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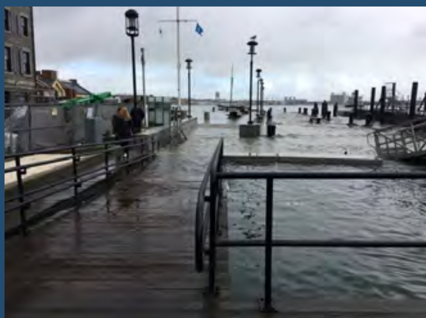

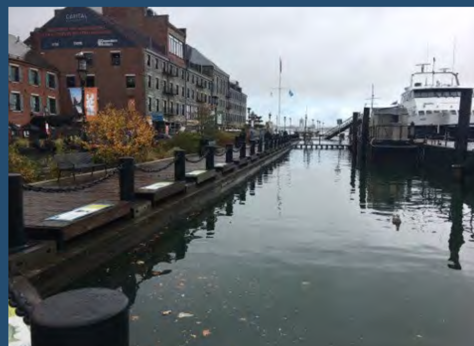

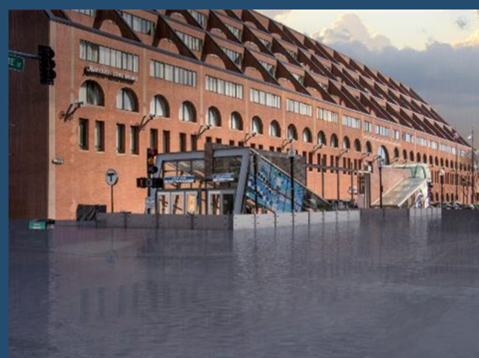

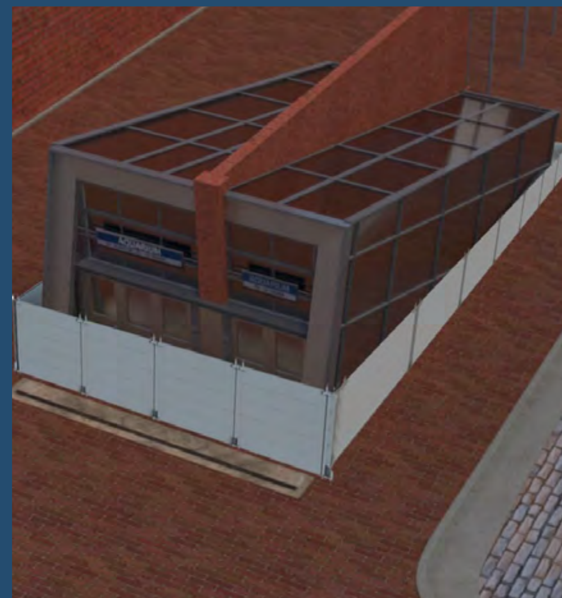

MassDOT- FHWA Resilience and Durability Pilot Project Report

Implementing Coastal Flood Resilience Solutions for the Tip O'Neill Tunnel Egress 434 and the MBTA Blue Line Aquarium Station

Massachusetts Bay Transportation Authority

Moving Massachusetts Forward. massDOT

U.S. Department of Transportation
Federal Highway Administration

DISCLAIMER

This report was developed by the Massachusetts Department of Transportation in accordance with a research project jointly funded by the Federal Highway Administration (FHWA). The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of FHWA or the U.S. Department of Transportation.

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16. Abstract

The primary objectives of this project included:

- Assessing the vulnerability to flooding of critical assets using the Boston Harbor – Flood Risk Model (BH-FRM) developed under a previous FHWA grant.
- Evaluating alternatives to address identified vulnerabilities.
- Developing bid documents for a selected alternative at the MassDOT Tunnel Egress TE-434 and MBTA Blue Line Aquarium Station.
- Constructing the selected floodproofing alternative as quickly as possible to make the TE-434 and MBTA Blue Line Aquarium Station resilient to coastal flooding.
- Developing Standard Operating Procedures for deployment of temporary flood barriers.

This report summarizes the project needs, the scope of work performed, interagency partnerships, the approach and methodology, development of Standard Operating Procedures for the deployment of Flood barrier systems, future monitoring and documentation and lessons learned over the course of this project.

A Standard Operating Procedure (SOP) is being developed, that identifies responsible parties for decision making, forecasted flood level thresholds used to trigger deployment, personnel in charge of barrier deployment and communication protocols.

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IMPLEMENTING COASTAL FLOOD RESILIENCE SOLUTIONS FOR THE TIP O'NEILL TUNNEL EGRESS 434 AND MBTA BLUE LINE AQUARIUM STATION

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Acknowledgements

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- Bella Purdy – Climate Resiliency Planner

Cover Photographs are all attributed to MassDOT

List of Acronyms

ADA	Americans with Disabilities Act
ADAAG	Americans with Disabilities Act Accessibility Guidelines
BFE	Base Flood Elevation
BH-FRM	Boston Harbor – Flood Risk Model
BH-SCM	Boston Harbor Storm Cast Model (BH-SCM)
BLC	Boston Landmarks Commission
CMR	Code of Massachusetts Regulations
CRU	MassDOT Cultural Resources Unit
DFE	Design Flood Elevation
EOEA	Massachusetts Secretary of the Executive Office of Environmental Affairs
FCI	Flood Control International
FHWA	Federal Highway Administration
FRP	Flood Response Plan
HOC	Highway Operations Center
LWCF	Land and Water Conservation Fund
MAAB	Massachusetts Architectural Access Board
MassDOT	Massachusetts Highway Department
MBTA	Massachusetts Bay Transportation Authority
MHS	MassDOT Metropolitan Highway System
MLLW	Mean Lower Low Water
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NTP	Notice-to-Proceed
NWS	National Weather Service
OCC	MBTA Operations Control Center
ROW	Right-of-Way
SHPO	State Historic Preservation Officer
SLR	Sea Level Rise
SOP	Standard Operating Procedures
TE-434	Tunnel Egress No. 434

Executive Summary

The Massachusetts Department of Transportation (MassDOT) received a grant under the Federal Highway Administration (FHWA) funding under the *Resilience and Durability to Extreme Weather Pilot Program, Type 3* for the **Implementing Coastal Flood Resilience Solutions for Highway Tunnels in Boston Project**.

Historically high coastal flooding on January 4, 2018 caused approximately $3.5 million in flood damage to the Massachusetts Bay Transportation Authority's (MBTA) infrastructure inside the MBTA Blue Line Aquarium Station. Another significant coastal flood event occurred again on March 2, 2018. These two significant flood events, which occurred one after the other, prompted MassDOT and the MBTA to partner on this project to design, construct, operate, and maintain floodproofing improvements for the MBTA Blue Line Aquarium Station, including MassDOT's Tip O'Neill Tunnel Egress-434 (TE-434), and the MBTA Blue Line Tunnel Emergency Egress on Long Wharf. See Figure 1 for a project location plan.

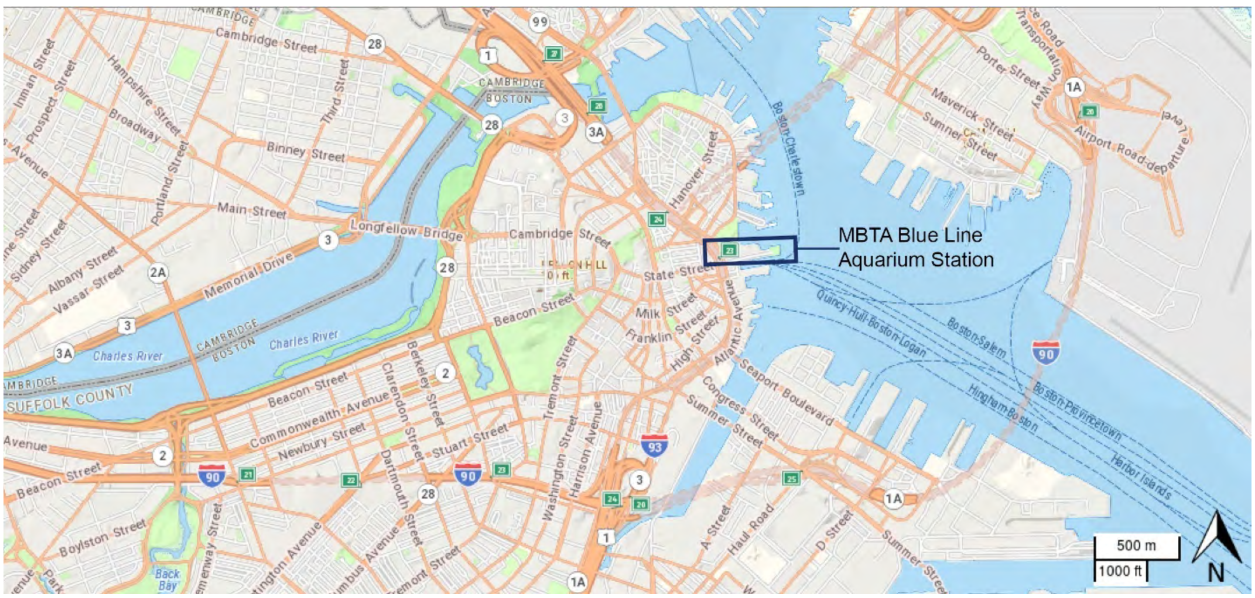

Figure 1 - Project Location Plan

The primary goal of the project is to prevent catastrophic damage to public transit and highway tunnel infrastructure in Downtown Boston from extreme coastal flooding events.

The primary objectives of this FHWA Resiliency and Durability pilot project include:

- Assess the vulnerability to flooding of critical assets using the Boston Harbor – Flood Risk Model (BH-FRM) developed under a previous FHWA grant
- Evaluate alternatives to address identified vulnerabilities
- Develop flood proofing bid documents for a selected alternative at the MassDOT Tunnel Egress TE-434 and MBTA Blue Line Aquarium Station
- Construct the selected floodproofing alternative as quickly as possible to make the TE-434 and MBTA Blue Line Aquarium Station resilient to coastal flooding

- Develop Standard Operating Procedures for deployment of temporary flood barriers

This FHWA Resiliency and Durability Pilot Project Report summarizes the project needs, the scope of work performed, interagency partnerships, the approach and methodology, development of Standard Operating Procedures for the deployment of Flood barrier systems, future monitoring and documentation and lessons learned over the course of this project.

1. Introduction

1.1 Project Motivation

MassDOT Metropolitan Highway System (MHS) tunnels and associated infrastructure in Boston are critical for the economic health and disaster preparedness, response, and recovery of the Metro Boston region, and are also at increasing risk of damage from coastal flooding due to extreme weather and relative Sea Level Rise (SLR). Much of the transportation system, including MassDOT's Central Artery and Tunnel system as well as the Massachusetts Bay Transportation Authority's (MBTA) subway system is underground and potentially susceptible to flooding from surface waters.

These identified risks were realized on January 4, 2018, when an astronomical high tide coincided with peak storm surge from a large extra-tropical cyclone, locally referred to as a nor'easter, to flood roadways, buildings and transit infrastructure in Boston and throughout coastal Massachusetts. This coastal flood event is now the flood of record in Boston, having passed the Blizzard of '78 flood. Although the MHS tunnel system as a whole did not accumulate significant volumes of water due to the rapid recession of the high tide, flood water entered two MHS tunnel egress openings.

