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Scour Considerations within AASHTO LRFD Design Specifications

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ABSTRACT

The Federal Highway Administration (FHWA) published a Technical Brief (TechBrief) summarized in the paper that provides programmatic and technical considerations for understanding the interaction of limit states and scour depths in foundation design related to provisions of the American Association of State Highway and Transportation (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications.
The paper describes how bridge owners and designers can consider scour-related provisions in AASHTO LRFD when designing foundations and align with compliance requirements of the Federal Highway Administration's (FHWA's) Design Standards and National Bridge Inspection Standards. AASHTO LRFD considers scour not as a force, but a change in foundation conditions (i.e., loss of bed material above the scour line). In other words, scour depth is a condition that has resulted from erosive forces and this condition is considered in limit states in AASHTO LRFD. There are currently no statistically-based factors applied to scour depth or its effect to foundation. This becomes more problematic as the design of bridge foundations to accommodate scour involves close coordination and collaboration of the hydraulics, geotechnical, and structural engineering disciplines. While each of these disciplines have specifications, guidance, and terminology specific to the topic, these are not necessarily well understood by members of the other two disciplines. Therefore, the paper provides clarification of scour and scour depths for these various disciplines. The paper describes various AASHTO LRFD and FHWA terms and scenarios to illustrate the various conditions including worst-case scour and limit states. Finally, the paper provides clarification on FHWA approaches and recommendations.

Keywords: Scour, Hydraulics, LRFD, Bridge Design

INTRODUCTION

The AASHTO LRFD Bridge Design Specifications (AASHTO, 2017) is the standard for highway bridge and structure design, evaluation, and rehabilitation practice. The LRFD specifications contain chapters, articles and commentary governing the engineering design of structural (e.g., bridge superstructures, decks, piers, etc.), geotechnical (e.g., foundations, abutments, retaining walls, etc.) hydraulic (e.g., hydrology, hydraulics, and scour), and other elements for these types of highway infrastructure.

This paper describes how scour are considered in the provisions of AASHTO LRFD when designing foundations and align with compliance requirements of the Federal Highway Administration's (FHWA's) Design Standards and National Bridge Inspection Standards.

AASHTO describes LRFD as "taking the variability in the behavior of structural elements into account in an explicit manner. LRFD relies on extensive use of statistical methods, but sets forth the results in a manner readily usable by bridge designers and analysts (AASHTO, 2017)". Additionally, AASHTO defines the term "Load and Resistance Factor Design" as a reliability-based design methodology in which force effects caused by factored loads are not permitted to exceed the factored resistance of the components. As the term "LRFD" denotes, quantification and probabilistic considerations related to forces (i.e., loads) and responses to those forces (i.e., resistance) that inform application of the design specifications. This is accomplished through consideration of limit states or, as defined by AASHTO LRFD, a "condition beyond which the bridge or component ceases to satisfy the provisions for which it was designed". In practice, bridge engineers would factor the capacity and demand upon bridge superstructures, substructure and foundation elements for evaluation at all applicable limit states. This is not the case for scour design.

The FHWA regulation Code of Federal Regulations (CFR), Title 23, Highways (23 CFR) § 650.305 defines scour as "erosion of streambed material due to flowing water; often considered as being localized around piers and abutments of bridges" (FHWA, 2018); "erosion" being the operative word. Similarly, AASHTO LRFD considers scour not as a force, but a change in foundation conditions (i.e., loss of bed material above the scour line). In other words, scour depth is a condition that has resulted from erosive forces and this condition is considered in limit states in AASHTO LRFD. There are currently no statistically-based factors applied to scour depth or its effect to foundation. The paper describes various AASHTO LRFD and FHWA terms and scenarios to illustrate the various conditions for limit states. Finally, the paper provides some clarification on FHWA approaches and recommendations.

SCOUR DESIGN FLOOD & SCOUR CHECK FLOOD

LRFD seeks to provide a buildable, serviceable bridge, capable of safely carrying design loads for a specified design life. This translates to satisfying various limits states, of which each consists of a unique combination of permanent, transient or extreme loads and/or conditions. Another way to look at this approach is that bridges must satisfy normal operational needs, but also address situations such as seismic events or vessel collisions. AASHTO LRFD accomplishes some of these such needs by designing at multiple limit states. For example, Strength III checks for a very high wind speed (design wind) condition, while Strength V prescribes a moderately high wind speed that allows normal operation. AASHTO LRFD applies this concept to scour design as well. The scour design flood, associated with the flood with an 1% annual exceedance probability (i.e., 100-year return period, or, Q_{100}), represents the "normal" scour depth condition. The scour check flood, associated with the 0.2% annual exceedance discharge probability (i.e., 500-year return period or Q_{500}), represents the "check" condition. AASHTO selected these 100-year and 500-year flood discharges based on recommendations from FHWA and in alignment with the National Bridge Inspection Standards (NBIS) regulation (23 CFR § 650 subpart C). Specifically, in the late 1980s, when developing the FHWA Scour Program, the FHWA recommended use of 100-year and 500-year exceedance discharges as the scour design flood and scour check flood.

SCENARIOS DEPICTING DIFFERENT SITUATIONS COVERED BY LRFD & SCOUR

AASHTO LRFD recognizes that the worst-case scour depth may not occur at the highest flow rate that the scour design flood or scour check flood may have (i.e., Q_{100} and Q_{500} events). So, the scour design flood might consist of some flood magnitude less than the Q100 that causes greater scour at the bridge. If so, the specifications require using that discharge as the scour design flood. Similarly, if there is a flood event less than the Q_{500} that causes the worst-case scour depth at the bridge, it should be used as the scour check flood. Another way of stating the above is that the scour design flood should be the worst-case scour for all floods up to and including Q_{100}. Likewise, the scour check flood should be the worst-case scour for all floods up to and including the Q_{500}.

