5 Engineering Criteria

This chapter reviews eight engineering criteria as follows:

- structural integrity
- vulnerability
- seismicity
- redundancy
- security
- emergency response
- navigation
- construction impacts
- life span
- compliance with design criteria

All of these criteria consider technical performance and compliance with codes, standards or agency requirements.

5.1 Structural Integrity

As defined in the Level 2 Screening, structural integrity is the degree to which the river crossing is in compliance with current structural performance requirements. For the purpose of this report, this definition is extended to include the degree to which the TZB is to be modified to extend its service life for an additional 150 years when considering Rehabilitation Options. This service life extension would be inherent with the Replacement Options through compliance with current structural code requirements.

5.1.1 TZB Rehabilitation Options

Performance Requirements

The governing NYSDOT standards include the *NYSDOT LRFD Bridge Design Specification – US Customary 2007* (*LRFD Blue Pages*) and the *LRFD Bridge Design Specification, 4th ed.* from the American Association of State Highway and Transportation Officials (*AASHTO Design Specification*). The following excerpts from Chapter 1 in the *AASHTO Design Specification* outline the design philosophy that establishes the requirements for structural integrity:

> *Bridges shall be designed for specified limit states to achieve the objectives of constructability, safety and serviceability with due regard for economy and aesthetics.*

Four limit states are identified including:

- **Service Limit State** – Restrictions on stress, deformation and crack widths
- **Fatigue and Fracture Limit State –** Restrictions on stress ranges due to repetitive truck loading
- **Strength Limit State** – Strength and stability requirements to resist statistically significant load combinations that a bridge is expected to experience during its life span
- **Extreme Events Limit State** – Structural survival during a major earthquake or flood or when impacted by a vessel, vehicle, or ice flow, possibly under scoured conditions

Specifically to prevent sudden failure, the *AASHTO Design Specification* requires that bridges are designed to exhibit ductile rather than brittle behavior:

> *The structural system of the bridge shall be proportioned and detailed to ensure the development of significant and visible inelastic deformations at the strength and extreme events limit states before failure.*
>
> *Multiple load paths and continuous structures should be used unless there are compelling reasons not to use them.*

The requirements of *AASHTO Design Specification* are minimum standards with applicability limited to bridge spans less than 500 feet. National bridge standards/specifications for longer span bridges do not exist and it is common that agencies/owners develop specific specifications on a case by case basis. These specifications typically include more stringent requirements than those required by the minimum standards set out in the *AASHTO Design Specification*.

At this stage in the TZB/I287 Environmental Review, specific standards for the TZB have not yet been developed but will be developed for the TZB options progressed into the DEIS. For the purposes of this report, the minimum standards outlined in *AASHTO Design Specification* are adopted.

The existing TZB was designed in accordance with the requirements of AASHO *Standard Specifications for Highway Bridges* (1949, fifth edition). As listed on the original bridge construction drawings and in accordance with the 1949 Specification, the TZB was designed to support its own weight (dead load), traffic (live load) and to resist the forces of wind, temperature, traction and friction. How the design of the bridge accounted for fatigue and extreme events including ship collision and earthquakes is not recorded on the drawings.

Modifications to the Existing TZB to Comply with Current Standards

Based on the bridge assessment conducted for this Environment Review (Chapter 2.4), the existing TZB does not comply with all the structural limit state requirements in the *AASHTO Design Specification*. The following modifications would be necessary for all the Rehabilitation Options to comply with this standard:

Service Limit State

1. The concrete deck on the Causeway (part of which is in the process of being replaced with deck of compliant thicknesses) and West Deck Truss do not comply with current requirements as follows:

   - The existing 6.75” deck is thinner than the minimum 8.5” required under NYSDOT standards
   - The existing 0.75” concrete cover (depth from surface to reinforcement) on the top of the concrete deck is less than the minimum 2” required
   - The existing 1” concrete cover at the soffit (underside) of the concrete deck is less than the minimum 1.5” required

   The non-compliant concrete covers on the deck, listed above, do not affect the structural functioning of the TZB. They are, however, indicative of reduced service life due to faster chloride intrusion (from de-icing salts) and consequent reinforcement rusting. The thin slab together with the high truck volumes on the TZB would further limit the service life of the concrete deck.

2. The existing 2” concrete cover on the Deck Truss substructures is less than the minimum 4” required. Again this would not affect the structural functioning of the TZB, but is indicative of limited service life. It is proposed that additional protection against chloride intrusion would form part of any of the Rehabilitation Options.

3. The timber piles supporting the existing Causeway were not treated with preservatives as currently required and are vulnerable to destruction by marine borers.

4. Rehabilitation Options assume replacement of the Causeway.

Fatigue Limit State

- The fatigue life of the weld detail at the base of the steel stingers supporting the deck on the Causeway is at or near its theoretical service limit. Deck stringers would be replaced for all Rehabilitation Options (Note: The NYSTA is currently undertaking a program to replace 55% of the stringers).
- Fatigue standards have changed substantially since the TZB was built in 1955. As a result, the TZB's trusses do not comply with current AASHTO stress range design criteria. The steel connections within the structure also do not conform with the current fatigue cycles limit (i.e., 10 million cycles) required by AASHTO. Quantifying the performance of the existing TZB under these requirements has not been conducted as part of the assessments performed for this Environmental Review.

- The steel material specifications (i.e. the carbon and silicon steels used on the TZB) do not conform to the minimum toughness requirements now defined by AASHTO. Quantifying the implications of these rules has not been conducted as part of the assessments performed for this Environmental Review.
- The exposure of the connection angles to roadway deck run-off has resulted in significant steel section loss at the back face of the angle. This loss of section is undesirable in a location that is subject to fatigue cycles resulting from live load deflection of the floor beam. Rehabilitation Options assume repair or replacement of corroded members and reconfiguration of deck drainage/run-off throughout the Main Spans.

Strength Limit State

1. Live Load
   The existing TZB superstructure cannot support HS-25 standard AASHTO loading with the necessary factors-of-safety in the *AASHTO Design Specification.* Initial assessment indicates that up to 12% of the members (stingers, steelwork, etc.) on the existing bridge would require strengthening in the Rehabilitation Options.

   Due to the volume of trucks using the TZB corridor and the length of the bridge span, the HS-25 truck loading distribution in the AASHTO Specifications may be insufficient for the TZB. Specific truck loading and distribution would need to be considered during later stages of design.

   Assessments for this report were conducted using HS-25 loads and not the larger HL-93 which is the current NYSDOT standard. Further assessment using the HL-93 loading would be expected to result in a larger number of members with reduced factors-of-safety.
2. Wind
   The existing TZB cannot resist current wind load in a manner that complies with current AASHTO requirements for factors of safety. Initial assessment indicates that up to 2% of the steelwork members on the existing bridge would require strengthening in the Rehabilitation Options. This 2% is in addition to those members requiring strengthening due to live load and overloaded vehicle requirements.
3. Overload Vehicles
   The existing TZB cannot support the standard NYSTA overload vehicle loading with required AASHTO factors of safety. Initial assessment indicates that less than 1% of the members on the existing bridge would require strengthening in the Rehabilitation Options. This 1% is in addition to those members requiring strengthening due to live load and wind requirements.

Extreme Events Limit State

1. Seismic
   The seismic assessment conducted should be considered an order of magnitude analysis only to establish the overall performance of the TZB. The results of the analysis indicate that the existing TZB does not comply with the NYSDOT performance requirements for critical infrastructure. Without retrofit, the potential for major damage to segments of the existing TZB cannot be ruled out under the safety level seismic event described in Chapter 2.4.4. Extensive retrofit is required for all of the Rehabilitation Options to meet seismic performance requirements. Modification or strengthening would be required to all parts of the bridge including superstructure steelwork, substructure concrete and steelwork and foundations.

   Further details of the seismic performance are included in Chapter 5.3.
2. Collision and Impact
   The existing TZB is vulnerable to a number of potential accidental or deliberate events that could result in sudden loss of service and substantial damage. The performance of the existing TZB in these events is in conflict with the AASHTO requirement that bridges be proportioned and detailed to ensure they exhibit significant and visible permanent deformations at the strength and extreme events limit states before failure.

Redundancy

The existing Main Spans and Deck Truss structures are structurally non-redundant. This structural performance is not in compliance with the current *AASHTO Design Specifications.* Modifications to the existing bridge to meet the current design, fabrication and construction requirements for non-redundant structures would require substantial modifications and the likely introduction of ancillary structural systems.

Further details regarding redundancy are included in Chapter 5.4.

Modifications to Extend Component Service Life

To ensure continued safe operation of a rehabilitated TZB, the following specific modifications are required to arrest repetitive repair of structural members and to ensure continued safe access for inspection and repair:

- Reconfiguration/replacement of the bearing stools supporting the deck stringers on the East Deck Truss spans
- Elimination of the open drainage along the full length of the TZB
- Redirection of drainage run-off
- Replacement of the safety barrier along the full length of the TZB
- Reconstitution and extension of the maintenance walkways and moveable platforms
- Installation of a modern structural monitoring system
- Repair and replacement of all steelwork with substantial section loss
- Refurbishment of the concrete piers supporting the Deck Truss Spans
- Painting of all steelwork
- Joint and joint controls reconstruction

Due to the continued growth in traffic on the TZB, the off-peak period available for repair and inspection is continuously shrinking. These modifications would reduce the subsequent repair work needed on the TZB in comparison to a no-build option for a notable period with reduced impact on traffic conditions. Subsequent repairs would still be more extensive and frequent than that required in the Replacement Options.

Other Structural Modifications

To support the addition of a Pedestrian and Bicycle Path along the full length of the TZB, modifications will be required for all four Rehabilitation Options including:

- Modification to the edge steelwork arrangements for the Deck Truss and Main Spans
- Strengthening of the beam trusses on the Deck Truss Spans

Rehabilitation Option 2 is the only option that adds substantial loads to the existing structure and would require substantial strengthening of the steelwork truss to support additional dead and live loads (weight). All truss members on the Deck Truss and Main Spans trusses would need to be modified and connections reconfigured.

5.1.2 TZB Replacement Options

The structure of the replacement TZB included in all the Replacement Options would fully comply with the current *AASHTO and NYSDOT Design Specification* requirements.

As a critical structure in the region's transportation network, the consideration of performance requirements above and beyond the minimum requirements in the *AASHTO Design Specifications* would be part of the design. For a new structure, there is the opportunity to incorporate specific performance requirements based on a cost/benefit assessment to ensure desirable strength, redundancy, ductility and other necessary measures to protect against possible accidental or deliberate events.

5.1.3 Comparison of Options

In the Rehabilitation Options, extensive modifications, strengthening and reconfiguration are required for the bridge to comply with the structural requirements of the *AASHTO Design Specification* and the *NYSDOT Blue Pages*. While extensive, these changes will result in a bridge structure that complies with all current limit state requirements.

Because of the lack of redundancy and the number and distribution of critical components, there is the potential for major damage in a number of deliberate event scenarios. Were such damage to occur, restoration of the crossing could take months to years to accomplish. The resulting traffic detours (40 miles from Nyack to Tarrytown) and associated disruption would have major effects upon the economies of the Mid-Hudson and New York City regions. As a critical link in the nation's transportation infrastructure, this level of structural performance warrants security and other countermeasures to reduce the potential for the specific event scenarios that is only achievable with the Replacement Options.

In the Replacement Options, the replacement TZB would fully comply with the requirements of the current AASHTO and NYSDOT specifications.

5.2 Vulnerability

Assessment of the vulnerabilities of the existing TZB was conducted in accordance with the requirements of the NYSDOT Vulnerability Manuals, supplemented by a Threat and Risk Assessment (TARA) analysis to establish the overall risk framework. When the project reaches the DEIS phase, a Design Threat Basis analysis, listing potential threats to the bridge will be developed and form part of the Bridge Design Criteria.

Vulnerability Assessment

The NYSDOT uses standardized procedures, outlined in six NYSDOT Vulnerability Manuals, to establish inspection, capital and safety priorities across all bridges for which they have responsibility. The procedures use generic and detailed information about individual bridges (geometry, configuration, details, age, soil, condition and load rating) to establish vulnerability ratings on a scale of 1-6. As shown in Table 5-1, the lower the rating value, the greater the vulnerability and the more significant the action required.

The Vulnerability Manuals encompass vessel and vehicle collisions, overload, seismic, concrete details, steel details and hydraulics; the vulnerabilities that have been the source of historical problems, or are the subject of revisions to design specifications. A rating of 4 is considered normal. A rating less than four indicates that a more detailed evaluation of the bridge is required or that there are factors that are cause for concern.

While the vulnerability ratings provide a useful tool for establishing priorities between bridges, the uniqueness and importance of the TZB requires a more detailed examination of possible risks.

Rating	Description
1	Safety Priority Watch
2	Safety Program Alert
3	Capital Program Action
4	Inspection Program Action
5	No Action
6	Not Applicable

Table 5-1

Vulnerability Rating Descriptions

Threat and Risk Assessment (TARA)

To supplement the results of the vulnerability assessments, establish risk priorities specific to the TZB and to encompass a broader range of vulnerabilities, a TARA analysis for the existing TZB was conducted.

A TARA analysis is a systematic approach to the ranking of risks, where the risk is a product of probability and criticality estimates. The process identifies hazards and specific event scenarios, establishes the consequence of these events based on known capacity and condition and assigns rankings (1-5) to both probability and criticality (Tables 5-2 and 5-3, page 38). The resulting product of the probability and criticality rankings is a risk value between 1 and 25 for every possible event scenario, which can be used to rank risks, with the lowest values being the most critical.