Flooding at one of these egress openings, Tip O'Neill Tunnel Egress 434 (TE-434), which is collocated with the MBTA Blue Line Aquarium Station subway head house on Long Wharf in downtown Boston, was extensively featured in national and local news media. (see Figure 2). Flood water entered both TE-434 and the MBTA Aquarium Station East headhouse, causing over $3.5 million dollars of damage to an elevator, stairway, escalator and electrical equipment in the station, as well as accelerated corrosion of infrastructure due to the corrosive effects of salt water.

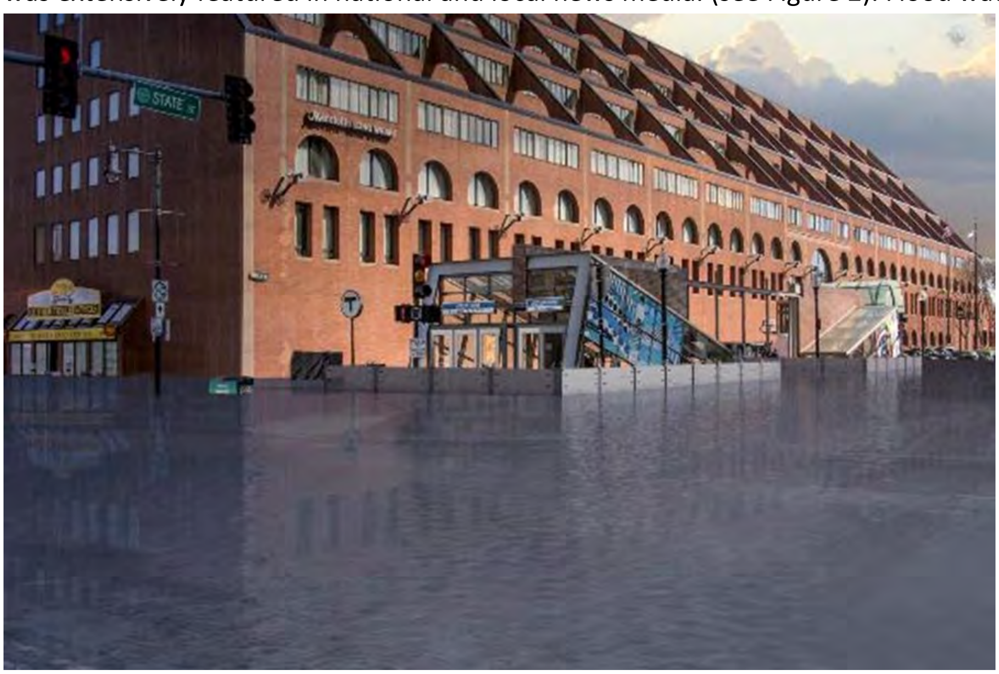

Figure 2 – Rendering of Flooding at Blue Line Aquarium Station East Headhouse and TE-434 (Credit: MassDOT)

A second near miss event occurred on March 2, 2018 during another nor'easter. The March 2, 2018 storm is now the third highest flood of record after the Blizzard of 1978. For this storm event, the MBTA deployed sandbags at entrance doors and elevators at street level to minimize intrusion of flood water into the station. Passengers were inconvenienced due to the East Station headhouse being shut down and the surrounding area being flooded. The MBTA noted that deployment of sandbags was very labor intensive and time consuming. Due to potential contamination from flood waters, sandbags also had to be disposed of as hazardous waste.

The National Oceanic and Atmospheric Administration (NOAA) has been monitoring monthly mean sea level data since 1921 at the Boston Harbor tide gauge located in the Fort Point Channel (No. 8443970). Figure 3 graphically shows a plot of monthly mean sea level data from 1921 to 2019 at this gauge. The relative sea level trend is 2.86 millimeters/year with a 95% confidence interval of +/- 0.15 mm/yr, which is equivalent to a change of 0.94 feet over the last 100 years. As a result of rising sea levels, storm surges have an increased "base" from which to exacerbate flooding. The severe storms of the 1930s through 1960s might have resulted in similar (or more) flood damages, but the sea level "baseline" was lower.

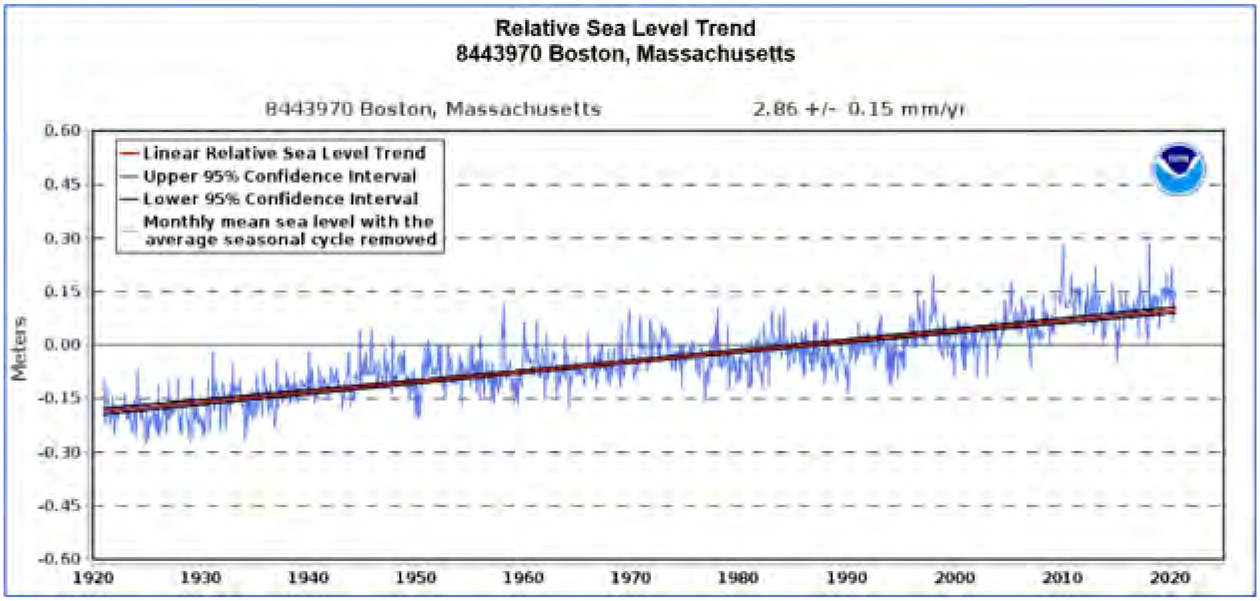

Figure 3 - Relative Sea Level Trend at Boston Tide Gauge (Credit: NOAA 2020)

These recent flood events, together with projections of continued rising of sea levels and the desire to make the Blue Line Aquarium Station more resilient to flooding, raised the urgency of designing and implementing less labor-intensive floodproofing solutions to address the increasing probabilities of higher and more frequent flooding at the MBTA Blue Line Aquarium Station and TE-434. In addition, once floodproofing solutions are constructed and made available for deployment, Standard Operating Procedures have to be implemented to ensure that the floodproofing solutions will be deployed in a timely manner prior to a flood event, and then properly cleaned, removed and stored for future reuse.

1.2 Building on Other FHWA-Funded Projects

Flood data used to establish the vulnerability to flooding of the TE-434 and MBTA Blue Line Aquarium Station was obtained from an earlier FHWA-funded pilot project ***Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery*** ("*Central Artery Pilot*

Project")[1]. The pilot project included development of the state-of-the-art hydrodynamic Boston Harbor Flood Risk Model (BH-FRM). BH-FRM meets the criteria for "Level of Effort 3: Modeling in a Probabilistic Risk Framework," as defined in *FHWA Hydraulic Engineering Circular No. 25 – Volume 2, Highways in the Coastal Environment: Assessing Extreme Events* (October 2014). MassDOT is currently updating and extending this model, which will be known as the Massachusetts Coast Flood Risk Model, to the entire Massachusetts coastline as part of MassDOT's *Coastal Transportation Vulnerability Assessment*.

The *Central Artery Pilot Project* also mapped and assessed the vulnerability of thousands of MassDOT assets under existing and future coastal flooding scenarios. All of the tunnel portals, egresses, and buildings to be protected as part of the this proposed pilot project were identified as critical vulnerabilities and priorities for adaptation in the *Central Artery Pilot Project* report. In evaluating adaptation strategies for these assets, the study recommended high-level, gray infrastructure concepts, valued at approximately $28 million, to ensure flood protection extending to the year 2030.

Subsequent to the *Central Artery Pilot Project*, MassDOT carried out an internal scoping exercise to identify protections that could be implemented today and provide flood protection to 2030 and hired a design consultant for the *MHS Tunnel Resiliency Project* to assist with the following tasks:

A. Assess the vulnerability of tunnel entrance drainage systems to backflow and overflow in coastal flooding scenarios,
B. Verify the vulnerability assessment findings for priority tunnel entrances and egresses,
C. Design deployable flood barrier solutions to address verified entrance and egress vulnerabilities, and
D. Develop an emergency response plan.

This scoping exercise completed Task A and Task B, and substantially advanced Task C and Task D. As part of Task C, MassDOT's design consultant conducted an analysis of alternative deployable flood barrier solutions along with a high-level cost-effectiveness estimate. Work on Task C to design the proposed physical solutions was funded through this FHWA Resiliency and Durability pilot project.

1.3 Project Objectives

To continue efforts to understand resilience of transportation systems for extreme events, in 2017 the FHWA solicited ideas for their *Resilience and Durability to Extreme Weather Pilot Program*: a joint FHWA-transportation entity collaborative effort. In February 2018, MassDOT submitted the **Implementing Coastal Flood Resilience Solutions for Highway Tunnels in Boston** project. The primary goal of this project is to reduce life-cycle damage and disruption costs from coastal flooding to MassDOT's Metropolitan Highway System (MHS) tunnels in Boston as well as other critical regional transportation infrastructure, where possible.

The primary objectives of this FHWA Resiliency and Durability pilot project include:

- Assess the vulnerability to flooding of critical assets using the BH-FRM model
- Evaluate alternatives to address identified vulnerabilities

[1] MassDOT-FHWA Pilot Project Report: Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery, June 2015, Woods Hole Group, UMass Boston, University of New Hampshire, MassDOT.
https://www.mass.gov/files/documents/2018/08/09/MassDOT_FHWA_Climate_Change_Vulnerability_1.pdf

- Develop floodproofing bid documents for a selected alternative at the MassDOT Tunnel Egress TE-434 and MBTA Blue Line Aquarium Station
- Construct the selected floodproofing alternative as quickly as possible to make the TE-434 and MBTA Blue Line Aquarium Station resilient to coastal flooding
- Develop Standard Operating Procedures for deployment of temporary flood barriers

The pilot project's geographic focus is the City of Boston, MA and is located within MassDOT Highway Division District 6. The project will likely benefit millions of users throughout Metro Boston, Massachusetts and New England who rely on this critical transportation infrastructure. In addition, it will benefit other stakeholder agencies, such as the MBTA whose infrastructure or operations are interdependent with MassDOT.

2. Project Scope

The scope of work performed under this FHWA Resiliency and Durability pilot project included preliminary and final design and preparation of bid documents for implementing floodproofing strategies, permitting, ROW acquisition services and construction phase services. The project also included the preparation of Standard Operating Procedures for deployment of temporary flood barriers to be incorporated into existing MassDOT and MBTA emergency response plans.

Design services for this project were funded through this FHWA Resiliency and Durability pilot project grant. The actual cost of construction was funded by the MBTA.

