TABLE OF CONTENTS – CONSIDERATIONS OF CLIMATE CHANGE AND COASTAL STORMS

CHAPTER 33

INTRODUCTION

It is the intent of this chapter to establish the practices and specific requirements of the Structure and Bridge Division for the design of structures for climate change and coastal storms.

Resiliency (or being resilient) as used in this chapter to describe highway bridges in Virginia shall be taken to mean the successful integration of transportation mobility, Sea Level Rise adaptation measures, and resistance to the extreme effects of coastal storms into design decisions at both the planning and project delivery levels.

References to AASHTO LRFD Specifications in this chapter refer to the AASHTO *LRFD Bridge Design Specifications* including current VDOT Modifications (IIM-S&B-80). References to AASHTO Guide Specifications in this chapter refer to the AASHTO *Guide Specifications for Bridges Vulnerable to Coastal Storms*.

The practices and specific requirements contained in this chapter have been established based on the Structure and Bridge Division's experience, industry standards and recommendations, research conducted by the Virginia Transportation Research Council (VTRC), Hampton Roads Hurricane Retrofit Study Phase 2 conducted on five bridges in VDOT's Hampton Roads District, and technological advancements made over the years.

Based on recommendations from the Virginia Institute of Marine Science and the Commonwealth Center for Recurrent Flooding Resilience, future projections for these events are based on the National Oceanic and Atmospheric Administration (NOAA) Intermediate-High scenario curve for the year 2070. This is in line with the Governor's Executive Order (EO) No. 24 followed later by EO No. 45, both of which aim to develop actions to help increase Virginia's statewide resilience to natural hazards and extreme weather.

The practices and requirements set forth herein are intended to supplement or clarify the requirements of the AASHTO LRFD Specifications and AASHTO Guide Specifications, and to provide additional information to assist the designer. In the event of conflict(s) between the practices and requirements set forth herein and those contained both in the AASHTO LRFD Specifications and AASHTO Guide Specifications, the more stringent requirements shall govern.

NOTE:

Due to various restrictions on placing files in this manual onto the Internet, portions of the drawings shown do not necessarily reflect the correct line weights, line types, fonts, arrowheads, etc. Wherever discrepancies occur, the written text shall take precedence over any of the drawn views.

GENERAL INFORMATION:

The need to adapt the U.S. infrastructure to accommodate the changing climate has become increasingly evident to scientists, legislators, government agencies, and communities. Among the predominant concerns are the effects of rising sea levels and increasing precipitation frequencies and intensities. In coastal states such as Virginia, sea-level rise (SLR) can also affect the salinity gradient, moving water with high concentrations of salt farther inland.

Climate scientists describe Virginia as a “hotspot” for sea-level rise, largely because of subsidence from glacial isostatic adjustment, groundwater extraction, and sediment compaction and changes to ocean currents. Salinity in the Chesapeake Bay and its tributaries will be affected by rising sea levels, increasing salinity concentrations farther inland. Projections by climate researchers also indicate a continuing rise in temperature and increases in the severity and intensity of precipitation events in the region.

These events have the potential to negatively affect commerce and the public. The Structure and Bridge Division is taking proactive steps to mitigate the risk of these events to bridges. The AASHTO LRFD Specifications defines the Design Life for a bridge to be the period of time (75 years) on which the statistical derivation of transient loads is based. With VDOT’s incorporation of corrosion resistant and corrosion free materials; low cracking and low permeability concrete; and sound maintenance measures, the Service Life is anticipated to exceed 100 years.

With the Service Life exceeding 100 years and the expectation of continual environmental changes the S&B Division requested the Virginia Transportation Research Council (VTRC) to provide information to help guide decisions regarding the design of more climate-resilient bridges given the predicted impacts of climate change. The specific information of interest was (1) how national and state transportation organizations have responded to the changing climate with regard to road infrastructure design decisions, and (2) climate change projections in Virginia for SLR, salinity in the tributaries to the Chesapeake Bay, precipitation, and temperature.

Using the information gathered from Virginia climate projections and transportation organizations, the study offers guidance for choosing a climate-based approach for bridge design, including projection-based recommendations for design standards.

The Structure and Bridge Division identified the following four factors that may affect bridges:

- Temperature Change
- Salinity
- Precipitation or Rainfall Intensity
- Sea Level Rise (SLR)

Several new terminologies pertaining to climate change will be used in this chapter.

The Representative Concentration Pathways (RCP) are widely used in the climate change themes. RCPs are the scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases, and aerosols and other chemically active gases, as well as land use/land cover. The word "representative" signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing (RF) characteristics.

GENERAL INFORMATION (cont'd):

The term "pathway" emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome. Radiative forcing (RF) is a measure of the net change in the energy balance of the Earth system in response to some external perturbation.

RCPs usually refer to the portion of the concentration pathway extending up to the year 2100. Four RCPs are commonly used (W/m^2 represents Watts per square meter):

- RCP2.6, a pathway where radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines;
- RCP4.5 and RCP6.0, two intermediate pathways in which radiative forcing is stabilized at approximately 4.5 W/m^2 and 6.0 W/m^2, respectively, after 2100;
- RCP8.5, a high pathway for which radiative forcing reaches greater than 8.5 W/m^2 by 2100 and continues to rise for some amount of time.

Some studies for SLR are based on so-called six representative Global Mean Sea Level (GMSL) scenarios that range from a low-end (Low) scenario of 0.3 m (1.0 foot) to a worst-case (Extreme) scenario of 2.5 m (8.2 feet) by 2100. Between these two scenarios, there are Intermediate-Low (0.5 m or 1.64 feet), Intermediate (1.0 m or 3.28 feet), Intermediate-High (1.5 m or 4.92 feet) and High (2.0 m or 6.56 feet) scenarios.

The Low and Extreme scenarios represent the scientifically plausible lower and upper bounds on 21st century GMSL rise, respectively; the remaining four scenarios (from Intermediate-Low to High), while simply placed at 0.5-m intervals, can be shown to correspond to different likelihood levels under RCP2.6, RCP4.5, and RCP8.5, as shown in the following table (from NOAA, Technical Report NOS CO-OPS 083) (see list of references).

GMSL Scenario	**RCP2.6**	**RCP4.5**	**RCP8.5**
Low (1.0 ft)	94%	98%	100%
Intermediate-Low (1.64 ft)	49%	73%	96%
Intermediate (3.28 ft)	2%	3%	17%
Intermediate-High (4.92 ft)	0.4%	0.5%	1.3%
High (6.56 ft)	0.1%	0.1%	0.3%
Extreme (8.2 ft)	0.05%	0.05%	0.1%

For instance, in 2100 the Low scenario has a 94% to 100% chance of being exceeded under RCP2.6 and RCP8.5, respectively, whereas the Extreme scenario has a 0.05% to a 0.1% chance of being exceeded.

GMSL scenarios are the baselines for the scenarios of the local relative sea level in Virginia which are illustrated in File No. 33.01-6 and -7.

TEMPERATURE CHANGE:

Currently, temperature projections are not available specifically for Virginia. However, regional temperature projections created by the Fourth National Climate Assessment (Vose et al., 2017) show an increase in southeast regional temperature trends well into the year 2100.

The annual average temperature of the southeast regional states is projected to rise throughout the century. Increases for the year 2100 relative to 1976–2005 (can be treated as current) are projected to be about 4.43°F for a lower scenario (RCP4.5) and 7.72°F for the higher scenario (RCP8.5).

It is also projected that by year 2065 in the southeast region, the coldest day of the year will see an increase of 4.97°F and warmest day of the year is expected to see an increase of 5.79°F.

For bridge design, VDOT specifies the temperature range 0°F to 120°F for steel or aluminum, and 0°F to 80°F for concrete. Since temperatures on the coldest and warmest days are projected to increase at similar rates, the temperature range for bridge design needs no adjustment at this point.

SALINITY:

Climate change may increase the intrusion of salty and brackish water up the rivers and streams in the Chesapeake Bay area. The salinity gradient is affected by salt water input from the Atlantic Ocean and freshwater from various rivers flowing into the Bay, most notably the Potomac, Rappahannock, York and James. These inputs have naturally worked in opposition to each other, moving the salinity gradient up and down the bay with the changing of seasons. As climate change continues to have an impact on SLR and precipitation, this natural balance will be affected.

