STAY CABLE REPLACEMENT OF THE HALE BOGGS BRIDGE

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Abstract

This paper summarizes an evaluation and cable replacement program to address deficiencies reported for the stay cables of the Hale Boggs Bridge, in Luling, Louisiana. Recent inspection uncovered a variety of critical damages to the protective sheathing and exposure of the stay cables main tension elements. The Louisiana Department of Transportation and Development decided to replace all stay cables. The construction project is ongoing.

Complete replacement of all 72 cables of this bridge is the first occasion attempted in North America. The unique construction sequence designed for this project addresses the traffic control limitations and uncertain condition of the existing cables. The replacement cables are expected to have a minimum of 75-year service life, and to allow individual strand installation, tensioning, inspection and replacement.

Introduction

The Hale Boggs Bridge, also known as the Luling Bridge, in Luling, Louisiana opened to traffic in 1983. At the time, it was the first cable-stayed bridge over the Mississippi River and had several unique features, including a weathering steel superstructure, distinguishing it from all other cable stayed bridges in North America.

After 25 years in service, the Luling Bridge undergoes a complete replacement of its stay-cable system. The potential for stay cable durability performance problems arose during the construction of this bridge. The most significant were those associated with damage to the protective high-density polyethylene (PE) sheathing of the main tension elements of the prefabricated stay cables. Repairs were performed on these damages. Later, cracks developed in these PE weld repairs. In 1990, all cables were wrapped with UV protection tape after existing splits and cracks were filled with epoxy. The first evidence of damage to the cable wrapping tape was detected in 1995. Subsequent inspections showed the existence of exposed and rusted stay cable wires, unplugged grout ports, and extensive water leakage, cementitious grout efflorescence, and rust at the deck level anchorage sockets. In 2002, the Louisiana Department of Transportation and Development (LADOTD) awarded a contract for comprehensive evaluation of the stay cable array.

The overall evaluation program was divided into phases. Phase I of the evaluation program had the objectives of assessing the extent of reported problems and ascertaining the overall integrity of the stay cable array. Phase II of the investigation completed in 2007 consisted of hands-on inspection of the suspect locations and critical elements including stay cables, anchorages and their vicinity, condition rating of the cables, and life-cycle-cost analysis for selection of the repair strategy. Design of repairs constituted Phase III.

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The inspections of the cables found an increasing rate of degradation of the protective sheathing and exposure of the main tension elements of the stay cables, and a timely action was necessary [Mehrabi 2006, Mehrabi and Ligozio 2007]. Details of the entire investigation can be found in reports submitted to LADOTD [Telang et al. 2004, Mehrabi et al. 2006, Mehrabi 2007].

The Luling Bridge is a critical regional link and a hurricane evacuation route, and traffic interruption had to be designed to be as unobtrusive to the public and commerce as practical. LADOTD asked for the design to include a complete, cost effective cable replacement scheme requiring minimal engineering on contractor's part. The effect of live load, wind load and construction load had to be taken in to account carefully.

The construction project for the cable replacement was awarded in 2009 and the project is progressing.

Bridge Description

The Luling Bridge is a twin-pylon, cable-stayed bridge with a main span of 1222 ft and two stayed side spans of 495 ft and 508 ft. The bridge crosses the Mississippi river at Luling, Louisiana, and carries four lanes of Interstate-310 traffic. Figure 1 shows an elevation of the bridge. The pylons are a modified A-shape, and the deck cross section is composed of twin 14-ft deep steel trapezoidal box girders with a total width of 82.33 ft., all made of weathering steel.

The stay cables are arranged in two planes and are grouped by pairs or fours. There are 24 such cable groupings and a total of 72 cables. Original stay cables that are being replaced are composed of parallel 1/4 in.-diameter wire bundles consisting of 103, 211, 271, or 307 wires. The wire bundle is encased in a black polyethylene (PE) pipe, and the space between is grouted. An Ultraviolet (UV) protection tape is helically wound around the PE pipe with 50 percent overlap. Figures 2 and 3 show a dissection of an existing cable and an anchorage socket, respectively. The replacement cables will have parallel individually sheathed strands encased in PE sheathing pipe without grout infill.

