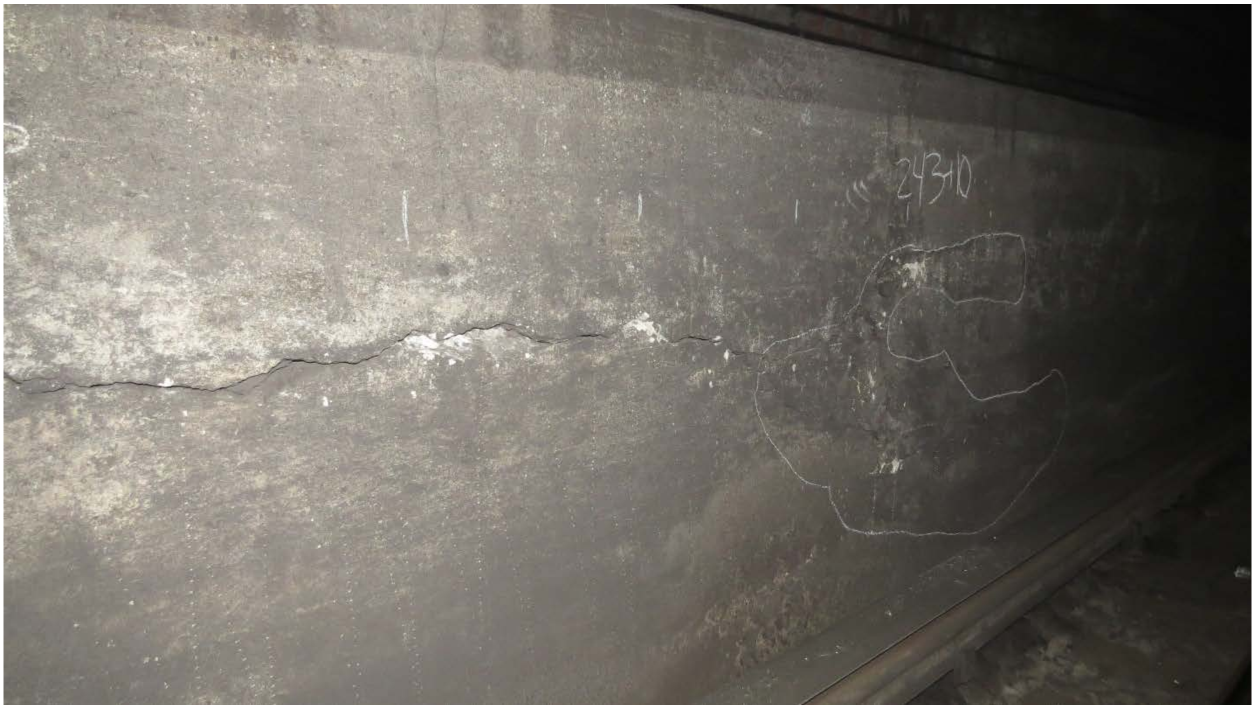


Photo N7: Longitudinal Severe Crack 110' long x up to 1/4" wide with scattered Moderate Spalls along crack and Concrete Delamination 8' long x 4' high near Station 243+10. North Bench Wall, South Tube Station 243+20. Photo Ref. GK05-035, looking Begin, North.

Photo N8: Two Severe Spalls with exposed rebar, 7' long x 1' wide x 4" to 5" deep and 2' long x 1' wide x 4" deep, near Crown, with adjacent Honeycombing and Active Moisture. South Wall, North Tube Station 251+75. Photo Ref. GK06-042, looking Begin, Up.

Photo N9: Three 4" deep Severe Spalls with exposed rebar, 6' long x 2' wide, 4-1/2' long x 1' wide and 3' long x 2' wide, on South Wall near North Tube Station 252+82. Delaminated Concrete 18' long x 5' wide between spalls. Photo Ref. GK06-047, looking Begin, South.

Photo N10: Severe Spall 6' long x 4' wide x 5" deep with exposed rebars on South Wall near North Tube Station 259+00. Areas of Concrete Delamination 6' long x 4' wide and 4' long x 3' wide adjacent to spall. Photo Ref. GK06-056, looking Begin, Up.

Photo N11: Two Severe Spalls with exposed rebar, 10' long x 4-1/2' wide x 4" to 5" deep and 6-1/2' long x 3' wide x 3" to 4" deep, on South Wall near South Tube Station 227+78. Photo Ref. GK04-020, looking End, Up.

Photo N12: Several Severe Spalls up to 4" deep with exposed rebar over a 37' length of the South Tube. Spalls occur between the 10:00 and 2:00 positions on the South and North Walls, beginning near South Tube Station 256+00. Photo Ref. GK05-060, looking End, Up.

Photo N13: **Severe Spalls up to 4” deep with exposed rebar between 10:00 and 2:00 positions on South and North Walls over a 50’ length of South Tube. A 1’ x 1’ area near South Tube Station 256+80 was a locally deep Void/Hole. Photo Ref. GK05-067, looking Begin, Up.**

Photo N14: **Close-Up of 4” deep Severe Spall with exposed rebar and 1’ long x 1’ wide locally deep Void/Hole in concrete lining, South Wall, near South Tube Station 256+80.**
Photo Ref. GK05-065, looking End, South, Up.