These factors affect VDOT's decisions with regard to the use of corrosion resistant materials. Currently, VDOT uses the borderline between fresh water and salt water to determine whether corrosion resistant materials in prestressed concrete piles are used or not.

VTRC (2018) studies suggested that the long-term predictions for salt water intrusion would shift the borderlines between fresh water and salt water in the rivers and streams that feed into the Chesapeake Bay from 8.5 miles to 11.2 miles farther inland by year 2100. Although these projections do not take into account changes in freshwater discharges because of changes in precipitation, the borderline for the use of corrosion resistant strands in prestressed concrete piles is adjusted based on the VTRC (2018) research (see the map in File No. 12.08-2).

RAINFALL INTENSITY AND DISCHARGE:

Climate change will affect rainfall intensity and discharge. As the air temperature rises, the capacity of the air to hold water vapor will increase. As a result, the frequency and intensity of storms will increase.

VTRC (2019) research suggested that there has been a consistent increase in rainfall intensity and discharge at the rainfall stations across the Commonwealth. There was a large variability in increases across these stations, however no apparent spatial trend was found in the records. Considering VTRC's research results and simplifying the design process, a 20% increase in rainfall intensity and a 25% increase in discharge shall be used in design of bridges. For design of culverts, refer to the Location and Design Guidance.

Not accounting for increases in rainfall intensity or discharge could have undesirable effects. For instance, under-design of deck drainage may cause a safety issue and underestimating discharge may cause washout of bridges.

Based on increased rainfall intensity and discharge, the following design parameters shall be adjusted.

- Deck drainage – the design storm intensity values from File No. 22.01-10, including actual rainfall intensity (in accordance with the VDOT Drainage Manual), shall be increased by 20%.

- Scour – the 200 year flood event shall be used for scour analysis.

- Stream pressure – the design velocity of water shall be based on the 200 year flood event.

- Buoyancy – the 200 year flood event for calculation of buoyancy.

Note: The 200 year flood event approximately corresponds to a 25% increase in discharge over the present-day 100 year flood event (which does not account for climate change).

The designer should consult with the hydraulics engineer to address impacts due to increased rainfall intensity and discharge.

If a project has constraints and cannot meet the above requirements, a design waiver must be submitted to the State Structure and Bridge Engineer. The identified factors in File No. 33.01-9 may be discussed in the design waiver.

SEA LEVEL RISE (SLR):

Climate change will cause sea level to rise globally. Virginia and other states along the East Coast have begun to experience rates of SLR higher than the global projected average.

Virginia Executive Order 24 (2018) states "studies show that water levels in the Hampton Roads region are now 18 inches higher than they were a century ago, and that they are expected to gain up to five more feet, …, by 2100."

Significant research on SLR has been conducted to predict SLR. The following three models cited by the VTRC account for variables specific to the coast of Virginia:

- Kopp et al. (2014)
- National Oceanic and Atmospheric Administration (NOAA) (2017)
- Virginia Institute of Marine Science (VIMS) (2013 and 2017)

The three models provide a wide range of projections (1.2 feet to 12 feet) for local SLR along the coast of Virginia. It is plausible to assume that SLR by 2100 in Virginia would be in the range of 4 feet and 7 feet. This range is the recommendation received from the Virginia Transportation Research Council in its white paper entitled *"CONSIDERATIONS FOR INTEGRATING CLIMATE ADAPTATION MEASURES INTO VDOT STRUCTURE DESIGN DECISIONS"* dated September 2018.

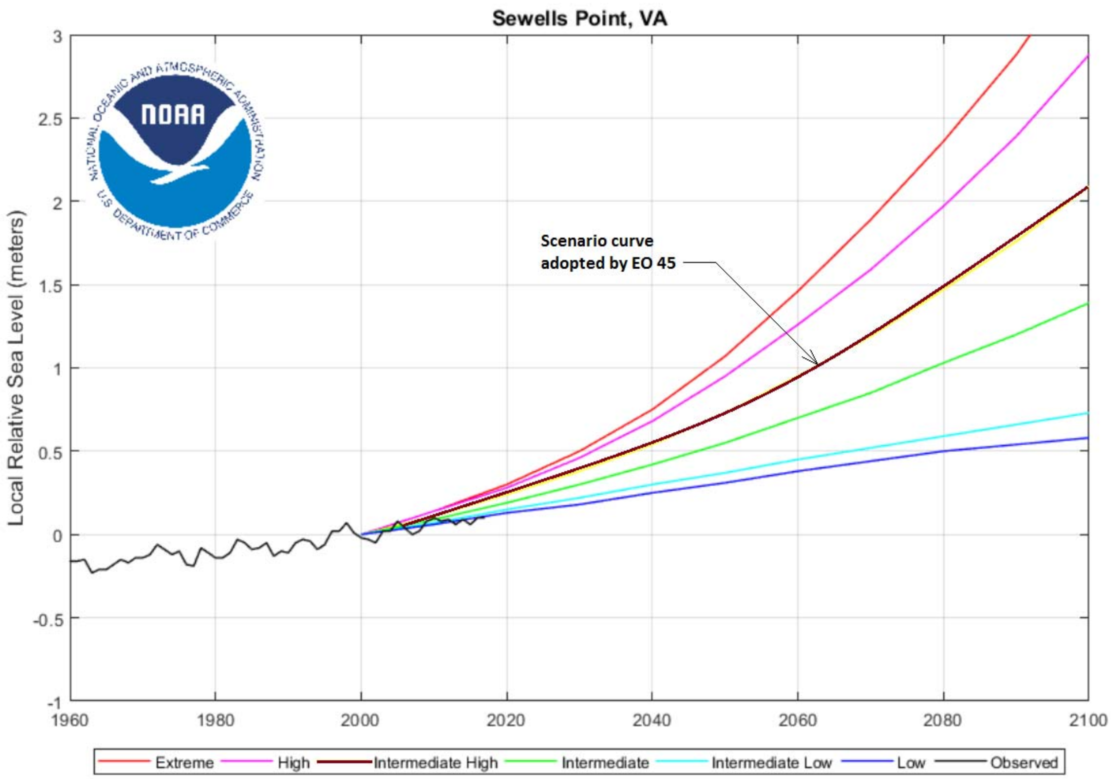
Virginia Executive Order 45 (2019) states "Based on recommendations from the Virginia Institute of Marine Science and the Commonwealth Center for Recurrent Flooding Resilience, the Commonwealth shall use the National Oceanographic and Atmospheric Administration (NOAA) Intermediate-High scenario curve, last updated in 2017, as the state standard for predicting sea level rise." It also says "When scoping, designing, siting, and constructing state-owned buildings, a 50-year mid-life estimate for building longevity shall be used, which, under the NOAA Intermediate-High scenario curve, last updated in 2017, equates to nearly four (4) feet of sea level rise by 2070."

The Structure and Bridge Division will use the NOAA Intermediate-High scenario curve as the state standard for predicting Sea Level Rise.

Since the design life of bridges is 75 years and their service life is to be greater than 100 years, a 50-year mid-life estimate for service life is to be used, which, under the NOAA Intermediate-High scenario curve, last updated in 2017, equates to nearly four (4) feet of sea level rise by 2070. Therefore, 4 feet of SLR shall be used for the design of bridges to mitigate the risks SLR will have on the operation and safety of these critical infrastructure elements.

The following chart shows the NOAA's Annual Mean Relative Sea Level since 1960 and regional scenarios at the Sewells Point station.

SEA LEVEL RISE (SLR) (cont'd):



The NOAA SLR curve referenced in Executive Order 45 may be found by clicking Regional Scenarios at https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8638610. The link is for Sewells Point.

There are four stations that have these kind of data in Virginia: Sewells Point (Station ID 8638610), Chesapeake Bay Bridge Tunnel (Station ID 8638863), Kiptopeke (Station ID 8632200), and Wachapreague (Station ID 8631044). The scenario curves for all four stations are similar (local relative sea level in year 2070 for the Intermediate-High scenario curve for all four stations is around 1.25 meters, which corresponds to approximately 4 feet).