2.1 Focused Project Scope from MassDOT Assets

Based on the vulnerability assessments and options explored in the *Central Artery Pilot Project Report*, work on this pilot project began with a focus on the most-at-risk MassDOT roadway infrastructure assets, which included:

- Sumner Tunnel (Route 1A) entrance portal in East Boston
- Callahan Tunnel (Route 1A) exit portal in East Boston
- Emergency Access Ramp entrance portal from Massport Haul Road to Ted Williams Tunnel (I-90) in South Boston
- Ramp CS-SA exit portal from the Tip O'Neill Tunnel (I-93) to John F. Fitzgerald Surface Road in Downtown Boston
- Tunnel Egress 434 from the Tip O'Neill Tunnel (I-93) and MBTA Blue Line Aquarium Station Headhouse on Long Wharf in Downtown Boston
- Tunnel Egress 425 from the Tip O'Neill Tunnel (I-93) on the Rose Kennedy Greenway in Downtown Boston

Work included preparing preliminary and final design packages to 90% level of completion for the deployment of temporary flood barrier systems at each of the above roadway assets and preparation of a draft operational Flood Response Plan (FRP) to define the actions and timelines required to deploy the temporary flood barriers. The FRP also included protective actions related to the MassDOT Highway Operations Center located in a flood-prone area of South Boston.

After meetings with MassDOT administrative and operations officials, it became clear that the time required to deploy temporary systems in advance of a flood event was too long. Problematic issues included the type of flood barrier being considered, traffic management and barrier storage and mobilization time. The deployment plan required initiating tunnel shut-downs of the Sumner Tunnel Entrance and Callahan Tunnel exit in East Boston about 6-12 hours in advance of the anticipated start of flooding to allow for flood barrier installation and de-energization of vulnerable electrical equipment. This early shutdown would cause substantial disruption to the City of Boston's and State of Massachusetts' evacuation plans, which was determined to be unacceptable.

The design team conducted additional studies and investigations into alternate temporary flood barrier systems that could be deployed at the tunnels entrances/exits much more rapidly. Alternative flood barrier systems that were investigated included:

- Passive flood barriers in the pavement that automatically raise as flood water rises (i.e. FloodBreak)
- A flexible Kevlar side-deployed flood barrier system where all components are stored at the point of use (i.e. FlexWall by ILC Dover)
- Interconnected vinyl tubes filled with water to create a temporary barrier (i.e. Tiger Dam)

While each of the above alternatives had various advantages and disadvantages, it was clear that the systems were more costly and disruptive than could be funded under this pilot project. For this reason, the scope of this pilot project was modified to focus on non-roadway assets, which are less impacted by advance deployment of temporary flood barriers.

MassDOT is continuing to investigate alternatives to improve resiliency from coastal flooding at these important roadway assets.

2.2 Design and Construction of Floodproofing Improvements to Non-Roadway Assets

Non-roadway assets included in this pilot project were:

- MassDOT Highway Operations Center (HOC) in South Boston
- Tunnel Egress 434 from the Tip O'Neill Tunnel (I-93) and MBTA Blue Line Aquarium Station Headhouse on Long Wharf in Downtown Boston

A draft Flood Response Plan was developed for Roadway and Non-Roadway assets that included proposed protective actions to prevent flood damage to the HOC. The plan was never officially approved as the Roadway assets were deleted from the floodproofing construction program. The HOC still refers to applicable elements of the plan, which included:

- Constructing sandbag barriers across two personnel doors along the HOC building's exterior to prevent lower levels of flood water from entering the electrical substation on the first floor, and
- Evacuating the HOC using MA Army National Guard high water emergency vehicles in the event that flood waters rose to such levels that the HOC could no longer be safely occupied.

At Flood Response Plan review meetings, MassDOT leadership and staff, as well as State Police, raised concerns regarding the HOC's vulnerability to coastal flooding and the adequacy of sandbags as a flood protection solution. Maintaining continuous functionality of the HOC through a coastal flooding event was seen as critical to the overall resilience and recovery of the MHS tunnel system.

In response to these concerns, the design consultant prepared a ***Highway Operations Center Flood Protection Strategies*** memo dated October 25, 2017 (See Appendix A), which studied several strategies for floodproofing the building to two possible Design Flood Elevations (DFEs). Figure 4 shows potential entry points around the HOC where water would enter the building below the DFEs.

The DFEs for the years 2030 and 2070 were calculated as the base flood elevation (BFE) plus a 2.0 ft. freeboard based on the ASCE 24-14 *Floodproofing Design Standard* for a critical structure. Using the BH-FRM projections for the 1% probability of exceedence as the base flood elevation (see Table 1), the DFEs were calculated as follows:

- DFE_{2030} = BFE 10.0 ft. + 2.0 ft. freeboard = 12.0 ft. NAVD88
- DFE_{2070} = BFE 12.8 ft. + 2.0 ft. freeboard = 14.8 ft. NAVD88

Table 1 – Probability of Exceedance Flood Data from BH-FRM at Highway Operations Center

	2030		2070	
Exceedance Probability	**Water Surface Elevation (ft- NAVD88)**	**Water Depth (ft)**	**Water Surface Elevation (ft-NAVD88)**	**Water Depth (ft)**
0.1	10.8	1.87	14.1	5.18
0.2	10.5	1.57	14.0	5.09
0.5	10.1	1.17	13.5	4.61
1	10.0	1.07	12.8	3.87
2	9.9	0.97	12.5	3.61
5	9.5	0.57	12.2	3.27
10	9.1	0.17	11.6	2.67
20	dry	dry	11.0	2.07
25	dry	dry	10.8	1.87
30	dry	dry	10.7	1.77
50	dry	dry	10.4	1.47
100	dry	dry	9.70	0.77

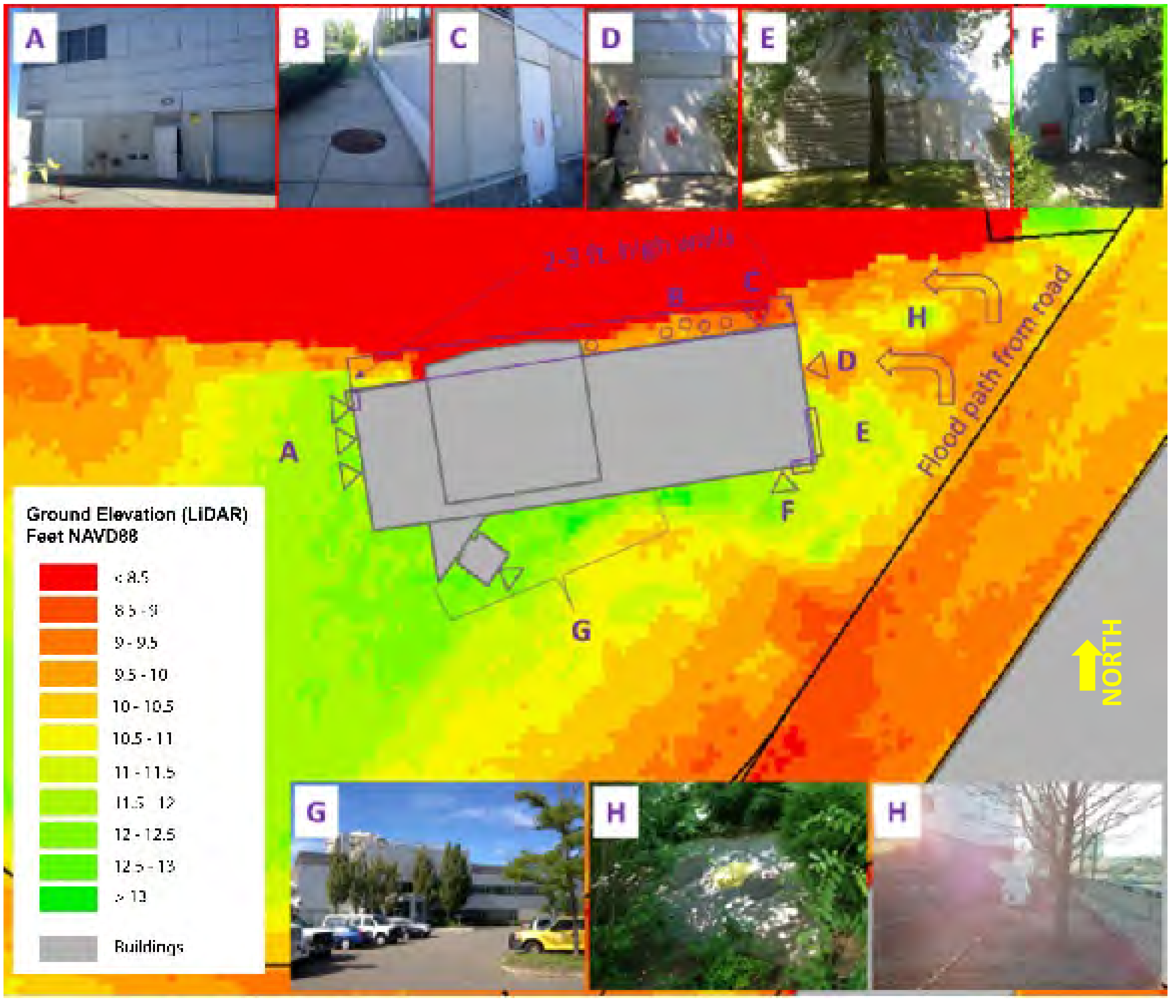

Figure 4 - Ground Elevation at Potential Flood Entry Points at MassDOT Highway Operations Center. (Credit: MassDOT)

Strategies for protecting to the 2030 DFE included: protecting vulnerable doorways with floodproof doors or temporary flood barriers; sealing electrical conduits; installing gate valves on sewer and drainage pipes entering the building to prevent sewer and storm drain back-ups into the building; installing water-tight manhole covers on exterior electrical vaults; installing water level sensor systems; and installing sump pumps.

Strategies for protecting to the 2070 DFE included: constructing a 1.5 ft. to 4 ft high perimeter flood wall with deployable flood barriers at access ways through the wall; sealing electrical conduits; installing gate valves on sewer and drainage pipes entering the building to prevent sewer and storm drain back-ups into the building; installing water-tight manhole covers on exterior electrical vaults; installing water level sensor systems; and installing sump pumps.

After reviewing this memo, MassDOT officials decided to reassess the costs of implementing the recommended strategies versus the feasibility of providing a back-up HOC or a new HOC in a less flood-prone area. Therefore, no further work related to HOC floodproofing was advanced under this pilot project. MassDOT is still pursuing passive flood protection at the HOC and is looking to identify funding and a construction mechanism for the installation of equipment and flood doors.

The design and construction for this project was therefore focused on floodproofing the Tip O'Neill Tunnel Egress 434 and the MBTA Blue Line Aquarium Station which are co-located at Long Wharf and State Street in downtown Boston. The project scope of work can be broken down into the following strategies at the four locations shown in Figure 5:

- Location 1: Long Wharf Blue Line Tunnel Emergency Egress Stair and Ventilation Structure. Replace glass block headhouse with floodproof concrete headhouse and flood door; install permanent flood protection panels at four emergency louvered ventilation shaft openings including anchorages.
- Location 2: East Headhouse, Elevator, and TE-434 Egress. Install perimeter drop-in flood plank systems, including concrete pavement foundations and anchorages.
- Location 3: Southwest Headhouse and Elevator. Install perimeter drop-in flood plank systems, including concrete pavement foundations and anchorages.
- Location 4: Marketplace Center Station Entrance. Install drop-in flood plank system (interior or exterior) including sills, foundations, and anchorages and/or construct a permanent floodproof entrance enclosure; or install an inflatable flood barrier system.