Photo N15: Longitudinal Severe Cracks, Delaminated Concrete 12’ long x 3’ high and localized Severe Spalls up to 4” deep in South Bench Wall near North Tube Station 222+64. Photo Ref. GK02-023, looking Begin, South.

Photo N16: Delaminated Concrete 21’ long x 3’ to 4-1/2’ high and a Severe Spall 5’ long x 3’ high x up to 4-1/2” deep on North Bench Wall near South Tube Station 222+54. Photo Ref. GK04-006, looking Begin, North.

Photo N17: Delaminated Concrete area, 20 square feet, and Severe Spalls with exposed steel, 10' long x 1' high x up to 5-1/2' deep and 6' long x 3' high x 4" deep on North Bench Wall near South Tube Station 238+50. Photo Ref. GK04-077, looking Begin, North.

Photo N18: Delaminated Concrete area, 40 square feet, and Severe Spalls with exposed steel on South Bench Wall, 4' long x 3' high x 3-1/2" deep and 2-1/2' L x 1' high x up to 6" deep, at South Tube Station 241+03. Photo Ref. GK05-020, looking South.

Photo N19: Cracked, Spalled Concrete on Top of Bench above location with Severe Spalls, South Bench Wall near South Tube Station 241+03. Up to 6" of concrete is missing, and top surface is severely cracked. Photo Ref. GK05-023, looking End, Down.

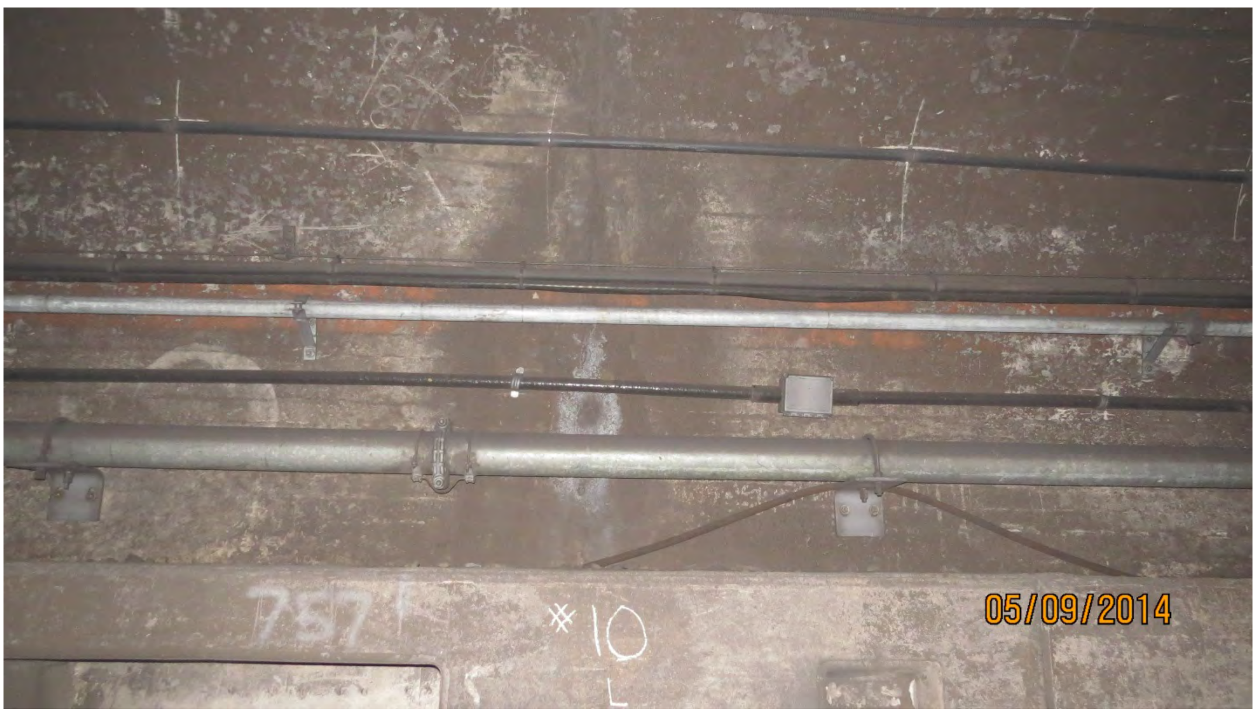


Photo N20: Light Efflorescence along transverse joint, on South Wall at South Tube Station 233+13. Photo Ref. GK04-046, looking South.