For the bridge design considering scour, AASHTO LRFD Section 2.6.4.4.2 has the following requirements:

> For the design flood for scour, the streambed material in the scour prism above the total scour line shall be assumed to have been removed for design conditions.
> The design flood storm surge, tide, or mixed population flood shall be the more severe of the 100-yr events or from an overtopping flood of lesser recurrence interval.

AASHTO LRFD Section 2.6.4.4.2 also requires:

> For the check flood for scour, the stability of bridge foundation shall be investigated for scour conditions resulting from a designated flood storm surge, tide, or mixed population flood not to exceed the 500-yr event or from an overtopping flood of lesser recurrence interval. Excess reserve beyond that required for stability under this condition is not necessary. The extreme event limit state shall apply.

To illustrate some (but not all) of the different situations covered by AASHTO LRFD and scour, this paper will cover several different scenarios.

Scenario 1: Scour Design Flood equals the Q_{100} Flood

Figure 1 illustrates the scour progression versus discharge that generates the worst-case scour depth, relative to the bridge foundation. The maximum scour depth is on the upstream side of the bridge structure.

In this scenario, the worst-case scour depth ($y_{S,Q_{100}}$) as depicted in the left-side plot and profile illustrations, occurs at Q_{100} and serves as the scour design flood.

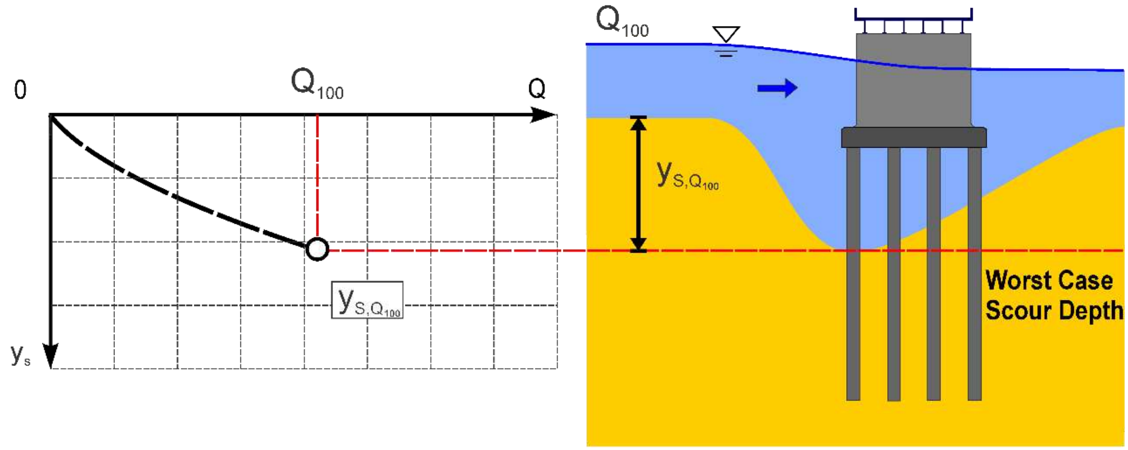

Figure 1. Worst-case scour depth for ≤ Q100 used for scour design flood.

Scenario 2: Scour Design Flood equals the Q_{OT} Flood

Figure 2 depicts an alternate scenario where incipient overtopping flood at the roadway approaches occurs, and the worst-case scour depth does not occur at Q_{100}, but rather at the incipient overtopping flood, labeled as Q_{OT}.

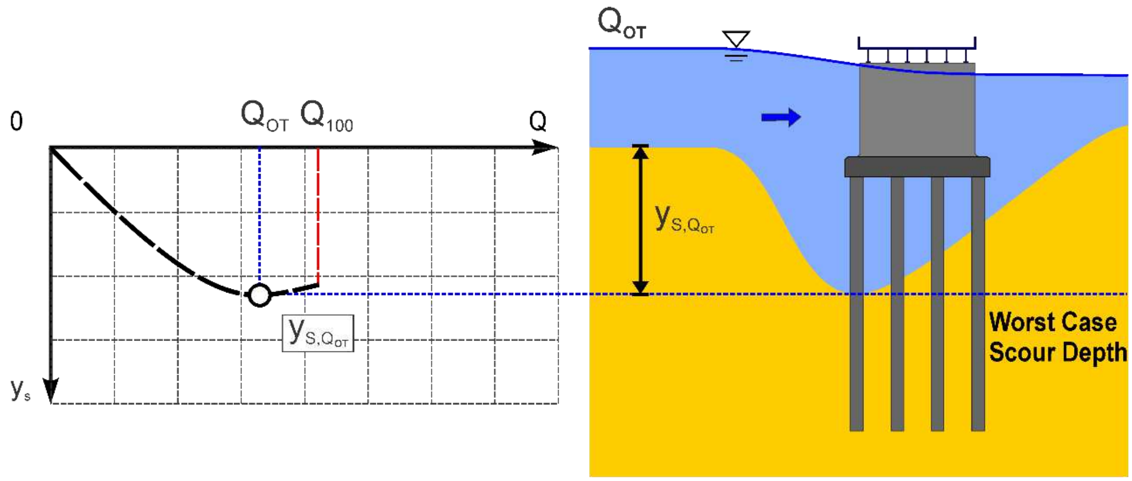

Figure 2. Incipient overtopping flood generates the worst-case scour depth for the scour design flood.

