Analysis of Scour Countermeasures from a Constructability Point of View on Bridges for the Puerto Rico Territory

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Abstract *— Bridge scour is considered the main reason for bridge failures due to the holes that can form and compromise the structure's stability. Federal regulations require all proposed bridges to be designed for scour resistance and all existing bridges to be evaluated for scour vulnerability. Scour evaluations are typically based on the 100-year recurrence of flood events. Bridges determined to be unstable due to observed scour or assessed the high potential for scour are deemed scour critical. Various equations to evaluate scour are available, however many of them are considered conservative and lead to overestimation of the scour depths. The passing of Hurricane Maria over Puerto Rico triggered catastrophic flooding in the magnitude of a 100-year recurrence flood and higher, hence replicating the conditions for which bridges are evaluated. To analyze evaluated against observed scour, a bridge within Maria's track was inspected and compared as a case study to its evaluation results. The outcome showed that the equations may have overestimated the scour depths, given no scour was found at the bridge; also implying that this overestimation could have an impact on the Puerto Rico Bridge Program, which currently has 495 scour critical bridges, all requiring flood monitoring and, consequently, greater resources.*

Key Terms *– Bridge Scour, Flood Monitoring, Hurricane Maria, Scour Critical Bridges.*

INTRODUCTION

Bridge scour is the removal of soil material around the abutments and/or piers of bridges, caused by the flowing water. Moreover, bridge scour is the most common cause of bridge failures [1]. Federal regulations require that all bridges over water have a documented evaluation of scour vulnerability and that bridges determined to be scour critical have a Plan of Action (POA) prepared to monitor them in accordance with said POA. Empirical methods have provided derived equations for the estimation of scour depth around bridge elements, which are often considered conservative and lead to overestimation of the depths [2].

On September 20, 2017, Hurricane Maria made landfall in Puerto Rico, moving across the island with widespread hurricane-force winds spread all over and extremely heavy rainfall that produced major to catastrophic flooding, especially across the northern part of Puerto Rico. Due to the devastation propagated by Hurricane Maria, many sources consider it the worst storm to hit Puerto Rico in the last century. Additionally, the magnitude of rain left by the storm is appreciably in the range of a 100-year recurrence event, resembling the design flood conditions used for bridge scour evaluations.

To analyze the contrast between estimated and observed scour depths, a bridge located in the northern part of Puerto Rico, within the storm trajectory, was selected and inspected for scour after the hurricane to compare the inspection findings with the scour evaluation results of the same bridge. This article analyzes the relationship among the scour variables and evaluates the impact of potentially overestimated results on the Puerto Rico Bridge Program.

OBJECTIVE

The main objective of this article is to determine the best countermeasures based on constructability based on the scour evaluation results of bridges and its observed scour after the strike of a 100-year storm event that had to have reproduced the conditions for which the bridge was evaluated. Furthermore, this article seeks to weigh the impact of scour overestimation on the evaluation of bridges in Puerto Rico for the implementation of countermeasures.

BRIDGE SCOUR

Bridge scour is the result of the erosive action of flowing water, which excavates and carries away the material from around the piers and/or abutments of bridges. Scour may occur in the bed and banks of streams, which are composed of different types of materials, each material having a scour rate; ergo, different materials scour at different rates. Generally, loose granular soils are rapidly eroded, whereas cohesive soils are more scour-resistant to flowing water. Maximum scour depth may occur in as short as hours in sand and gravel materials, while may take years in sandstone or limestone materials.

Bridge Scour Concepts

Bridge scour depends on whether it is occurring in clear-water conditions, where there is no transport of bed material from upstream of the bridge; or in live-bed conditions, where there is transport of bed material from upstream. Bridge total scour considers three primary components:

- Long-term Degradation
- Contraction Scour
- Local Scour

Degradation consists of elevation changes at the streambed due to natural or man-induced causes, which can affect the reach of the river on which the bridge is located. Long-term degradation occurs because of a deficit in sediment supply from upstream. The opposite process involving the deposition of material is called aggradation, although not considered a component of total scour.