BRIDGE DESIGN CONSIDERATIONS OF SEA LEVEL RISE (SLR):

SLR will affect the design of bridges in many ways along coastal Virginia. Bridges in the following areas may be directly affected by SLR:

Counties: Accomack, Caroline, Charles City, Chesterfield, Essex, Fairfax, Gloucester, Hanover, Henrico, Isle of Wight, James City, King and Queen, King George, King William, Lancaster, Mathews, Middlesex, New Kent, Northampton, Northumberland, Prince George, Prince William, Richmond, Southampton, Spotsylvania, Stafford, Surry, Westmorland, and York.

Cities: Alexandria, Arlington, Chesapeake, Colonial Heights, Franklin, Fredericksburg, Hampton, Hopewell, Newport News, Norfolk, Petersburg, Poquoson, Portsmouth, Richmond, Suffolk, Virginia Beach, and Williamsburg.

Bridge projects that are not in the above areas do not need to consider SLR.

Bridge projects in the above areas must account for SLR if either:

Case 1: The bridge crosses tidal waters
Case 2: The bridge crosses waters that will become tidal assuming 4 feet of SLR

The determination of whether a waterway is tidal (or will become tidal) is made by the hydraulics engineer. Mean High Tide (MHT) for a specific project location will not be necessarily increased by 4 feet because of 4 feet of SLR. The hydraulics engineer will provide a current MHT elevation and future MHT for bridges in Case 1, and a future MHT for bridges in Case 2.

The NOAA websites provide some information of SLR that may be used for estimating the impact of SLR to the project in the preliminary phase.

The NOAA SLR Viewer at https://coast.noaa.gov/digitalcoast/tools/slr may be used to visualize community-level impacts from SLR.

SLR's Effects on Layout and Profile of Bridges:

SLR shall be considered during pre-scoping. For example, shifting a roadway alignment along with a bridge to a higher elevation location may be a cost effective way to address SLR.

When accounting for SLR:

- The low chord must be at least 2 feet above the future MHT (the 2' clearance allows for bridge inspection).

BRIDGE DESIGN CONSIDERATIONS OF SLR (cont'd):

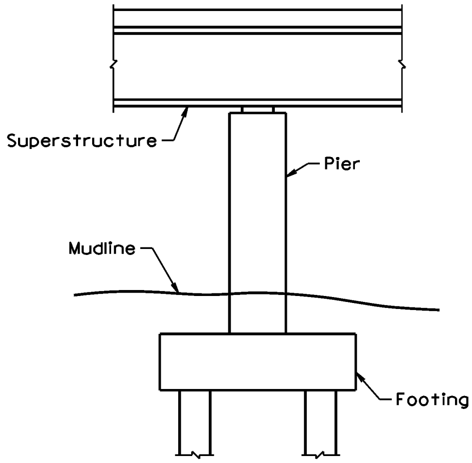
The requirement to account for 4 feet of SLR may be adjusted based on specific project conditions with an approved design waiver from the State Structure and Bridge Engineer. The adjustment may include reducing the future MHT or using an alternative design. Considerations will include potential SLR impacts, level of risk and potential consequences to the entire transportation system and community life. The following table lists factors that may affect the adjustment of the future MHT and may be discussed in a design waiver.

	Factors	**Towards using future MHT considering 4 feet of SLR**	➡	**Towards adjusting future MHT**
1	Redundancy/alternative route(s)	No redundant/alternative route		Redundant/alternative route
2	Anticipated travel delays	Substantial delays		Minor or no delays
3	Goods movement/interstate commerce	Critical route for commercial goods movement		Non-critical Route for commercial goods movement
4	Evacuation/emergencies	Vital for emergency evacuations; loss of route would result in major increases to emergency response time		Minor or no delay in the event of an emergency or evacuation
5	Environmental constraints	Minor or no increase in project footprint		Substantial increase in project footprint
6	Expenditure of public funds	Project is large investment		Project is small investment
7	Scope of project: point versus linear	Project scope is substantial e.g. new section of roadway		Project scope is not substantial e.g. bridge only project and not feasible to raise roadway
8	Effect of incorporating SLR on non-state highway (interconnectivity issues with local streets and roads)	Minor or no effect – adjacent local street and roads would not have to be modified		Substantial interconnectivity issues
9	Complexity of bridge project	High e.g. movable bridges		Low e.g. bridge only, conventional bridge replacement
10	Navigable routes	Yes		No
11	Project type	New construction		Maintenance

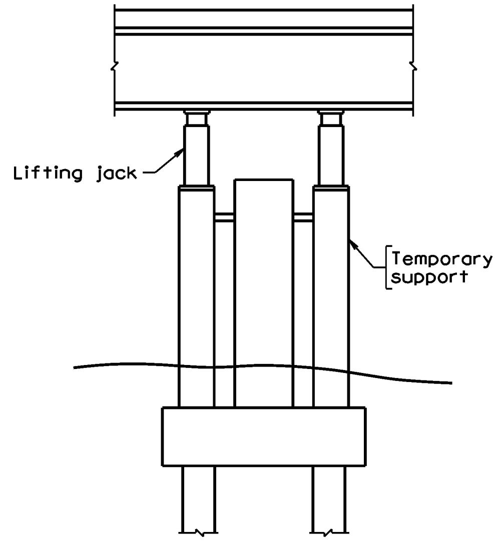
If a project has constraints that do not allow the low chord to account for 4 feet of SLR, a concept called "planned modification" may be considered. Use of this concept requires an approved design waiver from the State Structure and Bridge Engineer. As the following sketches illustrate, bridge elements must be designed to allow raising the superstructure and for:

- current conditions
- future conditions that account for 4 feet of SLR (the freeboard requirement in File No. 33.01-8 and structural requirements in File No. 33.01-11)

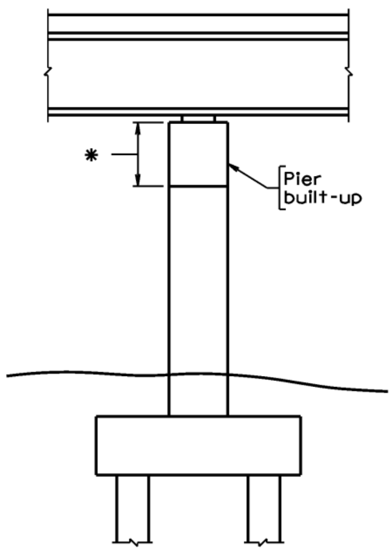
BRIDGE DESIGN CONSIDERATIONS OF SLR (cont'd):



Constructed at Current Grade



Raise Superstructure in Future



* Amount needed in order to meet the freeboard requirement in File No. 33.01-8

Reset Superstructure

Planned Modification

BRIDGE DESIGN CONSIDERATIONS OF SLR (cont'd):

SLR's Effects on Structural Design of Bridges:

SLR may not only increase the Mean High Tide (MHT) but also extend or broaden the stream channels. The structural elements shall be designed for the following forces both with and without considering 4 feet of SLR as well as other applicable loads.

- Vessel collision force
- Water load including: static pressure, buoyancy, stream pressure and wave force

Vessel collision force shall be applied considering both current conditions and conditions with 4 feet of SLR. Some bridge elements that currently do not have vessel collision risk may have such risk with 4 feet of SLR.

Static pressure of water shall be assumed to act perpendicular to the surface of the structural element. Pressure shall be calculated as the product of height of water above the point of consideration and the specific weight of water. Design water levels shall be based on both current conditions and conditions with 4 feet of SLR.

Buoyancy shall be considered to be an uplift force, taken as the sum of the vertical components of static pressures as specified above acting on all components below design water level considering current conditions and 4 feet of SLR.

The pressure of flowing water acting on substructures shall consider current conditions and 4 feet of SLR.

The effect of coastal storms on bridges shall be calculated in accordance with File 33.02, which includes 4 feet of SLR.

SLR may affect the design of abutments and riprap, erosion, slope stability and selection of materials or structure types (for example, MSE walls), etc. The designer should consult with the hydraulics engineer for potential impact of SLR.

ENVIRONMENTAL COORDINATION AND POTENTIAL IMPACTS:

The intrusion of salinity up rivers and streams may result in migration of endangered aquatic species (e.g. sturgeon) further inland to areas where, historically, they have not been present. Species (and associated essential habitat) coordination and associated mitigation of project impacts will take time and may increase project costs. For example, additional hydroacoustic assessments and underwater noise mitigation (e.g., air bubble curtain systems) for underwater construction activities such as pile driving may be necessary to address sturgeon impacts in areas of increasing salinity.