For example, an event that has catastrophic consequences and occurs frequently would have a risk ranking of 1. An event that is improbable and has negligible consequences would have a risk ranking of 25. The risk rankings undertaken reveal the relative risk to the bridge and to stakeholders of the various hazardous events. The range of hazards to the TZB include: natural events like earthquakes; operational incidents that are accidental, such as vehicle accidents, or deliberate, like terrorist bombings; and on-going deterioration – 69 separate event scenarios were included in the assessment.

While modifications to minimize the consequence of potential events would be incorporated in the Rehabilitation Options, desired performance requirements cannot be achieved for all event scenarios. In particular, the truss components are easily accessible from the travel way and therefore are susceptible to terrorist attack. Risks associated with deliberate intent are inherent in the Rehabilitation Options.

Probability Ranking	Probability Description	Probability	Return Period, (Years)
5	Improbable	Less than 0.0001	Greater than 10,000
4	Remote	0.001 – 0.0001	1000 – 10,000
3	Occasional	0.01 - 0.001	100 – 1000
2	Probable	0.1 - 0.01	10 – 100
1	Frequent	Greater than 0.1	Less than 10

Table 5-2

Probability Ranking for TARA Analysis

Criticality Ranking	Criticality Description	Structure		
		Extent of Structural Damage	Repair Costs	Traffic disruption Time
5	Negligible	Insignificant	< $1,000,000	Partial closures lasting hours
4	Marginal	Inspection required	< $10, 000,000	Partial closures lasting days
3	Moderate	Failure of Individual Members	< $50,000,000	Partial closures lasting weeks
2	Critical	Section collapse/unusable	< $ 250,000,000	Partial closures lasting months
1	Catastrophic	Multiple section collapse/unusable	> $ 250,000,000	Partial closures lasting year(s)

Table 5-3

Criticality Ranking for TARA Analysis

5.2.1 TZB Rehabilitation Options

The results of the vulnerability assessments (Table 5-4) indicate that the ratings for five of the six vulnerabilities considered would be sufficient to include the existing TZB on the NYSDOT capital and safety programs (ratings of 3 or less). For the Rehabilitation Options, the structural modifications, outlined in Chapter 5.1, would address many of these vulnerabilities:

- Overload and vehicle collision vulnerabilities would be eliminated with the introduction of new safety fences, impact attenuators and modifications to a small number of structural members
- Vessel collision vulnerabilities would be minimized by the inclusion of enhanced impact protection around the Buoyant Caissons
- Seismic vulnerabilities would be addressed by extensive retrofit measures
- Replacement of the Causeway structure substantially reduces the concrete vulnerabilities

Steel detail vulnerabilities, including the absence of load path redundancy, fatigue resistance and the salt environment with its consequent ongoing corrosion would remain in the retained structure. Modifications that reduce corrosion vulnerability concerns include improved drainage and run-off arrangements and improved paint condition.

Table 5-5 presents the summary risk ranking from the TARA analysis of the existing TZB, arranged from high to low. The risk assessment indicates that the highest risks are associated with deliberate actions, exposure and corrosion, and the 2500-year return period earthquake. Deck run-off, exposure to the environment and significant truck volume represent actions on the bridge that result in deterioration for which corrective actions are incorporated in the Rehabilitation Options.

Vulnerability	West Trestle	West Deck Truss	Main Spans	East Deck Truss	East Trestle	Lowest Rating	Action required
Collisions	2	4	2	4	6	**2**	Safety Program Watch
Overload	2	1	4	1	5	**1**	Safety Priority Alert
Seismic	3	2	2	2	3	**2**	Safety Program Action
Concrete	3	4	4	4	4	**3**	Capital Program Action
Steel Details	4	1	2	1	4	**1**	Safety Priority
Hydraulic	4	4	4	4	6	**4**	Inspection Program

Table 5-4

Vulnerability Assessment Results for Existing TZB

Priority	Event group
High	Deliberate actions Exposure and corrosion 2500-year seismic
Medium	500-year seismic Wind Accidental vessel collision Overload Accidental barge collision
Low	Accidental vehicle collision Accidental train collision Ice and water

Table 5-5

Summary Risk Ranking Results for Existing TZB

5.2.2 TZB Replacement Options

The structure of the replacement TZB included in all the Replacement Options would address all threats and be identified in a Design Threat Basis to be developed in the DEIS. In particular, specific structural countermeasures would be 'built-in' to the design of a replacement TZB to directly control the performance of the structure and ensure survivability and continued safe operation.

5.2.3 Comparison of Options

The mitigation of risks/vulnerabilities associated with various event scenarios resulting from extreme events is a major differentiator that favors the Replacement Options. While the risk/vulnerability framework for the Rehabilitated Options is improved over the existing conditions of the TZB, vulnerabilities will continue to be associated with the truss steelwork and overall steel details. These are core features of the TZB's design and construction; they could not be removed without its complete rebuilding.

5.3 Seismicity

5.3.1 Introduction

The seismicity criterion is a measure of the seismic performance of the TZB. As a 'critical' piece of infrastructure the TZB is required to meet the following performance levels:

- **Functional Event**: After a moderate seismic event the TZB should suffer no damage to primary members and be open for traffic within hours. A moderate event is defined as an earthquake with an approximate 500-year return period.
- **Safety Event**: After a major seismic event the TZB should have repairable damage and be open to emergency services within 48 hours and to general traffic within months. A major seismic event is defined as an earthquake with an approximate 2500-year return period.

To determine if the Rehabilitation and Replacement Options can meet these requirements, seismic assessments of representative sections of both the existing and possible replacement TZB were conducted. The magnitude and characteristics of the seismic events used in these assessments were in accordance with the NYSDOT standards for downstate New York (*NYSDOT 'Blue Pages' July 2003 Division 1A Section 6A and 'Blue Pages' September 2007 clause 3.10*). These were adopted from the work of the New York City Department of Transportation (NYCDOT) and Risk Engineering, Inc. who, together with the Port Authority of New York & New Jersey (PANYNJ) and the Metropolitan Transportation Authority (MTA), assembled a panel of seismic experts to establish a common seismic basis for the assessment of all major bridges in the New York City area.

The results of these assessments indicate that the existing TZB would experience considerable damage during either the seismic Functional Level or Safety Level events and would not meet the performance standards established by the NYSDOT as outlined above. The potential for major damage to or permanent misalignment/displacement of the TZB cannot be discounted and closure of the TZB for a substantial period, possible years, after the seismic functional or safety events would be expected.

For the Rehabilitation Options, retrofit of the TZB would be required to meet the seismic performance requirements. Retrofit requirements are extensive and include the removal of all of the Buoyant Foundations, their replacement with a different foundation system and the strengthening of all other foundations. For the Replacement Options, seismic assessment indicates that a replacement bridge could meet the performance requirements.

5.3.2 Seismic Performance of the Existing TZB

Though the NYSTA has conducted a number of seismic assessments of the TZB, an updated seismic assessment and Probabilistic Seismic Hazard Assessment (PSHA) was conducted for this study to take into account the updated recommendations of the latest NYCDOT expert panel. The assessment was based on a multimodal (frequency) analysis, from which potential seismic retrofit strategies were determined. These analysis results were supplemented by time-history analyses for the Causeway and Main Spans (Figure 5-1, page 42). Factors considered in these analyses included:

- Seismic rock motions applicable to downstate New York
- Potential liquefaction of the soils under the Hudson River
- Seismic amplification through the soft soils under the Hudson River
- Soil strain degradation
- Basin effects – overall motion of the soils in the Hudson riverbed
- Different arrival times of seismic waves
- Loss of foundation support due to scour
- Influence of the river/water surrounding the floating foundations
- Ductility – the ability of a material to deform beyond its theoretical yield without fracture
- Bridge condition and loss of capacity resulting from section losses recorded during inspections

5.3.3 Multimodal (Frequency) Analysis Results

Multimodal (frequency) analysis is the typical first step in the seismic assessment of large bridges and provided a general outline of the performance of the TZB. The analysis results in a series of capacity/demand (C/D) ratios for all components and members (Table 5-6, page 40) that are indicative of where potential structural failures are likely to occur in a seismic event if no structural modifications (retrofits) are made.

C/D ratios with a value greater than 1.0 indicate that the structural capacity is greater than the seismic demand and no retrofit or further assessment is usually necessary. Where the ratio is less than 1.0, the seismic demand exceeds capacity and failure of the component or member would be expected in the absence of bridge retrofit. The lower the C/D ratio, the greater is the seismic demand compared to capacity.

As shown in the example results included in Table 5-6, C/D ratios of less than 1.0 were extensive on all segments of the TZB with the lowest values at the steelwork bracing, piers and foundations (0.2-0.4). The extent of the C/D values below 1.0, particularly at piers and foundations is typical for older structures that have not been designed to modern standards. Because the effect of a seismic event is primarily to increase the horizontal forces on a bridge, the capacities of the bridge components that transfer horizontal loads to the ground (bracing, piers and foundations) are typically exceeded.

Overall, these results indicate that the designers of the TZB never intended that the bridge would need to withstand the demands associated with significant seismic events. In particular, as demonstrated by the low C/D ratios, the use of timber piles and Buoyant Caissons is incompatible with the high seismic demands resulting from current standards. If the original designers had had to account for current seismic standards, the timber piles and Buoyant Caissons would not have been the final foundation forms adopted.

Existing Causeway Spans

For the Causeway structure, this assessment indicates that the capacity of the existing horizontal load resisting system will be substantially exceeded and that the raked end piles at each pier will be significantly overstressed. This overstress of the end piles does not imply failure of the whole structure, as alternative horizontal load capacity exists in the multitude of vertical piles present in the foundations. Analysis that assumes continued functioning of these vertical piles indicates possible adequate foundation capacity to resist the seismic forces, though with substantial roadway displacements and damage to connections and details.

TZB Segment	Structural Component	Lowest Seismic Capacity/Demand Ratio (C/D)*	
		500-year event	2500-year event
Causeway Spans	Bearings (condition based)	-	<1
	Cap beam	>1	0.52
	Piers (top)	0.96	0.47
	Piers (base)	>1	0.69
	Foundations (Compression)	0.55	0.25
	Foundation (Tension)	<0.1	<0.1
Deck Truss Spans	**Superstructure**		
	Deck trusses	>1	0.81
	Truss beams	>1	0.61
	Bearings	-	<1
	Piers		
	Concrete Piers	0.5	0.2
	Foundations (displacement ratio)		
	Cofferdam foundations	>1	0.5-0.6
	Buoyant Foundations	0.6-0.9	0.3-0.4
Main Spans	**Superstructure**		
	Truss Lower Chord	0.9	0.4
	Truss Upper Chord	1.4	0.8
	Truss Verticals	1.1	0.4
	Truss Diagonals	1.1	0.8
	Deck Bracing Diagonals	0.6	0.4
	Top Bracing Struts	1.8	0.9
	Top Bracing Laterals	0.4	0.2
	Portal Bracing Horizontals	0.5	0.2
	Portal Bracing Diagonals	0.9	0.4
	Main Towers		
	Longitudinal Diagonals	0.53	0.41
	Transverse Diagonals	0.61	0.49
	Main Verticals	0.70	0.59
	Transverse Horizontals	>1	0.80
	Anchor Towers		
	Longitudinal Diagonals	>1	0.98
	Transverse Diagonals	>1	0.66
	Main Verticals	>1	0.70
	Foundations		
	Main towers	0.59	0.29
	Anchor towers	0.67	0.33

* Cells in blue indicate a C/D ratio less than 1.0

Table 5-6

Seismic Capacity/Demand Ratios for Existing TZB

Despite the alternative horizontal capacity, following a safety level seismic event, it is considered that the structure is likely to be out of position and unusable by general traffic. Further, the potential for major damage cannot be discounted as the connections and details inherently are non-ductile. The order in which damage would occur based on ranking the capacity/demand ratios and the severity of the overstress is as follows:

1. Anchor bolts of the fixed steel bearings at even numbered piers shear off and pedestals spall due to their poor condition.
2. End battered timber piles plunge into the soil and disconnect from the pile cap. The foundation softens and the force is re-distributed to other piles. While the softening decreases the force demands elsewhere in the structure, it does increase the displacements of the foundation, which are likely to be unrepairable for the design safety level event.
3. Pier columns crack (interior ones first, then exterior). Concrete cover may spall and re-bar may buckle due to lack of confinement.
4. Top of column/cap beam connection cracks and spalls.

Existing Deck Truss Spans

Assessment of the Deck Truss Spans indicates major overstress of bearings, some steel members and the supporting piers. The magnitude of the overstresses and the inability of these members to behave in a ductile manner may have major consequences resulting in potential major damage during a seismic Safety Level Event. The order in which damage would occur based on ranking the capacity/demand ratios and the severity of the overstress is as follows:

1. Deck finger joints become bent or fail due to contact
2. Truss bearing built-end caps on rocker pins damaged and fixed bearing anchor bolts fail in shear
3. Pier columns crack, concrete cover may spall and re-bar may buckle due to lack of confinement
4. Piles supporting the Buoyant Caissons begin to yield in bending
5. Isolated primary steelwork begins to yield
6. Piles supporting concrete cofferdams begin to yield
7. Top of column/cap beam connection cracks and spalls

Existing Main Spans

This assessment of the Main Spans indicates extensive overstress, with the greatest overstresses at the bearings, pier anchor bolts, steelwork in piers, main trusses and the Buoyant Foundations. The configuration of the tower legs, connections and piles do not indicate adequate ductile behavior, implying major damage from the governing safety level event with potential collapse.