Contraction scour occurs when the flow area of a stream is reduced, either by natural contraction of the channel or by the bridge elements projecting into the channel and blocking the flow area. A decrease in area results in an increase in velocity, thus also increasing the erosive forces in the contraction area and more removal of bed material. Generally, contraction scour involves the removal of material across all or most of the channel width. The process continues to lower the bed elevation until the velocity and shear stress decrease accordingly and relative equilibrium is reached.

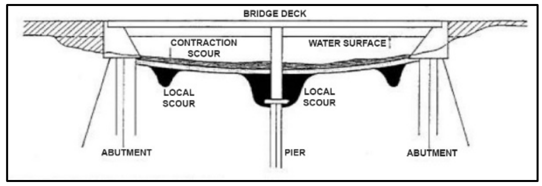

Figure 1
Bridge Elements with Components of Scour

Local scour consists of the removal of material from around substructure elements, including piers and abutments, due to the acceleration of flow and resulting vortices induced by the elements acting as obstructions. As the transport rate of sediment away from the base is greater than the transport rate of sediment into the base, a scour hole is formed. As the scour depth increases, the vortex strength reduces until equilibrium is reached. This occurs when bed material inflow and outflow are even, for the live-bed conditions; or when the vortex shear stress equals the sediment particle critical shear, for the clear-water conditions. Also, scour vortices can be either horseshoe vortexes, resulting from pileup of water upstream of the element, or wake vortex, resulting from the movement of water downstream. Regardless, both vortices remove the base material.

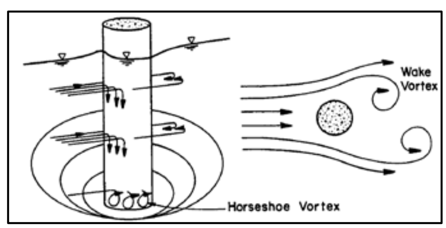

Figure 2
Horseshoe and Wake Vortices of Local Scour [1]

The three scour components previously described are added together to obtain the total estimated scour at a pier or abutment, assuming each component occurs independently of the other. In addition to these components, other types of processes should be assessed when evaluating scour, such as lateral stream migration, which consists of a naturally occurring displacement of the main channel of a stream. Lateral stream migration may affect the stability of piers in a floodplain, erode abutments and the approach roadway, and even affect the total scour by changing the flow angle of attack at the elements.

Bridge Countermeasures Design for Scour Resistance

The total cost of designing bridges less vulnerable to scour damage is small compared to the total cost of a bridge failure. Scour evaluations are concerned with the prediction of floods and with the complex physical processes between water and soil during the occurrence of such floods. During the preliminary design phase, hydrologic-hydraulic and site data collection assessments should be completed. The hydrologic section evaluates flood flows to assess flood hazards and meet applicable requirements, while the hydraulic section analyzes the stability of the stream and considers the effect of proposed channel or land use changes. Site data collection includes survey data upstream and downstream of the bridge, estimation of roughness coefficients, subsurface borings or sampling to classify soil, and consideration of previous evaluations or historical information. The recommended procedure for determining the total scour depth at bridge foundations is as follows:

1. Estimate the long-term degradation in the channel considering the bridge service life.
2. Determine the combination of conditions and flood events that might result in the maximum scour depth, and establish water surface profiles both upstream and downstream.
3. Determine the magnitude of contraction and local scour at the bridge elements, and modify the design according to the evaluation results.

With the estimated total scour depth, bridge foundations may be designed. Spread footings on soil shall be located with their bottom below the estimated scour depth, whereas on rock they shall be designed to maintain the integrity of the supporting rock. However, deep foundation footings shall be located with their top below the estimated scour depth. Since foundations are designed to resist bridge scour, it often results in deep foundations. In addition, foundations under design should consider scour countermeasures. Nevertheless, the design of bridge foundations may be modified where necessary, including relocating or redesigning bridge elements to avoid areas of deep scour or overlapping local scour holes in the first place. Bridge designs for scour resistance may also add river training structures, such as guide banks or dikes to provide smoother flow transitions or to control channel lateral movement.

Further, the American Association of State Highway and Transportation Official (AASHTO) design criteria addresses the problem of scour by requiring that the design of a bridge includes estimated scour depths at piers and abutments [3]. Also, federal regulations require that all existing bridges over water are evaluated for scour. Therefore, every bridge over water, whether existing or under design, must be assessed as to its vulnerability to scour.