Accommodating increased rainfall intensity or discharge may result in additional environmental impacts, which may escalate project costs and affect project schedules. Projects affected by SLR could require a larger footprint for analysis in the context of the National Environmental Policy Act and the Clean Water Act. Balancing the resulting potential environmental impacts (historic properties, threatened and endangered species, wetlands, streams, critical habitat, noise, etc.) with resiliency objectives is important to effectively manage project budgets and schedules. Early coordination with environmental staff is necessary to address these issues. This early coordination will allow the project team to consider strategies to minimize environmental impacts, such as:

- Reducing roadway fill width by considering retaining walls, stabilized slopes, reduced shoulder widths, or other width reduction methods.
- Modification of proposed alignment to avoid and minimize encroachment on protected resources.
- Avoidance and minimization of in-stream piers.
- Consideration of clear-spanning a channel to minimize impacts on aquatic passage.
- Reduction in riprap slope protection along abutments (if possible).

In general, a larger project footprint also may have an impact on noise mitigation requirements. For example, higher bridges and an extension of the roadway construction limits could require more noise barriers, resulting in increased project costs. Higher bridges could affect noise propagation and directly lead to an increase in noise-impacted sites within the project area, which could require additional noise barriers. In addition, an extension of the roadway construction limits would directly extend the noise project area (i.e., within 500 feet) that would need to be evaluated for noise impacts, and additional noise mitigation beyond 500 feet could also be required if neighborhood continuity exists.

GENERAL INFORMATION:

Coastal storms have the potential to cause significant damage to bridges in coastal areas. The bridge designer and hydraulics engineer work together to determine if coastal storm design is applicable. The hydraulics engineer is responsible for determining: the FEMA flood zone in which the bridge is located; if a bridge location is subject to storm surge; and the wave height a bridge is subjected to (if needed). The bridge designer must request this information at the project scoping phase.

Bridges in the following locations shall consider coastal storms.

- Bridges located in FEMA flood zone VE and between zones VE (including new or full replacement, superstructure replacement or maintenance projects)

- Bridges located in FEMA flood zone AE that are subjected to storm surge (not including superstructure replacement or maintenance projects)

Bridges that are not located in the above areas do not need to consider coastal storms.

If a bridge is partially located in the above areas, coastal storm design is only applicable to the portion in the area plus one adjacent span.

> Note: Wave heights in flood zone VE are 3 feet or higher. Flood zone V shall be treated the same as flood zone VE. Both are areas along the coastline subject to inundation by the 100-year flood event with additional hazards associated with storm-induced waves. For V flood zones, detailed hydraulic analyses have not been performed, therefore base flood elevations and storm depths are not available (unlike VE zones).

- <u>For new and full replacement bridges</u>, 4 feet of Sea Level Rise (SLR) shall be taken into account when assessing the flood zone and wave heights

- <u>For superstructure replacement and maintenance projects</u>, SLR does not need to be taken into account

Based on current FEMA flood zone maps (https://msc.fema.gov/portal/home), the hydraulics engineer can determine if a bridge is currently in flood zone VE. However, since FEMA flood zone maps accounting for SLR are not available, the hydraulics engineer may need to perform a level II hydrodynamic analysis (see File No. 33.02-8 for the details of Level II hydrodynamic analysis) to assess storm impacts that take into account SLR.

The process for determining if a bridge is vulnerable to coastal storms (and if coastal storm design applies) is outlined below and in the flowchart in File No 33.02-3.

<u>Superstructure Replacement or Maintenance Projects:</u>

A bridge shall be considered vulnerable to coastal storms if it is currently located in FEMA Flood Zone VE or between zones VE, and must be designed in accordance with the rest of this chapter and the AASHTO Guide Specifications.

GENERAL INFORMATION (cont'd):

New or Full Replacement Bridges:

Question 1: Is the bridge subjected to storm surge?

If NO: coastal storm design is not applicable

If YES: proceed to question 2

Question 2: Is the bridge currently in flood zone VE?

If YES: the bridge is vulnerable to coastal storms, and must be designed in accordance with the rest of this chapter and the AASHTO Guide Specifications.

If NO: proceed to question 3.

Question 3: Is the bridge currently in flood zone AE (wave heights less than 3')?

If NO: coastal storm design is not applicable

If YES: the bridge location could be subjected to 3' or higher wave actions when SLR is considered. Proceed to question 4.

Question 4: Does the bridge (and project) warrant a level II hydrodynamic analysis?

A level II analysis would need to be performed in order to determine if the bridge would be subjected to 3' or greater waves when SLR is taken into account. Based on available tools, this is not easily done. A consultant would need to develop a coastal model. Using the consideration factors outlined in the table in File No. 33.01-9, the project team will make a recommendation to the District Bridge Engineer (DBE) whether the bridge warrants the effort/expense of a level II analysis. The DBE will make the final decision.

If NO: the bridge will not be designed for coastal storms.

If YES: a level II hydrodynamic analysis must be performed that incorporates 4 feet of SLR. After it is completed, proceed to question 5.

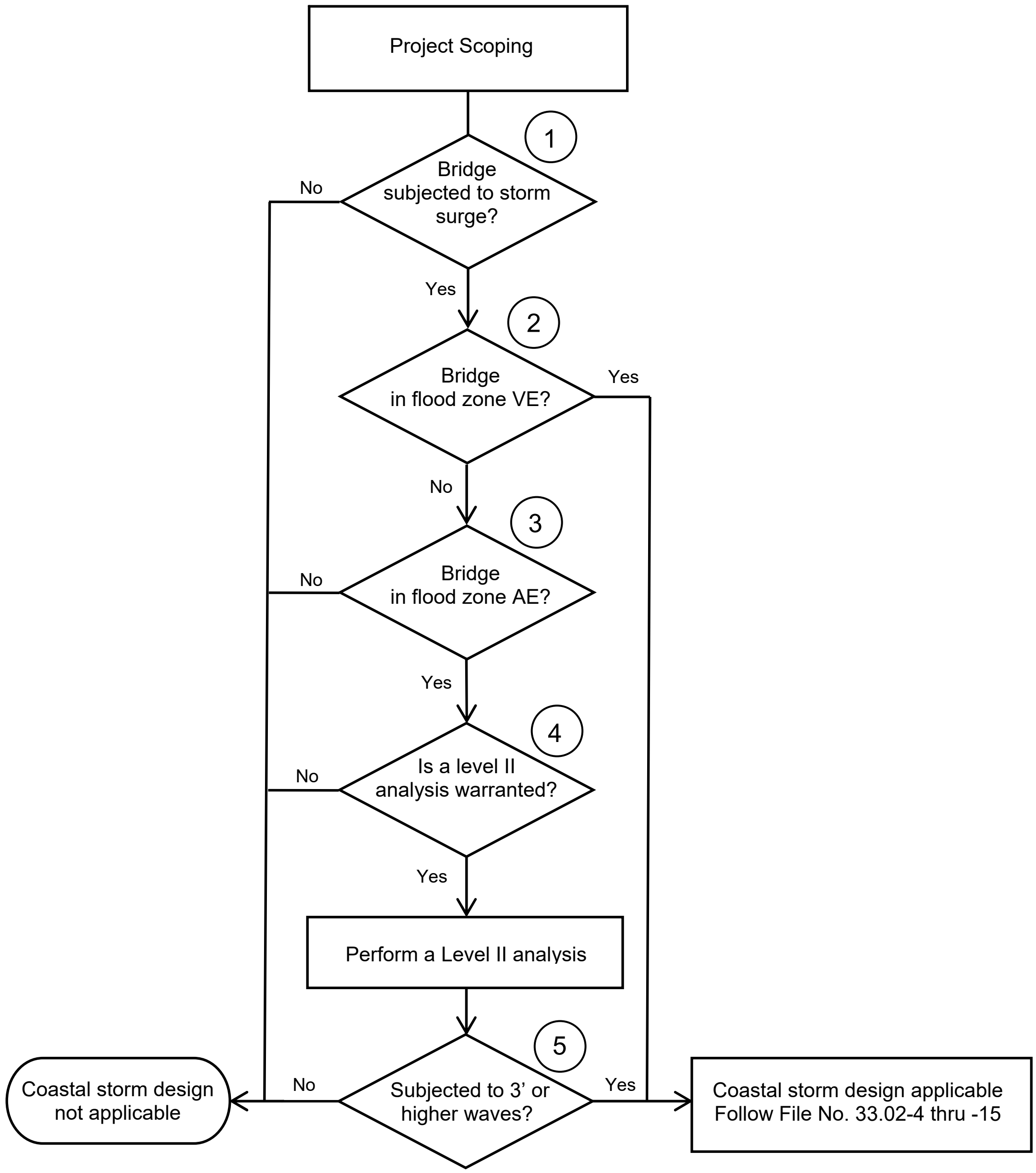
Question 5: Based on the level II hydrodynamic analysis, is the bridge subjected to 3' or higher waves?