Photo N21: **Incrustation and Active Moisture between 9:00 and 10:00 positions, South Wall at North Tube Station 220+09. Incrustation up to 7" deep on wall, top of bench with moderate leakage of several drops per minute. Photo Ref. GK02-006, looking End, South.**

Photo N22: **Damp incrustation up to 2" thick and minor Active Moisture along transverse joint below the 9:30 position on South Wall at South Tube Station 238+50. Photo Ref. GK04-080, looking South.**

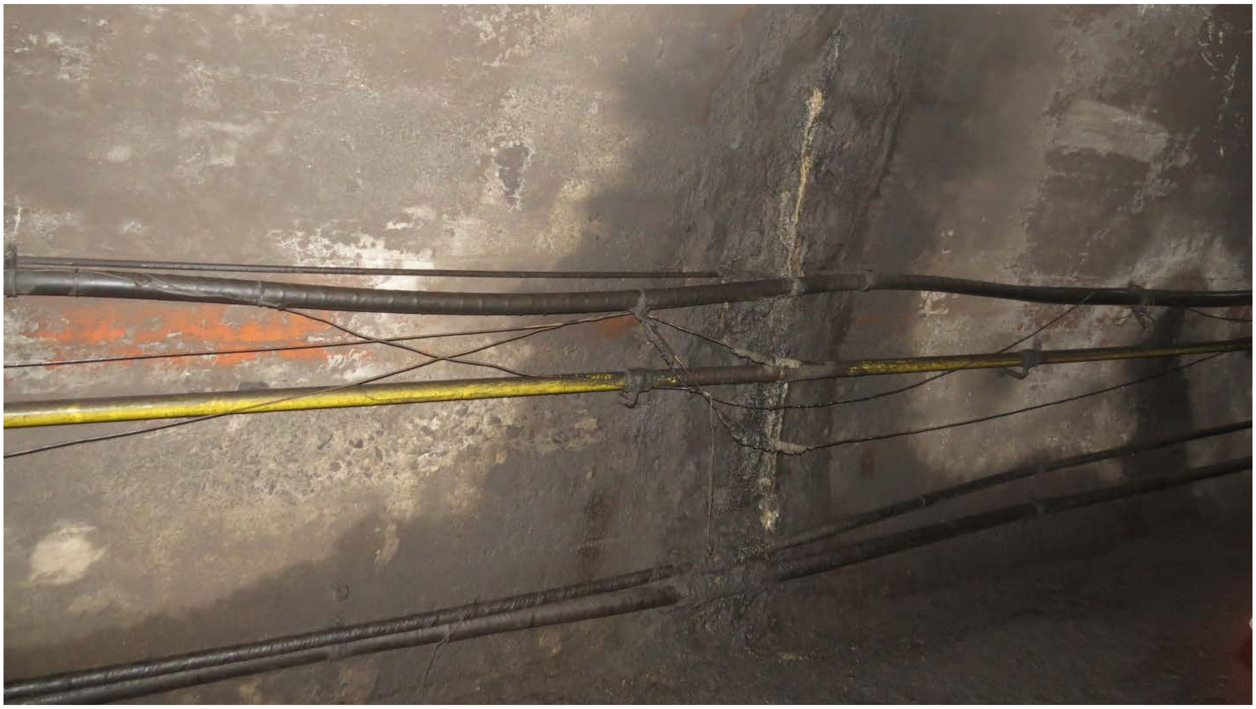


Photo N23: Wet Incrustation and Active Moisture below 2:00 position, with leakage of several drops per minute. Incrustation 3" to 4" thick was observed on wall and top of bench. North Wall, South Tube Station 238+67. Photo Ref. GK05-009, looking Begin, North.

Photo N24: Honeycombing 3' long x 1' wide on wall along top of bench, North Wall, near North Tube Station 230+24. Photo Ref. GK03-028, looking Begin, North.

Photo N25: Honeycombing over approximately 60% of surface area of bench wall between adjacent manhole refuge niches. North Bench Wall, near North Tube Station 230+24. Photo Ref. GK03-029, looking Begin, North.

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Material Testing

The tunnel linings and bench wall concrete were cored to retrieve test samples. These samples were tested for strength and chloride content. The results of these tests are presented in the Table below.

Sample No.	Tube	Exposed to Inundation	UC* Strength (psi)	Chloride Content** @ Depth in Concrete		
				Surface	0.5 inch	1.0 inch
ERT L1-1 STA 113+92	ERT Line 1	No	3489	1.2	0.64	0.32
ERT L1-2 STA 106+21	ERT Line 1	Yes	-	9.12	6.44	5.76
ERT L1-3 STA 102+08	ERT Line 1	Yes	-	35.4	-	-
ERT L1-4 STA 101+98	ERT Line 1	Yes	4078	4.72	2.16	5.92
ERT L1-5 STA 98+90	ERT Line 1	Yes	5852	11.44	39.32	>40
ERT L1-6 STA 89+30	ERT Line 1	Yes	5191	7.4	6.48	2.04
ERT L2-1 STA 112+87	ERT Line 2	No	5194	12.92	-	-
ERT L2-2 STA 106+42	ERT Line 2	Yes	-	8.08	37	29.16
ERT L2-3 STA 104+29	ERT Line 2	Yes	7446	-	-	-
ERT L2-4 STA 104+12	ERT Line 2	Yes	-	17.76	14.72	15.24
ERT L2-5 STA 102+22	ERT Line 2	Yes	7944	2.75	1.44	1.2
ERT L2-6 STA 87+19	ERT Line 2	Yes	5478	3.6	12.92	14.08
NRT NT-1 STA 216+24	NRT N. Tube	No	4477	1.04	-	-
NRT NT-2 STA 227+74	NRT N. Tube	No	-	9.04	7.2	1.96
NRT NT-3A STA 236+39	NRT N. Tube	Yes	4297	>40	-	-
NRT NT-3B STA 236+39	NRT N. Tube	Yes	-	23.28	9.16	28.8
NRT NT-4 STA 238+51	NRT N. Tube	Yes	3778	5.8	0.96	2.68
NRT NT-5 STA 241+81	NRT N. Tube	Yes	3471	8.96	0.96	0.88
NRT ST-1 STA222+07	NRT S. Tube	No	2339	1.52	-	-
NRT ST 2 STA 237+65	NRT S. Tube	Yes	-	6.04	2	0.72
NRT ST-3 STA 238+66	NRT S. Tube	Yes	-	29.04	>40	>40
NRT ST-4a STA238+98	NRT S. Tube	Yes	2108	4.08	6.92	4.16
NRT ST-4b STA 238+98	NRT S. Tube	Yes	3364	-	-	-
NRT ST-5 STA 241+69	NRT S. Tube	Yes	2692	0.44	-	-