Based on the analysis completed and the resulting capacity/demand ratios, damage would occur to the Main Spans of the TZB in a seismic event. The order in which damage would occur based on ranking the capacity-demand ratios and the severity of the overstress is as follows:

1. Steel roller expansion bearings exceed the anchor bolt shear capacity. Bolts may shear though it may be possible to sustain significant damage without compromising the overall structural integrity of the through truss spans
2. The anchor bolt connection between the pier column legs and the caisson pedestal loses its shear transfer capacity in an uplift condition. Shear load redistributes to neighboring anchor connections
3. Horizontal portal bracing in the superstructure begins to yield
4. Top bracing lateral compression members begin to buckle, loads redistribute to tension bracing and this redistribution begins to yield these members
5. Deck bracing diagonals begin to buckle and yield
6. Main pier column longitudinal diagonals begin to yield
7. Truss verticals begin to yield
8. Portal bracing diagonals begin to buckle and yield
9. The local discontinuity at the ends of the main truss bottom chord induces high transverse bending stresses in this primary load-carrying member. The lower chord begins to yield

10. Main pier column transverse diagonals begin to yield
11. The piled foundations supporting the caissons begin to fail in bending due to large horizontal displacement
12. Main pier column verticals begin to yield
13. Truss diagonals begin to yield
14. Truss upper chord begins to yield
15. Column transverse horizontals begin to yield
16. Top bracing struts buckle and yield

The above sequences are intended to identify the areas of the bridge at risk to the different levels of seismic hazard and to postulate the sequence in which damage is likely to occur. This sequence is necessary to clarify the retrofit strategies adopted for the Rehabilitation Options.

5.3.4 Time-History Analysis Results

To supplement the results of the multi-modal (frequency) analysis, further seismic assessment was conducted using time-history analysis. In time-history analysis, representative earthquakes can be applied directly to analytical models that not only include the bridge structure but also include the founding soils and the bedrock below. Representative earthquakes are applied to the bedrock that propagated through the soils and bridge structure above accounting for the complex soil-structure interactions that can occur.

This further analysis was warranted to account for newly identified soil properties resulting from geotechnical investigations, to incorporate site-specific requirements and to further refine the foundation requirements in the Rehabilitation and Replacement Options. Two specific investigations were conducted:

1. Analysis of the Main Spans of the existing TZB to confirm magnitude and performance of the retrofitted foundations for the Rehabilitation Options
2. Analysis of the replaced Causeway Spans to confirm magnitude and performance of the foundations for the replaced Causeway Spans in all options

Existing Main Spans Foundation Retrofit

The results from the multi-modal (frequency) analysis for the Main Spans foundations indicated that the normal safe capacity of the existing piles was only about 30% of that required to resist the demands of the safety level seismic event (a C/D ratio of 0.29 as shown in Table 5-6, page 40). To determine the size of the retrofitted foundations, the effectiveness of both demand reduction and strengthening strategies were analyzed with the following summary results:

- The introduction of isolation bearings was found not to be an effective measure in reducing the demands on the foundations. As the degree of isolation was increased, the demands on the foundations also increased, with the mass and stiffness of the individual foundations dominating the seismic response.
- Yielding of the steel at the top of the piles was identified in all piles in both the main and anchor piers but with rotations less than 0.01 radians. Yielding of steel indicates that the applied demands are beyond the safe static working capacity and is indicative of permanent damage. For seismic events, notable yielding/damage can be accommodated provided the structure is detailed to behave in a ductile manner and the resulting damage is acceptable.
- For the seismic Safety Level Event, damage to the base of the Buoyant Foundation was identified at the interface with the steel piles below. Specific local modeling of the damage indicated extensive cracking of the concrete with the maximum crack widths ranging from ¼ - ½ inch. The extent of cracking in some Buoyant Caisson to pile connections was not quantified for all locations due to limited information on the as-built drawings from the original bridge construction. The potential for extensive cracking of the Buoyant Foundations was considered unacceptable due to resulting loss of buoyant load compensation with potential consequences to the stability of the overall Main Spans.
- To limit demands on the existing piles under the Buoyant Caissons to below their safe static capacity analysis, twenty new 10-foot diameter piles were the minimum required in the analysis conducted.

Replacement Causeway Spans

Time-history analysis of the replacement Causeway focused on a representative segment of six spans in the area of the deepest soft soils in the western half of the Hudson River. Details of the analysis and summary results were as follows:

- Each foundation included nine steel piles each 48 inches in diameter with steel up to 1.5 inches thick. Two sets of nine piles would be required for each span; one set corresponding to each direction of traffic. Pile depths were up to 300 feet below the riverbed.
- Both isolated and non-isolated bearings were tested in various model runs
- Results indicated that the demands on the substructure and foundation components did not exceed their static safe working limits. Yielding of the foundation piles was not present.
- The results indicate that the tested foundations were oversized enabling a potential reduction in the required number of piles, steel thickness or overall pile depth. Optimization of the piles and overall foundation layout was not conducted but deferred until after the completion of scoping.

5.3.5 Rehabilitation Options

To comply with the NYSDOT seismic performance requirements for critical infrastructure, retrofit of the existing TZB is required in all of the Rehabilitation Options to overcome the capacity/demand overstresses identified. Retrofit includes measures to reduce seismic demands on the TZB by modifying its behavior as well as measures to increase the structural capacity of specific members or components. The retrofit measures proposed for the existing bridge as included in all the Rehabilitation Options are outlined in Table 5.7 (page 43).

These retrofit measures include major modifications to the superstructure steelwork and its articulation, strengthening or replacement of all piers and enlargement or replacement of all foundations. Compared to other bridges retrofitted in the New York area these retrofits are more extensive and are akin to retrofits for bridges in higher seismic zones on the west coast. The greater retrofits are not a consequence of larger seismic events in the downstate New York area compared to the west coast, but result from the ground conditions under the Hudson River, the existing TZB foundation types and the high performance standard required for critical infrastructure.

Soil Conditions

Soil conditions under the Hudson River are best described as poor. The deep soft soils act to amplify the seismic motions applicable to the TZB from the underlying rock. Amplifications of up to six times the base rock motions have been identified in the analysis conducted for this report.

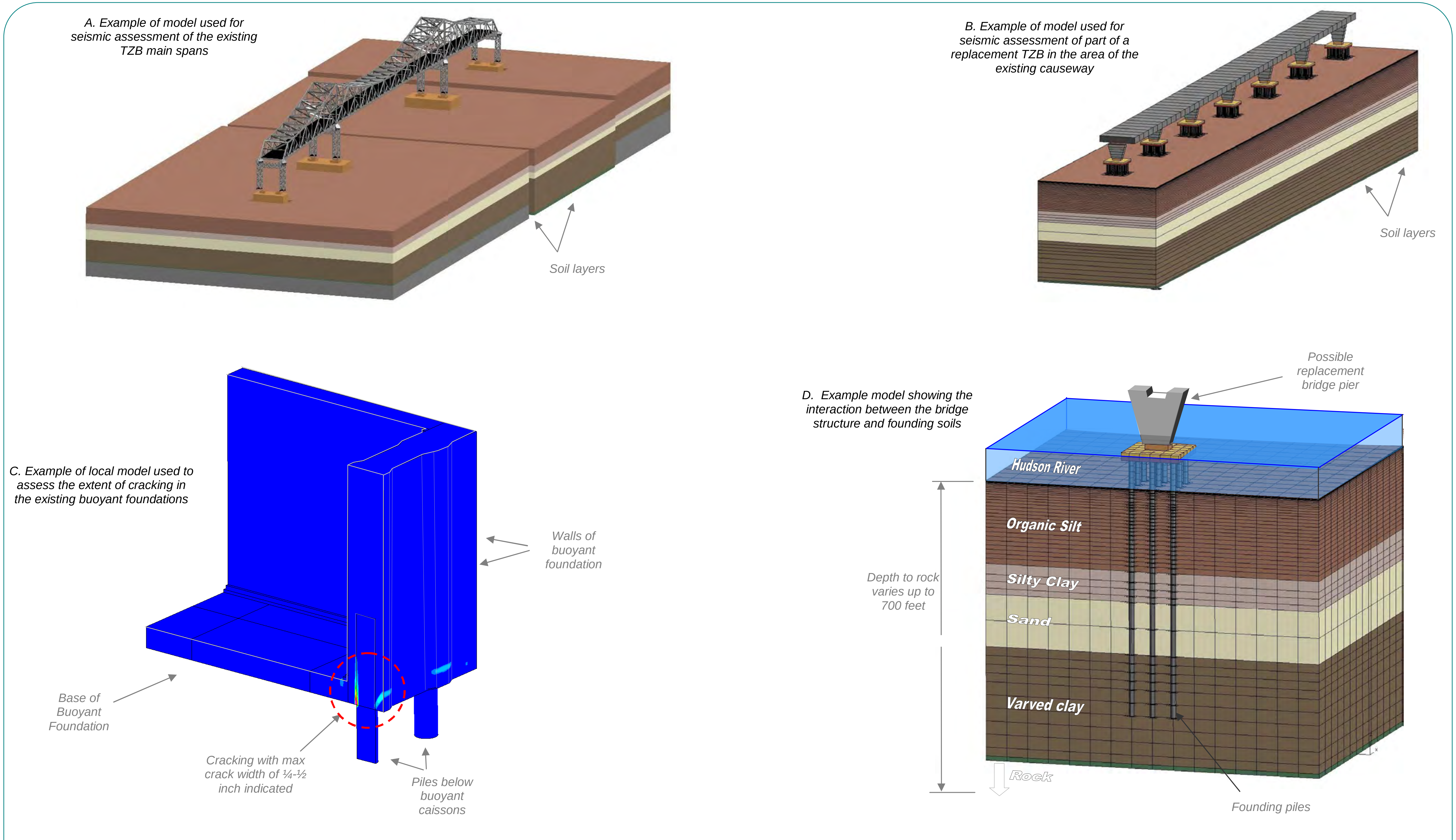


Figure 5-1
Representative Analytical Models used in Seismic Time-History Analysis

Buoyant Foundations

The Buoyant Caissons were a major innovation at the time of the original design of the TZB resulting in substantial cost savings. In the original design the designers were primarily concerned with large vertical and small lateral loads on the foundations. The buoyancy reduced the number of deep piles that were needed to carry the high vertical loads down to rock, thus saving cost and time. Buoyant caissons, however, are a major disadvantage when considering current design seismic events, which substantially increase the lateral demands on the bridge, while making retrofit complicated and risky. Disadvantages of Buoyant Caissons are outlined below.

1. Reduced Horizontal Capacity
   The reduction in the number of piles reduced the overall lateral capacity of the foundation. Had a more typical foundation been constructed, there may have been more residual capacity left to resist the increased horizontal demands.

2. Increase in Total Mass of the Foundation
   The Buoyant Caissons increased the overall mass of the TZB and therefore the corresponding seismic demands. The mass of the caisson was not a major concern to the original designers as the vertical weight was 'balanced' by the vertical buoyancy. But in a seismic event, where the motions are dominantly horizontal, the enlarged mass of the caisson is not balanced by any equivalent action. The full mass of the Buoyant Caissons is activated in a seismic event which results in substantially higher demands than would be expected with a more standard foundation.

Segments	Proposed Retrofits*
Causeway Spans	• Because the Causeway spans are replaced in all Rehabilitation Options, no further detail of the retrofit requirements for the Causeway spans is presented in this report.
Deck Truss Spans	• Replacement of the existing fixed and expansion bearings with seismic isolation bearings with the potential introduction of superstructure continuity • Modification of deck joints to accommodate seismic movements • Strengthening of superstructure steelwork and connections • Replacement of rivets at key connections • Strengthening of piers and cap beams • Strengthening of all cofferdam pile foundations • Replacement of all four of the Buoyant Foundations
Main Spans	• Replacement of existing fixed and expansion bearings with seismic isolation bearings with the potential introduction of full superstructure continuity • Modification of deck joints to accommodate seismic movements • Strengthening of superstructure steelwork and connections • Replacement of rivets at key connections • Introduction of transverse bracing at the main piers • Strengthening of pier steelwork • Replacement of all four of the Buoyant Foundations

* The modifications proposed here are initial retrofit strategies. The process of detailing the design of these retrofits may show that the level of modification required is less or more than that indicated.

Table 5-7

Proposed Seismic Retrofits

3. Mobilization of Water Mass
   The motion of the submerged Buoyant Caissons during a seismic event activates the mass of the water immediately surrounding the caisson increasing the seismic actions on the foundations. This effect is substantial because of the large areas of each face of each caisson.

4. Dominant Foundation Response
   On typical bridges, the largest mass is associated with the superstructure. It is the behavior of this mass that governs the seismic behavior and dominates retrofit strategies. For the TZB, it is not the superstructure but, instead, the foundation mass that dominates. The combined mass of the Buoyant Caissons is approximately twice that of the superstructure on the Main Spans. The options for the retrofit of structures dominated by foundation mass are more limited than for more typical bridges.

The net result of designing with Buoyant Caissons is a substantial increase in seismic forces. This occurs because of the much greater amount of moving mass coming from the caisson itself and the surrounding water. Meanwhile, overall horizontal capacity is inadequate because the number of foundation piles was reduced in the original design.

High Performance Standards

As a critical piece of the region's infrastructure, the TZB is held to the highest standard under the design seismic event. At the seismic Safety Level Event (2500-year return period) it is not just required that the TZB survive the event, it is required that the TZB survive the event intact and be open for traffic within months. For less critical bridges, the Safety Level Event is a smaller seismic event (500 or 1000-year return period) with allowable damage.

Even at the higher standards applicable to the TZB, some damage is acceptable as long as it is predictable and repairable.

Causeway Spans Retrofit

As outlined in Chapter 2 of this report, the Causeway is replaced in all the Rehabilitation Options and therefore is not considered further in this report.