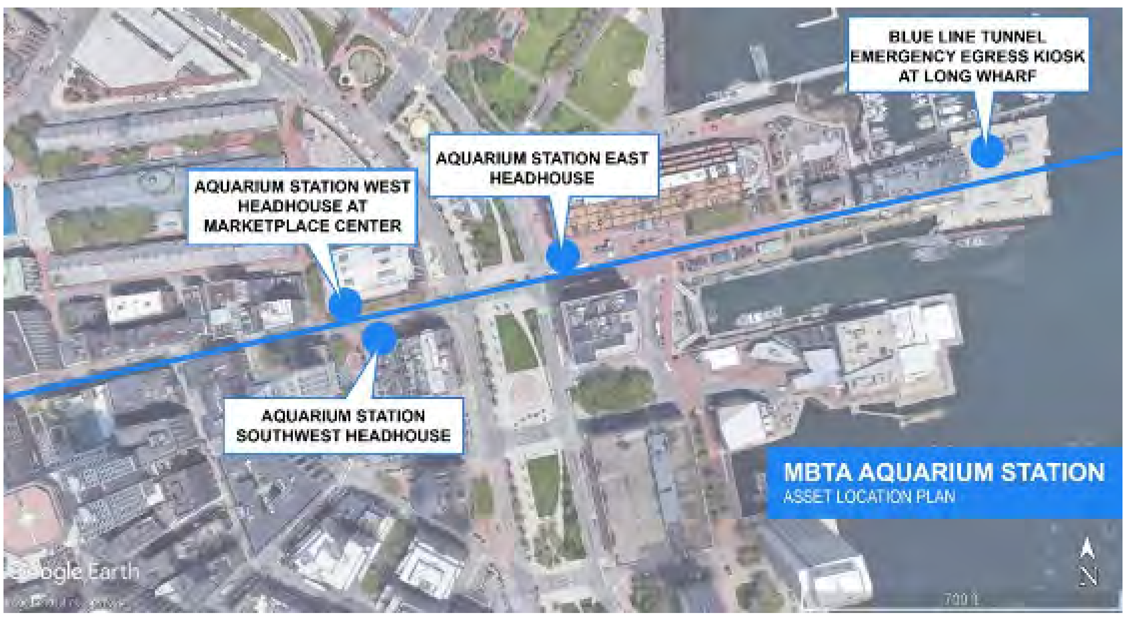

Figure 5 - Site Plan showing Aquarium Station Headhouses and Blue Line Egress Kiosk at Long Wharf (Credit: Google Earth, modified by MassDOT)

2.3 *Standard Operating Procedures for Deployment of Temporary Flood Barriers*

A Standard Operating Procedure (SOP) for the deployment and removal of flood barriers is being developed for the MBTA Blue Line Aquarium Station flood barrier deployment as part of this FHWA Resiliency and Durability pilot project. The SOP mirrors the organization of, and is coordinated with, the MBTA's governing emergency management plan(s) and SOPs. So as not to create parallel or conflicting emergency processes, existing frameworks regarding command structure, emergency public information, and inter-agency coordination were incorporated by reference or directly integrated into the SOP. Actions specific to flood response were developed through a participatory process engaging multiple MBTA organizational units and the MassDOT. Section 5 of this report has a more in-depth review of the contents of the SOP.

3. Interagency Partnerships

3.1 MassDOT and MBTA Collaboration

As an Authority, and connected to MassDOT, the MBTA provides bus, subway, and commuter rail services throughout Massachusetts and parts of Rhode Island. Due to the interconnected and systematic relationship of MassDOT and the MBTA's service lines, the resiliency of one agency and its services has a direct impact on the other.

As a result, collaboration between these two agencies went beyond financial support, and included meetings discussing the vulnerability of the MBTA Blue Line and Aquarium Station and the subsequent impact this vulnerability has on the overall functioning of Massachusetts' public transportation. These meetings included discussions about operations planning and flood barrier deployment and their impact on riders during a flood event. These conversations were imperative for gaining a better understanding of trickle-down impacts that a flood-related shutdown has on the entire transportation system. In addition, these workshops provided an opportunity to increase awareness and gain consensus around resiliency planning and implementation. These types of conversations are increasingly important as the Greater Boston area and coastal Massachusetts face increasing flood risk due to climate change.

3.2 Roles and Responsibilities

MassDOT was responsible for retaining a design consultant to perform vulnerability assessments, architectural and engineering services for preliminary design, final design, permitting, ROW coordination, surveys, preparation of bid documents, bid phase services, construction phase services and planning services associated with the development of the Standard Operation Procedures for the deployment of the temporary flood barriers. MassDOT also managed the FHWA pilot project grant and coordinated the project design with the Massachusetts Historical Commission.

MassDOT retained the firm of Kleinfelder Northeast, Inc. to perform the above design, permitting, operational planning and construction phase services under the direction of the MassDOT Project Manager.

The MBTA was responsible for procuring a construction contractor using a traditional Design–Bid–Build process under MBTA construction contract S17CN01. The MBTA was also responsible for the cost of the MBTA's internal administrative services, construction costs and providing a full-time Resident Engineer and inspection personnel during construction.

3.3 Interagency Agreements

There were no formal written memoranda of understanding or interagency agreements defining the specific roles of MassDOT and the MBTA with respect to development of the design or construction phase.

Once the MBTA took over management of design and construction, they were responsible for undertaking the project as a normal MBTA design project. They were responsible for:

- Defining the scope of construction work with the design consultant.
- ROW acquisition including permanent easements with adjacent landholders.
- Coordination with adjacent office and hotel properties to define mutually acceptable hours of operation and noise restraints.
- Coordination with Boston Duck Tours, which has a license to operate a tour service immediately adjacent to the Aquarium Station East Headhouse.
- Performing risk management.

The MBTA also coordinated the pre-purchasing and delivery of the drop-in flood barriers and flood door so that they would be on-site and ready to install as soon as the general contractor was under contract with the MBTA.

3.4 Cost Sharing Agreements

MassDOT funded the design, permitting with the Massachusetts Historical Commission, bid support and construction phase services using funds from this FHWA Resiliency and Durability pilot program grant.

The MBTA funded pre-purchasing of the drop-in flood barriers and flood door, internal administrative costs associated with procurement of the general contractor, acquisition of real estate easements, costs associated with construction of the project and full-time Resident Engineering and inspection services. MBTA costs were funded through the MBTA Capital Delivery Program and not through the FHWA pilot program grant.

4. Approach and Methodology

4.1 Design Flood Elevations

Design Flood Elevations (DFEs) for the MBTA Blue Line Aquarium Station and TE-434 project were established to assess vulnerability to flooding.

The MBTA is planning to do long-term capital improvements at Aquarium Station sometime in the next 10 years, at which time it plans to redesign the three station entrances (excluding the Long Wharf Blue Line Emergency Egress Kiosk) to be passively resilient to flooding with minimal need for temporary deployable flood barriers. Therefore, the MBTA decided to design for a shorter-term flood projection using 2030 data from the Boston Harbor – Flood Risk Model (BH-FRM). The DFE for the three headhouses was established as the 2030 Base Flood Elevation (BFE) with a 1% chance of exceedence of 10.0 ft. NAVD88 from the BH-FRM (see Table 1) plus 2.0 feet of freeboard based on ASCE 24-14 *Floodproofing Design Standard* for a critical structure for a DFE_{2030} of 12.0 ft. NAVD88.

For comparison, the current FEMA Flood Rate Insurance Map[2] for this project area shows that all four project work areas are located in a Zone AE (Base Flood Elevations determined) Special Flood Hazard Area subject to inundation by the 1% annual chance flood. The established Base Flood Elevation in this zone is 10.0 ft. NAVD88, which is the same as the 2030 BH-FRM flood elevation shown in Table 1.

The Long Wharf Blue Line Emergency Egress kiosk is being replaced with a permanent floodproof structure as part of this project. Therefore, the MBTA decided that using the longer-term 2070 BH-FRM

[2] FEMA Flood Map No. 25025C0081J, Effective Date 3/16/2016.

flood elevation data would be more appropriate as the expected life of the new structure will be at least 50 years. The DFE for the Long Wharf egress kiosk was established as the 2070 Base Flood Elevation (BFE) with a 1% chance of exceedence of 12.8 ft. NAVD88 from the BH-FRM (see Table 1) plus 2.0 feet of freeboard based on ASCE 24-14 *Floodproofing Design Standard* for a critical structure for a DFE_{2070} of 14.8 ft. NAVD88.

4.2 Vulnerability Assessment

As demonstrated during the 2018 flooding events and as reflected by the flood risk maps created by the BH-FRM, the greatest threat of damage and loss to Aquarium Station and the Blue Line subway and Tip O'Neill tunnels is from seawater flowing through the station headhouse entrances or from failure of the headhouse structures due to excessive water pressure. Another source of potential flooding is groundwater seepage through joints, utility openings and cracks in the tunnel structures. Although seepage is a long-term maintenance issue and source of concern to the MBTA and MassDOT, it is not a major source of flooding due to coastal flooding. The station and tunnel drainage systems handle secondary leakage but are not able to keep up with coastal flooding through the entrances. The MBTA is currently performing a separate project to study other pathways for water intrusion into the station and tunnels and will be undertaking a separate construction project to address these potential intrusion points.

The MBTA proposed protection for the four entrances into the tunnels and the MBTA Aquarium Station. The design consultant determined the critical elevations at entrances at which flood water would enter. The BH-FRM reflects the risk and depth of storm surge flooding based on the probabilistic analysis of thousands of historic and potential hurricanes and extra-tropical (nor'easter) storms and does not reflect any particular storm.

Figure 6 - East Station Headhouse (Credit: MassDOT)

The lowest and most vulnerable station entrance is the East headhouse (Figure 6) with existing door sill elevations of 8.8 ft. NAVD88 at the main entrance, elevator and TE-434 egress door. These elevations are 3.2 ft. below the DFE of 12.0 NAVD88. This was the headhouse that flooded during the January 4, 2018 storm and was inundated again during the March 2, 2018 storm. The design consultant determined that just protecting the doorways alone would be insufficient because the glass storefront headhouse walls would likely collapse under the water pressure of 3.2 ft. of water at the DFE. The proposed floodproofing solution at the East Headhouse is to encircle the east headhouse structures with temporary deployable flood barriers.

At the Long Wharf Blue Line emergency egress, the headhouse is a small structural glass block and steel structure sitting on a concrete roof slab with a wooden pavilion overhead (Figure 7). The existing door sill is at elevation 9.9 ft. NAVD88, which is 4.9 ft. below the 14.8 ft. NAVD88 DFE_{2070}. The roof of the egress structure is a metal grate to allow air to exhaust from the tunnel below. The glass blocks were mortared and approximately 4 inches thick. The extent of reinforcing was unknown.

Figure 7 - Long Wharf Blue Line Tunnel Emergency Egress Kiosk (Credit: MassDOT)

The design consultant approximated the maximum allowable wind load on a 50 sf glass block panel size using wind load data from Pittsburgh Corning Glass Block for comparable size mortared glass block. For a 50 sf, 4 inch mortared glass block wall the allowable wind resistance from the table was approximately 60 psf, which was equivalent to approximately a 135 mph wind speed. (Figure 8) The total allowable wind load on a 1 ft. strip of 8 ft. high vertical glass block would be approximately 480 lbs.