FIGURE 1- THE LULING BRIDGE

FIGURE 2- Dissection of existing cable

FIGURE 3- an existing anchorage socket

Summary Inspection Findings

The scope of the cable inspection included visual examination of the bearing plates, shim plates, and exterior and interior of the anchorage sockets in lower and upper anchorage zones, visual inspection of the anchorage boxes behind the bearing plates, and hands-on inspection and non-destructive testing of the cables free length. Damages observed in the anchorage zones were in the form of corrosion of sockets and button heads, missing or broken seals at the joint between the transition pipe and PE pipe, and open grout ports. Inspection of the cables free length (see Figures 4 and 5) discovered a variety of damages and anomalies including longitudinal and transverse split of the PE pipe, exposure and degradation/corrosion of grout filler and steel wires (Figures 6 and 7), bulges and holes in the PE pipe, tape damages, and grout voids and delamination. Most mechanisms causing these damages still existed and were active. It was verified later through subsequent inspections that the initiation and progression of damages will continue in time with an increasing rate. With the exception of locations where the steel wires were visible through splits, the inspections focused on damages related to the protective elements where a high probability for corrosion of steel wires exists at damaged locations and beyond.

FIGURE 4- Inspection along cable free length

FIGURE 5- NDT using Thermography

FIGURE 6- CORROSION OF WIRES AT PE SPLIT

FIGURE 7- PE JOINT SEPARATION

Stay Cable Condition Rating

Three levels of severity were established for condition rating of stay cables; Level 1, satisfactory, Level 2, poor, and Level 3, critical. Table 1 summarizes description of these severity levels.

TABLE 1- DAMAGE SEVERITY LEVELS

Severity Level	Status	Description
1	Satisfactory	Minor deterioration and anomalies with little or no likely impact on protection.
2	Poor	Deterioration of protective elements and potential for further degradation. Cables with this level of damages need to be routinely monitored and corrective action planned.
3	Critical	Deterioration or potential for deterioration of steel wires. Action (repair) is necessary. Cables with this level of damages shall be closely monitored until repairs are applied.

These levels pertain to the barrier elements, namely the UV protection tape, PE pipe, and cement grout, and their ability to protect the main tension element, and the condition of the steel wires based on the condition within the anchorage sockets, and the need for action. All cables contained damage and anomalies with severity level of 2 and higher. Thirty-nine out of 72 cables were rated as critical and the remaining cables as poor.

Life Cycle Cost Analysis

Prior to attempting to develop a detailed scope for repairs, it was necessary to investigate available repair concepts and methods, select repair/replacement strategies, and develop an understanding of associated costs. A life cycle cost analysis (LCCA) was performed to assist LADOTD in their decision making for bridge maintenance and management. A common problem faced in structural maintenance is determining whether an existing system or component should receive major repairs to extend its useful life, or whether it should be replaced with a new one. The analysis followed a general LCCA procedure related to bridge structures [Hawk 2003].

Bridge and its elements - This study focused on stay cables and their appurtenant structures, assuming that remaining portions of the bridge will be maintained operational within the anticipated service life of the bridge.

Planning horizon, analysis scenario, and base case - The Luling Bridge was opened to traffic in 1983. Assuming an overall expected service life of 100 years for the bridge, the remaining expected service life is assumed to be 75 years.

Because the region where the bridge is located is prone to strong storms and hurricanes, and because the bridge is an essential element in the regional storm evacuation system, the safety and functional reliability and integrity of the bridge are paramount. Therefore, storm related (and other) vulnerability costs for various repair/replacement strategies used in the LCCA can be definitive and should be considered in the analysis. In 2004, the ADT was 33,762. For the purpose of this analysis, an average ADT of 35,000 was assumed for the time of construction. Based on comparable projects, the real discount rate (inflation incorporated) was assumed 3.8%.