* UC-Unconfined Compressive Strength

** Chloride Content in Lbs. per Cubic Yard of Concrete

Table 2 – Concrete Test Results

The test results indicate that there is a degree of scatter in both the strength and salt content of the concrete. In general, the strength of the concrete in the East River Tunnel is markedly higher than that of the North River Tunnel, ranging from approximately 3,500 psi to nearly 8,000 psi in comparison to strengths ranging from approximately 2,100 psi to nearly 4,500 psi.

There is significant scatter in the chloride data as well and a number of surface readings indicating elevated chloride concentrations. Also, in a number of instances, the chloride concentration is elevated at depth in the concrete. This could be a reflection of the porous nature of the concrete at these locations.

In addition to the concrete core testing, a Portable Seismic Pavement Analyzer (PSPA) was used to measure the seismic modulus of the concrete. PSPA provides a rapid means of assessing the concrete modulus, and thus indirectly the concrete strength. The PSPA tests were conducted in the tunnels to supplement the compressive testing findings. PSPA tests were conducted at the core locations and used to verify published correlation relationships. These tests indicate the compressive strength of the concrete ranges from approximately 2,000 psi to 8,000 psi, with the lower strengths occurring in the North River Tunnel. The PSPA results are presented in Appendix A.

Impact of Inundation on Structural Loading

Over stressing of lining elements can cause immediate structural distress, or if sustained, reduce service life by the process of stress corrosion cracking. Stress corrosion cracking is when susceptible metals, such as cast iron and steel, are stressed in an environment containing chloride rich materials. In order to assess the level of stress increase in the critical lining elements, the bolts, numerical analyses were performed. Finite Element Method (FEM) program, MIDAS/GTS, was used to analyze the 'worst case' condition for both the East and North River Tunnels.

Changes to Tunnel Lining Stresses

The inundation of the tunnels with sea water resulted in two distinct stress changes to the tunnel structures. The first stress change was due to the water pressure imposed by the sea water on the inside face of the tunnel lining. This internal pressure counteracted the existing soil and water pressure exerted on the exterior of the tunnel lining. This counter pressure caused the tunnel to change shape and thus resulted in stress changes to the lining. From previous analyses for tunnels of similar construction, it has been shown that this loading condition is most severe where the lower half of a tunnel invert is in rock and the upper half is in soil. This configuration is commonly referred to as a mixed-face condition. Since this is the worst case condition, it has been analyzed for this assessment.

The second stress condition relates to the change in buoyancy of the tunnel due to the increased weight of the water. In areas where the tunnels are situated entirely in soil, the tunnels are free to move and compensate for the change in buoyancy. Issues arise at locations where the tunnels are supported on rock and an adjoining area is supported on soft soil. The change in buoyancy can cause the tunnel on the soft soil to displace downward relative to the adjacent rock supported section. This movement causes a bending moment to develop across the tunnel section with the result being an increase in bolt tension and an increase in lining compression.

Loads Resulting from Increases in Internal Pressure

The East River and North River Tunnel geologic pass-through records and inundation conditions were reviewed to identify the "worst case" mixed-faced conditions. The worst case conditions were identified to be in East River Tunnel, Line 1, at the four locations shown in Figure 13. At these locations, the tubes had their maximum inundation levels and spring lines in a mixed-face condition. Since these conditions are all similar, only one analysis was required to determine the increased stress condition.