The hydrostatic force of sea water (γ = 64 pcf) at a depth of 4.9 ft. plus wind at 60 mph from the top of water surface to the top of wall would yield an approximate total force on a 1 ft. wide strip of 954 lbs. This force is approximately twice as high as the allowable wind load. Being that the headhouse is located in an AE FEMA flood zone, the actual flood forces would be considerably higher due to the effects of water velocity and wave action, that were not taken into account in the simple analysis. The existing glass block walls were also not detailed with a panel restraint anchor system or a channel restraint system that would typically be required for a new glass block system to be able to achieve the allowable wind loads shown in Figure 8. In addition, the existing hollow metal door could not be replaced with a new flood door within the existing glass block and steel framing due to the high forces that need to be resisted at the door frame.

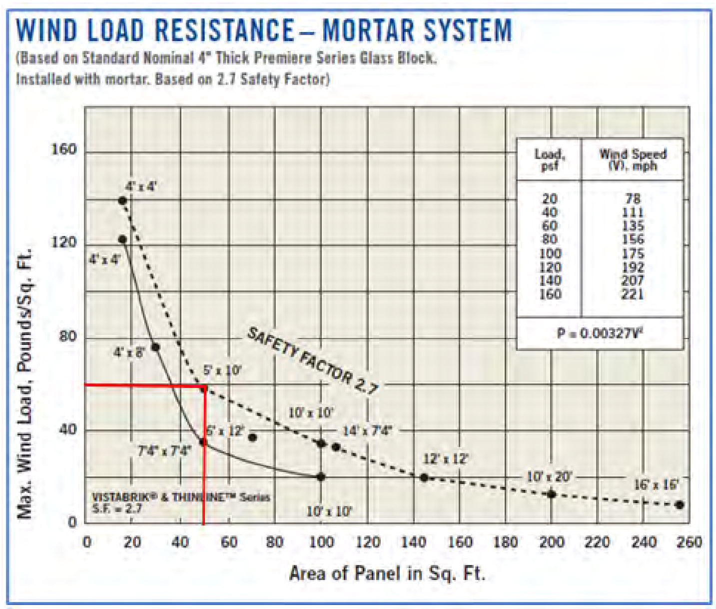

Figure 8 Glass Block Wind Load Resistance table (Source: Pittsburgh Corning Glass Block)

The proposed solution to floodproof this egress structure is to demolish the existing structure and replace it with a new 10” thick reinforced concrete, brick-faced structure fitted with a floodproof door. With the door in the closed position, the structure is passively protected from flooding, and no deployment of flood barriers is required

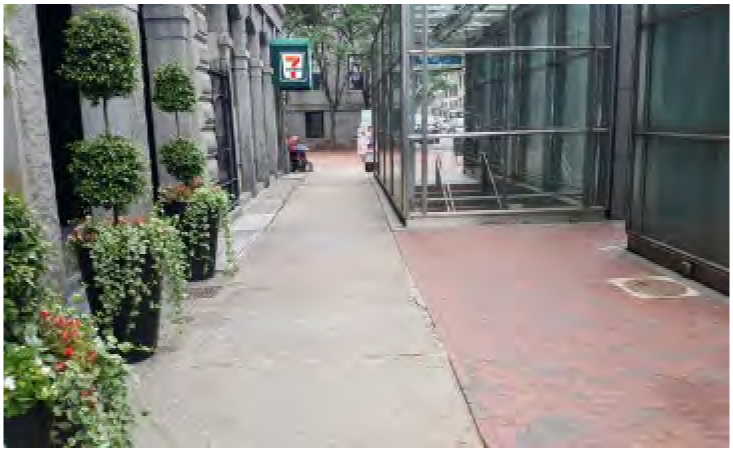

Figure 9 - Southwest Station Headhouse (Credit: MassDOT)

The existing door sill elevations at the Southwest headhouse (Figure 9) are 9.6 ft. NAVD88, which is 2.4 ft. below the DFE_{2030} of 12.0 ft. NAVD88. Like the East headhouse, the existing glass storefront walls are not designed to withstand 2.4 ft. of water pressure. The proposed floodproofing solution at the Southwest headhouse is to encircle the Southwest headhouse structures with temporary deployable flood barriers.

The Marketplace Center site is located inside a privately-owned commercial office building (Figure 10). The critical existing floor elevation is 10.2 ft. NAVD88, which is 1.8 ft. below the DFE_{2030} of 12.0 ft. NAVD88. Like the East headhouse, the existing glass storefront walls are not designed to withstand 1.8 ft. of water pressure.

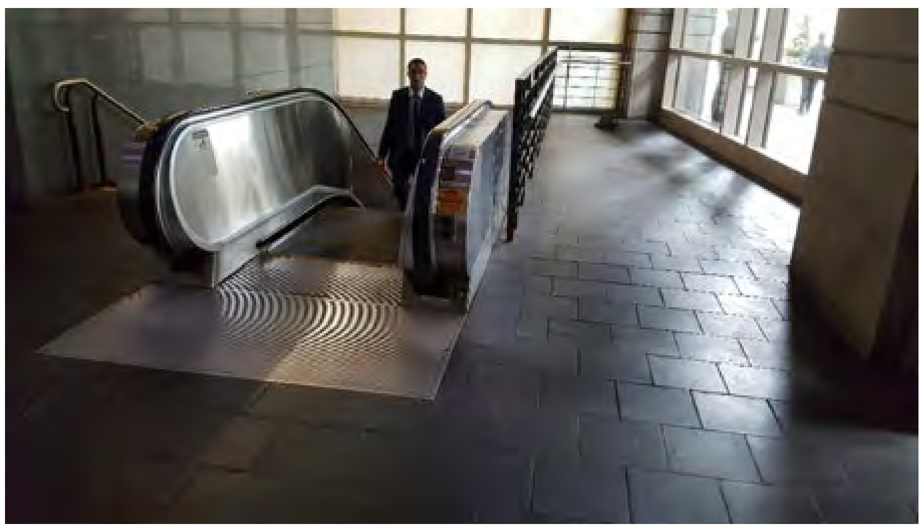

Figure 10 - Marketplace Center Station Entrance (Credit: MassDOT)

Vulnerability to the station and tunnels comes from flood water passing through multiple points of entry. The primary entry point for flood water would be the exterior doors to the station. In addition, 1.8 ft. of water pressure on the glass storefronts would result in complete failure of the storefront or severe leakage through joints not designed to withstand water pressure.

The proposed floodproofing solution at the Marketplace Center station entrance is to construct a granite-faced concrete wall around the two exposed sides of the stair/escalator opening that would be permanently in place, and then construct drop-in deployable flood barriers at the top of stairs to seal off the opening prior to a flood event.

4.3 Evaluation of Passive Versus Active Floodproofing Strategies (pros and cons)

The design consultant conducted research on various available products to provide flood protection, including temporary deployable and permanent passive flood barriers. Temporary deployable flood barriers, although generally lower in initial construction cost, have a higher labor cost to deploy. Permanent passive solutions are ideal solutions in areas that can be left in a closed position without impact to public spaces or station operations.

Flood barrier types investigated included:

- Composite, foldable, interlocking flood panels
- Water-filled barriers
- Drop-in flood barriers with anchored posts
- Permanent flood doors
- Permanent concrete walls

<u>Composite Flood Panels</u> - Composite, foldable, interlocking flood panels were investigated as an early option because of the complexity of underground utilities in the area. (Figure 11) The composite panels typically require minimal subsurface attachments, however because the sites would be subject to potential wave and wind action, the panels would need to be anchored to the ground. The ground surrounding the station headhouses is brick and does not make a strong enough sill for the panels to attach to. The composite panels are also more labor intensive to deploy and require more storage space than drop-in flood barriers. With insufficient on-site storage space available, the panels would have to be stored off-site, which would have required them to be transported to the site in advance of a flood, adding to the overall deployment time. In addition, the width of the panels would block the sidewalks in some very narrow areas along State Street. The City of Boston, which owns these narrow sidewalk areas, requires a minimum of 4 ft. of width to allow people to use the sidewalks when the flood barriers are deployed in advance of a flood event. For these reasons, foldable composite panels were not chosen for this project.

Figure 11 - Example of Deployed Composite Flood Panels (Credit: MassDOT)

Figure 12 - Water-Filled Flood Barriers During Test Deployment by MBTA in February 2019 (Credit: MassDOT)

<u>Water-Filled Flood Barriers</u> - Water-filled flood barriers to encircle the East headhouse (Figure 12) were purchased by the MBTA after the March 2, 2018 storm as an interim protective measure until this project construction was complete. The water-filled barriers take time to deploy and fill. Once filled the station entrance must be closed. Water-filled barriers are even wider than the composite, foldable barriers, and therefore, the issue of blocked sidewalks is the same. For these reasons, water-filled flood barriers were not considered as a permanent solution for this project.

<u>Drop-In Flood Panels</u> – Drop-in flood panels consisting of stacked, gasketed, extruded aluminum planks supported by steel posts anchored to the ground form a perimeter flood barrier (Figure 13). Posts are anchored to threaded connections embedded in a reinforced concrete ground slab. When not in use, blanking bolts are inserted into the threaded connections to protect the threads and prevent debris from filling the anchor bolt holes (Figure 14). The blanking bolts are flush with the adjacent concrete surface to prevent tripping and damage from snowplowing. Compression channels and hold-down clamps seal the system against all vertical and horizontal gaskets, creating a watertight system.

Figure 13 - Example of Drop-in Flood Barrier System (Credit: MassDOT)

Figure 14 - Blanking Bolts at Post Location when Posts not Deployed (Credit: MassDOT)

Drop-in flood panels have the smallest storage volume and are the easiest of the deployable flood barrier systems to be installed due to their light weight and small sized pieces. All the drop-in flood barrier components for the three Aquarium Station headhouses can be stored onsite in a single 8 ft. x 20 ft. steel storage container. Most of the drop-in-barriers can be installed prior to a flood event, leaving the barriers directly in front of the station doors and elevators un-deployed until just before the onset of flooding. This will minimize the need to close station entrances until flood water is just approaching the station entrance. This is important as predicting flood levels is very difficult. Based on the above reasons, drop-in flood barriers were selected as the perimeter flood barrier system for this project.

Figure 15 - Example of Permanent Flood Door (Credit: MassDOT)

<u>Permanent Flood Doors</u> - Permanent flood doors were only considered for the Long Wharf Blue Line Tunnel Egress kiosk. Because this door is always closed, except when used by MBTA staff or during an emergency to evacuate passengers from the Blue Line Tunnel, a permanent flood door is an ideal passive solution (Figure 15). A heavy-duty door designed to withstand the DFE will be fitted with a special frame into the new reinforced concrete kiosk walls.

<u>Permanent Concrete Flood Walls</u> – Permanent concrete flood walls are examples of passive flood barriers that are always in place and functioning. Concrete flood walls were considered as the preferred flood control system at the Long Wharf Blue Line Tunnel Egress and the Marketplace Center station entrance because of their durability and ability to withstand dynamic wave loading. The concrete walls will be clad with either brick or granite to match the surrounding building materials.

4.4 Evaluated Procurement Methodologies

With one of the project objectives to make the MBTA Blue Line Aquarium Station and TE-434 resilient to coastal flooding as quickly as possible, MassDOT, MBTA and the design consultant explored ways to accelerate procurement of flood barrier systems with long fabrication and delivery lead times.

Having the contractor procure the flood barriers using the traditional Design-Bid-Build method of contracting, would result in a 3-4 month longer project time line because the contractor would not start the procurement process until they received a Notice-to-Proceed, followed by submission and approval of shop drawings, fabrication and then delivery of barriers. There were also possibilities of additional delays in the fabrication and shipping process due to COVID-19 restrictions that could further extend the construction time.

Three options were explored to help expedite procurement of the flood barriers.