If NO: the bridge is not considered vulnerable, and therefore coastal storm design is not applicable.

If YES: the bridge is vulnerable to coastal storms, and must be designed in accordance with the rest of this chapter and the AASHTO Guide Specifications.

GENERAL INFORMATION (cont'd):

Coastal Storm Vulnerability Assessment for New or Full Replacement Bridges:



- Denotes Question Number in File No. 33.02-3

DESIGN REQUIREMENTS:

Bridge design for coastal storms involves hydrodynamic analysis, structural analysis and structural component design. The structural design shall be done in the Strength Limit State.

Superstructures:

If the low chord of the superstructure is at least 1 foot above the 100-year design wave crest elevation (with SLR accounted for new or full replacement bridges), the superstructure does not need to be designed for coastal storms. The design wave crest elevation is a function of the design storm water depth at or near the bridge. The hydraulics engineer will provide the design wave crest elevation.

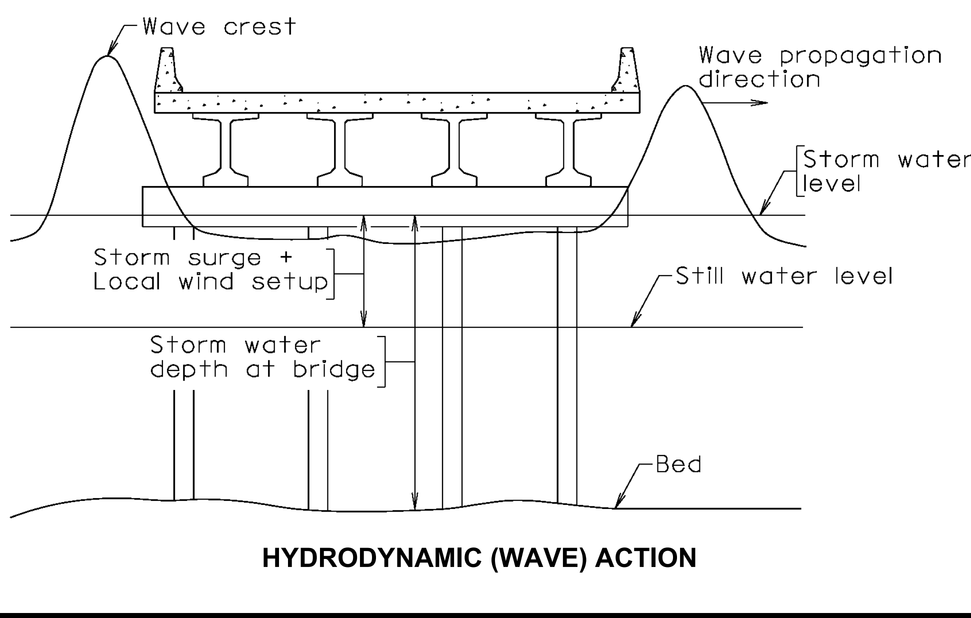
Buoyancy forces on partially or fully submerged superstructures can be reduced by venting span cells that could entrap air. Venting of entrapped air could be achieved by providing partial depth diaphragms and openings in concrete diaphragms and beam webs. These techniques may be used but will not be taken into the analysis calculation for new or full replacement bridges. Trapped Air Factor (TAF) specified in Article 6.1.2 of the AASHTO Guide Specifications is to be set to one for new and full replacement bridges with concrete superstructures; TAF for all others shall be calculated using Article 6.12 of the AASHTO Guide Specifications.

Substructures:

Substructure elements such as piers, pile bents etc. shall be analyzed structurally for the resulting forces due to exposure to storm surges and SLR (for new or full replacement bridges only). Such analysis shall be considered an integral part of the bridge analysis and design with additional measures taken to counter the effects of scouring on bridge foundation elements.

File No. 33.02-5 and -6 provide general flowcharts for designers when designing bridges vulnerable to coastal storms per the AASHTO Guide Specifications.

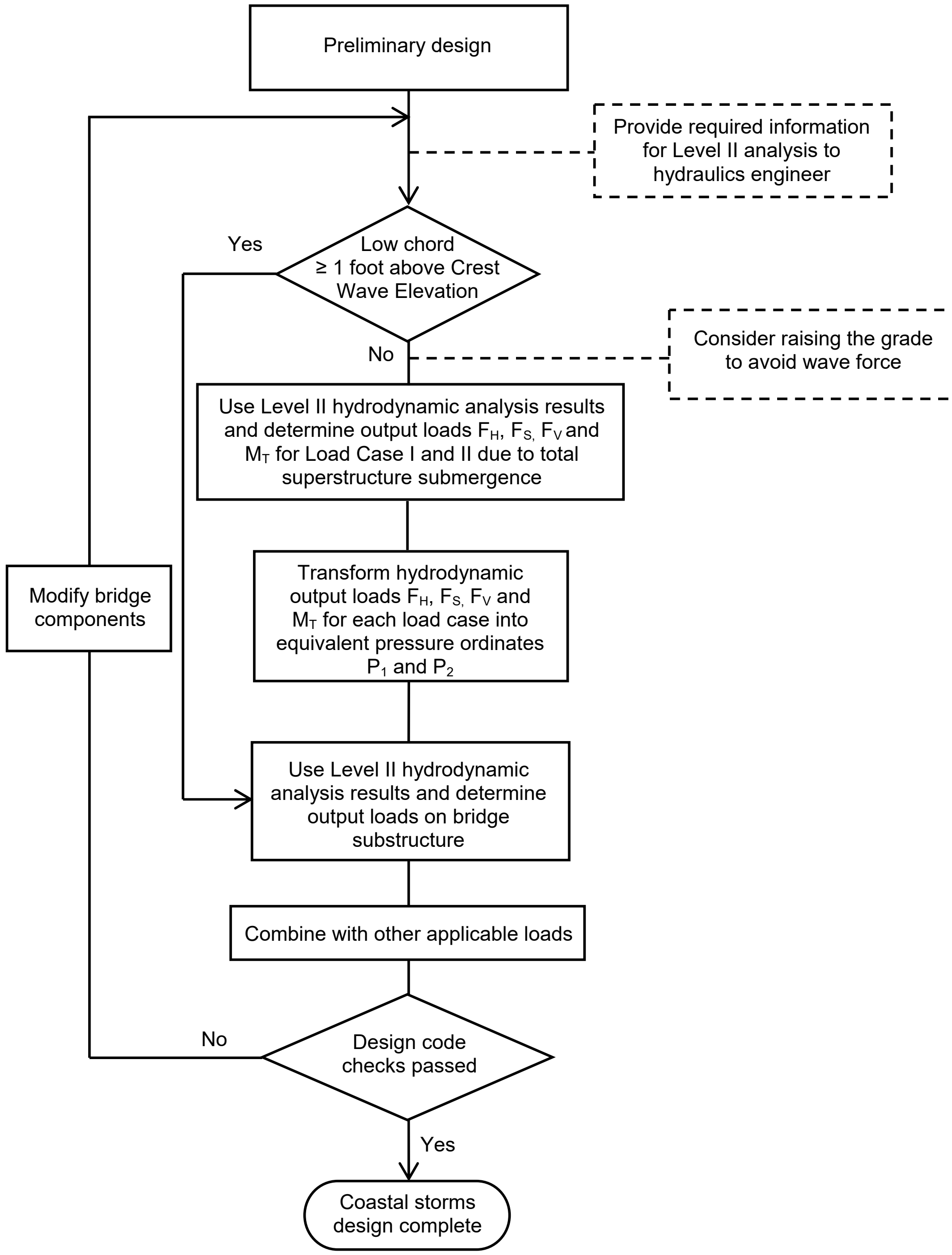
Where wave action is an issue and raising the roadway profile due to SLR is currently not feasible, the concept of “Planned Modification” in File No. 33.01-10 may be considered.