In this scenario, there is hydraulic relief provided at Q_{OT}, so that Q_{100} causes a shallower scour depth, as reflected in the plots on the left. The left plot and profile illustrations depict the worst-case scour depth ($y_{S,Q_{OT}}$) for this scenario. The flood discharge in this scenario shows the water level is higher relative to the bridge structure. For this case, the scour design flood uses the Q_{OT} condition.

Scenario 3: Scour Design Flood equals the Q_{LT} Flood

Figure 3 depicts a low tailwater (TW) flow condition case. In this scenario, a low flow generates higher velocities at the bridge structure for low TW conditions (Q_{LT}), while higher flows reduce velocities at bridge structure due to increasing TW. For example, a bridge structure is located at a tributary stream close to a river confluence.

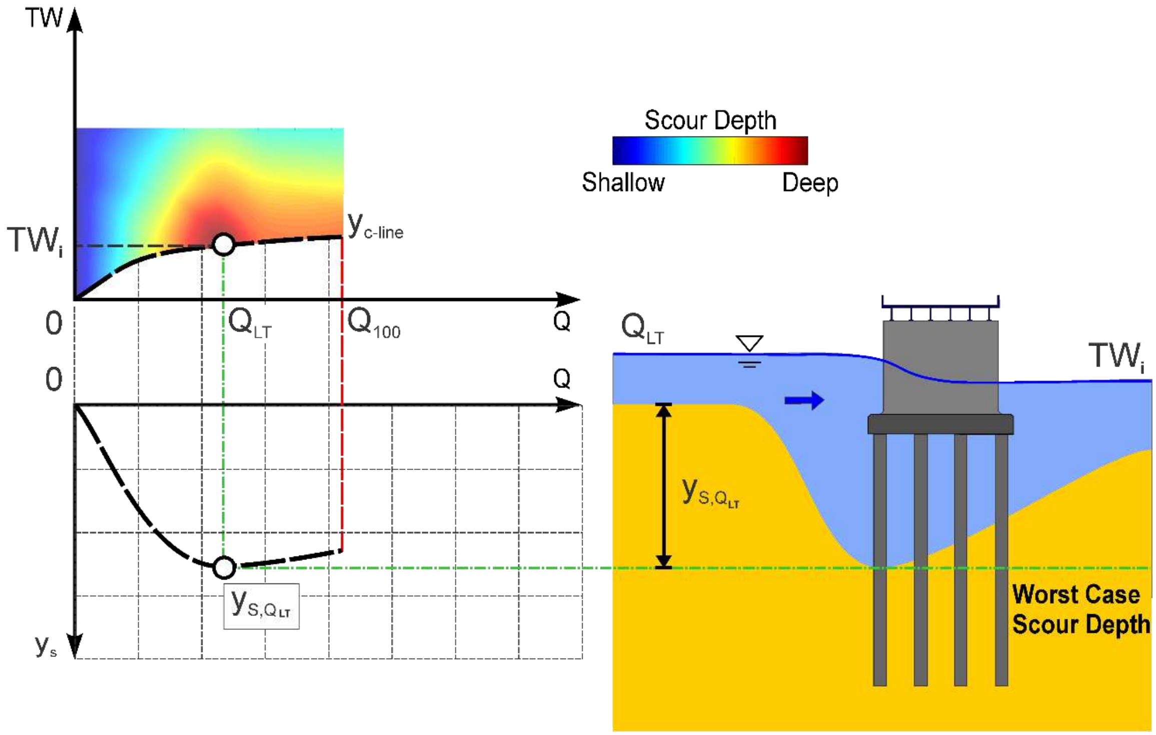

Figure 3. Low tailwater flow generates the worst-case scour depth for the scour design flood.

During a storm event, flow from the tributary goes through critical depth (y_c-line) before entering the receiving stream with low tailwater (low flow depth) generating high velocities at the bridge structure. As the storm progresses, the depth in the receiving stream increases, creating higher tailwater conditions for the tributary and reducing velocities at the bridge structure. In this case, the worst-case scour depth occurs at a low tailwater flow condition (Q_{LT}) and TW_i, which occurs for flows lower than the Q_{100}. Figure 3 designates this worst-case scour depth as $y_{S,Q_{LT}}$ (as depicted in the bottom plot and profile illustrations). Q_{LT} is used as the scour design flood.

Conditions in this scenario are similar to those that occurred in the April 1962 flood events that led to the I-29 Big Sioux River bridge collapse.

Scenario 4: Scour Check Flood equals the Q_{500} Flood

While Figures 1 thru 3 showed the worst-case scour depths related to Q_{100}, the following three figures depict similar scenarios, but for Q_{500}. Figure 4 illustrates the relationship between flood discharge and the associated scour depth up to Q_{500}. The illustrations below show the scour progression versus discharge that generates the worst-case scour depth relative to the bridge foundation. In this scenario, the worst-case scour depth occurs at the upstream side of the bridge structure at the Q_{500}; designated as $y_{S,Q_{500}}$ (as depicted in the plot and profile illustrations). These conditions would constitute the scour check flood.