100-year Flood & Overtopping Flood Scenarios

Both the Federal Highway Administration (FHWA) Evaluating Scour at Bridges (HEC-18) [1] and the AASHTO LRFD Bridge Design Specifications [3], require scour at bridge foundations to be assessed for two conditions:

- Scour Design Flood
- Scour Check Flood

Likewise, both publications require that the flow discharge to be selected as the basis for the scour design flood shall be the more severe of the 100-year event or from an overtopping flood of lesser recurrence interval. For the scour check flood, the stability of bridge foundations shall be investigated for scour conditions resulting from a designated flood storm not exceeding the 500-year event or from an overtopping flood of lesser recurrence interval. An overtopping flood occurring at a bridge results in a submerged bridge superstructure that can produce significant blockage or pressure because the depth available to convey flow through the opening under the bridge is reduced. The scour depth under pressure flow conditions can be significantly greater than that of non-pressure flow conditions, hence overtopping floods of lesser recurrence intervals than the 100-year or 500-year events are often selected as the scour design flood or scour check flood, respectively.

FEDERAL REGULATIONS & REQUIREMENTS

The National Bridge Inspection Standards (NBIS) [4], requires each state to inspect all bridges located on public roads within the state's boundaries. The Puerto Rico Highway and Transportation Authority (PRHTA) is the state agency in charge of compliance with the NBIS. FHWA employs the Metrics for the Oversight of the National Bridge Inspection Program [5] to determine compliance with said regulations, one of which is Metric #18: Inspection Procedures – Scour Critical Bridges. This metric requires that all bridges over water have a documented evaluation of scour vulnerability and those bridges determined to be scour critical have a Plan of Action (POA) prepared to monitor the bridge accordingly. A bridge is considered scour critical if the abutment and/or pier foundations are coded unstable due to either observed scour or an assessed high potential for scour.

Bridge Inspection and Coding of Scour

Under the NBIS, a bridge is defined as a structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between under copings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening [4].

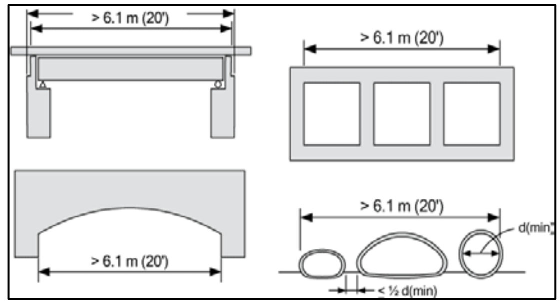

Figure 3
NBIS Bridge Configurations [4]

According to the AASHTO Manual for Bridge Evaluation (MBE) [6], the inspection of bridge substructures comprises the examination and recording of damage, deterioration, movement, and scour. The same also establishes the inspection procedures and policies for determining the condition of bridges. When assessing scour, the inspection findings and evaluated vulnerability are determined by the bridge rating and coding, as defined by FHWA's The Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges [7]. Codes are assigned to the bridge element and condition data. Among the items, the substructure is Item 60 and scour critical bridges is Item 113. Bridge scour focuses on these items because they describe the physical condition of piers, abutments, piles, and footings; and the current condition of the bridge regarding its vulnerability to scour, respectively. Item 113 consists of a rating factor scale from 9 to 0 besides the "tidal", "unknown foundation" and "not over waterway" ratings. As the ratings decrease, the scour condition worsens. 9 indicates the bridge foundations are well above flood elevations, 8 indicates foundations are stable, and 3 and below indicates the bridge is scour critical by either field review or calculated scour. Whenever a rating of 4 or below is assigned for this item, the rating for Item 60 should be revised to reflect the severity.