Alternative Strategies –Based on the current condition of the stay cables and available methods for repair or replacement, following strategies were selected:

1. *Base case* - Minimal repair only, to protect exposed wires along free length of the cables. Includes monitoring and inspection regimen prescribed for Level 3 (detailed inspection once a year and cable force measurement every four years) and Level 2 damages (detailed inspection once every two years and cable force measurement every four years); represents the highest potential for cable degradation and failure, and the highest vulnerability to storm related damage.
2. *Repair all* - Repair free length of all cables. Includes monitoring and inspection regimen prescribed for Level 2 damages. Repairs are assumed to be repeated for 75 percent of the presently-required extent every 20 years, due to limited durability of repairs and potential for new damages. This strategy represents moderate potential for cable failure and vulnerability to storm related damage. Level 3 damages in the anchorage zones are not addressed and remain critical but deterioration rate should be slowed by implementing drainage and water barriers.
3. *Repair-Replace 1* - Replace 20 cables, repair remaining cables. Includes monitoring and inspection regimen prescribed for Level 2 damages for the repaired population of the cables. Repairs are assumed to be repeated at a rate described in Item 2. Low to moderate potential for cable failure and low to moderate vulnerability to storm related damage are anticipated.
4. *Repair-Replace 2* - Replace all 39 cables with Severity Level 3 and repair all cables with Severity Level 2. Includes monitoring and inspection regimen prescribed for Level 2 damages for the repaired population of the cables. Repairs are assumed to be repeated at a rate described in Item 2. Low potential for cable failure and vulnerability to storm related damage is expected.
5. *Replace all* - Replace all cables. No potential for cable failure and no vulnerability to storm related damage (relative to other strategies). Visual inspection is prescribed only once every 20 years, force measurement every 5 years.

Deterioration models - Various methods and guidelines for estimating the remaining strength or remaining service life of cable elements are available, with most developed for main cables in suspension bridges [Mayrbaurl and Camo, 2004]. These methods require information about the condition of steel wires, which is usually collected through inspection of wires and statistical sampling and testing of the steel wires. In the absence of such information, a simple state-space deterioration model was adopted based on the observations and engineering judgment. Based on guidance on corrosion rate of steel in various environments and a generalized analysis, and as long as more rapid corrosion phenomena are not acting, it was assumed that wires exposed (or potentially exposed) to moisture in stay cables can transition from critical to failure within 20 years. The same transition period was assumed also between poor to critical states.

Cost estimate - The costs associated with the various options are divided into three groups; initial, distributed/periodic, and vulnerability costs. The initial costs are related to installation of monitoring system, repair, or replacement of cables that will occur one year after project begins. Distributed/periodic costs are related to inspection, cable force measurement, maintenance of the monitoring system, and future periodic repairs. Vulnerability costs are related to the potential cost of repair/replacement of cables and structural repair to the superstructure due to loss of load carrying capacity of the cables from ongoing corrosion-fatigue and extraordinary storm events.

Costs in each category have two elements, agency cost and users' cost. Agency cost refers to the actual cost of implementing an event such as contract cost for repair or inspection. Users' cost refers to cost borne by users of the bridge, i.e., drivers and cars/trucks, for delays or detours related to activities on the bridge. Cost to businesses around the bridge was ignored here.

Costs addressed in this investigation are direct (cable repair, replacement, inspection, etc.) and indirect (structural damage to superstructure from cable failure) costs related only to actions undertaken for cables. Costs associated with various activities were estimated based on previous experiences and relevant estimates obtained from repair contractors. Figure 8 shows a comparison among present value of costs associated with 5 different strategies when only initial agency and users' costs are considered. Clearly, cost of "doing nothing" is negligible compared to others, replacing all cables is the costliest strategy. However, as shown in Figure 9, when distributed, periodic, and vulnerability costs are added, the Base Case is almost twice as costly as the other strategies, and cost of the other four are comparable. Considering the LCCA results along with uncertainties in the level of potential damages, the effect of costs not included in the analysis, and more importantly, concerns related to highway network system and public safety, LADOTD decided to replace all cables.