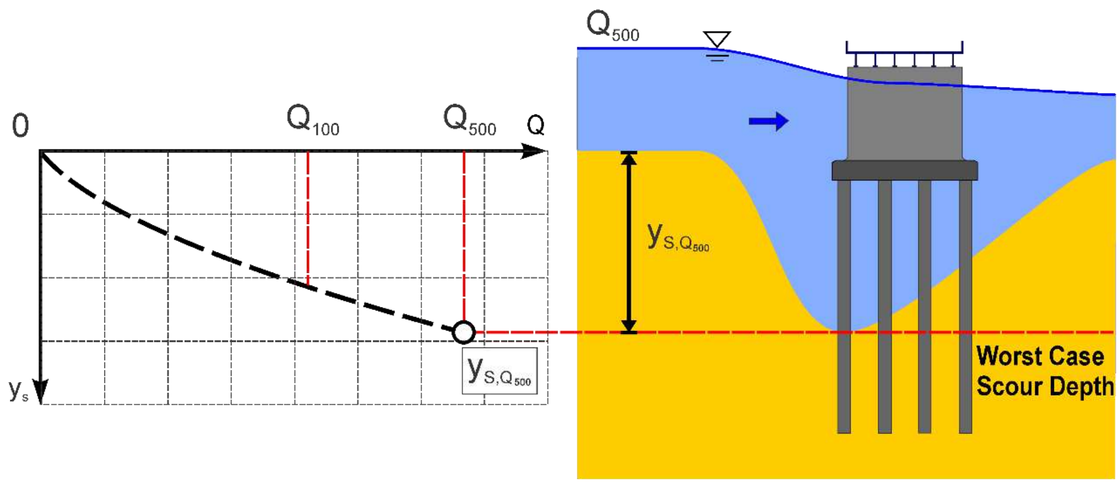

Figure 4. Q500 generates the worst-case scour depth for the scour check flood.

Scenario 5: Scour Check Flood equals the Q_{OT} Flood

Figure 5 shows the alternate scenario where incipient overtopping flood occurs. The worst-case scour depth does not occur at Q_{500}, but rather at a lesser incipient overtopping flood (greater than Q_{100}). Figure 5 labels this flood as Q_{OT}. Figure 5 designates this worst-case scour depth as $y_{S,Q_{OT}}$ (as depicted in the plot and profile illustration). For this case, the Q_{OT} is used as the scour check flood.

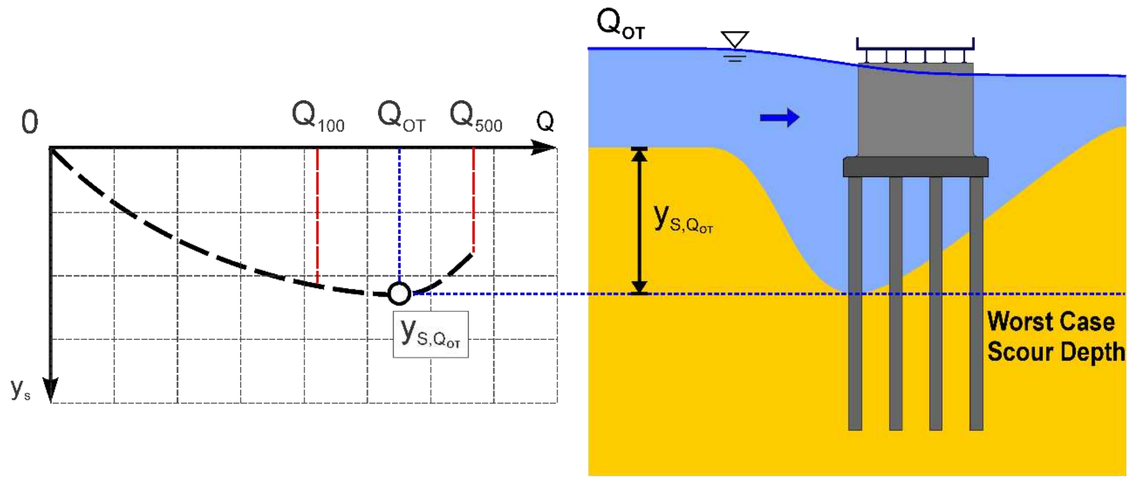

Figure 5. Incipient overtopping flood generates the worst-case scour depth for the scour check flood.

Scenario 6: Scour check flood equals the Q_{LT} flood

Figure 6 once again depicts the special case (see scenario 3), a low tailwater flow condition. In this scenario, the worst-case scour depth is at the Q_{LT} and TW_i, which occurs for flows greater than Q_{100} and lower than the Q_{500}, should be used as the scour check flood.