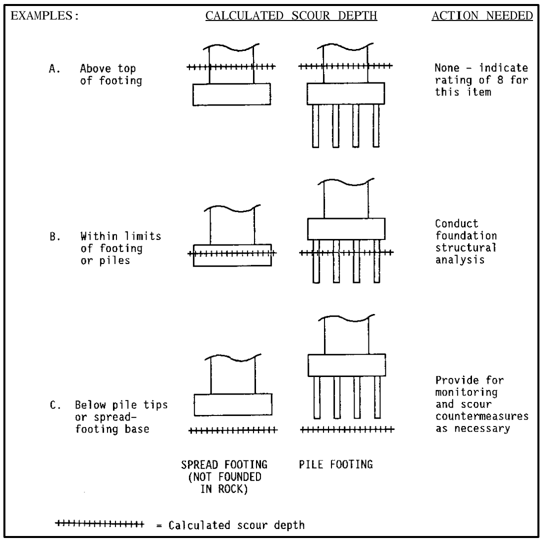

Figure 4
Item 113 – Scour Critical Bridges Rating [7]

Scour Evaluation of Bridges in Puerto Rico

As of 2018, the Puerto Rico National Bridge Inventory (NBI) comprises 2,306 bridges, with 1,602 of which, or approximately 70%, intersecting waterways, thereby requiring scour evaluation, in accordance with the NBIS. Bridge scour evaluation requirements are contained in the PRHTA Bridge Safety Inspection Manual [8]. The evaluation process is divided in the following four phases:

- Phase I – Data Collection and Qualitative Analysis
- Phase II – Hydrologic and Hydraulic Assessment for Scouring Analysis
- Phase III – Geotechnical and Structural Scour Assessment
- Phase IV – Plan of Action (POA)

During Phase I, the bridge is assessed for existing conditions, surroundings, topography, and cross sections. The evaluation could end if, for example, the bridge foundations are determined to be well above floodwater elevations and Item 113 is coded as 9. However, most bridges under study proceed to Phase II, where water surface elevations and scour depths are determined, at which point, there typically is enough data to rate the stability of the bridge. If determined stable, the scour evaluation ends, or otherwise proceeds to Phase IV, where a POA is prepared. Phase III is only performed when after completion of Phase II, there is insufficient data to define the stability; for example, when the calculated scour depth is within the limits of the footings or piles and thus requires further geotechnical and structural analyses.

Scour Critical Bridges in Puerto Rico

As a result of the scour evaluations, a total of 495 were determined to be scour critical, therefore have a POA prepared to monitor known and potential deficiencies. Flood monitoring is a component of utmost importance, as federal regulation requires that all scour critical bridges are monitored according to the POA. Each bridge has assigned thresholds that could be either rainfall events, which are triggered by a minimum precipitation value forecasted at the watershed; or stage events, which are triggered by a referenced water surface elevation occurring at the bridge site.

A well-implemented flood monitoring program requires real-time monitoring solutions during and after flood events, capable of constantly monitoring potential problem areas and providing alerts before scour becomes dangerous to determine which action should be undertaken. PRHTA will use a web-based system that allows it to predict, identify, monitor, manage, record, and prepare for potentially scour-causing events. The system will collect real-time data from weather-related sources such as the National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA), and United States Geological Survey (USGS), among others; compare it against the POA thresholds and alert key personnel via electronic medium to enact monitoring upon trigger events being highly probable to be met, met or exceeded. The program will cost a significant amount of resources to the PRHTA, given each bridge requires individual monitoring and management, hence requiring system cost, inspection personnel, and, in case of future outcomes, installing measuring devices on bridges to record conditions during events and indicate an inspection when warranted.

EVALUATING SCOUR

The most common cause of bridge failures is from floods scouring bed material from around bed foundations [1]. Evaluating bridge scour is complex due to the nature of the acting variables. The need to minimize bridge scour has resulted in a number of publications seeking to provide guidance in the evaluation of scour, one of which is the FHWA Evaluating Scour at Bridges (HEC-18) [1], whose guidance on the development and implementation of procedures for evaluating bridge scour are in accordance with the requirements of NBIS. Scour evaluation procedures are in constant update, as research and technology advances, including policy changes, countermeasure design considerations, alternative design approaches, and new guidance.

Introduction of Countermeasures and Constructability

Bridge scour is a major problem faced by the transportation industry worldwide. Scour is the result of water flow that causes erosion of the soil around the bridge piers, leading to a loss of soil and bedrock material. This loss of material can ultimately undermine the foundation of the bridge piers, leading to structural failure. As a result, it is critical to understand the causes of scour and implement effective countermeasures to prevent bridge failures. One such countermeasure is the use of HEC-23 countermeasures.