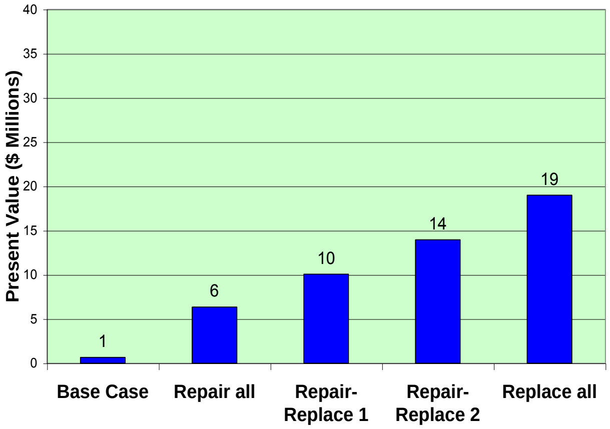

FIGURE 8- COMPARING INITIAL COSTS

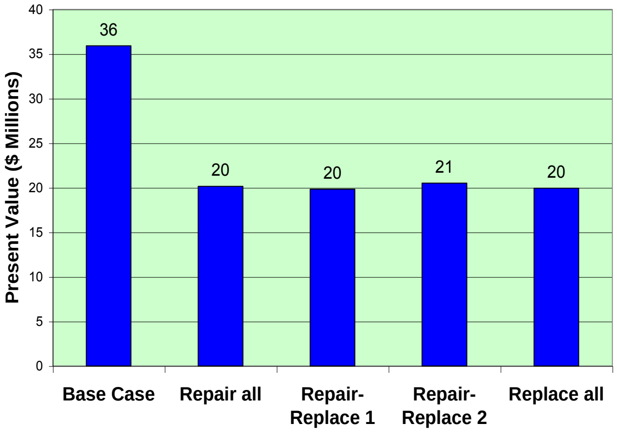

FIGURE 9- COMPARING ALL COSTS

Cable Replacement Design and Construction

The cable replacement design carried three main objectives:

- Development of a complete, cost effective cable replacement scheme
- Minimizing impact on traffic and Maintenance of Traffic (MOT) costs during stay replacement by maximizing the number of traffic lanes maintained on the bridge at all times.
- Analyzing the structure for live load, wind load and construction load effects for all stages.

Assessing current condition – Cable replacement shall restore load carrying capacity of the bridge to its as-designed state without detriment to the bridge structure. Hence, a review of the design and as-built drawings, and the current LADOTD and AASHTO Standards were performed to establish both the as-designed cable loads and target capacity of new cables. Additionally, the superstructure was inspected and tension forces in the cables were measured to determine the current state of structure, and for use in design process.

New cable design – New cables were designed according to the Post-tensioning Institute's (PTI) Recommendations for Stay Cable Design, Testing and Installation, 2007. The new parallel strand cables consist of seven-wire prestressing strands, individually greased/waxed and sheathed with PE, bundled and encased in a PE sheathing pipe. This system has dominated the medium span cable-stayed bridges in the last two decades. Individually sheathed strands, and the use of wedge retention system have allowed individual strand installation, tensioning, inspection and replacement. Parallel strand system however presented challenges due to the larger anchorage sockets and greater cable diameters when compared to parallel wire system of the existing cables. These required some modifications to the bridge structure in the anchorage zones, and altered the effect of wind loading and dynamic characteristics of the stays.

With an equivalent stiffness design, the existing cables are being replaced by 23, 45, 57 and 67- 0.62-in nominal diameter strand cables. Twenty four additional strands will be installed in various cables as reference strands for inspection purposes. Figures 10 and 11 show a lower anchor and strand bundle in a new cable being installed. Due to susceptibility to wind-induced vibrations, the new cables will be installed with external helical ribs, dampers, and spacers.

FIGURE 10- A NEW CABLE ANCHORAGE

FIGURE 11- STRAND BUNDLE IN A NEW CABLE

Temporary cables - The lulling Bridge, like many modern cable-stayed bridges, is designed to withstand loss of one cable, assuming that other cables are in good condition. This would have allowed replacement of cables without the use of temporary cables. However, inspection has shown that at the best, condition of the cables is uncertain. Also, spacing of the cable groups in this bridge is relatively large, and any unanticipated failure may have catastrophic consequence. Because of these, and LADOTD's determination to allow traffic during construction, the use of temporary cables to take the loading off the existing cables was inevitable. Support for temporary cables are provided by spreader beams bearing against the cross girders at the deck level (Figure 12), and a saddle fixture to be installed on top of the towers (Figure 13).