- <u>MassDOT Pre-Purchase Flood Barriers</u> – One option was to have MassDOT District 6 pre-purchase the flood barriers by redirecting available funding. A draft procurement document was prepared and circulated to obtain the required approvals and funding. After multiple discussions, MassDOT determined that it did not have available funds to make the purchase and this option was not advanced. One concern expressed by some MassDOT officials was the issue of liability if MassDOT purchased a product for installation under a MBTA contract for installation by a third-party contractor. If there were issues during construction, it was felt that the contractor would point to the product provided to him over which he had no control, resulting in a loss of accountability.

- <u>Design Consultant Pre-Purchase Flood Barriers</u> – The next option investigated was to have the design consultant pre-purchase the flood barriers under their Master Services Agreement with MassDOT. A draft procurement document was developed and appropriate modifications to the design consultant's agreement were drafted, but MassDOT purchasing department had concerns that this might have the effect of circumventing the intent of Massachusetts procurement laws. The design consultant also had concerns regarding liability and accountability issues if there were problems after installation that the contractor would say they were not responsible for because they did not purchase the barriers.

- <u>MBTA Pre-Purchase Flood Barriers</u> – The last option investigated was to have the MBTA pre-purchase the flood barriers from the same capital funding source funding the project's construction. This option was found to be viable and was implemented. The MBTA had earlier issued an RFP to flood barrier manufacturers soliciting price quotes to furnish flood barriers for the Aquarium Station project. The MBTA negotiated with several potential manufacturers and ultimately selected Flood Control International (FCI) as the successful bidder. After completing negotiations, FCI prepared shop drawings based on drawings provided by the design consultant and their own field measurements. The shop drawings were approved in early February 2020 and the flood barriers arrived on June 4, 2020 at the MBTA's Charlestown Bus Maintenance Facility, where they were temporarily stored until the contractor was ready to install them. Even with shipping delays due to COVID-19 restrictions, the flood barriers were on site well in advance of the start of construction.

4.5 Final Design Issues

The final flood barrier design incorporated considerations for a wide variety of complex issues. Due to the location of the Blue Line Aquarium Station entrances in downtown Boston, there are many constraints that had to be incorporated in the barrier design. Due to a crowded public right-of-way adjacent to the entrances, the barrier layout needed to accommodate ADA accessibility, existing bollards for traffic calming and pedestrian protective measures, and minimum dimensions required for egress in and out of the station during an emergency event.

Permitting and Approvals

Due to the location of the headhouse and proposed barriers in relation to adjacent properties and City of Boston-owned sidewalks, right-of-way issues and permitting requirements had to be addressed. The barrier layout was additionally constrained by existing utilities and infrastructure that are accessed through these public sidewalks.

Many architectural and public realm features in downtown Boston are protected by historic preservation regulations. A portion of the sidewalk adjacent to the Southwest headhouse was constructed with large historic granite slabs. The Boston Landmarks Commission was consulted, and they determined that the granite sidewalk slabs could not be removed. Ultimately, the flood barriers were designed to bolt down to the granite slabs, which were heavy enough to counterbalance the water pressure's overturning forces.

Another regulatory constraint was complying with Massachusetts Chapter 91, Waterways regulations, which requires that development on historic tidelands must remain in marine use or be accessible to the public. This was an issue at the Long Wharf Blue Line Tunnel Egress, which had been constructed under two previous Chapter 91 licenses. MassDOT, MBTA and the design consultant provided documentation that showed that the proposed modifications were an insignificant deviation from the original license specifications in terms of size, configuration and materials; there would be no change in use; and existing public benefits would be maintained. The Massachusetts Department of Environmental Protection issued an approval letter on April 13, 2020 indicating that no further review under Chapter 91 was required.

To allow for the improvements on City of Boston-owned sidewalks, the design team applied to the City of Boston Public Improvement Commission for approval. After review by multiple City agencies and a public hearing, the project was approved by the Public Improvement Commission.

The work at Long Wharf Blue Line Tunnel Egress kiosk occurs within a coastal resource as defined by Massachusetts 310 CMR 10.00, specifically Land Subject to Coastal Storm Flowage. As such, a Notice of Intent was filed with the City of Boston Conservation Commission, which administers the state wetland regulations on a local level. After a public hearing, the project was approved, and an Order of Conditions was issued by the Conservation Commission with requirements that had to be followed and documented to ensure no damage occurs to the coastal resource.

Land and Water Conservation Fund Act of 1965

The City of Boston redeveloped the east end of the National Historic Landmark Long Wharf into a public park in the 1980s with a federal grant from the Land and Water Conservation Fund (LWCF) administered by the National Park Service. The redevelopment included the restoration of the historic granite sea wall and ramps, removal of the existing wood deck surface, and replacement of the deck with granite and brick paving. The terms of the grant required that the land or feature to which the grant is applied must be maintained as open public recreational space in perpetuity. MassDOT, the MBTA and

Kleinfelder had to determine if the proposal to reconstruct the headhouse for the emergency egress for the Blue Line tunnel would comply with the terms of the nearly 40-year-old federal grant.

The MBTA provided matching funds to the LWCF grant to construct a pavilion on Long Wharf within a permanent easement granted by the City. The MBTA designed the pavilion to function as a ventilation structure and emergency egress for the Blue Line Tunnel and to serve as a shelter and gathering place for visitors to the wharf. Prior to constructing the pavilion, the MBTA constructed the below-grade ventilation system and an emergency egress stair tower for the tunnel. The emergency egress headhouse for the Blue Line tunnel was then incorporated into the design of the Long Wharf pavilion.

The Massachusetts Secretary of the Executive Office of Environmental Affairs (EOEA) consulted with the NPS in 1983 prior to the City's granting the permanent easement to the MBTA to determine if the construction of the MBTA pavilion would constitute a "conversion" of dedicated open recreational space into non-recreational use, pursuant to Section 6(f) of the LWCF Act of 1965. The NPS subsequently determined that the MBTA pavilion would not constitute a conversion under Section 6(f) and would "provide an increased benefit to public recreational opportunities," in correspondence to EOEA dated July 11, 1983.

Based on the above-noted decision made by the NPS in 1983, it was determined that no further consultation with the NPS was required under Section 6(f) of the LWCF Act of 1965 for the proposed replacement of the Blue Line Tunnel emergency egress headhouse under the roof of the Long Wharf Pavilion.

Section 106 of the National Historic Preservation Act of 1966 (as amended)

The funding source for the design of the current Resiliency and Durability Pilot Project is through a federal grant to MassDOT-Highway from the Technology and Innovation Deployment Fund administered by the FHWA. Section 106 of the National Historic Preservation Act of 1966, as amended (recodified as 54 USC § 306108 in 2014) requires a Federal agency having direct or indirect jurisdiction over a proposed Federal or federally assisted undertaking to take into account the effect of the federal undertaking on any historic property.

The MassDOT Cultural Resources Unit (CRU) staff coordinated with the MassDOT project manager, MBTA staff, and Kleinfelder to ensure that the project would not adversely affect the National Historic Landmark Long Wharf and Custom House Block Historic District or the National Register-listed Custom House Historic District. MassDOT CRU staff, on behalf of FHWA, consulted with the State Historic Preservation Officer (SHPO) at the Massachusetts Historical Commission, as required by Section 106, to ensure the SHPO's concurrence with the No Adverse Effect determination. MassDOT CRU staff submitted project plans, photographs, and a detailed scope of work to the State Historic Preservation Officer (SHPO) as part of the Section 106 consultation. On November 25, 2019 the SHPO concurred with the MassDOT CRU that the proposed project would have No Adverse Effect on any properties that are listed or may be eligible for listing in the National Register of Historic Places.

MassDOT CRU staff also consulted with the Executive Director of the Boston Landmarks Commission (BLC) in compliance with the Section 106 requirement for a federal agency to seek input from local governments. The Executive Director of the BLC objected to the MBTA proposal to remove the historic granite slab sidewalks around the Aquarium Headhouse within the Custom House Historic District.

When the MBTA and Kleinfelder developed an alternative design that did not require removal of the granite slab sidewalk, the Executive Director rescinded the BLC objection to the project. On November 25, 2019, the SHPO concurred with MassDOT's No Adverse Effect finding under Section 106 of the National Historic Preservation Act of 1966, as amended.

FHWA then notified the U. S. Secretary of the Interior, through the NPS, regarding Section 106 consultation involving a National Historic Landmark as required by federal regulations.

<u>Right-of-Way (ROW) Issues</u>

A portion of the sidewalk area on which the flood barriers will be erected at the East Headhouse is located on property owned by Sunstone Wharf LLC. The Marriott Long Wharf Hotel is also located on the Sunstone Wharf parcel. The MBTA negotiated a permanent volumetric easement with Sunstone Wharf to allow for the project. Costs associated with preparation of ROW plans and survey were funded by this FHWA Resiliency and Durability pilot project grant.

<u>Building Code Issues</u>

The project design was reviewed with the Massachusetts Department of Public Safety State Building Inspector who enforces the Massachusetts State Building Code for state projects. Because the Long Wharf Blue Line Tunnel Egress structure was less than 200 sf and is part of the transit tunnel infrastructure and not the station infrastructure, the inspector ruled that it did not fall under the jurisdiction of the State Building Code. Nevertheless, the structural design of the new structure was based on the MA Building Code loading requirements. The remaining work is exterior paving-related work, which did not affect the existing station infrastructure. The only thing that the Building Inspector was concerned with was maintaining station emergency egress during any entrance shutdowns to complete exterior paving work and maintaining accessible routes though the station. One requirement that was made was that the contractor had to submit an impairment plan for review by the Building Inspector prior to any planned elevator or entrance shutdowns.

The proposed design for flood barrier anchors at the East and Southwest headhouses requires removing the existing brick and concrete sub slabs under the sidewalk pavements, and replacing them with reinforced concrete slabs from the top of station roof slabs to match existing sidewalk grades. Prior to repaving, the existing station roof waterproofing membrane will be replaced or repaired as conditions warrant. After waterproofing is complete, the new full-depth concrete slabs can be installed, without brick pavers. (Figure 16) The grading of the new sidewalk concrete slabs will match the existing grading, while maintaining ADA and Massachusetts Architectural Access Board (MAAB) accessible slope and detail requirements.