HYDRODYNAMIC (WAVE) ACTION

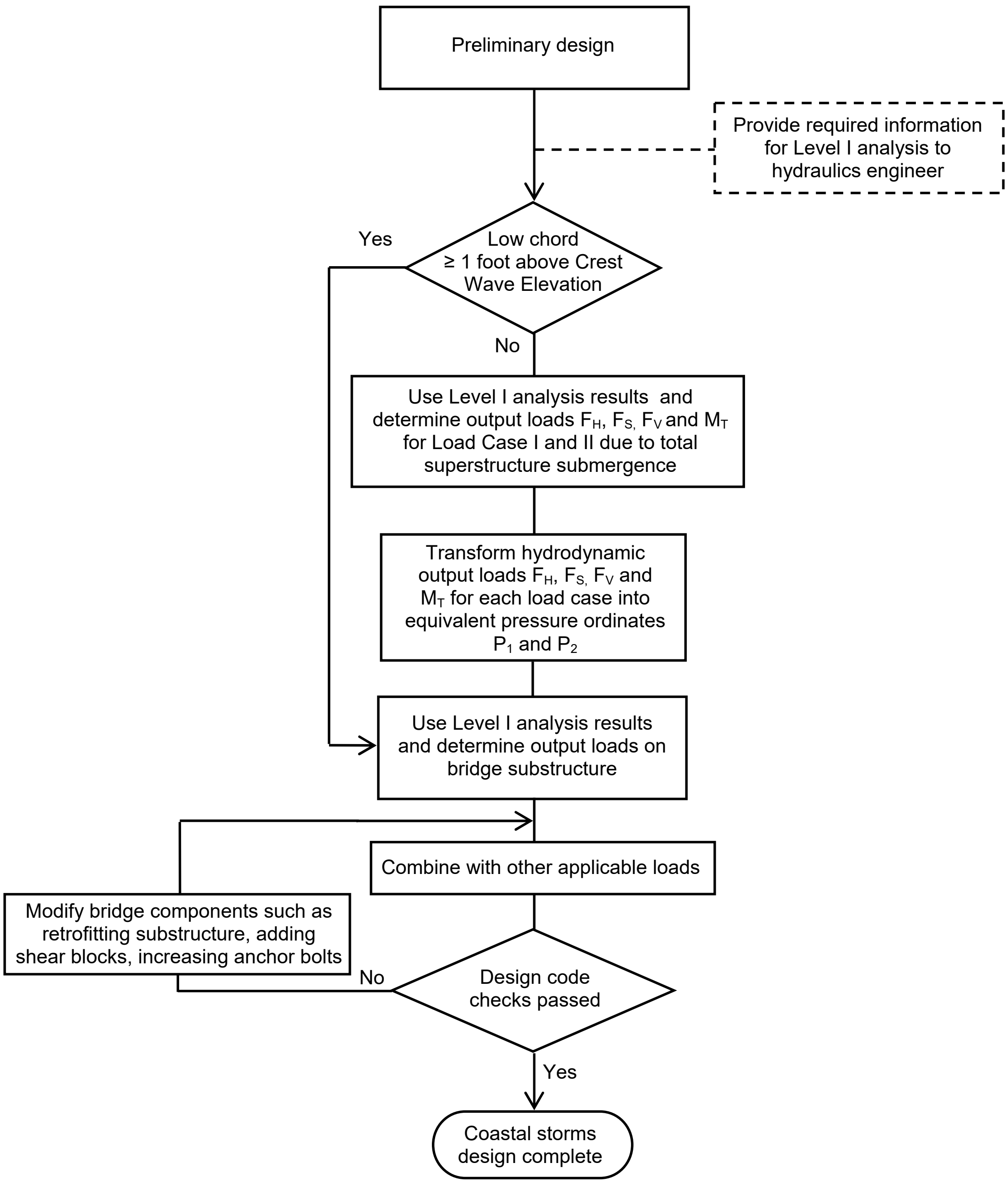
DESIGN REQUIREMENTS (Cont'd):

Design Procedure for New or Full Replacement Bridges:



DESIGN REQUIREMENTS (Cont'd):

Design Procedure for Superstructure Replacement or Maintenance Projects:



DETERMINATION OF WAVE PARAMETERS:

The AASHTO Guide Specifications include three analysis levels for determining wave parameters. A Level I analysis is the simplest and generally most conservative method. Level II hydrodynamic analysis is a mid-level approach based on using improved data usually determined through simulations of the sea state. Level III hydrodynamic analysis involves advanced numerical simulation of the sea state.

A Level I analysis is used for superstructure replacement or maintenance projects. A Level II hydrodynamic analysis is used for new or full replacement projects unless the State Structure and Bridge Engineer determines a Level III hydrodynamic analysis is necessary. The hydraulics engineer will perform the Level I, Level II or Level III analysis.

The following project specific design parameters are to be included for hydrodynamic analysis:

- Location of the bridge
- Elevation of the bridge
- Bridge span dimensions, shape, and low chord height above storm water level
- Water bathymetry
- Storm fetch length orientation relative to the bridge location
- Fetch and fetch angle for the wave segments
- Fetch and fetch angle segment for local wind set-up/set-down
- Design storm wave height and period (wave length)
- Design wind velocity
- Design storm water surface which comprises of astronomical tide, storm surge, and local wind set up
- Sea Level Rise projection for the design storm year (which shall be taken as 4 feet for all vulnerable new or full replacement bridges)
- Design water current velocity

The analysis will provide the following wave parameters for determination of wave forces:

T_p – period of the waves with the greatest energy exhibited in a spectrum (sec)
d_s – water depth at or near the bridge, including surge, astronomical tide and local wind set-up (ft)
H_{max} – maximum probable wave height (ft)
η_{max} – wave crest height for the 100-year event (ft)
λ – wave length (ft)

Level I Analysis:

Since Level I analysis uses the 100-year value for the storm surge, wind speed, wind set-up, current, wave height, and period simultaneously, the wave parameters from a Level I analysis produce the most conservative magnitude of hydrodynamic forces.

The required information for Level I analysis is:

- Bridge location
- 100-year design wind speed
- Maximum fetch length and orientation relative to the open coastline
- 100-year storm surge elevation and the mechanisms considered in its determination
- Bathymetry – submarine topography

DETERMINATION OF WAVE PARAMETERS (Cont'd):

Although the above information may be obtained from published resources, the hydraulics engineer will verify and provide the information. However, the 100-year design wind speed shall be determined as shown in Figure 3.8.1.1.2-1 of the AASHTO LRFD Specifications. The wind speed may be reduced with the reduction factors specified in Article 6.2.3.4 of the AASHTO Guide Specifications in consultation with the hydraulics engineer.

Level II Hydrodynamic Analysis:

The primary difference between Level I and Level II hydrodynamic analyses is the accuracy of the information used to compute the design water elevations and wave parameters. Since new or full replacement bridges are required to consider 4 feet SLR, a Level I analysis shall not be performed for such bridges. The hydraulics engineer shall perform a Level II analysis to simulate the resulting sea state due to SLR. The level II analysis shall produce all the wave parameters required by the bridge designer.

After Level I or Level II hydrodynamic analysis has been completed by the hydraulics engineer, the bridge designer shall calculate hydrostatic and hydrodynamic loads in accordance with Article 6.1 of the AASHTO Guide Specifications.

SUPERSTRUCTURE STRUCTURAL ANALYSIS:

For superstructures subjected to wave forces, each set of calculated superstructure wave forces for Cases I and II (for description of Cases, see Article 6.1.2.1 of AASHTO Guide Specifications) shall be transformed into an equivalent upward pressure load to simplify the structural analysis. The transformed pressure load F_P with ordinates P_1 and P_2 shall be assumed to act on the entire transverse section of the superstructure deck. Live Load is neglected.