Main Spans Retrofit

As listed in Table 5-7, the modifications to the Main Spans are extensive including all parts of the structure – superstructure, substructure and foundations. Within these modifications, there are two key strategic changes that are designed to control the seismic performance – reconfiguration of the articulation of the bridge and full reconstruction of the foundations.

1. Articulation
   Special friction pendulum bearings (isolation bearings) are introduced at the top of the each of the four piers at a location just under the superstructure. These bearings allow the superstructure above and substructure below to move separately in all horizontal directions during a seismic event. The result is a reduction in overall seismic demands on the superstructure with consequent reduction in the number of members to be modified. Construction risks and complexities include:

   - At all piers, it is necessary to move the superstructure off of its existing piers/supports to new temporary piers/supports while the existing piers are modified and bearings installed.
   - At the anchor spans, special details are required to allow superstructure and substructure to move separately while still restraining the superstructure from uplift.

2. Foundation Reconstruction
On typical bridges, it would be expected that the introduction of isolation bearings would reduce the overall seismic demands on the foundations and hence alleviate the overstresses (0.29 capacity/demand ratio) presented in Table 5.6 (page 40). However, the opposite is true for the TZB. The introduction of the isolation bearings results in increased seismic demands on the foundations because of the characteristics of the Buoyant Caissons. As a result, the C/D ratio would be even smaller than that indicated in Table 5.6. Retrofit options for the foundations were considered as follows with removal of the Buoyant Caissons and replacement with an alternative foundation identified as the preferred option:

- Addition of tuned mass dampers - This option was discounted due to the variability in behavior of the substructure, soil stiffness and water mass.
- Strengthening - This option was investigated but discounted because of the construction difficulties, performance unpredictability, risks and limits associated with maintaining the buoyancy of the caissons and existing piles undamaged during construction or during a seismic event, facilitating access for inspection, future risk and scale of construction. At a minimum, this option would have required the introduction of twenty five 10-foot diameter steel piles at each of the main pier Buoyant Foundations. This would double the footprint of the foundation and relocate the existing ship impact protection system. While this option was considered theoretically possible, it was determined to be practically infeasible and unreliable.
- Replacement - This option requires the reconfiguration of all four of the existing foundations and removal of the existing Buoyant Caissons as well as relocation of the ship impact protection system. Figure 3-1 (page 11) shows for one of the four piers the extent of structural reframing required to transfer the weight of the Main Spans from its Buoyant Foundation to new outrigger foundations. Once the load transfer is completed, the existing Buoyant Caisson would be demolished and the supporting piles cut-off. Successfully transferring the bridge loads will be an unprecedented undertaking for a structure of this size.

Deck Truss Spans Retrofit

Similar to the Main Spans, retrofit for the Deck Truss Spans also includes the introduction of isolation bearings and the removal and replacement of their four Buoyant Caissons with seismically upgraded foundations in conjunction with strengthening of the remaining cofferdam foundations.

5.3.6 TZB Replacement Options

Similar to the Rehabilitation Options, seismic assessment was completed for a representative section of the TZB in the Replacement Options with a particular focus on the foundation requirements in the poor soils in the area of the existing Causeway. The assessment used the same source earthquakes and performance standards as used for the Rehabilitation Options.

Results of these assessment indicate no C/D ratios below 1.0 and acceptable performance during seismic Functional and Safety Level events. Assessments were completed with and without superstructure isolation for a representative 230-foot span concrete deck structure.

While a number of foundation solutions were investigated, ranging from raked piles to soil replacement, the foundation solution adopted for the assessment was based on 4-foot diameter steel tubes. Depending on the replacement option, the number of piles in the replacement Causeway varied from 9-16 for each column in each pier. The piles were founded deep in the varved (layered) clays with the base of the piles approximately 250-350 feet below the river bed.

These foundations were considered practical and within the ability of current construction capabilities. By comparison, similar piles were used recently in the new Woodrow Wilson Bridge in Virginia and larger diameter piles (up to 10 feet) for the new San Francisco Oakland Bay Bridge in California.

One construction difficulty identified was the potential need to bring piles to the bridge site in short lengths, with the need for pile splicing on site. Additional costs were added in the cost estimates included later in this report to account for this construction activity.

5.3.7 Comparison of Options

For the Rehabilitation Options, retrofit of the TZB would be required to meet the current performance requirements of the *AASHTO Design Specification* and the *NYSDOT Blue Pages* . Retrofit requirements are extensive and include:

- Replacement of all of the Buoyant Foundations
- Strengthening of all other foundations
- Pier modifications and strengthening
- Modifications and strengthening of superstructure steelwork
- Replacement of existing bearings with special isolation bearings

For the Replacement Options, seismic assessment indicates that a replacement TZB could meet current performance requirements with feasible foundations sizes and pile depths. It is anticipated that if the proposed retrofits to the Rehabilitated Options are undertaken, a rehabilitated TZB will provide similar performance as the replacement options for the Functional and Safety Level seismic events.

For seismic events of larger magnitude or different characteristics, beyond the Functional and Safety Level seismic events, the engineering performance of the Rehabilitation and Replacement Options would differ substantially. Unlike modern bridges, the performance of the TZB in the Rehabilitation Options is based on strength and not ductility, and is therefore prone to the unexpected. In the Replacement Options, inherent ductility (the ability to accommodate repeated deformation) provides a measure of protection for even the largest events. The details that ensure ductility were not included in the original design of the TZB as seismic events were not considered a major factor.

The designation of the TZB as a critical bridge is at odds with its behavior as a non-ductile structure in the Rehabilitation Options, with potential for undesirable performance. Even after all the seismic modifications are implemented, a seismic event that is not constituted exactly as predicted, or is marginally larger than has been included in the design, has the potential to result in extended closure of the crossing because of the non-ductile behavior of the bridge form.

5.4 Redundancy

Redundancy is a measure of the ability of a service element to fulfill its function by secondary means after its primary functional mechanism is incapacitated. For the TZB, two aspects of its redundancy are important: its capacity after an event and the time required to permanently restore previous capacity. Table 5-8 (page 45) presents a comparison between the performance of the Rehabilitation and Replacement Options following various single events.

The major differentiator between the Rehabilitation and Replacement Options is the inability of the rehabilitated TZB to dissipate the effects of an explosion without major damage to the structure. The absence of alternate load path redundancy for gravity loads is an undesirable characteristic of the existing truss systems.

For Rehabilitation Options 1 and 2, damage or collapse of the Main Spans would result in the loss of the TZB for a number of years. In a similar scenario for Rehabilitation Options 3 and 4, the presence of service redundancy, namely a second span, would facilitate maintaining service in both directions. To recover from such an event, the lanes and shoulders on the parallel structure(s) could be reconfigured to temporarily accommodate 7 lanes during reconstruction.

For the Replacement Options, there are multiple design features that can be incorporated to provide many layers of redundancy:

- Offset and separation – The most efficient way to neutralize an explosion is to locate critical components at some distance from the source of the event. This could be accomplished on a new TZB by placing towers and trusses at some distance from the traveled lanes. Even a small distance greatly reduces the damage potential.

- Member redundancy – The bridge would be designed to account for the potential loss of a key member as a result of an explosive event. This would be achieved by over sizing surrounding members.
- Load path redundancy – Loads can be supported by multiple elements. For example, a deck truss below the deck and cables above the deck.
- Service redundancy – All of the Replacement Options incorporate a minimum of two parallel structures. Should one structure be damaged, the parallel structure would be capable of providing for service in two directions by the temporary reconfiguration of the lanes and shoulders.
- Hardening and dispersion – To minimize the effects of an explosion, the components and members of a replacement bridge would be 'hardened' to resist the forces of an explosion or may be shaped to direct energy away.

Should a single explosive event occur on a replacement TZB, particularly in Replacement Option 3 where an event could occur on the lower level, the time to re-establish full service would be weeks or months.

Sources of explosions include vehicle accidents or bombings; for which multiple events need to be considered. For the Replacement Options, the layers of redundancy noted above would be effective and many combinations of potential events would be considered. For the Rehabilitation Options, the effect of multiple events on the existing truss sections would result in much more extensive damage when compared to the consequences of a single event.

5.4.1 Comparison of Options

The layers of redundancy inherent in the Replacement Options reduce the feasibility, scope and scale of potential impacts when compared to the Rehabilitation Options, while the period to recover full service after a single event is reduced from years to only weeks or months. A lack of redundancy would remain a characteristic of the TZB in the Rehabilitation Options leaving it susceptible to extreme events including deliberate actions. In the Replacement Options adequate redundancy would be provided.

Scenario (Single Event)	Rehabilitation Options 1 and 2	Rehabilitation Options 3 and 4	Replacement Options 1, 2, & 3
Analyzed Explosion	Potential loss of all highway capacity for one or more years	Potential loss of one half of the TZB for one of more years On the half of the structure remaining, shoulders could be used to provide up to 7 lanes temporarily on the remaining structure	Potential loss of one half of the TZB for weeks or months On the half of the structure remaining, shoulders could be used to provide up to 7 lanes temporarily on the remaining structure
Main Spans[1] Ship Allision	No loss of service – impact protection provided	No loss of service – impact protection provided	No loss of service – impact protection provided
Seismic[2]	Loss of service for months	Loss of service for months	Loss of service for months

Notes:

1. Allision is an impact between a moving vessel and a fixed obstruction. It is similar to a collision, which is between two moving vessels.
2. The TZB is designated a "critical bridge" which, in accordance with the performance requirements in the NYSDOT LRFD Bridge Design Specification – US Customary 2007 (LRFD Blue Pages), means it must remain open to all traffic after the lower level design earthquake (500-year return period) and open to all emergency vehicles after a higher level earthquake (2500-year return period).

Table 5-8

Emergency Event Scenarios

5.5 Emergency Response

Provision for emergency response would be included in all options. Detailed emergency response plans would be developed in the course of final design and coordinated with the appropriate authorities based upon industry best practice. This criterion focuses on the ability of emergency services to access emergency events.

In all options, first responders to minor incidents on the rehabilitated or replaced TZB would be maintenance personnel who are permanently stationed at both ends. They would be supported by State Police and would form a first level of response, able to reach an incident from staging areas that would be permanently located on or adjacent to the TZB with dedicated access ramps. The expected response time would be within the first few minutes of an incident occurring.

For more significant incidents, second responders that include medical and fire services would access the TZB via local approaches on the same route as first responders, with response times expected to be in the range of 5 to 10 minutes after notification. In the event all lanes are blocked by the incident, access can be made from the opposing direction. For even more significant incidents, a further wave of responders would be expected to include the necessary specialist emergency personnel.

Key differentiators/similarities among the options are listed below.

1. **Shoulder access**
   - Emergency responders would access incidents along the highway shoulders in all options with the exception of Rehabilitation Option 1 for which shoulders are not present for approximately half of the overall crossing. Again, in the event all lanes are blocked by the incident, access can be made from the opposing direction.
2. **Highway Crossovers**
   - Highway crossovers are required for emergency access between the two travel ways and also to divert traffic onto the other travel way to bypass obstructions.
   - For Rehabilitation Options 1 and 2, both travel ways would be on a single structure so crossovers could be located at any location desired by the NYSTA or emergency services.
   - Rehabilitation Options 3 and 4 involve parallel structures, each carrying traffic in one direction. Due to the large offset (up to 300 feet) between the existing and proposed structures it would be impractical to construct crossover lanes between them.
   - Replacement Options 1 and 3 involve two parallel structures each carrying traffic in one direction. For these parallel structures, cross-over ramps would be incorporated at regular intervals to provide access between the two traffic directions.
   - For Replacement Option 2, configured with the CRT structure between the highway structures, crossover ramps could not be incorporated over much of the length of the crossing because of the clearance requirements for the CRT tracks between the highway travel ways. At locations where the highway and CRT are at the same elevation and a crossing can be effectuated, emergency access between the highway travel ways would require a disruption to CRT service for the incident duration. Replacement Option 2 could alternatively be configured with the CRT structure north of the highway structures. In such a configuration, the crossover ramps could be incorporated similar to Replacement Option 1.
3. **Access to CRT incidents**
   - Emergency access to the CRT tracks in Rehabilitation Option 4 and Replacement Option 3, where CRT is below the highway travel way, would be similar. Initial access to incidents for both options would be from stairways connecting the CRT level with the highway level. Additional access would be possible along the dedicated maintenance way included on the lower level between the two CRT tracks.
   - For Replacement Option 2, which incorporates rail in the center between the two highway travel ways, the difference in elevation and varying distance between the highway and CRT structures would restrict emergency access to the CRT tracks from the highway. Access would be along the 10-foot wide maintenance way, included between the tracks. Its limited width would constrain emergency vehicle maneuvers and staging.

5.5.1 Comparison of Options

The inclusion of shoulders on all options, with the exception of Rehabilitation Option 1, significantly improves emergency access and response. Emergency response in Rehabilitation Option 1 is subject to traffic congestion because of the absence of highway shoulders over approximately half of the crossing, or in the event of full directional closure, from the opposing direction.

In Replacement Option 2 and Rehabilitation Options 3 and 4, emergency access between the parallel structures is difficult because of the differences in vertical elevation and horizontal separation.

5.6 Navigation Clearance

The measure for this criterion is the level of conformance to navigational requirements of the US Coast Guard, who currently control the 600-foot wide and 139-foot high channel for shipping under the TZB. All Rehabilitation and Replacement Options would accommodate these minimum dimensions for shipping. The existing TZB provides the minimum 139-foot vertical clearance to the river.

At this stage in the Environmental Review process, the US Coast Guard has not changed these dimensional requirements but initial discussions indicate that some ships using the channel lower their uppermost equipment to pass under the TZB. If a replacement bridge is progressed, initial indication from the US Coast Guard is that an increase in the vertical clearance would be preferred, possibly to that of the Bear Mountain Bridge (155 feet), the next lowest clearance on the Hudson River. All Replacement Options would provide the 155-foot vertical clearance.