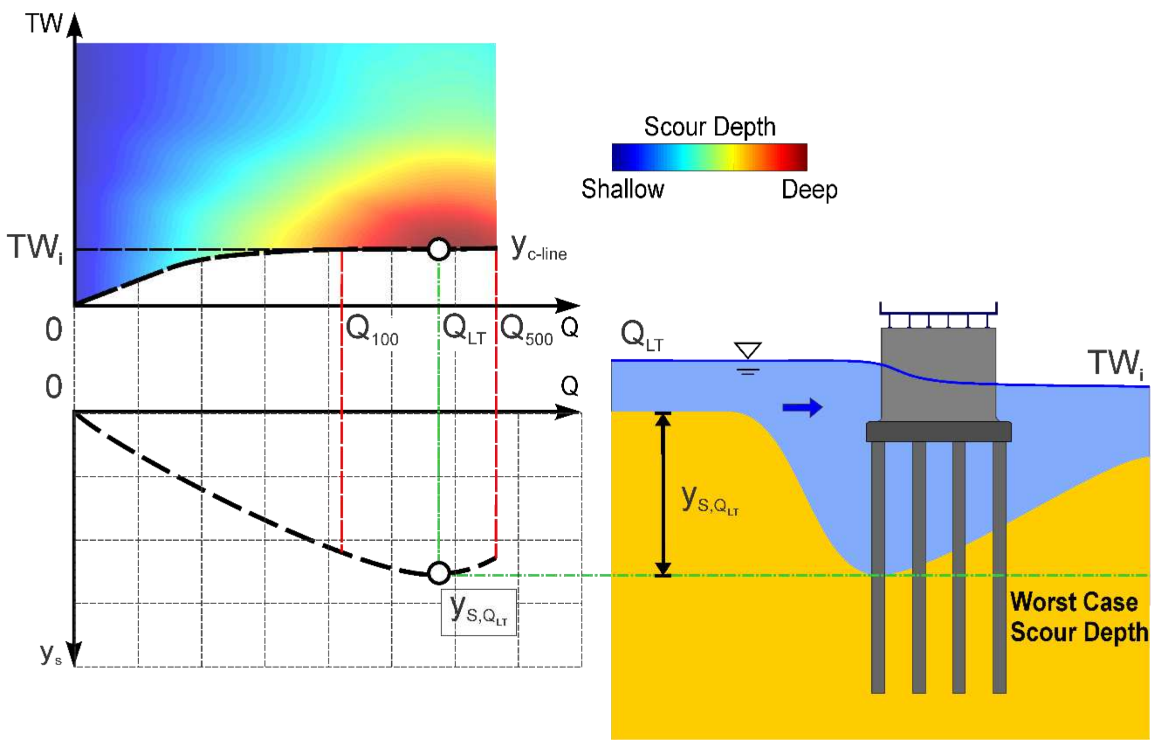

Figure 6. Low tailwater flow generates the worst-case scour depth for the scour check flood.

The table below (Table1) summarizes the scenarios (floods) that generate the worst case scour discussed above.

	$0 \leq Q \leq Q_{100}$	$0 \leq Q_{OT} \leq Q_{100}$	$0 \leq Q_{LT} \leq Q_{100}$	$0 \leq Q \leq Q_{500}$	$Q_{100} \leq Q_{OT} \leq Q_{500}$	$Q_{100} \leq Q_{LT} \leq Q_{500}$
Scenario 1	SDF = Q_{100}					
Scenario 2		SDF = Q_{OT}				
Scenario 3			SDF = Q_{LT}			
Scenario 4				SCF = Q_{500}		
Scenario 5					SCF = Q_{OT}	
Scenario 6						SCF= Q_{LT}

AASHTO LRFD DEEP FOUNDATION DESIGN

For illustrative purposes (Figure 7), let's begin by considering how AASHTO LRFD provisions would apply to deep foundation analysis under the scenario that scour does not affect the deep foundation. Figure 7 depicts a hypothetical example where a pile or shaft load for a specific limit state is determined resulting in a minimum pile or shaft penetration length, L_{MIN}. In the design of a deep foundation, AASHTO LRFD requires the consideration of structural and geotechnical conditions, and the load combinations specified in Service, Strength, and Extreme Events limit states. Note, the load combinations specified in the Fatigue limit state are not considered when designing deep foundations for scour.

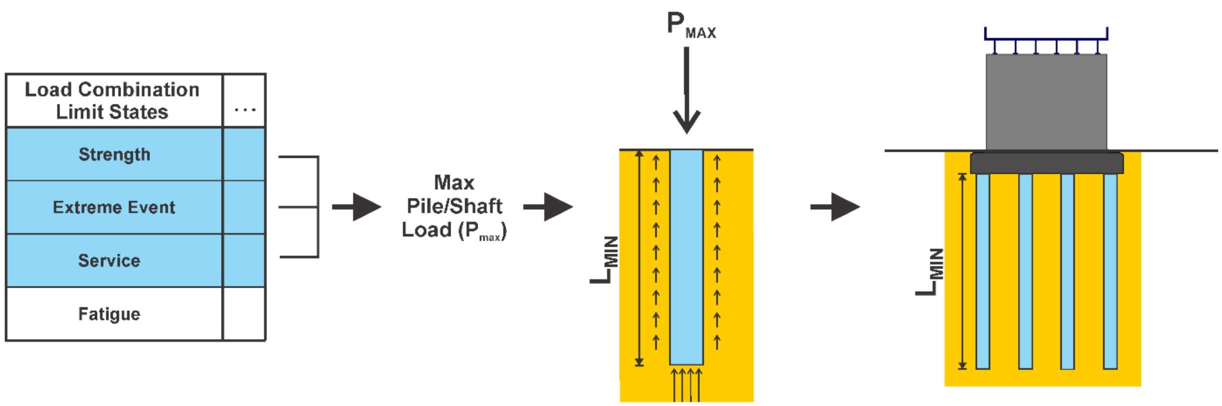

Figure 7. Schematic of LRFD pile/shaft design.

The LRFD design methodology uses load factors to account, primarily, for the variability of loads, the uncertainties in load evaluation, and the probability distribution for potential combinations of different loads, but also related to the statistics of the resistance through the calibration process. It uses resistance factors to account primarily uncertainties in material properties, geometric variation from fabrication process, and capacity analysis, but also related to the loads through the calibration process. The combination of factored loads (i.e., the sum of products of nominal loads and load factors) cannot exceed the factored resistance (i.e., nominal resistance of the component multiplied by a resistance factor). If it does, the bridge or bridge component no longer satisfies the specific limit state and therefore, no longer fulfils the target reliability embedded in AASHTO LRFD.

AASHTO LRFD SHALLOW FOUNDATION DESIGN

AASHTO LRFD provisions applied to shallow foundation analysis under the scenario that scour does not affect the shallow foundation are discussed. Figure 8 depicts a hypothetical example where a spread footing is shown whose soil resistance satisfies the loading conditions for specific limit states. In the design of a shallow foundation, AASHTO LRFD requires the consideration of structural and geotechnical conditions, and the load combinations specified in Service, Strength, and Extreme Events limit states.