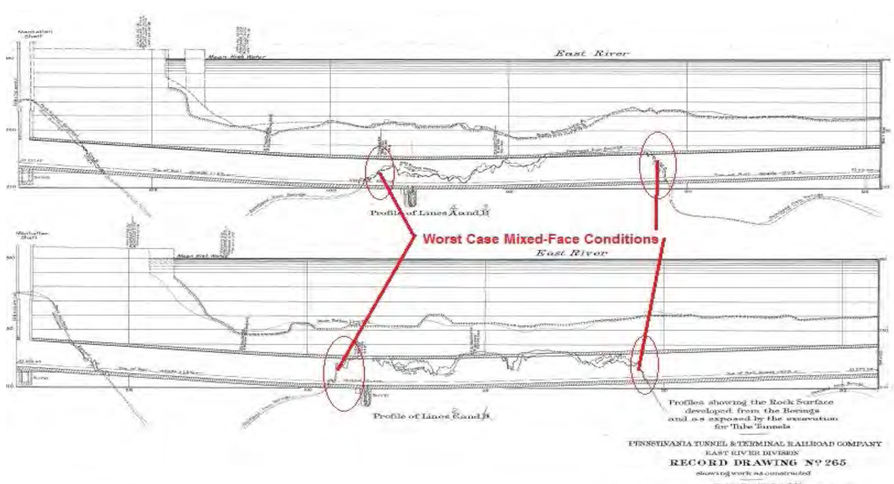

Figure 13 – Worst Case, Mixed-Face Locations

Numerical analyses, based on the Finite Element Method (FEM) - MIDAS/GTS, were performed to assess the stress increases in the tunnel lining resulting from the changes in internal pressure. The model was analyzed with the assumption of a plane strain condition, and the ground was modeled in accordance with the Mohr-Coulomb theory. The FEM model considered the complete loading history of the tunnels, from their original excavation, lining installation, time relaxation, to Sandy inundation.

The results of these analyses indicate that the Sandy inundation and resulting submergence of the tubes caused the lining and bolt stresses to increase, however these increases were minimal and of little consequence to the tunnel integrity.

Loads Resulting from Changes in Tunnel Buoyancy

In order to assess the stress conditions resulting from the change in tunnel buoyancy, an FEM model was developed using longitudinal beam elements to represent the cast iron lining and spring elements to model the rock or soil conditions supporting the tunnels. The "worst case" condition modeled represented the situation where a portion of the tunnel is supported on relatively inflexible (stiff) rock and an adjoining area is supported on "softer" soil. Since the sea water inundation loads are transmitted through the lining to the tunnel subgrade, difference in subgrade stiffness results in bending of the lining. Figure 14 illustrates the model used to simulate the tunnel support conditions as well as the extent of inundation loading.

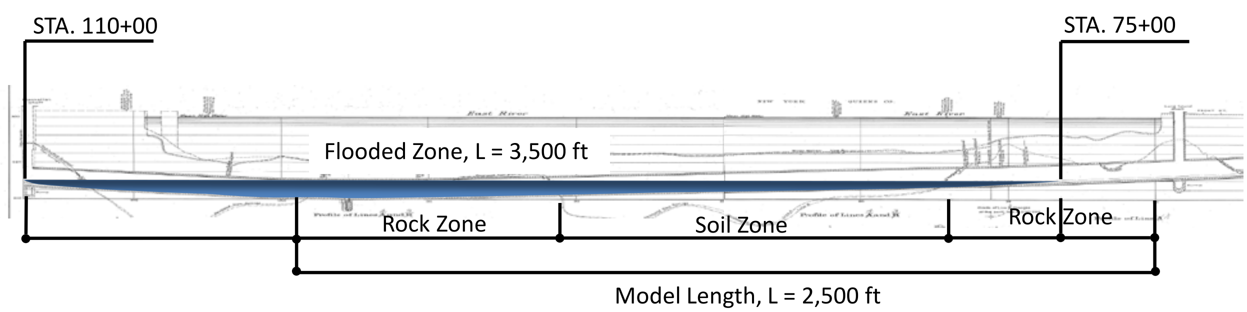

Figure 14 - Model Boundary and Inundation Condition for East River Tunnel

The tunnel structure was modeled as a pipe-shaped beam element. The equivalent thickness of the cast iron segments was calculated and used to develop the tunnel's sectional properties. Figure 15 presents an enlargement of the model to illustrate how the Midas/GTS model was configured to account for the difference in subgrade support. The model was made very long, 2,500 feet, to minimize any "end effects" influences.