The tributary upward demand loads (in kips per linear foot) from the equivalent pressure load for each beam is then compared with the tributary downward resisting capacity (i.e. resisting dead load). The equivalent pressure load transformation shall be achieved by establishing the following static conditions using an iterative solution technique for both Cases I and II loads:

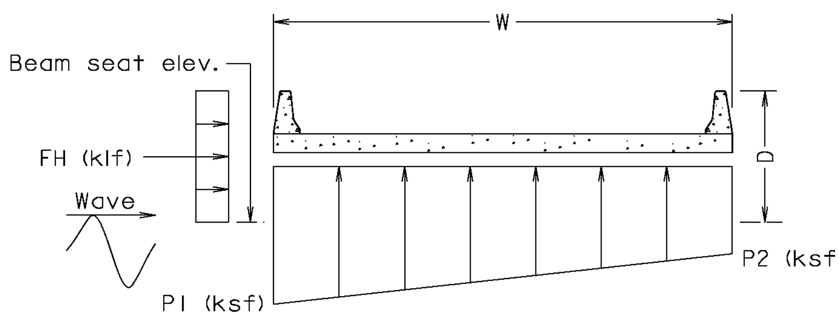
1. Equilibrium between equivalent vertical force F_P and output vertical force F_V

   $\sum F_P = F_V$

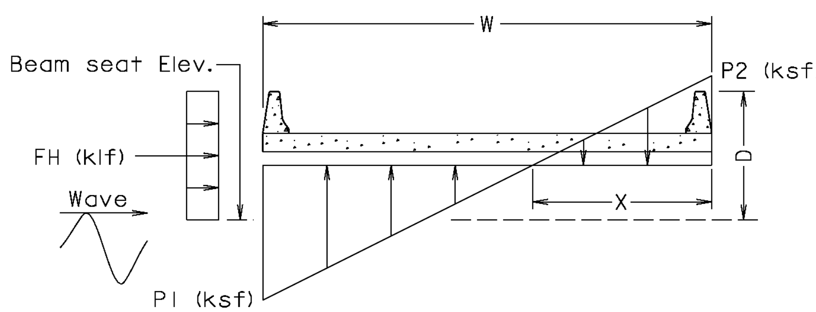
2. Equilibrium between the moments (about the trailing edge of the superstructure deck at the beam seat elevation) from equivalent vertical force F_P and horizontal output force F_H, and the output moment M_T

   $\sum M_P + M_H = M_T$

The transformation of the output hydrodynamic analysis forces into an equivalent upward pressure load can result in only one of four possible pressure distribution patterns shown below:

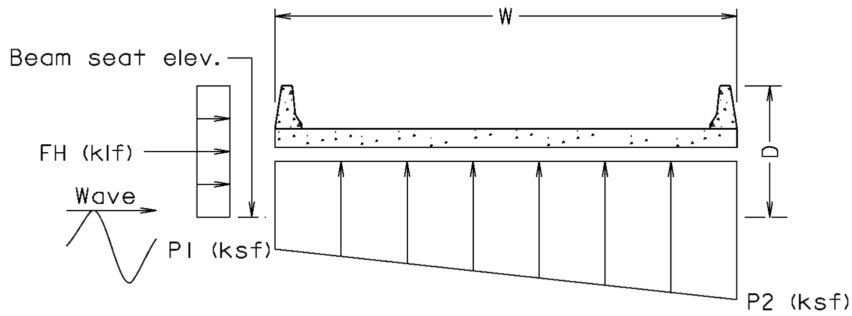


TRANSFORMED PRESSURE DISTRIBUTION 1

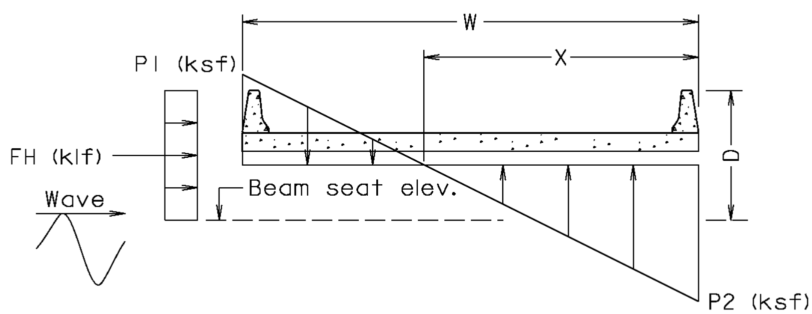


TRANSFORMED PRESSURE DISTRIBUTION 2

SUPERSTRUCTURE STRUCTURAL ANALYSIS (Cont'd):



TRANSFORMED PRESSURE DISTRIBUTION 3



TRANSFORMED PRESSURE DISTRIBUTION 4

The bridge designer may choose any iterative technique necessary to determine equivalent pressure distributions for Cases I and II loads. The goal of the iterative process is to transform the hydrodynamic forces and moments to equivalent pressure distributions using equilibrium of forces principles, which can then be used to compute tributary pressure loads for each beam. These tributary pressure loads are finally used to determine whether the beam/girder design and supports are adequate.

Spans with low chord above the wave crest elevation are not checked. As wave crest action has a finite length, the equivalent pressure distribution is typically applied to individual spans. Simultaneous application to multiple spans may be necessary where wave crest length can encompass multiple spans or portions of the superstructure are below the storm water level.

SUPERSTRUCTURE STRUCTURAL ANALYSIS (Cont'd):

A general flow of the iterative steps is provided below for illustrative purposes using Case I hydrodynamic loads:

1. Request wave parameters and calculate the hydrodynamic loads
   M_{T-AV}, F_{H-AV}, F_{V-MAX}, F_S for Case I
2. Select an incremental step value P_{STEP} for the iteration
3. Set $M_H = F_{H-AV} * 0.5 * D$
   D is the distance the between the top of the bridge barrier and beam seat elevation
4. Set the following initial pressure (ksf) ordinates
   $P_1 = 2 * (F_{V-MAX} + F_S) / W$
   $P_2 = 0$
5. Set "X" to zero and assume an initial triangular pressure distribution
   X is the distance between the trailing edge of the deck and the intersection of the assumed pressure distribution with the deck transverse section
6. Calculate the moment M_P of the resulting pressure distribution with the initial P_1 and P_2 ordinates. The moment shall be calculated about the deck trailing edge at the beam seat elevation
7. Check if $M_P + M_H$ converges to M_{T-AV}
8. Terminate if Step 7 is satisfied otherwise proceed to Step 9
9. Decrease P_1 by P_{STEP} and increase P_2 by P_{STEP}
10. Calculate the moment M_P of the resulting pressure distribution with the revised P_1 and P_2 ordinates
11. Calculate the force F_P and moment M_P of the resulting pressure distribution with the revised P_1 and P_2 ordinates
12. Check if $M_P + M_H$ converges to M_{T-AV}
13. Check if F_P converges to $F_{V-MAX} + F_S$
14. Terminate if Steps 12 and 13 are both satisfied
15. Otherwise, repeat Steps 9 to 13 until solution converges
16. If solution does not converge after several trials of positive P_1 and P_2 incremental values, change "X" and repeat Steps 6 to 9 with the revised "X" value until solution converges noting that P_1 and P_2 could be either positive or negative, and "X" at this point could be anywhere along the width of the deck transverse section i.e. $0 < X \leq W$

Generally the path to convergence for the iteration solution (i.e. whether to decrease P_1 and increase P_2 or vice versa by incremental steps) can be quickly determined from the sum of M_H and initial M_P values when compared to M_{T-AV} (and similarly, M_H and initial M_P values when compared to M_{T-AH} for Case II). The numerical sign of each contributing equivalent pressure area shall be taken into consideration when establishing force and moment equilibriums at each iteration step for the load case under consideration.