5.7 Construction Impacts

This discussion of construction impacts identifies the type, scale and duration of construction and the potential effects on local residents and businesses. The types of potential effects described here include the more general types of impacts typically associated with construction projects such as restricted access, noise and vibration, traffic disruption, and the presence of construction personnel. More specific construction impacts (e.g., property takings, visual, effects on historic properties and the Hudson River) are addressed in Chapter 6 (Environmental Criteria). Comparison between the Rehabilitation and Replacement Options is based on the type and extent of construction.

5.7.1 Rehabilitation Options

Rehabilitation Options 1 and 2 would have three primary construction activities (Figure 5-2, page 47): Causeway replacement, modifications to the Deck Truss and Main Spans and demolition of the existing Causeway. The overall schedule would be dictated by the duration required to complete modifications to the Deck Trusses and Main Spans, as these construction activities would need to be scheduled at night or at off-peak travel hours to maintain traffic operations. Activities affecting traffic would include: deck replacement, steelwork and connection strengthening, articulation reconfiguration, pier replacement and over-widening to facilitate temporary traffic requirements. The overall durations anticipated for Rehabilitation Options 1 and 2, respectively, would be approximately 7-8 and 10-12 years respectively.

To maintain full seven-lane operations during peak travel hours in both of these options, temporary over-widening of approximately 1000 feet of the West Deck Truss Spans would be required with associated new superstructure, piers and foundations, to allow full demolition of the Causeway.

Rehabilitation Options 3 and 4 would also have three primary construction activities (Figure 5-2, page 47): new Supplemental Bridge construction, Deck Truss and Main Spans modifications and existing Causeway demolition. To reduce the overall construction periods, the new Supplemental Bridge would be constructed first and configured to support the existing seven traffic lanes in a temporary arrangement. With all traffic on the Supplemental Bridge, the modifications to the existing TZB Deck Truss and Main Spans could be completed at a greater pace than compared to Rehabilitation Options 1 and 2. The overall duration for Rehabilitation Options 3 and 4 would be 6-7 years.

For Rehabilitation Option 4, which includes two CRT tracks, a fourth primary construction activity would be required encompassing track installation with the associated signaling, power supply and ancillary equipment.

5.7.2 Replacement Options

All three Replacement Options have the same three primary construction activities: replacement bridge construction, tie-in to the Thruway at the landings and demolition of the existing TZB. In the first of these activities, approximately 90% of at least one span of the replacement TZB would be constructed. The final 10% (the final tie-in), could not be completed until after partial demolition of the existing TZB at the landings. This is because the existing and replacement bridges occupy the same space. Similar to Rehabilitation Options 3 and 4, the existing 7 lanes of traffic would be temporarily shifted on to part of the replacement TZB to allow demolition of the existing TZB. The overall duration of these activities varies from 5-6 years, depending on the replacement option.

For Replacement Options 2 and 3, which include two CRT tracks, a fourth primary construction activity would be required encompassing track installation with the associated signaling, power supply and ancillary equipment.

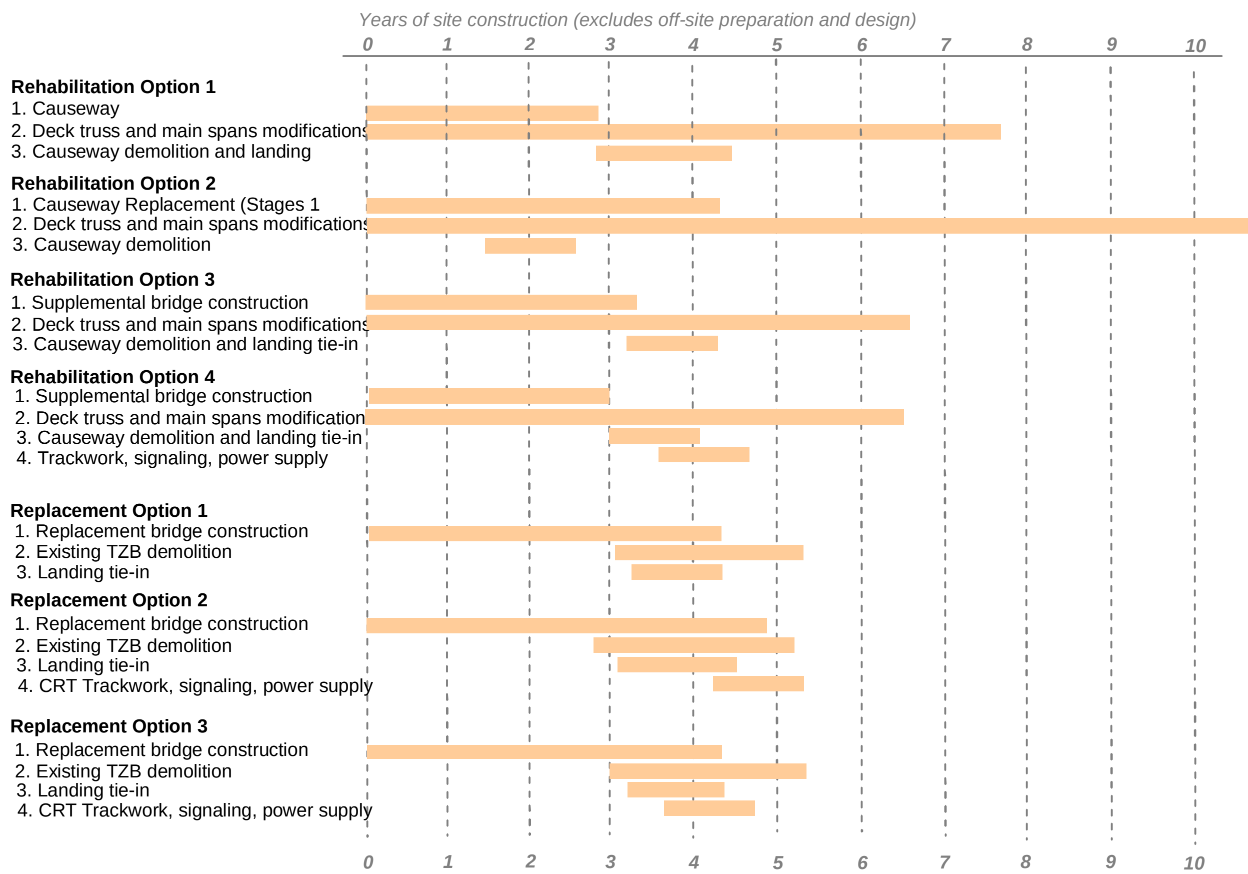


Figure 5-2

Indicative Construction Program

5.7.3 Comparison of Options

Construction Activities and Extent

For all seven options, major construction efforts are required across the full length of the crossing and at both the Nyack and Tarrytown landings. In the western half of the Hudson River, all Rehabilitation and Replacement Options remove and replace the Causeway with no difference in construction effort over the 8,400-foot extent.

It is only in the eastern half of the crossing (approximately 8,200 feet) where there is a difference in the activities to be conducted. Construction activities that differ among options include foundation construction, superstructure erection or modification and construction at the landings.

1. Foundation construction – Number of Piles

   All options include extensive foundation construction, either to strengthen/expand existing foundations or to construct new foundations. All of the foundation construction includes the installation of new steel piles with diameters up to ten feet. Installation of these piles would be by pneumatic or vibration techniques resulting in noise. Construction noise would be evident to TZB users and occupants of the residences and commercial buildings in the immediate shoreline communities in all options.

   Comparison of the number of piles to be constructed for all options is presented in Table 5-9. As shown, the number of piles to be constructed in Rehabilitation Option 1 (888) is significant but is notably less than all other options. In the other options, the numbers of piles are larger than Rehabilitation Option 1 (1,524 to 2,279) as all of these options support a much wider deck.

	Rehabilitation Options				Replacement Options		
	1	2[1]	3	4	1[2]	2[2]	3[1,2]
Number of Piles	888	1,588	1,604	1,408	1,660	2,279	1,524
Number of Cofferdams	60	60- 95	120	100	70	70	45- 80

1. The variation in the number of cofferdams reflects potential different construction methods.
2. Assumes cofferdams are required for the 8 floating foundations as part of the demolition of the existing TZB

Table 5-9

Comparison of Key Components

2. Foundation construction – Number of Cofferdams

   A cofferdam is a temporary watertight enclosure (Figure 5-5, page 51). To minimize impacts to the marine life and to fully control potential river bed disturbance, steel cofferdams would be temporarily installed around each individual foundation with all construction activities taking place within the enclosed cofferdams. While the size and type of these cofferdams varies, the minimum number of cofferdams is preferred. This will focus construction activities and reduce the extent of impacts to the river.

   As shown in Table 5-9, the number of cofferdams is largest (100-120) for Rehabilitation Options 3 and 4. This is because cofferdams for adjacent existing and supplemental foundations cannot be combined due to large separation or staging requirements. The smallest number of cofferdams (45) is associated with Replacement Option 3, assuming that adjacent piers use common cofferdams. The low number is a consequence of the longer spans resulting in a smaller number of piers required to cross the river.

3. Superstructure construction – Prefabrication

   Two methods of superstructure construction are employed among the options. Where a new bridge is required, construction of the superstructure would take advantage of modern pre-casting or prefabrication techniques to allow rapid erection of the superstructure at the bridge site. Regardless of whether the superstructure is concrete or steel, it would be manufactured off-site at a special facility and shipped to the bridge site on barges. Depending on the final form of the superstructure, complete spans could be pre-constructed with lengths exceeding 250 feet. These would be delivered to the bridge site and lifted into place using special cranes attached to the piers or directly from facilities on the barge. The exact nature of delivery and installation method will be developed once the bridge form is known.

   These construction techniques differ from those required for rehabilitation of the TZB where only small steelwork components could be modified/installed at any one time to maintain the overall stability of the existing structure. For each component to be modified or replaced, new steelwork would need to be cut and shaped to exactly match the existing steelwork. Positioning of rivets/bolt holes on new plates would be determined by survey of the existing plates. Despite the best plans and most accurate surveys, unexpected complexities can occur during the installation of new steelwork, resulting from either inaccurate fabrication or previously unidentified defects determined upon the removal of existing steel plates. The use of small components, the need for accurate survey and the complexities of actual installation of steelwork makes superstructure rehabilitation a slow process.

   For Rehabilitation Option 2, which incorporates widening of both sides of the existing TZB, substantial enlargement of the main truss members of the Main Spans would be required to carry the increased loading. Every member and connection would be modified over the full 2400 feet of the truss with construction activities staged to maintain the overall stability of the structure. This extensive modification of existing steelwork would be unprecedented and involves substantial risk.

4. Construction at Landings

   Because all options incorporate replacement of the Causeway, construction activities at the Rockland landing would be similar for all options with similar transit modes. Regardless of the final arrangement or width of the new Causeway Spans, all options would require use of the full width of the NYSTA property between the ROW boundaries to stage construction activities and to maintain full operation of the existing traffic lanes.

   At the Westchester Landings, construction activities associated with Rehabilitation Option 1 would be substantially less than those of all other options. In all other options, reconfiguration of the Toll Plaza, NYSTA maintenance area, security screening area, access roads and ramps would be required with substantial staging of traffic and facilities required. The necessary heavy construction, in the Rehabilitation and Replacement Options that include CRT, including rock excavation for a possible Tappan Zee Station, would be similar.

Construction Site Locations

Immediately adjacent to the river, two construction sites are required for each option, one located on each side of the Hudson River.

In Rockland, the construction site would be the same size for all options as the extent of construction work associated with the replacement of the Causeway is similar for options with the same transit modes. The construction site would be located in the available NYSTA property at Interchange 10 and would extend to the Hudson River where a temporary staging and access platform, distinct from the existing NYSTA maintenance facility, would be required to support construction activities.

In Westchester, the construction site would occupy the area of the current NYSTA maintenance facility and NYSP Troop T headquarters, which would be displaced. For all options, a temporary bridge over the existing Metro-North Hudson Line tracks that connects the construction site with a temporary platform in the Hudson River would be likely to allow for construction access, staging of equipment and emergency provisions. For Rehabilitation Options 1 and 2, the size of the temporary platform would be marginally smaller than that of other options as access for construction personnel would be along the walkway under the existing bridge deck.

Construction Duration

Figure 5-2 (page 47) presents a summary of the construction duration for all options. In summary, the duration of construction for the Rehabilitation Options is greater than that for the Replacement Options because of the limitations associated with the maintenance of traffic operations, stability requirements of the Main Spans under load and the extent of modifications required to the existing TZB.

Rehabilitation Option 2 has the longest construction duration (10-12 years) largely dictated by the pace of rehabilitation of the Main Spans. The construction duration for Rehabilitation Option 1 would be shorter (7-8 years) as the extent of modifications would be less but the pace of construction would still be dictated by the need to maintain stability of the Main Spans while supporting the full traffic loading.

The duration for Rehabilitation Options 3 and 4 (6-7 years) would be less than that of Rehabilitation Options 1 and 2 as the superstructure modifications could be implemented in the absence of traffic. This would allow an increase in the number of work locations on the Main Spans that can be conducted simultaneously as more space would be available for the associated temporary construction activities required to maintain stability.

Construction duration for the Replacement Options varies from 5-6 years, including the time needed for removal of the existing TZB. The primary activity dictating the construction durations is the initial construction of one-half of the replacement TZB and the temporary relocation of traffic from the existing to the new structure. Differences in the construction duration among the three Replacement Options are a consequence of the number of cofferdams required, as their construction period is limited to certain months of the year.