FIGURE 12- TEMPORARY CABLE SUPPORT AT DECK

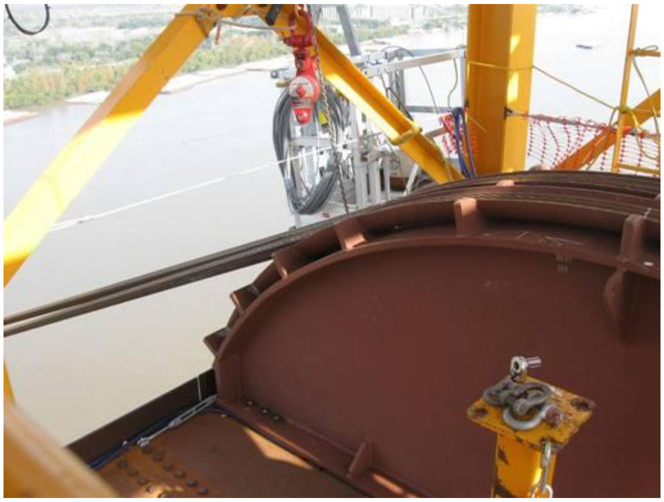

FIGURE 13- TEMPORARY CABLE SUPPORT AT TOWER

Construction sequence – A construction sequence was developed to serve the main objectives of the project. The construction is limited to one side of the bridge at a time, allowing a normal traffic on the other side. The use of temporary cables minimizes stress variation in the structure during cable replacement. A "highline" cable system was originally proposed in the design to facilitate lifting and installation of cables to minimize the use of heavy equipment, therefore, reducing the need for construction space on the deck with minimal interruption to traffic. Most of the operation is conveniently concentrated at the deck level where the temporary cable anchors and the live (stressing) end of existing and new cable are positioned.

There are four construction phases, each for replacing 18 cables in one quarter of the bridge. The sequence in each phase starts with placement of a temporary saddle support on top of one tower leg, followed by installation of the lifting system. The spreader beams are then installed at the first and last cross-girders (I and VI) in the first bridge quarter, and temporary cables are placed and stressed from both ends at the deck level against spreader beams. In the next stage, one of the existing stays in each group (I and VI) is destressed using a single large ram, lowered using lifting system and removed, any modification needed for the anchorage areas implemented, and new cables are installed and stressed, one on each side of the tower. This scheme continues until all old stays are removed and new cables are installed and stressed in one group. Then, temporary stays are destressed, supported by the highline and repositioned to the next panel point. The procedure is repeated until all cables in one quarter of the bridge are replaced. Figure 14 shows a rendering of construction process during lifting of a new cable. In lieu of the "highline" system proposed by design and shown in this figure, the construction contractor has utilized an alternative hoist and crane lifting system.

Modeling, structural analysis and design – The selected new stay cable installation process induces force variations and deflections at the cross girder ends and the tower. Design of the new and temporary cables and development of construction sequence was affected to varying degrees by this process. Additionally, there is variation in the wind load effects due to the larger diameter of the new cables compared to the existing cables, the effects of live load, and loads from construction equipment and activities. Structural analysis supported the design effort by determining the effect of these variations both locally and globally.

A 3-D finite element (FE) model of the bridge superstructure was used to generate member action envelopes under various load combinations. Figure 15 shows a view of the bridge FE model. The analysis led to limitation of construction loading, and determination of cable stressing patterns to keep the structural responses within allowable structural performance thresholds. It also necessitated design of strengthening at some locations on the structure, such as under the saddle support in the towers, to avoid overstressing. FE model was also used to determine geometry control variables at various construction stages.

Design checks, and design of structural modifications and new elements were carried out using working stress method consistent with the original bridge design. A CAD model of the bridge was used to determine the geometric conflicts during construction, especially in relation with the position of temporary cables with respect to the group configuration of existing cables.