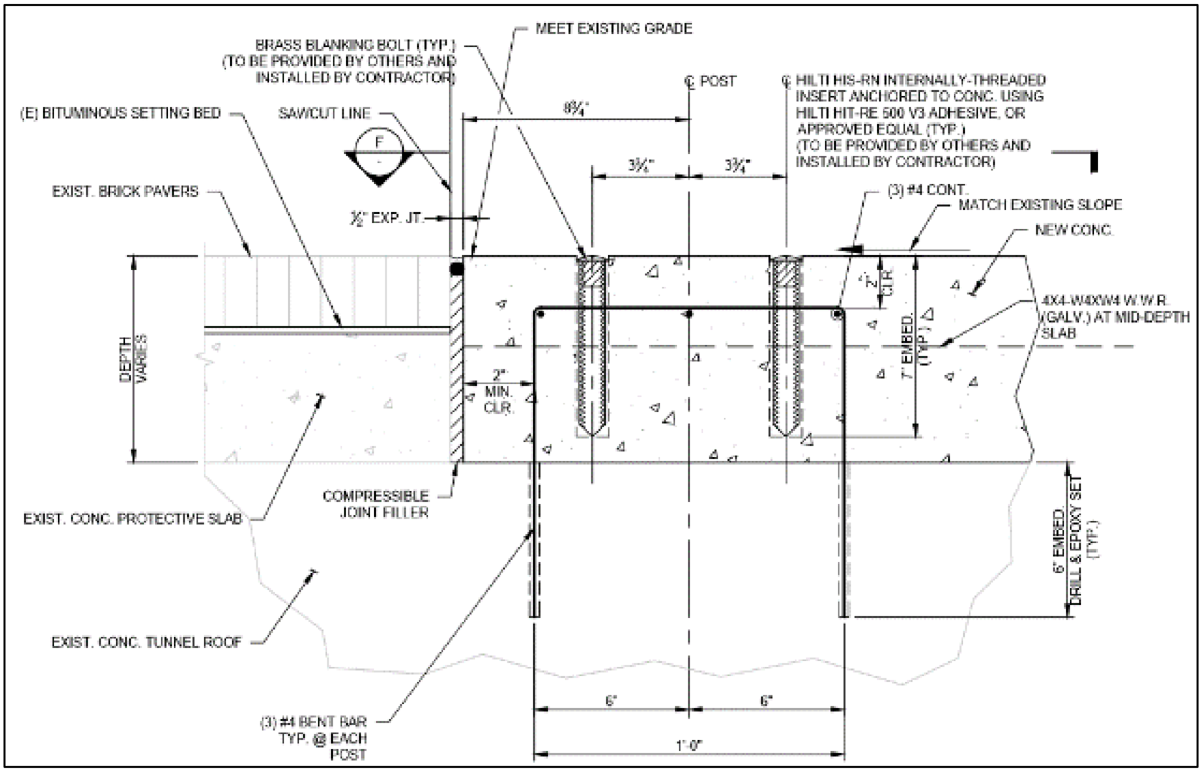

Figure 16 - Typical Detail of New Full-Depth Concrete Slab Replacing Existing Brick Pavement at East and Southwest Headhouses (Credit: MassDOT)

<u>Stakeholder Engagement</u>

The MBTA, MassDOT and the design consultant met with a number of public and private entities during the design of the project to ensure that appropriate restrictions would be included in the contract documents to protect the interests of abutters during construction and during deployment of flood barriers.

- *Boston Duck Tours* – Boston Duck Tours operates a popular amphibious vehicle tour of Boston. One of its stops is on State Street at the East Headhouse. The project team met with the tour operator to understand their operations. Based on these conversations, work time restrictions and notification requirements were included in the project phasing and construction documents. In addition, work was phased to provide space at the East Headhouse work area for MBTA-licensed vendors associated with the Boston Duck Tours. Since the Covid-19 pandemic began, Boston Duck Tours temporarily scaled back its operations and did not need the State Street stop during the summer and fall of 2020. This allowed the contractor more time to complete the work under less restricting conditions.
- *City of Boston* – As mentioned above, the design team coordinated the project design with various City of Boston Agencies including the Public Improvement Commission, Conservation Commission and Landmark's Commission.
- *Marriot Long Wharf Hotel* - The main concern with the Marriott Long Wharf Hotel was noise disturbance of guest rooms located directly adjacent to the East headhouse construction area. Based on discussions with hotel management, work restrictions were included in the contract

documents prohibiting jack hammering, sawcutting, backing-up trucks or other noisy construction activities between the hours of 7:00 pm and 9:00 am. This restriction also applied to work at the Southwest Headhouse in front of the Harborside Inn Hotel.

- *Marketplace Center Building* - The Marketplace Center entrance to the Aquarium Station is located inside the Marketplace Center building, a privately-owned office building. Based on discussions with building management, work restrictions were included in the contract documents prohibiting jack hammering, sawcutting, backing-up trucks or other noisy construction activities between the hours of 8:00 am and 5:00 pm. Also, demolition and construction activities associated with construction of the new flood wall and barriers adjacent to and over the station stair and escalator can only be performed during MBTA non-revenue hours, between approximately 1:30 am and 4:45 am.
- *MBTA Blue Line Operations, System-Wide Accessibility and Safety* – The design team met with these MBTA departments to coordinate requirements for maintaining emergency egress at the Long Wharf Blue Line Tunnel egress kiosk and to coordinate elevator shut down restrictions at the East and Southwest Station headhouses. Based on meetings with the MBTA System-Wide Accessibility and Safety department, permission was granted to allow elevators at the East Station and Southwest Station Headhouses to be each closed for 7 consecutive calendar days to allow pavement removal, waterproofing and concrete slab construction to occur immediately in front of the elevators. These restrictions were included in the contract documents.

<u>Bid Results</u>

MBTA Project No. S17CN01 was advertised for construction on April 15, 2020. The estimated construction cost for this Contract, as compiled by the design consultant, was $1,366,699.00. Bids were opened on May 15, 2020.

Four bids were received ranging from a low of $1,735,097.00 to a high of $2,025,312.00. None of the bidders had significant experience installing flood barrier systems, which combined with the multiple work areas and unknowns attributed to COVID-19, may have contributed to the bid prices coming in higher that the engineer's estimate. Due to the importance of the project, the MBTA accepted the low bid from McCourt Construction Co., Inc. and issued a Notice-to-Proceed (NTP) for construction to McCourt on August 5, 2020.

<u>Construction</u>

The project construction was determined to be Substantially Complete on January 22, 2021. Final completion occurred on March 7, 2021. Per the construction documents, the contractor was subject to Liquidated Damages of $1,870.00 /day for not meeting the Substantial Completion Milestone of 170 calendar days from NTP and $1,064 /day for not meeting the Final Completion Milestone of 214 calendar days from NTP.

5. Standard Operating Procedures for Flood Barrier Deployment

5.1 Need for Standard Operating Procedures

A Standard Operating Procedure (SOP) is critical for the successful deployment and breakdown of the flood barrier system prior to, during, and after a flood event. The SOP identifies responsible parties for decision making, the threshold in the flood forecast that should be used to trigger deployment, personnel in charge of installing the barrier, communication protocols for notifying other departments and agencies of the impending station shutdown, wayfinding and accessibility considerations for station closures, and alternative transportation accommodations for riders, if necessary.

Without clear delineation of the above elements, inefficiencies and errors may occur due to a lack of understanding regarding potential flood risks, lack of consensus regarding the need for deployment, unidentified personnel for deployment, incorrect installation and/or an absence of a contingency plan for riders seeking alternative means of transport. The SOP, being developed with the support of the design consultant, will serve as the MBTA's roadmap for successful deployment, while also providing quality control, and communication of emergency protocols.

5.2 Stakeholder Involvement

In order to ensure that the flood barrier deployment works in tandem with existing operations and emergency management protocols of the MBTA, MassDOT, City of Boston and Massachusetts Emergency Management Agency, the project team conducted stakeholder engagement meetings with internal departments of the MBTA and MassDOT that will be affected by flood barrier deployments. These meetings gave the opportunity for MBTA and MassDOT key stakeholders to provide feedback regarding how the deployment functions within existing MBTA and MassDOT emergency protocols.

An initial meeting with the MBTA Operations Control Center and Training was held to review a first draft of the SOP to get this key department's input on how decisions are made. Following this initial meeting and updates to the draft SOP, a larger stakeholder meeting was held in October 2020 with a number of MBTA and MassDOT departments that would be affected by or potentially have input into the decision to deploy temporary barriers. Attendees included:

MBTA Departments

- Office of the Chief Engineer
- Security and Emergency Management
- Operations Control Center & Training
- Rail, Heavy Rail Transportation (Blue Line)
- Transit Police
- Engineering and Maintenance
- Transit Facilities and Maintenance
- Customer Experience
- Safety
- Environment
- System-Wide Accessibility

- Bus Transportation

MassDOT

- Highway Division, District 6
- Highway Operations Center
- Office of Security and Emergency Management

Subsequent to the October 2020 stakeholder meeting, several meetings with a representative of the Transit Facilities and Maintenance department were held to discuss details of deployment.

Future meetings will be held with external stakeholders, including the City of Boston Fire, Police and Emergency Medical Services Departments as well as the Massachusetts Emergency Management Agency to review updated drafts of the SOP to obtain further input. Based on these meetings, a final version of the SOP will be developed.

5.3 How Flood Forecasts will be Monitored Prior to a Storm

The methodology for monitoring flood forecasts and predicting flood elevations in advance of a major flood event is one of the most important parts of the SOP. The process should also be flexible to allow for updates in the best available data/science. However, it is important that the general methodology be described in the SOP to ensure that deployment decisions are data-driven and based on flood forecasts in order to save money and time, minimize false alarms with their associated costs and disruptions, and maximize advance notice when the station is at risk.

For a major flood event, flood forecast lead time is typically about three days prior to the actual start of flooding. For some events, with unpredictable storm paths, the lead time may be as low as one day.

During stakeholder conversations, the MBTA specified a preference for a specific trigger to be identified and monitored by flood forecasting. The trigger flood elevation will be specified with one elevation datum (Mean Lower Low Water (MLLW)) to avoid confusion between different datums.

When the National Weather Service (NWS) reports that a hurricane, tropical storm or extra-tropical storm (nor'easter) is on track for Boston, the MBTA Operations Control Center (OCC) will begin monitoring the following authoritative sources of flood forecast information for the Boston Harbor tide gauge (NOAA Station ID: 8443970), which is located about 900 ft. from the Long Wharf area:

- All Storms: NOAA National Weather Service, Advanced Hydrologic Prediction Service:
  - http://water.weather.gov/ahps2/hydrograph.php?gage=bhbm3&wfo=box&refresh=true

- Extra-tropical Storms (Nor'easters): NOAA National Weather Service, Meteorological Development Laboratory, Probabilistic Extra-Tropical Storm Surge
  - https://slosh.nws.noaa.gov/etss/station/petss1.1/index.php?stid=8443970&datum=MLLW&show=1-1-0-1-1-1-1-1

- Tropical Storms and Hurricanes: NOAA National Hurricane Center
  - https://www.nhc.noaa.gov/?atlc

- National Weather Service Flood Advisories
    - o https://www.weather.gov/box/

Additional data/information sources will be added to the SOP as new sources are identified. One potential source of flood prediction data currently in development is the Boston Harbor Storm Cast Model (BH-SCM) - a derivative of the Boston Harbor - Flood Risk Model. If proven to be beneficial, the BH-SCM could be a new method to more precisely predict the arrival time and extent of storm surge flood waters within the City of Boston.

5.4 Identify who makes the decision to deploy flood barriers and when

The OCC will notify a Chain of Command with monitoring data related to the predicted flood levels and durations so that a decision can be made whether or not to deploy. The details of the Chain of Command structure, including back-up decision makers, are being finalized at this time. Due to the time-sensitive nature of deployment, having a defined decision making process is critical. The SOP will include communications protocols to notify all required departments and external agencies of any planned deployments and station closures.

5.5 Closing Aquarium Station and/or MBTA Blue Line during partial or full deployment of flood barriers

The Aquarium Station flood barrier system has been designed to maximize the amount of time that the station can safely remain open in advance of a coastal flood and to minimize the impact on transit riders and pedestrian use of public sidewalks. This can be accomplished through partial deployment of the flood barrier system, including installation of flood barrier posts and panels that do not pose an obstruction to passengers entering or exiting the station entrances or pedestrians traveling parallel to the right-of-way. In accordance with City of Boston rules, a minimum 4 ft path of travel must be provided on City of Boston public sidewalks when the barriers are deployed, and fire standpipes cannot be permanently blocked. The minimum 4 ft. clear path of travel at an obstruction also satisfies the ADA minimum clear path of travel on an accessible route, which is 3 ft. per ADAAG Section 403.5.1.