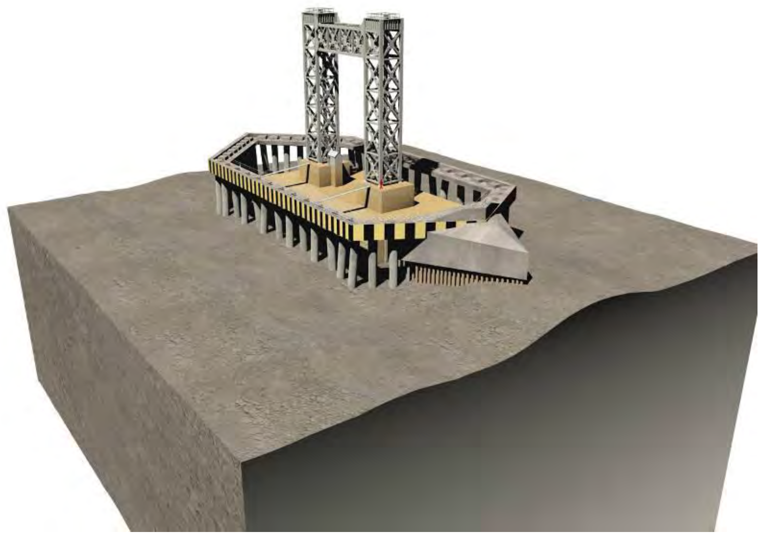
Traffic Disruption

The potential for traffic disruption is inherent in Rehabilitation Options 1 and 2. This is where extensive modifications are required to the deck and superstructure of the existing TZB. These construction activities would require regular closure of one or more of the existing seven traffic lanes primarily at night, and limited lane closures during the day, outside of peak traffic periods. Because of the complexity of some of the construction operations, some construction activities will require that all traffic lanes are closed for short periods (1-2 hours).

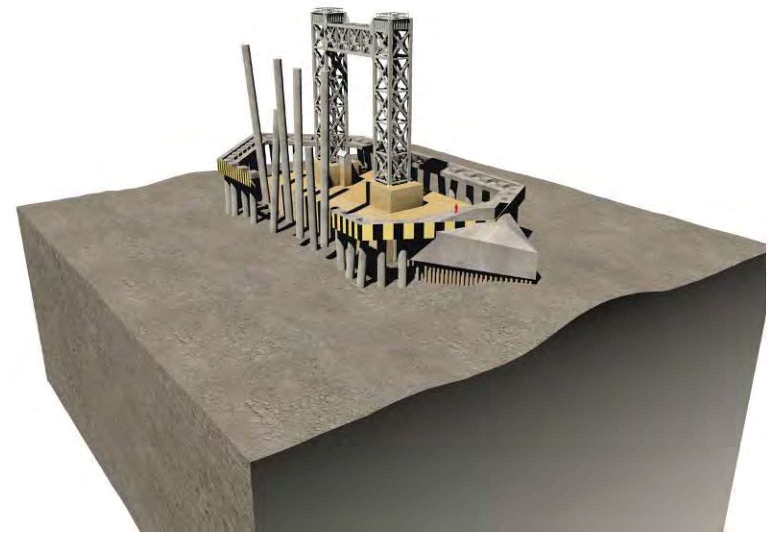
Because of the extent and complexity of the modifications to the Main Spans in Rehabilitation Option 2, there is a risk of possible closure of the full crossing for extended periods. This would be as a result of unpredictable or unwarranted movement of the structure due to the effects of construction activities. These potential risks and the overall potential for traffic disruption associated with the extended construction period are major disadvantages of this rehabilitation option.

In Rehabilitation Options 3 and 4, the inclusion of a new Supplemental Bridge allows all traffic to be moved from the existing TZB while the complex rehabilitation construction activities are completed. The reduction in overall traffic disruption and risk of closure are greatly preferred compared to Rehabilitation Option 2.

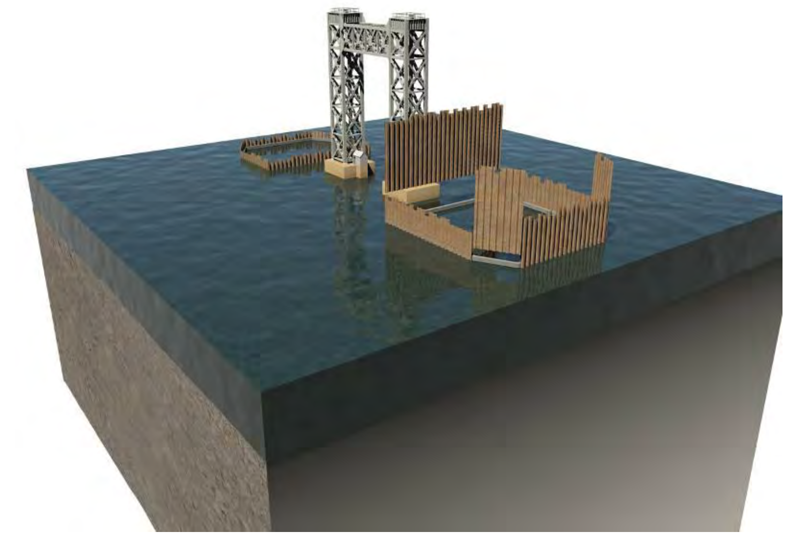
Similarly for the Replacement Options, no major traffic disruption, beyond that associated with regular maintenance and temporary construction during the transition between the new and existing bridges would result. Traffic would be maintained on the existing TZB in the existing configuration, while the replacement bridge was constructed. As soon as the northern half of the replacement structure was completed, all seven existing traffic lanes would be shifted on to the new structure.



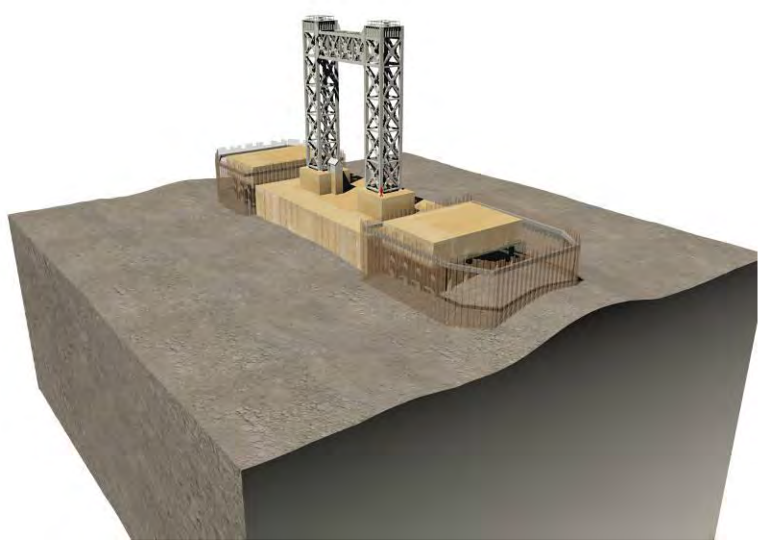
Stage 1: Existing Conditions



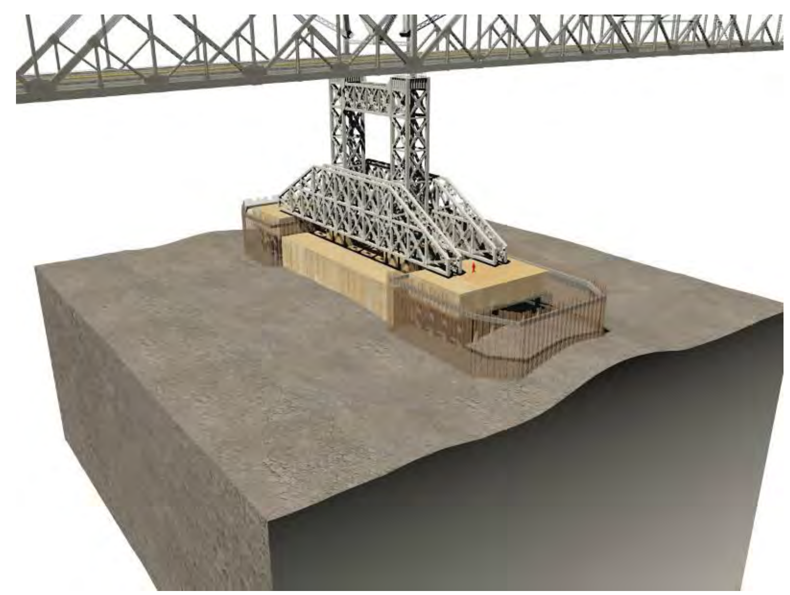
Stage 2: Remove Ship Collision Protection



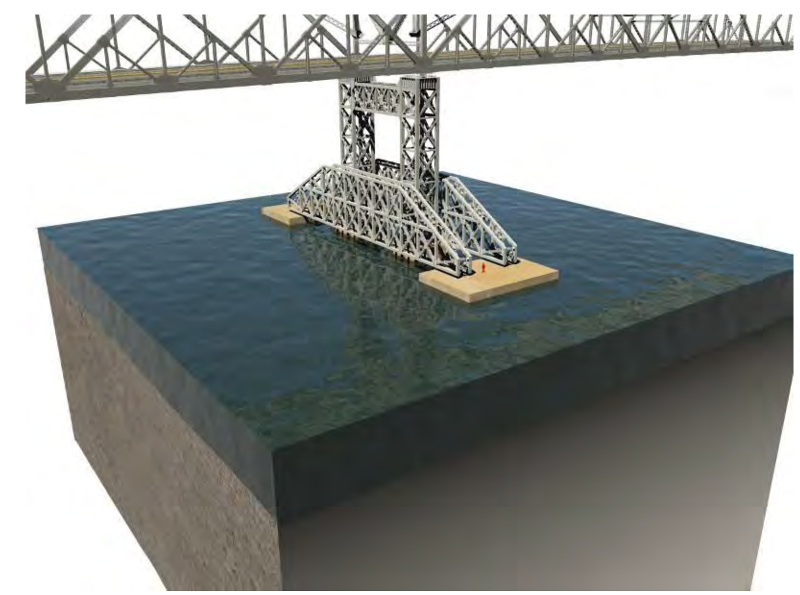
Stage 3: Install Cofferdams



Stage 4:Construct Additional Foundations

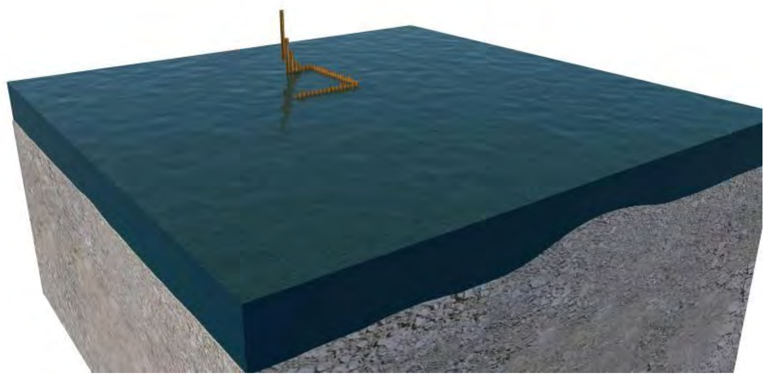


Stage 5: Connect Additional Foundations to Columns

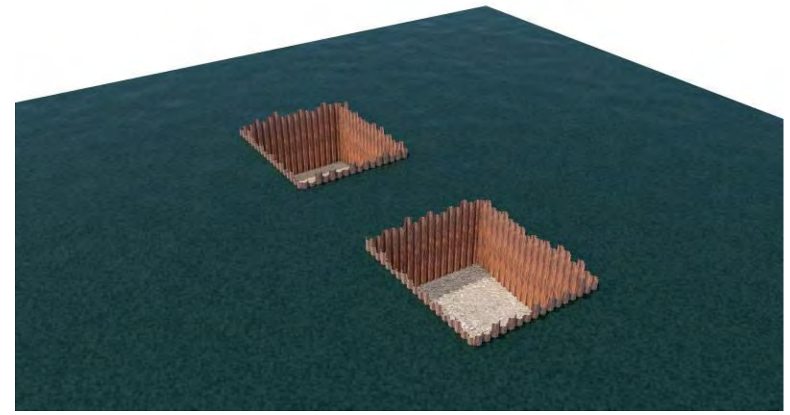


Stage 6: Remove Cofferdams and Buoyant Caisson

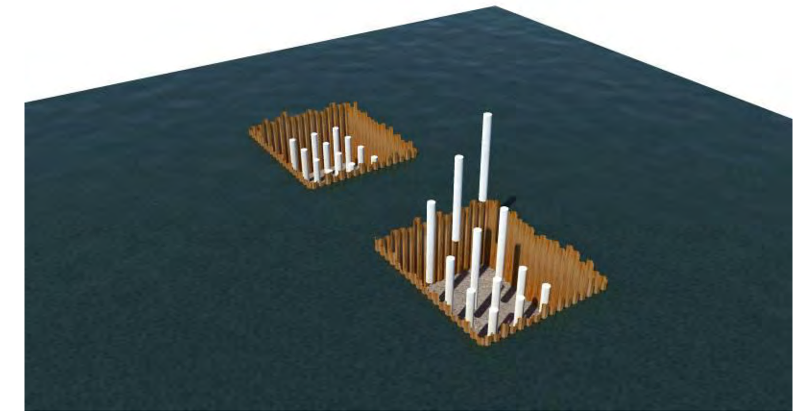
Figure 5-3
Rehabilitation Construction Sequence for Floating Caissons