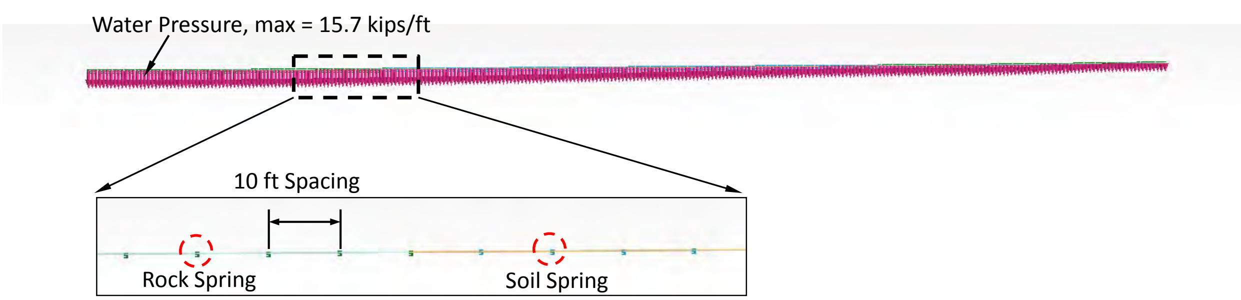

Figure 15 - GTS Model for the Deflection Analysis

The subgrade spring coefficients were derived from the elastic modulus of the support materials. The inundation loading corresponded directly to the level of sea water within the tunnel, Figure 16. For the worst case condition, this corresponds to the mid-river region of the East River Tunnel, which was inundated to the crown, in Lines 1 and 2. Note that the water level in the North River Tunnel was less severe with water reaching above the level of the bench walls. In the East River Tunnel, the sea water level reached the crowns of the tubes. The net increase in load on the tunnels was calculated based on the area of tube filled multiplied by the unit weight of sea water, 64 pounds per cubic foot.

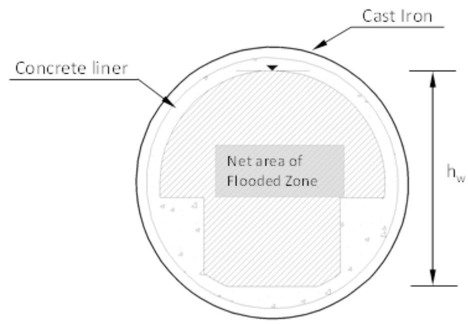

Figure 16 - Net Area Used to Calculate Inundation Loading

Deflection analyses were performed using the tube properties, seawater loading, and a range of subgrade properties. Since geotechnical testing of the in-situ soils was not possible for this assessment, a range of properties was analyzed to assess the sensitivity of the tubes to this loading. Of these analyses, the critical loading corresponds to the bending moment. Figure 17 presents the results of one of the cases analyzed.

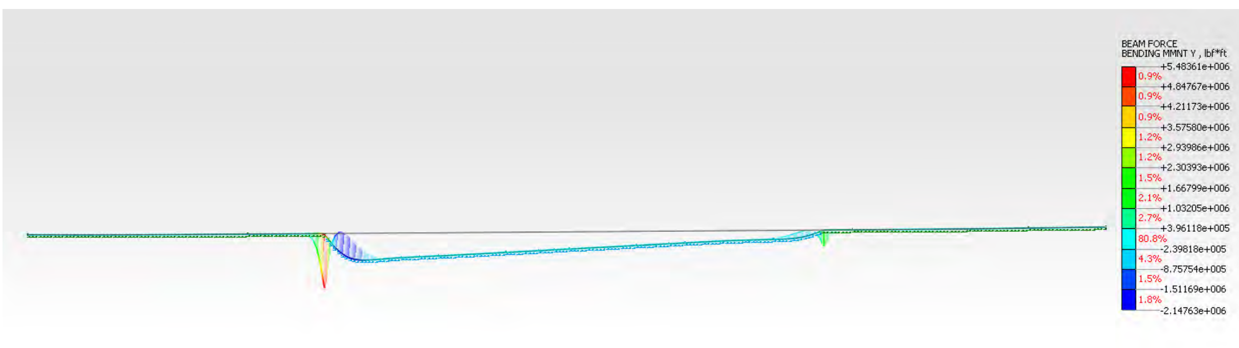

Figure 17 – Resulting Bending Moment in Lining

Increases in bending moment directly impact the stresses in the lining bolts. As the tube deflects downward under the weight of the sea water it rotates on the rock subgrade. This causes the crown of the tunnel to undergo increased tension and the tunnel invert to undergo increased compression. The tunnel's compressive capacity is significant with the combination of the full cast iron and concrete sections available to resist the increased compression. The tube's tensile capacity is not as robust; since the concrete linings in the East River Tunnel are not reinforced and the lining has numerous "cold joints", the tension is resisted solely by the bolts in the cast iron lining.

The maximum increase in bolt loading was calculated based on the bolt pattern geometry and the calculated bending moment. The corresponding increase in tension stress ranged from approximately 17,000 pound per square inch to approximately 24,500 pound per square inch, with the higher stress corresponding to the softer soil conditions. A review of historical data indicates that bolts manufactured in the 1910 timeframe typically had a yield strength of approximately 30,000 pounds per square inch. Even assuming very soft soil subgrade properties, the tunnel bolts approached, but did not exceed their yield stress levels. Thus, it can be concluded that the inundation loading did not cause damage to the tunnel lining components.

Assessment

Concrete Lining

The concrete linings in the two East River tubes were infiltrated with chlorides and sulfates for a significant portion of their under river lengths, while the North River tubes were infiltrated to a proportionally lesser extent. This includes the lining interior surfaces as well as significant cracks or joints in the concrete. The overall impact of this chloride and sulfate exposure is damage to the concrete linings and a reduction in their service lives.

The test data indicate that there are areas of the linings that have elevated chloride concentrations. These chlorides, along with sulfates and other substances, have caused and are causing damage to the concrete and embedded steel elements in the linings and bench walls. Thus, the chlorides, sulfates and other substances should be removed. The chlorides accelerate the corrosion of the embedded items and exposed steel members, while the sulfates deteriorate the concrete.