Predicting the exact times and elevations of a severe flood event are very difficult because storm paths and speeds can fluctuate, and predictions can vary from forecast to forecast. Each deployment decision therefore must be made using the best available data considering the MBTA's tolerance for risk. To reduce the risk of flood forecast under-prediction, the draft SOP triggers flood barrier deployment when forecast flood elevations are within 1.5 ft. of an entrance's critical elevation. Note that elevations referenced in the SOP are all based on Mean Lower Low Water (MLLW).

Table 2 shows the flood levels that trigger flood barrier deployment actions.

Table 2 - Flood Trigger Elevations for Flood Barrier Deployment Actions

Forecasted Flood Elevation (MLLW)	Proposed Flood Barrier Deployment Action
Below 12.8 ft.	No flood barriers deployed.
12.8 ft. to 13.5 ft	Deploy flood barriers at East Station Headhouse only. Aquarium Station remains open using Southwest and Marketplace entrances only.
13.6 ft. and above	Deploy flood barriers at East, Southwest and Marketplace Center entrances. Aquarium Station will be closed.

When flood barriers are installed at the East Headhouse only, Aquarium Station can remain operational with entrances at the Southwest and Marketplace Center entrances. When flood barriers are deployed at all three entrances, Aquarium Station must be closed because there will be no operational entrances/exits and no elevators will be operating. Once the station is fully evacuated, then the last of the flood barrier panels can be installed and the station shut down.

5.6 Incorporating the Standard Operating Procedures into Existing MBTA and MassDOT Emergency Operations and Security Plans

The MBTA and MassDOT have existing emergency operations and security plans that were considered in the development of the SOP for flood barrier deployment. Timelines and communication chains for emergency response are relevant to life safety issues that could arise during a flood event. In addition, there are overlaps in personnel responsible for emergency response during a non-flood related event.

6. Ongoing Monitoring

6.1 Annual Training and Table-Top Exercises

Depending on a storm's predictability and characteristics, the time between the decision to deploy flood barriers at MBTA Aquarium Station and the time that flooding starts can be a relatively short period. Therefore it is critical that the MBTA staff assigned to deploy flood barriers, as well as additional back-up personnel, need to be trained in how to quickly and efficiently deploy the system, and not do on-the-job training when time is running short. Of special importance is to ensure that supervisory personnel are well trained to help manage and direct deployment operations.

The MBTA will be establishing annual training drills to deploy the flood barrier system. Part of the training exercises will include inspecting the condition of the anchorages in the ground to ensure that if any are damaged that they can be repaired prior to a storm event. The annual training exercises will also be a chance to inventory and inspect all components of the flood barriers as well as any specialized installation equipment and signage stored in the storage container or in the station. Damaged or missing components can then be replaced prior to a flood. Training will include proper methods of cleaning barrier components and proper storage techniques, including the order pieces are stored, so that components can be quickly and efficiently deployed in the future.

Table-top exercises involving flooding scenarios will also be incorporated into regularly scheduled emergency management training sessions to test and exercise the decision making and communication protocols required for a successful deployment of the flood barriers.

6.2 Post-Storm Documentation After Deployment

After any deployment of the flood barrier system, including training exercises, the MBTA will keep a record of the particulars of the deployment, including times of deployment, problems encountered, times for removal and storage and confirmation of inventory. In addition, any lessons learned will be documented so that they can be brought up at the next training exercise.

7. Conclusions and Lessons Learned

7.1 Conclusion

This FHWA Resiliency and Durability pilot project has funded the design, permitting and design consultant's construction phase services for an important project to design and implement floodproofing of the MBTA Blue Line Aquarium Station and MassDOT TE-434. The project was an excellent cooperative effort between two important state transportation agencies - MassDOT and the MBTA.

7.2 Lessons Learned

- *Good to pre-purchase long lead-time flood barriers* – On any project with a goal of implementing floodproofing as quickly as possible, we found it very beneficial to pre-purchase long-lead time materials and equipment so that it is already on site when the contractor mobilizes in the field to start construction. This can significantly reduce time of construction because the time to prepare and approve shop drawings, fabricate and deliver the barriers to the project site is done independent of the contractor. For this project we estimate that we saved 3 to 4 months of construction time.
- *Standardize drop-in panel sizes to the maximum extent feasible* – A conscious effort was made on this project to use a single drop-in panel size. Although it might not have resulted in the most efficient layout, having one 7'-0" panel size will avoid confusion and sorting of panels during deployment. Panels will be interchangeable at any location because they are all the same size.
- *Clearly define in the SOP who is responsible for monitoring flood forecasts and who makes deployment decisions* – Major hurricanes and nor'easters can be very unpredictable at times with ever changing forecasts. It is very important to have someone responsible for monitoring not only wind, rain and snow forecasts, but also monitoring flood forecasts as early as possible to allow time for making deployment decisions.
- *Flood barrier deployment SOPs should clearly define minimum timelines for deployment* – Deployment of temporary flood barrier systems, especially across multiple sites, does not happen at the flip of a switch. It takes time to make the decision to deploy, especially when those decisions require coordination with various internal departments as well as multiple state, federal and local emergency management agencies. It then takes time to mobilize crews and

equipment, remove barriers from storage, pre-position components to designated locations, erect the flood barriers and do final inspection of the barriers to ensure that all components are properly installed. The SOP should clearly define the minimum time required to accomplish these tasks so that emergency management officials can work backwards from the time of predicted flooding to schedule the deployment work so that it will be completed in time. The times should also include some buffer to allow for the inevitable events that can slow down the perfect deployment.

- *Difficulty in meshing different agency procedures and processes* – On this project we learned that it can be difficult to mesh different procurement processes between two agencies and that one of the agencies really needs to take a lead on the project. For this project, the MBTA took the lead in procuring the general contractor as well as undertook early procurement of the flood barrier systems. Defining these roles earlier in the process might have sped up the advertising date for the bid documents.
- *Use Memoranda of Understandings to memorialize interagency responsibilities* – For this project, there was no formalized Memorandum of Understanding between MassDOT and the MBTA clearly defining roles and responsibilities. The project was delayed a bit by some early misunderstandings and overlap between the two agencies, especially related to early procurement of the flood barrier system. Having a formalized agreement describing each agencies roles and responsibilities would likely have shorten the design time.
- *On-site storage of flood barriers important for quick deployment* – Every effort should be made to store flood barrier components as close to the site being protected, especially in major urban centers, where time to transport from an off-site storage facility to the project site can add significant time to the overall deployment. For this project, a weather-tight, secured, 8 ft. x 20 ft. steel storage container will be used to store all flood barrier components on site at the East Station Headhouse.
- *Deployment of temporary flood barriers to protect major roadway infrastructure must balance deployment times with time required for emergency evacuations* – The project designed temporary flood barriers at the entrance to the Sumner Tunnel and the exit to the Callahan Tunnel in East Boston. These are two major highway tunnels connecting East Boston to downtown Boston and the regional highway system. Both tunnels are important components of the Massachusetts Highway System emergency evacuation system during a major storm event. The proposed flood barrier solutions required to shut down the tunnels about 6-12 hours before start of flooding to deploy the flood barriers and to de-energize electrical power in the tunnels. After discussions with MassDOT administrators, operations and emergency management personnel, it was determined that 6-12 hours of shutdown was too long to close down the tunnels just when they likely would be needed for possible evacuation of East Boston residents and other emergency services.
- *Used the BH-FRM as a key tool for calculating DFE's* – The BH-FRM, developed by MassDOT under a previous FHWA pilot grant, was used on this project to calculate the 2030 and 2070 DFEs. The design consultant used probability of exceedance flood elevation data generated by the BH-FRM from a representative node in the Aquarium Station area to calculate the 1% annual chance flood elevation for both 2030 and 2070. This was an excellent example of building on

previous FHWA-funded projects. This model has also been used to generate similar flood elevation data at other critical transportation locations within the Boston Harbor area.

- *Have a dedicated On-Call Construction Contract available to undertake smaller resiliency projects* – Over the course of this project, there were several smaller low cost floodproofing resiliency solutions, such as at the Highway Operations Center and at Tunnel Egress-425, that could have easily been implemented if there was a dedicated on-call construction contracting mechanism available to fund and execute the work. Funding an annual resiliency on-call construction contract would enable implementation of many low-cost floodproofing solutions.

7.3 Completed Construction

Construction of the project was completed on March 7, 2021. Some photos of the completed construction follow:

Figure 17 – Long Wharf Headhouse Complete (Credit: MassDOT)

Figure 18 – Long Wharf Flood Door – Exterior (Credit: MassDOT)

Figure 19 – Long Wharf Flood Door - Interior (Credit: MassDOT)

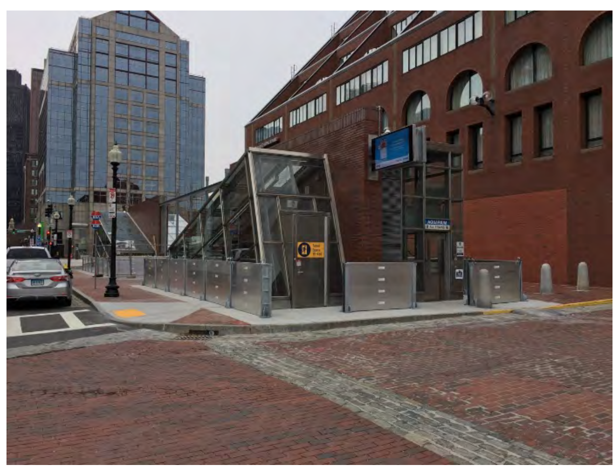

Figure 20 – East Headhouse Flood Barriers (Credit: MassDOT)

Figure 21 – East Headhouse Flood Barriers (Credit: MassDOT)

Figure 22 – Southwest Headhouse Flood Barriers (Credit: MassDOT)

Figure 23 – Southwest Headhouse Flood Barriers (Credit: MassDOT)

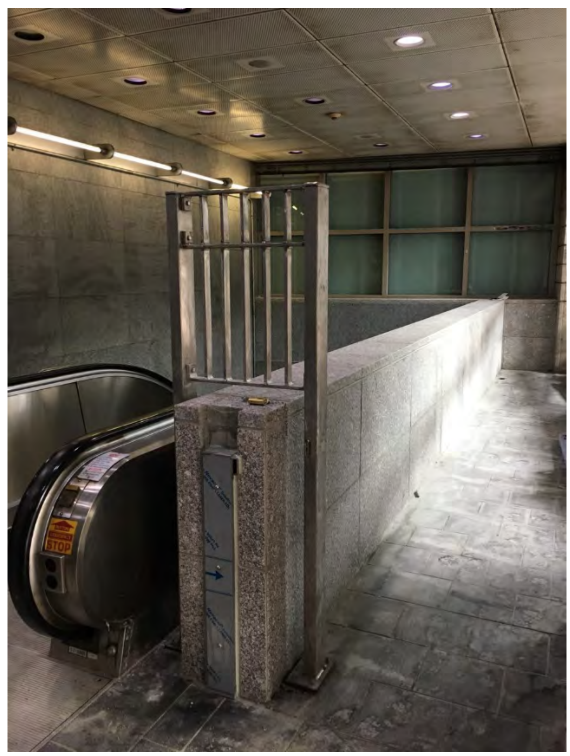

Figure 24 – Marketplace Center Concrete Floodwall (Credit: MassDOT)

MassDOT is continuing to investigate alternatives to improve resiliency from coastal flooding at important roadway assets including the Sumner Tunnel Entrance and Callahan Tunnel exit in East Boston and non-roadway assets such as the Highway Operations Center in South Boston.