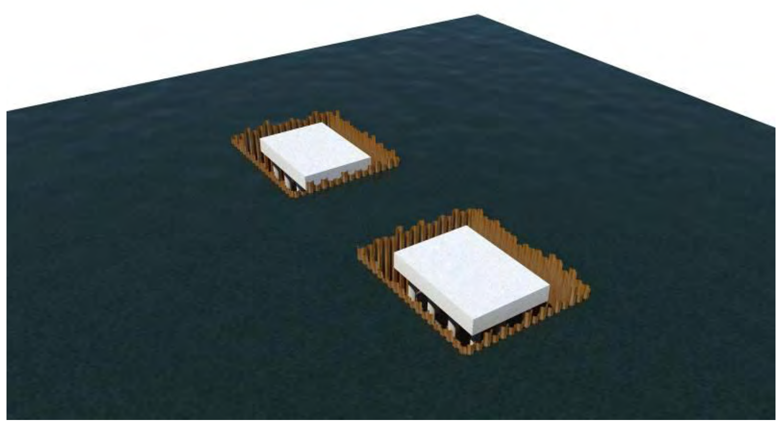
Stage 1: Install Cofferdams



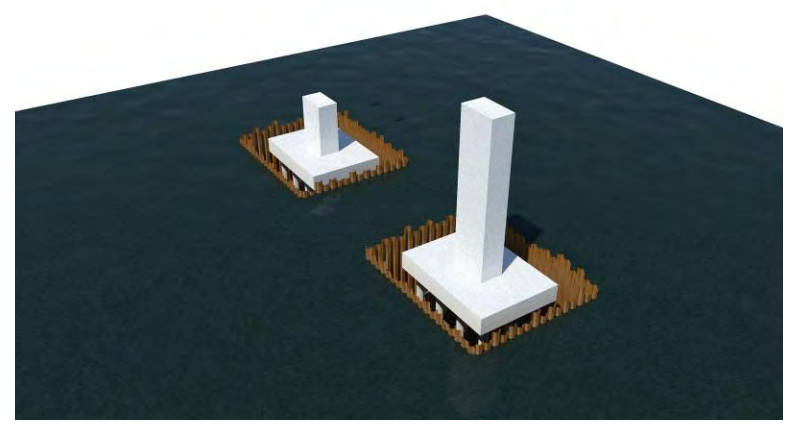
Stage 2: Pump Water from Cofferdams



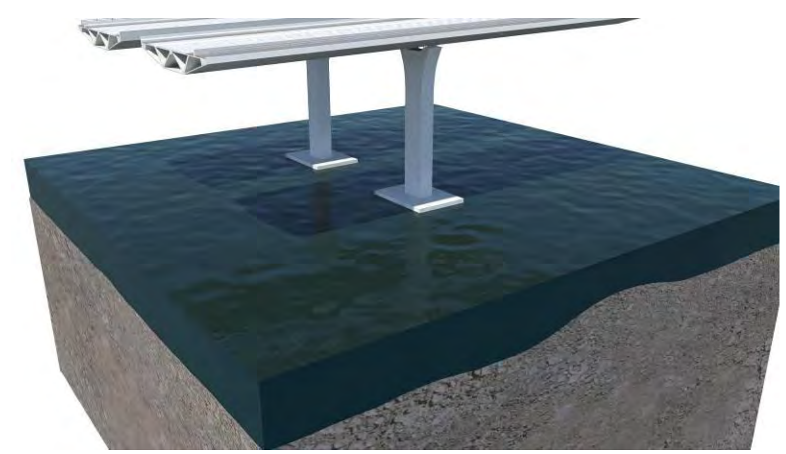
Stage 3: Install Piles



Stage 4: Construct Pile Cap



Stage 5: Construct Columns



Stage 6: Remove Cofferdams and Build Superstructure

Figure 5-4
Construction Sequence for Foundations & Sub-Structure of Replacement Bridges

River Impacts

The primary construction activities affecting river conditions and marine life result from the construction of new or expanded foundations, installation of temporary construction platforms and the removal of lead paint or asbestos from the existing TZB. These activities can cause resuspension of riverbed sediments and water vibrations. They can also introduce undesirable materials into the river environment affecting spawning and feeding grounds or fish migratory routes.

1. Sediment Containment

   To contain sediment disruption, all new or expanded foundations would be constructed within cofferdams. See Figure 5-5.

   For the Rehabilitation or Replacement Options cofferdams surrounding the foundations of the new structures would be constructed from special rigs floating on barges Each side of the cofferdam would be up to 100 feet long for each individual pier. For expansion of the foundations of the existing TZB, cofferdams would be constructed from under the TZB with particular attention to the limited head room. The largest foundations are at the Main Spans requiring cofferdams in excess of 400 feet to contain all the existing structures. Notable similarities or differences among the options include:

   - The extent of foundation construction in all options requires a major program of cofferdam construction extending over a number of seasonal construction windows, determined from the results of the ongoing marine survey and sediment dispersal assessments.
   - For Rehabilitation Options 3 and 4, the construction sequence would require two distinct periods for cofferdam construction – the first for construction of the Supplemental Bridge and second for the modifications to the existing TZB a number of years later.
   - For all the Replacement Options, two distinct periods of cofferdam construction are also required – the first for the construction of all replacement TZB foundations and the second for dismantling of the existing TZB Buoyant Caissons.
   - In the Rehabilitation Options, two cofferdams will be required adjacent to each of the eight Buoyant Foundations for construction of the replacement foundations. To allow the new foundations to be as close as possible to the existing piers, the existing ship protection will need to be demolished and the supporting piles removed to avoid conflicts (Figure 5-6, Page 52). New temporary ship protection measures will be required to protect the Buoyant Foundations during construction. Typical construction sequences for foundation construction are shown in Figures 5-3 and 5-4 (pages 49 & 50).

   In all options, all of the Buoyant Caissons are removed, either by demolition within cofferdams or by re-floating after the piles beneath are disconnected.

Figure 5-5
Cofferdams (Caltrans 2004)

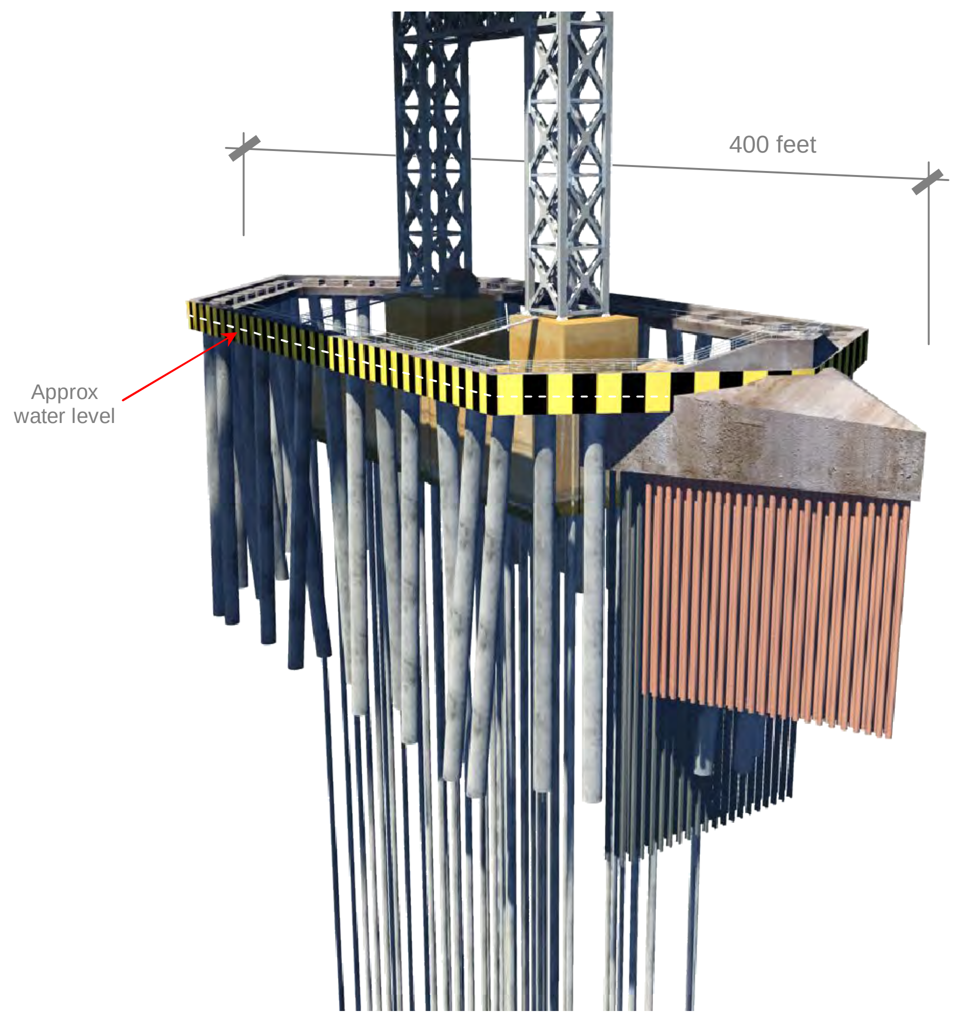


Figure 5-6

Existing TZB Foundation at the Main Spans (River and Riverbed Not Shown)

2. Acoustic Vibrations

   High-level acoustic exposures from pile installation can damage and/or kill fish. To limit vibrations, smaller diameter piles are desirable with additional mitigation techniques possible such as working within cofferdams.

3. Lead Paint Removal

   The existing bridge was originally painted with a lead based paint. Since construction, much of this paint has been removed as part of the NYSTA repainting schedule but lead paint still exists on parts of the Deck Truss and Main Spans.

   For all Rehabilitation Options, an extensive program of removal together with dust and particle containment is required to prevent existing paint from flaking and falling into the river. For all Replacement Options, all lead paint would be removed from the river environment with the removal of the existing TZB.

5.7.4 Summary

All options have major construction activities over the full crossing, including foundation enlargement or replacement, superstructure construction and landings reconfiguration. The impacts of these activities are:

- While Rehabilitation Option 1 supports substantially less deck width compared to other options (113 feet compared to 200-250 feet), its impacts, particularly river impacts, are comparable to all other options because of the extensive modifications required to the foundations and superstructure. Its construction duration is substantially longer than the Replacement Options with the potential for major traffic disruption and associated impacts during construction. Compared to other options, this option has the minimum impacts at the Westchester Landing.
- The construction impacts of Rehabilitation Option 2 are extensive and together with the risks associated with construction are considered sufficient to warrant elimination of this option when compared to the advantages of Rehabilitation Options 3 and 4. Major impacts include extensive river construction, the longest construction duration compared to other options (10-12 years) and the potential for ongoing traffic impacts and possible closure of the TZB.
- The extensive modifications required to the superstructure associated with Rehabilitation Options 1 and 2 and the resulting interaction between construction activities and traffic operations are in conflict with project goals to minimize adverse impacts.
- Rehabilitation Options 3 and 4 are recommended over Rehabilitation Option 2. The introduction of a Supplemental Bridge in both options substantially reduces conflicts between the construction activities and traffic operations. Construction duration is estimated at 6-7 years, taking advantage of the Supplemental Bridge to simplify construction activities on the existing TZB. Because of the wide separation between the existing and Supplemental Bridges, the number of cofferdams required is the largest of all options (see Table 5-9, page 47). The overall area of the river affected by construction activities is therefore also maximized (see Table 6-3, page 64).
- The Replacement Options have shorter construction durations (5-6 years) compared to the Rehabilitation Options. The number of cofferdams required is less than that for the comparable rehabilitation modal options, and traffic impacts are minimized.

5.8 Life Span

The life span of bridges is a function of the life span of their components, including steelwork, joints and bearings among others. No component lasts forever. Life spans can range from as low as 5-10 years for some types of deck joints to up to 100 years for steelwork and concrete that is adequately protected. To ensure a long life span for a bridge, a full program of maintenance, repair and replacement is necessary based on component inspections and expectations. As such, the life span of a bridge is the decision of the owner/operating agency that controls the maintenance regime. However, as bridges age, the rate of component repair and replacement can be unsustainable with extensive maintenance activities affecting overall traffic operation.

The current *AASHTO Design Specification* for highway bridges references a 75-year life span for standard bridges. For bridges of the scale of the TZB, the owner agency would be expected to prepare a life cycle plan. This plan would include a cost-benefit analysis for the various components and their expected life spans.

Among the operating criteria established by the NYSTA, the owner operator of the TZB, is the requirement for no major component replacement in the first 100 years in any of the Rehabilitation or Replacement Options. For the purposes of this report, maintenance and repair programs as well as consequent costs for each option have been developed to sustain the various crossing forms for 150 years..

Substantial sections of the existing TZB would be replaced in each of the Rehabilitation Options, including the 8,379-foot long Causeway. In the remaining 8,200 feet, major components will be fully replaced (for example the highway deck, joints, bearings and drainage system) or will be substantially replaced or modified (foundations). While many components are new and would be expected to have a life span akin to a new bridge, the retained details of the TZB and the interaction with other components would affect these new components' life spans.

5.8.1 Comparison of Rehabilitation and Replacement Options

Highway Deck
In the Rehabilitation Options, replacement of the highway deck on the remaining segments is anticipated. The deck type would differ from that used in the Replacement Options, because of the limits on the overall load carrying capacity of the existing TZB. The deck, particularly in the Deck Truss Spans, would be of lighter material, thinner and with fewer protective layers above the deck. A deck life span of up to 50 years would be expected before substantial areas would need to be replaced.

In the Replacement Options, the highway deck would be comprised of normal weight, full thickness concrete with the potential for multiple layers of waterproofing and protection, to extend the deck lifespan to 100 years or more.

Steelwork
The steelwork sections on the existing TZB are comprised of built up individual steel plates with many holes that were originally intended to reduce the overall weight of the TZB. These holes have allowed salt water spray and deck run-off (including de-icing salts) to penetrate inside the steelwork sections, into the areas between plates and deep into the complex connections of the main trusses.