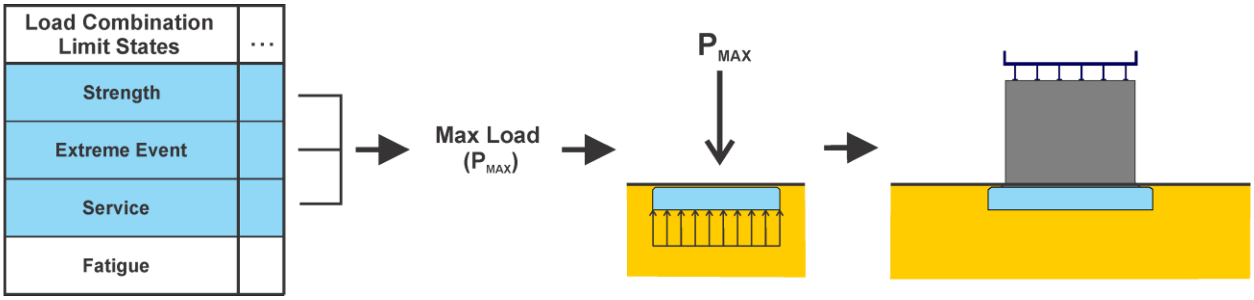

Figure 8. Schematic of LRFD shallow foundation design.

Bearing Depth for Spread Footings Considering Scour

For the shallow foundation design considering scour, AASHTO LRFD has the following requirements:

- Scour (Section 2.6.4.4.2)
  'Spread footings on soil or erodible rock shall be located so that the bottom of footing is below scour depths determined for the check flood for scour. Spread footings on scour-resistant rock shall be designed and constructed to maintain the integrity of the supporting rock'.

- Bearing Depth (Section 10.6.1.2)
  'Where the potential for scour, erosion or undermining exists, spread footings shall be located to bear below the maximum anticipated depth of scour, erosion, or undermining as specified in Article 2.6.4.4'.

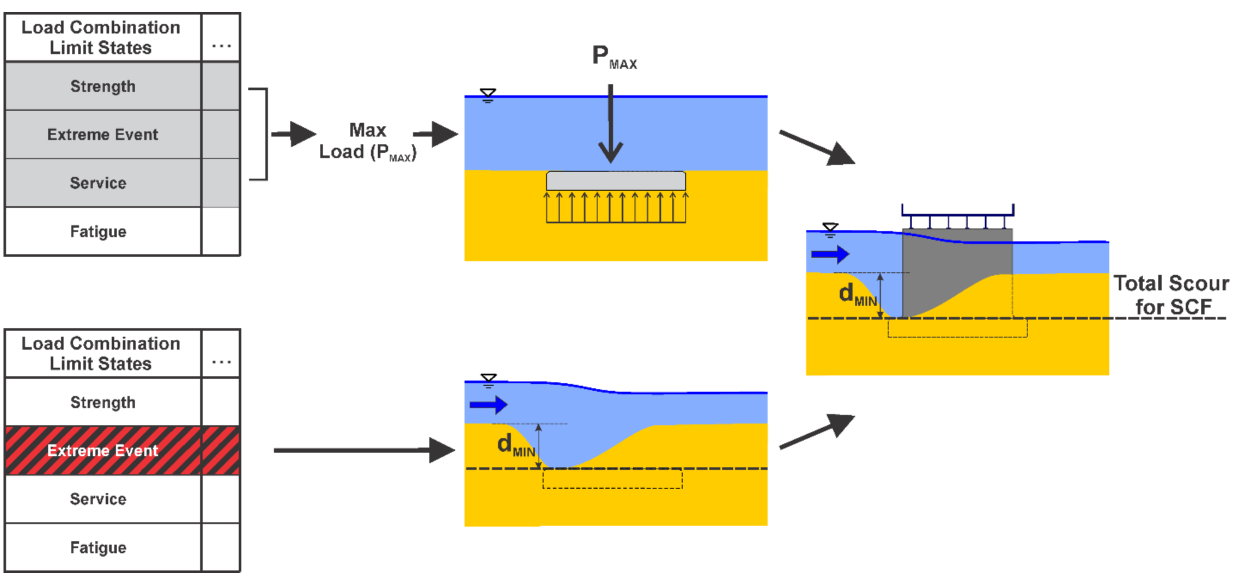

Figure 9. The minimum footing dimensions and minimum bearing depth (d_{MIN}) considering total scour for the scour check flood (SCF) linked to the extreme limit state.

Figure 9 illustrates the minimum bearing depth (d_{MIN}) considering total scour for the scour check flood linked to the extreme limit state. The minimum footing dimensions are determined by the maximum load for strength or service limit states and extreme limit states (Figure 9).

MINIMUM PILE/SHAFT PENETRATION LENGTH CONSIDERING SCOUR

For the bridge design considering scour, AASHTO LRFD has the following requirements:

- Change in Foundations Due to Limit State for Scour (Section 3.7.5)
- Scour (Section 10.7.3.6)

  'The pile foundation shall be designed so that the pile penetration after the design scour event satisfies the required nominal axial and lateral resistance'.

Change in Foundations Due to the Scour Design Flood and Associated Limit State for Scour

AASHTO LRFD Section 3.7.5 requires:

"The consequences of changes in foundation conditions resulting from the design flood for scour shall be considered at strength and service limit states".

Figure 10 shows an illustrative minimum pile/shaft penetration length considering total scour for evaluation at the strength or service limit states for the scour design flood. The minimum pile/shaft penetration depth considering scour is determined by the required pile/shaft penetration length for strength or service limit states, ignoring soil capacity within the total scour prism for the scour design flood at the bridge foundation. As indicated, the streambed material above the total scour line is assumed to be removed and does not contribute to the frictional capacity of the pile/shafts in the scour zone, which can result in extended pile/shaft penetration lengths. Note, scour is not necessarily the governing factor in foundation design.