HEC-23 Countermeasures: HEC-23, or Hydraulic Engineering Circular No. 23, is a document that provides guidance on the design and construction of countermeasures for bridge scour. The document outlines a range of countermeasures that can be used to reduce the impact of scour on bridge piers. These countermeasures can be classified into three categories: structural, non-structural, and monitoring.

Structural Countermeasures: Structural countermeasures are physical modifications made to the bridge piers to reduce the impact of scour. These modifications include the use of piles, collars, and footing extensions. Piles are installed around the bridge pier to provide additional support and increase the load capacity of the pier. Collars are installed around the pier to prevent the scour from reaching the foundation. Footing extensions are added to the base of the pier to increase the width of the foundation and reduce the impact of scour.

Non-Structural Countermeasures: Non-structural countermeasures are measures that do not involve physical modifications to the bridge piers. These measures include the use of riprap, geotextile, and vegetation. Riprap is a layer of rocks placed around the base of the pier to prevent erosion. Geotextile is a fabric that is placed around the base of the pier to prevent soil erosion. Vegetation is planted around the bridge pier to stabilize the soil and reduce the impact of scour.

Monitoring Countermeasures: Monitoring countermeasures are measures that are used to monitor the bridge pier and surrounding area for signs of scour. These measures include the use of scour sensors, scour cameras, and scour alarms. Scour sensors are installed around the pier to monitor changes in the soil and bedrock material. Scour cameras are used to monitor the bridge pier and surrounding area for signs of scour. Scour alarms are used to alert personnel when scour is detected.

Constructability: Constructability is the ability to construct a countermeasure that meets the requirements of the design. The HEC-23 guidelines provide detailed specifications for the design and construction of countermeasures. The guidelines include information on the materials, installation procedures, and quality control measures required to ensure that the countermeasures are constructed correctly. Constructability is critical to the success of the countermeasure. If the countermeasure is not constructed correctly, it may not provide the required level of protection against scour.

Conclusion: HEC-23 countermeasures are an effective way to prevent bridge failures caused by scour. The countermeasures include structural, non-structural, and monitoring measures that can be used to reduce the impact of scour on bridge piers. Constructability is critical to the success of the countermeasure. The HEC-23 guidelines provide detailed specifications for the design and construction of countermeasures to ensure that they are constructed correctly. By following these guidelines, it is possible to construct effective countermeasures that provide long-term protection against scour.

Countermeasures Comparison and Recommendations

When comparing the constructability of various methods for bridge abutment protection, such as riprap, semi-grouted riprap, grouted riprap, grouted mats, and sheet piling, several factors should be considered. Here's a comparison of these methods based on their constructability:

1. Riprap: Riprap involves placing large, durable stones or concrete blocks to protect bridge abutments from erosion. Constructability is relatively straightforward as it mainly involves placing the stones in a controlled manner. However, careful attention is required to ensure proper compaction and stability of the riprap layer.
2. Semi-Grouted Riprap: Semi-grouted riprap is similar to riprap, but with the addition of grout or mortar applied between the stones to enhance stability. Constructing semi-grouted riprap involves placing the stones and then filling the voids with grout. This process requires coordination to ensure proper grout flow, adequate compaction, and uniform coverage.
3. Grouted Riprap: Grouted riprap involves the use of small stones or aggregate mixed with cementitious grout to create a solid, durable layer. Constructing grouted riprap requires carefully proportioning the grout mix, placing it evenly over the stones, and compacting the layer. It may involve specialized equipment or techniques to ensure proper grout placement.
4. Grouted Mats: Grouted mats consist of interconnected concrete blocks or mats that are grouted together to form a stable surface. The constructability of grouted mats involves placing the precast mats in position and then filling the voids with grout. This method requires accurate alignment and grout flow control for proper interlocking and consolidation.
5. Sheet Piling: Sheet piling involves driving interlocking steel or concrete sheets into the ground to create a barrier against soil or water. Constructing sheet piling requires specialized equipment, such as pile drivers, to install the sheets. The process involves driving the sheets into the ground to the desired depth, ensuring proper alignment and interlock between adjacent sheets.