Although substantial repairs have been conducted, with further repair included in the initial modifications in any of the Rehabilitation Options, the need for steelwork repairs and continued inspection would continue. To arrest the rate of deterioration of the steelwork, the open drains at each side of the highway deck would be modified to prevent outwash on the steelwork below.

Due to the continued presence of steelwork openings, difficult access for painting and the potential for standing water on the steelwork, increased levels of corrosion may be expected in the Rehabilitated Options. Replacement Options will not have these types of corrosion susceptible details.

Should steel be the primary structural component of the Replacement Options, as is common with many modern bridges, closed steel sections would be used and a dehumidification system could be installed. This system would reduce and mitigate the ingress of water, a necessary component of corrosion. The outside of the steel sections would be painted with multiple layers of protection, with easy access for inspection and repainting.

Concrete Piers

The concrete piers supporting the deck truss spans would be retained in the Rehabilitation Options. These piers have been subject to extensive repairs in the last 20 years with substantial quantities of concrete removed and replaced. The source of this deterioration has included:

- Run-off of the de-icing salts from the highway deck above through the open joints and open drains. These salts fell onto the tops of the piers and were blown over the full height of the piers
- Ingress of seawater at the base of the piers where cracking of the concrete has occurred over time

While modifications to existing joints, drainage and corrosion protection systems as well as concrete repair would be part of the Rehabilitation Options, residual chlorides would be expected to still reside in the concrete. These residues would result in shortened repair cycles. In addition, failure of the waterproofing of the deck movement joints above the piers would be expected, with the potential for continued leakage of de-icing salts on to the top of the piers.

Another factor that will affect the life-cycle of the piers and the repair and maintenance requirements is carbonation of the existing concrete. As concrete ages, the presence of carbon dioxide in the air increases the depth of carbonation from the surface of the concrete. When the depth of carbonation reaches the reinforcement, the protection provided by the concrete to the steel reinforcement is exhausted, and the presence of any water and oxygen results in corrosion.

For the Replacement Options, the number of joints in the deck above would be substantially reduced to 4-5 (compared to the original 200). The drainage systems would be contained and the concrete design would take advantage of modern technologies to extend service life.

5.8.2 Summary

Overall, the life span of many of the components of the existing TZB that would be retained in the Rehabilitation Options would be less than that for the same components in the Replacement Options. While the life span of all options can be extended, more extensive repairs and shorter maintenance cycles would be expected in the Rehabilitation Options. It is expected that some components in the Rehabilitation Options would require major repair or replacement within 100 years conflicting with the objectives of the NYSTA.

5.9 Compliance with Design Criteria

Table 5-10 (page 54) compares the design of each of the Rehabilitation and Replacement Options for the TZB against the design criteria that were outlined in Chapter 2.3.4 of this report. As shown, all the options, except Rehabilitation Option 1 and 2, comply with these criteria. Rehabilitation Option 1 does not comply with lane widths and shoulders as the roadway remains the same as the existing TZB. For Rehabilitation Option 2, the vertical clearance over the CRT was limited to 17' 9".

	Element	Proposed Conditions on TZB & Approaches (from Table 2-1, Page 3)	Rehabilitation Option 1	Rehabilitation Option 2	Rehabilitation Option 3	Rehabilitation Option 4	Replacement Option 1	Replacement Option 2	Replacement Option 3
1	Design Speed	70 mph	Causeway – 70 mph Main Spans – 50 mph	70 mph	Eastbound – 50 mph Westbound – 70 mph	Eastbound – 50 mph Westbound – 70 mph	70 mph	70 mph	70 mph
2	Lane Width	12 ft	Causeway – 12 ft Main Spans – 10 ft	12 ft	12 ft	12 ft	12 ft	12 ft	12 ft
3	Shoulder Width	12 ft on both sides of travel way	Causeway – 12 ft both sides of travel way Main Spans – 0 ft	Causeway – 12 ft both sides of travel way Main Spans – 12 ft on one side of each split travel way	Causeway & new Main Spans – 12 ft both sides of travel way Existing Main Spans – 10 ft both sides of travel way	Causeway & new Main Spans – 12 ft both sides of travel way Existing Main Spans – 10 ft both sides of travel way	12 ft both sides of travel way	12 ft both sides of travel way	12 ft both sides of travel way
4	TZB Roadway Width	8 travel lanes, the approach roadway width	Causeway – 8 travel lanes Main Spans – 7 travel lanes (1 reversible lane)	8 GP Travel lanes 2 BRT/HOT lanes	8 GP Travel lanes 2 BRT/HOT lanes	8 GP Travel lanes 2 BRT/HOT lanes	8 GP Travel lanes 2 BRT/HOT lanes	8 GP Travel lanes 2 BRT/HOT lanes	8 GP Travel lanes 2 BRT/HOT lanes
5	Maximum Grade	Road - 3% CRT - 2%	3%	3%	Road - 3% CRT - 2%	New Crossing – 1.4% (CRT & Road)	3%	2% (CRT & Road)	1.78% (CRT & Road)
6	Horizontal Curvature	2500 ft or greater	2850 ft minimum	2850 ft minimum	2700 ft minimum	2700 ft minimum	2500 ft	2500 ft	2500 ft
7	Super-elevation Rate	6% max	6% max	6% max	6% max	6% max	6% max	6% max	6% max
8	Stopping Sight Dist.	>910 ft	>910 ft	>910 ft	>910 ft	>910 ft	>910 ft	>910 ft	>910 ft
9	Vertical Clearance	15 ft under Thruway 16'-6" over Thruway 23'-6" over CRT	15 ft under Thruway 16'-6" over Thruway 23'-6" over CRT	15 ft under Thruway 16'-6" over Thruway 17' 9" over CRT	15 ft under Thruway 16'-6" over Thruway 23'-6" over CRT	15 ft under Thruway 16'-6" over Thruway 23'-6" over CRT (TOFC)	15 ft under Thruway 16'-6" over Thruway 23'-6" over CRT	15 ft under Thruway 16'-6" over Thruway 23'-6" over CRT (TOFC)	15 ft under Thruway 16'-6" over Thruway 23'-6" over CRT (TOFC)
10	Pavement Cross Slope	2% max	2% max	2% max	2% max	2% max	2% max	2% max	2% max
11	Rollover	4% between lanes; 8% at EOT	4% between lanes; 8% at EOT	4% between lanes; 8% at EOT	4% between lanes; 8% at EOT	4% between lanes; 8% at EOT	4% between lanes; 8% at EOT	4% between lanes; 8% at EOT	4% between lanes; 8% at EOT
12	Structural Capacity	Road – HL-93, Rail-65,000lb axle load	Road – HL-93	Road – HL-93	Road – HL-93	Road – HL-93, Rail-65,000lb axle load	Road – HL-93	Road – HL-93, Rail-65,000lb axle load	Road – HL-93, Rail-65,000lb axle load
13	Control of Access	Full	Full	Full	Full	Full	Full	Full	Full
14	Pedestrian & Bicycle Path	north and south bridge paths, 15 ft (total width including rails	15 ft wide path on south side of crossing	15 ft wide paths on north & south side of crossing	15 ft wide paths on north & south side of crossing	15 ft wide paths on north & south side of crossing	15 ft wide paths on north & south side of crossing	15 ft wide paths on north & south side of crossing	15 ft wide paths on north & south side of crossing
15	Median Width	10 ft minimum	Causeway - Separate structures Main Spans – 2 ft (movable barrier)	Causeway - Separate structures Main Spans – 4 ft plus 12 ft shoulders	Varies, separate structures for each direction	Varies, separate structures for each direction	Varies, separate structures for each direction	Varies, separate structures for each direction	Varies, separate structures for each direction
16	Transit Provision	Provide Transit	No Transit	Dedicated BRT/HOT lanes	Dedicated BRT/HOT lanes	CRT and dedicated BRT/HOT lanes	Dedicated BRT/HOT lanes	CRT and dedicated BRT/HOT lanes	CRT and dedicated BRT/HOT lanes
17	Navigation Vertical Clearance	Minimum – 139 ft Desirable – 155 ft	139 ft	139 ft	139 ft	139 ft	155 ft	155 ft	155 ft

Table 5-10

Compliance with Design Criteria

5.10 Summary of Engineering Criteria

5.10.1 Structural Integrity

In the Rehabilitation Options, extensive modifications, strengthening and reconfiguration are required for the TZB to comply with the structural requirements of the *AASHTO Design Specifications* and the *NYSDOT Blue Pages*. While extensive, these changes will result in a bridge structure that generally complies with all current limit state requirements for service, fatigue and strength.

For the Rehabilitation Options, compliance with all requirements at the extreme event limit state is questionable because of the inherent nature of the truss structures used in the Deck Truss and Main Spans. Because of the lack of redundancy and extent of critical components, there is the potential for major damage in a number of deliberate event scenarios. Were such damage to occur, restoration of the crossing could take months to years to accomplish. The resulting traffic detours and associated disruption would have major effects upon the economies of the Mid-Hudson and New York City regions. As a critical link in the nation’s transportation infrastructure, this level of structural performance warrants security and other countermeasures to reduce the potential for and impact of the specific event scenarios.

In the Replacement Options, the replacement TZB would fully comply with the requirements of the current AASHTO and NYSDOT specifications and would comply with all current service, fatigue, strength and extreme events limit state requirements.

5.10.2 Vulnerability

The mitigation of risks/vulnerabilities associated with various event scenarios resulting from extreme events, either deliberate or accidental, is a major differentiator that favors the Replacement Options. While the risk/vulnerability framework for the Rehabilitated Options is improved over the existing conditions of the TZB, vulnerabilities will continue to be associated with the truss steelwork and overall steel details. These are core features of the crossing’s design and construction that could not be removed without its complete replacement.

5.10.3 Seismicity

For the Rehabilitation Options, retrofit of the TZB would be required to meet the current NYSDOT performance requirements. Retrofit requirements are extensive and difficult. They include:

- Replacement of all of the Buoyant Foundations with new foundations
- Strengthening of all other foundations
- Modification and strengthening of piers
- Modification and strengthening of superstructure steelwork
- Replacement of existing bearings with special isolation bearings

For the Replacement Options, seismic assessment indicates that a replacement bridge could meet current performance requirements with feasible foundation sizes and pile depths.

5.10.4 Redundancy

The layers of redundancy inherent in the Replacement Options reduce the likelihood, scope and scale of potential impacts when compared to the Rehabilitation Options. The period to recover full service after a single event is reduced from years with Rehabilitation to only weeks or months with the Replacement Options.

5.10.5 Emergency Response

The inclusion of shoulders in all options, with the exception of Rehabilitation Option 1, significantly improves emergency access and response. Emergency response in Rehabilitation Option 1 is subject to traffic congestion because of the absence of highway shoulders over approximately half of the crossing. In the event of full directional closure, access must be made from the opposing direction.

In Replacement Option 2 and Rehabilitation Options 3 and 4, emergency access between the parallel structures is difficult because of the differences in vertical elevation and horizontal separation.

5.10.6 Navigation Clearance

The measure for this criterion is the level of conformance to navigational requirements of the US Coast Guard, which currently controls the 600-feet wide and 139-feet high channel for shipping under the TZB. All Rehabilitation and Replacement Options would accommodate these minimum dimensions for shipping. The existing TZB provides the minimum 139-foot vertical clearance to the river. All Replacement Options allow for an increase to a 155-foot vertical clearance to allow larger ships to navigate the Hudson River.

5.10.7 Construction Impacts

All options have major construction activities over the full river width, including foundation enlargement or replacement, superstructure construction and landings reconfiguration.

While Rehabilitation Option 1 supports substantially less deck width compared to other options (113 feet compared to 200-250 feet for all other options), its impacts, particularly river impacts, are on a par with all other options because of the extensive modifications required to the foundations and superstructure. This option’s construction duration is substantially longer than the Replacement Options, with the potential for major traffic disruption during construction. Compared to other options, this option would have fewer impacts at the Westchester Landing.

The construction impacts of Rehabilitation Option 2 are extensive and together with the risks associated with construction are considered sufficient to warrant elimination of this option when compared to the advantages of Rehabilitation Options 3 and 4. Major impacts include extensive river construction, the longest construction duration compared to other options (10-12 years), and the potential for ongoing traffic impacts and possible closure. The extensive modifications required to the superstructure and the resulting interaction between construction activities and traffic operations are in conflict with project goals to minimize adverse impacts.

Rehabilitation Options 3 and 4 are recommended over Rehabilitation Option 2. The introduction of a supplemental structure in both options substantially reduces conflicts between the construction activities and traffic operations. Construction duration is estimated at 6-7 years, taking advantage of the Supplemental Bridge to simplify construction activities on the existing TZB. Because of the wide separation between the existing and Supplemental Bridges, the number of cofferdams required is the largest of all options. The overall area of the river affected by construction activities is therefore also maximized.

The Replacement options have shorter construction durations (5-6 years) compared to the Rehabilitation Options. The number of cofferdams required is less than that for the comparable rehabilitation modal options and traffic impacts are minimized.

5.10.8 Life Span

Overall, the life span of many of the components of the existing TZB that would be retained in the Rehabilitation Options, would be less than that for the same components in the Replacement Options. While the life span of all options can be extended, more extensive repairs and shorter maintenance cycles would be expected in the Rehabilitation Options. It is expected that some major components in the Rehabilitation Options would require major repair or replacement within 100-years, conflicting with NYSTA objectives.

5.10.9 Compliance with Design Criteria

All the Rehabilitation and Replacement Options, with the exception of Rehabilitation Option 1, comply with required design criteria.