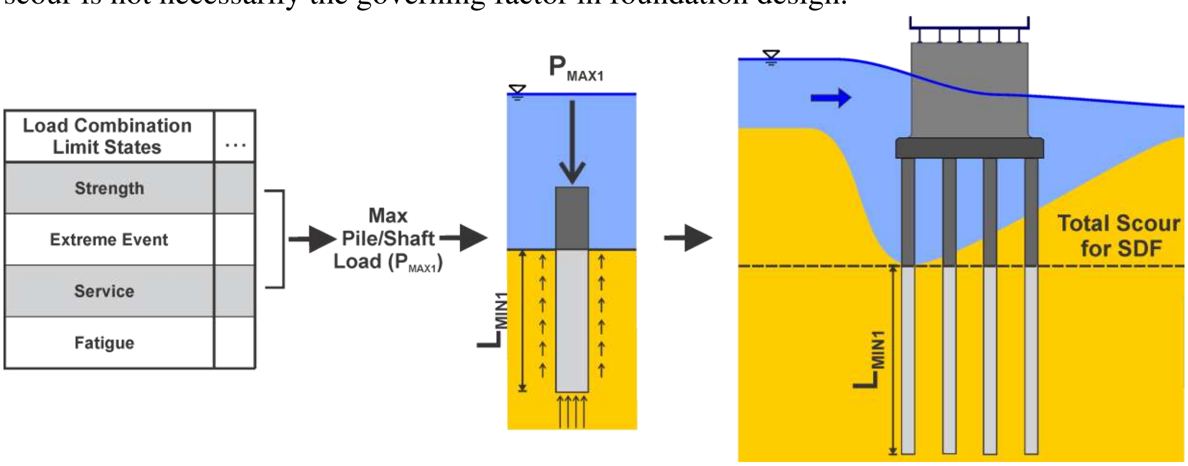

Figure 10. Pile/shaft penetration for strength or service limit states considering the scour design flood (SDF)

Refer to HEC-18 for detailed definitions of the individual scour components and conditions for foundation analysis and design, and for the various methods available to compute the scour magnitude for each component. Note, there is a pile drivability analysis that includes the total scour depth as one of the strength limit state checks. Figure 10 depicts a hypothetical example where the maximum pile or shaft loads for strength or service limit states are determined resulting in required pile or shaft penetration length, L_{MIN1}'.

Change in Foundations as a Result of the Scour Check Flood and Associated Limit State for Scour

AASHTO LRFD Section 3.7.5 requires:

"The consequences of changes in foundation conditions due to scour resulting from the scour check flood and from hurricanes shall be considered at the extreme event limit state".

Figure 11 shows the required pile/shaft penetration length, L_{MIN2}, for the extreme event limit state considering total scour for the scour check flood assuming this is the worst-case scour for this limit state. The pile/shaft penetration depth is determined by the required pile/shaft penetration length for extreme event limit state, ignoring soil capacity within the total scour prism for the scour check flood at the bridge foundation.

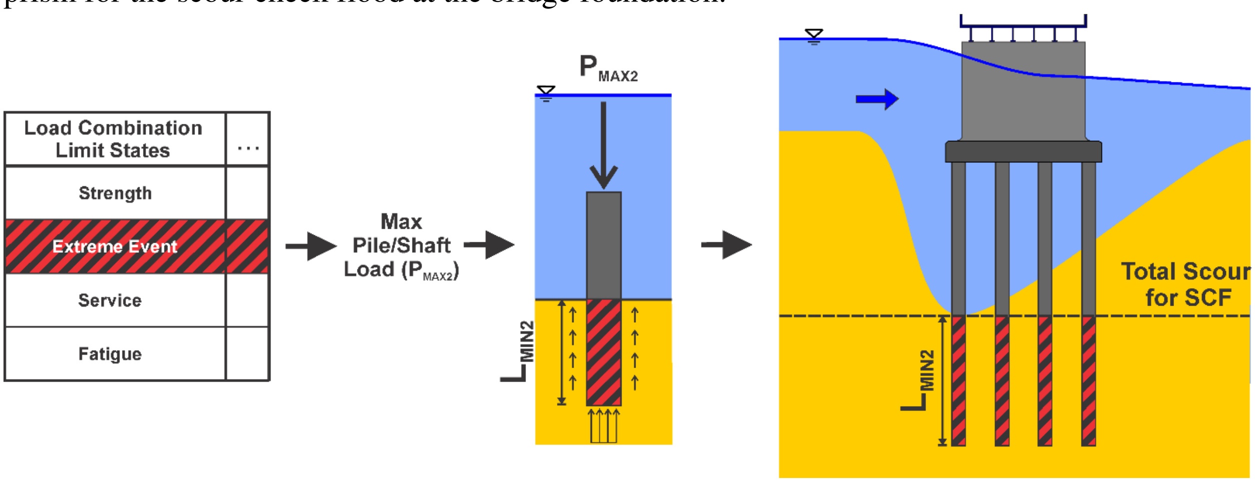

Figure 11. Pile/shaft penetration for extreme event limit state considering scour check flood (SCF)

Examples (for deep foundations only) of Governing Foundation Conditions due to Limit States for Scour

A deep foundation design is governed by considerations of the load combination at each limit state (strength, service, or extreme event limit state) and the corresponding scour depth (scour design flood or scour check flood).