Cast Iron Lining

The cast iron lining surrounding the tubes was designed to withstand external earth and water pressure loading. As such, the liner plate is substantial, with the minimum thickness of 1.5 inches. The intent was to measure the actual cast iron thickness using ultra-sonic measurements; however, the lack of access and a control sample made it impossible for the technician to obtain a reliable measurement. Fortunately, the inspection program included concrete cores drilled to the cast iron lining. At the base of these cores, there were no indications of corrosion of the cast iron.

The observations made above indicate that the cast iron linings are structurally sound. Except where the linings are exposed, they in all likelihood have not suffered damage. The likelihood that chlorides and sulfates reached the cast iron linings is remote. The only avenues for damage would have been the cracks that occur at the transverse cold joints. Since these joints occur at intervals of tens of feet and the cracks are only fractions of an inch, the potential for cast iron exposure is low. Thus, the chloride and sulfate inundation has had negligible, if any, chemical impacts to the cast iron linings.

Lining Bolts

The cast iron lining bolts have been cast in and surrounded by concrete. Concrete encasement protects embedded elements by isolating them from moisture in the tubes, and by providing an alkaline environment, which is a simple form of cathodic protection. Another indirect indication that there has not been significant corrosion of either bolts or for that matter cast iron lining is that there is little, if any, iron staining on the walls of the tubes. Thus, although not directly observed, it can be surmised that the lining bolts have not experienced significant, if any, chemical impacts.

Bench Walls

The tunnel bench walls consist of concrete surrounding clay ducts. The ducts are used to house electrical services for power, train operations, signal and communications. Steel members are present at the numerous splicing vaults, metal steps, and alignment clips of the conduit sections. The steel at the splicing vaults are structural members that support a facing of concrete spanning across the vault cavities. Steel is also set around the vault opening at the top of the bench walls.

The construction of the bench walls involved the staged placement of concrete and conduits. This staged construction resulted in the creation of numerous ‘cold’ joints, fresh concrete placed against set concrete, in the completed bench walls. In addition, as the bench walls were built up from the tunnel invert, a system of horizontal cold joints was cast in the concrete.

The bench walls in the under river portions of the East River Tunnel were inundated during Sandy, with each tube inundated for approximately 3,500 feet of its length. In the North River Tunnel, the inundation was less extensive with approximately 1,900 feet inundated in the North tube and 800 feet inundated in the South tube. Shortly after Sandy, each tunnel was dewatered.

Inspection has shown that the bench walls have significant damage, consistent with that of a century old tunnel. The damage consists of corrosion of embedded steel elements, most commonly at the splicing chambers, horizontal cracking within the bench walls, and erosion along the base of the bench walls. The damage is most severe at the splicing vaults. In a number of locations, the underlying steel is exposed and corroded. In many instances, this damage extends to the upper portion of the bench wall. In these instances, maintenance crews have placed steel plates.

The most common damage feature is horizontal cracking along the bench walls. These cracks are usually located in the middle third of the wall and are extensive in length, in some instances exceeding 100 feet. These cracks range from 1/8 to ¼ inch in width.

The other common feature is the erosion of the concrete where the bench walls intersect the track ballast. In these instances, the aggregate in the concrete is exposed in a honey comb pattern. It is apparent that the cement paste has been dissolved out of the concrete. This erosion does not extend sufficiently into the concrete to present a structural integrity issue at the present time, but it provides a potential means for chlorides and sulfates to penetrate deeper into the concrete. Furthermore, the clay conduits in the bench wall provided direct access for chlorides and sulfates to penetrate into the lining behind the bench wall.

Even though the water has been removed, the chlorides and sulfates have damaged and continue to damage the bench walls. The chlorides accelerate the corrosion of the embedded and exposed steel members, while the sulfates deteriorate the concrete. In addition, the presence of the chlorides in the ducts damages the electrical systems.

Rail and Ballast System

The rail system used in both tunnels consists of rock ballast, treated timber ties, tie plates and clips, running rail and third rail. These components are now coated with chlorides. Full removal of the chlorides from the ballast, including from the inaccessible surfaces, is not possible; therefore the ballast should be removed in its entirety. The tie and rail systems have to be removed in order to remove the ballast. It should all be replaced with a direct fixation rail system, which is the state of practice for rail tunnels. The direct fixation system should be installed for the entire length of the tunnels, e.g. portal to portal. This will provide Amtrak with a uniform track support system throughout each tunnel. In addition, this work should be accomplished in coordination with the bench wall replacement to minimize service interruptions.

Recommendations

Based on our investigations and professional opinion, we recommend that that the following actions be undertaken in the damaged tubes:

Perform the following immediate activities as soon as possible:

1. Inspect all splice vault areas and remove or secure delaminated concrete.
2. Remove all delaminated and loose concrete to sound material, clean all newly exposed surfaces and perform spall repair, apply protective coating to exposed metals, and patch concrete.
3. Pressure wash the tunnel linings to remove chlorides, sulfates, and other substances deposited on exposed surfaces.
4. Seal all leaks and all cracks greater than 1/8 inch wide.
5. Pressure wash and then patch any voids or holes in the concrete lining more than 1 inch deep.
6. Replace all electrical, mechanical systems, and equipment.