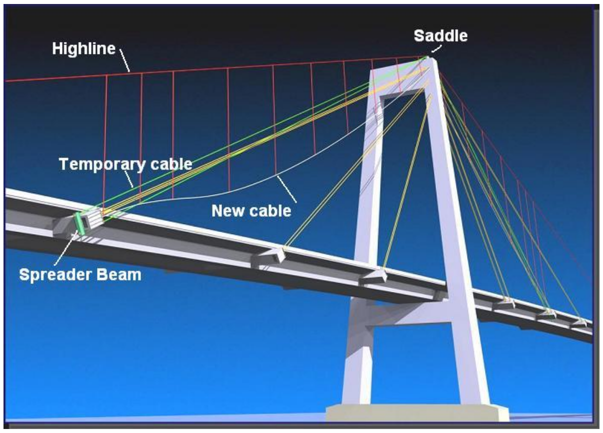

FIGURE 14- SCHEMATIC CONSTRUCTION SEQUENCE

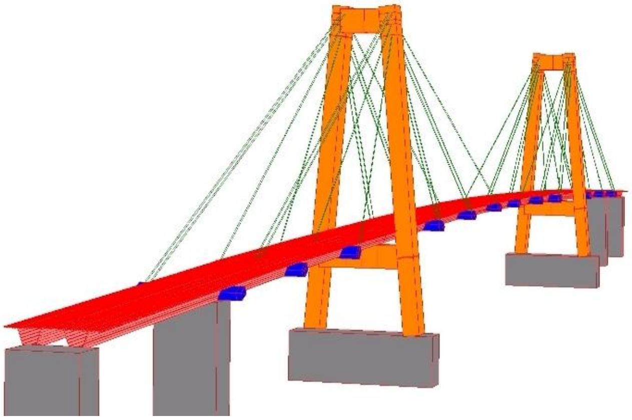

FIGURE 15- FE MODEL OF THE BRIDGE

Maintenance of traffic (MOT) – Maintenance of Traffic (MOT) was an essential part of the proposed construction. The bridge is a critical regional link and traffic interruptions need to be as unobtrusive to the public and commerce as is practical. More importantly, the Luling Bridge is located in a hurricane prone region and is a part of evacuation route. Limitations that impact evacuation capacity had to be taken into account.

Practical traffic control sequences were identified and their impact on traffic was determined and communicated with LADOTD. These sequences had to also accommodate for the construction activities. Among those considered, two sequences; for Peak and Off-Peak Traffic Operations, were identified that would serve both purposes; minimizing impact on traffic and allowing cost-effective construction operation.

The Luling Bridge carries two lanes of traffic on each bound with a 10-ft right shoulder and 4.25-ft left shoulder on each bound. It was determined that most of the cable replacement operation can be carried out within a 12.25-ft space separated on the right side of the deck by concrete barriers (2 ft wider than the existing shoulder). During Peak Traffic, this pattern allows two lanes of traffic, 11-ft each, on the construction side of the bridge without shoulders, and normal traffic pattern on the other side. Figure 16 shows Peak Traffic Operation sequence for the construction side of the bridge. When necessary, during Off-Peak Traffic in the evenings or weekends, the construction space is widened from 12.25 to 23.25 ft using plastic cones allowing operation of heavier and wider equipment and other activities. This pattern allows one 11-ft lane of traffic lane without shoulder on the construction side while traffic on the other side of the bridge flows normally. These patterns have been working smoothly without significant interruptions to traffic since the start of the construction activities on the bridge.

Few instances of short-term bridge closures were anticipated in design. The contractor has used these occasions for lifting heavy and large equipment and framework to the top of the tower. With the construction sequence and MOT design developed for this project, there has been no restriction to the river main navigation channel.

FIGURE 16- MAINTENANCE OF TRAFFIC FOR CONSTRUCTION SIDE FOR PEAK TRAFFIC OPERATION SEQUENCE

Summary

Inspections of Luling Bridge found a variety of critical damages to the protective sheathing and exposure of the main tension elements of the stay cables, with an increasing rate of degradation. Prior to attempting repairs, a life-cycle-cost analysis (LCCA) was performed to assist the decision making for maintenance. Considering the LCCA results along with uncertainties in the level of potential damages, the effect of costs not included in the analysis, and more importantly, concerns related to highway network system and public safety, LADOTD decided to replace all cables.

The cable replacement design, the first occasion of its kind in North America, is heavily influenced by the geometric restrictions and cost. A cost-effective construction sequence was developed that minimizes the impact on traffic. The construction is limited to one side of the bridge at a time, allowing two-lane traffic during peak hours on each bound. The new parallel-strand cable system allows individual strand installation, tensioning, inspection and replacement. The use of temporary cables minimizes stress variation in the structure during cable replacement. Most of the operation is conveniently concentrated at the deck level where the temporary cable anchors and the live (stressing) end of existing cables and new cable are positioned.

The construction project for replacement of the stay cables is ongoing and to date, six out of seventy two cables of the bridge have been replaced.

Acknowledgements

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