STRUCTURAL CAPACITY OF SUPERSTRUCTURE AND CONNECTIONS:

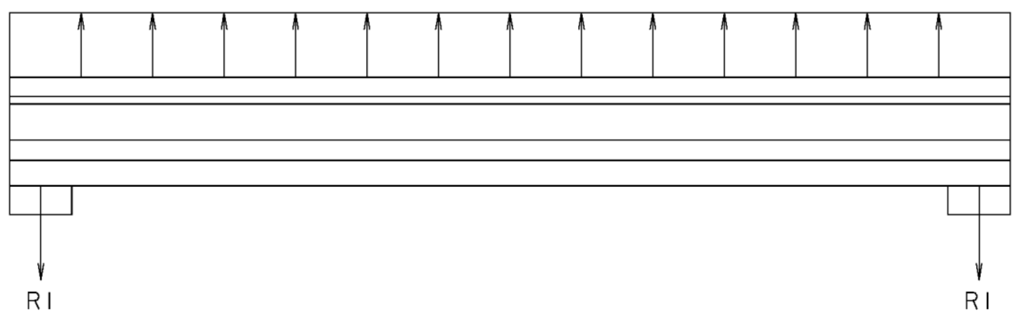
Superstructure structural capacity checks at the Strength Limit State shall be done using methods outlined in the AASHTO LRFD Specifications for the beams, and anchor bolts at beam supports. Vertical uplift and horizontal shear at the bearings, pullout failure of the anchor bolts from pier cap concrete, susceptibility of the superstructure to total span lift-off at those locations, and negative moment (upward bending) in the beams shall be assessed. The type of superstructure to substructure connection (i.e. degree of freedom in X, Y, Z axis) shall also be considered.

Vertical Uplift at Bearings:

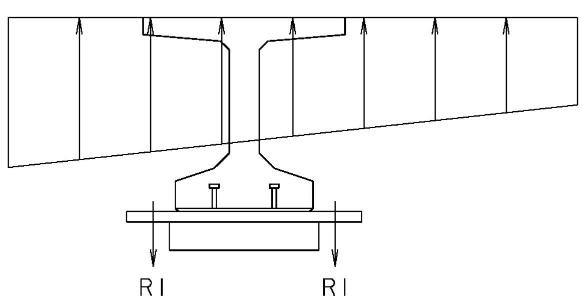
The equivalent pressure distribution over each beam/girder's tributary width is used. The fascia beam/girder is normally the critical among the set of beams due to the magnitude of the equivalent pressure distribution. The tributary width for the fascia girder is the sum of the deck overhang and half the beam spacing. The resulting tributary load is applied along the entire length of beam as a uniformly distributed load in kips per linear foot (klf).

Capacity assessment performed shall include checks for:

- Tension failure in the anchor bolts
- Tension failure of the welds between bearing sole plate and either the bottom flange for steel beams/girders or beam insert plates for prestress concrete beam
- Tension failure of headed studs at the base weld connection to inserts plates for prestress concrete beams, and of the studs themselves
- Pullout failure of headed stud-insert plate assembly from bottom of prestress concrete beams
- Pullout of the anchor bolts from the substructure (abutment, pier cap etc.) concrete



ELEVATION – BEAM UPLIFT



SECTION – BEAM UPLIFT

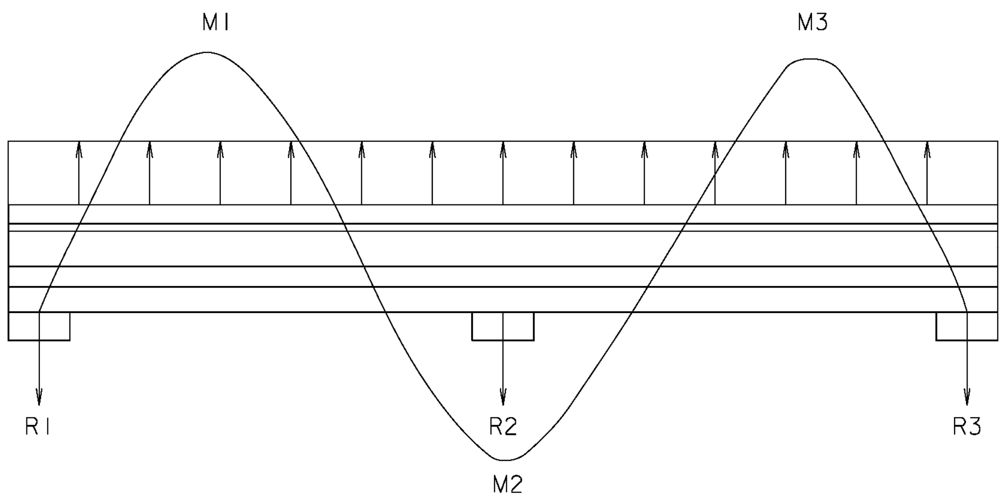
STRUCTURAL CAPACITY OF SUPERSTRUCTURE AND CONNECTIONS (Cont'd):

Finally, the susceptibility of the entire superstructure to total span lift-off should be investigated and mitigated with shear/keeper blocks and/or other solutions as needed to prevent walking of the beams.

Negative (Reverse) Moment in Beams/Girders:

Bridge superstructure units with fixed intermediate supports have some additional stiffness capacity due to their ability to laterally distribute the applied loads by taking advantage of the full depth concrete deck and concrete intermediate diaphragms. Therefore, negative moment capacities of the beam/girders shall be evaluated taking into consideration the continuity of the superstructure span units.

Uplift of the span is initially checked assuming the span of a unit is from bent to bent. If there is no uplift, the superstructure is considered satisfactory and no further moment checks are required.



ELEVATION – UPWARD BENDING

However, if there is net uplift the whole superstructure length (between the extreme supports for units which are continuous) is taken as the unit length and the upward bending calculations revised to determine if the beam moment capacity is adequate under the revised condition.

Horizontal Shear at Bearings:

The maximum horizontal force F_H in klf is applied over the entire span. The ability of the span to resist the applied force is then checked for the following:

- Shear failure in the anchor bolts
- Shear failure in the welds connecting the headed studs to the embedded insert plate, and of the studs themselves for prestress concrete beams
- Tear-out of the stud and insert plate from the side of prestress concrete beams
- Shear failure of the welds connecting sole plates to either the bottom flange of steel girders/beams or beam insert plates in prestressed concrete beams

STRUCTURAL CAPACITY OF SUPERSTRUCTURE AND CONNECTIONS (Cont'd):

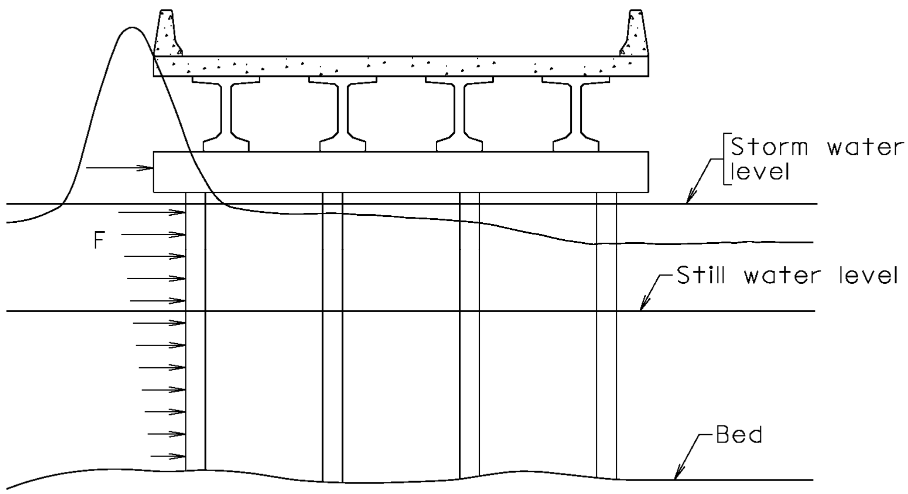
The capacity for each span is the sum of the contributing bearings for the substructure unit on both sides of the span, reduced to 75 percent to account for the potential of unequal force distribution between bearings. This reduced capacity is compared with the horizontal force F_H multiplied by the span length.

Tension-Shear Interactions Check at Bearings:

Interaction formulae considering simultaneous action of tension and shear shall be checked for both the anchor bolts and welds when the tributary vertical pressure load is greater than the superstructure resisting dead load.

SUBSTRUCTURE:

The substructure elements of vulnerable bridges to coastal storms shall be designed for the factored hydrodynamic loads transferred from the superstructure, and those applied directly to the substructure by the waves. These hydrodynamic forces on substructure shall be calculated using Article 6.1.3 of the AASHTO Guide Specifications.



SUBSTRUCTURE HYDRODYNAMIC FORCES

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