Perform the following work as soon as possible and as tunnel access allows:

7. Remove the bench walls and replace with new bench walls, sized to conform to the requirements of NFPA 130 for the entire length of the tunnels (portal to portal).
8. Remove tunnel ballast and rail systems and replace them with a direct fixation rail system for the entire length of the tunnels (portal to portal).
9. In concealed areas (e.g. behind the bench walls and the tunnel invert) inspect the areas after exposure, pressure wash them and perform structural repairs of cracks, spalls and delaminations.
10. Perform regularly scheduled inspections of the tunnel linings in order to monitor the condition of any repairs/replacements and to identify areas in which damage continues to occur and to identify evidence of any new damage.

The logistics of accomplishing these recommendations requires that these activities be phased to get the work done as soon as possible, while minimizing disruptions to passenger service. Thus, the phasing of the repair/replacement work should be as follows:

1. Immediately develop contract documents and procure a contractor to perform pressure washing and interim delamination repairs, bench wall repairs and crack repairs, as necessary, in the East River and North River Tunnels during evening and weekend outages.

2. Prepare design and contract documents for the removal and replacement of the bench walls and the track system for the East River Tunnel, Lines 1 and 2. Plan to remove and replace the bench walls and the track system, one tube at a time, on a 24/7 accelerated schedule, with full closure and as soon as possible. Preparatory works such as rail operations planning, temporary tracks, temporary switches, access, power and signal sectionalization, etc. should be done in advance of the tube closure.

3. Prepare design and contract documents for removal and replacement of the bench walls and the track system for the North River Tunnel. Plan to remove and replace the bench walls and the track system, one tube at a time, on a 24/7 accelerated schedule, with full closure as soon as possible. Preparatory works such as rail operations planning, temporary tracks, temporary switches, access, power and signal sectionalization, etc. should be done in advance of the tube closure.

Cost Estimate

The recommended actions listed in the previous section have been cost estimated for each of the damaged tubes. The table below presents a summary of the work that has been identified so far, and the estimated costs in 2014 dollars. Detailed estimates are presented in Appendix B.

2014 $'s				
Tube	**Pressure Washing**	**Cracks and Delaminations**	**Bench Wall Replacement**	**Direct Fixation Track**
ERT Line 1	$2,700,000	$3,200,000	$119,000,000	$47,800,000
ERT Line 2	$2,700,000	$3,200,000	$111,000,000	$44,500,000
NRT- North	$1,900,000	$1,500,000	$124,700,000	$50,000,000
NRT- South	$1,700,000	$400,000	$124,700,000	$50,000,000
Subtotals	$ 9 million	$ 8.3 million	$ 479.4million	$192,300,000
Grand Total	**$ 689 million**			

Key assumptions used to develop these estimates include:

1. Costs include "soft cost", with Engineering (10%), Construction Management (8%), and Amtrak Force Account protection (25%).
2. The estimates reflect a 30% contingency to account for the conceptual level of the design elements.
3. The estimate was based on a developed schedule of track system and bench wall replacement requiring approximately one year of full closure per tube.
4. Evening and weekend interim repair work will be performed during evening and weekend outages, with evening work window of 4 hours and a weekend work window of 50 hours.
5. Full closure work will be 24/7 for the duration of the construction. It is assumed that the work will be performed by 3 shifts a day, 7 days a week.
6. Costs assume that work will be performed in one tube at a time. (i.e. one East River Tube at a time and one North River Tube at a time, but work can be concurrent in East River and North River Tunnels)
7. These estimates assume no HAZMAT issues.
8. These estimates are prorated to account for areas that were not available for visual inspection such as behind the bench walls and in the invert.
9. These estimates do not include potential loss of revenue or operational impacts.
10. Majority of the work will be performed by a 3rd party contractor
11. All necessary track work, yard, roadway and any other "early" predecessor infrastructure will be identified and installed by Amtrak forces prior to the closure of the tubes, and the cost for this work is not included in this report.

References

1. *National Fire Protection Association, NFPA 130 - Standard for Fixed Guideway Transit and Passenger Rail Systems*

2. *U.S. Department of Transportation. Highway & Rail Transit Tunnel Inspection Manual. U.S. Department of Transportation, Federal Highway Administration/Federal Transit Administration, 2005.*

3. *American Concrete Institute. ACI CT-13 Concrete Terminology. Farmington Hills, MI: American Concrete Institute, 2013.*

4. *CreteDefender. "How Salt Damages Concrete." 2012. http://www.cretedefender.com (accessed April 24, 2014).*

5. *Portland Cement Association. "Corrosion of Embedded Materials." 2014. http://www.cement.org (accessed April 24, 2014).*

Appendix A

Advanced Infrastructure Design (AID) Findings
(Provide electronically in accompanying thumb drive)

Appendix B

Cost Estimate
(Provide electronically in accompanying thumb drive)