Figure 12 and Figure 13 show two cases considering the hypothetical example from Figure 10 and 11 resulting pile/shaft penetration length L_{MIN1} or L_{MIN2} to determine a governing foundation condition due to limit states of scour (there may be other geotechnical considerations that may govern the final pile lengths). In Figure 10, the required pile/shaft penetration length (L_{MIN1}) satisfying strength and service limit states are longer than that for the extreme limit state (L_{MIN2}). The illustrations in the middle and on the right, show the scour estimate of the deep foundation during scour design flood and scour check flood as well as the required pile/shaft penetration length under strength or service and extreme event limit states, respectively. Figure 12 shows a case in which the pile/shaft penetration design is dominated by strength or service limit states and scour design flood. Figure 13 shows a scenario where the pile/shaft penetration design is governed by extreme event limit states and scour check flood. In practice, the required pile/shaft penetration lengths are site specific and could be different as illustrated.

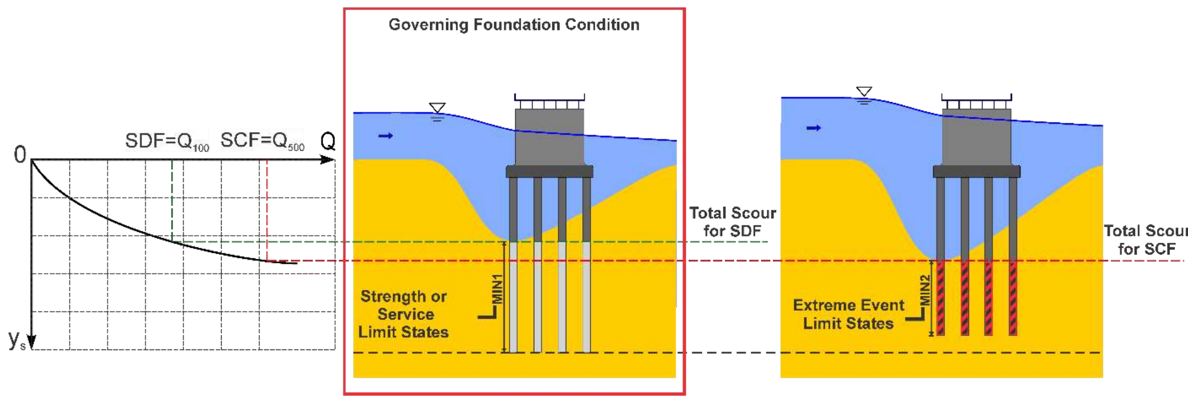

Figure 12. Pile/shaft penetration governed by strength or service limit states and scour design flood (SDF)

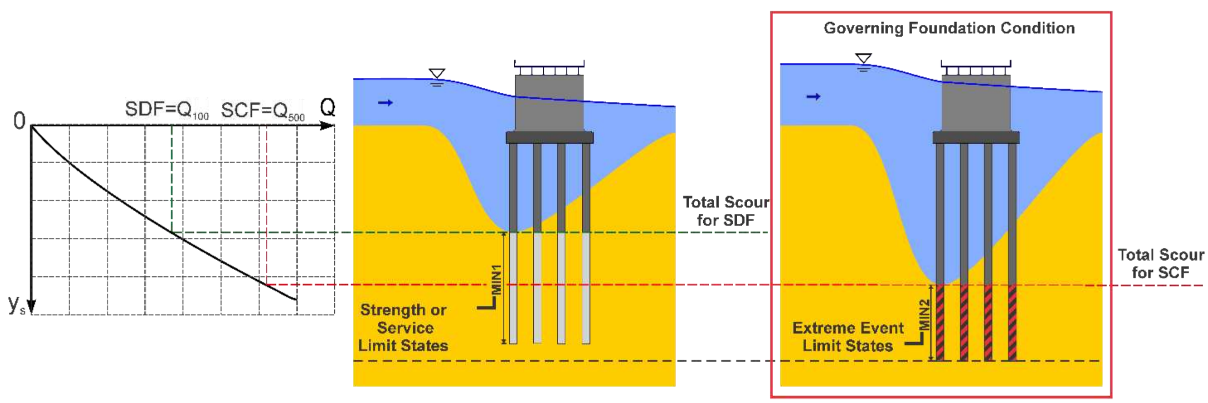

Figure 13. Pile/shaft penetration governed by extreme event limit states and scour check flood (SCF)

Comparing Figure 12 to Figure 13, although in both cases the worst-case scour for scour design flood and scour check flood coincide with Q100 and Q500, the difference between scour design flood and scour check flood is greater than the difference between the pile/shaft penetration length required for strength or service limit states and that for extreme event limit states, thus the pile/shaft penetration design is governed by extreme event limit states and scour check flood in Figure 13.

CONCLUSION

This paper provides the following summary for considering scour and AASHTO LRFD.

- The AASHTO document "Load and Resistance Factor Design Bridge Design Specifications" (LRFD) (AASHTO, 2017) forms the basis for nearly all recent highway bridge and structure design practices and standards. Under 23 CFR §625.4, the FHWA incorporates by reference the 2017 AASHTO LRFD as a design standard for bridges on the National Highway System.
- Bridge engineers factor the capacity (resistance) and demand (load) upon bridge superstructure, substructure and foundation elements for all limit states.
- AASHTO LRFD considers scour not as a force, but a change in foundation conditions. There are currently no statistically-based factors applied to scour.
- The scour design flood should be the flood that produces worst-case scour for all floods up to and including Q100 and tailwater variation. The scour check flood should be the flood that produces worst-case scour for all floods up to and including the Q500 and tailwater variation.
- This document clarifies the role of the scour design flood and scour check flood and how they relate to LRFD's Strength or Service limit states and Extreme Event limit states, respectively.
- A few hypothetical examples discuss how shallow and deep foundation design is governed by considerations of load combinations and the corresponding scour depth prescribed in various limit states.

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