In terms of constructability, riprap is generally the simplest method, as it primarily involves placing stones or blocks without the need for specialized equipment. Semi-grouted riprap and grouted riprap require additional steps for grout placement, but they are still relatively straightforward. Grouted mats and sheet piling involve more complex processes, including alignment, interlocking, and driving operations, requiring specialized equipment and skilled labor.

Overall, the choice of abutment protection method should consider not only constructability but also factors such as site conditions, erosion potential, environmental considerations, and design requirements. Consulting with engineers and considering the specific project constraints will help determine the most suitable method for bridge abutment protection.

Here's a matrix comparing the constructability of different methods for bridge abutment protection.

Method	Constructability
Riprap	Simple
Semi-Grouted Riprap	Moderate
Grouted Riprap	Moderate
Grouted Mats	Complex
Sheet Piling	Complex

Figure 5
Constructability Different Methods and Levels

In this matrix, constructability is categorized into three levels: Simple, Moderate, and Complex.

- Simple: The riprap method is considered simple as it involves relatively straightforward placement of stones or blocks.
- Moderate: Semi-grouted riprap and grouted riprap fall into the moderate category due to the additional steps involved in grout placement.
- Complex: Grouted mats and sheet piling are considered complex due to the involvement of specialized equipment, alignment, interlocking, and driving operations.

It's important to note that this matrix is based on a general assessment of constructability and can vary depending on project-specific conditions, site constraints, and available resources.

It's important to note that the advantages and disadvantages mentioned above are general in nature and can vary depending on site-specific conditions, design considerations, and project requirements. Consulting with engineers and conducting a detailed assessment of the project can help determine the most suitable method for bridge abutment protection.

These recommendations provide a general guideline for the constructability of each method. However, it's important to consult with engineers, refers to project-specific requirements, and follow manufacturer guidelines for a detailed and accurate construction process.

The selection of the appropriate method for bridge abutment protection depends on several factors, including site conditions, hydraulic characteristics, design requirements, and project constraints. Here are some general guidelines on when to use each method:

1. Riprap:
   - Riprap is suitable for moderate flow conditions where erosion protection is needed.
   - It is commonly used in natural watercourses, streams, or rivers with stable banks.
   - Riprap is preferred when a more natural appearance is desired, or when budget constraints are a consideration.
   - It is effective for abutments that are not subjected to high-velocity flows or significant scour potential.
2. Semi-Grouted Riprap:
   - Semi-grouted riprap is recommended when additional stability is required compared to traditional riprap.
   - It is suitable for areas with moderate flow velocities and potential for erosion.
   - Semi-grouted riprap provides better resistance against stone displacement and enhances erosion control compared to riprap alone.
   - It is often used when a balance between performance, aesthetics, and cost is desired.
3. Grouted Riprap:
   - Grouted riprap is suitable for areas with higher flow velocities and increased scour potential.
   - It is commonly used in areas with significant hydraulic forces, such as bridge piers or abutments near high-velocity channels.
   - Grouted riprap provides superior erosion protection and stability compared to traditional riprap.
   - It is recommended when a higher level of performance and durability is required, even at a higher initial cost.
4. Grouted Mats:
   - Grouted mats are preferred when a more uniform and interlocked surface is needed for erosion control.
   - They are suitable for areas with moderate to high flow velocities, steep slopes, or complex geometries.
   - Grouted mats provide excellent resistance against scour and can accommodate irregular subgrade conditions.
   - They are often used when a balance between hydraulic performance, aesthetics, and ease of installation is desired.

5. Sheet Piling:
    - Sheet piling is recommended when structural integrity and water tightness are critical considerations.
    - It is suitable for areas with high-velocity flows, significant scour potential, or when soil retention is required.
    - Sheet piling provides a rigid barrier against water or soil infiltration and is commonly used in marine or coastal environments.
    - It is preferred when long-term durability, stability, and structural strength are key factors.

It's important to note that these guidelines are general in nature, and the selection of the appropriate method should be based on a thorough engineering analysis, site-specific conditions, and project requirements. Consulting with experienced engineers and considering the input of relevant stakeholders will help determine the most suitable method for bridge abutment protection in a given scenario.

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